IFC14

# BOOK OF ABSTRACTS

# FATIGUE 2026

14th International Fatigue Congress

Funchal, Madeira, Portugal

28 JUNE – 3 JULY 2026

## Committees

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Universidade de Brasília, Brasil

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# Program Overview

| | Monday 29/06 | Tuesday 30/06 | Wednesday 01/07 | Thursday 02/07 | Friday 03/07 |
|---|---|---|---|---|---|
| 8:00-8:30 | REGISTRATION | REGISTRATION | REGISTRATION | REGISTRATION | |
| 8:30-8:45 | | PLENARY LECTURE III | PLENARY LECTURE VI | | |
| 8:45-9:00 | OPENING SESSION | | | | |
| 9:00-10:30 | PLENARY LECTURE I<br>PLENARY LECTURE II | PLENARY LECTURE IV<br>PLENARY LECTURE V | PLENARY LECTURE VII<br>PLENARY LECTURE VIII | PLENARY LECTURE IX<br>PLENARY LECTURE X | CONFERENCE TOUR optional |
| 10:30-11:00 | COFFEE-BREAK | COFFEE-BREAK | COFFEE-BREAK | COFFEE-BREAK | |
| 11:00-12:45 | 1 A, 1 B, 1 C, 1 D, 1 E | 4 A, 4 B, 4 C, 4 D, 4 E | 6 A, 6 B, 6 C, 6 D, 6 E | 9 A, 9 B, 9 C, 9 D, 9 E | |
| 12:45-14:00 | LUNCH | LUNCH | LUNCH | LUNCH | |
| 14:00-15:45 | 2 A, 2 B, 2 C, 2 D, 2 E | 5 A, 5 B, 5 C, 5 D, 5 E | 7 A, 7 B, 7 C, 7 D, 7 E | 10 A, 10 B, 10 C, 10 D, 10 E | |
| 15:45-16:15 | COFFEE-BREAK | | COFFEE-BREAK | COFFEE-BREAK | |
| 16:15-18:00 | 3 A, 3 B, 3 C, 3 D, 3 E | QUINTA MAGNOLIA<br>MADEIRA WINE<br>16h30 – 18h30 | 8 A, 8 B, 8 C, 8 D, 8 E | 11 A, 11 B, 11 C, 11 D, 11 E | |
| | | | | CLOSING SESSION | |
| 19:00-20:30 | WELCOME COCKTAIL<br>NINI DESIGN CENTRE | | CONFERENCE BANQUET<br>O LAGAR RESTAURANT | | |
| 20:00-23:00 | | | | | |

Remark: Early registration available on Sunday 28/06, 16h30 – 18h00

# Technical Program

*June 20th, 2026 version*

Monday, 29d June 2026

| MON, 08:45 - 09:00 | OPENING SESSION | Room Funchal |
|---|---|---|
| Welcome to Participants<br>**(Conference Co-Chairs)**<br>Welcome Address | | |

| MON, 09:00 - 09:45 | PLENARY LECTURE I | Room Funchal |
|---|---|---|
| **The Role of Defects on Fatigue Strength and Modeling of Their Effects with Applications to AM Metals**<br>**Prof. Ali Fatemi* & Yukitaka Murakami****<br>*Ring Companies Endowed Professor, University of Memphis (USA)<br>**Emeritus Professor at Kyushu University<br>Chair: Luís Reis (IST, Portugal) | | |

| MON, 09:45 - 10:30 | PLENARY LECTURE II | Room Funchal |
|---|---|---|
| **Phase field modelling of fatigue and hydrogen-assisted fatigue**<br>**Prof. Emilio Martinez-Pañeda**<br>Department of Engineering Science, University of Oxford, Oxford (UK)<br>Chair: Alex (Univ. Brasilia, Brasil) | | |

| **Monday, 10:30 - 11:00** | **COFFEE-BREAK** | **Lounge** |
|---|---|---|

| Mon | Session 1A 11:00-13:00 | Room Funchal |
|---|---|---|
| TOPIC: Symposium A - Fatigue and Fracture in Metal Additive Manufacturing<br>Chair: Meysam Haghshenas - DEFECTS | | |
| Ref: | Title and Author (s) | |
| 221 | Towards Unravelling the Multiscale Nature of Fatigue in Additively Manufactured Metals: Assessing Defects, Residual Stress, and Microstructural Scatter<br>Enrico Salvati, Alessandro Tognan, Marco Pelegatti, Emanuele Avoledo, Jasen Zenzerovic<br>Invited Talk – 30 min | |
| 232 | From the surface defect population to an efficient fatigue life prediction: effects of defect geometrical characteristics and material variability<br>David Mellé, Etienne Pessard, Franck Morel, Daniel Bellett | |
| 345 | Mechanical Behaviour and Fracture Characterisation of a WAAM-Produced Tool Steel in the As-Fabricated and Heat-Treated Condition<br>Filipe Esteves, Gonçalo Rosa, Valdemar Duarte, André Ramalho, Eduarda Gomes, | |
| 322 | A universal effect of defect model for various engineering alloys made with additive manufacturing<br>E. Amsterdam, W.W. Wits | |
| 054 | Fatigue behavior of 3D-printed metals: bulk, lattice and hybrid structures<br>Yoshihiko Uematsu | |
| 305 | Fatigue damage tolerance and defect-based lifetime of additively manufactured metals<br>S. Stammkoetter, P. Karentzopoulos, S. Mrzljak, F. Walther<br><br>Invited Talk – 30 min | |

| Mon | Session 1B 11:00-12:45 | Room Berlim (1st floor) |
|---|---|---|
| TOPIC: Symposium I - Numerical simulation of fatigue crack growth<br>Chair: Aleksandar Sedmak; Aleksandar Grbovic; Simon Sedmak | | |
| Ref: | Title and Author (s) | |
| 068 | Three-dimensional fatigue crack propagation simulation based on a nonlocal algorithm of P91 steel<br>Masayuki Arai, Akihiro Motoki | |
| 107 | Influence of an Inclined Notch on Through-Thickness Fatigue Crack Propagation in PRNB Specimens Aimed at Improving Crack-Front Uniformity<br>Darko Damjanovic, Nenad Gubeljak, Josip Stojšić, Andrijana Milinović, Domagoj Opačak | |
| 207 | Meso-aggregate Model Relating Local and Global Material Properties for Fatigue Analysis<br>Juan Julio Gonzalez-Frias, Jinseok Kim, Daniel Kujawski | |
| 349 | Peridynamic modeling of corrosion-assisted fatigue and fracture<br>Han Wang, Licheng Guo | |
| 451 | Numerical simulation of fatigue crack growth in AA2024 T6 stringer panels<br>Aleksandar Sedmak, Aleksandar Grbovic, Đorđe Zrnić | |
| 403 | Phase-field modeling of fatigue life for SLM-fabricated Ti6Al4V alloy: synergistic effect of defects and microstructure<br>Zhongwen Tao, Hao Xin, Xiaofan He | |
| 411 | Peridynamic Analysis of Stop-Hole Effects on Fatigue Crack Growth in Aerospace Structures<br>Mehmet Dördüncü, Hasan Hüseyin Camuz, Uğur Altay, Erdogan Madenci | |

| Mon | Session 1C 11:00-12:45 | Room Sidney (2nd floor) |
|---|---|---|
| TOPIC: Symposium N - Fatigue Model Verification and Validation – FABER Perspective<br>Chair: Jan Papuga; Kris Hectors; Luís Reis | | |
| Ref: | Title and Author (s) | |
| 151 | Benchmarking Fatigue Life Estimation: The FABER and FABEST Initiative<br>Jan Papuga | |
| 049 | Application of the Averaged Strain Energy Density Approach to Variable Amplitude Rotating Bending Fatigue of S690 Steel<br>Kris Hectors, Wim De Waele | |
| 150 | Coupling Size and Stress Gradient Effects in Notch Fatigue Assessment<br>Jan Papuga, Petr Vaněk, Martin Nesládek, František Fojtík, Marius Müller, Alexander Hasse | |
| 222 | Artificial Neural Networks in Fatigue Modeling: Challenges in Validation and Engineering Interpretation<br>Marohnić Tea, Basan Robert, Cernescu Anghel-Vasile | |
| 057 | A novel temperature field reconstruction method for multi-pass welding simulation<br>A.A. Akay, K. G. F. Janssens | |
| 180 | A novel variable amplitude fatigue crack growth model applied to fatigue damage accumulation<br>E. Amsterdam | |
| 429 | Methodology for Real-Time Remaining Fatigue Life Estimation: From Deterministic to Probabilistic Models<br>D. Díaz-Salamanca, M. Muñiz-Calvente, A. Cebada-Relea, E. Martínez-Puente, M. López, I. Llavori, M. Aenlle | |
| 487 | From Collaborative Network to Research Infrastructure: A Vision for FABER in Fatigue Benchmarking and Lifetime Engineering<br>Theo Zacharis, Jan Papuga | |

| Monday, 12:45 - 14:15 | LUNCH | Restaurant |
|---|---|---|

| Mon | Session 1D<br>11:00-12:45 | Room Paris<br>(1st floor) |
|---|---|---|
| TOPIC: Emerging materials and advanced manufacturing<br>Chair: Luís Borrego | | |
| Ref: | Title and Author (s) | |
| 311 | Tracking Fatigue Damage Evolution in AISI 4140 Using Magnetic Barkhausen Noise for Non-Destructive Machine Learning–Based Remaining Useful Life Estimation<br>Mehdi Khabou, Volker Schulze, Stefan Dietrich | |
| 169 | Fatigue Life Prediction Methodology for Welded Joints Considering Residual Stress Relaxation<br>Xiaogang Liu, Qiang Hu, Jinhong Li | |
| 473 | FEM analysis of the threaded sleeve with the compressed air tank<br>Tadeusz Smolnicki, Paweł Maślak | |
| 390 | Raster angle effects on creep and low-cycle fatigue behaviour of FDM 3D-printed polymers<br>I. S. Silva, K. Sales de Oliveira, A. C. Santos, T. Doca | |
| 350 | Effect of Heat Treatment on the Tensile Properties and Fatigue Life of Explosion-Welded Zr–Steel Bimetallic Composites<br>Mariusz Prażmowski, Aleksander Karolczuk, Henryk Paul | |
| 442 | Vibration fatigue assessment method for high-speed service-damaged axle<br>Feifei Hu, Junjiang Liu, Yizhong Ma, Feng Kang, Shengchuan Wu | |
| 484 | Fatigue and Fracture Performance of Additively Manufactured Ti-6Al-4V via Laser Powder Directed Energy Deposition<br>Nikolaos D. Alexopoulos, Ioannis Goulas, Alexis Kermanidis, Denys Zhumar, Olena Karpovych, Yevhen Karakash, Olexandr Grydin | |

| Mon | Session 1E<br>11:00-12:45 | Room Lisboa |
|---|---|---|
| TOPIC: Symposium J - Very High Cycle Fatigue: Experimental methods, specimens and machines, and damage mechanisms<br>Chair: H. Mayer; Pedro Costa; Ulrich Krupp; Eberhard Kerscher | | |
| Ref: | Title and Author (s) | |
| 024 | Reliability of additively manufactured martensitic and precipitation-hardenable steels under very high cycle fatigue loading<br>Sebastian Schettler, Sebastian Schoene, Leonhard Stampa, Martina Zimmermann | |
| 199 | Very-high-cycle fatigue (VHCF) predictions in the presence of mean stresses and non-metallic inclusions<br>J.A. Araújo, M.V. Pereira | |
| 121 | Fatigue behavior of a maraging steel under multiaxial ultrasonic loading: crack initiation mechanisms and dissipative effects<br>Nicholas Lemos de Carvalho, Cainã Bemfica de Barros, Cédric Doudard, Loïc Dimithe | |
| 164 | Order-of-Magnitude Enhancement in VHCF Life of Bearing Steel Enabled by Tailored Deformation Compatibility<br>Binxun Xu, Tengyuan Liu, Zhonghua Jiang, Pei Wang, Dianzhong Lia | |
| 170 | VHCF of QT steel in hot hydrogen<br>M. Fitzka, B.M. Schönbauer, J. Vaara, T. Frondelius, H. Mayer | |
| 395 | Quantification of the influences of composition and microstructure on the mechanisms of FGA formation in quenched and tempered steels by in situ testing and high-resolution analysis<br>Praveen Velliyangiri, Marion Kreins, Ulrich Krupp | |
| | | |

| Monday, 12:45 - 14:15 | LUNCH | Restaurant |
|---|---|---|

| Mon | Session 2A 14:15-16:15 | Room Funchal |
|---|---|---|
| TOPIC: Symposium A - Fatigue and Fracture in Metal Additive Manufacturing<br>Chair: Nima Shamsaei – NON-FERROUS ALLOYS (I) NICKEL | | |
| Ref: | Title and Author (s) | |
| 008 | Defect-Microstructure Interplay in Fatigue Crack Formation of PBF-LB IN718<br>Richard W. Neu<br>Invited Talk – 30 min | |
| 182 | Understanding the effect of skin removal on total fatigue life in LPBF AlSi10Mg parts for accurate life prediction<br>Ninian Sing Kok Ho, Tong Liu, Yi Zhou, John Hock Lye Pang | |
| 109 | Influence of Heat Treatment and Hot Isostatic Pressing on Fatigue Strength of Additive Manufactured Inconel 718<br>Janine Wischek | |
| 209 | In-situ optical tomography and fatigue of PBF-LB IN718<br>Jinghao Xu, Arda Baytaroglu, Dmitri Riabov, Emmy Cao, Mattias Calmunger, Mats Delin, Lars Nyborg | |
| 263 | Effect of wall thickness on the multiaxial fatigue of additively obtained tubular IN718 specimens<br>B. Bouzid Souihli, N. Saintier, O. Ciobanu | |
| 026 | Can the plain S–N behaviour and uniaxial/multiaxial notch fatigue strength of additively manufactured metals be estimated?<br>Luca Susmel<br><br>Invited Talk – 30 min. | |

| Mon | Session 2B 14:15-16:00 | Room Berlim (1st floor) |
|---|---|---|
| TOPIC: Symposium I - Numerical simulation of fatigue crack growth<br>Chair: Aleksandar Sedmak; Aleksandar Grbovic; Simon Sedmak | | |
| Ref: | Title and Author (s) | |
| 420 | A Peridynamic Framework for Fatigue Damage Prediction in Composites under Constant and Variable Amplitude Loading<br>Erdogan Madenci, Atila Barut, Amin Yaghoobi | |
| 447 | Prediction of Critical Defect Size in Additively Manufactured AISI 316L Using a Coupled Peridynamic – Chappetti Fatigue Model<br>Luka Ferlič, Nenad Gubeljak, Erdogan Madenci, Mirco D. Chapetti, Filip Jerenec | |
| 448 | Fatigue Crack Growth Prediction in AISI 316L Using a Peridynamic KTF Approach<br>Filip Jerenec, Nenad Gubeljak, Erdogan Madenci, Luka Ferlič | |
| 449 | Fatigue crack growth in a torque link simulated by SMART<br>Aleksandar Grbovic, Nikola Raicevic, Aleksandar Sedmak, Gordana Kastratovic, Nenad Vidanovic | |
| 450 | Fatigue crack growth in hip implants – numerical analysis by FEM<br>Simon Sedmak, Katarina Colic, Aleksandar Sedmak, Tamar Smoljanic | |
| 367 | On the Consistency of Numerical Fatigue Crack Growth Increments with Plastic CTOD Evolution in 2D Numerical Simulations<br>Jose Sandino-Egea, Antonio Gonzalez-Herrera, Daniel Camas, Jose Garcia-Manrique | |
| 423 | Three-Dimensional Numerical Study of Load Influence on the Evolution of Plastic CTOD in CT Specimens under Cyclic Loading<br>Jose Sandino-Egea, Alonso Camacho-Reyes, Jose Garcia-Manrique, Daniel Camas | |

| Mon | Session 2C 14:15-16:00 | Room Sidney (2nd floor) |
|---|---|---|
| TOPIC: Symposium F - Fatigue and Fracture of Weldments<br>Chair: Mauro Madia; Igor Varfolomeev | | |
| Ref: | Title and Author (s) | |
| 196 | Effect of Welding Pressure on Microstructure and Properties of Linear Friction Welded Joints of 7050-T7451 Aluminum Alloy<br>Xinwei Wang, Chuanchen Zhang, Ju Li | |
| 204 | A Dynamic Bayesian Network Framework for Fatigue Life Prediction of Welded Connections<br>Caroline Correa de Faria, Cláudio Carlos da Silva Horas, Túlio Nogueira Bittencourt | |
| 236 | On the use of Thermoelastic Stress Analysis for fatigue crack growth modelling<br>Lorenzo Bercelli, Bruno Levieil, Cédric Doudard, Sylvain Calloch, Florent Bridier | |
| 334 | Weld Metal Axial and Torsion Deformation and Fatigue Properties and Predictions for Durability Analysis of Weldments<br>Tarek M. Diab, Ahmad Razi, Ali Fatemi | |
| 404 | Environmental Effect on Fatigue Behaviour of FSW Joints For Battery Packs<br>Rodrigo J. Coelho, André Dias, Beatriz Silva, Carolina Francisco, Tiago Domingos, Pedro Sousa, Paulo J. Tavares, Daniel Braga, Pedro M.G.P. | |
| 415 | The ENLO-SED Large-Scale Shell-Element Models for Predicting the Strain Energy Density (SED) of Welded Joints<br>Lucertini, G. Morettini, F. Cianetti | |
| 418 | Influence of Hydrogen-Induced Embrittlement on the Fatigue strength of 316L Stainless-Steel Welded Joints<br>M. António, J.S. Jesus, L.P. Borrego, L. Vilhena, R. Branco, J. D.M. Costa, J.A.M. Ferreira | |

| Monday, 16:00 - 16:30 | COFFEE-BREAK | Lounge |
|---|---|---|

| Mon | Session 2D 14:15-16:00 | Room Paris (1st floor) |
|---|---|---|
| TOPIC: Symposium C - Research into the fatigue life of materials and components in cooperation between companies, research organisations and academia<br>Chair: Miloslav Kepka; Vladimir Chmelko | | |
| Ref: | Title and Author (s) | |
| 053 | Optimization of the Warm Peening Process for Inductive Hardened Samples of C55 using the Concept of Local Fatigue Strength<br>Benjamin Dollhofer, Stefan Dietrich, Volker Schulze, Philipp Reeh, Stefano Bucci, Vallentina Dellaca, Marcel Egger, Ilaria Torquati, Ainhoa Errasti | |
| 093 | Probabilistic approach to fatigue life estimation of bus components, including elimination of fatigue failures based on service loading analyses<br>Miloslav Kepka, Miloslav Kepka jr., Jaroslav Vaclavik | |
| 094 | Fatigue tests of railway structures and components made of steel and composites<br>Jan Chvojan, Miloslav Kepka, Miloslav Kepka jr., Vaclav Kraus | |
| 116 | Development and Implementation of a High-Resolution, Full-Field, Near-Bore Digital Image Correlation (DIC) Process to Capture the Strain Response of the Split Sleeve Cold Expansion (SsCxTM) Process<br>Scott Carlson, Dave Backman, Milan Djordjevic, James Prather | |
| 156 | Multiaxial fatigue of polymeric pressure sheaths for oil and gas applications: a case study on polyvinylidene fluoride (PVDF) using the Fatemi–Socie criterion - Tiago Lima Castro, Camila Alves Farias, Celio Albano da Costa | |
| 158 | Effect of hydrogen concentration and pressurized hydrogen environment on the fatigue behavior of Inconel718 L-PBF at room and intermediate temperatures<br>D. Tade, V. Bonnand, A. Marano, X. Feaugas, A. | |
| 165 | Process–Structure–Fatigue Relationships in MIM 17-4PH: From Porosity to δ-Ferrite<br>Tobias Hajeck, Christian Weck, Alexander Bezold, Christoph Broeckmann | |

| Mon | Session 2E 14:15-16:00 | Room Lisboa |
|---|---|---|
| TOPIC: Symposium J - Very High Cycle Fatigue: Experimental methods, specimens and machines, and damage mechanisms<br>Chair: H. Mayer; Pedro Costa; Ulrich Krupp; Eberhard Kerscher | | |
| Ref: | Title and Author (s) | |
| 241 | Ultrasonic fatigue testing of single-phase materials with elastic-plastic and metastable materials behavior in the VHCF regime<br>Marek Smaga, Elen Regitz, Tilmann Beck | |
| 266 | Fatigue analysis and prediction with applied work energies<br>Hyung-Jun Chang, Flavien Ghiglione | |
| 277 | Heat dissipation and entropy accumulation in a polymer matrix composite under cyclic three-point bending at low and ultrasonic frequencies<br>Aravind Premanand, Hanna Schimmelpfeng, Frank Balle | |
| 278 | Challenges in specimen and experimental design for on- and off-axis fatigue testing of a polymer matrix composite at low and ultrasonic frequencies<br>Aravind Premanand, Hanna Schimmelpfeng, Frank Balle | |
| 317 | Ultra-High Cyclic Fatigue of Nanobainitic Steels<br>Bali Nagya Regmi, Eberhard Kerscher | |
| 377 | VHCF four-point bending test system design and improvement<br>Martin Bartelt, Sebastian Heimbs | |
| 400 | An Innovative Ultrasonic Fatigue Test towards the Characterization of Lap Joint Adhesives in Shear<br>Catarina Faria, Pedro R. da Costa, J. Henrique Lopes, Rosemere Lima, Luís Reis | |

| Monday, 16:00 - 16:30 | COFFEE-BREAK | Lounge |
|---|---|---|

| Mon | Session 3A 16:30–18:30 | Room Funchal |
|---|---|---|
| TOPIC: Symposium A - Fatigue and Fracture in Metal Additive Manufacturing Chair: Stefano Beretta - NON-FERROUS ALLOYS (II) ALUMINUM | | |
| Ref: | Title and Author (s) | |
| 153 | Cold Spray Solid-State Deposition of AA7075 on Magnesium: Residual Stress and Fatigue Performance<br>Hamid Jahed, Bahareh Marzbanrad, Sugrib Shaha, Siavash Borhan-Dayani, Jie Wang<br>Invited Talk – 30 min. | |
| 082 | Effects of Surface Finish and Post-Processing Heat Treatment on the Fatigue Performance of AM AlSi10Mg<br>Martin Matušů, Bastian Roidl, Jan Papuga, Jakub Rosenthal, Jürgen Koch, Feng Chen, Wolfgang Blöchl, Martina Koukolíková & Vladimír Mára | |
| 105 | Mechanical Behaviour of Thin-Walled AlSi10Mg Specimens Fabricated by Laser Powder Bed Fusion<br>S. Cravo, V. Duarte, C. Santos, R.F. Martins, R.A. Claudio | |
| 347 | Surface defect driven fatigue lifetime prediction for additively manufactured titanium alloy miniature components<br>Yixuan Hou, Xiaoqin Zhou, Qiang Liu, Talemi Reza | |
| 083 | Fatigue Performance of L-PBF Nickel-Based Superalloy: Effects of Surface Finish and Mean Stress<br>Bastian Roidl, Martin Matušů, Jakub Rosenthal, Ivana Zetková & Miroslav Zetek | |
| 034 | Ultrasonic Fatigue and Crack Initiation Mechanisms in LPBF Cu–30Ni<br>Meysam Haghshenas<br><br>Invited Talk – 30 min. | |

| Mon | Session 3B 16:30–18:30 | Room Berlim (1st floor) |
|---|---|---|
| TOPIC: Symposium B - Advances in Offshore Renewable Energy Chair: Mário Vieira | | |
| Ref: | Title and Author (s) | |
| 047 | NOFM: A Physics-Augmented Neural Operator for Zone-Resolved Fatigue Life Prediction in Grade R4 Mooring Chain Weldments<br>Alejandro Fernández de Castro, Melih Kandemir, Halid Can Yıldırım | |
| 202 | Supporting the construction and wet-storage of concrete-manufactured platforms for floating offshore wind using advanced finite element simulations<br>Arjun Janardhanan, Tiago Mota, Mário Vieira | |
| 212 | Real-Time Structural Performance Estimation of Concrete-Based Floating Offshore Wind Platforms Using Inertial Loads in Finite Element Analysis<br>Ricardo Pinto, Mário Vieira, Tiago Mota, Luís Reis | |
| 252 | Integrated Cellular Automaton and Progressive Damage Analysis for Corrosion Fatigue Life Prediction in Marine Environment<br>Rui Deng, Xuejiao Chen, Yifei Deng, Chi Hou, Meiying Zhao | |
| 167 | Structural Simulation of a Concrete-Based Floating Offshore Wind Platform under Hydrodynamic and Aerodynamic Loadings<br>Luís Carrasco, Mário Vieira, Tiago Mota, Luís Reis | |
| 342 | Multiaxial fatigue evaluation of mooring chains<br>Eguzkiñe Martinez-Puente, Iñigo Llavori, Alaitz Zabala, Jon Ander Esnaola, Markel Penalba | |
| 405 | Experimental fatigue assessment of carbon fiber–reinforced polyvinylidene fluoride (CF/PVDF) composites for offshore flexible pipe applications<br>Tiago Lima Castro, Geovane de Almeida da Silva, Camila Alves Farias, Gabriela Ribeiro Pereira, Marysilvia Ferreira da Costa, Celio Albano da Costa | |
| 438 | Development of fatigue load spectra for FOWT moorings based on crack growth<br>Abhemanyu P C, Bjørn.H.Skallerud, Gunnstein.T.Frøseth | |

| Mon | Session 3C 16:30–18:30 | Room Sidney (2nd floor) |
|---|---|---|
| TOPIC: Symposium F - Fatigue and Fracture of Weldments Chair: Mauro Madia; Igor Varfolomeev | | |
| Ref: | Title and Author (s) | |
| 078 | Fracture-Mechanics-Based Fatigue Life Assessment of Butt-Welded Joints: A Comparison of Standard-Based, Analytical, and Numerical Approaches<br>Antoni Artinov, Mauro Madia, Andreas Pittner, Aayush Askhedkar, Egla Bregu, Thomas Kannengießer, Matthias Baeßler | |
| 128 | Numerical Modelling of the Influence of Shot Peening on the Fatigue Performance of Welded Joints<br>G. Cortabitarte, I. Llavori, M. Larrañaga, J.A. Esnaola, X. Telleria, I. Ulacia | |
| 157 | Microstructure-Driven Variability in Probabilistic Fatigue Crack Growth Analysis of Welded Structural Steel Joints<br>Kamal Harb, Julien Baroth, Rafael Estevez, Arnaud Isaac, Vincent Michaud | |
| 160 | Fatigue strength assessment of full-scale arc-welded steel booms for agricultural trailed sprayers using the Peak Stress Method<br>Filippo Coppola, Davide Della Volpe, Andrea Ruffin and Giovanni Meneghetti | |
| 166 | Multiaxial fatigue strength assessment of dissimilar GJS500-7 ductile iron-to-S355 steel arc-welded joints according to the Peak Stress Method<br>S. Bolner, A. Campagnolo, A. Visentin, G. Meneghetti | |
| 168 | The Peak Stress Method applied to the fatigue characterization of dissimilar arc-welded AISI 316L joints made of additively manufactured and wrought plates<br>L. Contiero, L. Vecchiato, A. Campagnolo, V.Babini, G. Meneghetti | |
| 185 | A new fatigue damage evaluation for multiaxial variable amplitude fatigue lifetime assessment of steel welded joints according to the Peak Stress Method<br>Alberto Campagnolo, Alberto Visentin, Giovanni Meneghetti | |
| 059 | Crack tip detection algorithms based on DIC displacement field analysis<br>A. Camacho-Reyes, D. Camas, B. Moreno, P. López-Crespo, J.M. Vasco-Olmo, F.A. Diaz | |

| Mon | Session 3D<br>16:30-18:30 | Room Paris<br>(1st floor) |
|---|---|---|
| TOPIC: Symposium C - Research into the fatigue life of materials and components in cooperation between companies, research organisations and academia<br>Chair: Miloslav Kepka; Vladimir Chmelko | | |
| Ref: | Title and Author (s) | |
| 206 | Robotic 3D printing of continuous flax fibers composites<br>Zouheyr Belouadah, Marcelo Tanglao, Ahmed Sarwar, Toubal Lotfi, Donatus Oguamanam, Habiba Bougherara | |
| 211 | Rapid estimation of fatigue limit in metallic materials using thermographically instrumented cyclic tensile tests: experimental framework and perspective<br>Lydia Sadeg, Arnaud Duchosal, Guillaume Altmeyer | |
| 213 | Defect tolerance of thick high-strength steels for truck chassis assessed by fatigue notch sensitivity and fracture toughness - Sergi Parareda, David Frometa, Daniel Casellas, Henrik Sieurin | |
| 216 | Effect of Environment on Fatigue Crack Growth in High Strength Steels<br>Monisha Manjunatha, Tugrul Comlekci, Yevgen Gorash & Donald Mackenzie | |
| 220 | Assessment of crack closure during fatigue crack growth under large scale yielding and negative strain ratio<br>Théotime Asselin, Olivier Ancelet, Valery Valle, Florence Hamon, Guillaume Benoit, Gilbert Hénaff | |
| 246 | Fatigue Performance of the New Leaf Spring Steel 45SiCrV9Ni for Applications in Battery Electric Vehicles<br>Niki Nouri, Christos Gakias, Borja Escauriaza, Javier Isach, Roberto Elvira, Georgios Savaidis, Stefan Dietrich, Volker Schulze | |
| 249 | Influence of the Surface Hardening Depth on the Tooth Root Fatigue Strength of Induction Hardened Sintered Steel Gears<br>Moritz Klug, Stefan Dietrich and Volker Schulze | |
| 254 | Behaviour of an Aeronautical Component Produced by PBF-LB/M<br>Ricardo Cláudio, Tiago Alves, Pedro Pêcego, Rodolfo L. Batalha, Paulo Moita, Pedro Rendas, Susana Cravo, Ana Ferramacho, Carla Ferreira, Luís Reis, Aníbal Valido | |

| Mon | Session 3E<br>16:30-18:30 | Room Lisboa |
|---|---|---|
| TOPIC: Symposium J - Very High Cycle Fatigue: Experimental methods, specimens and machines, and damage mechanisms<br>Chair: H. Mayer; Pedro Costa; Ulrich Krupp; Eberhard Kerscher | | |
| Ref: | Title and Author (s) | |
| 402 | Very high cycle fatigue of high strength steels applied to aeronautic rolling bearings<br>Hugo Behlal, Daniel Nélias, Naïm Naouar, Jean-Baptiste Coudert, Arnaud Ruellan, Geoffray Deterre | |
| 409 | On the fatigue crack growth rate threshold in the very high cycle fatigue regime<br>Bernd M. Schönbauer | |
| 432 | Very high cycle fatigue properties of thin steel sheets<br>Afshin Khatammanesh, Christina Mamagkinidou, Suraj S. More, Martin Rester, Maximilian Prunbauer, Michael Proschek, Bernd M. Schönbauer | |
| 441 | Gas pore-based fatigue strength and fatigue life prediction models of laser additive manufactured Ti-6Al-4V alloy in very high cycle fatigue regime<br>Guanze Sun, Zihua Zhao | |
| 453 | Effect of heat treatment on very high cycle rotating bending fatigue properties of rail steel<br>Noriyasu Oguma, Mitsuru Hosoda, Jun Mizutani, Tadashi Deshimaru | |
| 460 | Damage detection in ultrasonic very high cycle fatigue testing by analysing vibration properties<br>Lopes, J. H.; Fitzka, M.; R. da Costa, P.; Schönbauer, B.; Mayer, H.; Reis, L. | |
| 025 | Thermoelasticity-based full-field fatigue damage identification<br>Janko Slavič, Klemen Zaletelj, Jaša Šonc | |
| 124 | Investigations into influencing factors on the VHCF behavior of ship propeller materials under seawater exposure<br>Lea Riess, Christopher Benz, Lars Radtke | |

| Monday, 19:00 - 20:30 | WELCOME COCKTAIL | Funchal, "DESIGN CENTER – NINI ANDRADE SILVA" |
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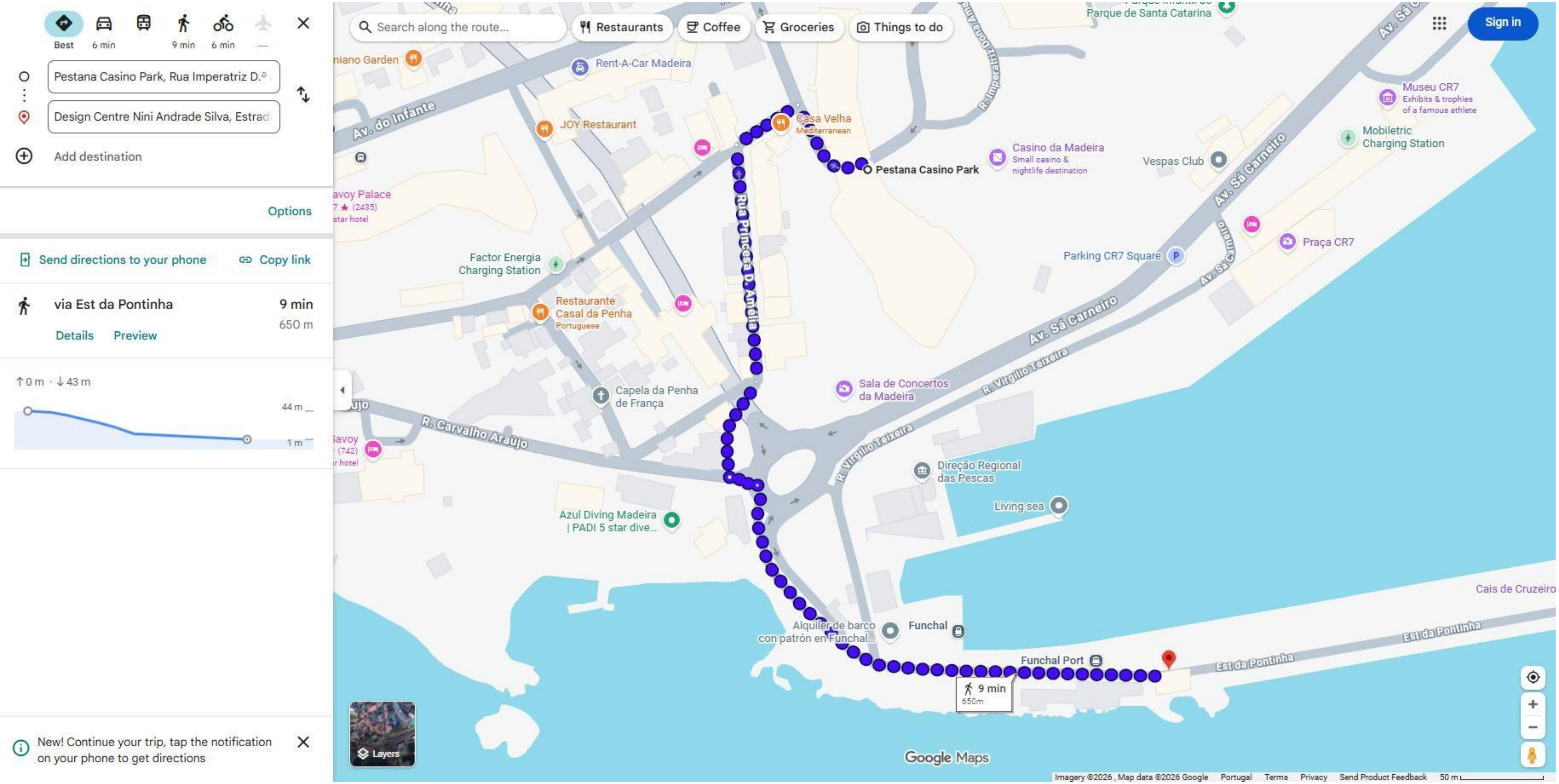

## Tuesday, 30 June 2026

| TUE, 08:30 - 09:10 | PLENARY LECTURE III | Room Funchal |
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**Achieving the highest fatigue strength in metals**
**Prof. Zhefeng Zhang**
Division head of Materials Fatigue and Fracture; Institute of Metal Research (IMR)
Chinese Academy of Sciences (CAS)
Chair: Luca Susmel (Sheffield Hallam University, UK)

| TUE, 09:10 - 09:50 | PLENARY LECTURE IV | Room Funchal |
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**Fretting fatigue life in complex loading conditions, experiments and modelling**
**Prof. Sylvie Pommier**
Professeure des Universités à l'Ecole Normale Supérieure Paris-Saclay
Chercheuse au laboratoire de Mécanique Paris-Saclay (LMPS)
Chair: Manuel Freitas (Universidade Atlântica, PT)

| TUE, 09:50 - 10:30 | PLENARY LECTURE V | Room Funchal |
| --- | --- | --- |

**The Use of Light as Surface Technology to extend Fatigue Life in Aerospace Industry - The Residual Stress Engineering from Historical Review, current Applications and Future Prospective**
**Dr. Domenico Furfari**
Airbus Operations GmbH, Kreetslag 10, 21129 Hamburg, Germany
Chair: Gilbert Hénaff (Institute Prime, Université de Poitiers, France)

| **Tuesday, 10:30 - 11:00** | **COFFEE-BREAK** | **Lounge** |
| --- | --- | --- |

| Tue | Session 4A 11:00-13:00 | Room Funchal |
|---|---|---|
| TOPIC: Symposium A - Fatigue and Fracture in Metal Additive Manufacturing<br>Chair: Jean-Charles Stinville – THEORY & MODELING | | |
| Ref: | Title and Author (s) | |
| 048 | Spatial Encoding of Microstructure and Plasticity for Data-Driven Fatigue Properties Prediction and Governing Mechanisms identification of AM microstructure<br>M.Calvat, D. Anjaria, J.C. Stinville<br>Invited Talk – 30 min. | |
| 335 | Numerical study on the defects and surface condition competition affecting the fatigue strength of L-PBF 316L steel, assessed by means of synchrotron X-ray tomography<br>Marion Auffray, Camille Burton, Franck Morel, Linamaria Gallegos Mayorga | |
| 214 | Application of the DCPD technique to monitor crack propagation from volumetric CAD-seeded defects in PBF-LB Scalmalloy® - Luca Mariotti, Andrea Zanon, Stefano Beretta, Luca Patriarca | |
| 224 | Statistical average strain energy density method applied to a computational efficient finite element framework to estimate lattice structure fatigue resistance<br>Raffaele De Biasi, Simone Murchio, Matteo Benedetti, Filippo Berto | |
| 273 | Geometrical Considerations for Fatigue of Laser-Based Powder Bed Fusion Metal Components<br>Aloysius Tay, Ninian Sing Kok Ho, Yi Zhou, Zhen Lu, Alexander ZhongHong Liu, Mohsen Seifi, John Hock Lye Pang | |
| 301 | Dislocation Glide Theories (CRSS) Relevant to Fatigue<br>Huseyn Sehitoglu<br><br>Invited Talk – 30 min. | |

| Tue | Session 4B 11:00-12:45 | Room Berlim (1st floor) |
|---|---|---|
| TOPIC: Symposium D - Laser Peening and Related Residual Stress Engineering Processes for Fatigue Improvement<br>Chair: Yuji Sano – Industrial Applications | | |
| Ref: | Title and Author (s) | |
| 117 | Scott Carlson (Lockheed Martin): Qualification & Implementation of Laser Peening on F-35 Fatigue and Fracture Critical Structure | |
| 136 | Qiang Fu (Airbus): Managing Residual Stresses to improve Fatigue Performance in Airframe Structures with the use of Numerical Simulations | |
| 135 | Jonas Lehmann (Leuphana Uni): Fatigue Crack Propagation under Different Residual Stress Modification Techniques: A Comparative Study of Deep Rolling, Hammer Peening, and Laser Shock Peening | |
| 343 | Che Zhigang (AVIC): Performance of Aluminum alloys components of preventive treatment by laser peening | |
| 361 | Nadezhda Likhareva (Hereon): Fatigue life extension of refill friction stir spot welded AA6082-T6 joints using laser shock peening | |

| Tue | Session 4C 11:00-12:45 | Room Sidney (2nd floor) |
|---|---|---|
| TOPIC: Advanced modelling, simulation, and life prediction methods<br>Chair: Sylvie Pommier | | |
| Ref: | Title and Author (s) | |
| 259 | Force–Heat Equivalence Energy Density Principle and Its Application to the Characterization of Material Fatigue and Fracture under Extreme Conditions<br>Weiguo Li | |
| 271 | Investigating the correlation between wear and fatigue properties of cryogenically treated tool steel Vanadis 4E using cyclic indentation testing<br>F. Tadross, R. Walther, J. Heidrich, S. Winter, M. Smaga, T. Beck, B. Blinn | |
| 018 | Fatigue Evaluation of Fuel Cladding Considering Pellet–Clad Interaction<br>Min Jeong Park, Dong-Hyun Kim, Yoon-Suk Chang | |
| 019 | Computational Prediction of Total Fatigue Life with An Integrated Approach<br>Siqi Li, Rong Liu, Zhong Zhang, Xijia Wu | |
| 021 | A probabilistic-dynamic fatigue life prediction framework for SLM alloys based on extreme defect statistics and natural frequency degradation<br>Yuqi Yang, Haibiao Yin, Piao Li, Weixing Yao | |
| 031 | Stop-Drilling Fatigue Cracks Under Load<br>Hooman Pakdaman, Derek Warner, K.T. Ramesh | |
| 040 | Nanocomposite Conductive Tough Hydrogel Based on Metal Coordination Reinforced Covalent Pluronic F-127 Micelle Network for Human Motion Sensing<br>Zhicheng Dong, Xiaopeng Wan | |

| Tuesday, 12:45 - 14:15 | LUNCH | Restaurant |
|---|---|---|

| Tue | Session 4D<br>11:00-12:45 | Room Paris<br>(1st floor) |
|---|---|---|
| TOPIC: Symposium K - Mechanism-based fatigue analysis including AI approaches<br>Chair: Frank Walther | | |
| Ref: | Title and Author (s) | |
| 113 | An Incremental learning-driven few-shot method for predicting fatigue life of AA7050-T7451 aluminum alloy<br>Xuejiao Chen, Rui Deng, Chi Hou, Meiying Zhao | |
| 282 | Data-Driven Life Prediction for Thermomechanical Fatigue: From Material Specimens to Industrial Structures<br>Fabien Szmytka, Baris Telmen, Agathe Forré | |
| 295 | A Hybrid Structural Mechanics and Genetic Algorithm Method for Analyzing Local Stresses in Cracked Welded Plate Joints<br>Liuyang Feng, Tao Suo, Xudong Qian | |
| 313 | Machine learning-based fatigue crack path evaluation in high-speed steel<br>J. Zitz, L. Walch, T. Klünsner, G. Ressel, A. Hohenwarter, S. Marsoner, M.J. Cordill, A. Hackl, R. Pippan, C.O.W. Trost | |
| 426 | Modeling fatigue crack growth using machine learning<br>B. Moreno, P. Caballero de Leiva, I. Gonzalez-Tiviño, A. Camacho | |
| 233 | Predicting fatigue lifetimes of additively manufactured metallic parts with few experiment data: A multi-fidelity machine learning model<br>Shiyi Mao, Binchao Liu, Rui Bao | |

| Tue | Session 4E<br>11:00-12:45 | Room Lisboa |
|---|---|---|
| TOPIC: Fatigue mechanisms and crack propagation<br>Chair: Gilbert Henaff | | |
| Ref: | Title and Author (s) | |
| 002 | Cyclic deformation mechanisms of a 3D-printed high-entropy alloy<br>D. Bajaj, A.H. Feng, S.J. Qu, D.Y. Li, and D.L. Chen | |
| 003 | On the Role of Hydrogen in Plasticity Mechanisms Associated with Cyclic Creep of a 304L austenitic stainless steel<br>A. Radi, S. Park, A. Oudriss, P. Osmond, G. Girardin, F. Lefebvre, H. Matsunaga, X. Feaugas | |
| 009 | Crack Growth Behavior of Microstructurally Graded PBF-LB/M Austenitic Steel Components<br>Nico Möller, Florian Loebich, Thomas Wegener, Julia Richter, Jens Gibmeier, Thomas Niendorf | |
| 010 | Stress Scaling of Initiation Life<br>Anthony D. Rollett | |
| 011 | Advances toward a comprehensive understanding of fatigue induced crack initiation mechanisms in f.c.c. alloys: influence of plastic strain localization and hydrogen content<br>X. Feaugas, A. Radi, M. Risbet, A. Oudriss, G. Henaff | |
| 022 | Effect of Long-term Aging on Low-cycle Fatigue Behavior of GH4169 Alloy<br>Lei Wang, Yang Liu, Xiu Song, Guohua Xu, Jinlan An | |
| 055 | LCF behavior of fine-grained L-PBF 316L steel with a plentiful occurrence of twin boundaries<br>J. Man, J. Brůža, M. Jambor, M. Šmíd, M. Laleh, A.E. Hughes, I. Šulák, J. Polák | |

| Tuesday, 12:45 - 14:15 | LUNCH | Restaurant |
|---|---|---|

| Tue | Session 5A 14:15-16:00 | Room Funchal |
|---|---|---|
| TOPIC: Symposium A - Fatigue and Fracture in Metal Additive Manufacturing<br>Chair: Aeriel Leonard - NON-FERROUS ALLOYS (III) | | |
| Ref: | Title and Author (s) | |
| 069 | Gas- vs Plasma-Atomized Powder Effects on Very High Cycle Fatigue of L-PBF AlSi7Mg: Defects-Informed Stress-Life Modeling and Graph Convolutional Networks<br>Md Mehide Hasan Tusher, Ayhan Ince<br><br>Invited Talk – 30 min | |
| 184 | Effective Crack Size and Fatigue Limit estimation of Ti–6Al–4V specimens produced by PBF-LB/M with different surface roughness condition<br>Daniele Rigon, Filippo Mioli, Nicolò Bonato, Rachele Bertolini, Enrico Savio and Giovanni | |
| 240 | Corrosion-Fatigue Behavior of L-PBF Ti-6Al-4V Lattice Struts in Physiological Media<br>Simone Murchio, Farnoosh Farhad, Melika Babaei, Alessandro Albertini, Devid Maniglio, Filippo Berto, Matteo Benedetti | |
| 237 | High-Cycle Fatigue of LPBF CuCrZr for Nuclear Fusion Components<br>L. Salvò, A. Pepato, M. Benedetti | |
| 376 | Understanding Fatigue Crack Initiation and Growth in an Additively Manufactured Cu Based Alloy<br>Aeriel Leonard, Nathan Heniken, Jiashi Miao<br><br>Invited Talk – 30 min. | |

| Tue | Session 5B 14:15-16:00 | Room Berlim (1st floor) |
|---|---|---|
| TOPIC: Symposium D - Laser Peening and Related Residual Stress Engineering Processes for Fatigue Improvement<br>Chair: Domenico Furfari: Industrial Revolutionary Laser Peening Systems & Alternative Applications | | |
| Ref: | Title and Author (s) | |
| 074 | Yuji Sano (SANKEN): Ultra-compact Laser Peening with Microchip Lasers: From System Development to Structural Fatigue Enhancement | |
| 102 | Kiyotaka Masaki (Saitama Uni): Fatigue Properties of Anodized A6061-T6 Alloy after Peening Treatment | |
| 195 | Yoshio Mizuta (SANKEN) Effect of Laser Peening on Residual stress and Fatigue properties of Metal Additive Manufacturing Materials | |
| 286 | Claudia Polese (Witwatersrand Uni) Development of Industrial Coaxial Laser Shock Processing | |
| 205 | Mario Guagliano (Politecnico Milano): The role of shot peening for a better fatigue behavior of additive manufactured materials and components | |
| 118 | Selen Unaldi (Airbus): The LASAT: Measuring Adhesion at the Speed of Light | |
| 370 | Tomoharu Kato (National Institute of Technology): In Situ Laser Peening Using a Portable Device for Fatigue Improvement under Dead Loads | |

| Tue | Session 5C 14:15-16:00 | Room Sidney (2nd floor) |
|---|---|---|
| TOPIC: Fatigue Analysis and Life Prediction<br>Chair: Yu `e Ma | | |
| Ref: | Title and Author (s) | |
| 037 | Heat resistant ultra-strong Al-Si alloy and its application in additive manufacturing<br>Zhicheng Dong, Heyuan Huang | |
| 485 | Enabling Reliable Fatigue Data - Shimadzu's Contribution to Testing Excellence<br>Sebastian Fürst - SHIMADZU | |
| 038 | Influence of forced assembly gaps on the fatigue behavior of aluminum alloy multi-bolted joints under random loading<br>Heyuan Huang, Jinpen Chen | |
| 067 | Research of physics-informed data-driven methods for multiaxial fatigue life prediction<br>Xingyue Sun, Xueyu Han, Yu'e ma, Xu Chen | |
| 092 | Fast and accurate quantitative risk analysis method for damage-tolerant airframe structures<br>Yan Bombardier | |
| 101 | Lifetime Evaluation of Coke Drums considering the specifically determined S-N-Curve of the Shell<br>Johanna Steinbock, Stefan Pfeffer, Wieland Holzer, Jürgen Bär, Jona Schmögner, Gerald Zehethofer, Roland Scharf, Lidia-Cornelia Winking | |
| 262 | LEFM prediction and atomic-scale K-field simulation of crack-tip behaviors/mechanisms in titanium<br>Jiaping Ma, Yu E. Ma | |

| Tue | Session 5D<br>14:15-16:00 | Room Paris<br>(1st floor) |
|---|---|---|
| TOPIC: Symposium C - Research into the fatigue life of materials and components in cooperation between companies, research organisations and academia<br>Chair: Miloslav Kepka; Vladimir Chmelko | | |
| Ref: | Title and Author (s) | |
| 328 | A rapid assessment of the fatigue strength of specimens and components through damage evolution monitoring in stepwise loading tests<br>Sergi Parareda, Milad Bemani, Marc Marés, David, David Fróemta, Daniel Casellas | |
| 337 | Notch support effects in specimens and rotors made of electrical steel sheets<br>Peter Haefele, Patrick Schwarz | |
| 397 | Evaluation of the Fatigue Behaviour of 3D-printed PEEK Cranial Reconstruction Implants<br>P. Rendas, R. Jordão, R. F. Martins, L. Figueiredo, R. Cláudio, B. A. Soares | |
| 410 | Challenges in Specimen Representativeness for Aerospace Qualification of PBF-LB/M AlSi10Mg<br>Ana Ferramacho, António Garcês, Paulo Machado, Pedro Rendas, Rodolfo Batalha, Ricardo Cláudio, Célio Pina | |
| 413 | Case study of subsurface fatigue crack in a case-hardened bevel gear<br>Erkka Virtanen, Jarno Jokinen, Gabor Szanti, Auezhan Amanov, Mikko Kanerva | |
| 427 | Automotive Subframe Fatigue Testing Multi-Axial Compression<br>Patrick Tremoureux | |
| 131 | Fatigue analysis of extruded HDPE in bare and welded conditions<br>K. Sales de Oliveira, L. Carneiro, F.C. Castro, M.A. Garcia, F. Vicent, L.C. Randrianarivony, C. Bonini, J.A. Araújo, T. Doca | |

| Tue | Session 5E<br>14:15-16:00 | Room Lisboa |
|---|---|---|
| TOPIC: Fatigue mechanisms and crack propagation<br>Chair: Manuel Freitas | | |
| Ref: | Title and Author (s) | |
| 174 | Fatigue crack propagation mechanisms in ductile bulk metallic glasses and ductile polycrystalline metals: a comparison<br>Reinhard Pippan, Simon Pillmeier, Anton Hohenwarter | |
| 125 | Effect of Specimen Geometry on Fatigue Crack Growth of High-Density Polyethylene<br>Sang Min Lee, Ilhyun Kim, Byoung-Ho Choi | |
| 480 | Fatigue crack measurement using polarimetric imaging<br>Carolina Francisco, João M. A. F. Campos, Susana Dias, Pedro J. S. C. P. Sousa, Paulo J. Tavares, Pedro M. G. P. Moreira | |
| 251 | Fatigue of metallic glasses: In-situ investigations in the SEM<br>M. Marx, R. Busch, C. Motz | |
| 388 | Hetero-deformation mechanisms and GND-associated plastic strain partitioning across single/polycrystal hetero-boundary in nickel-based superalloys<br>Xiaoxian Zhang | |
| 035 | In situ observation of persistent slip in the initial stages of fatigue of PBF-LB/M austenitic 316L steel<br>Jaromír Brůža, Anja Weidner, Tomáš Vražina, Ladislav Poczklán, Ivana Zetková, Horst Biermann, Jiří Man | |
| 046 | Fatigue crack growth behavior of a selective laser melted Zr-based bulk metallic glass<br>Simon Pillmeier, Mirjam Spuller, Reinhard Pippan, Jürgen Eckert, Anton Hohenwarter | |
| 483 | Fatigue Testing of Fiber Reinforced Composite Materials on Higher Testing Frequency - RUMUL | |

| **Tuesday, 16:30 - 18:30** | **Madeira Wine Cocktail Reception** | Restaurant Jardim Magnolia |
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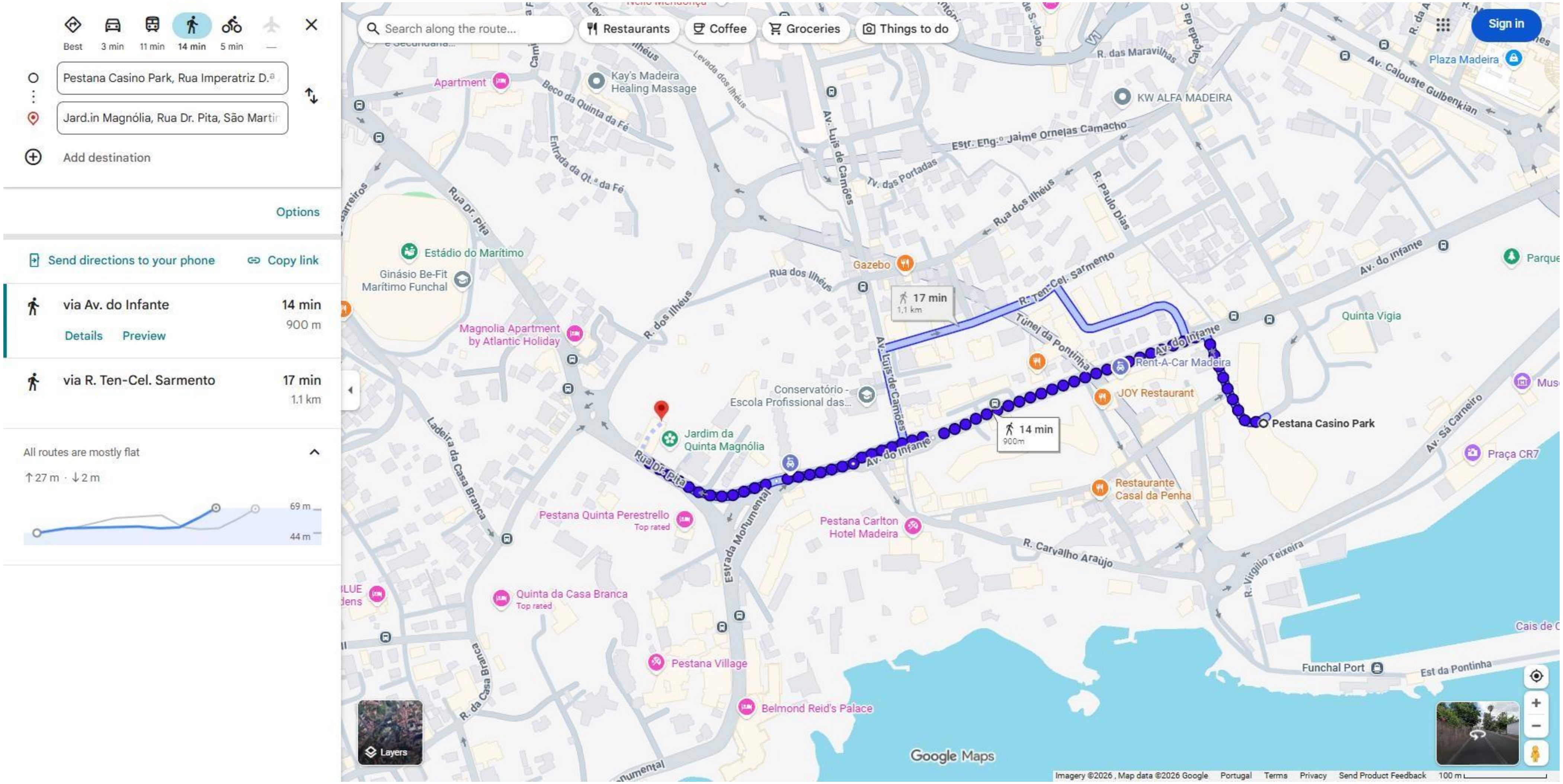

## Wednesday, 1 July 2026

| WED, 08:30 - 09:10 | PLENARY LECTURE VI | Room Funchal |
|---|---|---|

**Fatigue Characteristics of Additive Manufactured Lightweight Structures – Challenges and Opportunities from Damage Tolerance Perspectives**
**Prof. Raj Das**
Centre for Additive Manufacturing, Department of Aerospace Engineering, RMIT University, Melbourne, Victoria 3000, Australia
Chair: Yoshihiko Uematsu (Gifu University, JP)

| WED, 09:10 - 09:50 | PLENARY LECTURE VII | Room Funchal |
|---|---|---|

**Dwell fatigue of aero-engine Titanium alloys: integrated in-situ characterisation, crystal plasticity modelling and mechanisms**
**Prof. Fionn Dunne**
Chair in Micromechanics at Imperial College, UK
Chair: Richard W. Neu (Georgia Institute of Technology, USA)

| WED, 09:50 - 10:30 | PLENARY LECTURE VIII | Room Funchal |
|---|---|---|

**Integrity of Additive Manufacturing TC4 Alloy Material and Lattice Structure**
**Prof. Yu’e Ma**
Professor and Director of Institute of Structure Integrity Analysis in Northwestern Polytechnical University (NWPU), China
Chair: Youshi Hong, (Chinese Academy of Sciences, China)

| **Wednesday, 10:30 - 11:00** | **COFFEE-BREAK** | **Lounge** |
|---|---|---|

| Wed | Session 6A 11:00-12:45 | Room Funchal |
|---|---|---|
| TOPIC: Symposium A - Fatigue and Fracture in Metal Additive Manufacturing<br>Chair: Marta Kurek – FERROUS ALLOYS | | |
| Ref: | Title and Author (s) | |
| 331 | Fatigue behaviour of 17-4PH martensitic stainless steel additively manufactured by Metal Binder Jetting<br>Pierre Merot, Benoit Roman, Hugo Roirand, Denis Vincent, Vincent Bonnefoy, Thomas Landron, Franck Morel | |
| 104 | Fatigue Behaviour of ER70S-6 WAAM Carbon Steel under Variable Amplitude Loading: Effect of Build Orientation and Critical Internal Defects<br>Mariela Mendez-Morales, Ricardo Branco, Joel Jesus, Trayana Tankova, Emilia Grochowska, Grzegorz Ziółkowski, Carlos Rebelo | |
| 306 | Strut-dependent fatigue behavior of PBF-LB/M 316L steel with regard to lattice structure properties<br>P. Karentzopoulos, G. Mao, S. Stammkötter, S. Mrzljak, S. Münstermann, F. Walther | |
| 316 | Use of multi-material additive manufacturing to produce complex dual steel parts with superior fatigue properties<br>Lucy Farquhar, Jürgen Bär, Eric A. Jägle | |
| 217 | Correlating In-situ Monitoring with Defect Formation in SLM: A Comparative Study of EOSTATE Optical Tomography Outputs and Unprocessed Monitoring Data<br>Yusuf Bakir, I. Zetková, Adam Polansky | |
| 467 | Effect of build orientation and loading conditions on the fatigue behaviour of additively manufactured 18 Ni300 maraging steel – part 1<br>Marta Kurek, Andrzej Kurek, Mihiretu Ganta, Tadeusz | |
| 468 | Effect of build orientation and loading conditions on the fatigue behaviour of additively manufactured 18 Ni300 maraging steel – part 2<br>Andrzej Kurek, Marta Kurek, Abdullah El Sabea | |

| Wed | Session 6B 11:00-12:45 | Room Berlim (1st floor) |
|---|---|---|
| TOPIC: Symposium D - Laser Peening and Related Residual Stress Engineering Processes for Fatigue Improvement<br>Chair: Domenico Furfari: Industrial Applications | | |
| Ref: | Title and Author (s) | |
| 122 | Nikolai Kashaev (Hereon): Laser peening for fatigue enhancement in the aerospace industry | |
| 288 | Carina Lopes (Wits): Laser Peen Forming for Deformation Correction in Aeronautical Structures | |
| 089 | Yuhui Fan (NUAA University): Fatigue Strength Evaluation of Laser Shock Peened Blades Subjected to Foreign Object Damage | |
| 070 | Zbyněk Špirit (Centrum výzkumu Rez s.r.o.): Extending the Fatigue Properties of Water and Steam Turbine Blade Materials by Laser Peening | |
| 315 | Dominik Pöltl (Leuphana Uni): Residual stress engineering for fatigue crack retardation by laser shock peening in additively manufactured aluminum | |
| 319 | Fahem BOUDRIES (Imagine Optic): High-Energy, High-Repetition-Rate Laser Shock Peening Enabled by Optical Fiber Delivery | |
| 470 | Donato Gallitelli (Euro Technologies): Fibred laser shock peening without coating: Analysis of the homogeneity of residual stresses related to process parameters. | |

| Wed | Session 6C 11:00-12:45 | Room Sidney (2nd floor) |
|---|---|---|
| TOPIC: Advanced modelling, simulation, and life prediction methods<br>Chair: Ricardo Claudio | | |
| Ref: | Title and Author (s) | |
| 041 | Longer life censored P-S-N curve experiment and fitting method<br>Liyang Xie, Ningxiang Wu | |
| 042 | StressLifeEBA: An Accelerated Energy-Based Lifetime Prediction Method for the Estimation of Trend S-N Curves for Various Testing Conditions<br>Jonas Anton Ziman, Fabian Weber, Aline Wagner, Janina Koziol, Peter Starke | |
| 051 | Multiaxial fatigue strength estimation of plasma-nitrided carbide-rich PM tool steels: comparison of failure hypotheses and mean stress sensitivity<br>Frederik Tegeder, Christoph Broeckmann | |
| 061 | Modeling of Dissipative Mechanisms Related to Fatigue of 3D Woven Composites<br>B. S. Barini, M. Le Saux, Y. El Archi, L. Navrátil, N. Carrere | |
| 062 | Numerical investigation of defect population effect on the fatigue strength anisotropy of Ti64 fabricated by Laser Powder Bed Fusion<br>S.S Penkulinti, N. Saintier, M. Bonneric, B. Verquin, T. Palin-Luc, F. Lefebvre, P. Ghys | |
| 071 | Evaluation of Transient Creep and Oxidation Damage in Thermomechanical Fatigue of Nickel-Based Superalloys<br>Jiaqi Lu, Huang Yuan | |
| 075 | Application of a Probabilistic Fatigue Strength Model to Case-hardened Steel<br>Oliver Schenk, Jean-André Meis, Christoph Broeckmann | |

| Wednesday, 12:45 - 14:15 | LUNCH | Restaurant |
|---|---|---|

| Wed | Session 6D<br>11:00-12:45 | Room Paris<br>(1st floor) |
|---|---|---|
| TOPIC: Material behavior under complex loading conditions<br>Chair: Bernd M. Schönbauer | | |
| Ref: | Title and Author (s) | |
| 268 | Influence of the Load Type on the Fatigue Behavior of Additively Manufactured AISI 316L<br>Paula Rahm, Andreas Warth, Roman Teutsch, Tilmann Beck, Bastian Blinn | |
| 269 | Notch effects on the dwell-fatigue behavior of the Ti-6Al-4V alloy<br>Julie Bouillon, Samuel Hémery, Patrick Villechaise, Benjamin Dod | |
| 352 | The influence of molybdenum and silicon on thermo-mechanical fatigue performance of ferritic compacted graphite iron<br>E. Kihlberg, V. Norman, R. Romero Ramirez, J. Moverare, P. Skoglund | |
| 389 | Simulation of complex fatigue specimen geometries and comparison with deformation induced martensite density mapping for steels used in nuclear components<br>Jens Arndt, Viktor Lyamkin, Kai Donnerbauer, Klaus Heckmann, Fabian Weber, Peter Starke, Frank Walther | |
| 079 | Experimental investigation of mixed-mode fatigue crack growth under variable amplitude loading<br>Naveen Kumar Kanna, Christopher Benz, Lars Radtke | |
| 272 | Effects of Porosity Defects on the Fatigue Behavior of Al-Si Alloy Castings by Conventional and Ultrasonic Fatigue Testing<br>I.S Cho, S.I Yun, J.S Choi, H.S Song, J.S Park, Y.R Cho, J.Y Lee, H.S Kang, A. Amanov | |
| 076 | Effect of microstructure on pre- and post-punching fatigue behavior of hot-rolled thick-plate advanced high-strength steels<br>Nader Heshmati, Mohammad Hoseini-Athar, Annika Borgenstam, Henrik Sieruin, Joachim | |

| Wed | Session 6E<br>11:00-12:45 | Room Lisboa |
|---|---|---|
| TOPIC: Symposium M - Criteria for multiaxial fatigue and fatigue damage accumulation rules<br>Chair: Luís Pallarés, Vladimir Chmelko, Tadeusz Lagoda | | |
| Ref: | Title and Author (s) | |
| 028 | Fatigue damage accumulation rule based on absorbed hysteresis energy<br>Chmelko, V., Margetin, M., Hujavý, J. | |
| 162 | Mean Stress Effects in Multiaxial HCF Methods: Stress Measures and Calibration<br>Luis Pallarés-Santasmartas | |
| 203 | Application of energy-based damage accumulation rule for fatigue monitoring of structure under variable amplitude loading<br>Matus Margetin, Vladimir Chmelko, Jakub Hujavy | |
| 027 | Absorbed hysteresis energy - parameter of fatigue damage<br>Chmelko, V., Margetin, M., Hujavý, J. | |
| 175 | The limit notch radius in mixed mode I+III loadings and an effective stress for multiaxial fatigue design<br>Pietro Foti, Michele Zappalorto, Filippo Berto | |
| 146 | Parasitic effects in cyclic testing of samples for fatigue damage accumulation<br>Koščo, V., Margetin, M., Chmelko, V. | |
| 435 | Hybrid Global Optimization for Critical Plane Identification under Multiaxial Random Loading<br>Adam Niesłony, Dariusz Skibicki | |

| Wednesday, 12:45 - 14:15 | LUNCH | Restaurant |
|---|---|---|

| Wed | Session 7A 14:15-16:00 | Room Funchal |
|---|---|---|
| TOPIC: Symposium A - Fatigue and Fracture in Metal Additive Manufacturing<br>Chair: Reza Talemi - STRUCTURES | | |
| Ref: | Title and Author (s) | |
| 327 | Influence of Deposition Sequence on the Fatigue Performance of WAAM SS309L–IN625 Bimetallic Materials<br>Ozan Can Ozaner, Abhay Sharma, Tegoeh Tjahjowidodo, Reza Talemi - Invited Talk – 30 min. | |
| 364 | Optimal range of processing parameters and a dimensionless factor in AM to dominate fatigue performance of AMed parts<br>Youshi Hong, Yu Xia, Aiguo Zhao | |
| 186 | Impact of Heat Treatments on the Fatigue Behaviour of AlSi10Mg Processed by PBF-LB/M<br>João Marques, Afonso Leite, Pedro Jesus, Carla M. Ferreira, José Simões, Maria J. Carmezim, Célio Pina, Rodolfo Batalha, Luís Reis, Ricardo Cláudio | |
| 320 | Design-for-Inspection of a Topology-Optimized PBF-LB/M Nose Landing Gear Fork and Component-Level Fatigue Life Validation<br>Felix Scholz, Lea Strauß, Günther Löwisch, Isabel Bayerdörfer | |
| 318 | Comparison of Room and High Temperature Fatigue Behavior of the New Ni-based Superalloy VDM 780 Fabricated by Laser Powder Bed Fusion<br>Louis Hébrard, Mauro Madia, Itziar Serrano-Munoz, Hans Jordan, Birgit Rehmer, Juri Munk, Joachim Gussone, Jan Haubrich | |
| 172 | Effect of post-processing heat treatments on the fatigue crack growth resistance of an AlSi10Mg alloy produced by laser-based powder bed fusion<br>Sidney Araújo, Geraldo Faria, Leonardo Godefroid, Ricardo Claudio, Rodolfo L. Batalha | |
| 194 | Melt Pool Signatures as Indicators of Defects and their Impact on Rotating-Bending Fatigue Samples Produced by PBF-LB/M<br>Carla M. Ferreira, Afonso Leite, João Marques, José Simões, Pedro Jesus, Rodolfo Batalha, Luís Reis, Ricardo Cláudio | |

| Wed | Session 7B 14:15-16:00 | Room Berlim (1st floor) |
|---|---|---|
| TOPIC: Symposium D - Laser Peening and Related Residual Stress Engineering Processes for Fatigue Improvement<br>Chair: Nikolai Kashaev - High Strength Alloys | | |
| Ref: | Title and Author (s) | |
| 084 | Hackel Lloyd (Curtiss Wright): Laser peening to mitigate hydrogen driven fatigue cracking of steel | |
| 300 | Klemen Pregeljc (Ljubliana Uni): Laser shock peening effect on mechanical response of a superelastic NiTi alloy | |
| 293 | Yunji Cho (KIMS): Effect of Surface Treatment on Residual Stress Distribution and High-cycle Fatigue Properties of Lap-welded DP600 Steel Joints | |
| 291 | Dong Jun Lee (KIMS): Effects of Surface Treatment on Microstructure, Residual Stress Relaxation, and High-Temperature Creep Behavior of Powder Metallurgy René 95 | |
| 020 | Aoki Tomofumi (Keio University): Effects of Surface Modification on Residual Stress Stability during Fatigue in AISI 4140 Steel | |
| 163 | Henry Boyle (Linköping University): Influence of Surface Treatments Fatigue Life of the Ni-Based Superalloy AD730® | |

| Wed | Session 7C 14:15-16:00 | Room Sidney (2nd floor) |
|---|---|---|
| TOPIC: Advanced modelling, simulation, and life prediction methods<br>Chair: Giovanni Meneghetti | | |
| Ref: | Title and Author (s) | |
| 086 | A universal formula to estimate the fatigue crack growth rate in arbitrary metals at arbitrary R-values and temperatures<br>Hans-Jakob Schindler | |
| 052 | Fatigue Life for Three-Point Bending of Rubber Composites with Different Reinforcement Layers<br>Tadeusz Lagoda, Karolina Głowacka, Marko Nagode, Marta Kurek, Jernej Klemenc | |
| 088 | Fatigue fractures of cracked rubber composites after three-point bending<br>Joanna Małecka, Karolina Głowacka, Andrej Škrlec, Marko Nagode, Jernej Klemenc, Tadeusz Łagoda | |
| 148 | Numerical fatigue strength investigation of wire and arc additive manufactured (WAAM) specimens based on 3D-scans and implicit gradient model<br>Sulaiman Shojai, Hessam Moshayedi, Moritz Braun, Elyas Ghafoori | |
| 171 | Automated implementation of the PSM combined with shell finite element models for the fatigue design of complex welded structures<br>Alberto Visentin, Alberto Campagnolo, Vittorio Babini and Giovanni Meneghetti | |
| 123 | A Phenomenological Approach of the Shear-Cutting Influence on the Fatigue Properties of Steels<br>Marc Stolzenburg | |
| 176 | A phase-field numerical study on the effects of Thermal Growth Oxide thickness and composition on thermal fatigue failure of thermal barrier coatings<br>Lang Gao, Jiewei Lin, Junhong Zhang, Lin Yu, Tianci Wang, Huwei Dai | |

| Wednesday, 16:00 - 16:30 | COFFEE-BREAK | Lounge |
|---|---|---|

| Wed | Session 7D 14:15-16:00 | Room Paris (1st floor) |
|---|---|---|
| TOPIC: Case studies, industrial applications, and reliability analysis<br>Chair: Adam Niesłony | | |
| Ref: | Title and Author (s) | |
| 481 | Condition assessment of the Firing Control Handle Socket and Pivot in the Portuguese Air Force F-16 aircraft<br>Inês M. F. de Carvalho, T. Barros, B. Santos, L. Reis | |
| 177 | Dynamic response and life analysis of a reverse flow type pulse detonation combustor<br>Jing Xin, Zheng Longxi | |
| 230 | Mechanical Characterisation and Fatigue Testing of Material from a Historical Metallic Railway Bridge<br>Patrícia Freitas, José Oliveira Pedro, João Pedro Martins, Luís Reis, Ricardo Branco | |
| 457 | Using statistical methods from Aeroengine material allowables development for improved characterization of fatigue properties<br>Ryan L Smith, Balajee Ananthasayanam, Kazuki Nagao, | |
| 141 | Multiaxial fatigue of C45 steel under constant amplitude and random loadings<br>Łukasz Pejkowski, Adam Niesłony, Dariusz Skibicki | |
| 421 | WAAM Repair of GJS 400 Cast Iron: Mechanical Strength and Fatigue Performance<br>Zoé Bourgain, Fabien Szmytka, Philippe Feraud, Nicolas Thurieau | |
| 452 | Fatigue Behavior of Tube-Extracted Specimens: From Experimental Testing to Strain–Life Curve Development<br>Sebastian Raczek, Adam Niesłony, Krzysztof Kluger, Tomasz Łukasik | |

| Wed | Session 7E 14:15-16:00 | Room Lisboa |
|---|---|---|
| TOPIC: Fatigue mechanisms and crack propagation<br>Chair: Franck Morel | | |
| Ref: | Title and Author (s) | |
| 043 | Study on the critical defect identification and life prediction for selective laser melted Ti-6Al-4V alloy<br>Jun Zou, Xiaoyu Xia, Zhenyu Feng, Peng Luo | |
| 126 | A Damage-Based Fatigue Life Model for Additively Manufactured AlSi10Mg Considering Mean Stress, Residual Stress, and Defect Size<br>Lea Strauß, Günther Löwisch | |
| 056 | Effect of shot peening and anodizing on the fatigue life of aerospace aluminum alloys<br>Tissot Maxime, Surand Martin, Mabru Catherine, Chaussumier Michel | |
| 314 | An Experimental Investigation on Small Fatigue Crack Growth Behavior and Mechanism in Al 2024-T3<br>Mi Wang, Lindong Chai, Yihai He, Jing Lin, Wei Zhang | |
| 143 | Improved predictability of near-threshold fatigue crack growth rate data by distinguishing crack closure mechanisms<br>Tomáš Vojtek, Pavel Pokorný, Radek Kubíček, Michal Jambor, Pavel Hutař | |
| 250 | Application of the Effective Critical Plane approach to welded joints<br>Andrea Chiocca, Michele Sgamma, Francesco Frendo | |
| 285 | Crack initiation and propagation characterisation in Inconel 718 at high temperature<br>Julien Lasgorceux, Pascale Kanoute, Charles Bianchetti, Vincent Bonnand, Emmanuel Fessler, Franck Morel | |

| Wednesday, 16:00 - 16:30 | COFFEE-BREAK | Lounge |
|---|---|---|

| Wed | Session 8A 16:30–18:30 | Room Funchal |
|---|---|---|
| TOPIC: Symposium A - Fatigue and Fracture in Metal Additive Manufacturing<br>Chair: Onome Scott-Emuakpor | | |
| Ref: | Title and Author (s) | |
| 247 | Influence and Handling of Process Interruptions in PBF-LB/M - Martin Moser, Vesna Nedeljkovic-Groha | |
| 369 | Macroscopic Fatigue Crack Propagation in Additively Manufactured BCC Lattice Structures<br>Hao Xin, Lei Gao, Xiaofan He | |
| 430 | Tooth Root Fatigue of Topology-Optimized Low-Alloyed Steel Gears Manufactured by Conventional and Additive Manufacturing<br>Philipp Schüßler, Volker Schulze, Stefan Dietrich | |
| 463 | Effect of Post Treatments on the High Cycle Fatigue Behavior of Material Extrusion Additively Manufactured H13 Tool Steel<br>Mahmoud Naim, Mahdi Chemkhi, Delphine Auzene, Julien Boussel | |
| 201 | Accelerated Fatigue Test Comparison for Additively Manufactured Aluminum and Aluminum Matrix Composite<br>Onome Scott-Emuakpor, Philip Johnson, Harshith Vadrevu, and Troy Krizak | |
| 063 | Low-cycle fatigue properties of laser powder bed fusion–manufactured TiB2-modified nickel-based superalloy<br>I. Šulák, L. Pelikán, M. Malý, L. Poczklán, T. Vražina, T. Slezák, M. Bartošák | |
| 482 | Integration of Additive Manufacturing in the production of aeronautical components and systems: Regulatory requirements for metallic materials<br>C.Monteiro, T.Barros, B.Santos, D.Salgado, P.Morais | |
| 351 | Fatigue Behavior of Copper Components Manufactured by Fused Filament Fabrication<br>P. Gast, P. Schüßler, A. Klassen, V. Schulze, S. Dietrich | |

| Wed | Session 8B 16:30–18:30 | Room Berlim (1st floor) |
|---|---|---|
| TOPIC: Symposium D - Laser Peening and Related Residual Stress Engineering Processes for Fatigue Improvement<br>Chair: Domenico Furfari; Nikolai Kashaev; Yuji Sao | | |
| Ref: | Title and Author (s) | |
| 242 | Anna Garambois (ONERA): Experimental study and modeling of SMAT-treated Inconel 718 fatigue behavior | |
| 369 | Jiewei Gao (Xihua University): Damage Tolerance Assessment of Induction-Hardened High-Speed Railway Axles Considering Gradient Structures | |
| 336 | Jai Prakash Gautam (Hyderabad University): Thermal stability of peening induced residual stress and microstructure evolution in Inconel 718 for fatigue life improvement | |
| 287 | Angel Prado (Institute of Thermomechanics CAS): Simulation of Hybrid Selective Laser Melting and Plasma Shock Peening | |
| 274 | Jan Kaufman (HiLASE): Hybrid Laser Shock Peening | |
| 228 | Mauro Madia (BAM): Influence of ultrasonic-assisted milling on surface integrity and fatigue strength of a low alloy steel | |
| 381 | Fatigue and Crack Propagation Behavior of Gradient Structures on Induction-Hardened High-Speed Railway Axles<br>Jiewei Gao, Chengye Wang, Weicheng Xia, Junfu Zhang, Shunpeng Zhu | |
| 368 | Damage Tolerance Assessment of Induction-Hardened High-Speed Railway Axles Considering Gradient Structures<br>Xue Lin, Jiewei Gao, Mingsong Wang, Junfu Zhang, Shunpeng Zhu | |

| Wed | Session 8C 16:30–18:30 | Room Sidney (2nd floor) |
|---|---|---|
| TOPIC: Symposium E - Beyond the empirical Kitagawa-Takahashi diagram: New insights into defect-driven fatigue behaviour<br>Chair: Mauro Madia; Jurgen Bar; Franck Morel | | |
| Ref: | Title and Author (s) | |
| 309 | Influence of Cyclic Hardening Behavior on Fatigue Performance<br>Danton Buticosihz Müller, Pierre Osmond, Daniel Irmer, Pierre Mérot, Yves Nadot, Franck Morel | |
| 329 | A unified non local approach to interpret defect's size and shape effects on fatigue crack initiation<br>Pierre Merot, Franck Morel, Camille Burton, Etienne Pessard, Linamaria Gallegos Mayorga | |
| 372 | Evaluating the effects of film cooling hole manufacturing defects on the high-cycle fatigue strength of a turbine blade specimen<br>Yue Wang, Rong Jiang, Mo Chen, Xiaoyu Li, Yingdong Song | |
| 382 | Influence of Hard Chrome Coating Thickness on the Fatigue Resistance of Steel Shafts: Experimental Study and Kitagawa–Takahashi Based Assessment<br>Driss El Khoukhi, Isabel Huther, Guillaume Elbe, Gérard Weber, Philippe Magat, Julien Delgado, Christophe Reynaud, Yanneck Suchier, Fabien Lefebvre | |
| 392 | Fatigue threshold prediction through inverse multiscale construction of the Kitagawa–Takahashi diagram and cyclic R-curve<br>Kazuki Shibanuma, Qingzhi Yao | |
| 396 | Fractographic observation of small crack propagation in conventional and additively manufactured Ti<br>Ondřej Kovářík, Anna Kimlová, Milan Kocáb, Aleš Materna | |
| 431 | Influence of mean stress on the defect-driven fatigue strength<br>Suraj S. More, Herwig Mayer, Joona Vaara, Miikka Väntänen, Tero Frondelius, Bernd M. Schönbauer | |
| 462 | Determination of the Kitagawa-Takahashi Diagram by means of short crack models<br>Mauro Madia, Jürgen Bär, Larissa Duarte | |

| Wed | Session 8D<br>16:30-18:30 | Room Paris<br>(1st floor) |
|---|---|---|
| TOPIC: Material behavior under complex loading conditions<br>Chair: Ulrich Krupp | | |
| Ref: | Title and Author (s) | |
| 454 | Theoretical Model for the Temperature-Electric Field dependent Ultimate Tensile Strength of Metallic Materials<br>Ru Li, Weiguo Li, Tianzi Shi | |
| 006 | Evaluation of Tribo-Fatigue Properties of Alumina-Coated 316L Stainless Steel Using Two Thermal Spray Deposition Processes<br>Halima Ghorbel, Radouane Akrache, Jinan Charafeddine | |
| 332 | Intergranular Cracking during Dwell-Time Fatigue of Nickel-Based Superalloys at Elevated Temperatures – The Dynamic Embrittlement Mechanism<br>Ulrich Krupp, Lars Bähren, Charleen Baumann, Thomas Seifert, Hans-Jürgen Christ, Ken Wackermann, Aljoscha F. Baumann, Daniel Urban | |
| 394 | Fatigue behaviour of annealed AA5083 aluminium alloy specimens under block testing sequence<br>Zbigniew Marciniak, Ricardo Branco, Rui F. Martins, Wojciech Macek, Cândida Malça | |
| 120 | From Wrought to Additive: Comparing Thermal Fatigue Damage in AISI 430 Using an Optimized Specimen Geometry<br>Nicolas Thurieau, Baris Telmen, Fabien Szmytka | |
| 132 | A Critical Review of Coupled Mechanical, Thermal and Electrical Stress in Electrical Insulation Systems<br>Tetjana Tomaskova, Jaroslav Hornak, Pavel Trnka | |
| 231 | Low-Cycle Fatigue Assessment of thin plates extracted from aluminium sheets and from Mega-castings<br>Maria Margarita Mitsi, Yu Cao, Johan Ahlström | |
| | | |

| Wed | Session 8E<br>16:30-18:30 | Room Lisboa |
|---|---|---|
| TOPIC: Fatigue mechanisms and crack propagation<br>Chair: Reinhard Pippan | | |
| Ref: | Title and Author (s) | |
| 238 | Fatigue Crack Characteristics in Gradient Predeformed Pearlitic Steel under Multiaxial Loading<br>Daniel Gren, Johan Ahlström, Magnus Ekh | |
| 244 | Thermomechanical Fatigue: Early Irreversible Deformation and Its Impact on Lifetime<br>Stefan Guth, Jan Lars Riedel, Dhruv Anjaria, Mathieu Calvat, Jean-Charles Stinville | |
| 307 | In-situ Crack Propagation of Pearlitic Rail Steel Subjected to Large Shear Deformation<br>Tsering Wangmo, Daniel Gren, Anton Hohenwarter, Ehsan Ghassemali, Christer Persson, Johan Ahlström | |
| 142 | Micro Scale Investigation of Fatigue in TiAl Alloys<br>Pascale Kanoute, Anna Ask, Louise Toualbi | |
| 465 | Effect of cyclic pre-strain on the functional fatigue in superelastic NiTi alloys<br>Tianyi Hu, Xiaoxian Zhang, Jinsong Leng | |
| 281 | Ultra-high fatigue strength steel enabled by coherent nanoprecipitates and Mo-enriched grain boundaries<br>Suihe Jiang, Yuewu Li, Zhaoping Lu | |
| 289 | Short crack growth from deep and shallow notches in a multi-phase high-strength steel<br>Lukas Walch, Thomas Klünsner, Bernhard Sartory, Stefan Marsoner, Larissa Egger, Anton Hohenwarter, Harald Leitner, Reinhard Pippan, Gerald Ressel | |
| 401 | Effect of Dynamic Strain Aging-mediated Thermomechanical Treatments on the Fatigue Properties of Notched Commercially Pure Titanium<br>Nafiseh Ghavidel, Phanuphak Seensattayawong, Eberhard Kerscher | |

| Wednesday, 19:00 - 22:00 | Conference Banquet | O LAGAR - Restaurant |
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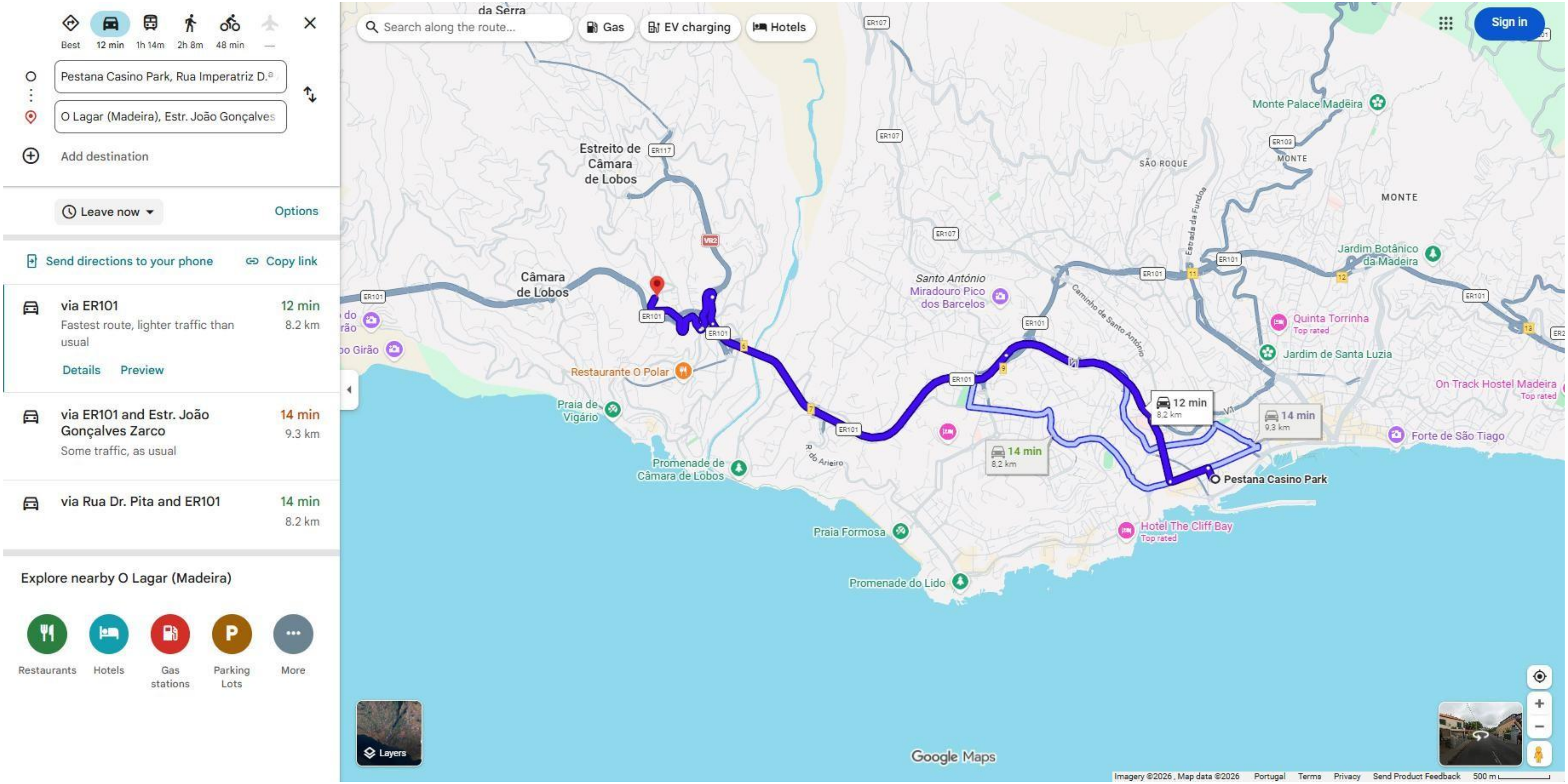

## Thursday, 2 July 2026

| THU, 09:00 - 09:45 | PLENARY LECTURE IX | Room Funchal |
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**Ultrasonic fatigue testing of superelastic Nitinol and in-situ observation of VHCF damage in the synchrotron**

**Prof. Herwig Mayer**

Institute of Physics and Materials Science, BOKU University, Peter-Jordan-Str. 82, 1190 Vienna, Austria

| THU, 09:45 - 10:30 | PLENARY LECTURE X | Room Funchal |
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**Fatigue of AM materials: from fundamental mechanisms to component assessment**

**Prof. Stefano Beretta**

Politecnico di Milano, Dept. Mechanical Engineering, IT

Chair: Ali Fatemi (University of Memphis, USA)

| **Thursday, 10:30 - 11:00** | **COFFEE-BREAK** | **Lounge** |
| --- | --- | --- |

| Thu | Session 9B<br>11:00-12:45 | Room Berlim (1st floor) |
|---|---|---|
| TOPIC: Symposium G - Mechanics of Fretting Fatigue<br>Chair: Sean Leen; Camille Gandiolle; Reza Talemi | | |
| Ref: | Title and Author (s) | |
| 139 | Size Effects and Subsurface Defects in the Fretting Fatigue Response of Additively Manufactured Ti-6Al-4V from Coupon-Scale Specimens to Dovetail Joint Connections<br>Grzegorz Glodek, Tomáš Karas, Martin Nesládeka, Brecht Van Hooreweder, Reza Talemi | |
| 198 | Application of a computationally efficient fretting wear-fatigue analytical model to submarine power cables<br>S.M. Uí Mhurchadha, C. Poon, S.B. Leen | |
| 226 | Study on the mechanics of fretting crack initiation for flat-on-flat contacts<br>Denny Knabner, Marius Matthias Müller, Alexander Hasse | |
| 227 | Mitigation of fretting fatigue: Effects of case-hardening on the durability and failure modes<br>Marius Müller, Denny Knabner, Jiří Čapek, Karel Trojan, Alexander Hasse | |
| 333 | A High-Fidelity 3D Modeling and Life Prediction Framework for Fretting Fatigue–Wear Interaction<br>Samira Ghadar, Jim Lua, Ali Fatemi | |
| 275 | Crystal plasticity modelling of defect effects on fretting fatigue in laser powder bed fusion of Ti6Al4V<br>Sunil Kumar Yadav, Majid Kavousi, Sean Leen, Reza Talemi | |

| Thu | Session 9A<br>11:00-12:45 | Room Funchal |
|---|---|---|
| TOPIC: High-cycle and very high cycle fatigue<br>Chair: Jan Papuga | | |
| Ref: | Title and Author (s) | |
| 065 | Influence of fatigue limit under pulsating tension loading on Multiaxial Fatigue Models<br>P. Apodaka, M. Abasolo, E. Tabares, L. Pallares, X. Orue | |
| 072 | General Relation between Fatigue Strength and Tensile Strength of Metallic Material<br>Jianchao Pang, Chong Gao, Xiaoyuan Teng, Shouxin Li, Zhefeng Zhang | |
| 103 | Statistical Generation of Virtual Scatter Bands within Accelerated Lifetime Prediction Methods<br>Aline Wagner, Fabian Weber, Peter Starke | |
| 461 | Very high cycle fatigue life of high strength steels exposed to different levels of corrosion<br>Jan Klusák, Kamila Kozáková, Anna Sandnerová, Stanislav Seitl | |
| 338 | Effect of microstructural changes on fatigue limit in early stage of fatigue process of austenitic stainless steels<br>Shota Oikawa, Noriyasu Oguma, Kenichi Masuda, Masaki Okane | |
| 106 | Size effects on fatigue life of additve manufactured Ti6Al4V<br>Wenbo Sun, Yu'e Ma, Weihong Zhang | |
| 340 | Machine learning-based correction for non-proportional multiaxial high-cycle fatigue criteria<br>Antoine Chambrey, Lorenzo Bercelli, Cédric Doudard, Yohan Cosquer, Shabnam Arbab Chirani | |

| Thu | Session 9C<br>11:00-12:45 | Room Sidney (2nd floor) |
|---|---|---|
| TOPIC: Advanced modelling, simulation, and life prediction methods<br>Chair: Gubeljak Nenad | | |
| Ref: | Title and Author (s) | |
| 179 | Using small crack growth to calculate high cycle fatigue life for different maximum stress and stress ratios<br>E. Amsterdam | |
| 341 | Fatigue Assessment of High Strength Windmill Studs Considering Process Residual Stresses and Cold Formed Layer<br>.A. Esnaola, J. Mendiola, M. Larrañaga, N. Otegi, X. | |
| 215 | Non-destructive Material Property Measurements for Meso-aggregate Fatigue Model<br>Isaiah Zebrowski, Juan Julio Gonzalez-Frias, Jinseok Kim, Daniel Kujawski | |
| 219 | Numerical Investigation of the Fatigue Behaviour of TPMS Structures<br>Žiga Žnidarič, Branko Nečemer, Srečko Glodež | |
| 253 | Fatigue characterization of tread braked railway wheels by experimental and numerical analysis<br>G. Megna, A. Bracciali, A. Francesconi, A. Lanzutti, F. Sordetti | |
| 256 | An impact fatigue model for TC18 titanium alloy considering stress gradient and load dynamic effects<br>Xulong Chen, Xiongfei Li, Yupei Guo, Qiang Yang, Weiping Hu, Zhixin Zhan, Qingchun Meng | |
| 187 | A local approach to understanding the bimodal fatigue behavior of gear teeth made from case-hardened steel<br>Aniclelson Alves De Moura, Franck Morel, Etienne Pessard, Daniel Bellett, Louis Augustins, Damien Herisson | |

| Thursday, 12:45 - 14:15 | LUNCH | Restaurant |
|---|---|---|

| Thu | Session 9D<br>11:00-13:00 | Room Paris<br>(1st floor) |
|---|---|---|
| TOPIC: Environmental effects, corrosion, and hydrogen embrittlement<br>Chair: Rui Martins | | |
| Ref: | Title and Author (s) | |
| 095 | Critical Assessment of Cracking Hydrogen Storage Vessel and An Evaluation of Critical Crack Size<br>Un Bong Baek, Jaeyeong Park, Kyung-Oh Bae, Thanh Tuan Nguyen | |
| 129 | Characterization of two high-strength austenitic stainless steels in fatigue and damage tolerance in hydrogen conditions at cryogenic temperatures<br>D. Willem, G. Henaff, C. Parrens, R. Walter, A. Oudriss, X. Feaugas, C. Berziou | |
| 279 | Environmentally Assisted Fatigue of austenitic Weld Material<br>Petr Gál, Ivana Schnablová, Radek Novotný, Miroslav Pejša, Radim Kopřiva | |
| 235 | Can oxidation damage be beneficial to cracking resistance under long-dwell fatigue loading at elevated temperature?<br>Binchao Liu, Qiuyi Wang, Rui Bao | |
| 477 | Effect of fiber orientation on stiffness reduction in cracked composite laminates subjected to hygrothermal aging<br>Billel Boukert, Mohamed Khodjet Kesba, Amina Benkhedda, El abbes adda Bedia | |
| 029 | Preventing Hydrogen Embrittlement in Hydrogen Gas Pipelines through Trace Carbon Monoxide Addition<br>Juan Shang, Hiroto Hayashi, Masanobu Kubota | |
| 154 | Thermomechanical and isothermal fatigue of 316L stainless steel with long hold periods in LWR environment<br>Tomáš Babinský, Philippe Spätig, Hans-Peter Seifert | |
| 283 | Fatigue crack initiation mechanisms in 7XXX Aluminum Alloys in representative aircraft environment (temperature, humidity)<br>F. Mazerolle, G. Hénaff, J. Rousset | |

| Thu | Session 9E<br>11:00-12:45 | Room Lisboa |
|---|---|---|
| TOPIC: Fatigue mechanisms and crack propagation<br>Chair: Luca Susmel | | |
| Ref: | Title and Author (s) | |
| 108 | NDT-Based Hysteresis Measurements as a Key to Multiparametric Fatigue Characterization of Metallic Materials<br>Peter Starke, Riko Schanzenbach, Aline Wagner, Jan-Erik Nebel, Jonas Anton Ziman, Janina Koziol, Fabian Weber | |
| 267 | Effect of Hydrogen Pressure and Loading Frequency on Fatigue Crack Growth in Nickel Alloy 625<br>Pierre Osmond, Marie Lemaitre, Thomas Landron, Théo Larue, Daniella Guedes Sales, Ayoub El Moutaouakkil, Anthony Nakhoul | |
| 344 | In-situ Experimental Investigation on Crack Initiation and Small Crack Propagation from Corrosion Pits<br>Dian Wang, Lindong Chai, Wei Zhang | |
| 358 | Fatigue deformation and crack growth behavior in Al-containing high manganese austenitic steels<br>Lihe Qian | |
| 326 | A Fatigue Crack Growth Analysis Accounting for R-ratio Effects<br>Daniel Kujawski | |
| 060 | The Effect of Prior Low Cycle Fatigue on the Creep Resistance of a 10% Cr Martensitic Steel<br>Mishnev Roman, Wu Kaiming, Rustam Kaibyshev, Nadezhda Dudova | |
| 375 | Hydrogen-Assisted Fatigue in Vintage API 5L X60 Pipeline Steel Containing Micro-Defects: Experiments and Defect-Based Life Assessment<br>H. Wang, R. Best, D. Engelberg, I. Hajirasouliha, N. O. Larrosa, F. Scenini, L. Susmel | |
| 471 | Probabilistic Fatigue Life Assessment of Additively Manufactured Maraging Steel<br>F. Bumba, V. Anes, P. Morais, R. Batalha, K. Trojan, L. Reis | |

| Thursday, 12:45 - 14:15 | LUNCH | Restaurant |
|---|---|---|

| Thu | Session 10B 14:15-16:00 | Room Berlim (1st floor) |
|---|---|---|
| TOPIC: Symposium G - Mechanics of Fretting Fatigue / Damage<br>Chair: Sean Leen; Camille Gandiolle; Reza Talemi | | |
| Ref: | Title and Author (s) | |
| 385 | 3D kinematics fields in fretting contact from X-ray tomography<br>Jérémy Grondin, Camille Gandiolle, Youssef Younes, Benjamin Smaniotto, Jean-Christophe Teissedre, Jan Neggers, Pierre Arnaud | |
| 399 | Numerical analysis of crack initiation in the nub–groove contact of marine risers including wear<br>Arthur Ferreira Padilha Sette, Jose Alexander de Araujo, André Luis Rodrigues Araújo, Raphael Araujo Cardoso | |
| 192 | Non-uniform deformation and damage evolution of gradient nano-grained metals: A crystal plasticity simulation<br>Jie Qu, Zhixin Zhan, Weiping Hu, Qingchun Meng | |
| 459 | A Phase-Field Framework for Multiaxial Fatigue Crack Initiation and Propagation for Fretting Problems<br>Iñigo Llavori, Gorka Ruiz-de-Egino, Nagore Otegi, Eguzkiñe Martinez-Puente, Sean Leen | |

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| 303 | Effects of microstructural characteristics on the fatigue behavior of un- and low alloyed steel<br>Janina Koziol, Fabian Weber, Peter Starke | |
| 304 | Slip band influence on grain size effect in Inconel 718<br>Tom L'hermite, Flavien Ghiglione, Jean-Michel Scherer, Henry Proudhon | |
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| 310 | Combining Modal Decomposition and Gaussian Approximation for Fatigue Analysis of Non-Stationary Multi-Channel Random Vibration using Multivariate Moments<br>Josef Weber, Arvid Trapp, Peter Wolfsteiner | |
| 353 | A framework for fatigue life prediction of fiber reinforced composites with limited testing data<br>Lu Yubin, Wu Zhen, Zheng Xitao | |
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| 161 | Estimating fatigue crack location, size, and shape in axially loaded cylindrical specimens using a multi-probe Direct Current Potential Drop method<br>Vecchiato Luca, Campagnolo Alberto, Rollo Matteo, Meneghetti Giovanni | |
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| 190 | Influence of microcracks on fatigue behaviour of welded joints<br>Simon Sedmak, Mihajlo Aranđelović, Stefan Dikić, Lazar Jeremić, Još Neko | |
| 456 | Deformation Mechanisms and Fatigue Behavior of Rubber Composites Investigated Using Digital Image Correlation (DIC)<br>Karolina Głowacka, Andrzej Kurek, Andrej Škrlec | |
| 486 | Fracture Surface Analysis of LPBF-produced Ti-6Al-4V by XPS and AES<br>Yu Cao and Lars Nyborg | |

| Thu | Session 10E<br>14:15-16:00 | Room Lisboa |
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| 087 | Effects of Different Damage States on the Vibration Characteristics of a Composite Containment Casing under Blade-Off Loading<br>Feng Jin, Jianhao Zhang, Yan Zhang, Ying Zhang, Lulu Liu, Zhihao Xie, Wei Chen | |
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| 200 | Advancing VHCF Characterization of Cantilevered Bending Specimens via Ultrasonic Fatigue Testing<br>A. Oliveira, J. H. Lopes, P. Costa, R. Cláudio, R. Batalha, L. Reis | |

| Thursday, 16:00 - 16:30 | COFFEE-BREAK | Lounge |
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| Thu | Session 11A 16:30–18:30 | Room Funchal |
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| 439 | Fatigue performance degradation of rafted nickel-based single crystal superalloys: tensorial microstructure, constitutive modeling, and fatigue life prediction<br>Luo Cheng, Yuan Huang | |
| 384 | Fatigue Life Prediction of Ceramic Matrix Composites Based on Early-Cycle In-Situ Electrical Resistance Monitoring<br>Jiaming Li, Guoqiang Yu, Tao Wu, Wenxuan Qi, Yingdong Song, Xiguang Gao | |
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| TOPIC: Symposium E - Beyond the empirical Kitagawa-Takahashi diagram: New insights into defect-driven fatigue behaviour<br>Chair: Mauro Madia; Jurgen Bar; Franck Morel | | |
| Ref: | Title and Author (s) | |
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| 099 | Validation of the Kitagawa-Takahashi Diagram – A New Method using DC Potential Drop Measurements<br>Jürgen Bär, Mauro Madia | |
| 155 | What is Kitagawa-Takahashi diagram? Remaining anomalies and biases<br>Joona Vaara, Miikka Väntänen, Kimmo Kärkkäinen, Jukka Kemppainen, Tero Frondelius | |
| 159 | An Experimental Evaluation of Fatigue Life Models for Small Defects<br>Roberto Azevedo da Costa, Fábio Comes de Castro | |
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| Thu | Session 11E 16:30-18:30 | Room Lisboa |
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| 346 | Fatigue behaviour of flow drilling screw joints for automotive applications<br>Rita Dantas, Roya Darabi, Inês Guedes, Rui Amaral, Rúben Santos, José Machado, Abílio de Jesus, Ana Reis | |
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| Thursday, 18:45 | CLOSING SESSION | Room Funchal |
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| | **Conference Organising Committee** | |

| Friday, 3 July 2026 | | |
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| Friday, 09:00 | Conference Tour | departure at the hotel |
| "Madeira Sightseeing, Wonders of the East – Santana" | | |

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# The Role of Defects on Fatigue Strength and Modeling of Their Effects with Applications to AM Metals

**Ali Fatemi[1] and Yukitaka Murakami[2]**

[1] *Chair of the Mechanical Engineering Department at the University of Memphis in Tennessee*

[2] *Emeritus Professor at Kyushu University*

**Abstract** Defects and nonmetallic inclusions are the main sources of fatigue strength reduction and data scatter in metals. Although their effects have been studied for many years, there has been much recent interest in the topic due to the advent of additive manufactured (AM) metals where porosity and lack of fusion defects often control the fatigue behavior. Traditional crack initiation approaches, such as the S-N and strain-life methods, do not explicitly consider presence of defects. In this talk, first defects are characterized in terms of their type, shape, size, and location, with examples from metal castings and AM metals. Then, modeling approaches from simple S-N method where defects will be explicitly accounted for, to more sophisticated fracture mechanics approaches will be presented. Life predictions using these methods will be compared with experimental results from castings and AM metals. Effects often present in structural applications, such as multiaxial stresses, mechanical notches, and surface finish, will also be considered.

# Phase field modelling of fatigue and hydrogen-assisted fatigue

**Emilio Martínez-Pañeda[1]**

[1]*Department of Engineering Science, University of Oxford, Oxford (UK)*

*Phase field* *Fatigue crack growth* *Hydrogen embrittlement*

**Abstract** Predicting fatigue failures remains one of the most elusive challenges for scientists and engineers. In this work, we develop a comprehensive phase field model capable of predicting fatigue failures of arbitrary complexity [1]. Through comparison with experiments, the model is shown to accurately predict the fatigue behaviour of materials, including S-N curves, Paris law crack growth, the influence of the load ratio, mean stress effects, stress concentrator factors and the endurance limit. In brittle and quasi-brittle solids, the model is able to predict fatigue crack growth rates from S-N curves, and vice versa. Aspects of the numerical implementation will also be discussed, showing how complex fatigue cracking phenomena in 2D and 3D can be captured, over millions of cycles, through the development and use of new acceleration schemes.

Moreover, the framework is extended to account for the presence of hydrogen, an area of notable interest. Two aspects have mainly motivated this interest: (i) the pervasive observation of hydrogen-assisted failures across the construction, transport, defence and energy sectors, partly due to the higher susceptibility of modern, high-strength alloys; and (ii) the role that hydrogen is deemed to play in our road towards net-zero, which has fostered a notable interest in the design and prognosis of infrastructure for hydrogen transportation and storage. The phase field fatigue framework described in the first part of the talk will be extended to incorporate the role of hydrogen in increasing fatigue crack growth rates and decreasing the number of cycles to failure [2,3]. Without any additional parameters, the model is shown to quantitatively agree with experiments conducted for a wide range of hydrogen pressures, load ratios and loading frequencies. Moreover, *Virtual Tests* are also conducted on full-scale components, showing a remarkable level of agreement with the outcome of full-scale testing campaigns. The computational framework development can be used to efficiently assess the behaviour of structures and components exposed to hydrogen-containing environments, preventing catastrophic failures and mapping safe regimes of operation

## References

[1] A. Golahmar, C.F. Niordson, E. Martínez-Pañeda. A phase field model for high-cycle fatigue: total-life analysis. International Journal of Fatigue 170, 107558 (2023)

[2] A. Golahmar, P.K. Kristensen, C.F. Niordson, E. Martínez-Pañeda. A phase field model for hydrogen-assisted fatigue. International Journal of Fatigue 154, 106521 (2022)

[3] C. Cui, P. Bortot, M. Ortolani, E. Martínez-Pañeda. Computational predictions of hydrogen-assisted fatigue crack growth. International Journal of Hydrogen Energy 72, 315-325 (2024)

# Achieving the highest fatigue strength in metals

**Zhan Qu1, Peng Wang1, Zikuan Xu1, Xiaolin Su1, Peng Zhang1,2, Zhefeng Zhang1,2***

[1]*Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences; Shenyang, 110016, China.*

[2]*School of Materials Science and Engineering, University of Science and Technology of China; Shenyang, 110016, China.4These authors contributed equally to this work.*

**Abstract** Nearly 90 per cent of service failures of metallic components and structures are caused by fatigue. The improvement of fatigue strength could help to reduce the risk of fatigue failure to engineering structures and human lives, and contribute to lightweight design, thereby enhancing the efficiency of resource use. Despite numerous attempts, scientists and engineers have struggled to make significant improvements in this area. Here we propose four principles for anti-fatigue design of metals, including: 1) high elastic modulus; 2) fine, uniform and stable microstructure; 3) smallest possible inclusion or defects size and 4) optimal tensile properties. Guided by the four principles above, we successfully achieved the highest fatigue strength and specific fatigue strength to date in additive manufacturing TC4 alloy, 2024Al alloy, GCr15 bear steel, cold-drawn pearlitic steel with oriented nano-scale lamellar microstructure and extremely small inclusions, respectively. Consequently, the extremely high fatigue strength achieved by these principles could provide significant guidance for anti-fatigue design of all metallic materials in the future.

1. Z Qu, Z Zhang, R Liu, L Xu, Y Zhang, X Li, Z Zhao, Q Duan, S Wang, S Li, Y Ma, X Shao, R Yang, J Eckert, RO Ritchie, Z Zhang. High fatigue resistance in a titanium alloy via near-void-free 3D printing. Nature 626 (2024) 999-1004.

2. Z Qu, Z Zhang, R Liu, Z Zhang. Naturally high fatigue performance of a 3D printing titanium alloy across all stress ratios. Sci. Adv., 11 (2025) ady0937

3. Z Xu, X Su, P Wang, P Zhang, B Wang, Z Qu, A Wang, Z Zhang. How high can the fatigue strength of metals be achieved? National Sci Rev., 12 (2025) nwaf332.

4. Wang P, Zhang P, Wang B, Liu XC, Zhu YK, Liu R, Liu Y, Luan YK, Wang P, Li DZ, Ritchie RO, Zhang ZF. The highest fatigue strength for steel. Acta Mater., 289 (2025) 120888.

5. Z Xu, P Wang, P Zhang, B Wang, Y Liu, Y Luan, D Li, R Ritchie, Z Zhang. Fatigue strength optimization of high-strength steels by precisely controlling microstructure and inclusions. J Mater Sci Technol., 230 (2025) 165-176.

# Fretting fatigue life in complex loading conditions, experiments and modelling

**Sylvie Pommier**

*Professor of Mechanical Engineering at ENS Paris-Saclay, France*

**Abstract** A novel method to account for stress gradient effects in fretting fatigue was first proposed by C. Montebello (2015). This approach was subsequently extended by G. Rousseau (2020) to predict fretting fatigue life under multiaxial and non-proportional loading conditions. The framework introduces a constitutive model designed to capture the non-linear behavior of the partial slip zone. Stress gradients are incorporated into the model through intensity factors, which serve as non-local variables, ensuring consistent predictions across diverse contact geometries. These intensity factors are derived from the displacement field at each time step, analyzed within a reference frame attached to the moving contact edge. This allows the model to account for mobile contact fronts - a critical feature in variable loading scenarios. The model's validity was confirmed through 3D finite element analyses for a wide range of contact conditions. Experimental campaigns were then conducted to challenge the model under varying normal loads, revealing two key insights: first, the displacement of the contact edge during testing has a beneficial effect on fretting fatigue life; second, history effects—linked to micro-crack interactions—significantly influence damage progression.

# The Use of Light as Surface Technology to extend Fatigue Life in Aerospace Industry - The Residual Stress Engineering from Historical Review, current Applications and Future Prospective

**Domenico Furfari**

*Airbus Operations GmbH, Kreetslag 10, 21129 Hamburg, Germany*

**Abstract** High Energy pulsed lasers inducing residual stresses into metallic Airframes can be used as surface technology to ensure salvage for identified hot spots in terms of fatigue and crack growth performance as design feature for next generation aircraft (Application Scenario Design) as well as to extend the operational life of Aircraft in service (Application Scenario Repair) .

This paper provides an historical overview of the Laser Peening Technology from the earliest works in the 60', when the laser pulse forming plasma pressure at Lebedev Physic Institute was discovered until, the more recent industrial applications in the Aerospace and Nuclear Industries across the USA and Asia. In the decade from 70' to early 80' the plasma pressure induced by high energy pulsed laser and the consequent compressive residual stresses generated by pressure shock waves travelling into Aluminum alloys (Al7075) was observed at Battelle Memorial Institute in Columbus, Ohio. The High Energy Lasers used did not economically justify applications in industrial environment (very low repetition rates). In the early 90' the US AirForce experienced several Foreign Object Damage (FOD) problems, in particular with F101 and B1-B bomber. Research Institute (such as Battelle Memorial Institute, Lawrence Livermore Research Laboratories) and US spin off Companies under commission of US AirForce industrialized laser systems to make the application of such technology commercially viable to enhance fatigue at Engine Fan Blades produced at GE Aerospace Industry. In the early 2000 Rolls Royce implemented Laser Peening as surface treatment of Engine Fan Blades with a laser system developed by Metal Improvement Company (MIC) subsidiary of Curtiss and Wrights and this represents the first application of laser peening in Aerospace Commercial Industry. Nowadays MIC provides Laser Peening services for all blades of Trent 500-800-1000-XWB Engines. In 1999, Toshiba Corporation in Japan developed a laser peening system capable of delivering the surface treatment in core shrouds of Boiling Water Reactors (BWRs) to prevent Stress Corrosion Cracking using novel pulsed lasers with beam light delivered by means of optical fibers to ensure treatment at 50m distance from laser source in very high contaminated environment.

Next Generation Aircraft can be designed with residual stress engineering induced by Laser Peening treatment to extend the fatigue crack initiation at critical locations of the airframes or to slow down the crack propagation obtaining extension of the Inspection threshold and longer interval of inspections which represent one of the most important economical advantages for Airlines. Structural Joints are one of the most fatigue critical locations on Airframes, this paper will present a novel application of "engineered" residual stresses induced by laser peening process to extend fatigue life of structural joints compared with "classic" cold expansion process on typical aerospace aluminium alloys. The compressive residual stresses induced by laser peening can be also managed at a critical location of airframes to achieve the greatest reduction of Stress Intensity Factors leading to crack growth slow down and as a consequence maximise the propagation life and interval of inspection of aircraft. Test campaign on different ranges of thickness of Middle Tension coupons made of aerospace aluminium alloys will be presented.

# Fatigue Characteristics of Additive Manufactured Lightweight Structures – Challenges and Opportunities from Damage Tolerance Perspectives

**Raj Das[1*], Laboni. Afroz[2], Ma Qian[2], and Mark Easton[2]**

[1]*Centre for Additive Manufacturing, Department of Aerospace Engineering, RMIT University, 124 La Trobe Street, Melbourne, Victoria 3000, Australia - raj.das@rmit.edu.au*

[2]*Centre for Additive Manufacturing, School of Engineering, RMIT University, Melbourne, Victoria 3000, Australia*

**Abstract** Additive Manufacturing (AM) has become a popular technology in the manufacturing of various engineering structures, with primary applications being in aerospace, automotive, biomedical and other industries. For example, it is highly applicable to aerospace industry for both new aircraft structural components and repair of existing parts. It has the potential to save almost 30% of the fuel costs compared to traditional fabrication techniques by introducing intricate lightweight design and reducing assembly and machining operation. However, the use of AM in safety critical applications is still limited due to an incomplete understanding of failure mechanisms of AM-built materials, sensitivity to process-induced defects, and in-service damage from complex dynamic multi-directional loads.

Damage tolerance analysis is essential for aerospace and other capital-intensive industries to ensure requisite operational life. In this context, the effects of dynamic cyclic loads on critical structural components made by AM need to be thoroughly evaluated. Fracture and fatigue behaviour associated with components produced by AM is more complex than that with conventional fabrication techniques because of numerous influencing factors, such as defects, microstructures and anisotropy. Various types of defects, including porosity, are inherent and often unavoidable in bulk AM fabricated parts that impart lower fatigue strength and fracture toughness in as-built AM materials compared to conventionally fabricated materials. These defects accelerate crack initiation and propagation, which hinders the reliability of AM parts from the damage tolerance perspective. Each combination of the AM method and the material introduces unique defects and damage mechanisms into the product, making the assessment of fracture or fatigue failure modes complex.

To obtain the potential benefits of additive manufacturing in critical load bearing applications, such as aerospace, automotive, marine and other industries, the fracture and fatigue performance of additively manufactured materials must be evaluated under different loading conditions. In this context, this work aims to focus on contemporary developments in the characterisation of defects, damage, and failures for additively manufactured materials.

The work addresses major challenges in the integrity and durability of contemporary engineering structures produced using the AM process. It thus encompasses the characterisation of fracture and fatigue properties of different types of metal alloys produced using the common metal additive manufacturing processes. The different stages of work broadly include types and characteristics of defects, modelling of defects, damage, and cracks, fracture mechanisms and fatigue behaviour of AM metal alloys. The effects of various parameters, such as build orientation, microstructure, heat treatment, surface roughness and defects (e.g., porosity, voids, and lack of fusion defects) on the fracture and fatigue properties, including fatigue strength and crack growth characteristics, of AM metal alloys are critically evaluated in relation to the structural integrity of engineering components. The application of fracture mechanics based damage tolerant principles in understanding the mechanical behaviours of AM components and structures will reduce the effective risk of failures and improve the structural integrity.

# Dwell fatigue of aero-engine Titanium alloys: integrated in-situ characterisation, crystal plasticity modelling and mechanisms

**Fionn Dunne**

*Chair in Micromechanics at Imperial College, UK*

**Abstract** Cold dwell fatigue in Titanium aero-engine alloys is the degradation and failure process in which microcracks, or facets, nucleate typically within 15º of basal planes of (hard) HCP grains orientated with their c-axes at or about parallel to principal stress direction. A key driving force has been argued, through use of crystal plasticity (CP) modelling methods, to be creep deformation in an adjacent (soft) grain well-orientated for slip leading to stress redistribution onto the hard grain which occurs during cycle hold times (the dwell period), and over progressive cycling. In addition, dwell facet nucleation and growth has been found to be associated with macrozones (or 'MTRs') which are mm-sized polycrystal regions with strong texture. So far as we are aware, the key mechanistic arguments for soft-grain creep and load shedding onto an adjacent hard grain have not yet been demonstrated or measured in experiment. Similarly, the effect of temperature on dwell fatigue sensitivity has relied on CP modelling which suggests peak load shedding occurs at about 120ºC but which largely diminishes away at about 220ºC, but this also has yet to be demonstrated by experiment and explained. The new work presented in this paper addresses these important questions and provides the latest mechanistic understanding.

# Integrity of Additive Manufacturing TC4 Alloy Material and Lattice Structure

**Yu'e Ma**

*Professor and Director of Institute of Structure Integrity Analysis in Northwestern Polytechnical University (NWPU), China*

**Abstract** Additive manufacturing technology can give the structure designer more chances and freedom to make their design come true. Additive manufacturing Ti6Al4V titanium alloy has a great potential to be applied in aviation structural components. During additive manufacturing process because of its intrinsic features, the deposition layers present, which can lead to defect, anisotropic, residual stress and so on. These integrity parameters can affect mechanical properties of additive manufactured parts and lattice structures. Different build direction Ti6Al4V samples and lattice structures were designed and manufactured in this work. Distributions of defect, residual stress were measured and studied. Tensile, compression and fatigue tests were performed. Effects of build direction, defect, residual stress on mechanical and fatigue properties were investigated and evaluated.

# Plenary Lecture: Ultrasonic fatigue testing of superelastic Nitinol and in-situ observation of VHCF damage in the synchrotron

**Herwig Mayer**

*Institute of Physics and Materials Science, BOKU University, Peter-Jordan-Str. 82, 1190 Vienna, Austria, herwig.mayer@boku.ac.at*

**Abstract** Ultrasonic fatigue testing is uniquely suited to study the VHCF properties of materials. Even under intermittent loading, which is necessary for many materials to avoid excessive self-heating, typical effective cycling frequencies in the kHz range make experiments in the VHCF regime easily accomplishable. Experiments under axial, torsional and biaxial cyclic loading as well as tests with superimposed static loads have been realised in different environments and temperatures. Studies at lifetimes beyond $10^{10}$ cycles and mean crack growth rates in the range of $10^{-15}$ m/cycle were observed with this method.

In most ultrasonic investigations, the specimen is stimulated to a resonance vibration where the design of the specimen meets resonance criteria. However, thin sheets or wires with small diameters cannot be tested in this way. Specimen resonance lengths are in the range between 50 and 130 mm, depending on material and specimen design, and thin specimens would inevitably buckle during vibration, prohibiting well defined loading. For some materials, carrier specimens are successfully used to cycle thin sheet specimens at different load ratios. The presently investigated superelastic Nitinol used in self-expandable biomedical stents, however, cannot be tested in this way due to the limitations for loading the carrier specimen. Very large strains are necessary to replicate the compression into small diameter catheters required to transport the implant to the target anatomical sites, where it is cyclically loaded by the pulsating blood pressure by about $10^9$ cycles in 25 years. Ultrasonic testing of thin sheet Nitinol specimens is performed by mounting the specimen directly to the vibrating ultrasonic horn on one side and on a load cell on the other side. The whole load train is mounted into a spindle driven miniaturized load frame, which serves to perform pre-loading procedures as well as static and low frequency cyclic loading. Ultrasonic cyclic loading is superimposed to the static deformation and used to perform HCF and VHCF fatigue tests. Closed loop control of vibration amplitude and frequency as well as control of specimen's temperature guarantee reproducible testing conditions.

However, it needs to be proven that cyclic loading of superelastic Nitinol at ultrasonic frequency leads to similar mechanical conditions as conventional testing. Moreover, lattice forward and back transformations are important for the process of fatigue damage in Nitinol, and it needs to be confirmed that they can be reproduced at the very high strain rates of ultrasonic testing. One special benefit of ultrasonic fatigue testing setups are their relatively small dimensions, which facilitates transportation and makes the installation of the load train in synchrotrons possible. Experiments at the European Synchrotron Research Facility have been performed and showed similar lattice deformations cycling at 0.1 Hz and 18 kHz for elastic loading conditions. Phase transformations from austenite lattice to martensite via an intermediate R phase could be confirmed at ultrasonic strain rates using a frame summation technique to acquire X-ray diffraction patterns. In-situ ultrasonic fatigue studies served to investigate the progress of fatigue damage, which was found to be related to a back-transformation of martensite to austenite in the progress of the fatigue experiment.

# Fatigue of AM materials: from fundamental mechanisms to component assessment

**S. Beretta**[1,2]

[1]*Politecnico di Milano, Dept. Mechanical Engineering, IT*

[2]*Auburn University, Dept. Mech. Engineering, Nat. Center for Additive Manuf. Excellence, US*

*AM materials* *Defects* *Components* *Failure probability*

**Abstract** A substantial body of experimental and analytical evidence indicates that fatigue performance in metal additive manufacturing (AM) is strongly controlled by the presence, size, and morphology of process-induced anomalies and defects. The success of defect-sensitive approaches, including Murakami's √area parameter and Kitagawa–Takahashi-type diagrams, in predicting fatigue limits across multiple AM alloys provides additional quantitative evidence that fatigue in AM metals is defect-driven.

The topic of the presentation is the assessment of AM, that needs to take into account the presence of inherent anomalies together with *rogue* or *process-escape* defects (Fig. 1). In details, many lessons have been learned from recent analyses aimed at providing tools for component design: extreme value statistics is a useful tool but its application for prognostics is very sensitive to the presence of different anomaly types and their relative occurrence rate, XCT detection of defects is heavily affected by voxel size and segmentation tools, the sizing error can have a significant influence.

The approaches for the transfer of fatigue properties from specimens to components will be discussed considering that in most cases a probabilistic assessment is the prescribed route due to the relatively large size of the detection limits of NDE equipment.

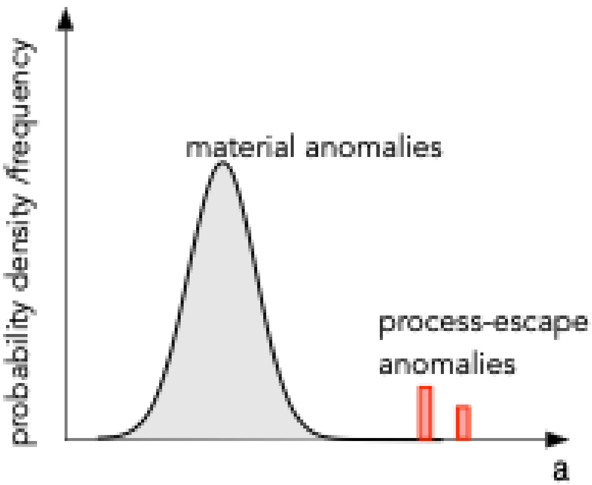


***Figure 1 -*** *Scenario for fatigue assessment under different anomaly types.*

# Cyclic deformation mechanisms of a 3D-printed high-entropy alloy

**D. Bajaj[1], A.H. Feng[2], S.J. Qu[2], D.Y. Li[3], and D.L. Chen[1]**

[1]*Department of Mechanical, Industrial and Mechatronics Engineering, Toronto Metropolitan University, Toronto, Ontario M5B 2K3, Canada*

[2]*Shanghai Key Laboratory of D&A for Metal-Functional Materials, School of Materials Science and Engineering, Tongji University, Shanghai 201804, China*

[3]*Department of Chemical and Materials Engineering, University of Alberta, Edmonton, Alberta T6G 2H5, Canada*

*Low cycle fatigue* *Additive manufacturing* *High-entropy alloy*

**Abstract** The discovery of high-entropy alloys (HEAs) has markedly helped advance of materials science over the past two decades. In parallel, the rise of additive manufacturing (also known as 3D printing) has revolutionized the manufacturing landscape. These converging innovations have sparked global interest among materials scientists in 3D-printed HEAs, which exhibit unique hierarchical microstructures comprising large columnar grains, melt pools, and cellular dislocation networks. Such features significantly influence their mechanical behavior compared to conventionally processed counterparts. Among these, the additively-manufactured CrMnFeCoNi HEA stands out for its adjustable and well-balanced strength-ductility combination, attributed to the activation of multiple slip systems and a variety of deformation mechanisms. Although numerous studies have explored the monotonic deformation behavior of 3D-printed HEAs, investigations into their cyclic deformation responses remain limited. To address this gap, the present study examines the low-cycle fatigue behavior of a CrMnFeCoNi HEA fabricated via laser-beam powder bed fusion (PBF-LB). Scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) analyses were conducted on microstructurally small secondary cracks, revealing key dislocation mechanisms such as dislocation glide (evidenced by slip traces in Fig. 1), grain rotation, and deformation twinning. Further details of this work will be presented at the upcoming conference.

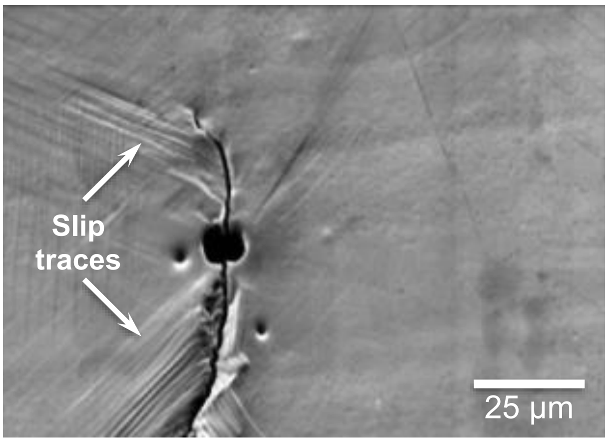


***Figure 1*** *– SEM image of a microstructurally small secondary crack in cyclically deformed PBF-LB fabricated CrMnFeCoNi high-entropy alloy.*

# On the Role of Hydrogen in Plasticity Mechanisms Associated with Cyclic Creep of a 304L austenitic stainless steel

**A. Radi[1,2,4], S. Park[3], A. Oudriss[4], P. Osmond[1], G. Girardin[1], F. Lefebvre[1], H. Matsunaga[2], X. Feaugas[4]**

*[1] Cetim, Senlis, France*

*[2] Research Center for Hydrogen Industrial Use and Storage (HYDROGENIUS), Department of Mechanical Engineering, Kyushu University, Kyushu, Japan*

*[3] Research Center for Hydrogen Industrial Use and Storage (HYDROGENIUS), Kyushu, Japan*

*[4] Laboratoire des Sciences de l'Ingénieur pour l'Environnement LaSIE, La Rochelle Université UMR-CNRS 7356, La Rochelle, France*

*Cyclic creep* *Hydrogen* *Austenitic steels*

Decarbonized hydrogen is a key energy carrier in the transition to low-carbon energy systems. Austenitic stainless steels, widely used in hydrogen-related applications, exhibit good resistance to embrittlement, though not complete immunity. This study investigates the effect of hydrogen on the ratcheting behavior of 304L stainless steel at room temperature. The material was pre-charged with 100 wppm solute hydrogen in a pressurized $H_2$ environment. Three loading paths—single-step, increasing, and decreasing multi-step—were applied to evaluate the influence of maximum and mean stresses on the steady-state cyclic creep rate. Flow stress decomposition (back stress and effective stress) and TEM analyses revealed changes in dislocation structures and phase transformation as a function of mechanical loading and hydrogen content. Additionally, EBSD and XRD quantified phase evolution and linked surface and bulk responses. Hydrogen caused solid-solution hardening by hindering dislocation motion and influenced the creep rate in a stress-dependent manner−either accelerating or decelerating it−through its combined effect with strain-induced phase transformation, whose dominant pathway ($\gamma \rightarrow \alpha'$ or $\gamma \rightarrow \varepsilon \rightarrow \alpha'$) depends on both hydrogen presence and applied stress.

# Microstructural evolution and fatigue response of friction stir welded hybrid aluminum joints after T6 heat treatment

**Marcel Krochmal[1], T. Wegener[1,2], T. Niendorf[1], G. Moeini[3]**

[1]*University of Kassel, Institute of Materials Engineering – Metallic Materials, Mönchebergstraße 3, 34125 Kassel, Germany*
*e-mail: krochmal@uni-kassel.de*

[2]*Now at: Center for Structural Materials (MPA-IfW), Technical University of Darmstadt, Ottilie-Bock-Straße 3, 64287 Darmstadt, Germany*

[3]*Westphalian University of Applied Sciences, Institute of Mechanical Engineering, Neidenburger Straße 43, 45897 Gelsenkirchen, Germany*

*Friction stir welding* *Hybrid joints* *Heat treatment*

## Abstract

The size limitations associated with additive manufacturing (AM) often necessitate hybrid designs, which integrate AM parts with conventionally manufactured components, thereby leveraging the complementary strengths of each fabrication method. A comprehensive understanding of the mechanical behavior of hybrid joints, particularly under cyclic loading conditions, is essential for a reliable application of such components. The strength of dissimilar welded AM-cast aluminum joints has been shown to be governed by the as-cast material, which exhibits a very coarse microstructure and consequently inferior hardness, tensile and fatigue properties. In this work, the impact of a post-welding T6 heat treatment on the microstructure and mechanical properties of a friction stir welded joint of additively manufactured AlSi10Mg and cast AlSi8MnMg was analyzed. Microstructurally, the heat treatment led to abnormal grain growth in the weld zone. While the silicon phases transformed into a globular morphology throughout most parts of the joint, they preserved their coarse, needle-like appearance in the cast region. Artificial aging yielded a mostly homogeneous hardness distribution throughout the joint. Compared to as-welded joints, increased yield and tensile strengths and improved fatigue performance were observed. However, the macroscopic ductility remained limited due to the brittle cast zone. Failure under low-cycle fatigue loading was primarily governed by defects in the cast region, which served as the main sites for crack initiation. The results demonstrate that heat treatment can effectively reduce potentially undesirable heterogeneity, thereby enhancing joint performance for specific applications.

# Evaluation of Tribo-Fatigue Properties of Alumina-Coated 316L Stainless Steel Using Two Thermal Spray Deposition Processes

**Halima Ghorbel[1], Radouane Akrache[2], Jinan Charafeddine[3]**

[1]*Laboratoire Atmosphères, Milieux, Observations Spatiales, Université de Versailles Saint-Quentin, France*
halima.ghorbel-feki@uvsq.fr

[2]*Radouane Akrache, Laboratoire d'Ingénierie des Systèmes de Versailles, Université de Versailles Saint-Quentin, France*
radouane.akrache@uvsq.fr

[3]*De Vinci Higher Education, De Vinci Research Center, Paris, France,*
jinan.charafeddine@devinci.fr

*Friction* *Wear* *Alumina coating*

**Abstract** The long-term reliability of orthopedic implants is closely linked to the tribo-fatigue behavior of their load-bearing materials. This study investigates uncoated 316L stainless steel and the same alloy coated with Alumina bioceramic layers deposited by two thermal spray processes, High-velocity oxy-fuel spray « HVOF » and Atmospheric Plasma Spraying « APS ». Dry pin-on-disk tests were conducted in combination with fatigue analyses to evaluate how sliding-induced wear affects crack initiation and durability under cyclic loading. Results show that alumina coatings significantly enhance tribo-fatigue performance by reducing friction, limiting wear-particle generation, and delaying surface damage. Among the two deposition methods, the HVOF coating exhibited superior resistance to wear and crack nucleation. These findings demonstrate the critical influence of surface engineering and coating deposition techniques on improving the functional lifetime of hip and knee prosthesis components operating in complex mechanical and tribological conditions.

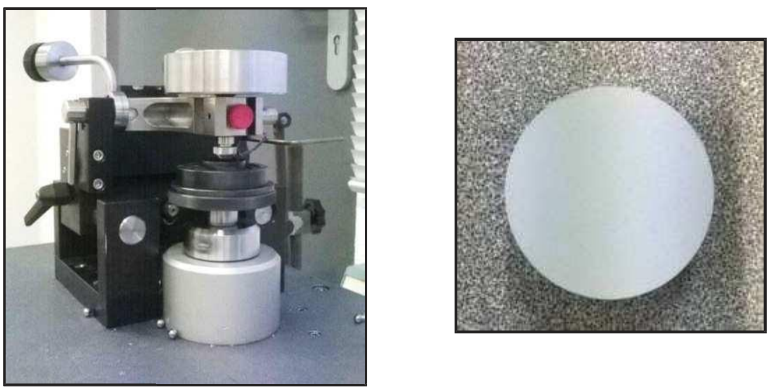

***Figure 1 -*** *Tribological test on a stainless-steel specimen coated with $Al_2O_3$.*

# Defect-Microstructure Interplay in Fatigue Crack Formation of PBF-LB IN718

**Alexander N. Caputo[1], Xiayun Zhao[2], Richard W. Neu[3]**

[1]*Georgia Institute of Technology, Atlanta, GA, USA, acaputo7@gatech.edu*

[2]*University of Pittsburgh, Pittsburgh, PA, USA, xiayun.zhao@pitt.edu*

[3]*Georgia Institute of Technology, Atlanta, GA, USA, rick.neu@gatech.edu*

*Additive Manufacturing* *Fatigue Crack Formation* *Defect Sensitivity*

**Abstract** Additive manufacturing (AM) of Ni-base superalloys such as laser beam powder bed fusion (PBF-LB) of IN718 produces complex microstructures that differ fundamentally from those of wrought materials. The rapid solidification conditions and layerwise deposition inherent to AM generate crystallographic texture variations, elongated or refined grains, and, in many process conditions, residual surface or volumetric defects including lack-of-fusion features and keyhole porosity. These heterogeneous microstructural and defect populations strongly influence fatigue performance because crack formation occurs at the material's weakest microstructural location.

This work examines the relative and competing roles of defects and non-defect microstructural features on high-cycle fatigue (HCF) life in PBF-LB IN718. More than one hundred fatigue specimens were extracted from AM coupon walls produced using ten distinct process parameter combinations. Each pedigree was characterized using SEM and EBSD to document grain morphology and texture, while XCT was used to quantify porosity in the gage sections of fatigue specimens. Fatigue tests were conducted at 538 °C to isolate the crack-formation mechanisms active under service-relevant thermomechanical conditions.

The results show that HCF performance cannot be correlated to defect metrics alone, even when isolated lack-of-fusion or keyhole pores are present at highly stressed locations. Above approximately 99.8% density, reductions in porosity do not necessarily yield improved fatigue behavior. Instead, the crystallographic texture, grain morphology, and local resolved shear stress states exert a controlling influence on crack formation when defects are small or absent. These trends highlight the need for microstructure-based lifing models that incorporate both defect populations and intrinsic microstructural anisotropies arising from AM processing.

Collectively, the findings reveal that fatigue-critical behavior in PBF-LB IN718 emerges from an interplay between defect characteristics and non-defect microstructural drivers. This integrated understanding is essential for developing physics-informed fatigue prediction methodologies capable of supporting the design and qualification of AM components for fatigue- and fracture-critical applications.

# Crack Growth Behavior of Microstructurally Graded PBF-LB/M Austenitic Steel Components

**Nico Möller[1], Florian Loebich[2], Thomas Wegener[1], Julia Richter[1], Jens Gibmeier[2], Thomas Niendorf[1]**

*[1]Institute of Materials Engineering - University of Kassel, Mönchebergstraße 3, 34125 Kassel, Germany*
*e-mail: n.moeller@uni-kassel.de*

*[2]Institute for Applied Materials -Karlsruhe Institute of Technology, Engelbert-Arnold-Straße 4, 76131 Karlsruhe, Germany*

*Crack Growth Behavior* *PBF-LB/M 316L* *Microstructural Gradation*

**Abstract** Laser-based powder bed fusion of metals (PBF-LB/M) is an additive manufacturing process that allows the production of components tailored to specific applications. Numerous interacting parameters influence the process during fabrication, leading to complex thermal histories. Eventually, these give rise to characteristic microstructures that strongly determine the resulting mechanical properties. Hence, a thorough understanding of the interrelation between process, microstructure, and properties is essential. The present study investigates the fatigue crack growth behavior of microstructurally graded and non-graded compact-tension specimens made of austenitic steel 316L. The focus is on the impact of microstructural differences and residual stress fields on fatigue crack growth. Components are manufactured by utilizing a dual-laser system, consisting of a 400 W gaussian and a 1 kW top-hat laser. In 316L fabricated via PBF-LB/M, strengthening is predominantly driven by the formation of substructures, i.e., characteristic dislocation networks enriched by chromium and molybdenum segregations. Consequently, the material exhibits superior quasi-static mechanical properties compared to conventionally manufactured 316L. Differing cooling rates prevailing in areas processed either with the 400 W or the 1 kW laser significantly influence the grain morphology, substructure size and crystallographic texture, eventually resulting in distinctive fatigue crack growth properties. Post-mortem fracture analysis reveals fracture surfaces considerably differing from conventionally processed 316L.

# Stress Scaling of Initiation Life

**Anthony D. Rollett**[1]

*[1]Carnegie Mellon Univ., Dept. Matls. Sci. & Eng.,*
*5000 Forbes Ave., Pittsburgh PA 15213 USA*
*rollett@cmu.edu*

*Initiation Life* *Stress Scaling* *2024-T4*

**Abstract** A 1985 report by Shimokawa & Hamaguchi[1] on 4-point bend fatigue in aluminum alloy 2024-T4 includes measurement of the initiation fraction, *i.e.*, the extent of life up to which no crack was observed. The initiation fraction decreases monotonically from less than one half at 75 % of the yield stress down to effectively the entire life at 40 %. Similar behavior for aluminum alloy 6061 was reported by Hunter and Fricke in 1956. Dividing median values of the total life into an initiation portion and a long-crack portion revealed that the latter scaled with stress amplitude according to published data[3] for the Paris Law behavior, *i.e.*, scaling with a stress exponent of ~4, as expected. The initiation life, however, followed a scaling similar to strain-amplitude cyclic deformation albeit in the so-called elastic, *i.e.*, Basquin regime, Fig. 1. About thirty tests were performed at each stress level which was enough to demonstrate a log-normal spread in total life at all except the three lowest stress levels with no indication of a fatigue limit. Full field simulations with crystal plasticity of tensile deformation in the pre-yield regime revealed a power law variation in slip rate as a function of stress that obeys a similar scaling to that of cyclic deformation in the elastic range with a stress exponent of ~7. The key result is that stress scaling of short crack life points to the importance of micro-plasticity in this regime.

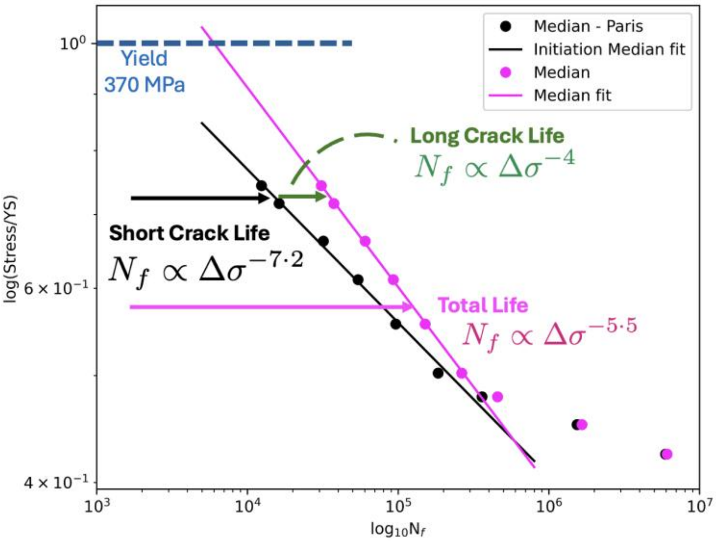


*Fig. 1.* Log-log plot of Δs versus Nf where the total life is divided between short crack growth and long-crack growth.

1. T. Shimokawa and Y. Hamaguchi, Relationship Between Fatigue Life Distribution, Notch Configuration, and S-N Curve of a 2024-T4 Aluminum Alloy, *J. Eng. Matls. Tech.* **107** 214-220 (1985)

2. C. Wang, X. Wang, Z. Ding, Y. Xu, and Z. Gao, Experimental investigation and numerical prediction of fatigue crack growth of 2024-T4 aluminum alloy, *Intl. J. Fatigue* **78** 11-21 (2015).

# Advances toward a comprehensive understanding of fatigue induced crack initiation mechanisms in f.c.c. alloys: influence of plastic strain localization and hydrogen content

**X. Feaugas[1], A. Radi[1,2], M. Risbet[3], A. Oudriss[1], G. Henaff[4]**

[1]*Laboratoire des Sciences de l'Ingénieur, La Rochelle Université, CNRS UMR 7356, La Rochelle, France. xfeaugas@univ-lr.fr*

[2]*CETIM, pôle Fatigue Optimisation Durabilité, Senlis, France.*

[3]*Laboratoire Roberval, Université de Technologie de Compiègne, Alliance Sorbonne Universités, Compiègne Cedex, France.*

[4]*Institut Pprime UPR 3346 CNRS, ENSMA, Université de Poitiers, Futuroscope Chasseneuil, France*

*Plastic strain irreversibility* *Crack initiation* *Hydrogen*

**Abstract:** Although it is a long-standing issue, slip localization occurring during plastic deformation remains a complex phenomenon, involving numerous elementary plasticity processes, the nature and distribution of dislocations, and the internal stress state. It is now well established that this deformation localization governs the intragranular initiation of surface damage, in direct connection with environmental effects. In this context, hydrogen as well as oxygen can be considered a key factor influencing the processes leading to such damage. Whether present intrinsically or extrinsically, hydrogen interacts with the elastic and plastic properties of the material, inducing significant alterations in the nucleation and multiplication of defects (vacancies, dislocations, etc.). The distribution of these defects (dislocation structures, slip localization, vacancy clusters, …) and the resulting internal stress fields are directly affected, thereby modifying the conditions required for crack initiation. This talk summarizes current knowledge on intra-granular crack initiation under cyclic loading in f.c.c. alloys and highlights key challenges for future research. After reviewing the roles of elementary plasticity, dislocation structures, and internal stresses along with the concepts of shielding, defactants, and hydrogen-enhanced vacancy clustering we examine how hydrogen influences slip localization and thereby promotes intra-granular damage initiation. Crack initiation conditions in the vicinity of cyclic slip bands linked to local plastic strain irreversibility are determined using atomic force microscopy to track surface topography evolution and transmission electron microscopy to characterize deformation localization, in nickel-based alloys spanning a broad range of grain sizes, precipitate sizes, and hydrogen contents. The local slip irreversibility required for crack initiation, $\gamma_{\mathrm{irr,pl,loc}}$, is formulated in terms of surface energy, the elastic energy stored by mobile dislocations, applied stress amplitude, dislocation mean free path, hardening rate, and elastic properties. The results indicate that the effect of hydrogen on $\gamma_{\mathrm{irr,pl,loc}}$ is inherently multifactorial.

# Rainflow-Calibrated Meta-Statistics for Spectral Fatigue Damage

**Tom Irvine**

*Vibrationdata, 136 Wellington Dr., Madison, AL, USA. Email: tom@irvinemail.org*

*Spectral Fatigue* *Rainflow Cycle Counting* *Meta-statistics*

**Abstract** Spectral methods are widely used for fatigue damage estimation under random vibration loading, but their accuracy depends strongly on power spectral density (PSD) bandwidth, modal content, and statistical structure. No single spectral formulation provides reliable agreement with rainflow damage across narrowband, broadband, and multimodal conditions.

This paper presents a rainflow-calibrated meta-statistical framework that adaptively combines multiple classical spectral fatigue estimators into a single damage prediction. Method weights are determined using a feature-conditioned softmax model based on PSD characteristics, including bandwidth measures, spectral entropy, effective modal count, and higher-order spectral moment ratios. The framework is calibrated using amplitude-based rainflow damage computed from time-domain stress histories synthesized from the PSDs.

The approach is evaluated using a large Monte-Carlo dataset of random PSDs with one to five resonant modes and varying damping. Across Basquin fatigue exponents $k = 4,6,8$, the meta-statistic reduces median absolute error by approximately 2.6× relative to equal averaging and 1.5× relative to the best individual spectral method, while maintaining negligible bias. This method improves accuracy without sacrificing computational efficiency.

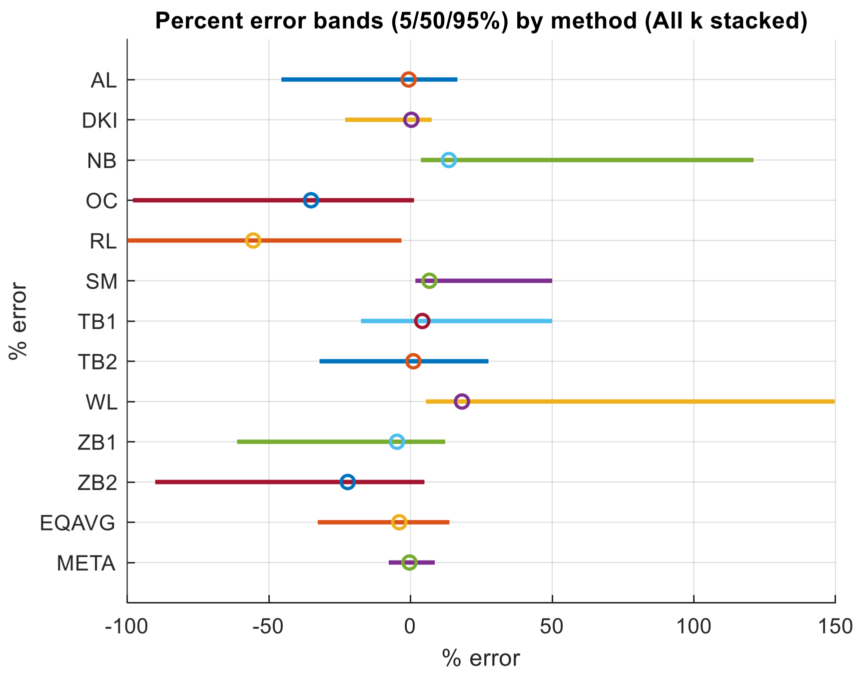


***Figure 1.*** *Signed percent error of spectral fatigue methods relative to rainflow damage. The META method shows the smallest bias and tightest error spread.*

# Influence of staircase test parameters on fatigue limit estimation

**Oussama Ouizour, Leila Khalij, Christophe Gautrelet**

INSA Rouen Normandie, Normandie Université, LMN UR 3828, F-76000 Rouen, France

*Staircase method* *Strain fatigue limit* *High cycle fatigue*

**Abstract**. The fatigue limit is fundamental to mechanical design, as it allows for 'infinite life' dimensioning by ensuring that operational stress remain below a material threshold. It also enables service life prediction using Wöhler curves to estimate the number of cycles to failure. Among current experimental techniques, the staircase method is widely used to provide the median of fatigue limit and its scatter (e.g. standard deviation) based on an assumed prior probability distribution. However, the accuracy of these estimates is highly sensitive to the test configuration, particularly the initial stress level and the stress increment. Experimental tests were carried out to investigate how these parameters affect the estimation of the fatigue limit of DC01 low-carbon steel. Four series of staircase fatigue tests were conducted on an electrodynamic shaker (see figure 1). Specimens were submitted to a continuous sinusoidal vibration at the first bending resonant frequency, controlled using a strain gauge mounted on the reduced section of the specimens. The fatigue tests were carried out until a 5% drop in the resonant frequency, adopted as the crack-initiation criterion. The staircase data were post-processed in Matlab to estimate fatigue-limit distributions using the Dixon-Mood procedure and other statistical methods (e.g., maximum likelihood). Based on the results, an optimal combination of initial stress level and stress increment was identified, leading to a reduced dispersion in the estimation of both the median fatigue limit and its associated standard deviation.

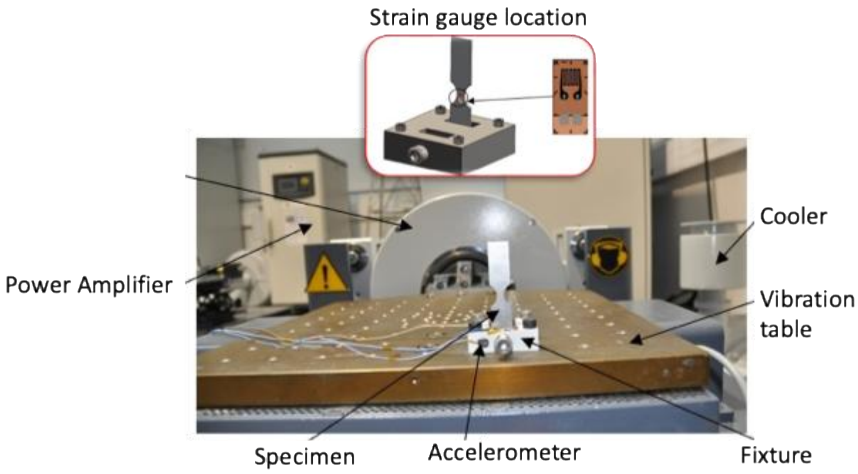


***Figure 1** – Electrodynamic bench for fatigue tests*

# Integrating Vibration Testing and Fatigue Analysis in Undergraduate Education

**Raúl Muñoz[1], Pablo Sánchez-Vázquez[2], Felicidad García-Sánchez[3]**

[1]*Departamento de Ingeniería Mecánica, Universidad de Salamanca, Salamanca, 37008, Spain.* raul.munoz@usal.es

[2]*E.T.S. de Ingeniería Industrial, Universidad de Salamanca, Béjar,37700, Spain*

[3]*Departamento de Bellas Artes, Universidad de Salamanca, Salamanca, 37005, Spain*

*Dynamic Shaker* *Finite Element* *Fatigue analysis*

**Abstract.** Fatigue failure driven by vibratory loading remains a critical concern in mechanical systems, yet undergraduate instruction often treats vibration and fatigue as disconnected topics, limiting students' ability to assess fatigue damage under realistic dynamic conditions. This work addresses this gap through the development and implementation of an integrated experimental–computational learning framework that links structural vibration behavior directly to fatigue life estimation.

The approach combines low-cost experimental vibration testing with computational modeling and fatigue analysis. Students excite a simplified structural system using a dynamic shaker and measure its response with an Arduino-based data acquisition system. Frequency-domain signal processing is performed using Python to identify resonant behavior and dynamic amplification. A finite element (FE) model of the structure is then developed to perform modal and transient dynamic analyses. Experimentally validated stress time histories obtained from the FE simulations are subsequently used for fatigue life prediction.

Implementation results show improved student understanding of resonance-induced stress amplification, better validation of finite element models using experimental data, and increased confidence in fatigue life estimation, including identification of fatigue-critical hot spots. The study concludes that integrating low-cost vibration testing, FE modeling, and fatigue analysis provides an effective and accessible approach for teaching fatigue in undergraduate Mechanical Engineering courses

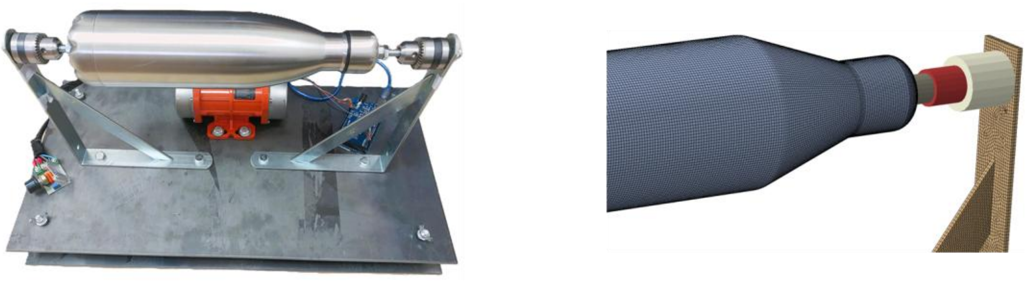

***Figure 1** – (left) Experimental vibration test setup for vibration and fatigue analysis; (right) corresponding finite element (FE) model detail.*

# Fatigue Evaluation of Fuel Cladding Considering Pellet–Clad Interaction

**Min Jeong Park[1], Dong-Hyun Kim[1], Yoon-Suk Chang[2]**

[1]*Graduate School, Kyung Hee University, 1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do 17104, Republic of Korea, alswjd1019@khu.ac.kr; okkdh0123@khu.ac.kr*

[2]*Department of Nuclear Engineering, Kyung Hee University, 1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do 17104, Republic of Korea, yschang@khu.ac.kr*

*Cladding integrity* *Pellet-clad interaction* *Transportation loads*

**Abstract** Pellet–clad interaction (PCI) generates localized contact pressures, relative motion, and residual damage that concentrate strain at cladding hot-spots. Under transportation loads such as vibration spectra and shock pulses, the resulting response fields—combined with irradiation- and hydride-induced embrittlement—can markedly reduce the integrity of spent-fuel cladding. In this study, a multi-physics framework was developed to quantify PCI contributions to fatigue and crack propagation during transport.

First, constitutive laws for a typical zirconium alloy were established by synthesizing published test data, and modifiers capturing reduced uniform elongation and cyclic hardening/softening trends were parameterized to reflect degradation severity. Key PCI drivers—including pellet geometry, irradiation-driven swelling, fragmentation state, and zirconia/oxide layer presence—were modeled explicitly to produce time-dependent local contact pressures and slip histories.

High-fidelity three-dimensional finite element (FE) models of segmented pellet-clad assemblies were developed and optimized. Fatigue lives subjected to representative transport loading spectra were evaluated using strain-life relations with embrittlement corrections, and parametric trends were analyzed. Crack propagation was also evaluated using a fracture mechanics model by Paris.

Finally, machine-learning surrogates trained on FE response datasets were constructed to enable efficient identification of dominant integrity drivers. The surrogate predictions of PCI loads, initiation sites, and fatigue life estimates were benchmarked against available reference data. The proposed framework improves understanding of PCI-sensitive factors and their roles in fatigue damage. It can be extended to probabilistic integrity assessment by integrating PCI physics, material degradation, and scenario uncertainties.

# Computational Prediction of Total Fatigue Life with An Integrated Approach

**Siqi Li[1], Rong Liu[1], Zhong Zhang[2], Xijia Wu[1]**

[1]*Department of Mechanical & Aerospace Engineering, Carleton University 1125 Colonel By Drive, Ottawa, Ontario, Canada K1S 5B6, Rong.Liu@carleton.ca*

[2]*Aerospace Research Center, National Research Council Canada, 1200 Montreal Road, Ottawa, Ontario, Canada K1A 0R6*

*Crystal plasticity FEM* *Tanaka-Mura-Wu model* *Microstructural variability*

**Abstract** This research tackles the fundamental issue of computational fatigue studies by developing an effective approach that combines the crystal plasticity finite element method (CPFEM) with the Tanaka–Mura–Wu (TMW) model for crack nucleation and the Tomkins model for fatigue crack propagation, to provide Class-A predictions (fatigue life prediction without using experimental fatigue data) of the total coupon-fatigue life (crack initiation and growth lives) for a nickel-based superalloy, Haynes 282. To gain a statistical significance accounting for the microstructure inhomogeneity, twenty-five 3D Representative Volume Elements (RVEs) containing Σ3 twin or excluding Σ3 twin are created utilizing a software package, Dream.3D, to represent the polycrystalline material with different grain structures and orientations in equivalence to the real or experimental microstructure data. The CPFEM model is calibrated to the material's hysteresis behavior, and then, the microstructural plastic strain from the RVE is taken to compute the fatigue life of the material. The prediction is found overall in good agreement with the fatigue test data under strain-controlled or stress-controlled conditions at various stress ratios ($R$ = 0, and $R$ = -1), validating the effectiveness of the proposed approach in predicting fatigue life and its scatter due to microstructural variability for Haynes 282 alloy. In addition, the effects of local grain attributes including grain orientation and adjacent grain arrangement on fatigue crack nucleation are analyzed quantitatively. It is suggested that grain orientation influences plastic deformation by inducing active slip systems, and the slip transfer across grain boundaries also contributes to fatigue crack nucleation. Moreover, the role of twinning in fatigue crack initiation is investigated by analyzing the plastic strain distribution around the twinning boundary, which indicates that plasticity tends to concentrate around the twinning boundary due to a high Schmid factor, significant local stiffness mismatch between adjacent grains, and a high slip transfer factor in the region. However, the strengthening of micro-plasticity only affects the local region and has a minor impact on the fatigue life determined using the proposed approach. Stress-controlled high cycle fatigue (HCF) simulations at different stress ratios reveal that local plasticity at the microscale is the key factor in physically explaining crack initiation. The predicted fatigue life tends to decrease with increasing stress ratios, which is consistent with the experimental observations. Furthermore, machine learning algorithms including Random Forest (RF), Support Vector Machine (SVM), and XGBoost are leveraged to model the likelihood of crack initiation based on microstructure-sensitive parameters obtained from 160 random grains. These parameters include the Schmid factor, local elastic modulus, grain size, slip transfer factor, and the elastic modulus mismatch between adjacent grains. The results demonstrate that all three machine learning algorithms are capable of quantitatively assessing crack initiation, with $R^2$ values exceeding 0.7.

* Corresponding author: Rong Liu, Tel.: +1-613-2189862

*E-mail address*: Rong. Liu@carleton.ca

# Effects of Surface Modification on Residual Stress Stability during Fatigue in AISI 4140 Steel

**Tomofumi Aoki[1], Jun Komotori[2]**

[1]*Graduate School of Keio University, 3-14-1 Hiyoshi, Kohoku, Yokohama, Kanagawa 223-8522, Japan, ao.tomofumi@keio.jp*

[2] *Keio University, 3-14-1 Hiyoshi, Kohoku, Yokohama, Kanagawa 223-8522, Japan*

*Surface modification* *In situ measurement* *Residual stress relaxation*

**Abstract** The generation of compressive residual stress (CRS) by surface modification is effective in improving fatigue properties. However, preventing CRS relaxation during the fatigue process is crucial. *In situ* X-ray stress measurements were performed during strain-controlled axial fatigue tests to clarify the effects of different surface modification methods on CRS stability and its underlying mechanisms. This approach enables an indirect assessment of changes in the yield strength of the surface-modified layer, in addition to evaluating residual stress changes during cyclic loading. Axial fatigue tests with a total strain amplitude of 0.4% were carried out on AISI 4140 steel specimens in which CRS was induced by fine-particle peening (FPP) and surface quenching (SQ), referred to as the FPP series and SQ series, respectively. Figure 1 shows significant CRS relaxation on the surface of the FPP series specimens, in contrast to the SQ series. *In situ* X-ray stress measurements revealed a decrease in the yield strength of the surface-modified layer under cyclic loading only in the FPP series specimens. These results suggest that CRS relaxation during fatigue is related to a gradual decrease in the compressive yield strength of the surface-modified layer, resulting in repeated exceedance of the yield strength by the stress acting on the surface-modified layer during compressive loading. The measurement results further indicate that increasing the yield strength of the surface-modified layer and preventing its reduction are crucial for maintaining stable CRS under cyclic loading.

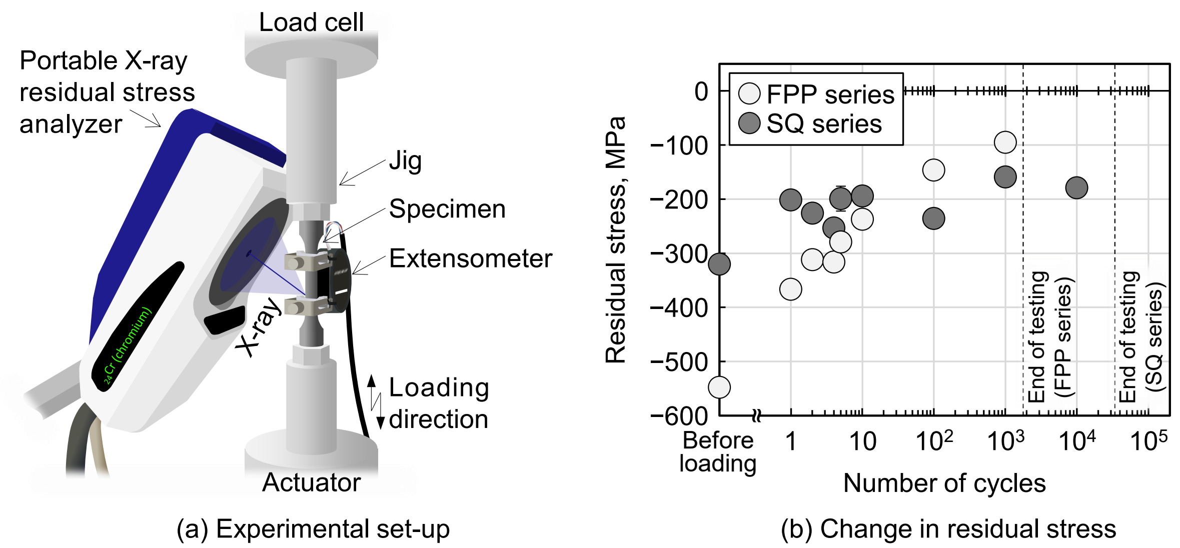


***Figure 1*** *– (a) Experimental set-up for the in situ X-ray stress measurement under strain-controlled conditions and (b) change in residual stress on the specimen surface during axial fatigue testing with a total strain amplitude of 0.4% for the FPP and SQ series specimens.*

# A probabilistic-dynamic fatigue life prediction framework for SLM alloys based on extreme defect statistics and natural frequency degradation

**Yuqi Yang[1], Haibiao Yin[1], Piao Li[2], Weixing Yao[1]**

*[1] State Key Laboratory of Mechanics and Control for Aerospace Structures， Nanjing University of Aeronautics and Astronautics, No. 29 Yudao Street, Nanjing 210016, China*

*[2] Zhejiang-Italy Joint Lab for Smart Materials and Advanced Structures, School of Mechanical Engineering and Mechanics, Ningbo University, Ningbo 315211, China*

*Selective Laser Melting* *POT method* *Fatigue life prediction*

**Abstract** Selective Laser Melting (SLM) technology are widely used in high-performance aerospace components. In this work, a probabilistic-dynamic framework is proposed to link extreme defect statistics with fatigue damage evolution. The Peak Over Threshold (POT) method is employed to characterize the occurrence probability of large-scale defects, representing the statistical extremes governing crack initiation risk. Subsequently, a frequency-based fatigue damage model is developed, in which the degradation of natural frequency is used as a global indicator of stiffness loss induced by defect-activated crack propagation. The predicted extreme defect is further incorporated into damage parameter to calculate fatigue life. High-cycle vibration fatigue tests coupled with X-ray computed tomography (CT) are conducted to validate the proposed approach. Model calculation results indicate that crack growth and brittle fracture stages account for approximately 80% and 20% of the total fatigue life of SLM aluminum alloys, respectively. This approach has proven reliable, as the predicted fatigue lives fall within a factor-of-two scatter band and coefficient of determination $R^2$ is all around 0.9.

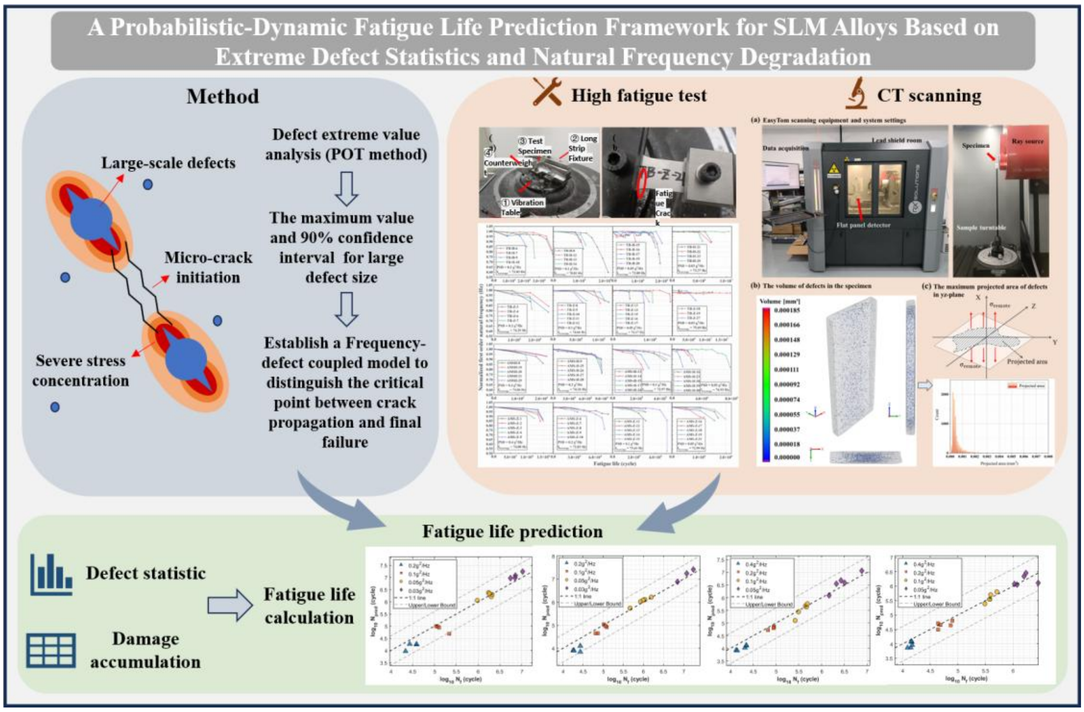


*Figure 1 – The graphical abstract of this work*

# Effect of Long-term Aging on Low-cycle Fatigue Behavior of GH4169 Alloy

**Lei Wang[1*], Yang Liu[1], Xiu Song[1], Guohua Xu[2], Jinlan An[1]**

[1]*Northeastern University, Shenyang 110819, China, *e-mail: wanglei@mail.nue.edu.cn*

[2]*Gaona Aero Material Co., Ltd., Beijing, 100081, China*

*Keyword: Long-term ageing, GH4169 alloy, LCF, microstructure evolution*

**Abstract** Since the turbine disc usually bears overloading which will lead to the low cycle fatigue (LCF) damage in real working, and because it is added with high ratio alloying elements, it is meaningful to decide the relationship between the LCF degradation and microstructure evolution. GH4169 superalloy is one kind of important metallic materials used for manufacturing turbine discs in aero-engine. The effect of long-term aging on the LCF (the strain waveform is sine wave, total strain $\Delta\varepsilon_t/2=\pm0.5\%$, strain ratio $R$=1, cyclic frequency $f$=0.3Hz.) behavior of GH4169 alloy was studied, during long-term aging at 750 ℃ for 500, 100, 1500 and 2000 h, respectively, and the mechanism was also discussed. The results show that the size of γ″ phases increases and the volume fraction decreases with the increasing of aging time, at the same time, both size and volume fraction of δ phases increase, compared with that after standard heat treatment (SHT). Both the fatigue strength and low-cycle fatigue life of the alloy decrease with the increase of aging time. The LCF behavior of the alloy is mainly depended on the evolution of γ" phase and δ phase, as well as the changing of precipitate free zone during the long-term aging of the GH 4169 alloy

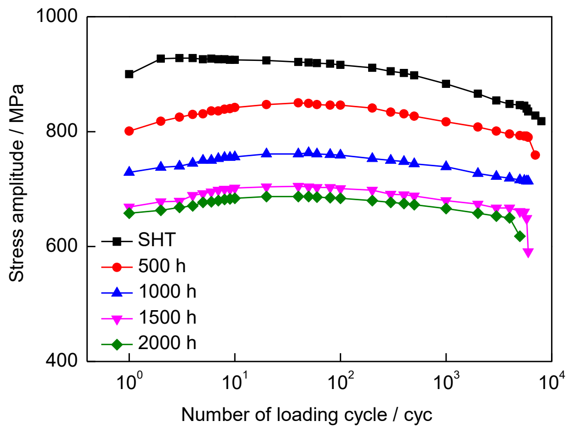


***Figure 1*** *Cyclic stress response to* $\Delta\varepsilon_t/2=\pm0.5\%$ *of alloy aged at 750 ℃ for different times*

# Reliability of additively manufactured martensitic and precipitation-hardenable steels under very high cycle fatigue loading

**Sebastian Schettler[1], Sebastian Schoene[1,2], Leonhard Stampa[1,2], Martina Zimmermann[1,2]**

*[1]Fraunhofer Institute for Material and Beam Technology IWS, Winterbergstraße 28, 01277 Dresden, Germany, sebastian.schettler@iws.fraunhofer.de*

*[2]TU Dresden, Chair of Mechanics of Materials and Failure Analysis*

*VHCF* *high strength steel* *PBF-LB*

**Abstract** High-strength steels from conventional manufacturing processes exhibit special characteristics under cyclic mechanical loads. These steels show a multiple drop in strength in the S-N curve. This study investigates the precipitation-hardened martensitic steels X3NiCoMoTi18-9-5 (1.2709) and X5CrNiCuNb17-4-4 (1.4548), manufactured by laser beam powder bed fusion (PBF-LB) in different building directions and surface conditions.Their fatigue behavior is characterized for cyclic mechanical loading up to > $10^{10}$ cycles using ultrasonic fatigue testing technology under laboratory conditions. These results are benchmarked against conventional wrought material. A detailed fracture surface analysis and quantification of the crack-initiating defects were performed according to Murakami's $\sqrt{\ }$area-concept. Using the Kitagawa-Takahashi diagram, $\sqrt{\ }$area-values and experimental fatigue strength values are linked and can be compared.

The results show that the Kitagawa–Takahashi diagram correctly models the fatigue behavior of additively manufactured specimens. A clear correlation between defect type and size and fatigue strength was proven by the experimental results. However, it was also proven that standard laboratory specimens may not fully cover the potential scattering of the size distribution of interior defects.–Rather, surface irregularities can be regarded as basis for a conservative estimates of the largest critical defects.

# Thermoelasticity-based full-field fatigue damage identification

**Janko Slavič[1], Klemen Zaletelj[1], Jaša Šonc[1]**

[1] *University of Ljubljana, Faculty of Mechanical Engineering, Slovenia*

*Thermoelasticity* *vibration fatigue* *high-speed thermal camera*

**Abstract** In vibration fatigue, identifying damage with high spatial density is challenging because fatigue is localized and loads often change direction. Thermoelasticity addresses this by measuring the relationship between minute temperature fluctuations and elastic deformation. Specifically, these temperature changes correspond to the sum of normal stresses (the first stress invariant), providing a potential window into the multiaxial stress state.

This research introduces a thermoelasticity-based multiaxial criterion that converts complex loading into an equivalent uniaxial load. This load is then integrated into established spectral-domain theories for vibration-fatigue damage estimation.

Key findings of this contribution: The proposed thermoelectricity based method was compared against the standard Equivalent von Mises stress criterion. Theoretical and experimental results show that the thermoelastic criterion is highly effective when surface shear stresses are significantly lower than normal stresses. Leveraging advancements in high-speed thermal imaging and signal processing, this methodology enables close-to real-time fatigue damage estimation across the entire surface of a component.

By providing a natural multiaxial-to-uniaxial conversion, this approach opens new possibilities for fatigue damage identification.

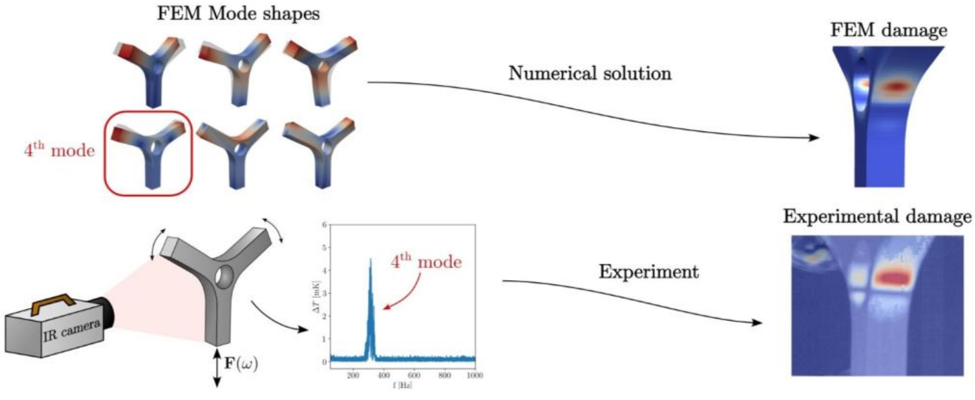


***Figure 1 -*** *Comparison of calculated damage intensity by thermoelastic criterion FEM and measured thermoelastic effect.*

# Can the plain S–N behaviour and uniaxial/multiaxial notch fatigue strength of additively manufactured metals be estimated?

**Luca Susmel**

*[1]School of Engineering and Built Environment, Sheffield Hallam University, Harmer Building, Sheffield, S1 1WB, United Kingdom*

*Additive Manufacturing* *Metals* *Notch*

**Abstract.** This paper reviews the research we have led on the uniaxial and multiaxial fatigue behaviour of additively manufactured (AM) metals [1, 2, 3]. The focus is on providing reliable methods to predict the fatigue performance of 3D-printed components. This contribution addresses two aspects: (i) estimating S–N curves of AM metals using statistical analysis and artificial intelligence [3], and (ii) applying the Theory of Critical Distances (TCD) to assess fatigue strength of notched AM metals under uniaxial [1] and multiaxial [2] loading.

For the first aspect, the study evaluates whether meaningful fatigue design curves can be obtained from extensive experimental data on AM aluminium, steel, and titanium. Build orientation, heat treatment, and surface finishing were considered, with results for low ($R = 0.1$) and fully reversed ($R = -1$) loading. Statistical regression and machine learning methods—including Decision Trees, Support Vector Machines, k-Nearest Neighbours, Multi-Layer Perceptrons, Partial Least Squares, and Gaussian Process Regression—were used to develop predictive models. The findings show that conventional design approaches for traditional metals are insufficient for AM materials, and highlight the need to account for microstructure, defects, and material properties to improve AI-based predictions.

For the second aspect, TCD was applied to notched AM components. For uniaxial loading, Ti6Al4V specimens with as-built notches were tested under fully reversed and positive mean stresses, demonstrating that the material length scale concept can capture notch effects on fatigue life. For multiaxial loading, notched AISI 316L specimens were tested under constant and variable amplitude biaxial loading, including out-of-phase loading and superimposed static stresses. Agreement with experiments confirms the method's suitability for practical multiaxial fatigue assessment of 3D-printed components.

Overall, combining statistical and AI-based analyses with mechanistic approaches such as TCD provides a robust toolkit to predict fatigue behaviour of AM metals, enabling safer and more efficient design of 3D-printed components.

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# Absorbed hysteresis energy - parameter of fatigue damage

**Chmelko, V.[1], Margetin, M.[1], Hujavý, J.[1]**

[1] *Slovak University of Technology, Faculty of Mechanical Engineering, Institute of applied mechanics and mechatronics, Námestie slobody 17, 812 31 Bratislava, Slovak republic, vladimir.chmelko@stuba.sk*

*Hysteresis energy* *fatigue* *damage*

**Abstract** External loading forces cause visible or invisible changes in the dimensions of components. From a physical point of view, they perform work or supply energy that must be absorbed by the material. This energy causes changes at the atomic grid level. From a macroscopic point of view, part of this energy causes elastic deformation of the external dimensions and part causes irreversible changes in dimensions. Irreversible changes in dimensions are manifested by a hysteresis loop in the s-e diagram. Experiments show that the accumulation of this energy is directly correlated with the accumulation of fatigue damage and fatigue life. In any method of detecting its area (analytical, experimental), it is a function of stress amplitude and therefore not a constant that would be a criterion for fatigue fracture. Experimental results of hysteresis energy measurements obtained from continuous stress-strain recordings during all loading cycles until fracture will be presented for a wider range of stress amplitudes and multiple materials.. The energy values obtained by direct measurement of the hysteresis loop areas are compared with the Morrow approximate analytical relationship.

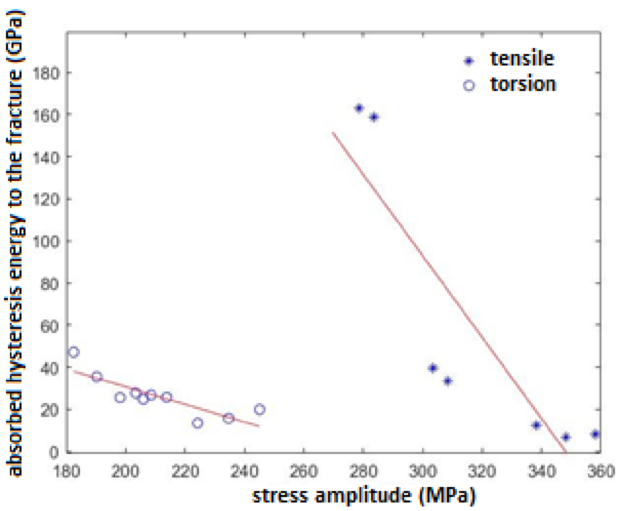



***Figure 1 -*** The dependence of the absorbed hysteresis energy on the stress amplitude (normal and shear)

# Fatigue damage accumulation rule based on absorbed hysteresis energy

**Chmelko, V.[1], Margetin, M.[1], Hujavý, J.[1]**

[1] *Slovak University of Technology, Faculty of Mechanical Engineering, Institute of applied mechanics and mechatronics, Námestie slobody 17, 812 31 Bratislava, Slovak republic, vladimir.chmelko@stuba.sk*

*Hysteresis energy* *damage cumulation* *Tension, torsion*

**Abstract**

For each stress amplitude, there is a different value of hysteresis energy absorbed by the material during its fatigue life. This paper presents the results of measurements of hysteresis energy absorbed during alternating tension-compression cyclic loading, alternating torsion cyclic loading, and combined alternating tension and torsion cyclic loading.

Based on these findings, it is possible to formulate a cumulative rule that respects the variability of the absorbed hysteresis energy. For a random load amplitude curve, it is possible to calculate the contributions from individual cycles as the accumulation of relative hysteresis energy relative to the maximum load amplitude energy.

A comparison of the courses of absorbed hysteresis energies under tensile-compressive loading and torsion loading reveals the nonlinearity of their possible combinations. This provides an interesting perspective on the criteria for multiaxial fatigue.

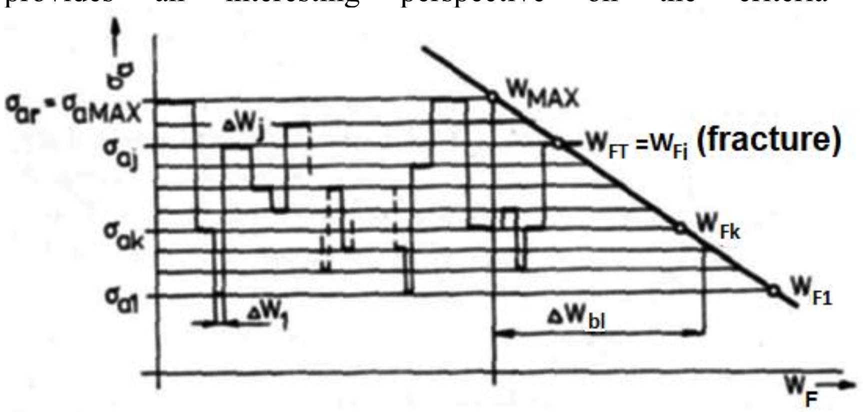



***Figure 1*** *-Hysteresis energy into fatigue fracture and block of non-harmonic amplitude loading*

# Preventing Hydrogen Embrittlement in Hydrogen Gas Pipelines through Trace Carbon Monoxide Addition

**Juan Shang[1,2], Hiroto Hayashi[3], Masanobu Kubota[1,2]**

[1]*International Institute for Carbon-Neutral Energy Research (WPI-I2CNER), Kyushu University, Fukuoka, 819-0395, Japan, shang.juan.061@m.kyushu-u.ac.jp*

[2]*The Center for Energy Systems Design (CESD), International Institute for Carbon-neutral Energy Research (WPI-I2CNER), Kyushu University, Fukuoka, 819-0395, Japan*

[3] *Graduate School of Engineering, Kyushu University, Fukuoka 819-0395, Japan*

*Hydrogen embrittlement* *Fatigue crack growth* *Hydrogen pipeline*

**Abstract** As hydrogen ($H_2$) emerges as a key energy carrier for carbon-neutral technologies, mitigating gaseous hydrogen embrittlement (GHE) in existing structural materials remains a critical challenge for a seamless transition to a hydrogen economy. This work combined experimental studies and first-principles molecular dynamics simulations to investigate the role of carbon monoxide (CO) in mitigating GHE of the JIS STPG370 pipeline steel, offering a systematic analysis of the influence factors including CO concentration, gas pressure, and temperature. Fatigue crack growth (FCG) tests revealed that adding 1% by volume of CO to a 1 MPa hydrogen at room temperature significantly suppressed hydrogen-induced of acceleration of fatigue crack growth in this pipeline steel. Over a stress intensity factor range of $\Delta K$ = 21 ~ 40 MPa・$m^{1/2}$, the crack growth rate in CO-mixed hydrogen was reduced by approximately one order of magnitude relative to high-purity hydrogen, approaching the level measured in air. This suppression remained effective at a reduced pressure of 0.5 MPa and at temperatures of 263 K and 323 K. Scanning electron microscopy analysis indicated that fracture surfaces in the CO-mixed hydrogen at $\Delta K$ = 30 MPa・$m^{1/2}$ exhibited ductile transgranular fracture, contrasting with the quasi-cleavage fracture features observed in CO-free hydrogen, confirming the protective effect of CO. Computational simulations indicated that, in the CO-$H_2$ system, increasing the number of CO molecules led to preferential occupation of adsorption sites on the iron surface by CO, resulting in a marked decrease in the number of adsorbed hydrogen atoms. CO exhibited a relatively high affinity for the iron surface, and its adsorption rate was only weakly affected by the hydrogen partial pressure. Consequently, under both high- and low-pressure conditions, CO rapidly adsorbed on the iron surface and inhibited hydrogen adsorption. These results suggest that trace amounts of CO can act as a practical GHE inhibitor, offering new perspectives for enhancing the reliability of structural materials in hydrogen-rich environments.

# Fatigue strength assessment of steel processed by L-PBF under multiaxial loadings: impact of defects

**S.S Penkulinti[1,2], M. Bonneric[1,2], N. Saintier[1,2], B. Verquin[3], T. Palin-Luc[1,2], F. Lefebvre[3], P. Ghys[4]**

[1] *Arts et Metiers Institute of Technology, CNRS, Bordeaux INP, I2M, UMR 5295, France, FR*

[2] *Univ Bordeaux, CNRS, Bordeaux INP, I2M, UMR 5295, France, FR*

[3] *CETIM, France, FR*

[4] *ALSTOM, France, FR*

*L-PBF* *Defect* *Multiaxial Fatigue*

**Abstract** The use of Laser Powder Bed Fusion (L-PBF) process inevitably generates defects (lack of fusion, gas pores) which have significant impact on the fatigue behavior. The consideration of such defects is therefore an important challenge for a safe design of additively manufactured components against fatigue. In the present study, fatigue specimens with different defect populations have been obtained by varying the process parameters for the low-alloyed steel E185. These specimens have been subjected to fatigue tests under multiaxial loading conditions (tension, torsion, and combined tension-torsion) in the High Cycle Fatigue regime. A Kitagawa-Takahashi diagram was determined for each loading type, describing the evolution of the fatigue strength at 1 x $10^6$ cycles with respect to the defect size. These results evidenced that the sensitivity to the defects depends on the loading type, torsion dominated loadings being less sensitive to the defect size than tension dominated ones. In addition, a numerical methodology aiming at predicting the fatigue strength from finite-element (FE) simulations was proposed, considering explicitly the geometry of L-PBF defects, or idealized defect shapes. It was found that the experimental results can be satisfyingly reproduced using synthetic ellipsoidal defects (see Figure 1).

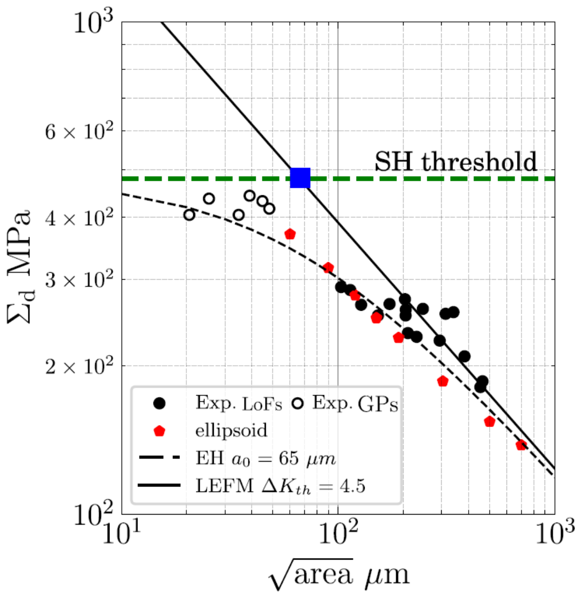



***Figure 1 -*** Comparison of the fatigue strengths obtained numerically with ellipsoidal defect with the experimental results – Kitagawa-Takahashi diagram

# Stop-Drilling Fatigue Cracks Under Load

**Hooman Pakdaman[1], Derek Warner[1], K.T. Ramesh[2]**

[1] *Canterbury Fracture Group, Civil and Environmental Engineering Department, University of Canterbury, Christchurch 8140, New Zealand. E-mail: hooman.pakdaman@pg.canterbury.ac.nz,, derek.warner@canterbury.ac.nz,*

[2] *Department of Mechanical Engineering, Johns Hopkins University, Latrobe 200, Baltimore, MD 21218, USA. E-mail: ramesh@jhu.edu*

*Stop-drilling* *Fatigue crack repair* *Finite element analysis*

## Abstract

Stop-drilling is a widely recognized, rapid, and cost-effective method for repairing fatigue cracks by reducing crack tip stresses. Prior to drilling, the structure is typically unloaded and often disassembled, which can be time-consuming, costly, and even impractical in some cases. This study investigated the efficacy of performing stop-drilling repair while the component remains under service load, as a practical alternative to conventional unload-then-repair procedures.

As a first step, this study examined the stop-drilling procedure with a nonlinear finite element model using the FEniCS software package. An Al 6061-T6 plate was modeled assuming isotropic von Mises (J2) elasto-plastic behavior with linear isotropic strain hardening. Both plane-stress and plane-strain conditions were considered. Repair performance for the component under load and in unloaded conditions is characterized using crack-opening measures and plasticity-based indicators. Prior to the simulation of drilling, a configuration with crack wake residual stresses was obtained with progressive node release under cyclic loading.

The results suggest that the effectiveness of the stop- drilling technique is largely independent of whether the structure is loaded or unloaded at the time of drilling, indicating that unloading might be unnecessary for effective stop-drilling repair.

# A High-Throughput Method for Standardized Uniaxial Fatigue Testing

**Amir Mousavi[1], Ahmed Bilal[1], Grant West[2], Derek Warner[1,2]**

[1]*Canterbury Fracture Group, Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand*

[2]*Cornell Fracture Group, School of Civil and Environmental Engineering, Cornell University, Ithaca, USA*

*High Throughput* *Fatigue* *Novel Experiment Setup*

**Abstract** Reliable fatigue-life prediction is key to mechanical integrity and safety-critical design. An obstacle to achieving this goal is that fatigue failures are governed by stochastic crack initiation with high variability even under nominally identical test conditions. This is particularly problematic in safety-critical applications where the avoidance of low-probability events is key to the design, yet knowledge of the probabilities is highly uncertain. Expanding calibration datasets is a direct way to reduce this uncertainty; however, conventional uniaxial fatigue testing is costly and time-consuming, limiting dataset size and making low-probability behavior difficult to characterize.

To address these limitations, we present a uniaxial mechanical fatigue testing concept that targets more than an order-of-magnitude improvement in throughput while maintaining comparable cost and consistency with widely used testing standards (ASTM E466 and ISO 1099). The concept is based on a stack of compliant cylinders, each encircled by a ring-shaped specimen. Under cyclic axial compression, the rings resist the cylinders' Poisson expansion, generating an approximately uniaxial tensile stress state in the rings. The system is designed to maintain stable cyclic loading over long durations and to limit interactions between neighboring specimens so that failure of one ring does not significantly alter the loading of the others. Key design objectives include maintaining consistent cyclic loading over long tests, minimizing sensitivity to specimen position within the stack, and ensuring stack stability while operating at standardized test frequencies.

A prototype was developed and demonstrated with 39 aluminum 6061-T6511 test specimens subjected to $2\times10^6$ loading cycles. Performance was evaluated through extensive strain-gauge measurements over the duration of testing and by comparing the resulting fatigue-life distribution with a conventional *Metallic Materials Properties and Development Standardization* (MMPDS) dataset. The prototype produced fatigue-life behavior in general agreement with the reference data, supporting the feasibility of the approach. This work establishes a practical foundation for generating larger, standardized fatigue datasets to improve statistical characterization, model calibration, and fatigue-life prediction in high-reliability applications.

# Ultrasonic Fatigue and Crack Initiation Mechanisms in LPBF Cu–30Ni

**Meysam Haghshenas (meysam.haghshenas@utoledo.edu)**

*Fatigue, Fracture, and Failure Laboratory (F3L), College of Engineering, University of Toledo, OH, USA*

*Ultrasonic Fatigue* *LPBF* *Cu-30Ni*

**Abstract** This work investigates the vibration-induced fatigue behavior of laser powder bed fusion (LPBF) Cu–30Ni alloy under fully reversed, high-frequency ultrasonic loading. Ultrasonic fatigue testing at 20 kHz is employed as a controlled vibration fatigue framework to examine crack initiation and damage evolution under extreme cyclic loading conditions. Specimens were fabricated in vertical and horizontal build orientations and evaluated in both as-built and post heat-treated conditions to quantify the coupled effects of process-induced anisotropy and thermal history on fatigue performance. Stress–life (S–N) data were generated to characterize vibration fatigue resistance across multiple stress regimes. The fatigue response was correlated with LPBF-induced defect populations, microstructural alignment, and residual stress states arising from build orientation and heat treatment. Advanced post-mortem characterization, including scanning electron microscopy, electron backscatter diffraction, and detailed fracture-surface analysis, was performed to identify dominant crack-initiation sites and fracture mechanisms under vibratory loading. Results reveal a pronounced sensitivity of vibration fatigue performance to both build orientation and thermal condition. Post heat treatment improves vibration fatigue resistance by mitigating residual stresses and microstructural heterogeneity, while build orientation governs fatigue life through anisotropic defect morphology and microstructural alignment relative to the vibration loading direction. Furthermore, the analysis showed that at lower stress levels, crack initiation is dominated by internal process-induced defects. These findings provide mechanistic insight into vibration fatigue crack initiation in additively manufactured Cu-based alloys and establish structure–process–fracture relationships essential for the reliable design of LPBF components subjected to high-frequency vibratory environments.

# *In situ* observation of persistent slip in the initial stages of fatigue of PBF-LB/M austenitic 316L steel

**Jaromír Brůža[1,2], Anja Weidner[3], Tomáš Vražina[1,2], Ladislav Poczklán[1], Ivana Zetková[4], Horst Biermann[3], Jiří Man[1]**

[1]*Institute of Physics of Materials, Czech Academy of Sciences, Žižkova 22, 616 00 Brno, Czech Republic, bruza@ipm.cz*

[2]*Institute of Material Sciences and Engineering, Brno University of Technology, Czech Rep.*

[3]*Institute of Materials Engineering, TU Bergakademie Freiberg, Germany*

[4]*Regional Technological Institute, University of West Bohemia, Pilsen, Czech Republic*

*Persistent slip* *In situ deformation* *PBF-LB/M 316L*

**Abstract** Laser powder bed fusion (PBF-LB/M) is a widely used additive manufacturing (AM) technique that enables the production of complex geometries by selective melting of metal powders, layer by layer, using a focused laser beam. This process is characterized by highly localized heating, rapid solidification, and extreme thermal gradients, which result in a unique and often anisotropic hierarchical microstructure. These microstructural features differ significantly from those found in conventionally manufactured materials and can have a pronounced impact on the material's mechanical behavior, particularly under cyclic loading conditions. Given the growing adoption of PBF-LB/M for structural applications, especially in the aerospace, biomedical, and energy sectors, understanding the fatigue performance of PBF-LB/M-fabricated materials is of critical importance. In this study, we investigate the early fatigue damage mechanisms in additively manufactured 316L austenitic stainless steel, with a focus on the formation and evolution of persistent slip markings (PSMs). These localized surface features serve as precursors to crack initiation and can provide valuable insight into the deformation behavior of the material under cyclic loading. To observe the development of PSMs in real time, we employed an in-situ cyclic loading module integrated within a scanning electron microscope (SEM), enabling direct visualization of surface changes during fatigue testing. The surface evolution of PSMs was monitored from the virgin (unloaded) state up to 200 load cycles. In addition, specimens pre-cycled for 50 and 500 cycles were examined to capture the progression of slip activity over extended fatigue exposure. Advanced characterization techniques, including electron back-scattered diffraction (EBSD), electron channeling contrast imaging (ECCI), and a combination of focused ion beam (FIB) and transmission electron microscopy (TEM), were used to investigate the intricacies of localized deformation of the PBF-LB/M 316L microstructure.

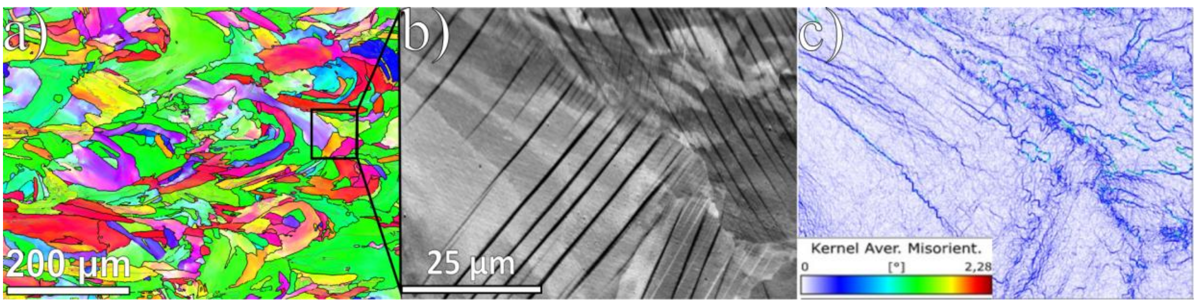



***Figure 1*** *– (a) IPF colored map, (b)FSD detail example, and (c) Kernel Average Misorientation map of PBF-LB/M 316L steel.*

# Residual stress relaxation and dislocation density evolution of additively manufactured titanium alloy during very high cycle fatigue loading

**N. Ranc[1], I. Koutiri[1], M. Celikin[2], O. Castelnau[1], V. Jacquemain[3], C. Cheuleu[3], V. Michel[1], C. Mocuta[4], D. Thiaudière[4]**

*[1]PIMM, Arts et Métiers, CNRS, 151 bd de l'Hôpital, 75013 Paris, France*

*[2]University College Dublin, School of Mechanical and Materials Engineering, Engineering Building Belfield Dublin 4, Ireland*

*[3]E-PIEZO, 19 rue de la Prévoyance, 94300 Vincennes, France*

*[4]Synchrotron SOLEIL, L'Orme des Merisiers, D128, 91190 Saint-Aubin, France*

*Residual stress relaxation* *Dislocation density* *Very high cycle fatigue*

**Abstract** Very high cycle fatigue concerns the study of the rupture of materials and structures subjected to cyclic stresses of more than $10^7$ cycles. Current structures, whether in the fields of transport, energy and biomedical industries, are indeed very often loaded with a number of cycles up to one billion. For some materials, especially high-strength steels, fracture in the gigacycle fatigue regime is characterized by a transition from surface fatigue crack initiation to initiation at internal defects. This transition is not well understood by the scientific community but it is nevertheless a key point for understanding and modelling of fatigue lifespans at very high cycle numbers. One possible explanation for this transition is related to the rate of residual stress relaxation on the specimen's surface during the cyclic loading. Residual compression stresses associated with the manufacturing process, or heat treatment of the specimen, or microstructure could significantly affect this transition. Materials obtained through additive manufacturing processes such as Laser Powder Bed Fusion (LPBF), generally exhibit significant residual stresses in their initial state. The issue of residual stress relaxation during cyclic loading in these materials is therefore more crucial. Additionally, crack initiation at the surface is related to the formation of persistent slip bands, which are characterized by the formation of dislocation structures and the stabilization of the evolution of the dislocation density as a function of the number of cycles. Therefore, measuring the evolution of the dislocation density at the surface of the material is a good way to determine the mechanism of surface crack initiation.

This paper, therefore, aims to conduct an experimental study using X-ray diffraction, at beamline DiffAbs of the synchrotron SOLEIL, to quantify the evolution of residual stresses and dislocation density during cyclic loading involving a very high number of cycles. The material under study is the Ti64 titanium alloy produced using the LPBF process. Analysis of the diffraction patterns provides information on the evolution of residual stresses, dislocation density and the material's microstructure.

# Heat resistant ultra-strong Al-Si alloy and its application in additive manufacturing

**Zhicheng Dong[1], Heyuan Huang[2,*]**

[1]*School of Civil Aviation, Northwestern Polytechnical University, Xi'an 710072, China*
[2]*School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, China*

**Corresponding Author Email: huangheyuan@nwpu.edu.cn*

*Additive Manufacturing* *Aluminum Alloy* *Fatigue Resistance*

**Abstract** This study develops an Al-Si-Fe-Mn-Ni alloy featuring fine grains and stable grain boundaries to meet the stringent load-bearing requirements of additively manufactured components operating in high-temperature environments. By leveraging solid-solution and precipitation-strengthening mechanisms, we introduce Fe and Ni, two common transition-metal elements, to form high-density, thermally stable intermetallic compounds, which subsequently stabilize the grain boundary structure of the SLM-printed alloy. Mn addition further facilitates the precipitation of $Al_6Mn$ strengthening phases. These synergistic strengthening mechanisms lead to exceptional mechanical performance, with the Al-Si-Fe-Mn-Ni alloy maintaining or even improving its stability at high temperatures, indicating a temperature-dependent fatigue mechanism. This study proposes a straightforward, reliable, and cost-effective strategy for designing a high-performance Al-Si alloy, offering a promising pathway for enhancing fatigue reliability and expanding industrial applications in extreme environments.

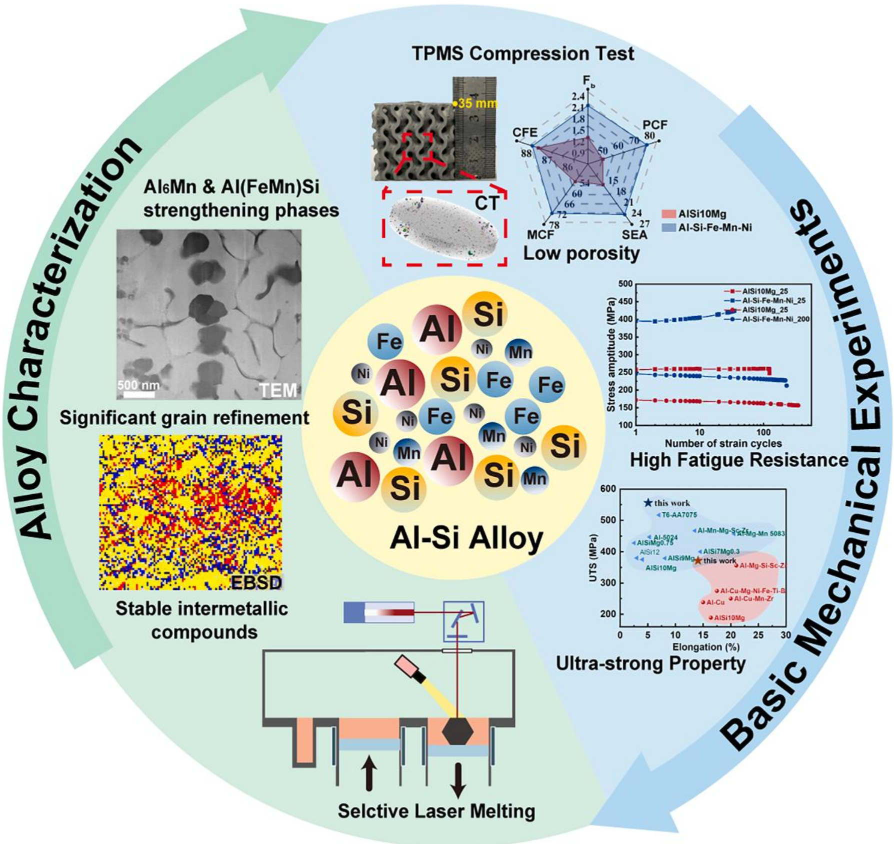



***Figure 1 -*** *Graphic Abstract*

# Influence of forced assembly gaps on the fatigue behavior of aluminum alloy multi-bolted joints under random loading

**Heyuan Huang[1,2,*], Jinpen Chen[1,2]**

[1] *School of Aeronautics, Northwestern Polytechnical University, Xi'an, Shaanxi 710072, PR China*
[2] *National Key Laboratory of Aircraft Configuration Design, Xi'an, Shaanxi 710072, PR China*

**Corresponding Author Email: huangheyuan@nwpu.edu.cn*

*Random fatigue* *Multi-bolted joints* *Fatigue behavior*

**Abstract** Assembly-induced misfit gaps are a practical but often under-quantified source of durability loss in aviation aluminium bolted joints, especially under service-representative random spectra. Here, a two-row/three-column multi-bolted joint configuration was investigated under broadband random loading to clarify how forced assembly gaps reshape load transfer and fatigue damage evolution. Four conditions were considered: 0 mm, 0.3 mm, 0.5 mm, and 0.5 mm with solid compensation shims. A combined approach integrating spectrum fatigue testing, fracture-surface examination and numerical simulation was employed to resolve the governing mechanisms and their consequences on life, crack kinetics and failure patterns. The results reveal a strong monotonic degradation with increasing gap: when the gap increased from 0 to 0.5 mm, the fatigue life dropped by 45.91%, while the crack growth rate rose by 203%, reaching $2.66 \times 10^{-3}$ mm/cycle. This acceleration is primarily linked to gap-driven non-uniform stress redistribution and the associated amplification of local tensile (Mode I–dominated) driving forces. Introducing solid compensation shims effectively reconstructs the stress field, alleviates peak concentration near critical holes, and increases the damage-based life of the 0.5 mm-gap joint by 49.035%. These findings provide quantitative guidance for fatigue assessment and qualification of multi-bolt joints, and highlight the need for strict control of assembly gaps to suppress early spectrum-driven damage.

# Nanocomposite Conductive Tough Hydrogel Based on Metal Coordination Reinforced Covalent Pluronic F-127 Micelle Network for Human Motion Sensing

**Zhicheng Dong[1,*], Xiaopeng Wan[1]**

[1]*School of Civil Aviation, Northwestern Polytechnical University, Xi'an 710072, China*

**Corresponding Author Email: zhichengdong@mail.nwpu.edu.cn*

*High-strength hydrogel* *Anti-fatigue* *Human motion sensors*

**Abstract** The design of conductive hydrogels integrating anti-fatigue, high sensitivity, strong mechanical property and good sterilization performance remains a challenge. We innovatively introduced metal coordination in covalently crosslinked Pluronic F-127 micelle network and synthesized nanocomposite conductive tough hydrogel through the combination of covalent crosslinking, metal coordination and silver nanowire reinforcement. Compared with pure diacylated PF127 hydrogel (PF127), the tensile strength of PF-AA-AM-$Al^{3+}$/Ag0.25 hydrogel reaching 1.4 MPa was about 10 times than that of PF127. The toughness of PF-AA-AM-$Al^{3+}$/Ag0.25 reaches 1.88 MJ/$m^3$. Compared with PF-AA-AM-$Al^{3+}$, the introduction of silver nanowires increased the fatigue life of PF-AA-AM-$Al^{3+}$/Ag0.25 by 200% (31837 cycles), 170% (12804 cycles) and 1022% (511 cycles) under 100%, 120% and 150% ultimate tensile strains, respectively. Besides, the PF-AA-AM-$Al^{3+}$/Ag0.25 showed strain sensitivity to small deformation (Gauge factor = 2.42) in wearable tests on hands and knees. Finally, a viscoelastic numerical constitutive model was established based on finite element method to study the damage failure history of the material. Comparative analysis showed that local stress concentration was the main factor leading to the failure of hydrogel.

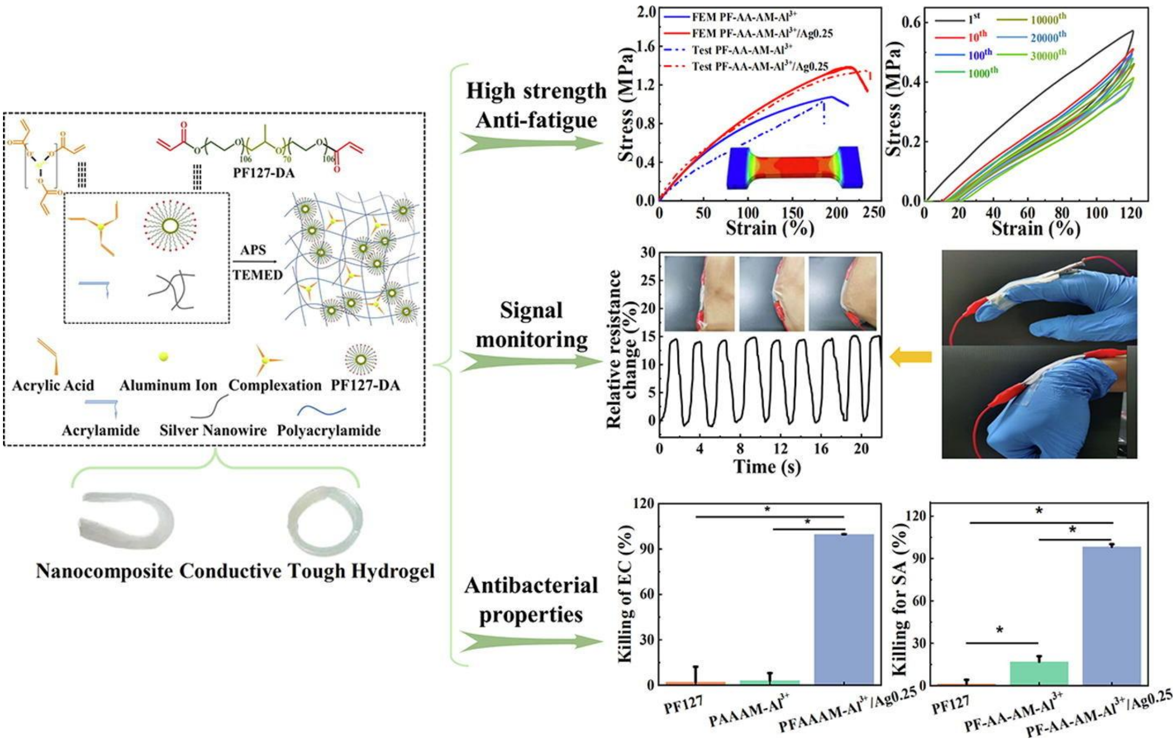



***Figure 1 -** Graphic Abstract*

# Longer life censored P-S-N curve experiment and fitting method

**Liyang Xie[1], Ningxiang Wu[1]**

[1]*Northeastern University, Shenyang, China, lyxie@me.neu.edu.cn*

[2]*Northeastern University, Shenyang, China, nxwu@me.neu.edu.cn*

*Fatigue life* *Failure probability* *Experiment method*

**Abstract** Fatigue life reliability design and probabilistic fatigue life evaluation of mechanical components and structural parts rely on the respective relationship between cyclic stress amplitude and fatigue life associated a particular survival probability such as 0.9, 0.99 or 0.999. To obtain such a relationship, what are really needed are the minimum lives or those corresponding to a particular high survival probability under the every cyclic stress levels assigned for the P-S-N curve (the relationship between stress amplitude and the fatigue life corresponding to particular survival probability P) test, not necessarily the fatigue life distributions under each of the cyclic stress levels. This paper presents a time-saving scheme to obtain the necessary life data to establish a particular P-S-N curve and the statistical analysis method to fit the P-S-N curve based on such life data. Such an experiment acquires only the minimum lives under each of the several different cyclic stress levels. The P-S-N curve is fitted according to these test data and appropriate statistical analysis technique. The assigned survival probability *P* is guaranteed by the number of the test specimens under each of the cyclic stress levels and fitting the P-S-N curve (the red line in the Figure) by means of the least sequares method; or the number of all the test specimens under the every cyclic stress levels and fitting the P-S-N curve (the black line in the Figure) by means of a one-side least sequares method. The latter is an innovative method of the present paper.

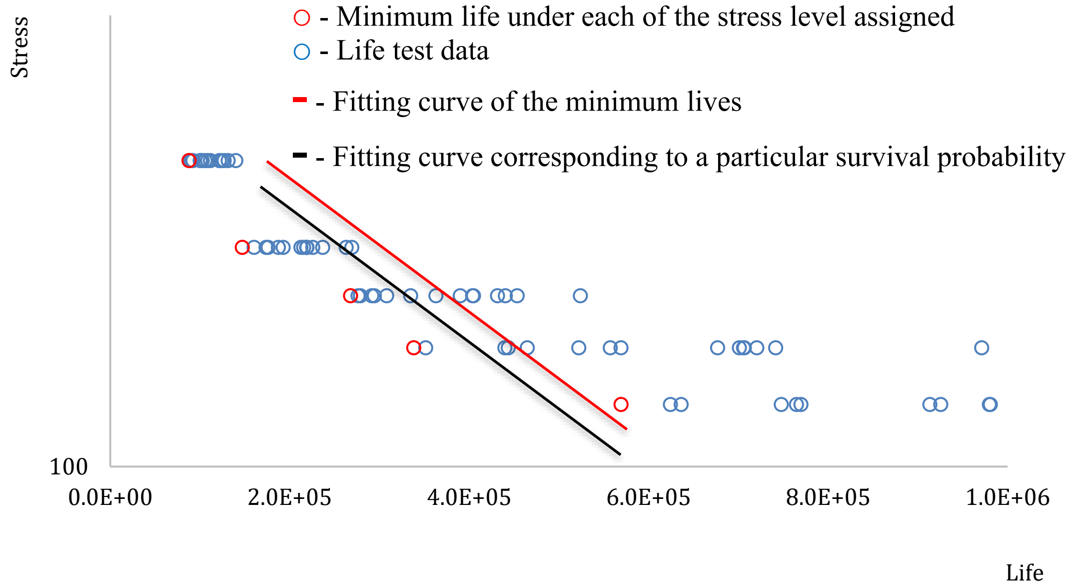



***Figure 1*** *– P-S-N curve fitting with minimum order statistics*

# StressLifeEBA: An Accelerated Energy-Based Lifetime Prediction Method for the Estimation of Trend S-N Curves for Various Testing Conditions

**Jonas Anton Ziman[1,2,*], Fabian Weber[1], Aline Wagner[1], Janina Koziol[1,2], Peter Starke[1,2]**

*[*]Jonas Anton Ziman, Department of Materials Science and Materials Testing (WWHK), Institute QM³, University of Applied Sciences, 67659 Kaiserslautern, Germany. jonas.ziman@hs-kl.de*

*[1]Department of Materials Science and Materials Testing (WWHK), Institute QM³, University of Applied Sciences Kaiserslautern, Kaiserslautern, Germany*

*[2]Faculty of Natural Sciences and Technology, Saarland University, Saarbrücken, Germany*

*Fatigue Life Calculation* *High-Cycle-Fatigue* *Non-Destructive Testing*

**Abstract** Reliable prediction of fatigue life remains a key challenge under various testing conditions affecting the material response under cyclic loading. To address this challenge, an innovative energy-based approach, denoted as StressLifeEBA, was developed. The method enables a process-oriented evaluation of fatigue life based on one load increase and two constant amplitude tests according to Figure 1, reducing the experimental effort compared to the conventional determination of S-N curves. Non-destructive-based measurement techniques were used to determine an energy-based damage parameter derived from the respective material response under cyclic loading. The approach was validated on normalized SAE 1045 steel and quenched and tempered 20MnMoNi5-5 steels over a wide frequency range, using both unnotched and notched geometries. The results demonstrate that StressLifeEBA yields consistent parameters and accurate trend S-N curves across different microstructure and testing conditions and provides a robust and efficient basis for an accelerated fatigue lifetime prediction.

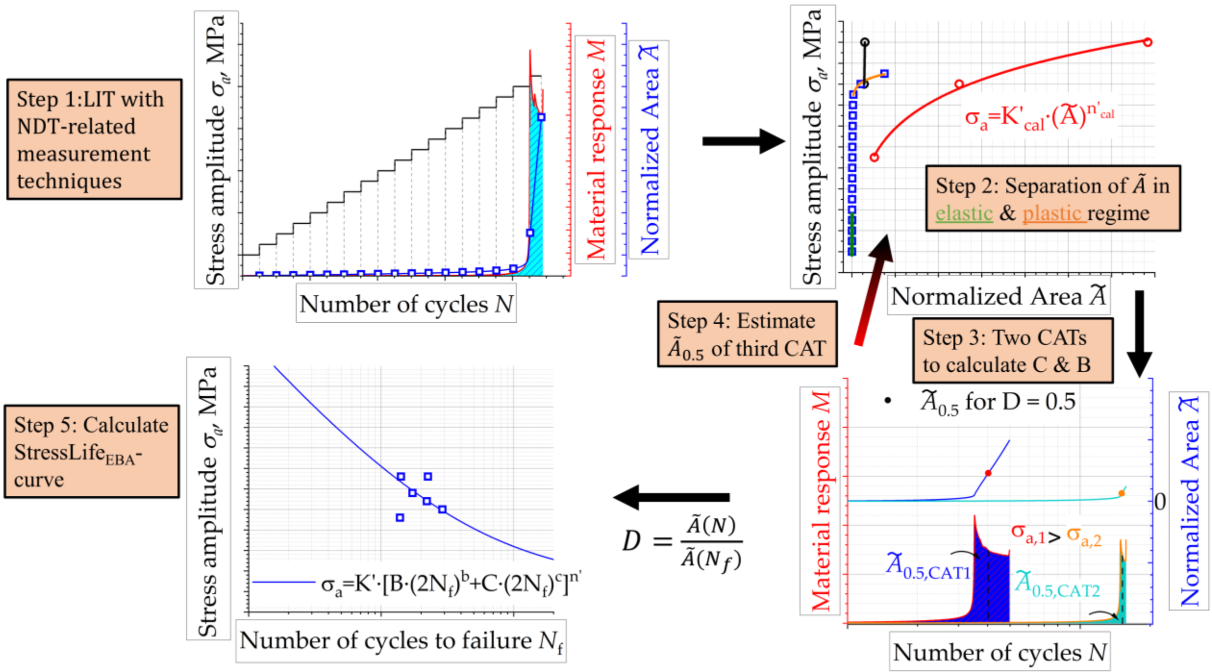



***Figure 1*** *- Schematic representation of the StressLifeEBA method for calculating S-N curves based on the damage state derived from cyclic deformation curves.*

# Study on the critical defect identification and life prediction for selective laser melted Ti-6Al-4V alloy

**Jun Zou[1], Xiaoyu Xia[1], Zhenyu Feng[2], Peng Luo**

*[1]College of Safety Science and Engineering, Civil Aviation University of China, Tianjin 300300, China, xiaoyu_xia2022@163.com*

*[2]Science and Technology Research Institute, Civil Aviation University of China, Tianjin 300300, China*

*[3]AECC Hunan Aviation Powerplant Research Institute, Zhuzhou 412002, China*

*Defect geometric characteristics* *Fatigue life* *Critical defect identification*

## Abstract

The manufacturing defects are the primary reason for the significant scatter in fatigue life of additive manufacturing (AM) materials. However, accurately identifying the critical defect and predicting fatigue life remains a significant challenge. The fatigue behavior of selective laser melted (SLM) Ti-6Al-4V alloy was investigated using two specimen geometries: tangentially blending fillets (TF) and continuous radius (CR). Uniaxial stress-controlled fatigue tests demonstrated significant life scatter, with CR specimens generally outperforming TF specimens. Fractographic analysis confirmed that all fatigue failures originated from surface defects. Correlation analysis identified that defect size as the most influential factor on fatigue life, followed by stress level, defect orientation and circularity. A fatigue life model incorporating stress and defect characteristics was established, and most data was located in the factor of 2 error bounds for both TF and CR specimens. Furthermore, the life model combined with the XCT data successfully identified the actual critical defect in six out of eight specimens. The study concludes that the TF specimen is more suitable for standardized fatigue test of AM materials, and the established life model can effectively support the fatigue life assessment and critical defect identification.

# Fatigue crack growth behavior of a selective laser melted Zr-based bulk metallic glass

**Simon Pillmeier[1], Mirjam Spuller[2], Reinhard Pippan[1], Jürgen Eckert[1,3], Anton Hohenwarter[3]**

*[1]Erich-Schmid-Institute of Materials Science, Austrian Academy of Sciences, Jahnstraße 12, 8700 Leoben, Austria, simon.pillmeier@oeaw.ac.at*

*[2]Joanneum Research Forschungsgesellschaft mbH, Materials-Institute for Sensors, Photonics and Manufacturing Technologies, Leobner Straße 94a, 8712 Niklasdorf, Austria*

*[3]Department of Materials Science, Montanuniversität Leoben, Jahnstraße 12, 8700 Leoben*

*Fatigue crack growth* *Selective laser melting* *Bulk metallic glass*

**Abstract** Additive manufacturing methods like selective laser melting (SLM) are particularly interesting for bulk metallic glasses (BMG) since high cooling rates during the process circumvent any size limitations that may arise from their glass forming ability. However, oxygen contaminations, partial crystallization or artefacts like pores from the SLM process may induce deteriorated mechanical properties like fracture toughness and fatigue properties, and are detrimental for a damage tolerance design. For this study a Zr-based BMG, commercially known as Vitreloy 105, was investigated. Test cubes were built and compact tension specimen were machined such that the loading direction is parallel to the building direction. It could be shown that with adequate processing parameters a fracture toughness of 27.7 ± 4.1 MPam$^{1/2}$, comparable to traditionally casted plate material, is achievable. Scatter in the fracture toughness data could be positively linked to pore size and frequency within the plastic zone ahead of the crack tip. Similarly, fatigue crack growth (FCG) properties were found to be unaffected by the SLM processing. A slope of 1.7 in the Paris regime and striations found on the fracture surface confirmed blunting and re-sharpening of the crack tip as the main propagation mechanism of FCG. A hierarchy of striations could be associated with the monotonic plastic zone size. Raising the load ratio from 0.1 to 0.7 induced no change in the overall crack growth rates, the slope in the Paris regime as well as the effective threshold of stress intensity factor range $\Delta K_{th,eff}$ of 1.21 MPam$^{1/2}$. The latter was found to follow the same trend line with the Young´s modulus as many polycrystalline metals, hinting at a more general mechanism governing the onset of FCG.

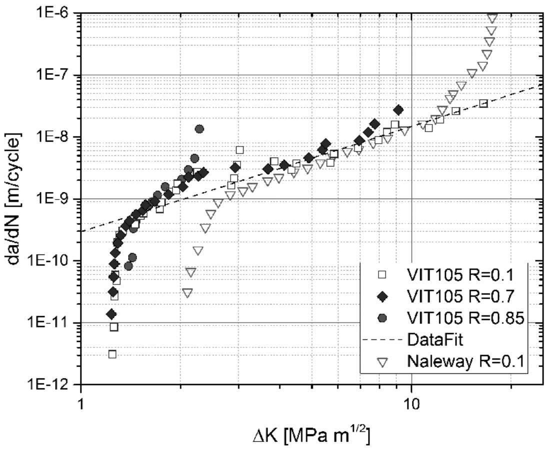



***Figure 1** – FCG diagram comparing SLM processed and casted plate Vitreloy 105 [1].*

*[1] Naleway et al., A highly fatigue-resistant Zr-based bulk metallic glass, Metall. Mater. Trans. A 44A (2013) 5688-5693*

# NOFM: A Physics-Augmented Neural Operator for Zone-Resolved Fatigue Life Prediction in Grade R4 Mooring Chain Weldments

**Alejandro Fernández de Castro[1], Melih Kandemir[2], Halid Can Yıldırım*'[1]**

[1]*Department of Civil and Architectural Engineering,*
*Aarhus University, Aarhus, 8000,*
*Denmark*

[2]*Department of Mathematics and Computer Science,*
*University of Southern Denmark, Odense, 5230 , Denmark*

**corresponding & main author :* halid.yildirim@cae.au.dk

*Fatigue and fracture* *Welds* *Machine Learning*

**Abstract**

Grade R4 mooring chains are safety-critical offshore components whose fatigue life is governed by the interplay between weld-zone metallurgical heterogeneity and stress amplification from corrosion pits — a combination that empirical S-N design curves cannot resolve with quantified uncertainty.

This paper introduces NOFM (Neural Operator for Fatigue Mechanics), a physics-augmented surrogate delivering zone-resolved, uncertainty-quantified fatigue life predictions for R4 chains.

Three advances distinguish NOFM: (i) a Grain-Boundary Length Density (GBLD) descriptor encoding grain shape, misorientation, and HAGB fraction into a 14x range in effective Paris crack-growth constant without zone-level da/dN measurements; (ii) hardness-dependent Coffin-Manson parameters revealing that the initiation-critical zone differs from the propagation-critical zone through a stress-dependent ´hardness-strain antagonis´ that single-zone models cannot capture; and (iii) a unified neural network trained across eight stress levels with nominal_stress/E as an explicit feature, eliminating the non-monotone S-N artefact of independently trained surrogates.

A physics-informed loss enforces Griffith and Paris-slope consistency via backpropagation; Monte-Carlo dropout provides 16-84% epistemic credible intervals. Predictions lie within the experimental R4 scatter band over $\Delta\sigma$=70-140 MPa, while the analytical Paris baseline under-predicts life by 2-4x at low stress.

# Spatial Encoding of Microstructure and Plasticity for Data-Driven Fatigue Properties Prediction and Governing Mechanisms identification of AM microstructure.

***M.Calvat[1], D. Anjaria[1], J.C. Stinville[1]***

*[1]University of Illinois at Urbana-Champaign, Urbana, IL, USA, jcstinv@illinois.edu*

*Machine learning* *Fatigue* *Plasticity*

To accelerate alloy design, rapid prediction of mechanical properties and associated governing mechanisms identification are essential, particularly for measurement time-intensive properties such as fatigue. In this work, we propose a novel data-driven framework that encodes metal microstructure and plasticity under elementary loading conditions to train a convolutional neural network-based model for predicting macroscopic properties. A large, spatially resolved, and multi-modal dataset of AM microstructure and plasticity was generated, combining EBSD-based microstructural maps with high-resolution digital image correlation, measurements of plastic response under monotonic loading and after a few fatigue cycles. To effectively represent this complex data, we employed machine learning-based scanning probe encoding using variational autoencoders, which enable high-fidelity and low-dimensional representations of metal microstructure and plasticity fields in a latent space. In parallel, macroscopic mechanical properties (fatigue and monotonic strengths), were also measured for each alloy. We assess prediction accuracy and demonstrate the benefits of incorporating both spatially encoded microstructural and plasticity information for rapid prediction of fatigue properties of AM microstructure. A**dditionally, attention-based machine learning methods were developed to identify, in a fully data-driven manner, the microstructural features that govern fatigue behavior.** These models enable the systematic weighting and interpretation of spatially resolved microstructure and plasticity descriptors, thereby revealing the most influential microstructural attributes controlling fatigue response.

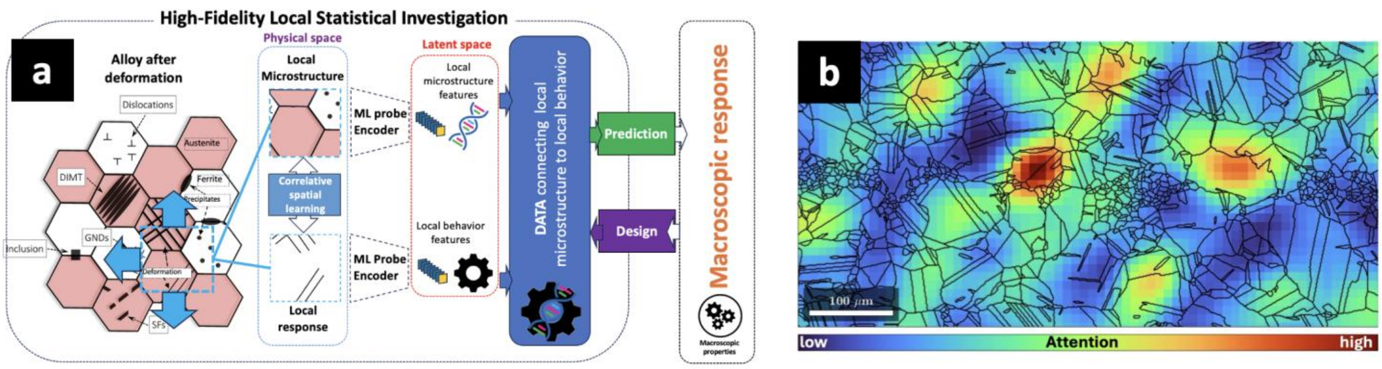



***Figure 1 – (a) Materials Spatial Intelligence for property prediction and governing principle identification.*** *Alloy microstructures, resolved at fine scales over large fields of view, are encoded in a spatially consistent manner to capture the full distribution of microstructural features using a VAE data-driven approach. Plasticity fields obtained after simple mechanical loading are similarly encoded and, together with microstructure descriptors, projected into latent-space feature maps. These latent representations are then used to predict macroscopic mechanical properties.* ***(b) Identification of governing microstructural features.*** *Once accurate property prediction is achieved, attention-based learning mechanisms are employed to identify the microstructural features most influential in the model's predictions. This enables the generation of spatial maps highlighting governing features and provides interpretable insights into the microstructure–property relationships driving the predicted behavior.*

# Application of the Averaged Strain Energy Density Approach to Variable Amplitude Rotating Bending Fatigue of S690 Steel

**Kris Hectors[1,2,*] , Wim De Waele[1,2]**

*[1]Ghent University, Faculty of Engineering and Architecture, Department of Electromechanical, Systems and Metal Engineering, Laboratory Soete, Technologiepark 46, Zwijnaarde, 9052, Belgium.*

*[2]Flanders Make @Miro, Ghent, Belgium.*

* *Kris.Hectors@UGent.be*

*Strain energy density* *Variable amplitude fatigue* *Damage accumulation*

## Abstract

Accurately assessing fatigue damage accumulation under variable amplitude loading remains a critical challenge in structural engineering. This is particularly true for components subjected to rotating bending where stress gradients significantly influence fatigue life. Conventional stress-based Palmgren-Miner fatigue life predictions, frequently yield unsatisfactory predictions due to their inability to account for load sequence and interaction effects. Previous experimental studies have demonstrated that the Palmgren-Miner rule tends to be non-conservative for high-to-low block loading sequences and conservative for low-to-high sequences. While local energy-based approaches, specifically the averaged strain energy density (SED) method, have been successfully validated for notched components under constant amplitude rotating bending and for uniaxial tension-tension variable amplitude loading, their application to notched components under variable amplitude rotating bending remains unexplored. This work addresses this gap by applying the average SED approach to a comprehensive database of block-loading experiments to evaluate its predictive accuracy compared to traditional stress-based methods.

The study utilizes an extensive open-access dataset comprising >160 rotating bending block-loading fatigue experiments on S690 steel specimens. The specimens were tested under constant amplitude loading and two-level, three-level and five-level block loading sequences. Finite element analysis is employed to calculate the averaged SED ($\Delta\overline{\mathrm{W}}$) in a notched specimen for each stress block (e.g., 260 MPa and 235 MPa). The radius ($R_0$) of the control volume at the notch is calibrated using constant amplitude benchmark data. Damage accumulation is then reassessed using the SED-based Miner's rule, summing energy-based damage fractions ($n_i/N_{\Delta \mathrm{W,i}}$) derived from the master SED-N curve.

Preliminary analysis suggests that the SED approach provides a more robust framework for assessing sequence effects in rotating bending. By incorporating the volume-dependency of the stress gradient, the SED method inherently accounts for the reduced highly-stressed volume typical of rotating bending, potentially correcting the non-conservative bias observed in stress-based high-to-low predictions. The results aim to demonstrate that the SED-based damage accumulation model yields life predictions with reduced scatter and improved accuracy compared to the standard Palmgren-Miner rule. These findings support the validity of local energy methods for rotating bending loading in notched components.

# Enhancing Battery Durability through Smart Virtual Sensing for Input Force Prediction

**Şafak Has[1], Xiaoting Kou[2], Michael Hack[3]**

*[1]Şafak Has, Siemens Digital Industries Software, Interleuvenlaan 68, 3001-Leuven/Belgium,* safak.has@siemens.com

*[2]Xiaoting Kou, Siemens Digital Industries Software, 19 bd Jules Carteret Lyon/France* Xiaoting.kou@siemens.com

*[3]Michael Hack, Siemens Digital Industries Software, Luxemburger Str. 7, 67657 Kaiserslautern/Germany,* michael.hack@siemens.com

*Virtual sensing* *Battery Durability* *Load prediction*

**Abstract**

The increasing demand for high-performance and durable battery systems in various applications necessitates robust methods for predicting and mitigating structural stresses. A critical challenge in battery design and validation is accurately characterizing the dynamic input forces experienced by the battery structure, which directly influence its mechanical integrity and operational lifespan. Traditional physical force measurement techniques can be intrusive, costly, and limited in their spatial resolution, particularly in complex battery geometries. This presentation addresses this problem by introducing a novel smart virtual sensing framework designed to predict battery input forces and structural strain, thereby offering a more efficient and comprehensive approach to structural validation.

We present a hybrid approach combining physical measurements with advanced virtual sensing techniques. Strain gauges and accleremeters strategically placed at specific locations on the battery structure provide sparse physical data. This data is then fed into the smart virtual sensing solver to perform data fusion between mesurement and simulation, , to predict full-field strain distributions across the battery structure and, crucially, to estimate fatigue at the critical positions. Additionally the dynamic input forces acting on the system can be extruded for futher analysis and testing. To validate the efficacy of this framework, a comprehensive correlation study is performed. The virtually predicted strain data is directly compared against physically measured strain data from identical locations on the battery. Furthermore, physical force cells are integrated at each attachment point of the battery structure to independently measure the actual input forces. These physically measured input forces are then rigorously compared with the forces predicted by the smart virtual sensing system, providing a robust validation of the model's accuracy and predictive capabilities.

The major results demonstrate a strong correlation between the virtually predicted and physically measured strain and input forces, highlighting the significant potential of this smart virtual sensing approach. This methodology not only offers a non-intrusive and cost-effective alternative to extensive physical instrumentation but also provides a powerful tool for comprehensive structural validation and optimization during the battery design phase. The successful implementation of this framework promises to enhance the understanding of battery mechanical behavior, leading to improved durability, reliability, and accelerated development cycles for next-generation battery systems.

# Multiaxial fatigue strength estimation of plasma-nitrided carbide-rich PM tool steels: comparison of failure hypotheses and mean stress sensitivity

**Frederik Tegeder[1], Christoph Broeckmann[1]**

*[1] Institute for Materials Applications in Mechanical Engineering (IWM), RWTH Aachen University, D-52062 Aachen, Germany*

*Carbide-rich tool steel* *Multiaxial-fatigue* *failure hypotheses*

**Abstract** Carbide-rich powder-metallurgical (PM) tool steels are widely used in highly loaded forming and cutting applications, where components are subjected to combined axial and torsional loading and are often plasma nitrided to improve surface performance. However, the influence of such surface treatments on multiaxial fatigue strength and on the predictive capability of common multiaxial failure hypotheses is still not fully clarified.

This work investigates the multiaxial fatigue strength of three carbide-rich PM tool steels (D2, M3 and A11 PM), in both nitrided and non-nitrided conditions, under synchronous axial–torsional loading. A three-dimensional finite element model of the laboratory specimen is created in ABAQUS to accurately resolve the near-surface stress gradients in the gauge section.

Several multiaxial fatigue criteria are implemented and compared: Normal Stress Hypothesis (NH), Shear Stress Hypothesis (SSH), Distortion Energy Hypothesis (DEH), the FKM guideline (linear combination of NH and DEH), the Quadratic Failure Hypothesis (QFH) and the Shear Stress Intensity Hypothesis (SIH). Material parameters are derived from axial and torsional fatigue strengths and from Haigh diagrams. Plasma nitriding is introduced numerically by superimposing measured near-surface compressive residual stress profiles onto the finite element stress tensors in the surface layer.

The degree of utilisation or failure potential predicted by each criterion is evaluated as a function of axial load amplitude and compared with available experimental multiaxial fatigue limits. For non-nitrided specimens, NH and QFH show the best agreement with experiments under combined axial–torsional loading, whereas SSH and DEH are overly conservative and SIH and FKM tend to underestimate the multiaxial fatigue limit. For the nitrided condition, all criteria predict an increase in multiaxial fatigue strength due to the compressive surface stresses, but the quantitative gain depends strongly on the chosen hypothesis. The study demonstrates that accurate multiaxial fatigue assessment of nitrided PM tool steels requires both a suitable multiaxial failure criterion and a consistent representation of surface-induced residual stresses.

# Fatigue Life for Three-Point Bending of Rubber Composites with Different Reinforcement Layers

**Tadeusz Łagoda[1], Karolina Głowacka[1], Marko Nagode[2], Marta Kurek[1], Jernej Klemenc[2]**

[1]*Opole University of Technology, ul.Prószkowska 76, 45-756 Opole, j.malecka@po.edu.pl*

[2]*University of Ljubljana, Kongresni trg 12, 1000 Ljubljana*

*Equivalent strain* *Fatigue characteristic* *Rubber composite*

**Abstract** In this study, fatigue tests were performed on rubber composites reinforced with cords arranged at a 0/90° angle and subjected to bilateral three-point bending. The belts were prepared with single- and double-layer reinforcement. However, due to the rubber's high deformation, a special test stand was designed and constructed. As a result of tests performed on this stand, the composite belts were primarily in tension. To ensure a wide range of cycles to failure, some samples were tested without pretension, while others were tested with pretension, and various displacement values of the loading punch were set (displacement-controlled). To determine fatigue characteristics as a function of the number of cycles, three strain parameters were proposed for analysis: (1) strain amplitude, (2) maximum strain value, and (3) the geometric mean of the amplitude and maximum value. Analysis of fatigue tests reveals that the strain parameter, defined as the geometric mean of the amplitude and maximum values, best describes the fatigue performance of the tested composites with both single- and double-layer reinforcement.

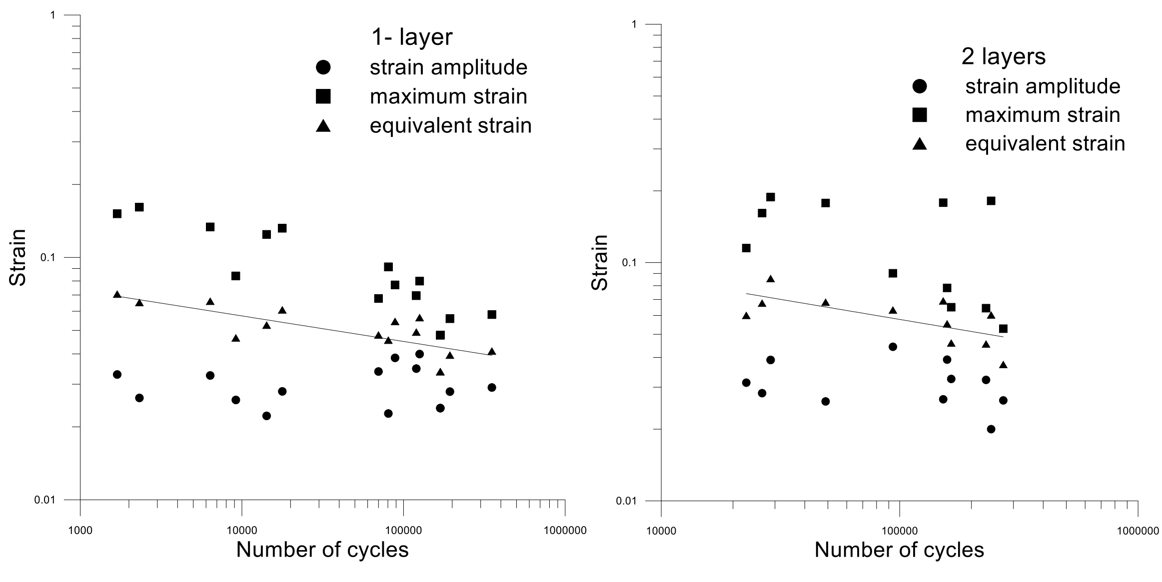



***Figure 1** – strain in rubber composite according number of cycles*

# Optimization of the Warm Peening Process for Inductive Hardened Samples of C55 using the Concept of Local Fatigue Strength

**Benjamin Dollhofer[1], Stefan Dietrich[1], Volker Schulze[1], Philipp Reeh[2], Stefano Bucci[3], Vallentina Dellaca[3], Marcel Egger[4], Ilaria Torquati[4], Ainhoa Errasti[5]**

*[1] Institute for Applied Materials - Materials Science and Engineering (IAM-WK), Karlsruhe Institute of Technology (KIT)*

*[2] STRESSTECH GMBH (STRESSTECH),*

*[3]CENTRO RICERCHE FIAT SCPA (CRF)*

*[4] I2M UNTERNEHMENSENTWICKLUNG GMBH (i2M)*

*[5] SIDENOR INVESTIGACION Y DESARROLLOSA (SIDENOR I+D)*

*Shot peening* *Tempering* *Fatigue Strength*

**Abstract** Within engineering disciplines, and particularly in the automotive industry, there is a strong demand for cost-effective and energy-efficient methodologies aimed at extending the operational service life of components.

The objective of surface hardening treatments is to induce compressive residual stresses in the near-surface region of the material, thereby enhancing the fatigue life and overall service performance of the components. Subsequently, these components are often tempered, which leads to a reduction of the initial compressive residual stresses at the surface and also to a reduction of detrimental tensile residual stresses within the component interior. If high compressive residual stresses at the surface remain necessary after tempering, they can be reintroduced or further increased by applying a shot peening process. The combined application of tempering and simultaneous shot peening is intended to synergistically optimize the outcomes of both processes.

In this work, the rotating bending test samples of C55 were first inductive surface hardened and then warm peened using different process parameters. The hardness and residual stress depth profiles were then determined for all sample conditions. The optimum process parameters were determined using the concept of local fatigue strength. A reference process was also examined in which tempering was performed first, followed by conventional shot peening. The two most promising conditions from the warm peening process and the reference process were then further investigated in the LCF and HCF in interrupted cycle tests with regard to their residual stress stability and fatigue strength.

# Fatigue behavior of 3D-printed metals: bulk, lattice and hybrid structures

**Yoshihiko Uematsu**

*Gifu University, 1-1 Yanagido, Gifu 501-1193, Japan, uematsu.yoshihiko.z3@f.gifu-u.ac.jp*

*Bulk structure* *Lattice structure* *Hybrid structure*

**Abstract** Additive manufacturing (AM), also known as 3D printing, has recently become popular, with the use of metal powder as a raw material. Powder bed fusion (PBF) is the most common type of AM, including selective laser melting (SLM) and electron beam melting (EBM). Other methods, such as direct energy deposition (DED) and binder jetting (BJ), have also attracted attention in recent years. When using 3D-printed metals in mechanical structures, their fatigue strength and fracture mechanisms become important issues. This research focuses on the fatigue behavior of three kinds of 3D-printed metallic structures, namely bulk, lattice and hybrid structures. In bulk structure, defect-dominated fatigue crack initiation mechanism controls total fatigue life, resulting in inferior fatigue strengths to conventional wrought alloy as shown in Fig. 1 (Example of type 630 stainless steel). In compression-compression fatigue tests of lattice structures (Ti-6Al-4V), the size effect appeared in the fatigue strengths due to the local buckling of vertical pillars, where larger lattice structures had higher fatigue strength than small ones. In hybrid structure, raw metal powder was deposited on the conventional wrought alloy, which induced high residual stress. Consequently, the effect of residual stress was the highest among three different structures. As such, the fatigue failure characteristics are different for each of the three different structures. In the present research, those characteristics of 3D-printed metals with three different structures were reviewed and discussed.

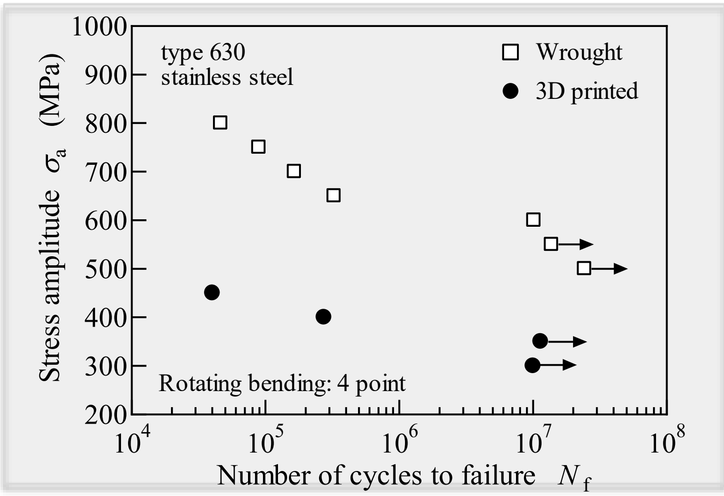



***Figure 1*** *– S-N diagram of 3D-printed and conventionally wrought type 630 stainless steel*

# LCF behavior of fine-grained L-PBF 316L steel with a plentiful occurrence of twin boundaries

**J. Man[1], J. Brůža[1,2], M. Jambor[1], M. Šmíd[1], M. Laleh[3], A.E. Hughes[4], I. Šulák[1], J. Polák[1]**

[1]*Institute of Physics of Materials, Czech Academy of Sciences, Žižkova 22, 616 00 Brno, Czech Republic,* man@ipm.cz

[2]*Institute of Material Sciences and Engineering, Brno University of Technology, Czech Rep.*

[3]*University of Wollongong, New South Wales, Australia*

[4]*Deakin University, Victoria, Australia*

*Additive manufacturing* *316L stainless steel* *Cyclic plasticity*

**Abstract** Laser powder-bed fusion (L-PBF) belongs to the most frequently utilized metal additive manufacturing technologies. High solidification rates and thermal gradients inherent to this technique lead to non-equilibrium microstructural states. In the case of single-phase 316L austenitic stainless steel the hierarchical microstructure is typically characterized by long columnar grains with numerous sub-grain boundaries (=low-angle grain boundaries (LAGBs)) – see Fig. 1a. Another feature typical for this microstructure represents a significant anisotropy of mechanical performance with respect to the SLM building direction.

The present work deals with the cyclic plasticity of 316L steel manufactured using also L-PBF. However, contrary to the typical characteristics described above, in the present case the L-PBF 316L steel exhibits also fully austenitic microstructure but with considerably finer grains and weaker texture [1] (see Fig. 1b) resulting in a more isotropic tensile performance. Another unusual and important feature is the frequent occurrence of twin boundaries [1].

Low-cycle fatigue (LCF) tests were conducted on flat sheet specimens at room temperature in symmetrical push-pull mode under strain control with constant strain rate of $4\times10^{-3}$ $s^{-1}$ and constant total strain amplitude ranging from 0.2% to 0.8%. LCF behavior was characterized by cyclic hardening/softening curves and fatigue life curves. After completion of fatigue tests the surface fatigue damage was studied using scanning electron microscopy (SEM) and atomic force microscopy (AFM). Microstructural changes in the bulk of cyclically strained specimens were documented using high-resolution transmission electron microscopy (TEM). Results of microscopic observations are confronted with the stress-strain response of the grain-refined material and compared with those obtained earlier for L-PBF 316L steel with coarse columnar grains [2].

[1] M. Laleh et al.: Scripta Mater. 192 (2021) 115–119. https://doi.org/10.1016/j.scriptamat.2020.10.018
[2] M. Pelegatti et al.: Mater. Charact. 228 (2025) 115448. https://doi.org/10.1016/j.matchar.2025.115448

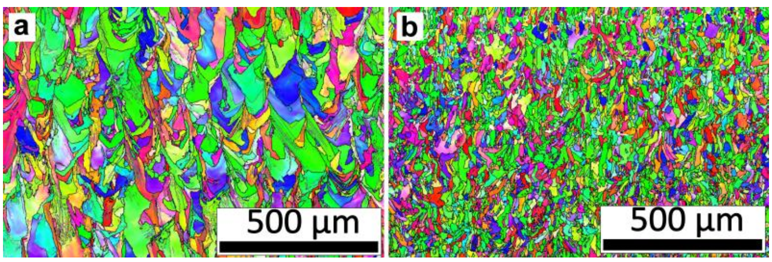



***Figure 1*** *– EBSD IPF orientation maps of (a) coarse- and (b) fine-grained L-PBF 316L steel.*

# Effect of shot peening and anodizing on the fatigue life of aerospace aluminum alloys

**Tissot Maxime[1,2,*], Surand Martin[2], Mabru Catherine[1], Chaussumier Michel[1]**

[1]*Institut Clément Ader (ICA) ; Université de Toulouse ; CNRS, UPS, INSA, ISAE-SUPAERO, IMT Mines Albi ; 3 rue Caroline Aigle, 31400 Toulouse, France*

**maxime.tissot@safrangroup.com*

[2]*Safran Landing Systems, Vélizy-Villacoublay, France*

*Residual stresses* *Surface cavities* *Stress concentration*

**Abstract**

The fatigue performance of aerospace-grade aluminum alloys is strongly influenced by surface treatments such as shot peening and anodizing. While anodizing is widely used to improve corrosion resistance, it modifies the surface topography by creating cavities resulting from the dissolution of intermetallic particles, which can negatively impact fatigue behavior. Shot peening, in contrast, introduces beneficial compressive residual stresses that can delay both fatigue initiation and propagation.

This study aims to quantify the effects of these surface treatments on fatigue properties. To address this, 7010-T7451 aluminum specimens were prepared with various surface conditions, including as-machined, shot-peened, and machined or shot-peened followed by anodizing. Axial fatigue tests were conducted under force-controlled cyclic loading. Surface characterization included topography mapping and residual stress measurements to assess the effects of each treatment. Fracture surface analysis using scanning electron microscopy (SEM) was performed to identify initiation mechanisms, initiation sites, and failure modes. Additionally, three-dimensional finite elements models were developed to calculate the local stress distributions and quantify stress concentration effects caused by surface features.

Results show that anodizing reduces fatigue resistance due to the surface cavities formed primarily by the preferential dissolution of CuFe particles during the etching step, which act as local stress concentrators. When shot peening is applied prior to anodizing, the overlap between peening imprint zones and surface cavities modifies local stress distribution. Compressive residual stresses from shot peening partially mitigate these effects, although stress relaxation over time can reduce their benefit. The combined experimental–numerical analysis captures the interaction between surface cavities, peening imprint zones, residual stresses, and stress concentrations, providing an enhanced understanding of the fatigue behavior under complex surface conditions. The extension of the finite elements model provides preliminary results suggesting a predictive capability for distinguishing the crack initiation and propagation phases during fatigue.

In conclusion, while anodizing enhances corrosion protection, it can reduce fatigue life by up to 30% whereas shot peening increases fatigue resistance. Even considering residual stress relaxation, the fatigue performance of specimens that were shot peened and anodized remains comparable to that of the as-machined material. These findings provide a framework for predicting fatigue performance, optimizing surface treatments, and ensuring the structural integrity of aerospace aluminum components under realistic service conditions.

# A NOVEL TEMPERATURE FIELD RECONSTRUCTION METHOD FOR MULTI-PASS WELDING SIMULATION

**A.A. Akay[1], K. G. F. Janssens[1]**

*[1]PSI Center for Nuclear Engineering and Sciences, CH-5232 Villigen PSI, Switzerland,*
*Corresponding Author: arda.akay@psi.ch*

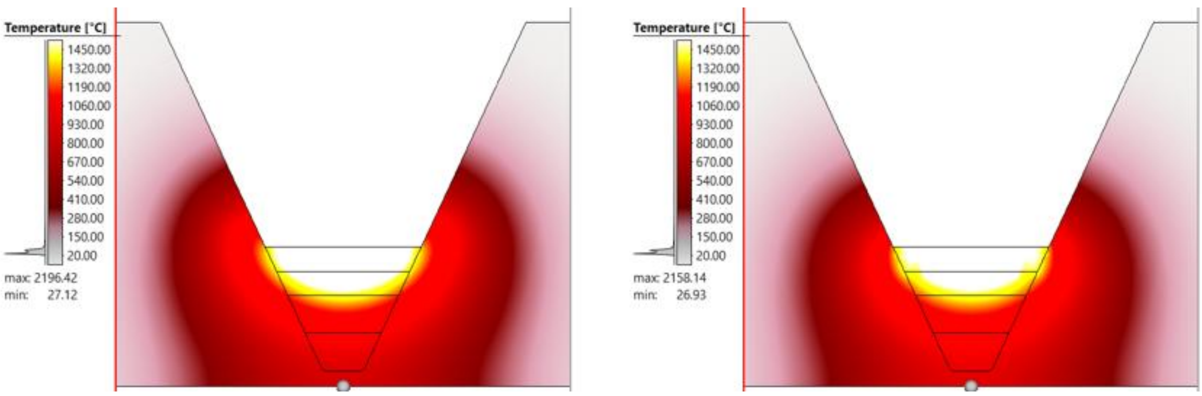
*Reduced-order modeling* *Multi-pass welding simulation* *Computational efficiency*

## Abstract

Welding residual stresses can significantly affect fatigue-life predictions. Reliable numerical prediction of these stresses depends strongly on an accurate representation of the applied heat input during welding simulations. Therefore, the accurate transient temperature fields are a prerequisite for predictive multi-pass welding simulations. Although the 3D Goldak double-ellipsoid moving heat source model is widely used, long pass sequences can lead to high computational cost, which becomes a key bottleneck in practical analyses involving tens to hundreds of passes. Numerous acceleration strategies have been proposed in the literature; however, the main challenge in reducing computational cost is preserving sufficient accuracy. This work presents a Proper Orthogonal Decomposition reduced-order modeling (POD-ROM) approach from computational engineering for efficient reconstruction of transient temperature fields and quantifies the associated accuracy–runtime trade-offs through systematic parametric studies. The proposed reconstruction approach also provides a foundation for combining reduced-order thermal loading with additional acceleration concepts (e.g., pass reduction strategies) in extended multi-pass workflows. Potential extensions beyond weld-bead temperature reconstruction are also discussed, including integration with submodeling approaches.

The POD-ROM reconstruction is assessed against a high-fidelity reference simulation based on a 3D Goldak moving heat source. Accuracy is evaluated using (i) cross-sectional thermal footprints (see Fig. 1 for an example) and (ii) time-dependent temperature histories at selected nodes, including peak temperatures and cooling trends. The parametric studies examine how key modeling choices (e.g., number of retained POD modes and snapshot sampling strategy) influence reconstruction fidelity and computational savings.

The results show that POD-ROM reconstruction reproduces the dominant thermal features of the reference solution while reducing thermal simulation time. For a 7-pass 3D benchmark, an approximately 30% reduction in thermal runtime was observed while maintaining good agreement in field and nodal comparisons.




(a) Reference (b) POD-ROM reconstruction

***Figure 1** – Cross-sectional thermal footprints at the time of maximum temperature, comparing the reference 3D Goldak simulation and the POD-ROM temperature reconstruction.*

# Crack tip detection algorithms based on DIC displacement field analysis

**A. Camacho-Reyes[1], D. Camas[1], B. Moreno[1], P. López-Crespo[1], J.M. Vasco-Olmo[2], F.A. Diaz[2]**

*[1]Departamento de Ingeniería Civil, de Materiales y Fabricación, Universidad de Málaga (Málaga, Spain)*
*acamacho@uma.es*

*[2]Departamento de Ingeniería Mecánica y Minera, Universidad de Jaén (Jaén, Spain).*

*Crack tip* *Digital Image Correlation* *Crack tip displacement field*

## Abstract

This work introduces two algorithms designed to locate the tip of growing fatigue cracks using Digital Image Correlation (DIC) data. The objective is to develop methods that are accurate, mathematically simple, easy to implement, and computationally efficient, while also reducing experimental complexity and avoiding invasive measurement techniques so that all relevant information is obtained directly from DIC analyses. Both algorithms rely on the evaluation of displacement fields around the crack tip, using the displacement discontinuity along the crack path during fatigue propagation as the key indicator for identifying the crack tip location. The methods were validated in two representative scenarios: a straight-propagating fatigue crack in a Compact Tension specimen made of commercially pure titanium, and an inclined fatigue crack in a Double Cantilever Beam specimen of 2024-T3 aluminium alloy. The results show strong agreement between the crack tip positions estimated using the proposed algorithms and those obtained with an independent reference method, yielding relative deviations of approximately 2%.

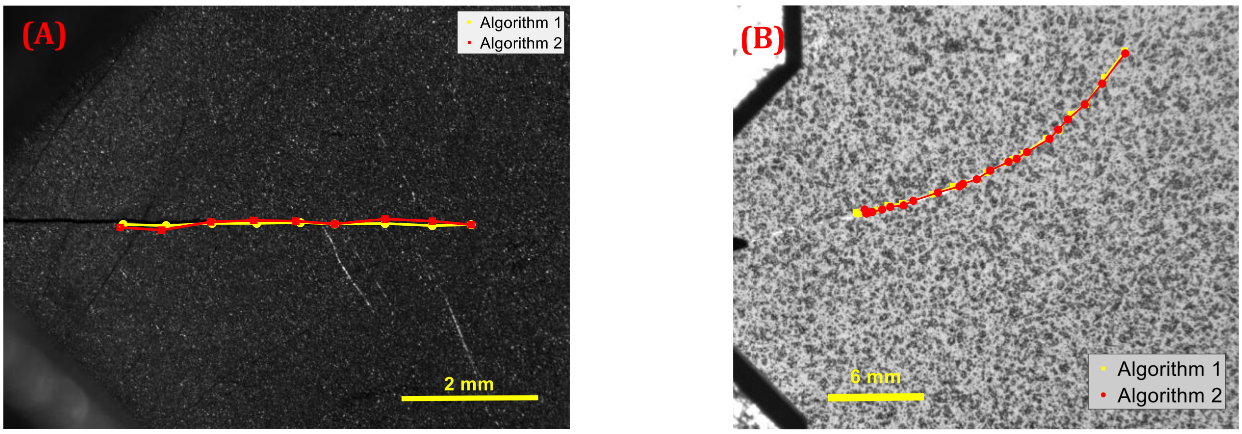



***Figure 1*** *– Estimated crack tip locations from both algorithms superimposed over DIC speckle images. (A) straight growing crack and (B) variable inclination growing crack.*

# The Effect of Prior Low Cycle Fatigue on the Creep Resistance of a 10% Cr Martensitic Steel

**Mishnev Roman[1], Wu Kaiming[2], Rustam Kaibyshev[3], Nadezhda Dudova[3]**

*[1]Wuhan University of Science and Technology, Wuhan 430081, China*
*roman_mishnev@wust.edu.cn*

*[2]Wuhan University of Science and Technology, Wuhan 430081, China*

*[3]Belgorod State National Research University, Belgorod 308015, Russia*

*Martensitic Steel* *Low Cycle Fatigue* *Creep*

**Abstract** This study systematically investigates the effect of prior low cycle fatigue (LCF) on the subsequent creep behavior and microstructural stability of a 10% Cr martensitic steel, a candidate material for advanced ultra-supercritical (A-USC) power plants. Specimens were subjected to strain-controlled LCF pre-deformation (±0.2%) at 650 °C for 5 to 2500 cycles (up to 50% of fatigue life), and then subjected to creep rupture testing at 650 °C/140 MPa.

The results showed that cyclic pre-deformation significantly accelerated creep degradation in the subsequent creep tests. With an increase in the number of cycles from 5 to 1250, the minimum creep rate increased by 1.7 to 5.4 times, while the time to rupture decreased by approximately 10% to 2.5 times (from 1425 h to 586 h). This was correlated with an accelerated transient creep stage, evidenced by an increase in the exhaustion coefficient ($r'$) by 10 to 91%, indicating the enhanced recovery processes.

Microstructural analysis revealed that the main reasons for the reduced creep resistance are the pronounced weakening of dislocation strengthening (drop to ~60% of its initial value after 2500 cycles+creep test) and a moderate decrease in the lath boundary strengthening. In contrast, dispersion strengthening from the boundary $M_{23}C_6$ carbides and Laves phase particles remained effective despite their coarsening. The summary pinning pressure from these particles on lath boundary migration, equal to 0.17 MPa, which was higher than the critical threshold value required for the lath stability (0.12 MPa) under short-term creep conditions.

The study concluded that the negative effect of previous cyclic loading on creep life is primarily due to the acceleration of recovery processes at the transient creep stage caused by softening under LCF. The results obtained are of critical importance for assessing the durability of high-temperature components subjected to combined creep-fatigue loading.

# Modeling of Dissipative Mechanisms Related to Fatigue of 3D Woven Composites

**B. S. Barini[1,2], M. Le Saux[2], Y. El Archi[1], L. Navrátil[1], N. Carrere[2]**

*[1] IRDL, UMR CNRS 6027, ENSTA, Institut Polytechnique de Paris, ENIB-INP, UBO, UBS, 2 rue François Verny, F-29200, Brest*
*bruno.simoes@ensta.fr, nicolas.carrere@ensta.fr and matthieu.le_saux@ensta.fr*
*[2] SAFRAN Composites*
*33 rue de la gare, F-91760, Itteville*
*libor.navratil@safrangroup.com and youssera.el-archi@safrangroup.com*

*3D woven composites* *Self-heating* *Multi-scale approach*

**Abstract:** Three-dimensional (3D) woven polymer matrix composites are used in applications requiring high fatigue resistance over more than $10^7$ cycles. However, characterizing fatigue over such long periods is costly and time-consuming. The self-heating method can greatly accelerate this process, but its effective use demands a deep understanding of the dissipative mechanisms involved and their correlation with fatigue. This is particularly challenging for 3D woven composites due to the complexity of their mesostructure and the thermomechanical behavior of their constituents. This work aims to improve the understanding and prediction of the fatigue performance of 3D woven carbon/epoxy composites by identifying and quantifying the dissipative mechanisms that govern their thermomechanical response (self-heating) under cyclic loading. A fatigue criterion for high-cycle fatigue life prediction is established using a combined experimental and multiscale modeling approach.

First, an experimental campaign was conducted to characterize the thermomechanical response and fatigue performance of the 3D woven composite and its individual constituents. Temperature measurements were taken during these tests using infrared cameras to analyze changes in heat sources, including dissipation. In addition, damage in the composite was examined based on X-ray tomography observations.

Second, a two-scale modeling approach was developed to capture the thermomechanical and dissipative behavior of the composite. Regarding the constituents, carbon fibers were modeled as transversely isotropic linear elastic and the epoxy matrix behavior is described by an isotropic nonlinear viscoelastic spectral model written within a thermodynamic framework to account for dissipation. The homogenized thermomechanical response of the yarns was then described by a transversely isotropic nonlinear viscoelastic model identified from unit cell simulations. Lastly, full-field simulations at the mesoscopic scale were performed on realistic 3D mesostructures reconstructed from X-ray tomography, representing the homogenized yarns and the surrounding matrix.

The model was used to assess the contributions of several factors to the temperature evolution under cyclic loading: matrix viscoelasticity, crack initiation and propagation, post-cracking friction, and heat exchange. These results provide new insights into the relation between the dissipative mechanisms and fatigue damage, and support the proposal of a self-heating-based accelerated protocol for estimating the fatigue performance of 3D woven composites.

# Numerical investigation of defect population effect on the fatigue strength anisotropy of Ti64 fabricated by Laser Powder Bed Fusion

**S.S Penkulinti[1,2], N. Saintier[1,2], M. Bonneric[1,2], B. Verquin[3], T. Palin-Luc[1,2], F. Lefebvre[3], P. Ghys[4]**

[1] *Arts et Metiers Institute of Technology, CNRS, Bordeaux INP, I2M, UMR 5295, France, FR*

[2] *Univ Bordeaux, CNRS, Bordeaux INP, I2M, UMR 5295, France, FR*

[3] *CETIM, France, FR*

[4] *ALSTOM, France, FR*

*L-PBF* *Anisotropy* *Multiaxial Fatigue*

**Abstract** Defects induced by the fabrication process, which are dependent on the input process parameters, remain a critical issue in the fatigue design of industrial components processed by Laser Powder Bed Fusion (L-PBF). The present work aims to use numerical simulations to assess the impact of typical L-PBF defects on the High Cycle Fatigue strength of a high-strength material. To do so, real defect geometries have been explicitly integrated in the simulations, using X-ray tomography observations of different defect populations of Ti64 alloy processed by L-PBF. The fatigue strengths of the different defects have then been determined numerically for different types of loadings (tension, torsion, and tension-torsion) by using appropriate multiaxial fatigue criteria. A non-local analysis of the calculated stress fields was also included in the calculation of the Fatigue Indicator Parameter in order to account for the severe stress gradients at the vicinity of defects. By considering the overall defect population and combining an extreme statistic approach, a general framework is proposed to account for the defect morphology on the fatigue strength for any type of proportional mulatiaxial loading. For example, the proposed approach allow to predict the fatigue strength anisotropy induced by LOF (see figure 1) defects and to evaluate its sensitivity to the type of loading (tension, torsion, tension-torsion, etc). Numerical results are compared to experimental data from the literature and from new set of results obtained during this study on specimen in which controlled defect population was introduced thanks to the control of process parameters.

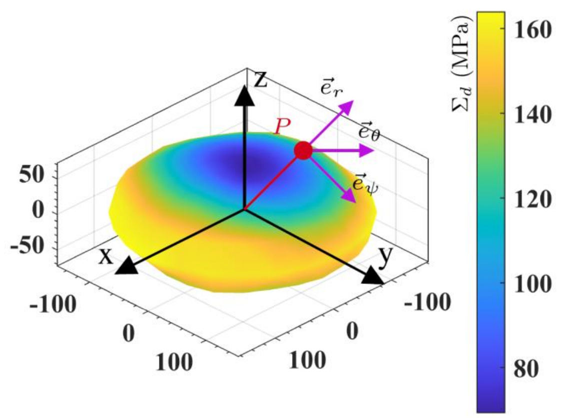



Figure 1 - Evolution of the mean fatigue strength associated to the LoF defect population with respect to the loading direction (illustrated with the red vector) - Local analysis

# Low-cycle fatigue properties of laser powder bed fusion–manufactured $TiB_2$-modified nickel-based superalloy

**I. Šulák[1], L. Pelikán[2], M. Malý[1,3], L. Poczklán[1], T. Vražina[1], T. Slezák[1,3], M. Bartošák[2]**

[1]*Institute of Physics of Materials, Czech Academy of Sciences, Žižkova 513/22, 61600 Brno, Czech Republic, sulak@ipm.cz*

[2]*Faculty of Mechanical Engineering, Czech Technical University in Prague, Technická 4, 166 07 Praha 6, Czech Republic*

[3]*Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic*

*Metal matrix nanocomposite*  *High temperature fatigue*  *Additive manufacturing*

**Abstract:** Additive manufacturing (AM), and especially laser powder bed fusion (LPBF), enables near-net-shape production of nickel-based superalloys with complex geometries, but widespread adoption is still constrained by printability issues such as hot cracking and defect formation under steep thermal gradients. Recently, the introduction of titanium diboride ($TiB_2$) as a ceramic inoculant/reinforcement (typically in the nano- to submicrometer regime) has been proven to simultaneously improve the printability of nickel-based superalloys by suppressing both solidification and solid-state cracking. In addition, $TiB_2$ contributes to higher hardness and improved yield/ultimate tensile strengths at room and elevated temperatures through combined Hall–Petch strengthening, dislocation bypass (Orowan-type) mechanisms, grain-boundary pinning, and load sharing across a stiff ceramic–metal interface. As such, $TiB_2$-modified superalloys represent a next-generation class of nanostructured high-performance materials, offering a viable pathway to overcome the intrinsic cracking limitations of additively manufactured nickel-based systems. However, studies focus only on comparing quasistatic properties, leaving more complex, dynamic loading, such as low-cycle fatigue, untouched. In this work, metal matrix nanocomposites (MMC) are produced by reinforcing the nickel-based superalloys (Inconel 939 and Haynes 230) with 1.5 wt.% $TiB_2$ nanoparticles and processed by LPBF. For the first time, the low-cycle fatigue behaviour of the MMCs, including a study of damage mechanisms, is presented. Strain-controlled push-pull tests with a constant strain rate were performed at room temperature and elevated temperatures up to 850°C in air. The results show that MMCs have superior mechanical properties compared to their counterparts without $TiB_2$.

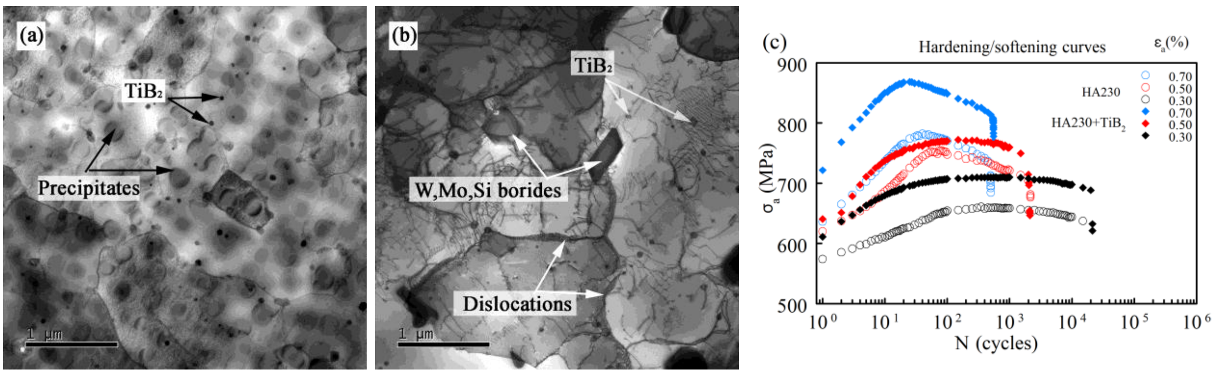



***Figure 1 -*** *(a) Microstructure of $TiB_2$-modified Inconel 939, (b) Microstructure of TiB2-modified Haynes 230, (c) Fatigue hardening/softening curves for $TiB_2$-modified and unmodified Haynes 230.*

# Influence of fatigue limit under pulsating tension loading on Multiaxial Fatigue Models

**P. Apodaka[1], M. Abasolo[2], E. Tabares[1], L. Pallares[3], X. Orue[1]**

[1]*Unit of Mechanical Engineering, Fundación Tekniker, Iñaki Goenaga St., 5, 20600 Gipuzkoa, Spain* pedro.apodaka@tekniker.es, eduardo.tabares@tekniker.es, xabat.orue@tekniker.es

[2]*Department of Mechanical Engineering, Engineering School of Bilbao, University of the Basque Country, Alameda de Urquijo s/n, 48013 Bilbao, Spain.* mikel.abasolo@ehu.eus

[3]*Department of Technology, I.E.S. María Telo, Educantabria, San Fernando 49, 39400 Los Corrales de Buelna, Spain* luispallares.bilbao@gmail.com

*Multiaxial fatigue    High-cycle fatigue    Mean stress effect    Experimental database*

*Haigh criteria*

**Abstract** Several Multiaxial Fatigue Methods (MFMs) currently in use employ the fatigue limit under pulsating tension loading as a characteristic test to evaluate the adjustment parameters they use in defining their damage function. However, in case this test is not available, an approximation criterion must be applied to obtain an estimate based on other more common characteristic data, such as the fatigue limit under fully reversed tension loading and the ultimate tensile strength of the material. This may affect the equivalent alternating stress, and its influence depends on the weight of this parameter in the MFM itself. Thus, this work aims to analyse the effect on eight MFMs (three of the Ilyushin deviatoric space analysis type and five of the critical plane method type) that include this test in their adjustment parameters, such as Sines, Kakuno-Kawada, Susmel, QCP or Papuga PCr, using a database of 350 constant amplitude and non-zero mean stress tests, including cast irons, aluminum alloys and steels. First, the Haigh diagram criterion that best fits each material is defined by comparing six well-known criteria, leading to the conclusion that the most accurate criteria for cast irons, aluminum alloys, and steels are Smith, Dietmann, and SWT, respectively. Then, the eight MFMs are evaluated for all the tests collected in the database, for both the actual and estimated fatigue limit under pulsating tension loading using the Haigh criterion deduced in the previous step, and the difference between them is calculated. As can be seen in Figure 1, methods such as Sines or Kakuno-Kawada are strongly influenced by variations in its estimation, whereas QCP or Papuga PCr exhibit negligible dispersion. Thus, the lower sensitivity of the latter MFMs makes them the most suitable option when the fatigue limit under pulsating tension loading test is unavailable.

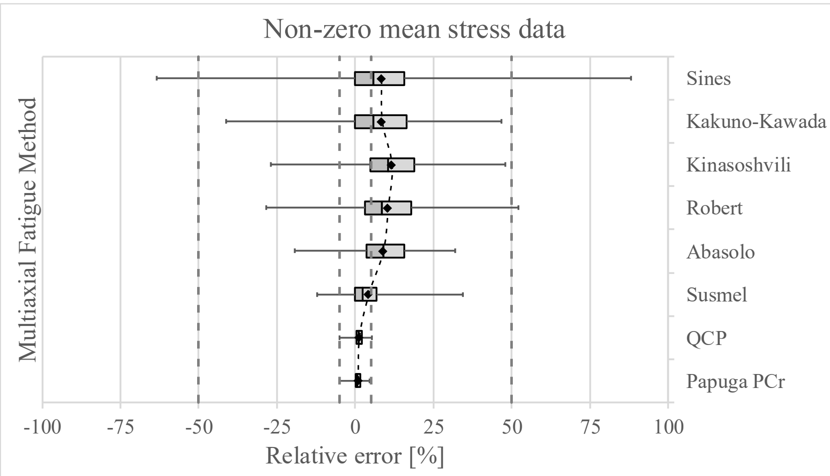



***Figure 1** – Influence on MFMs.*

# Effect of burrs on the fatigue strength of metallic structures: experimental study on open hole Ti-6Al-4V specimens with burrs

**S. Frutos-Taravillo[1,2], E. Paroissien[2], Y. Landon[2], S. Schwartz[2], M. Fressinet[1], C. Chirol[3]**

*[1]Airbus Operations SAS, 316 Route de Bayonne, Toulouse 31300, France,*

*santiago.frutos-taravillo@airbus.com*

*[2] Institut Clément Ader (ICA), CNRS, 3 Rue Caroline Aigle, 31400 Toulouse, France*

*[3] Airbus Atlantic, 1 Bd de l'Europe, Colomiers 31770, France*

*Burrs* *One-Way-Assembly* *Titanium*

**Abstract** One-Way-Assembly (OWA) accelerates aerospace production cycles but risks leaving drilling burrs at joint interfaces. While burrs are known to significantly degrade fatigue life, the explanatory rationale remains unclear. This study investigates the fatigue behavior of Open-Hole Ti-6Al-4V specimens with burrs as a fundamental step towards understanding their effect on mechanical joints, combining extensive experimentation with numerical analysis.

The methodology isolated three potential drivers: macrogeometric stress concentration, residual stresses and microgeometric burr tip features. Constant amplitude fatigue tests covered exit burrs of varying heights (0.2, 0.4, and 1.1 mm), entry burrs and configurations subjected to Stress-Relief (SR) heat treatment or secondary processing (indentation and crushing). The comparison of test results to a burr-free reference revealed a non-monotonic relationship (Figure 1): small burrs caused severe strength reduction, whereas larger burrs surprisingly exhibited life comparable to the burr-free reference. SR treatments failed to mitigate these effects, ruling out residual stresses as a primary governing factor. The results for all detrimental configurations are grouped in a single S-N cluster

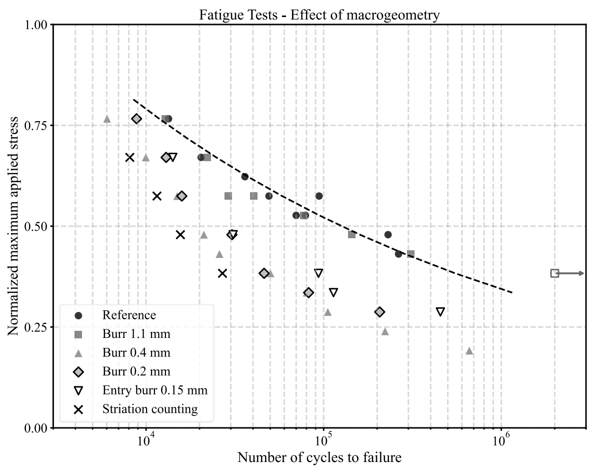



***Figure 1*** *- Fatigue test results for burred open hole specimens compared to a reference without burr*

Numerical simulation helped to rationalize these findings, confirming that macroscopic stress concentration cannot explain the experimental "knock-down" and discarding macrogeometry as the primary driver. Instead, fracture mechanics simulations, together with striation counting, validated that the fatigue life of detrimental configurations corresponds to pure crack propagation. A unified mechanism drives this effect: specific microgeometric features at the burr tip act as immediate initiators, severely shortening the nucleation phase and explaining why all detrimental configurations collapse into a single S-N cluster. These findings imply that manufacturing criteria based solely on burr height may be insufficient to guarantee structural integrity, motivating future work on complex structural joints.

# Research of physics-informed data-driven methods for multiaxial fatigue life prediction

**Xingyue Sun[1], Xueyu Han[2], Yu'e ma[3], Xu Chen[4]**

[1]*School of Aeronautics, Northwestern Polytechnical University, 710072, Shaanxi, China,* xysun@nwpu.edu.cn

[2]*Air and Missile Defense College, Airforce Engineering University, 710072, Shaanxi, China*

[3]*School of Aeronautics, Northwestern Polytechnical University, 710072, Shaanxi, China*

[4]*School of Aeronautics, Tianjin University, 710072, Tianjin, China*

*Multiaxial fatigue* *Life prediction* *Neural network*

**Abstract** As loading forms and service environments become increasingly complex, traditional empirical models also face issues of insufficient descriptive capability and overly complex parameters. To over these shortcomings, the data-driven methods have been provided as new and powerful tools for fatigue life prediction. With the development of intelligent algorithms, constructing relationships between multiaxial non-proportional loading and fatigue life with data-driven methods, particularly neural network models, has become a focus of attention. they are particularly adept at establishing nonlinear regression relationships between complex factors such as loading conditions, environmental influences, and fatigue life. This ability allows neural networks to effectively capture intricate patterns and interactions that traditional methods might overlook, making them a valuable tool for fatigue life prediction under multifaceted and variable conditions. The fatigue life prediction model and factors such as non-proportionality provide strong support for the construction of physics-informed neural networks. To move beyond purely data-driven fitting and address remaining challenges such as limited extrapolation ability, robustness under variable conditions, and the risk of overfitting, recent studies increasingly integrate prior physical knowledge into learning-based models. The explicit consideration of fatigue-relevant physical factors, such as non-proportionality effects, also provides a solid basis for physics-informed neural networks. In practice, physical knowledge can be incorporated through explicit or implicit strategies at multiple levels, including feature construction, loss function design, and model architecture formulation. By embedding physically meaningful constraints and mechanisms into the learning process, physics-informed data-driven models have demonstrated improved prediction accuracy and generalization capability, while effectively mitigating overfitting. These advances underscore the promise of combining data-driven intelligence with physical insight for robust fatigue life prediction under complex loading and service conditions.

# Three-dimensional fatigue crack propagation simulation based on a nonlocal algorithm of P91 steel

**Masayuki Arai[1], Akihiro Motoki[2]**

*[1]Department of Mechanical Engineering, Tokyo University of Science, 6-3-1 Niijyuku, Katsushika-ku, Tokyo 125-8585, Japan, marai@rs.tus.ac.jp*

*[2]Graduate School of Mechanical Engineering, Tokyo University of Science*

*Creep-fatigue* *Fatigue crack simulation* *Finite element analysis*

**Abstract** This study conducted a three-dimensional crack propagation simulation based on a nonlocal algorithm of P91 steel under fatigue and creep–fatigue loading. A damage-coupled inelastic constitutive model incorporating fatigue and creep damage parameters into a Chaboche-type viscoplastic law was implemented in commercial finite element software MARC. The nonlocal algorithm mitigates damage localization near a crack tip by averaging the damage parameter within a characteristic domain, thereby enabling a stable crack growth simulation without excessive propagation rates. Finite element analyses were performed for two configurations: (i) a cylindrical bar with a circumferential notch and (ii) a plate containing a semi-elliptical surface crack. For the notched bar, the fatigue and creep–fatigue crack propagation behavior (Fig. 1), hysteresis loops, and stress relaxation behavior showed good agreement with experimental results, thereby validating the developed approach. Crack growth simulations of the semi-elliptical surface crack revealed three propagation stages and showed that creep damage accelerated crack penetration through the plate thickness under strain-hold conditions. Furthermore, the evolution of the crack aspect ratio indicated that the semi-elliptical crack tended to become semi-circular during cyclic loading, which was consistent with well-known experimental observations. These findings confirm that the nonlocal algorithm combined with the damage-coupled constitutive model provides an effective framework for simulating three-dimensional fatigue and creep–fatigue crack growth in high-temperature components.

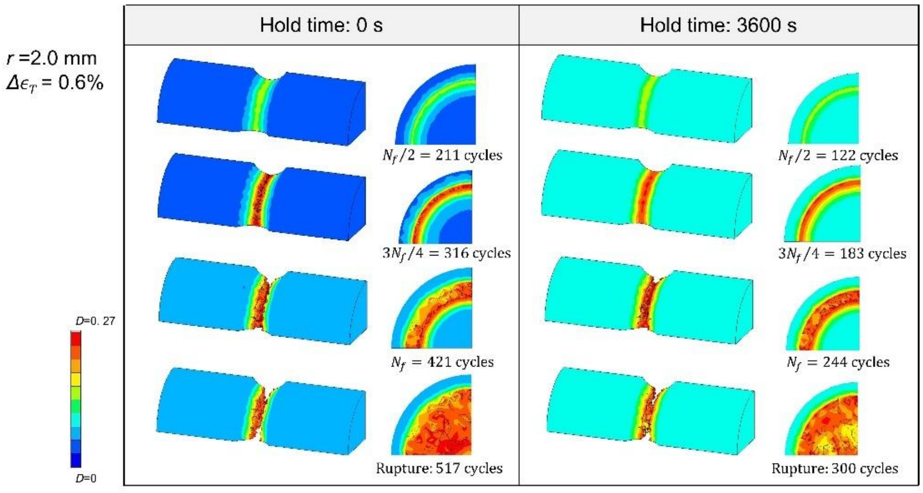



***Figure 1*** *– The distribution of non-local damage value in the FE model and the progression of fatigue crack on the notch root cross-section until complete fracture of the notch root.*

# Gas- vs Plasma-Atomized Powder Effects on Very High Cycle Fatigue of L-PBF AlSi7Mg: Defects-Informed Stress-Life Modeling and Graph Convolutional Networks

**Md Mehide Hasan Tusher[1], Ayhan Ince[1]**

[1]*Mechanical, Industrial & Aerospace Engineering, Concordia University, Montreal, Canada, H3G 1M8*

*e-mail: ayhan.ince@concordia.ca*

*Very High Cycle Fatigue* *L-PBF AlSi7Mg* *Graph Networks*

**Abstract** Laser powder bed fusion (L-PBF) AlSi7Mg components contain surface, near-surface, and internal defects that strongly govern fatigue performance particularly in very high cycle fatigue (VHCF) regime. In this study, defect populations and their spatial distributions were obtained for test specimens using X-ray computed tomography (CT) for two powder techniques as gas-atomized powder and plasma-atomized powder. Fatigue experiments were then conducted to establish fatigue behavior in the VHCF regime. The results show that plasma-atomized specimens exhibit longer fatigue lives and reduced scatter compared with gas-atomized specimens by showing consistent with differences in defect size, morphology, and distribution.

To incorporate effects of defect distribution into fatigue life prediction, two different modeling approaches are developed. First, a defect-informed stress–life (DISL) model extends the classical Basquin framework by introducing a scalar severity defect index. This index combines defect size and morphology features such as maximum equivalent diameter, a shape–size severity index, number of defect clusters, and maximum cluster volume. These features are computed separately within surface, sub-surface, and internal regions and then aggregated using physically motivated defects severity weighting. This formulation enables a defect-dependent stress–life formulation that reduces scatter relative to a stress-only Basquin fit. Thus, the DISL model accounts for specific defect features and locations for improved fatigue life predictions.

Second, a graph convolutional network (GCN) model is proposed to capture the spatial nature of defects beyond what a simplified severity index can represent. Each fatigue specimen is represented as a graph in which nodes correspond to distinct material regions (e.g., surface, sub-surface, internal) and edges encode neighborhood node connectivity. This approach allows the GCN model to learn how local defects interact to control crack initiation and fatigue performance. Node features are extracted from CT data and include defect count density, defect volume, defect surface area, and defect aspect ratio, thus providing a multi-feature description of defect distributions. By performing message passing across connected nodes, the GCN aggregates local defect information into a global graph representation that incorporates defect distributions across each specimen. Compared with conventional fitting models that use only stress amplitude or spatially averaged defect metrics, the GCN achieves improved fatigue life prediction accuracy and greater robustness to scatter in the VHCF regime. Together, the DISL and the GCN frameworks provide interpretable and spatially informed predictive models for fatigue assessment of additively manufactured alloys when CT-based defect statistics are available.

# Extending the Fatigue Properties of Water and Steam Turbine Blade Materials by Laser Peening

**Zbyněk Špirit[1], Josef Strejcius[2], David Bricín [2], Zdeněk Fulín [2]**

[1]*Centrum výzkumu Rez s.r.o., Morseova 1245/6, Pilsen, 30100, Czech Republic*

[2] *Centrum výzkumu Rez s.r.o., Morseova 1245/6, Pilsen, 30100, Czech Republic*

Laser Shock Peening *Hight Cycle Fatigue* *Stainless steel*

Peening technologies represent an effective tool for increasing the fatigue life of blade materials used in both steam and water turbines. This paper focuses on the assessment of the effect of peening on the fatigue resistance of stainless steel T671, employed for rotating blades of steam turbines, and, a martensitic steel used for water turbine blades in the Czech Republic. Based on the results of non-destructive testing, material characterization, and fractographic analyses of blades subjected to long-term service loading, the dominant mechanisms of fatigue crack initiation and propagation were identified in the fir-tree root regions and contact surfaces. Although the chemical composition, microstructure, and bulk mechanical properties of both materials comply with the relevant material specifications, fatigue damage is repeatedly initiated in surface and subsurface layers at locations characterized by high stress concentration, local plastic deformation, and an unfavorable residual stress state. Fractographic analyses revealed transcrystalline fatigue crack propagation, with crack initiation sites located in the immediate vicinity of the surface, frequently at the interface between the blade root contact region and the rotor disc. These findings confirm the key role of surface condition and residual stresses in the fatigue damage process. Peening, when applied using appropriate technologies (shot peening, laser peening), introduces beneficial compressive residual stresses, enhances surface hardening, and reduces material sensitivity to surface defects and microcracks. The paper also presents the results of high-cycle fatigue tests under bending loading, focused on evaluating the effect of peening on the crack initiation phase and on the fatigue crack growth rate. The most stressed surfaces were strengthened using Laser peening technology using a nanosecond laser. The obtained results contribute to a deeper understanding of life-extension mechanisms for T671 and materials and support their practical application in the reliable operation of steam and water turbines. Fatigue tests on martensitic steel showed that untreated specimens exhibited early surface and subsurface crack initiation, strongly influenced by stress concentration, surface defects, and unfavorable residual stress states, leading to rapid fatigue crack propagation. Laser shot peening significantly increased fatigue resistance, requiring approximately 50% higher cyclic loading for crack initiation and propagation compared to the untreated condition. The introduction of deep compressive residual stresses and surface hardening effectively suppressed the influence of surface and subsurface defects and reduced the fatigue crack growth rate. As a result, peened specimens exhibited markedly improved high-cycle fatigue performance and enhanced durability under bending loading conditions. Fatigue tests on T671 steel are being completed and will be included in the conference paper. It can be tentatively said that the improvement in fatigue properties will be similar to that of water turbine steel material.

# Evaluation of Transient Creep and Oxidation Damage in Thermomechanical Fatigue of Nickel-Based Superalloys

**Jiaqi Lu[1], Huang Yuan[1,2]**

[1]*Institute for Aero Engines, Tsinghua University, Beijing, China*

[2]*School of Aerospace Engineering, Tsinghua University, Beijing, China*

*Thermomechanical fatigue*    *Transient cyclic creep*    *Creep-oxidation-fatigue*

**Abstract** This study systematically investigates the transient creep behavior of nickel-based superalloys under the coupled loading conditions of oxidation, creep, and fatigue. Experimental results demonstrate that cyclic loading induces distinct transient creep characteristics: the material exhibits periodic transient creep stages, with creep rates 2–3 times higher than the steady-state values. This phenomenon is attributed to the regeneration of primary creep mechanisms and damage accumulation effects induced by reverse plastic deformation. As the stress ratio increases, the transient effect gradually diminishes and approaches steady-state creep. Microstructural analysis confirms that cyclic hardening/softening and dynamic dislocation reorganization are the key mechanisms driving the regeneration of transient creep. A novel constitutive model integrating cyclic hardening/softening and damage evolution is proposed, and its correlation coefficient with experimental data exceeds 0.93. The model reveals that neglecting the transient creep effect leads to a life prediction deviation of 45–60%, highlighting the necessity of incorporating transient creep kinetics into the life assessment framework. In addition, grain boundary degradation caused by oxidation at crack tips is identified as the dominant factor accelerating intergranular fracture, resulting in a reduction of 40–60% in fatigue life in air compared to that in a vacuum environment. By coupling the linear damage accumulation criterion with the ductility exhaustion theory, this study establishes a unified life prediction method capable of quantifying the synergistic damage of oxidation, creep, and fatigue. The research findings provide important theoretical support for the design of high-reliability nickel-based superalloys under extreme service conditions involving multi-mechanism coupling.

# General Relation between Fatigue Strength and Tensile Strength of Metallic Material

**Jianchao Pang, Chong Gao, Xiaoyuan Teng, Shouxin Li, Zhefeng Zhang**

*Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang, China，jcpang@imr.ac.cn*

*Parabolic relation* *Fatigue Strength* *Tensile Strength*

**Abstract:** Focusing on the questions of long time, high cost, and low accuracy in fatigue strength (high cycle fatigue or very high cycle fatigue) of materials and components, a series of simple, rapid, and accurate methods for predicting the fatigue strength have been proposed after systematic exploration and research: 1) It was found that the fatigue ratio (the ratio of fatigue strength to the tensile stength) decreases linearly with the increase of tensile strength, challenging the "traditional cognition" that the fatigue ratio remains constant (that is, the linear relation between fatigue strength and tensile strength). For the first time, a general relationship (parabolic curve) between fatigue strength and tensile strength was proposed, which is applicable to more than 800 sets of metal materials and components; 2) Instead of the traditional optimization method of "orthogonal experiment", the optimal fatigue strength can be quickly predicted through two sets of tensile and of fatigue strength tests at least, thereby achieving cost reduction and efficiency improvement; 3) Based on the key parameter of fatigue ratio, the relationship between fatigue strength, average stress, notch factor, and tensile strength is established, enabling rapid prediction of component fatigue strength. These original methods have attracted the attention, citations (nearly 300 times), and development of fatigue experts both domestically and internationally, and software systems have been developed for promotion and application in industries such as generators, internal combustion engines, gas turbines, and aero-engines.

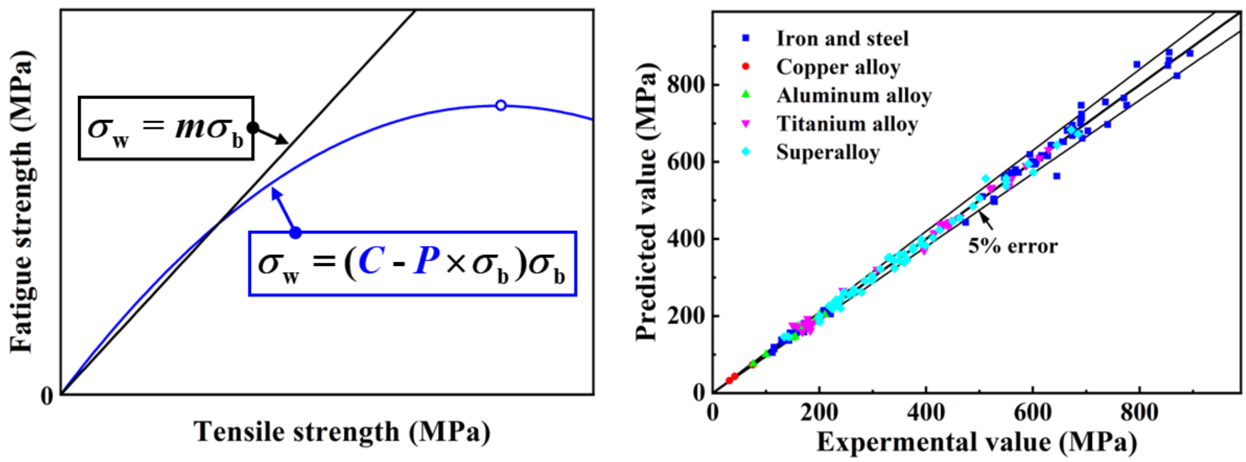



***Figure 1*** *– the general relation between fatigue strength and tensile strength and corresponding application.*

# Analytical Modeling of Acceleration Factors for Random Vibration Fatigue Testing

**Piao Li [1], Weixing Yao [2]**

[1]*Smart Materials and Advanced Structures Laboratory, School of Mechanical Engineering and Mechanics, Ningbo University, Ningbo 315211, China*

[2]*Jiangsu Xinyang New Materials Co., Ltd., Yangzhou 225127, China*

*Random Vibration* *Acceleration Factor* *Fatigue Testing*

**Abstract** Conventional vibration fatigue acceleration tests commonly rely on a two-parameter S–N curve. However, this model fails to accurately characterize the fatigue behavior of materials in the high-cycle regime, leading to inherent systematic bias in the prediction of long-term structural fatigue life and consequently limiting predictive accuracy. This limitation is particularly pronounced for vibration fatigue problems in which high-cycle fatigue dominates the failure mechanism. To enhance the physical fidelity of the predictive model, this study introduces a three-parameter S–N curve capable of more accurately representing material fatigue characteristics in the high-cycle domain under both broadband and narrowband random vibration loading conditions (Fig. 1). On this basis, a high-precision analytical model for vibration fatigue acceleration factors, compatible with the proposed material model, is developed. Through rigorous theoretical derivation, a closed-form expression of the acceleration factor is obtained in the form of a generalized inverse power law.

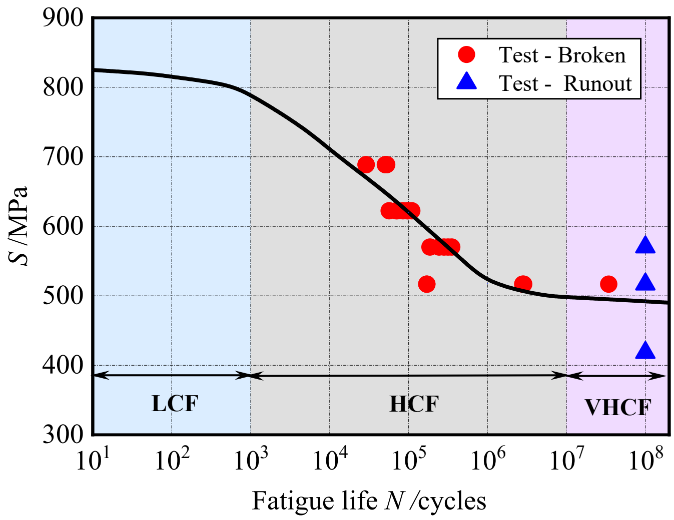



***Figure 1*** *– Three parameter S-N curve*

To validate the effectiveness of the proposed model, narrowband random vibration accelerated fatigue tests were conducted on aluminum and titanium alloy specimens fabricated using selective laser melting (SLM). The results indicate that, for SLM titanium alloy, the discrepancies between experimentally measured and predicted acceleration factors under two acceleration spectra are −7.19% and 5.21%, respectively, with all errors remaining below 10%. For SLM aluminum alloy, the corresponding errors are −25.33% and 8.26%. In addition, broadband random vibration accelerated fatigue tests were performed on 2024-T3 and 7075-T6 aluminum alloys under three fatigue loading spectra. The results demonstrate that the maximum deviation between experimental and theoretical acceleration factors is only 4.48%. Overall, the theoretical predictions of the proposed model show excellent agreement with experimental data, significantly improving the accuracy of fatigue life assessment under vibration-accelerated loading conditions.

# Ultra-compact Laser Peening with Microchip Lasers: From System Development to Structural Fatigue Enhancement

**Yuji Sano[1,2,3], Yoshio Mizuta[1]**

[1]*SANKEN, The University of Osaka, 8-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan*
*yuji-sano@sanken.osaka-u.ac.jp*

[2]*Nagoya Industrial Science Research Institute*

[3]*National Institutes of Natural Sciences*

*Microchip Lasers* *Laser peening* *Fatigue life enhancement*

**Abstract** Recent progress in high-power microchip laser technology has enabled a new class of ultra-compact laser peening (LP) systems designed not only for factory production but also for field deployment and in situ processing. Building on three decades of advances in reducing pulse energy and eliminating ablative coatings, we have developed a microchip-laser-based LP platform that integrates compact optical architectures with robust packaging techniques. Despite its finger-sized form factor, the system delivers sub-nanosecond pulses with sufficient peak power to induce compressive residual stress, achieving performance comparable to current large-scale LP systems.

The portability and vibration tolerance of this platform allow LP to be applied outside controlled laboratory environments, including direct processing of structural components under service-like loading conditions. When mounted on miniature robotic arms, the system enables flexible access to confined regions, expanding the applicability of LP to infrastructure maintenance, aerospace components, and steel structures. Fatigue experiments on various materials—including steels, titanium alloys, nickel-based alloys, and aluminum alloys—demonstrate that microchip-laser-based LP can extend fatigue life by more than an order of magnitude, underscoring its potential to enhance the durability of critical load-bearing members.

This talk will present the development concept, laser architecture, and system integration of the ultra-compact LP platform, followed by its demonstrated applications in fatigue enhancement and its prospects for next-generation on-site structural integrity management.

# Application of a Probabilistic Fatigue Strength Model to Case-hardened Steel

**Oliver Schenk[1], Jean-André Meis[2], Christoph Broeckmann[1]**

[1] *Institute for Materials Applications in Mechanical Engineering (IWM), RWTH Aachen University, D-52062 Aachen, Germany, o.schenk@iwm.rwth-aachen.de*

[2]*Flender GmbH*

*Case hardening steel* *Probabilistic fatigue model* *Fracture analysis*

**Abstract** Case hardening significantly alters fatigue strength of gears or drive shafts that are primarily subjected to bending loads. The formation of a martensitic surface layer induces compressive residual stresses that are due to the volume dilatation accompanying the martensitic phase transformation. The compressive stresses counteract tensile loads during bending and hereby reduce the local effective stress ratio. Meanwhile martensite increases the load bearing capacity which is further enhanced by the notable increase of carbon content close to the surface. The effect of case hardening on fatigue strength has already been quantified for various materials, case hardening depths and for both gas carburization and low pressure carburization. Furthermore, numerous studies reported the feasibility of numerical models of the case hardening process to predict both the phase distribution and residual stress distribution. Such a simulation approach has already been successfully combined with a numerical assessment of the fatigue strength of sintered gears, employing the concept of the highly loaded volume. While little variation in defect populations may be expected for sintered steels, continuously casted steels exhibit pronounced variations in cleanliness, chemical homogeneity, texture and grain size distribution, whose superimposition may induce notable variations in fatigue strength. Due to the complexity being inherent to the fatigue strength of case hardening steels, a validated quantitative prediction of the effect of a given carburization and quenching process on fatigue strength of a specific steel grade based on numerical simulations has not yet been proposed.

In this work, a numerical framework is presented that allows for the probabilistic prediction of fatigue strength of 18CrNiMo7-6. The model incorporates a heat treatment simulation that provides locally resolved information on phase composition and residual stresses. The latter are superimposed with the cyclic loads occurring during rotating bending tests. Following this, inclusions of various size are randomly distributed within the geometric domain of the test sample utilizing a Monte Carlo method. In addition, the prior austenite grain size distribution being deduced from metallographic investigations of fatigue test samples is reproduced within the test geometry. Based on the $\sqrt{area}$-Konzept introduced by Murakami and Endo, the admissible load limit is then computed based on the predicted local hardness, stress ratio and the defect area assuming that both the grains as well as the inclusions may act as crack initiation sites. This assumption is proven by extensive scanning electron microscopy investigations in conjunction with laser scanning microscopy and electron backscatter diffraction, revealing that crack initiation occurs at the transgranular fracture site of a single, large bainitic grain.

The validity of the concept is demonstrated with investigations of three distinct steel grades of 18CrNiMo7-6 that underwent identical case hardening processes. Both the simulation as well as experimental investigations of these variants reveal that fatigue fracture initiates preferentially at fractured bainitic grains, whereas inclusions barely affect fatigue strength. It is concluded that variations in fatigue strength are primarily due to microstructure variations, particularly abnormal grain growth of few austenitic grains. A good correspondence was found between simulation and experiment with respect to the fatigue limit and the location of crack initiation sites, being consistently situated underneath the case hardening depth.

# Effect of microstructure on pre- and post-punching fatigue behavior of hot-rolled thick-plate advanced high-strength steels

**Nader Heshmati[1,2], Mohammad Hoseini-Athar[2], Annika Borgenstam[2], Henrik Sieruin[2,3], Joachim Larsson[4], Peter Hedström[2]**

*[1] Swerim AB, Isafjordsgatan 28A, 164 40 Kista, Sweden, nader.heshmati@swerim.se*
*[2] Department of Materials Science and Engineering, KTH Royal Institute of Technology, Brinellvägen 23, 8 Stockholm, SE-100 44, Sweden*
*[3] Scania CV AB, Materials Technology, Södertälje, SE-151 87, Swede*
*[4] SSAB, Borlänge, SE-781 84, Sweden*
*Advanced high-strength steel* *Fatigue crack initiation* *Hope punching*

**Abstract** Advanced high-strength steels (AHSSs) are increasingly used to achieve superior strength-to-weight ratios in automotive structures, yet their application in thick-plate components, such as heavy-duty truck chassis, is challenged by property degradation caused by sheet shearing operations (e.g., punching and trimming). This study investigates the role of microstructure on pre- and post-punching fatigue behavior of three AHSSs (800CP, 700MC, and 700MCPlus) with distinct microstructures but similar strength levels, and compares them with a conventional HSLA steel (500MC). Comprehensive microstructural characterization, tensile testing, high-cycle fatigue (HCF) testing before and after punching, fatigue crack growth rate (FCGR) testing, and neutron residual stress measurements were performed.

Punching significantly modifies the edge region, inducing microstructural refinement, sub-grain formation, defect generation, residual stresses, and the formation of a work-hardened shear-affected zone and a rough fracture surface. At higher applied stresses and shorter lives (~$10^5$ cycles), post-punching fatigue performance is governed primarily by the intrinsic fatigue crack growth resistance of the base microstructure. In this regime, 700MCPlus, exhibiting the slowest FCGR, shows the highest fatigue strength, while the other steels with similar FCGR display nearly identical performance. The superior behavior of 700MCPlus is attributed to its specific texture, which limits slip activity, and to martensite at grain boundaries promoting crack deflection.

At lower applied stresses and longer lives (~$2\times10^6$ cycles), post-punching fatigue performance is dominated by punching-induced effects. In homogeneous microstructures (e.g., ferritic 500MC), surface roughness and especially residual stresses control fatigue behavior, with crack initiation occurring at mid-thickness parallel to the punching direction, coinciding with the location of maximum tensile residual stress. In heterogeneous microstructures, strain localization becomes critical when large strength mismatches exist between microconstituents (e.g., martensite and ferrite in 700MCPlus), promoting sub-grain formation, reducing the local threshold stress intensity range ($\Delta K_{th}$), and facilitating crack initiation. For microstructures with smaller strength contrasts (ferrite–bainite in 800CP and 700MC), sub-grains, together with surface roughness and residual stresses, jointly contribute to fatigue strength reduction.

These findings provide valuable insights into the mechanisms underlying punching-induced fatigue performance degradation, offering potential strategies for optimizing the fatigue properties of AHSSs for new applications.

# Fracture-Mechanics-Based Fatigue Life Assessment of Butt-Welded Joints: A Comparison of Standard-Based, Analytical, and Numerical Approaches

**Antoni Artinov[1], Mauro Madia[1], Andreas Pittner[1], Aayush Askhedkar[1], Egla Bregu[1], Thomas Kannengießer[1], Matthias Baeßler[1]**

*[1]Bundesanstalt für Materialforschung und-Prüfung (BAM), Unter den Eichen 87, 12205 Berlin, Germany,* antoni.artinov@bam.de

*Fatigue life assessment* *Weld geometry effects* *Fracture mechanics*

**Abstract**

Traditional fatigue design is based on S-N curves, providing a robust and well-established tool for structural design. However, the applicability of this approach to remaining life assessment is limited, as the presence and growth of fatigue cracks cannot be explicitly considered. In inspection-based assessments, cracks below the detection limit must often be assumed to exist in the structure, requiring methods that allow the prediction of crack propagation and thus residual fatigue life. In contrast, approaches based on linear elastic fracture mechanics provide a suitable framework for such assessments, although the practical implementation depends strongly on the chosen modelling strategy and underlying assumptions.

In this contribution, three fracture-mechanics-based fatigue assessment approaches of increasing modelling complexity are compared using 10 mm thick butt-welded dogbone specimens manufactured from structural steel S355NL. High-resolution laser scanning is used to capture the as-built weld geometry, providing the geometric input for all approaches considered. The methods differ primarily in how this geometric information is incorporated into the fatigue assessment.

The first approach is based on a fracture mechanics-based assessment following BS 7910, in which the weld geometry is represented by single or averaged geometric parameters derived from the scan data. The second approach employs the IBESS methodology, which evaluates discrete local weld geometry measurements along the weld seam, typically at millimeter-scale spacing, and describes fatigue damage using a phenomenological crack initiation and growth concept. The third approach introduces a newly developed three-dimensional numerical framework in which the complete, continuous weld geometry obtained from reverse engineering is directly integrated into linear elastic crack propagation simulations.

All approaches aim at specimen-specific fatigue life prediction but differ in their treatment of weld geometry, crack modelling concepts, and computational effort. Experimental fatigue tests with crack monitoring based on strain measurements and beach marks are used to validate the obtained theoretical results and support the comparison. The results illustrate the influence of modelling assumptions and geometric representation on fatigue life predictions and highlight the advantages and limitations of the different fracture-mechanics-based assessment approaches.

# Experimental investigation of mixed-mode fatigue crack growth under variable amplitude loading

**Naveen Kumar Kanna[1], Christopher Benz[1], Lars Radtke[1]**

[1]*Chair of Structural Mechanics, University of Rostock, Albert-Einstein-Str. 2, 18059 Rostock, Germany, naveen.kanna@uni-rostock.de*

*Mixed-mode fatigue* *Subcycle loading* *Thermo-mechanical fatigue*

**Abstract** Fatigue crack propagation under mixed-mode loading and variable amplitude conditions remains a critical challenge for fatigue life assessment of components subjected to complex service loads. In particular, the interaction between subcycle loading and mixed-mode crack driving forces remains insufficiently understood due to limited experimental data.

This work presents an experimental investigation of fatigue crack growth in a nickel-based superalloy for turbine applications under mode I and combined tension–torsion mixed-mode loading. The study focuses on constant and variable amplitude loading sequences, including subcycles, at room temperature and elevated isothermal temperatures. Crack growth is monitored using potential drop technique in combination with image-based automatic crack detection and measurement methods, supported by fracture surface analysis to elucidate dominant crack growth mechanisms.

First experimental results provide initial insight into the effects of mixed-mode loading and subcycle characteristics on fatigue crack growth behavior. The ongoing work aims to establish a robust experimental framework for the assessment and modeling of mixed-mode fatigue crack propagation in nickel-based superalloys under realistic mechanical and thermal loading conditions.

# Anti-fatigue design of additively manufactured titanium alloys

**Z. J. Zhang[1,2], Z. Qu[1,2], Z. F. Zhang[1,2]**

[1] *Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, PR China*

[2] *Department of Materials Science and Engineering, University of Science and Technology of China, Shenyang, 110016, PR China*

*Anti-fatigue* *Additively manufacturing* *Titanium alloy*

**Abstract** Additive manufacturing (AM) is regarded as a disruptive technology in the manufacturing field. However, the generally poor fatigue performance of additively manufactured materials under cyclic loading severely restricts the application of this technology in load-bearing components. This report systematically introduces the team's recent progress in enhancing the fatigue resistance of additively manufactured titanium alloys. First, by proposing a synergistic microstructural defect control strategy, the team invented a novel NAMP (Net AM preparation) process that enables stepwise regulation of defects and microstructure. This process not only refines the lamellar microstructure but also effectively suppresses grain boundary α-phase enrichment and pore recurrence. As a result, a nearly pore-free Net-AM microstructure was successfully produced in TC4 alloy. Its tension-tension fatigue strength increased from the initial 475 MPa to 978 MPa, surpassing all known titanium alloys and setting a record-breaking specific fatigue strength among all reported materials. Second, this report also introduces the team's latest finding that the NAMP microstructure exhibits exceptional fatigue resistance under different stress ratios, which is attributed to its nearly pore-free nature and fine α-lamellar structure. Finally, the report covers the team's recent systematic research progress on fatigue resistance in various titanium alloy systems (dual-phase TC4 and TC11, near-α TA15, and near-β Ti5553) as well as related engineering application cases. These achievements highlight the unique advantages of additive manufacturing in fatigue-resistant design and manufacturing, demonstrating its broad application prospects. The results have been published in journals such as Nature 626 (2024) 999, Science Advances 11 (2025) eady0937, and Additive Manufacturing 61 (2023) 103355.

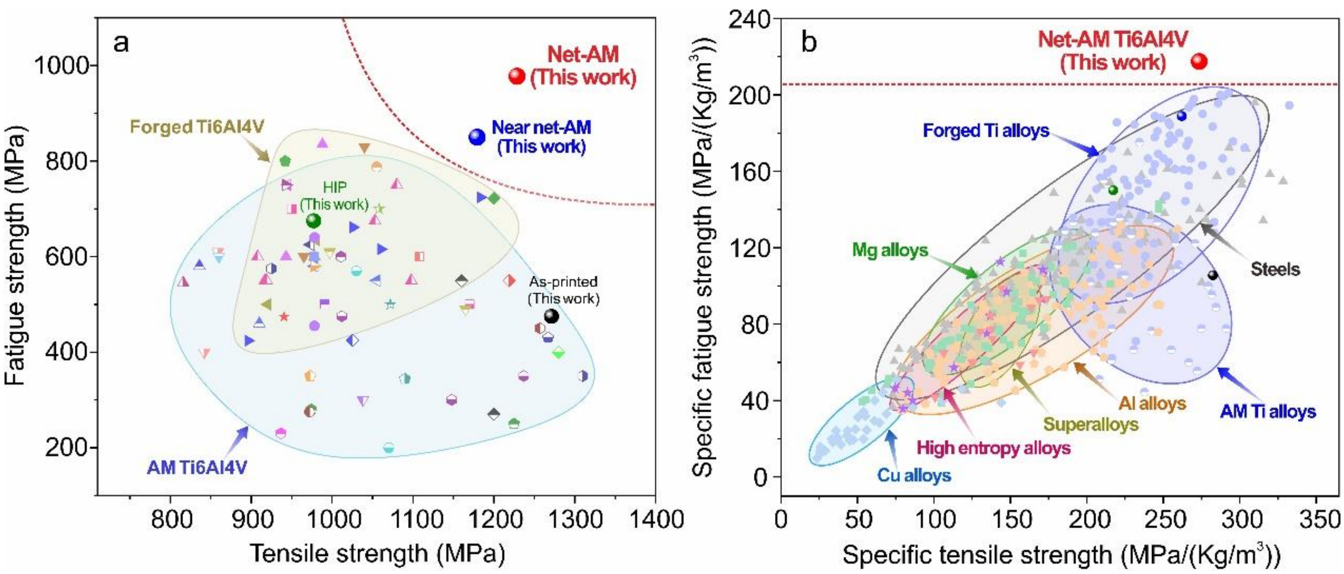



***Figure 1 -*** *Ultrahigh tension-tension fatigue strength (a) and specific fatigue strength (b) of titanium alloy with Net-AM microstructure*

# Effects of Surface Finish and Post-Processing Heat Treatment on the Fatigue Performance of AM AlSi10Mg

**Martin Matušů[1,2*], Bastian Roidl[1], Jan Papuga[2], Jakub Rosenthal[1], Jürgen Koch[1], Feng Chen[1], Wolfgang Blöchl[1], Martina Koukolíková[3]& Vladimír Mára[2]**

*[1]OTH Amberg-Weiden, Kaiser-Wilhelm-Ring 23, Amberg 92224, Germany*

*[2]Czech Technical University in Prague, Technická 4, Prague, 160 00, Czech Republic*

*[3]COMTES FHT, Průmyslová 995, Dobřany, 334 41, Czech Republic*

*High-Cycle Fatigue* *Additive manufacturing* *AlSi10Mg*

**Abstract** This contribution investigates the fatigue behaviour of additively manufactured AlSi10Mg produced by Laser Powder Bed Fusion (L-PBF), with particular emphasis on the combined effects of surface machining, post-process heat treatment, and elevated printing bed temperature. Specimens were manufactured using two different L-PBF systems, powder conditions, and heat treatment strategies, including platform preheating up to 220 °C in one of the two printers. Fatigue tests were performed under constant-amplitude loading in the high-cycle fatigue (HCF) regime using a resonant testing machine. A direct comparison of as-built, non-heat-treated (NoHT) specimens manufactured on different L-PBF systems (Aconity – C01, C02 and C03 and Concept Laser M2 - 4X and 9X series) reveals pronounced differences in fatigue performance despite the absence of thermal post-processing (Fig. 1, left). In particular, specimens produced with elevated printing bed temperature exhibit fatigue resistance by 10% lower compared to that of specimens manufactured at room temperature in the area from $10^5$ to $10^7$ cycles and even lower at lower lifetimes. The influence of surface machining and post-process heat treatment is illustrated in Fig. 1 (right). For specimens manufactured with a preheated build platform (220 °C), machining dominates the fatigue response, while subsequent stress-relief heat treatments (240 °C) provide only limited additional benefit. In contrast, for specimens printed at room temperature, heat treatment at 200°C – series 93 or 240°C – series 92 significantly improves fatigue performance compared to NoHT – 91$^{st}$ variant. These results demonstrate that fatigue behaviour of L-PBF AlSi10Mg is strongly governed by printer-specific process strategies and thermal history.

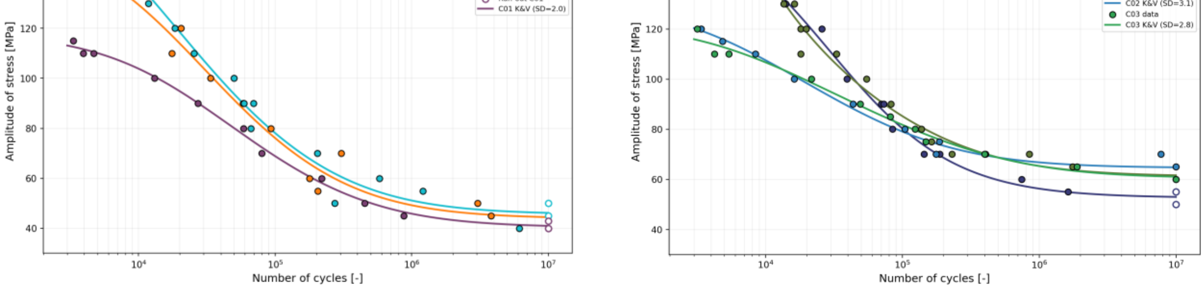



***Figure 1 - Left:*** *NoHT - As-built: C01 (220 °C platform), 41 and 91 (platform not preheated).* ***Right:*** *C02 (NoHT - Machined), C03 (T240 - Machined) printed at 220 °C; 93 (T200 – As-built) and 92 (T240– As-built).*

# Fatigue Performance of L-PBF Nickel-Based Superalloy:

# Effects of Surface Finish and Mean Stress

**Bastian Roidl[1], Martin Matušů[1,2*], Jakub Rosenthal[1], Ivana Zetková[3] & Miroslav Zetek[3]**

[1]*OTH Amberg-Weiden, Kaiser-Wilhelm-Ring 23, Amberg 92224, Germany*

[2]*Czech Technical University in Prague, Technická 4, Prague, 160 00, Czech Republic*

[3]*University of West Bohemia, Univerzitní 22, Pilsen, 301 00, Czech Republic*

*L-PBF* *High-Cycle-Fatigue* *Surface condition*

**Abstract** Laser Powder Bed Busion (L-PBF) Inconel 718 is increasingly employed in fatigue-critical components; however, the combined influence of surface condition, build orientation, and mean stress remains insufficiently understood. This work examines the high-cycle fatigue behavior of heat-treated L-PBF Inconel 718 considering different surface states (as-built, sandblasted, and machined), build orientations, and load ratios. Constant-amplitude fatigue tests were conducted at room temperature and evaluated using Kohout–Věchet regression.The results (see Fig. 1) indicate that fatigue performance is predominantly controlled by surface condition, while build orientation plays a secondary role when low porosity levels and optimized heat treatment are achieved. Machined specimens show the highest fatigue strength, whereas as-built surfaces result in reduced fatigue life due to early surface crack initiation. Sandblasting yields a partial improvement but remains inferior to machining. Tensile mean stress markedly decreases fatigue life in the low-cycle regime, with a progressively reduced effect at higher cycle counts.

These results demonstrate that, when properly optimized, L-PBF Inconel 718 can reach high fatigue performance, highlighting the dominant role of surface condition in fatigue design under tensile mean stress in the high cycle fatigue.

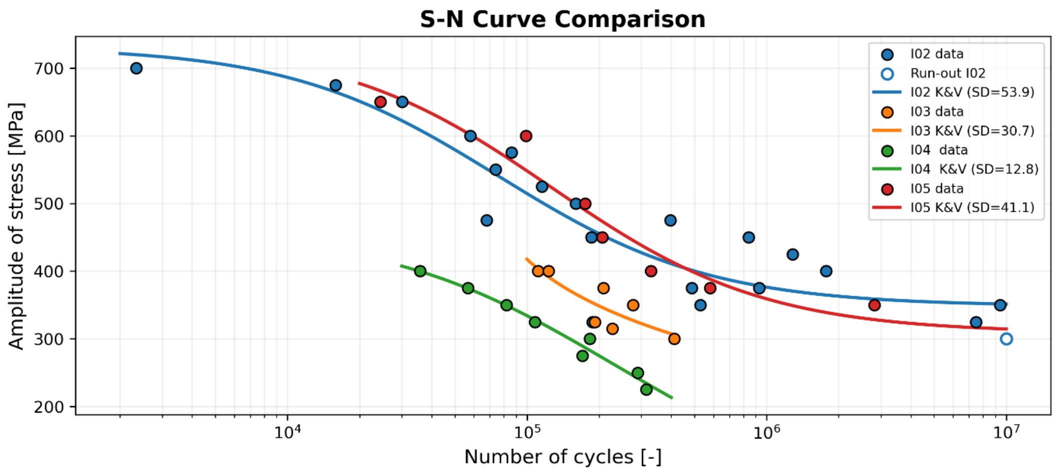



***Figure 1*** *– XY-built (horizontal) specimens printed on EOS M290: I02—machined + polished; I03—sandblasted; I04—as-built; I05—machined. All heat treated.*

# Laser peening to mitigate hydrogen driven fatigue cracking of steels

**Lloyd Hackel[1], Ali Tajyar[1], Carlos Nava[1], Jochen Fuhr[1]**

[1]*Metal Improvement Company LLC, A Division of Curtiss Wright Corporation*

*7655 Longard Rd. Livermore CA 94551*

*Fatigue failure 1* *Hydrogen 2* *Corrosive 3*

**Abstract:** We present recent work discussing how hydrogen, somewhat unexpectedly, is important in specific circumstances in corrosion fatigue cracking of metals, especially steels. Because atomic or ionic hydrogen is 5-times smaller and at least 5-times more mobile than corrosives such as sodium or chlorine, hydrogen easily gets into tiny cracks, migrates to crack tips, forms hydrides that weaken the steels and results in rapid crack growth and component failure. Our work has shown that hydrogen can be generated under somewhat unexpected conditions such as hydrogen generated in components exposed to rainwater and even vehicles exposed to mud. Atomic or ionic hydrogen will dissociate from water in the presence of specific corrosives enabling hydrogen to dominate fatigue crack growth and component failure. Thus hydrogen can become the unexpected driver of fatigue cracking. We begin discussion first with test results for a non-hydrogen driven cracking situation. In this ASTM G36 test, 316L stainless steel plates were loaded in bending and then exposed placing a cylinder of $MgCl_2$-$6H_2O$ heated to 155C against the steel plate. Magnesium chloride does not dissociate water to form atomic or ionic hydrogen, so minimal atomic hydrogen (H) or ionic hydrogen (H+) is generated. Thus, cracking in this situation is driven by intergranular stress corrosion cracking (IGSCC) requiring the combination of a corrosive and tensile stress. The situation significantly changes when atomic or ionic hydrogen is generated. In corrosion-fatigue tests of high strength steels exposed to seawater or a water-based corrosive, atomic hydrogen or ionic hydrogen will form, flow into and drive the overall crack growth rate. Ionic hydrogen ($H^+$)frequently forms in both rainwater and even mud, as marine muds often contain Sulfate-Reducing Bacteria (SRB), which are active in anaerobic (oxygen-free) environments. These bacteria create corrosive, anaerobic conditions at the metal surface, which can promote hydrogen permeation into the steel primarily as a result of acid dissociation and natural water chemistry. Exposure to seawater occurs in marine environments for ships and for aircraft gears and landing gear exposed to salt air and even rainwater. The tests we ran in which hydrogen drove the cracking ranged from steels with yield stress of 700 MPa to carburized gear steels with yield strength over 960 MPa. In one case of hydrogen driven fatigue cracking, the specimens were loaded in fatigue with the tensile side of specimens submerged in seawater and in another test, a salt solution was mixed in water and sprayed on to the tensile face of 4-point bend test specimens. In these corrosion-fatigue tests with atomic or ionic hydrogen, laser peening increased the lifetime of the test specimens in the range of 10 to well over 100-times. We present test results and discuss the significance of hydrogen generation and fatigue cracking

# A universal formula to estimate the fatigue crack growth rate in arbitrary metals at arbitrary R-values and temperatures.

**Hans-Jakob Schindler**

*Mat-Tec AG, Huob 18, 8782 Rueti, Switzerland; schindler@mat-tec.ch*

*Fatigue crack growth rate* *R-effect* *universal*

**Abstract** To predict fatigue crack growth (FCG) in a structural component, the so-called “Paris law” is still frequently used, despite of its known severe drawbacks and limited accuracy. Actually, the approximation of a real da/dN-curve to be linear (in a log-log-plot) in the range between the threshold $\Delta K_{th}(R)$ and $K_{max} = K_f$ is too much of a simplification. Correspondingly, the required material-dependent constants, which often are hard to find in the literature anyway, exhibit a pronounced scatter. Therefore, the calculated fatigue life of a structural component can be wrong by orders of magnitude. As a much more reliable and accurate alternative to estimate the FCG-rate in metals, the following universal formula is suggested:

$$\frac{da}{dN} = \begin{cases} \dfrac{1.5 \cdot 10^{-4} \cdot \Delta K_{eff}^{2.7}}{\Delta\sigma_D^2 \cdot \left(K_f^2 - K_{\max}^2\right)^{0.35}} & for\ \Delta K_{eff} > \max\left[\Delta K_{th,0} \cdot (1 - R_{eff}); \Delta K_{th,i}\right] \\ 0 & for\ \Delta K_{eff} < \max\left[\Delta K_{th,0} \cdot (1 - R_{eff}); \Delta K_{th,i}\right] \end{cases} \quad (1)$$

where $\Delta K_{eff} = \Delta K_{\max} - \Delta K_{\min,eff}$ , $K_{\min,eff} = \max\left(K_{DCC}; K_{PCC}; R \cdot K_{\max}\right)$ , $R_{eff} = \dfrac{K_{\min,eff}}{K_{\max}}$ , $K_{DCC} = \Delta K_{th,0} - \Delta K_{th,i}\ or\ 2 \cdot \Delta K_{th,i} + K_{ORCC}$ , $K_{PCC} = f_{PCC} \cdot K_{\max}$ and $\Delta K_{th,i} = 0.89 \cdot E \cdot \sqrt{b}$ , with E and b denoting E-modulus and Burgers vector, respectively.

Being based on simplified analytical relations to describe the complex process of FCG, the above formula has the advantages of dimensional consistency and containing no unknown “fudge-factors”. All the parameters that appear in (1) are physically well defined and can be identified from a single da/dN-curve at an arbitrary R-value: $\Delta\sigma_D$ is the stress range of endurance at R = -1, $K_f$ the value of $K_{max}$ at unstable crack extension in a da-dN-test, $\Delta K_{th,0}$ the FCG-threshold at R=0, $K_{DCC}$ the inherent damage-induced crack closure (CC), $K_{ORCC}$ the oxide and roughness induced CC and $K_{PCC}$ the remote plasticity-induced CC. However, if no da/dN-curve is available for the considered material – which is usually the case – the values of these material- and environment-dependent parameters can be estimated with usually sufficient accuracy as follows: $\Delta\sigma_D$ from the well-established correlation with the ultimate tensile stress and $K_f$ as being somewhat smaller than or equal to $K_{Ic}$ or $K_i$. Without experimental data, $K_{DRCC}$ and $K_{ORCC}$ as well as $f_{PCC}$ should be chosen as zero for the sake of conservatism,

In the proposed presentation, the derivation of (1) is explained and methods to estimate the required material parameters are shown. The results in terms of da/dN are shown by examples to be in surprisingly good agreement with experimental data from the literature and the behaviour of cracks in real structural parts.

# Effects of Different Damage States on the Vibration Characteristics of a Composite Containment Casing under Blade-Off Loading

**Feng Jin[1], Jianhao Zhang[1], Yan Zhang[1,2], Ying Zhang, Lulu Liu[1*], Zhihao Xie[1], Wei Chen[1]**

[1] *State Key Laboratory of Mechanics and Control for Aerospace Structures, College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*

[2] *AECC Shenyang Engine Research Institute, Shenyang 110015, China*

*Composite casing* *Damage status* *3D-DIC* *Vibration characteristics*

Composite aero-engine casings are susceptible to delamination, through-thickness perforation, and rub-induced scoring under extreme events such as blade-off. These damage modes can alter vibration characteristics and potentially compromise flight safety. This study examines multiple damage states generated under different blade-off conditions, with damage area ratios ranging from 0 to 34.4%. Under free–free boundary conditions, hammer-impact modal testing and three-dimensional digital image correlation (3D-DIC) are used to identify the first six natural frequencies and corresponding mode shapes. Mode-shape comparison across conditions is then used to evaluate differences between the two methods and to interpret the mechanisms underlying frequency reductions. The results show that natural-frequency decreases correlate weakly with damage type and are primarily governed by the damage area ratio; reduced thickness lowers natural frequencies across all modes considered. Both methods agree well in identifying low-order natural frequencies and yield consistent low-order mode-shape patterns. Unlike hammer-impact testing, which reconstructs mode shapes from relative displacement responses, 3D-DIC measures full-field absolute displacement over the damaged region and captures local features such as displacement localization and spatially non-uniform deformation near the damage. These observations suggest that damage degrades local stiffness and redistributes modal deformation toward softened regions, thereby reducing modal equivalent stiffness and shifting natural frequencies downward; this effect becomes more pronounced at higher damage area ratios. This work provides guidance for assessing the vibration characteristics of composite casings following blade-off damage and for selecting appropriate experimental identification methods.

# Fatigue fractures of cracked rubber composites after three-point bending

**Joanna Małecka[1], Karolina Głowacka[1], Andrej Škrlec[2], Marko Nagode[2], Jernej Klemenc[2], Tadeusz Łagoda[1]**

[1]*Opole University of Technology, ul.Prószkowska 76, 45-756 Opole, j.malecka@po.edu.pl*
[2]*University of Ljubljana, Kongresni trg 12, 1000 Ljubljana*

*Fracture* *SEM* *Rubber composite*

**Abstract:** To determine the nature of fatigue crack propagation, observations of the fracture zone were made using an electron microscope. The studies were performed using secondary electron emission to create images of the analyzed surfaces. Figures 1-2.a show fractures of the tested 3mm-thick rubber composites in their initial state reinforced with one and two layers of interwoven nylon cords arranged in a 0/90° configuration. The results of morphological examination of the samples after fatigue testing (b-d) reveal the degree of material degradation. The fracture structure shows a heterogeneous structure with local fiber clusters. Observations at lower magnifications revealed fiber agglomerations corresponding to the cord architecture embedded in the composite (b). Analysis of the fractures reveals the fatigue nature of the cracks, with progressive propagation, rather than a single brittle fracture. Visible long, thin fibers "hanging" from the crack edge indicate ductile rupture of the matrix, a phenomenon typical of rubber and elastomers. Observations did not reveal extensive debonding at the matrix–fiber interface, indicating satisfactory interfacial adhesion. Crack propagation proceeded abruptly, with local arrest and reinitiation of the crack. In both cases, only a few holes are visible, resulting from the fibers being pulled out of the matrix (d) at the moment of fracture. This suggests that matrix cracking initially occurred in the form of localized microcracks, which subsequently coalesced, leading to partial fiber release. The reinforcing fibers "bonded" to the matrix remain in approximately equal proportions in both parts of the damaged sample, indicating a relatively uniform load transfer during fatigue loading.

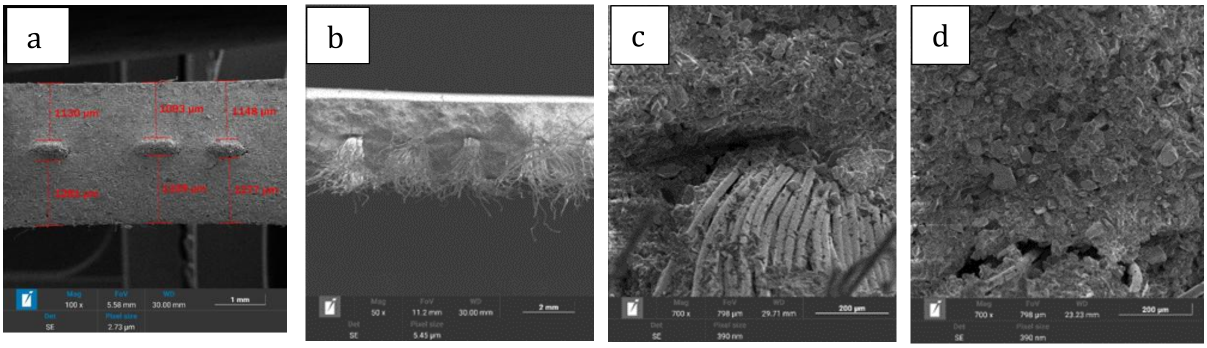



***Figure 1*** *- 3mm thick composite fracture with one layer of reinforcement*

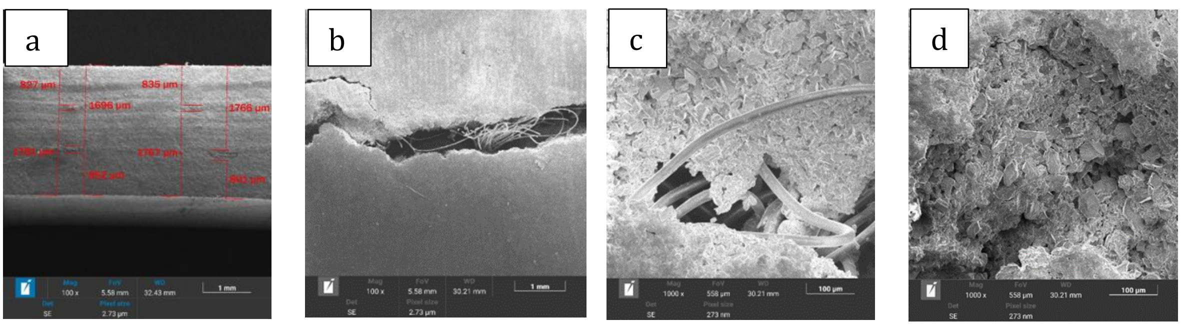



***Figure 2*** *- 3mm thick composite fracture with two layers of reinforcement*

# Fatigue Strength Evaluation of Laser Shock Peened Blades Subjected to Foreign Object Damage

**Yuhui Fan[1,2], Chao You[1,2], Rong Jiang[1,2], Yingdong Song[1,2,3,4]**

[1] *Key Laboratory of Aero-Engine Thermal Environment and Structure, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China, yuhuifan@nuaa.edu.cn*

[2] *Jiangsu Province Key Laboratory of Aerospace Power system, College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics Nanjing 210016, China*

[3] *State Key Laboratory of Mechanical and Control Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*

[4] *Harbin Engineering University, Harbin 150001, China*

*laser shock peening (LSP)* *residual stress construction* *foreign object damage (FOD)* *high cycle fatigue (HCF)*

**Abstract** Laser shock peening (LSP) is widely applied to the leading edges of fan and compressor blades in aero-engines to enhance their high-cycle fatigue (HCF) performance after foreign object damage (FOD). However, the variable thickness characteristics of the leading-edge structure complicate the distribution of residual stresses and work-hardening fields induced by LSP, making it challenging to be accurately characterized and thereby limiting the effective evaluation of the extent to which LSP improves the fatigue resistance of blades after FOD. To address this issue, a method for reconstructing the residual stress and work-hardening fields in variable-thickness LSP leading edge specimens is established in this study. Based on this, the fatigue strength after FOD can be accurately achieved. Firstly, double-sided LSP treatment was conducted on a set of TC4 titanium alloy plates with different thicknesses as well as on the leading edge specimens. The variation characteristics of residual stress and gradient microstructure with plate thickness under the same LSP process was systematically investigated using X-ray diffraction (XRD) and electron backscatter diffraction (EBSD). Subsequently, eigenstrain and microhardness models depending on the thickness of the LSP-treated region were developed, and the residual stress and work-hardening fields of the leading-edge specimen were reconstructed via the finite element method. Finally, the influence of LSP on the fatigue strength of FOD notches in leading-edge specimens was experimentally studied. A fatigue strength analysis method for LSP-treated leading-edge specimens containing FOD notches was established, quantifying the respective contributions of residual stress and work hardening to fatigue strength. The results demonstrate that the proposed reconstruction method for residual stress and work-hardening fields improves the accuracy of fatigue strength prediction for LSP-treated blades after FOD.

# Fast and accurate quantitative risk analysis method for damage-tolerant airframe structures

**Yan Bombardier**[1]

[1]*National Research Council Canada, 1200 Montreal Road, Ottawa, Canada, K1A 0R6,*
*yan.bombardier@nrc-cnrc.gc.ca*

*Reliability analysis* *Crack growth predictions* *Damage tolerance analysis*

**Abstract** Damage tolerance is a design and structural integrity philosophy widely used in the military aerospace industry to ensure continued airworthiness throughout the service life of the airframe. This philosophy assumes that all structures contain initial damage at the most critical locations, and that damage must be detected through schedule inspections before it becomes critical under the expected operational loads. Over the past decades, deterministic damage-tolerance analysis requirements have progressively evolved toward risk-based requirements.

MIL-STD-1530D, issued by the United States Air Force (USAF), now mandates the use of quantitative structural risk analyses across the entire Aircraft Structural Integrity Program (ASIP) as a decision-support mechanism for inspection planning, life-extension decisions, maintenance prioritization, and airworthiness certification. These data-driven physics-based quantitative risk analyses must account for uncertainties related to all significant variables affecting structural risk, including equivalent initial damage size distributions, load spectra, chemical and thermal environments, material properties, and the performance of nondestructive inspection and/or structural health monitoring systems, as characterized by their probability of detection.

Numerous tools, methods, and equations have been proposed to perform quantitative structural risk analyses. Simplified equations developed in the 1990s to estimate the primary risk metric for decision support, the hazard rate, are still widely used today; however, these formulations are often overly conservative and may lack accuracy. More rigorous and accurate analytical approaches have also been proposed, but their adoption has been limited due to their mathematical complexity and, in some cases, high computational cost when inefficiently implemented.

This paper presents newly-developed equations and algorithms intended to facilitate the practical adoption of risk-based methods in support of ASIP while providing accurate risk metrics, including probability of failure and reliability functions. The equations were derived from fundamental principles and tailored to damage tolerance analyses of aerospace structures. Efficient and robust numerical solution techniques were developed and optimized to ensure accuracy and high computational efficiency. Implementation details of the proposed numerical schemes are presented in this paper. The equations and algorithms were verified against Monte Carlo simulations for multiple test cases, the results demonstrated that the proposed approach is accurate, computationally efficient, and numerically stable.

# Fatigue tests of railway structures and components made of steel and composites

**Jan Chvojan[1], Miloslav Kepka[2], Miloslav Kepka jr. [2], Vaclav Kraus[3]**

*[1]Research and Testing Institute Pilsen Ltd., Tylova 1581/46, 30100 Pilsen, Czech Republic*
chvojan@vzuplzen.cz

*[2]Regional Technological Institute, Faculty of Mechanical Engineering,*
*University of West Bohemia, Univerzitni 2632/8, 30100 Pilsen, Czech Republic*

*[3]SKODA TRANSPORTATION a.s., nam. Emila Skody 2922/1, 301 00 Pilsen, Czech Republic*

*Fatigue tests* *Railway bogie frames* *Railway components*

**Abstract** Testing of railway structures in laboratories is a crucial aspect of rail vehicle development and innovation. Some tests are prescribed and specified in standards and regulations. Some of them must be designed and implemented individually, as needed.

In Pilsen, there are currently two laboratories with the potential for conducting strength and fatigue tests on components of rail vehicles. The Dynamic Testing Laboratory of the Research and Testing Institute Pilsen is a traditional test center, cooperating with producers and operators of rail vehicles worldwide. It is designed for testing of complete bogies and large parts of vehicles. The Strength and Fatigue Life Laboratory of the Regional Technological Institute (university research center) is a new workplace, adapted for testing smaller components. Both of these laboratories cooperate together and with various producers of rail vehicles.

The paper formulates fundamental findings from the implementation of a wide range of fatigue tests of various components carried out commercially and within publicly supported grant projects. The figure documents fatigue tests of several different bogie frames.

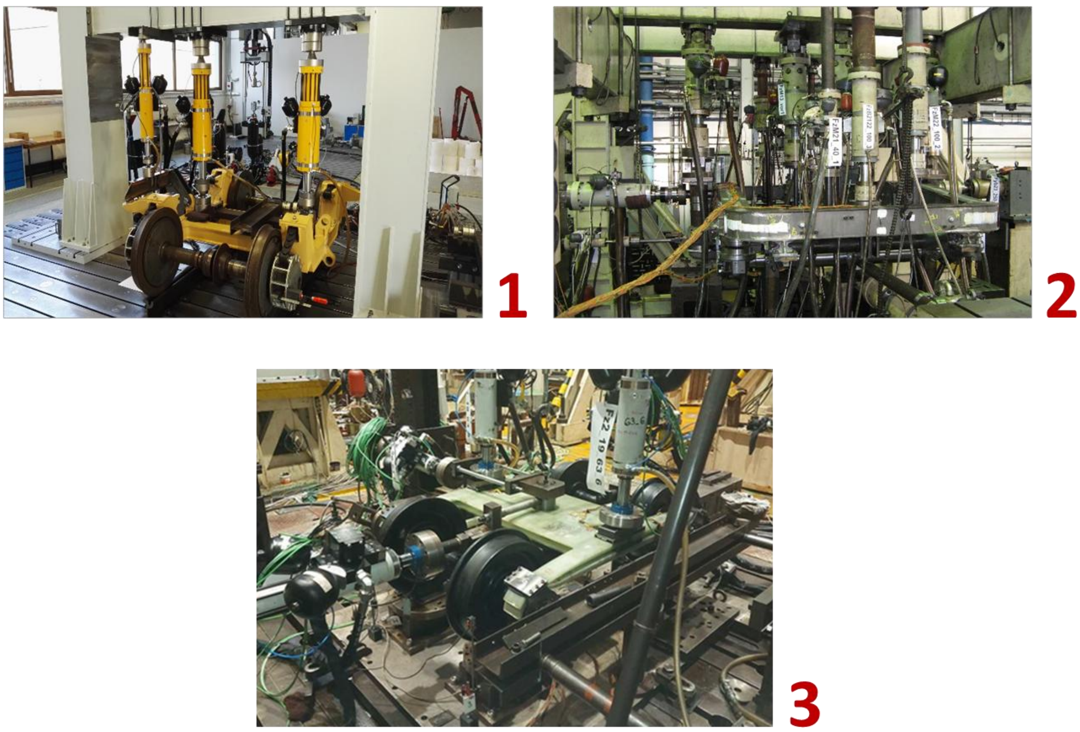



***Figure 1** – Various fatigue tests of bogie frames:*
*1 – tram (steel), 2 – locomotive (steel), 3 – wagon (glass fibre reinforced plastic)*

# Critical Assessment of Cracking Hydrogen Storage Vessel and An Evaluation of Critical Crack Size

**Un Bong Baek[1], Jaeyeong Park[1], Kyung-Oh Bae[1], Thanh Tuan Nguyen[2]**

[1]*Hydrogen Energy Group, Korea Research Institute of Standard and Science, 267 Gajeong-Ro, Yeseong-Gu, Daejeon 34113 Rep. of Korea*

[2]*School of Mechanical Engineering, Hanoi University of Science and Technology, Hanoi 10000, Vietnam*

*Hydrogen storage vessel* *Surface crack* *Stress intensity factor*

**Abstract** Structural analyses and crack assessments of a Type I hydrogen storage vessel were conducted using finite element analysis (FEA). The maximum stress amplitude was identified at the transition region between the nozzle and hemispherical head. A fillet radius ranging from 40 to 80 mm in the transition region between the nozzle and hemispherical head was identified as an optimal design parameter for improve the structural integrity and safety of the hydrogen vessel. Semi-elliptical surface cracks were introduced at this high-stress region. The distribution of stress intensity factors (SIF) along the crack front was analyzed for various crack geometries, including different crack depths and aspect ratios. The crack located at the transition between the nozzle and hemispherical head was determined to be the most critical compared to those further from this discontinuity. Due to the high-stress concentration in this region, the SIF in the transition zone between the nozzle and hemispherical head was significantly higher than that for cracks of similar size in the hemispherical head and cylindrical sections. By correlating the SIF magnitudes with elastic-plastic fracture toughness test results on the actual material, the critical crack length was accurately determined.

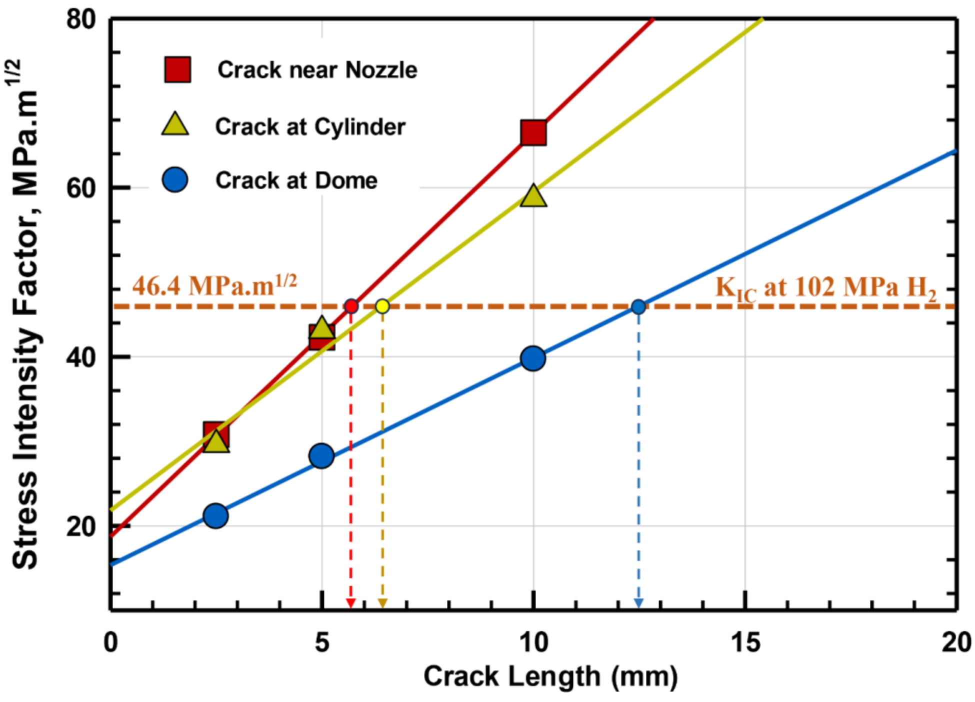



***Figure 1 -*** *Relationship between the SIF at the deepest point of the surface crack and crack length for a crack with an aspect ratio of 1/3 located at three different surface regions.*

# Validation of the Kitagawa-Takahashi Diagram

# – A New Method using DC Potential Drop Measurements

**Jürgen Bär[1], Mauro Madia[2]**

[1]*Universität der Bundeswehr München, Institute of Materials Science, D-85579 Neubiberg,* *juergen.baer@unibw.de*

[2]*Bundesanstalt für Materialforschung und -prüfung (BAM), D-12205 Berlin*

*Fatigue limit* *Kitagawa-Takahashi Diagram* *Potential Drop*

The Kitagawa-Takahashi Diagram is an important tool for describing the fatigue limit of components containing defects. The limit line in this diagram can be described using various models, but these differ significantly in the technically important region. For this reason, the KT diagram must be verified in this area through experiments. However, the stair-case method requires a large number of samples and has a long test duration. In addition, many samples with identical notches must be produced. In this work, a method is presented that allows a simpler and faster validation of the Kitagawa-Takahashi Diagram in the region of short cracks.

Notches with a defined width and depth were manufactured in flat samples of a low-alloyed steel with two different heat treatments using an engraving laser. This method allows to produce very sharp notches without plastic deformation and with only a slight thermal influence on the surrounding material. The samples prepared in this way were fatigued with blockwise increasing loads until failure. Crack initiation and propagation is monitored with a direct current potential drop method. The number of cycles in each loading block is determined by the measured potential drop. When in a defined interval no potential increase and therefore no crack propagation is detected, the program switches automatically in the next loading block. For each sample, it is therefore possible to determine a stress at which a crack is arrested and a stress that causes the specimen to fail. This procedure enables a reliable and precise determination of the limit stress for the respective notch size with a low experimental effort and time consumption.

The method is evaluated on a low alloyed steel in the hardened and normalized condition. In order to investigate the influence of the method used to manufacture the notch, notches of the same width and depth were introduced in the samples using both an engraving laser and Electrical Discharge Machining (EDM). The experiments showed no significant difference between the EDM and laser notches, although the laser notches were significantly sharper. The differences compared to values determined using the staircase method were slightly conservative, but still negligible. This demonstrates the suitability of the method presented here, which, due to the use of laser notches, the significantly shorter test time and the use of less specimens compared to the staircase method, results in a significant reduction in test time and thus also an enormous cost reduction.

# Lifetime Evaluation of Coke Drums considering the specifically determined S-N-Curve of the Shell

**Johanna Steinbock[1], Stefan Pfeffer[1], Wieland Holzer[1], Jürgen Bär[2], Jona Schmögner[3], Gerald Zehethofer[3], Roland Scharf[3], Lidia-Cornelia Winking[3]**

*[1]TÜV SÜD Industrie Service GmbH, Westendstr. 195, D-80686 München, Johanna.Steinbock@tuvsud.com*
*[2]Institute for Materials Science, Universität der Bundeswehr München, D-85577 Neubiberg*
*[3]OMV Deutschland Operations GmbH & Co. KG*

*Coke Drum* *Lifetime Prediction* *S-N-curve of 15Mo3*

This work investigates the fatigue behaviour of longterm operated coke drums in a delayed coking unit and evaluates the applicability of commonly used fatigue design standards for lifetime assessment of pressurised equipment. The coke drums, which have been subjected to approximately 35 years of daily thermal-mechanical cycling, exhibit operating conditions in which creep-fatigue mechanisms interact. To verify the material integrity and to reduce uncertainties inherent to ageing equipment, mechanical testing was performed on shell material removed during a shutdown. The mechanical characterisation, including tensile strength, impact toughness, etc. confirmed that the base material remains in sound condition without indications of ageing-related degradation. The experimentally determined fatigue behaviour of the shell material was compared with fatigue curves prescribed in major international standards, including API 579-1/ASME FFS- 1, ASME Section VIII Devision 2, EN 13445-3, and AD 2000 S2.

The study demonstrates that the experimentally determined fatigue behaviour is within the scatter band of the standards but emphasises the importance of improving the material-models used for describing the curves in the standards. While the American standards exhibit consistently more conservative fatigue limits, European standards provide less conservative predictions but show regions where their applicability becomes uncertain. When safety factors are removed, the normative curves align closely with the experimentally derived mean-curve; however, discrepancies in slope indicate that standardised design curves may not fully reflect the actual fatigue behaviour of this specific material after decades of service exposure. The results support the continued safe operation of the old drums as the experimental prove of the fatigue curve takes out an inherent risk in the lifetime calculation and such in the hole process of lifetime extension. This is one step ahead in comparison to most equipment in use.

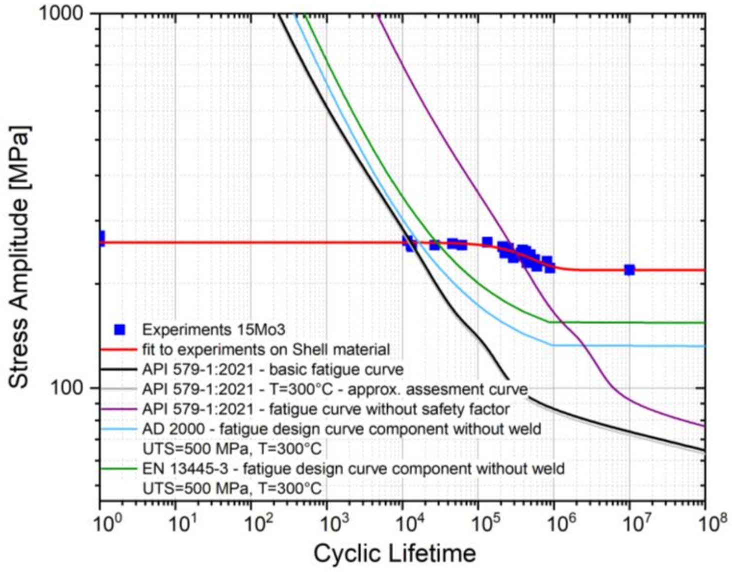



***Figure 1** – determined fatigue curve of 15Mo3 vs. fatigue curves of assessment standards*

# Fatigue Properties of Anodized A6061-T6 Alloy after Peening Treatment

**Kiyotaka Masaki[1], Yuji Sano[2,3,4], Yoshio Mizuta[2], Satoshi Tamaki[2], Yuji Kobayashi[5]**

*[1]Saitama Institute of Technology, Fusaiji 1690, Fukaya, Saitama, JAPAN, masaki-k@sit.ac.jp*
*[2]SANKEN, Osaka University*
*[3]Institute for Molecular Science*
*[4]Nagoya Industrial Science Research Institute*
*[5]SINTOKOGIO, LTD*

*Microchip Laser Peening* *Aluminum Alloy* *Anodic oxidation treatment*

**Abstract** Aluminum alloys are widely used as mechanical structural materials to achieve weight reduction. To further enhance their strength, surface treatments such as shot peening and laser peening have attracted increasing attention. The authors have also investigated the application of microchip laser peening (hereafter referred to as handheld laser peening, HH-LP) as well as shot peening. In general, aluminum alloys are susceptible to corrosion due to reactions with atmospheric moisture; therefore, anodic oxidation treatment is commonly applied. In this study, anodic oxidation treatment was applied to an A6061-T6 alloy subjected to shot peening and handheld laser peening treatments, and the resulting fatigue properties were investigated. The results of the rotating bending fatigue tests are shown in Fig. 1. The anodized base material exhibited a clear difference in fatigue life above and below a specific stress level. The shortened fatigue life in the high-stress regime is attributed to cracking of the anodized film. In contrast, the peening-treated specimens showed no distinct transition stress, and the fatigue lives were well represented by a single smooth S-N curve. Furthermore, a marked improvement in fatigue life was observed for the HH-LP treated specimens. An investigation of the peening effects revealed that the most significant difference between shot peening (SP) and laser peening (HH-LP) treatments was the magnitude of residual stress at the specimen surface. Anodic oxidation treatment significantly reduced the compressive residual stress in the SP treated specimens, whereas no pronounced reduction was observed in the HH-LP treated specimens.

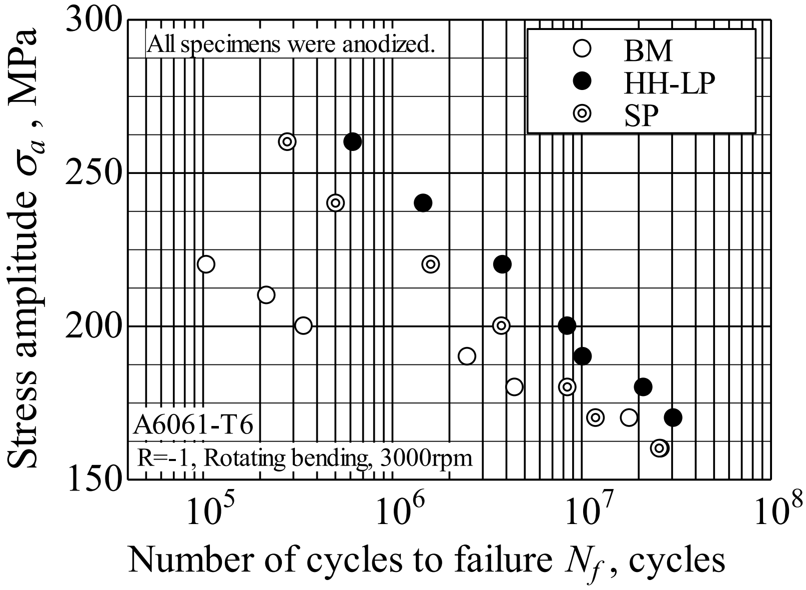



***Figure 1 -*** *The results of the rotating bending fatigue tests of materials*

# Statistical Generation of Virtual Scatter Bands within Accelerated Lifetime Prediction Methods

**Aline Wagner[1], Fabian Weber[2], Peter Starke[2,3]**

[1]*Aline Wagner, Department of Materials Science and Materials Testing (WWHK), Institute QM³, University of Applied Sciences, 67659 Kaiserslautern, Germany, aline.wagner@hs-kl.de*

[2]*Department of Materials Science and Materials Testing (WWHK), Institute QM³, University of Applied Sciences, 67659 Kaiserslautern, Germany*

[3]*Faculty of Natural Sciences and Technology, Saarland University, Saarbrücken, Germany*

*Lifetime Prediction Methods* *Statistical Validation* *Scatter Bands*

**Abstract** Accelerated lifetime prediction methods are increasingly employed, as they enable the determination of S-N curves with significantly reduced time and cost compared to conventional methods. However, as a result of the significant reduction in the number of required tests and fatigue specimens, a statistical and reliable assessment of the S-N curves as well as the determination of different failure probabilities becomes complicated. To overcome this limitation, a combinatorial approach is applied to calculate the number of cycles to failure for virtual constant amplitude tests (CATs), which are statistically validated against experimental CATs using a parametric or non-parametric significance test. By combining validated virtual and experimental CATs, a sufficiently large database is obtained to statistically validate the accelerated S-N curves and to characterize the distribution function of scatter. Depending on the number of available experimental CATs, either a single statistically characterized scatter band or multiple statistically characterized load level dependent scatter bands can be derived. It is also possible to calculate statistically characterized lifetime prediction bands for load level ranges. The proposed statistical approach is applied to the accelerated lifetime prediction methods MiDAcLife and StressLife. Lifetime prediction bands with statistically characterized distributions are determined for unnotched specimens of an unalloyed SAE 1045 steel and a low-alloyed 20MnMoNi5-5 steel. Furthermore, multiple statistically characterized scatter bands are derived for notched specimens of the SAE 1045 steel at different load levels, enabling a differentiated assessment of scatter behavior within the S-N curve.

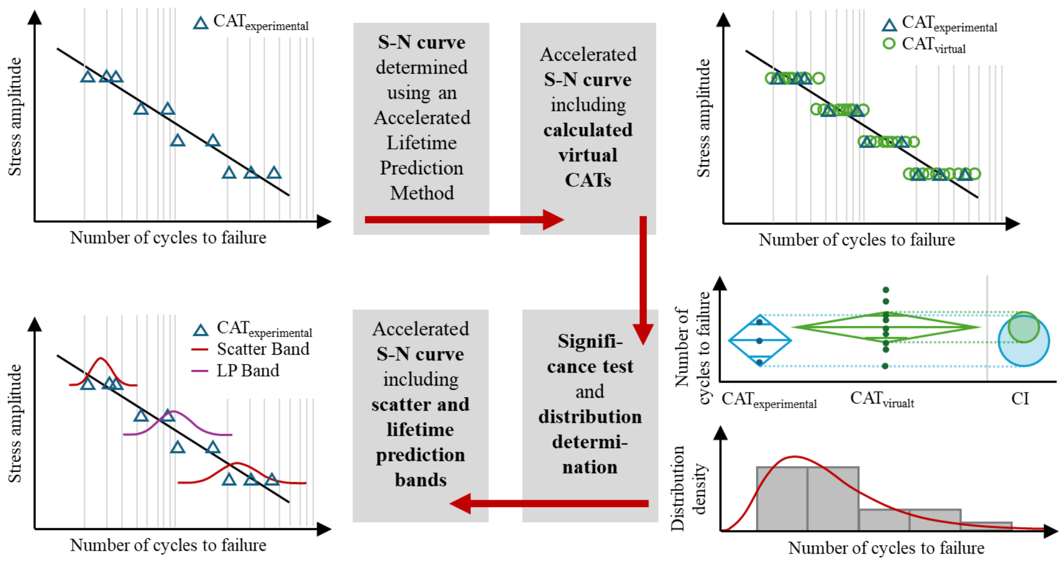



***Figure 1** – Schematic representation of the statistical generation of virtual scatter bands within accelerated lifetime prediction methods*

# Fatigue Behaviour of ER70S-6 WAAM Carbon Steel under Variable Amplitude Loading: Effect of Build Orientation and Critical Internal Defects

**Mariela Mendez-Morales[1], Ricardo Branco[2], Joel Jesus[2], Trayana Tankova[3], Emilia Grochowska[4], Grzegorz Ziółkowski[4], Carlos Rebelo[1]**

*[1]University of Coimbra, ISISE, ARISE, Department of Civil Engineering, Rua Luis Reis Santos, 3030-790 Coimbra, Portugal [mendezmorales@dec.uc.pt; crebelo@dec.uc.pt]*

*[2]University of Coimbra, CEMMPRE, ARISE, Department of Mechanical Engineering, Rua Luis Reis Santos, 3030-788 Coimbra, Portugal [ricardo.branco@dem.uc.pt; joel.jesus@uc.pt]*

*[3]Delft University Technology, Department of Engineering Structures, Stevinweg 1, 2628 CN Delft, the Netherlands [t.tankova@tudelft.nl]*

*Faculty of Mechanical Engineering, Department of Advanced Manufacturing Technologies, Wrocław University of Science and Technology, Wyb. Wyspiańskiego 27, 50370 Wrocław, Poland [emilia.grochowska@pwr.edu.pl; grzegorz.ziolkowski@pwr.edu.pl]*

*WAAM carbon steel* *Variable amplitude loading* *ER70S-6*

**Abstract** Despite recent advances in metal additive manufacturing, and in particular in direct energy deposition processes such as Wire Arc Additive Manufacturing (WAAM), fabrication-inherent internal imperfections such as gas porosity, voids and lack-of-fusion defects remain unavoidable. In the absence of dominant surface imperfections, these internal defects have been shown to govern fatigue performance. More importantly, fatigue crack initiation is controlled by so-called critical defects, defined by a specific combination of size and location within the component. In WAAM ER70S-6 carbon steel, the interaction between critical defect characteristics and build orientation, which corresponds to loading applied parallel or perpendicular to the deposition direction, has not yet been fully investigated, particularly under variable amplitude loading conditions.

In the present study, WAAM ER70S-6 carbon steel specimens manufactured in different build orientations were characterised by X-ray computed tomography (XCT) before and after fatigue testing., Variable amplitude fatigue tests were performed under stress-controlled conditions using two block-loading spectra. Additionally, full-field strain measurements were obtained by digital image correlation (DIC) during cyclic loading, and fracture surfaces were examined by scanning electron microscopy (SEM). The combined XCT, DIC and SEM analyses enabled the identification and characterisation of the life-controlling internal defect in terms of size and spatial location. Based on this information, a finite-element model was developed in which the critical defect was incorporated to capture its effect on the local stress field. The validated model was subsequently used to account for cycle-by-cycle fatigue damage accumulation under variable amplitude loading, through a new topology-fatigue optimisation tool, accounting explicitly for the presence of internal defects. The experimental and numerical results confirm that internal fabrication defects play a decisive role in the fatigue behaviour of WAAM ER70S-6 carbon steel; withal, for specimens produced under optimised fabrication conditions, their influence on fatigue life shows no significant dependence on build orientation. Furthermore, when the effect of the critical defect is incorporated into established fatigue-life assessment models, accurate and conservative life predictions can be achieved. These findings support the safe and reliable application of WAAM components in fatigue-critical structural applications.

# Mechanical Behaviour of Thin-Walled AlSi10Mg Specimens Fabricated by Laser Powder Bed Fusion

**S. Cravo[1], V. Duarte[1,2], C. Santos[1,3], R.F. Martins[2,4], R.A. Claudio,[1,5,6]**

[1]*Escola Superior de Tecnologia de Setúbal, Instituto Politécnico de Setúbal, 2910-761 Setúbal, Portugal;*
[2]*UNIDEMI, Department of Mechanical and Industrial Engineering, Nova School of Science and Technology , Universidade NOVA de Lisboa, 2829-516 Caparica, Portugal;*
[3]*CQE, IMS, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal;*
[4]*Laboratório Associado de Sistemas Inteligentes, LASI, 4800-058 Guimarães, Portugal;*
[5]*IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal;*
[6]*DICE Lab - Escola Superior de Tecnologia de Setúbal, Instituto Politécnico de Setúbal, 2910-761 Setúbal, Portugal*

*LBPF* *Thin walls* *AlSi10Mg*

**Abstract:**

Thin-walled components manufactured by metal additive manufacturing (AM) enable significant weight reduction and functional integration but raise major challenges for fatigue and fracture integrity, particularly as wall thickness approaches sub-millimeter scales. While previous studies have shown that wall thickness effects are often muted in low- and medium-cycle fatigue (LCF/MCF), pronounced sensitivity emerges in high-cycle fatigue (HCF) and fracture-dominated regimes, driven by surface roughness, near-surface defects and microstructural constraints imposed by limited ligament thickness [1–4].

This work builds on the current understanding of fatigue and fracture behaviour of AM thin walls by presenting an experimental and numerical investigation of ultra-thin LPBF AlSi10Mg specimens with wall thicknesses below 0.25 mm, extending well beyond the thickness range typically reported in the literature. Axial fatigue tests were performed to construct stress–life (S–N) curves, enabling direct comparison with data previously reported for thicker thin-wall geometries in Al–Si alloys [5–7]. Particular attention is paid to scatter and endurance limits, where the combined influence of geometric variability and surface-driven initiation mechanisms becomes dominant.

Fracture surfaces were systematically examined using optical microscopy and scanning electron microscopy (SEM) to identify fatigue crack initiation sites, dominant crack propagation modes and the role of surface roughness, partially melted particles and subsurface defects. The observed mechanisms are discussed in the context of plane-stress-dominated fracture, early crack initiation and interaction between surface features and eutectic Si morphology, as reported in prior studies on thin-walled Al–Si systems [5–7].

In parallel, finite element simulations of the fatigue specimens were conducted to quantify local stress concentrations arising from the nominal geometry and to assess the sensitivity of stress distributions to small variations in wall thickness. Experimental results are compared with numerical predictions to evaluate the adequacy of conventional nominal stress approaches when applied to ultra-thin AM walls, where accurate definition of the effective load-bearing section is critical [1].

The results provide new insight into fatigue performance and fracture mechanisms of AM walls below 0.25 mm, a thickness regime largely unexplored to date. The findings highlight the transition towards initiation-controlled fatigue behaviour, the limitations of standard design assumptions, and the need for geometry-aware fatigue assessment and fracture-informed design methodologies when qualifying ultra-thin AM components for cyclic loading applications.

# Size effects on fatigue life of additve manufactured Ti6Al4V

**Wenbo Sun[1], Yu'e Ma[2], Weihong Zhang[1]**

[1] *State IJR Center of Aerospace Design and Additive Manufacturing, School of Mechanical Engineering, Northwestern Polytechnical University, 710072, Xi'an, China, wenbo-sun@nwpu.edu.cn*

[2] *School of Aeronautics, Northwestern Polytechnical University*

*Size effect* *Surface roughness* *fatigue life*

**Abstract** This study examines the effect of specimen size on the fatigue performance of Ti6Al4V alloy produced by laser powder bed fusion (LPBF). Cylindrical specimens with different diameters were designed to evaluate size-dependent variations in defect distribution and surface roughness. Microstructural and surface analyses were conducted to characterize defect size, morphology, and surface topography. A fatigue life prediction model is developed that incorporates the combined effects of surface roughness and internal defects. The model has been applied to predict the fatigue life of additively manufactured titanium alloys under the influence of size effects, and its predictions have been validated experimentally. The results indicate that the size dependence of surface roughness in LPBF alloys is markedly stronger than that of internal defects. As specimen size decreases, surface roughness increases significantly, resulting in reduced fatigue life. In contrast, internal defects tend to concentrate near the specimen surface, and their distribution area shows little variation with decreasing specimen size, which reduces the effective load-bearing area. By accounting for adjustments in both surface roughness and effective load-bearing area, the accuracy of fatigue life predictions is significantly improved.

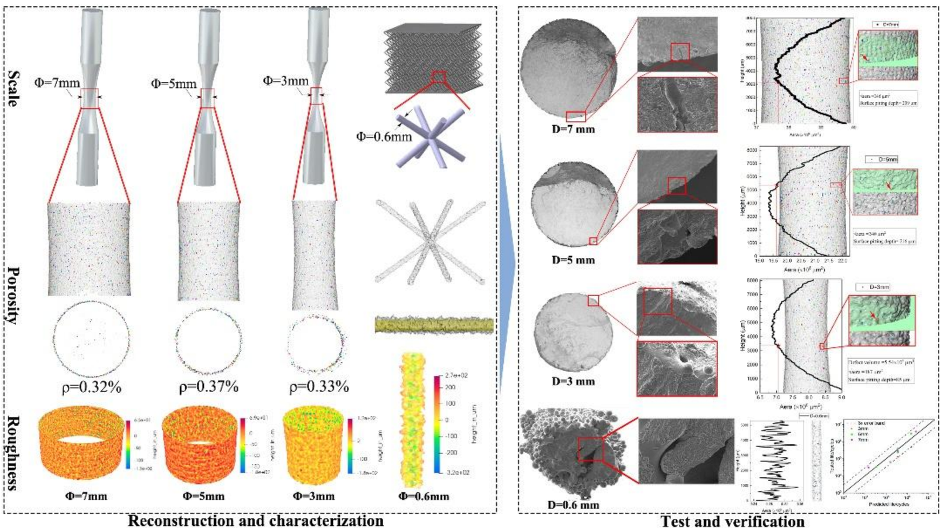



***Figure 1 -****Size effect on surface roughness and fatigue life*

# Influence of an Inclined Notch on Through-Thickness Fatigue Crack Propagation in PRNB Specimens Aimed at Improving Crack-Front Uniformity

**Darko Damjanovic[1], Nenad Gubeljak[2], Josip Stojšić[1], Andrijana Milinović[1], Domagoj Opačak[1]**

*[1]108. brigade ZNG 36, 35 000 Slavonski Brod, Croatia, University of Slavonski Brod, Mechanical Engineering Faculty in Slavonski Brod, ddamjanovic@unisb.hr*

*[2] Smetanova 17, 2000 Maribor, Slovenia, University of Maribor, Faculty of Mechanical Engineering*

*PRNB specimen* *Inclined notch* *Fatigue crack propagation*

**Abstract** This work addresses one of the main limitations of the Pipe Ring Notched Bend (PRNB) specimen when used for fracture toughness evaluation of pipe materials: the uneven fatigue crack propagation through the wall thickness. Due to the curved geometry of specimen and specific loading conditions during three-point bending, the crack often initiates and propagates non-uniformly, which affects the accuracy of fracture parameters evaluation and reduces the reliability of PRNB specimens in comparison to standard SENB specimens.

To overcome this issue, a modified PRNB configuration with an inclined through-thickness notch is proposed. The objective is to improve crack-front uniformity by promoting a more homogeneous stress state across the wall thickness during loading. The investigation combines experimental three-point bend tests with finite element analysis to evaluate the influence of the inclined notch on crack-tip fields and fracture parameters.

The experimental and numerical results obtained so far show a clear improvement in the stability and uniformity of crack-front evolution when using the inclined notch configuration. These findings appear highly promising, indicating that the proposed modification can significantly enhance the performance and reliability of the PRNB specimen. As such, the inclined-notch design represents an important step forward in the ongoing development and refinement of PRNB specimens for fracture toughness assessment of pipe materials.

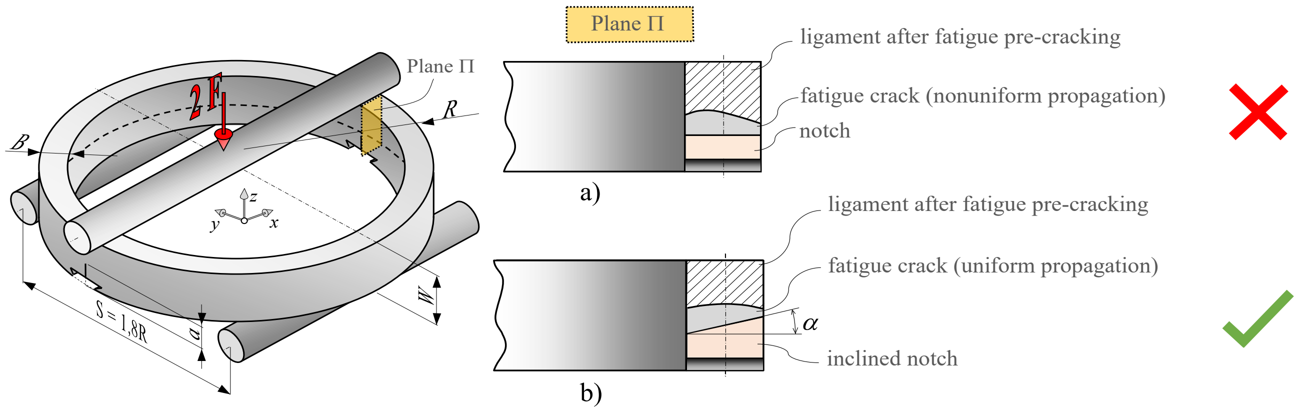



***Figure 1** – PRNB specimen, a) uneven fatigue crack propagation with straight notch, b) more even fatigue crack propagation with inclined notch*

# NDT-Based Hysteresis Measurements as a Key to Multiparametric Fatigue Characterization of Metallic Materials

**Peter Starke[1,2], Riko Schanzenbach[1], Aline Wagner[1], Jan-Erik Nebel[1], Jonas Anton Ziman[1,2], Janina Koziol[1,2], Fabian Weber[1]**

[1] *Department of Materials Science and Testing (WWHK), Institute QM³, University of Applied Sciences Kaiserslautern, Schoenstr. 11, 67659 Kaiserslautern, Germany*

[2] *Faculty of Natural Sciences and Technology, Saarland University, 66123 Saarbrücken, Germany*

*Hysteresis measurement*    *Fatigue characterization*    *Non-destructive testing*

**Abstract –** A reliable assessment of the metallic materials' fatigue behaviour is essential for a reliable and resource-efficient component design. While destructive testing methods remain prevalent, non-destructive testing (NDT) approaches are gaining importance, as they enable early damage detection and can serve as a basis for accelerated lifetime prediction methods. This contribution presents innovative approaches to multiparametric fatigue characterization based on complementary hysteresis measurements of mechanical, thermal, and electrical parameters.

Traditional stress-strain hysteresis analysis is complemented by temperature and electrical resistance hysteresis measurements conducted simultaneously during fatigue loading. The thermal signature captured through high-resolution infrared thermography reveals both, thermoelastic and dissipative effects, with particular sensitivity in early fatigue stages. The dissipated plastic deformation energy (90-95% converted to heat) directly reflects microstructural evolution and internal friction phenomena. Electrical resistance measurements, based on 4-wire measurement technology, are sensitive to the defect evolution and dislocation density changes within the volume of the material.

Figure 1 provides a schematic insight into the development of the temperature hysteresis as a function of the applied loading amplitude.

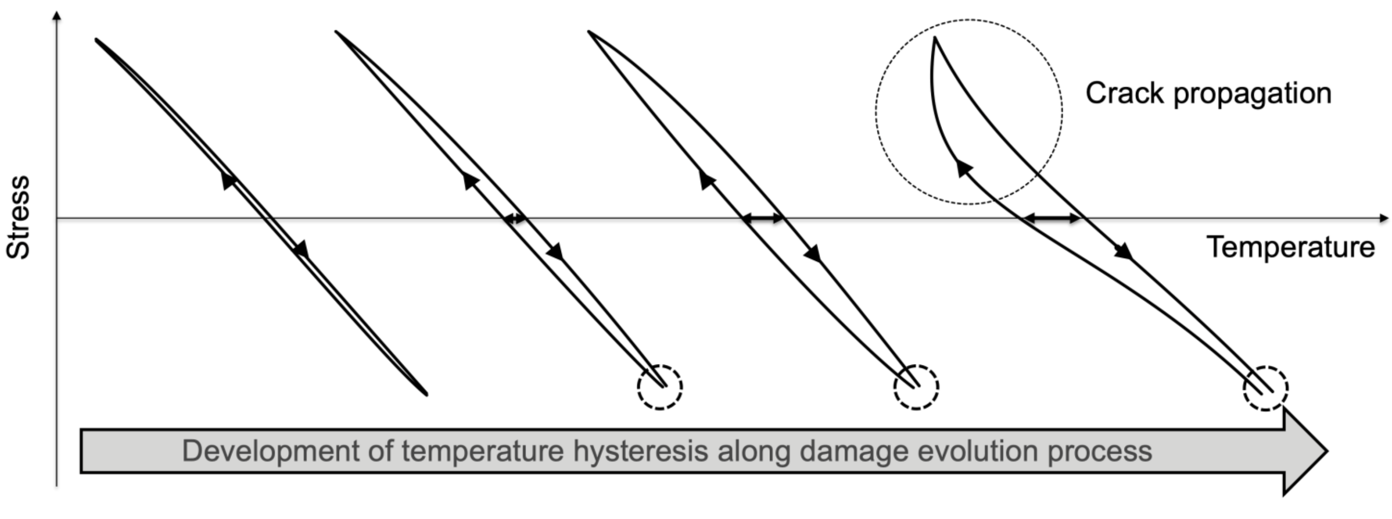



***Figure 1** – Stress-temperature hysteresis development along the fatigue life of metallic materials*

# Influence of Heat Treatment and Hot Isostatic Pressing on Fatigue Strength of Additive Manufactured Inconel 718

**Galina Kasperovich, Yasuko Besel, Janine Wischek, Joachim Gussone, Marion Bartsch, Jan Haubrich**

*Institute for Frontier Materials on Earth and in Space,*

*German Aerospace Center (DLR), Linder Hoehe, D-51147 Cologne, Germany*

*Additive manufacturing* *Inconel 718* *Post-processing*

**Abstract** Additive manufacturing (AM) enables production of highly complex structural components while offering significant flexibility in design and customization. The mechanical performance of AM parts strongly depends on printing setup, raw powder material, processing parameters, and scanning strategies. However, AM components may exhibit thermally induced residual stresses and inherent defects such as pores, both of which can adversely affect fatigue strength.

Fatigue samples were manufactured of nickel-based superalloy Inconel 718 (IN718) using laser powder bed fusion (LPBF) technique with optimized processing parameters to ensure minimal porosity, residual stress, and surface roughness. To improve the materials properties, post-processing treatments such as heat treatments and hot isostatic pressing (HIP) are commonly applied. In this study, the influence of different post-processing routes on the fatigue strength of LPBF IN718 was systematically investigated. Three post-processing conditions were examined: double aging (DA), HIP, and HIP followed by double aging (HIP+DA) and were compared with the as-built (AB) condition. Fully reversed fatigue tests (stress ratio R = −1) were performed at room temperature using a resonant fatigue testing machine. The HIP treatment resulted in grain coarsening while the DA heat treatment was performed below the recrystallization temperature and caused no significant change of the grain morphology. Both HIP and DA affected the composition and morphology of the precipitation phases compared to in the initial AB condition and significantly improved the fatigue strength of LPBF IN718. Although fatigue crack initiation in some double-aged specimens occurred at internal defects, these samples nevertheless exhibited superior fatigue performance compared to the other samples. The findings highlight the critical role of post-processing in tailoring the fatigue behaviour of LPBF IN718. The gained insights in the interplay between porosity, microstructure, phase composition, and fatigue performance contribute to a reliable qualification of additively manufactured IN718 components for fatigue-critical applications.

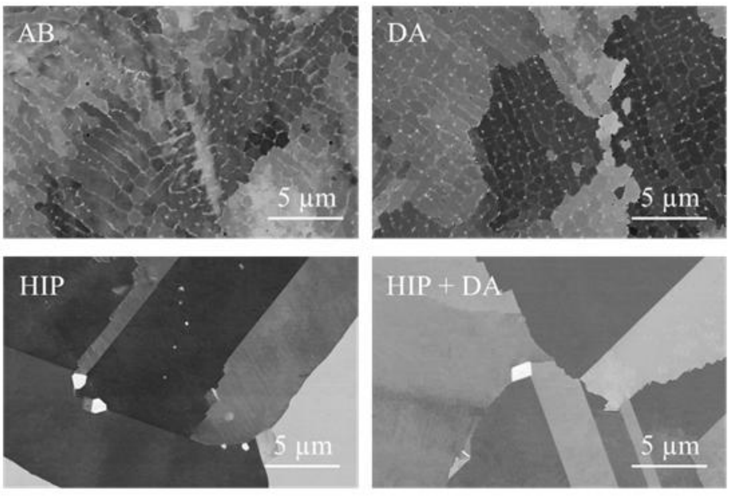



***Figure 1** – Microstructures of LPBF IN718*

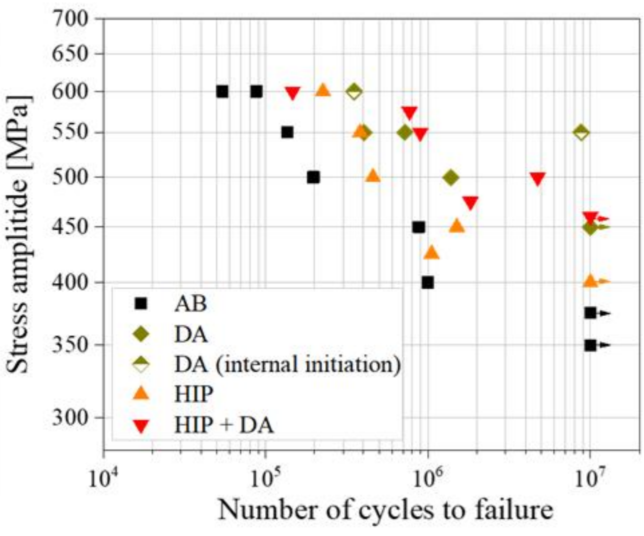



***Figure 2** – S-N data (R = −1)*

# Energy-Based Accelerated Lifetime Prediction According to MiDAcLife Incorporating Damage-Relevant Influencing Factors

**Fabian Weber[1], Peter Starke[1,2]**

[1] *Department of Materials Science and Testing (WWHK), Institute QM³, University of Applied Sciences Kaiserslautern, Schoenstr. 11, 67659 Kaiserslautern, Germany*

[2] *Faculty of Natural Sciences and Technology, Saarland University, 66123 Saarbrücken, Germany*

*Lifetime Prediction* *Modelled Surface Roughness* *Virtual S-N Curves*

**Abstract** Reliable fatigue assessment remains a key challenge in mechanical and materials engineering, particularly in view of increasing demands for resource efficiency and sustainable product development. Conventional fatigue testing is time- and resource-intensive and mostly relies on conservative safety factors to compensate for uncertainties in damage-relevant parameters such as surface condition. Within this contribution, an advanced accelerated lifetime prediction method (MiDAcLife) is presented and extended by the systematic integration of surface roughness as a damage-relevant parameter. MiDAcLife is an energy-based approach that quantifies microstructurally driven damage accumulation under cyclic loading using physically motivated damage descriptors. The method enables a significant reduction in experimental effort by combining non-destructive with destructive testing and robust numerical modelling, thereby enabling efficient prediction of fatigue life over a wide range of load amplitudes. In the present work, modelled roughness parameters are incorporated into MiDAcLife to account for their influence on material degradation. This integration enables the generation of virtual S-N curves without the need for extensive experimental testing across all relevant surface conditions. The proposed approach provides deeper insights into fatigue damage mechanisms by explicitly linking surface integrity to energy-based damage evolution. As a result, it supports an optimized component design with reduced safety factors while maintaining a high level of reliability. Beyond the methodological advances in lifetime prediction, MiDAcLife contributes significantly to sustainability in materials science by reducing material consumption, experimental resources, and development time. The combination of physically based modelling, virtual testing, and surface-sensitive damage assessment represents a promising pathway toward more efficient and sustainable fatigue design strategies. The methodical strategy is illustrated in Figure 1.

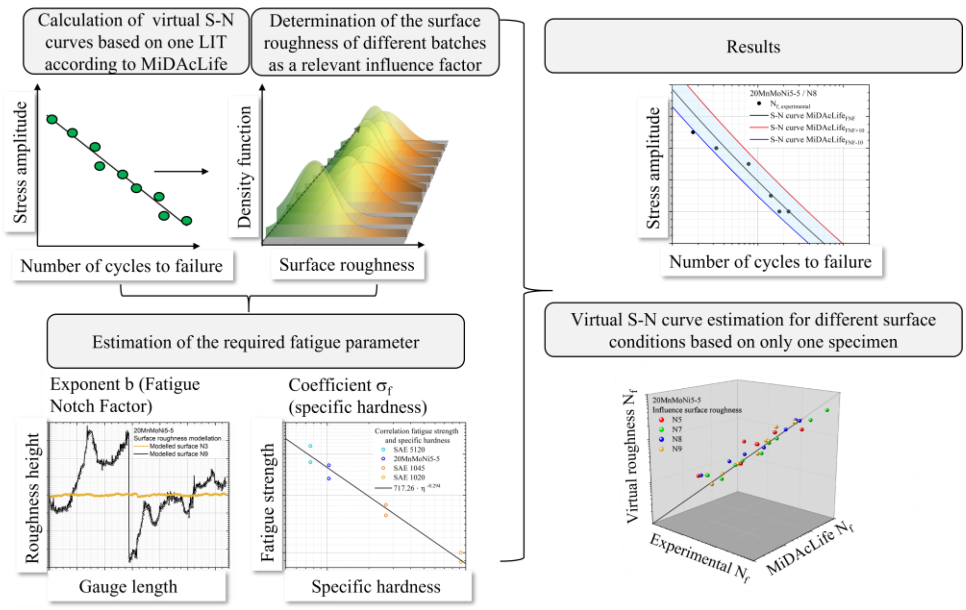



***Figure 1*** *– Integration of modelled surface roughness into the accelerated lifetime prediction according to MiDAcLife to estimate virtual S-N curves*

# High-Throughput Design and Composition Optimization of Gradient Rod Specimens by Additive Manufacturing

**Yuzheng Xiong[1], Lei Xu[1], Mingjie Sun[1], Yile Luo[1], Shuai Wang[1], Jiewei Gao[1,*], Shunpeng Zhu[2,*]**

[1] *School of Materials Science and Engineering, Xihua University*

*#9999, Hongguang Avenue, Pidu District, Chengdu, 610039, China*

[2] *School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China*

*#2006, Xiyuan Ave, West Hi-Tech District, Chengdu, 611731, China*

*17581706602@163.com; jieweig@126.com; zspeng2007@uestc.edu.cn*

*Additive Manufacturing* *High-Throughput Fabrication* *Gradient Material Design* *Micro-Shear* *Composition Optimization*

**Abstract** Continuous gradient rod specimens with axial linear distributions of Cr17Ni10 and Cr17Ni1 ratios were fabricated using coaxial dual-channel powder-fed laser additive manufacturing technology. The microstructure of the cross-section of the 4 mm-diameter rod specimen prepared in one minute exhibited a fine-grained zone at the edges, a columnar grain zone, and an equiaxed grain zone at the center. As the Cr17Ni1 composition gradient ranged from 0% to 100%, the microstructure progressively transformed from pure austenite to austenite-martensite dual-phase, ultimately forming ferrite-martensite dual-phase. The microhardness monotonically increased from 224HV to 718HV, while the shear strength peaked at 727MPa at 70% Cr17Ni1 content, with plasticity monotonically decreasing. Step-gradient wall specimens and homogeneous bulk specimens (Cr17Ni1 content ratios of 0%, 30%, 50%, 70%, and 100%) were prepared simultaneously to validate the hardness and strength trends at the critical junctions. The 70% Cr17Ni1 sample exhibited the highest tensile strength of 1562 MPa, which is consistent with the variations in the shear properties. This study establishes a closed data loop from continuous mapping to discrete verification through synergistic design and cross-validation of multiple gradient specimens, providing an efficient method for rapid composition screening and performance optimization of gradient materials.

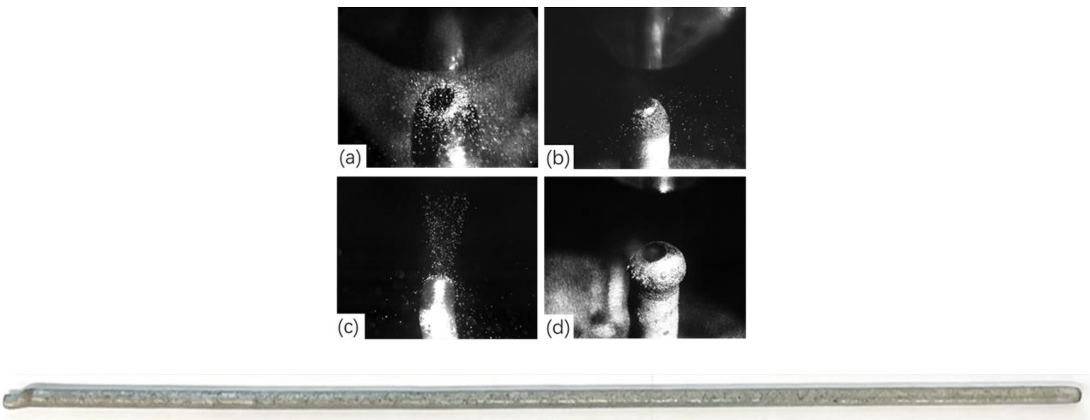



***Figure 1 -*** *Laser Additive Manufacturing Vertical Gradient Composition Rod Specimen*

# An Incremental learning-driven few-shot method for predicting fatigue life of AA7050-T7451 aluminum alloy

**Xuejiao Chen[1], Rui Deng[1], Chi Hou[1], Meiying Zhao[1]**

[1]*School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, China.*
*chenxuej@mail.nwpu.edu.cn*

*Life prediction* *Incremental learning* *Data-driven*

**Abstract** Fatigue failure constitutes a predominant failure mode of engineering components during service, and accurate fatigue life prediction is pivotal for safeguarding structural integrity and operational safety. Traditional experiment-based fatigue life prediction methodologies are constrained by their prolonged testing cycles, substantial economic costs and heavy reliance on extensive datasets. Meanwhile, the predictive accuracy of existing data-driven machine learning models tends to decrease significantly when extended to new loading environments or other kinds of material. This is primarily due to its inadequate generalization capabilities and poor domain adaptability. Consequently, the effective knowledge transfer from established fatigue data spaces to novel data domains has emerged as a critical challenge for fatigue life assessment. To tackle this issue, the present studies propose an incremental learning-driven approach for predicting the fatigue life of aluminum alloys. Initially, a baseline data-driven model was developed utilizing 1958 pieces of literature-derived data about aeronautical aluminum alloys. The data encompassed 24 input features such as material information, chemical composition, mechanical properties, and loading conditions. The XGBoost algorithm model was employed for training, and the SHAP (SHapley Additive Explanations) analysis method was applied to perform feature dimensionality reduction, thereby achieving model optimization. Subsequently, constant amplitude tension-tension fatigue tests were conducted on AA7050-T7451 aluminum alloy using an INSTRON8801 testing machine, and a total of 51 experimental samples were obtained. Three incremental learning strategies—experience replay, regularization, and structural optimization—were integrated to fine-tune the pre-trained model with limited experimental data. The aim was to strike a balance between predictive accuracy on the new task (AA7050-T7451 fatigue life prediction) and the forgetting rate of prior knowledge from the literature dataset. The results demonstrate that the coefficient of determination ($R^2$) is merely 0.04 when using the original XGBoost model to predict the fatigue life of AA7050-T7451 based on experimental data, indicating a poor generalization ability. After fine-tuning via the proposed incremental learning strategies, the model's $R^2$ for AA7050-T7451 fatigue life prediction exceeds 0.80, with the majority of predicted values falling within the three-fold error band. Further analysis of the influence of experimental data volume reveals that fine-tuning with 60% of the experimental data achieves an optimal trade-off between predictive accuracy and forgetting rate. The adjusted R-squared value reaches 0.86, with predictive accuracy (Ac) at 0.88 and forgetting rate (F) at 0.022. This study validates that incremental learning strategies can significantly enhance the generalization capability of data-driven models, providing a robust and efficient methodology for fatigue life prediction with few-shot experimental data. This method has important engineering significance for reducing testing costs and improving the efficiency of fatigue life assessment in practical applications.

# High-cycle fatigue behavior of A6061-RAM2 alloy considering surface condition and build orientation

**Duda Szymon[1], Dziuba Szymon[1], Zielonka Paweł[1], Szymczyk-Ziółkowska Patrycja[1], Lesiuk Grzegorz[1]**

*[1]Wroclaw University of Science and Technology, Faculty of Mechanical Engineering, Ignacego Lukasiewicza St. 5, 50-371 Wroclaw, Poland, szymon.duda@pwr.edu.pl*

*Fatigue fracture* *Aluminum alloy* *Additive Manufacturing*

**Abstract:** The additive manufacturing (AM) technique is gaining popularity in many industrial sectors. Apart from rapid prototyping, an increasing number of structural applications should be highlighted, which require more sophisticated design due to the alternative loading acting on the structure. One of the major advantages of the technology is that complex geometry can be manufactured by one machine, which allows for tailored designs for various applications. However, in the case of additively manufactured (AM) materials, surface quality plays a critical role, as fatigue damage typically initiates at surface imperfections acting as stress concentrators. Therefore, the influence of surface conditions should be experimentally evaluated and explicitly considered in the design process. Moreover, build orientation significantly affects the microstructure and defect distribution, leading to anisotropic mechanical and fatigue behavior.

The research presented is devoted to experimentally and numerically analyzing the effects of surface quality and build orientation on the fatigue behavior of AM 6061-RAM2 alloy. Uniaxial reverse cycling loading has been applied to deliver the S-N curves in the high-cycle fatigue (HCF) regime. The investigation showed the impact of surface quality by comparing as-built and machined surfaces and build orientation, i.e., vertical and horizontal. A resonant testing machine has been used for fatigue testing, along with optical methods (such as SEM and digital microscopy) for analyzing the roughness and fractured surface, and numerical modeling. Obtained results impact the design process of additively manufactured A6061-RAM2 in terms of crack initiation and its sensitivity to surface integrity and fabrication orientation, which is significant in terms of material tailoring in structural applications.

**Acknowledgment:** This research was funded in whole or in part by the Polish National Science Centre grant no 2023/51/B/ST8/02039.

# Development and Implementation of a High-Resolution, Full-Field, Near-Bore Digital Image Correlation (DIC) Process to Capture the Strain Response of the Split Sleeve Cold Expansion (SsCxTM) Process

**Scott Carlson[1], Dave Backman[2], Milan Djordjevic[2], James Prather[1]**

*[1]Lockheed Martin Aeronautics Company, 1 Lockheed Blvd, Fort Worth, TX 76101, USA*

*[2]National Research Council – Canada, Institute for Aerospace Research, 1200 Montreal Rd., Ottawa, ON, Canada K1A0R6*

*Cold Expansion* *Digital Image Correlation* *Residual Strain*

**Abstract** Although the F-35 Program continues to manufacture aircraft for the many Partners and Foreign Military Sales (FMS) Customer, the program is forward focused to develop the essential validation data needed to address repair design and life extension. The Split Sleeve Cold Expansion (SsCx™) process a fatigue and fracture critical processes being applied during the sustainment phase of the F-35A to enable the extension of recurring inspection intervals. In order to take greater crack growth life credit for the application of the SsCx™ process, a validated residual stress field and life prediction must be developed. The F-35 Program and the Engineered Residual Stress Implementation (ERSI) community has identified the experimental limitations associated with capturing strains at the edge of the hole after the SsCx™ process as one of the vital gaps in the development of a validated residual stress field.

This presentation will outline recent advancements in Digital Image Correlation (DIC) that have allowed for an exponential leap in capturing full-field, high resolution strains to within 0.005inch from the edge of a SsCx™ hole. This data provides a grounding set of elastic residual strains that can be used for Finite Element Analysis (FEA) process simulation and residual stress determination validation. Historically, it has not been possible to capture residual strain data this close to the edge of a hole because both surface and thru-thickness residual strain/stress determination methods all broken down as they get to within this distance of the edge of the hole. This presentation will provide full-field, high resolution residual strain for two aluminum alloys, at a range of edge margins and hole diameters, showing common trends post-SsCx™ and after final ream.

# Qualification & Implementation of Laser Peening on F-35 Fatigue and Fracture Critical Structure

**Scott Carlson[1], Vince Sherman[2], Drake Baldwin[2], Tyler Walkins[2]**

*[1] 1Lockheed Martin Aeronautics Company, 1 Lockheed Blvd, Fort Worth, TX 76101, USA*

*[2] Metal Improvement Company Co LLC., 7655 Longard Rd, Livermore CA, 94551, USA*

*Laser Peening* *Fatigue* *Residual Stress*

**Abstract** Since 2014 the F-35 Service Life Analysis Group has developed a team to investigate, certify and implement one of the largest aerospace structural engineered residual stress (ERS) projects on record. This project has included over 300 building block fatigue tests in both notched and un-notched test coupon configurations, in 7085 aluminum forging and Ti-6Al-4V Beta Annealed ELI forging material. These fatigue tests reduced the risks associated with qualifying Metal Improvement Company's (MIC) Laser Peening (LP) process to be applied on the F-35 airframe. Each test had specific marker band sequences applied at the end of each test spectrum block. Through the use of post fracture quantitative fractography it was possible to quantify the effect of laser peening on crack formation, short crack growth, and stable crack growth.

This presentation will provide the final life results for the work performed for the F-35B and C variants, covering both material classes. Lessons learned from coupon design, spectrum development, fatigue testing, quantitative fractography, and the design of the engineered residual stress field from the LP process will all be discussed. Specific focus will be on methods used to address the formation of subsurface cracking due to a specific LP process setting and how new LP processing parameters were developed, analyzed, applied and tested to address the formation of subsurface cracking, while still required to meet a specific fatigue life requirement. This work was performed within a significantly restricted timeframe due to the closure of the F-35's Structural Design and Demonstration (SDD) phase and the induction of the first F-35C that was to require LP.

This presentation will also review the digital engineering methods which were developed and utilized to enable a rapid transition from laser peening in the "lab" to being deployed within a depot environment. Through the use of advanced digital tools it was possible to develop quality control methods and checks that allow the laser operator, quality inspector, and structural integrity engineer the type and quality of engineering data needed to ensure that the laser peening process applied the correct process to each defined spot on the aircraft. This digital thread is an enabler for a future state where a validated FEA-developed residual stress field can be applied within the digital twin environment. Through the lessons learned during coupon design, LP process development and allowables, and the digital thread environment it will be possible to more rapidly assess, qualify and implement the LP process for other short life locations found throughout the life of the F-35 and other weapon systems.

# The LASAT : Measuring Adhesion at the Speed of Light

**Selen UNALDI[1], Domenico FURFARI[2], Laurent BERTHE[3]**

[1]*Dr. Selen UNALDI, Airbus Operations SAS, Toulouse, France, selen.unaldi@airbus.com*

[2]*Dr. Domenico FURFARI, Airbus Operations GmbH, Hamburg, Germany, domenico.furfari@airbus.com*

[3]*Dr. Laurent Berthe, PIMM, UMR8006 ENSAM, CNRS, CNAM, 151 bd de l'Hôpital, 75013 Paris, France laurent.berthe@cnrs.fr*

*Laser Shock Laser Paint Adhesion Test Laser Bond Adhesion*

At its core, LASer Adhesion Test (LASAT) method uses laser-plasma interactions to send shock waves through a sample, generating targeted tensile stress at the interfaces [1]. This is achieved by concentrating a 1–40 J laser pulse using a focal lens and a DOE, while enhancing the effect through either liquid or solid confinement layers [2,3].

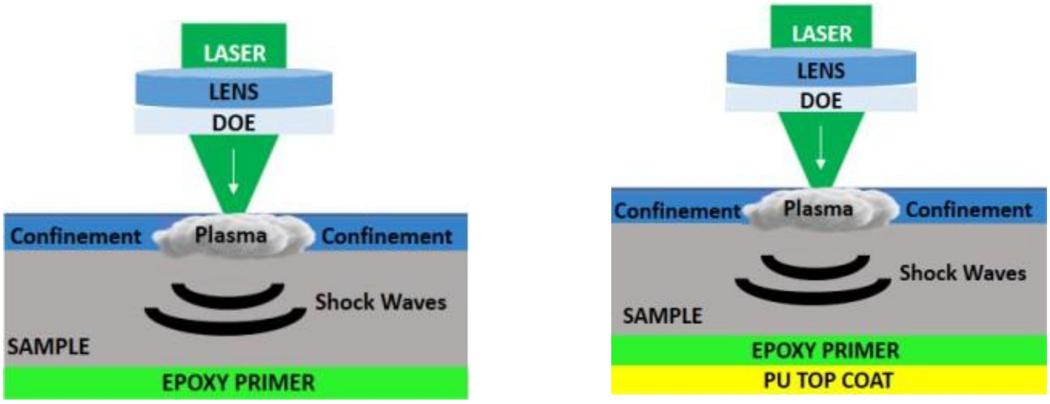



***Figure 1 -*** *Paint Adhesion Process Based on Different Layer Structures*

LASAT technology is highly versatile, providing a non-contact, sensitive, and quantitative upgrade to conventional paint adhesion testing [4]. The ability to fine-tune laser parameters allows for pinpoint accuracy at the material interface. This study is based on testing of material manufacturing to control specific properties. To help in the overall comprehension of the physics behind the laser paint adhesion tests, numerical simulations are performed using LS-Dyna to discriminate the effect of layer thickness and influence of the thermal ageing configuration on chemical and mechanical properties. As a future work, by feeding the databases, a Virtual Design of Experiments approach can be implemented. This allows for the numerical prediction of adhesion behavior and the optimization of stress localization through simulated parametric studies.

# From Wrought to Additive: Comparing Thermal Fatigue Damage in AISI 430 Using an Optimized Specimen Geometry.

**Nicolas THURIEAU[1,*], Baris TELMEN[1], Fabien SZMYTKA[1]**

*1 ENSTA, IMSIA UMR 9219, Institut Polytechnique de Paris, 91120 Palaiseau, FRANCE*
** Corresponding author: Nicolas.Thurieau@ensta.fr*

*Thermal Fatigue* *Experimental set-up* *Additive Manufacturing*

**Abstract** Thermal fatigue is a critical factor limiting the lifetime of structural components operating in severe high-temperature environments. However, reproducing realistic damage gradients in a laboratory setting often requires complex, non-standardized equipment. This presentation introduces a versatile thermal fatigue testing protocol that utilizes a conventional tensile test rig, ensuring reproducibility and precise control of mechanical boundary conditions.

The methodology was first established and **validated on a baseline geometry** using two reference materials: XC48 carbon steel and AISI 430 ferritic stainless steel. Building on these initial findings, the protocol was further developed through the design of an **optimized specimen geometry**. The thinning of the new design significantly reduces thermal inertia, allowing for higher heating rates and sharper thermal gradients, thereby accelerating the fatigue damage mechanisms.

The application of this accelerated protocol to characterize the thermal fatigue resistance of **AISI 430 stainless steel in two distinct conditions** is here detailed: conventional wrought material and specimens manufactured via **Laser Powder Directed Energy Deposition (LP-DED)**. The discussion will focus on comparing crack initiation sites and propagation paths either in the bulk material or the additive microstructure. Finally, the analysis of these first results validates the setup for a broader objective: qualifying the structural integrity of components **repaired by additive manufacturing**.

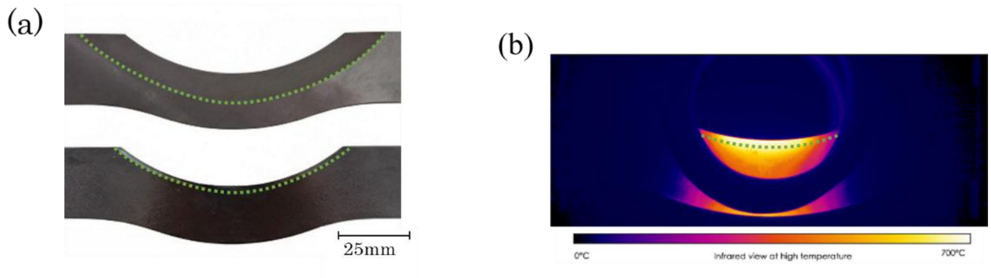



***Figure 1 -*** *Overview of the accelerated thermal fatigue protocol (a) Specimen geometry optimization: comparison between the innovative thinned design (top) and the original baseline geometry (bottom). (b) Infrared Thermography of the thermal gradient: demonstration of the thermal gradient during a cycle on the baseline geometry, confirming the effectiveness of the induction heating control.*

# Fatigue behavior of a maraging steel under multiaxial ultrasonic loading: crack initiation mechanisms and dissipative effects

**Nicholas LEMOS DE CARVALHO[1,2], Cainã BEMFICA DE BARROS[2], Cédric DOUDARD[1], Loïc DIMITHE ABOUMOU[2], Vincent ROUE[2], Sylvain CALLOCH[1]**

*[1]Institut de Recherche Dupuy de Lôme (IRDL) UMR 6027, ENSTA, 29200 Brest, France – nicholas.lemos@ensta.fr*

*[2]Safran Aircraft Engines, Villaroche, 77550 Moissy-Cramayel, France*

*Very-high cycle fatigue* *Tension-torsion cyclic loading* *Self-heating*

**Abstract:** Understanding the fatigue behavior of Maraging Steels in the Very High Cycle Fatigue (VHCF) regime is critical for applications in the aerospace industry. While uniaxial ultrasonic fatigue testing is well-established, structural components often endure complex multiaxial stress states. Within this context, this study focuses on the implementation of a multiaxial ultrasonic testing methodology.

The method utilizes a specific specimen geometry designed to convert longitudinal ultrasonic vibration (20 kHz) into a combination of tension and torsion modes. The design phase was conducted using Finite Element Analysis (FEA) to optimize the specimen geometry. The primary objective was to tune the resonant frequency to the testing system (20 ± 0.5 kHz) and to achieve specific biaxiality ratios. Particular attention was paid to the dynamic response of the assembly, specifically the modal landscape and the proximity of non-longitudinal modes.

The experimental setup is currently entering the commissioning phase. This presentation will outline the design process, numerical validation, and experimental implementation of the multiaxial setup. Preliminary experimental results regarding the S-N curves of the analyzed Maraging Steel under multiaxial loading will be presented and compared to existing uniaxial data, along with infrared measurements during testing. This work contributes to the broader validation of this testing technique and provides critical VHCF data for maraging steels.

# Laser peening for fatigue enhancement in aerospace industry

**Nikolai Kashaev**

*Institute of Materials and Process Design, Department of Laser Processing and Structural Assessment, Helmholtz-Zentrum Hereon, Max-Planck-Str. 1,*

*21502 Geesthacht, Germany*

*E-Mail: nikolai.kashaev@hereon.de*

*Laser shock peening* *Fatigue life* *Welded joints* *Residual stress*

**Abstract** Aeronautical structures are subjected to cyclic loading during service and are therefore prone to fatigue damage. Fatigue cracks typically initiate at critical locations with high stress concentrations, where tensile stresses promote crack initiation and propagation, leading to a significant reduction in structural fatigue life. Introducing compressive residual stresses in these regions is an effective approach to reduce crack-driving forces, retard crack growth, and potentially arrest existing cracks. In this study, laser shock peening (LSP) is investigated as an advanced surface treatment technique for enhancing the fatigue performance of metallic aerospace components. LSP is an effective residual stress engineering technique for introducing deep compressive residual stresses, making it particularly suitable for fatigue-critical applications. Several representative aerospace-relevant application scenarios are examined to assess the effectiveness of LSP in both preventive and restorative contexts. The results demonstrate that LSP can significantly extend fatigue life, with increases of several hundred percent observed in selected cases. Moreover, when applied to components containing small surface fatigue cracks, LSP is shown to restore fatigue life to levels comparable to those of undamaged or as-manufactured conditions. The beneficial effects of LSP are consistently observed across different aluminum alloys commonly used in aerospace structures, indicating the robustness and broad applicability of the technique. Overall, the findings confirm that LSP is an efficient and reliable residual stress engineering technique for improving the fatigue performance of structural components, particularly in critical areas such as joints, welds, and other stress concentrators. As a residual stress engineering technique, LSP offers considerable potential for extending the service life of aging aircraft structures. In addition, its application may enable a reduction in conservative safety margins for fatigue-critical components, thereby contributing to structural weight reduction and improved efficiency in aerospace design.

# A Phenomenological Approach of the Shear-Cutting Influence on the Fatigue Properties of Steels

**Marc Stolzenburg**[1]

[1]*Hyundai Motor Europe Technical Center, mstolzenburg@hyundai-europe.com*

*Cutting-Edge* *Shear-Cutting* *GISSMo*

**Abstract** To accurately predict the fatigue behavior of metal structures by Finite Elements (FE), all key effects of investigated components have to be incorporated within the utilized models. These key effects include the influence of manufacturing like heat treatment, plastic deformation or pre-damage. The applied cutting process significantly impacts the fatigue properties at the cutting edge. This study focusses on the shear-cutting process which exhibits severe non-uniform deformation until fracture within the narrow cutting zone.

Within this study, a phenomenological approach to estimate the cutting-edge fatigue properties of different steel and aluminum alloys is presented. Based on detailed material characterizations from literature, the fatigue properties of the uncut base material are described on basis of its quasistatic mechanical properties. To transform the derived E-N-curve of the base material based on the non-uniformly deformed cutting zone a damage model is incorporated. In this study, the damage is described in close relation to the GISSMo (Generalized Incremental Stress State dependent damage Model), a widely established model applied in automotive crash simulation. Combining the stress state dependent damage and its evolution with the mechanical properties of the base material gives an estimation of the fatigue properties of the cutting-edge. The resulting E-N-curves are compared to experimental data.

# Investigations into influencing factors on the VHCF behavior of ship propeller materials under seawater exposure

**Lea Riess[1], Christopher Benz[1], Lars Radtke[1]**

[1]*University of Rostock, Chair of structural mechanics, Albert-Einstein-Str. 2, 18059 Rostock, Germany,* *lea.riess@uni-rostock.de*

*VHCF* *Corrosion* *Ship propeller materials*

**Abstract** Due to the typical service life of approximately 25 years, ship propellers need to withstand loading of up to $10^9$ load cycles. An additional challenge is their operation in a corrosive seawater environment. Consequently, both factors must be considered in the design of ship propellers. At present, however, no corresponding data are available on the fatigue strength of cast alloys used for propellers in seawater at very high cycle numbers. Due to the complex mechanisms of corrosion fatigue, the only way to generate knowledge of the fatigue properties of these materials is through systematic experimental investigation.

In order to obtain results at $10^9$ load cycles within a reasonable time, an ultrasonic fatigue testing machine is used for these investigations. In addition, two further testing machines operating at lower frequencies are employed. The primary influencing factor to be investigated is the influence of the test medium (air versus seawater) on the fatigue life of the material. Since electrochemical processes during accelerated lifetime testing in a corrosive environment are time-dependent, the test frequency and thus the residence time of the specimen in the medium until failure also represent a significant influencing factor. The results obtained from ultrasonic fatigue testing are therefore compared with those obtained from tests conducted in seawater at lower frequencies. For this purpose, the number of load cycles and the time to failure, as well as the damage mechanisms observed in tests at three different test frequencies using different testing machines, are evaluated. The position of crack initiation is specifically analyzed to gain insight into damage mechanisms.

First experimental results of the ongoing work suggest a significantly lower fatigue strength under seawater exposure.

# Effect of Specimen Geometry on Fatigue Crack Growth of High-Density Polyethylene

**Sang Min Lee[1], Ilhyun Kim[1], Byoung-Ho Choi[1]**

[1] *School of Mechanical Engineering, College of Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul, 02841, Republic of Korea, sangmin727@korea.ac.kr*

*Fatigue crack growth* *High-density polyethylene* *Stiff-constant K specimen*

**Abstract** Traditionally, assessing the lifetime of thermoplastic pipes, such as the most widely utilized high-density polyethylene pipes (HDPE), relies on tests that require substantial time and resources. With the introduction of multimodal polyethylene grades, the resistance to slow crack growth has significantly improved. This improved resistance in newer materials such as PE 100 RC makes conventional testing methods highly impractical. For example, while 500 hours of life in notched pipe testing (NPT) are required for PE 100 grade, 8760 hours are required for PE 100 RC grade, with some formulations achieving NPT results exceeding 17000 hours. Therefore, a need arises, now more than ever, for an experimental and theoretical framework capable of assessing the residual lifetime of thermoplastic pipelines based on intrinsic material properties. However, when HDPE is subject to fatigue loading, a wedge-shaped damage zone, or process zone (PZ) forms ahead of the crack tip. This PZ is composed of highly oriented fibrillar structures transformed from the pristine spherulitic structures. A fatigue crack of HDPE propagates through sequential formation and rupture of the fibrillar structures in PZ, producing discontinuous crack growth and relatively large dependence on specimen geometry. These distinctive features of HDPE invalidates direct application of conventional methods such as Paris's law in assessing crack growth behavior. In this study, the effect of specimen geometry on fatigue crack growth (FCG) of HDPE is investigated experimentally using cracked round bar (CRB) specimens and stiff constant K (SCK) specimens. While the discontinuous crack growth was observed on both specimen geometries, a large discrepancy in overall FCG rate was observed showing the inadequacy of the conventional approaches in addressing the FCG behavior of HDPE. Applying crack layer theory, a numerical model is developed to capture the complex interaction between the PZ and the crack, reproducing discontinuous crack growth and specimen geometry dependence. The thermodynamic driving forces for PZ evolution and crack propagation are examined separately, providing a theoretical explanation for the experimentally observed geometry dependence of FCG in HDPE.

# A Damage-Based Fatigue Life Model for Additively Manufactured AlSi10Mg Considering Mean Stress, Residual Stress, and Defect Size

**Lea Strauß[1*], Günther Löwisch[1]**

*[1]University of the Bundeswehr Munich, Werner-Heisenberg-Weg 39, 85577 Neubiberg, Germany,*

**lea.strauss@unibw.de*

*Additive Manufacturing* *Fatigue Life Prediction* *Damage Parameter*

**Abstract** Laser-based powder bed fusion of metals (PBF-LB/M) is a widely used additive manufacturing process that enables the fabrication of complex, lightweight structures. However, the process inherently induces characteristic microstructural features such as surface roughness, residual stresses, and process-related inhomogeneities, which strongly affect the fatigue behavior of additively manufactured components. In combination with the comparatively low ductility of aluminum alloys such as AlSi10Mg, these effects complicate a reliable fatigue life assessment using conventional design approaches.

In this study, an experimentally based fatigue life model for PBF-LB-manufactured AlSi10Mg is presented, which explicitly accounts for surface condition, residual stress state, mean stress effects, and geometric influences. Extensive fatigue experiments were conducted on specimens with different surface states (as-built and machined), heat treatment conditions, stress ratios, and loading types. The crack-initiating inhomogeneities were systematically identified by fracture surface analysis and quantified using the $\sqrt{area}$ approach according to Murakami.

Based on the experimental findings, a damage parameter was developed that relates the applied stress amplitude and mean stress to the material-specific mean stress sensitivity, residual stress state, characteristic defect size, and geometry-dependent stress concentration. The proposed parameter enables a consistent normalization of fatigue data obtained under varying boundary conditions, allowing different loading ratios, surface states, and geometries to be described by a unified fatigue life relationship.

The results demonstrate that the developed damage parameter significantly improves the comparability and predictability of fatigue behavior for additively manufactured AlSi10Mg compared to conventional stress-based approaches. The model provides a physically motivated framework for fatigue life assessment and represents a promising step toward more reliable fatigue design of PBF-LB/M aluminum components.

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# Numerical Modelling of the Influence of Shot Peening on the Fatigue Performance of Welded Joints

**G. Cortabitarte[1*], I. Llavori[1], M. Larrañaga [1], J.A. Esnaola[1], X. Telleria[1], I. Ulacia[1]**

*[1]Mechanical and Industrial Manufacturing Department, Mondragon Unibertsitatea, Loramendi 4, 20500 Mondragón, Spain. gcortabitarte@mondragon.edu*

Welded joints Shot peening Residual stresses Multiaxial fatigue

**Abstract** Multipass welded joints are widely used in structural applications, where fatigue performance is strongly influenced by welding-induced residual stresses and post-weld surface treatments. Shot peening (SP) is commonly applied to improve fatigue resistance by introducing compressive residual stresses near the surface; however, the combined effects of welding and SP are complex and remain challenging to model accurately with reasonable computational cost.

In this work, a numerical framework is presented to simulate the thermal–mechanical behaviour of multipass welded joints and the subsequent application of shot peening, with the aim of predicting residual stress fields and their impact on fatigue life. Multipass butt welds were manufactured on S275JR steel plates using a CNC-controlled welding process to ensure repeatability and consistent heat input. Temperatures during welding were recorded, and residual stresses were measured after welding and after shot peening. In addition, fatigue tests were carried out on as-welded and shot-peened specimens to assess the treatment effectiveness.

A transient thermo-mechanical finite element model was developed to reproduce the welding process, showing good agreement with experimentally measured temperature histories and post-weld residual stress distributions. The shot peening process was simulated using the Contact Force Mapping (CFM) method, a modelling method previously developed and published by the authors. This method enables the efficient prediction of near-surface plastic deformation and residual stresses with significantly reduced computational cost compared to explicit impact-based approaches, while accounting for pre-existing residual stresses originating from prior manufacturing processes such as welding. This capability allows the simulation of the complete welding–shot peening process chain with reduced computational effort and good accuracy in the resulting residual stress fields. The predicted residual stresses after SP showed good correlation with experimental measurements.

The base material S275JR was experimentally characterised under fatigue loading to obtain the material parameters required for life prediction. The numerically obtained residual stress fields were then used to perform fatigue life estimations for both as-welded and shot-peened joints using the Smith–Watson–Topper (SWT) multiaxial fatigue criterion. The results demonstrate the capability of the proposed modelling strategy to capture the beneficial effect of shot peening on fatigue performance and to provide reliable life predictions with limited computational effort. The presented framework offers a practical tool for the design and optimisation of post-weld treatments aimed at enhancing fatigue resistance in welded structures.

# Characterization of two high-strength austenitic stainless steels in fatigue and damage tolerance in hydrogen conditions at cryogenic temperatures

**D. Willem[1,2], G. Henaff[1], C. Parrens[2], R. Walter[1], A. Oudriss[3], X. Feaugas[3], C. Berziou[3].**

[1] *Institut Pprime UPR 3346 CNRS - ENSMA - Université de Poitiers, Poitiers, France.*

*david.willem@airbus.com*

[2]*Airbus Operations SAS: MP&T, Titanium & Special alloys, Toulouse, France.*

[3]*LaSIE, CNRS, La Rochelle Université, La Rochelle, France.*

*Austenitic stainless steels*    *Hydrogen Embrittlement*    *Cryogenic temperature*

**Abstract** With the increasing interest in using Liquid Hydrogen (LH2) as fuel for aeronautical applications, material selection is critical to ensure both a proper mechanical resistance and a limited Hydrogen Embrittlement (HE) susceptibility from Room Temperature (RT) to LH2 temperature (20K). Airbus investigates the use of ferrous alloys for such applications, which are known for their good weldability compared to aluminum alloys. The use of austenitic stainless steels is particularly relevant for such applications due to their retained ductility at low temperature and their relatively low susceptibility to hydrogen embrittlement compared to other steel grades [1], [2], [3].

This study focuses on two high strength austenitic stainless steels, called material A and material B, with addition of nitrogen, so that they are nearly similar to a 316LN grade. Both materials are provided in thin sheets with a thickness ranging from 1.3mm to 4mm. The difference between both materials A and B lies mainly in the nickel content, which is higher in material B. Specimens have been precharged at 350 bars of hydrogen gas at 350°C for 2 to 7 days depending on the thickness, resulting in a global concentration of 80 wppm hydrogen, and then tested through Slow Strain Rate Tests at RT and -70°C, to assess the combined effect of HE and low temperature in a static loading. No significant ductility changes were observed for both materials in the conditions described above.

However, as the vessel goes through internal pressure variations, fatigue strength has to be investigated for various hydrogen exposure conditions. With this aim, fatigue tests (R=0.1) on uncharged and precharged specimens have been performed at RT and -30°C, to assess any combined effect of HE and low temperature in dynamic loading cases. Up to now, no signifant effect of hydrogen precharging on the fatigue performance has been noticed. Fatigue tests under hydrogen pressure and Fatigue Crack Growth tests on precharged specimens are still in progress.

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# Fatigue analysis of extruded HDPE in bare and welded conditions.

**K. Sales de Oliveira[1*], L. Carneiro[1], F.C. Castro[1], M.A. Garcia[1], F. Vicent[2], L.C. Randrianarivony[2], C. Bonini[3], J.A. Araújo[1], T. Doca[1]**

[1]*University of Brasilia, Brasilia, Brazil, * karoline.gusmao@aluno.unb.br*
[2] *SBM Offshore, Nice, France*
[3] *SBM Offshore, Rio de Janeiro, Brazil*

*HDPE* *Bare polymer* *Welded polymer* *Fatigue*

**Abstract** The growing use of extruded High-Density Polyethylene (HDPE) in structural and offshore applications has intensified the need for a reliable assessment of its fatigue performance, particularly in the presence of welded joints. Although HDPE components are frequently subjected to cyclic loading in service, fatigue design remains predominantly empirical, with limited incorporation of predictive models capable of supporting life estimation and structural integrity evaluations. Uniaxial fatigue tests were performed on bare and welded HDPE specimens in accordance with ASTM D7799. All tests were conducted under controlled laboratory conditions, with the temperature in the gauge-length region maintained within 22–26 °C to minimize thermal effects on the mechanical response. Load-controlled fatigue tests were carried out at a nominal temperature of 24 ± 2 °C using two stress ratios: fully reversed loading (R = −1) and tension–tension loading (R = 0.1), enabling the evaluation of mean stress effects. The applied stress ranges were defined based on preliminary testing, spanning 41.5–46.0 MPa for R = −1 and 17.8–19.5 MPa for R = 0.1. Considering the pronounced sensitivity of polymers to loading frequency and self-heating phenomena, a base frequency of 0.5 Hz was adopted to balance testing efficiency and thermal stability. To better represent in-service conditions of HDPE pipes, which typically experience lower frequencies, complementary tests were conducted at 0.10 Hz and 0.05 Hz. This approach enabled a systematic evaluation of frequency effects on fatigue life. Stress–life (S–N) curves were obtained for both material conditions, and fatigue resistance was evaluated in terms of fatigue strength and endurance limit. An assessment of models for fatigue life prediction is also presented. The results indicate a pronounced degradation of fatigue performance due to welding, manifested by reduced fatigue strength and endurance limit, which is attributed to welding-induced microstructural modifications, residual stresses, and stress concentration effects.

# A Critical Review of Coupled Mechanical, Thermal and Electrical Stress in Electrical Insulation Systems

**Tetjana Tomaskova[1], Jaroslav Hornak[2], Pavel Trnka[3]**

[1]*Faculty of Electrical Engineering, University of West Bohemia, tomaskot@fel.zcu.cz*

[2]*Faculty of Electrical Engineering, University of West Bohemia, jhornak@fel.zcu.cz*

[3]*Faculty of Electrical Engineering, University of West Bohemia, pavel@fel.zcu.cz*

| *Keyword 1* | *Keyword 2* | *Keyword 3* |
|---|---|---|
| *Coupled Stressors in Electrical Insulation Systems* | *Advanced Insulation Materials* | *Ageing Mechanisms and Diagnostics* |

**Abstract** Electrical insulation systems (EIS) are exposed to a complex combination of mechanical, thermal, electrical, chemical, and environmental stresses during operation, which together significantly accelerate the aging, degradation, and failure processes of various types of equipment, including rotating electrical machines, power transformers, converters, and extra-high voltage equipment. Despite advances in insulation materials and design, the interaction of these multi-physical stress conditions remains one of the main factors affecting the reliability and service life of EIS.

This review critically analyzes current knowledge on the interaction of mechanical, thermal, electrical, chemical, and environmental stresses, including thermal-mechanical expansion, electromechanical forces, partial discharge mechanisms, heat-induced molecular degradation of polymers (depolymerization), chemical degradation, and aging processes of polymer insulators and composite materials with micro- and nano-fillers, including fatigue-like mechanisms. The article evaluates available modeling approaches, experimental methods, and diagnostic techniques with a special emphasis on the usability of advanced simulation tools, multiphysics numerical methods, and modern data-driven approaches.

At the same time, it identifies key gaps in knowledge, in particular the absence of unified constitutive models, insufficiently accurate predictions of long-term aging under combined loading conditions, and a lack of standardized protocols for combined and accelerated aging. The review systematically compares topics that are frequently addressed in the literature (e.g., electro-thermal interactions, temperature-controlled degradation processes) with areas that have long been underestimated or incompletely covered (e.g., electro-mechanical-chemical bonds, synergistic effects of environmental humidity and mechanical fatigue, multiparametric analysis of the behavior of modern composite and nano-filler insulations).

An important output of the work is a comprehensive synthetic table that clearly maps the advantages and disadvantages of individual approaches, related risks, and, above all, the interrelationships between mechanical, thermal, electrical, chemical, and environmental stresses. This table highlights critical interaction mechanisms that have so far been described only fragmentarily or inconsistently in the literature and provides a unified framework for understanding the multiphysical degradation of EIS.

The review concludes with an overview of recommended directions for further research identified in the available literature, including in particular the need to develop multiscale modeling, test combined stress regimes, modernize hybrid diagnostic approaches, and broaden the application of machine learning methods in the field of failure prediction and life cycle management of insulation systems.

# Microstructure and Corrosion Effects on ZW12 Fatigue Performance

**J.J. Trujillo[1], J. Goitia[2], J. Victoria-Hernández[1], D. Letzig[1]**

[1]*Helmholtz-Zentrum Hereon GmbH, Institute of Material and Process Design, Geesthacht, Germany*

[2]*Mechanical and Manufacturing Department, Faculty of Engineering, Mondragon Unibertsitatea, Arrasate/Mondragon, 20500, Spain*

**Juan-Jose.Trujillo-Tadeo@hereon.de*

*High Cycle Fatigue* *Corrosion* *Mg alloys*

**Abstract**

Magnesium (Mg) alloys are increasingly attractive for automotive and aerospace lightweighting due to their high specific strength, good dimensional stability, and recyclability. Their broader deployment under cyclic loading, however, is constrained by the hexagonal close-packed (HCP) crystal structure, which limits the number of readily activated slip systems at ambient temperature. As a result, thermomechanical processing often produces pronounced deformation textures, leading to strong mechanical anisotropy and marked tension–compression yield asymmetry—features that can critically influence fatigue damage accumulation and crack initiation.

Although the fatigue behavior of common Mg alloy families (e.g., Mg–Al–Zn and Mg–Al–Mn) is well documented, far fewer studies have examined Mg–Zn alloys with yttrium additions under cyclic loading. Although not strictly a rare-earth element—is often used because it can alter recrystallisation and weaken basal texture during extrusion, which may improve fatigue resistance. However, the combined influence of extrusion-controlled microstructure (recrystallisation state, grain size, second phases, texture) and corrosion-induced surface damage on the fatigue performance of Mg–Zn–Y alloys is still not well understood.

This study examines how extrusion-controlled microstructure and corrosion affect the fatigue performance of the ZW12 magnesium alloy (Mg–1Zn–2Y wt.%). Three processing conditions were produced by varying extrusion parameters. The resulting bars were characterized by SEM/EDS, while crystallographic texture was quantified by EBSD. Mechanical behavior was assessed in tension and compression, followed by high-cycle fatigue testing in air (R = 0) and after pre-corrosion in 0.5 wt.% NaCl solution.

The fatigue results show a strong, microstructure-dependent sensitivity to pre-corrosion. In air, the non-recrystallized condition reached run-out (107 cycles) at 70% of the yield strength (YS), whereas the recrystallized conditions with grain sizes of 25 µm and 50 µm sustained (107) cycles at 90% YS. After pre-corrosion in 0.5 wt.% NaCl, fatigue life dropped drastically for the non-recrystallized condition and for the recrystallized condition with 26 µm grain size: all specimens failed between ~ 5×104 and 1.7×105 cycles, representing a reduction of more than two orders of magnitude compared to the run-outs in air. In contrast, the recrystallized condition with 50 µm grain size still achieved run-out (107 cycles) at 90% YS after pre-corrosion. These results indicate that corrosion-induced surface damage (like pitting) strongly accelerates crack initiation in some microstructures, while the coarser-grained recrystallized condition shows higher tolerance to corrosion-assisted fatigue damage.

# Fatigue Crack Propagation under Different Residual Stress Modification Techniques: A Comparative Study of Deep Rolling, Hammer Peening, and Laser Shock Peening

**Jonas Lehmann[1], Volker Ventzke[2], Benjamin Klusemann[1,2], Nikolai Kashaev[2] and Noomane Ben Khalifa[1,2]**

[1]*Leuphana University Lüneburg, Universitätsallee 1, 21335 Lüneburg, Germany*

[2]*Helmholtz-Zentrum Hereon, Max-Planck-Straße 1, 21502 Geesthacht, Germany*

*Correspondence email address: jonas.lehmann@leuphana.de*

*Surface Treatment* *Residual Stress* *Crack Propagation*

**Abstract** Fatigue crack propagation can be effectively retarded by the introduction of compressive residual stresses, which can be generated using various mechanical surface treatment processes. However, the resulting depth-resolved residual stress profiles strongly depend on the specific treatment technique. While Deep Rolling and Machine Hammer Peening typically induce high, non-equibiaxial compressive residual stresses in the near-surface region, Laser Shock Peening generates nearly equibiaxial residual stresses with significantly deeper penetration depths. To investigate the influence of different residual stress modification techniques on fatigue crack propagation, aluminum AA7075-T6 sheet specimens treated by Deep Rolling, Machine Hammer Peening, or Laser Shock Peening were experimentally examined using various process parameter sets. Electron backscatter diffraction (EBSD) analyses confirmed that the selected parameter sets produced comparable representative microstructures. Depth-resolved residual stress profiles were characterized using the incremental hole-drilling method combined with electronic speckle pattern interferometry, as well as high-energy synchrotron X-ray diffraction employing a conical slit cell. Fatigue crack propagation experiments were conducted on C(T)100 specimens in accordance with the ASTM E647 standard. Fractographic analyses were performed to identify indications of crack closure associated with the presence of residual stresses. A comparative evaluation of residual stress characteristics and fatigue crack propagation behavior revealed that both higher maximum compressive residual stresses and deeper penetration depths contribute to increased crack growth retardation. Notably, Laser Shock Peening, despite inducing lower maximum compressive residual stresses, achieves fatigue crack propagation behavior comparable to that of Deep Rolling and Machine Hammer Peening due to its substantially deeper penetration depth. These findings highlight the importance of considering both longitudinal and transverse residual stress components when assessing the effectiveness of residual stress modification techniques on fatigue crack growth behavior.

# Managing Residual Stresses to improve Fatigue Performance in Airframe Structures with the use of Numerical Simulations

**Qiang Fu[1], Jon Mardaras[2], Domenico Furfari[3]**

[1]*Airbus Operations Ltd, Pegasus House, Aerospace Ave, Filton, Bristol BS34 7PA, UK,* *qiang.fu@airbus.com*

[2]*Airbus Operations SAS 316 route de Bayonne, 31060 Toulouse Cedex 9, France,* *jon.mardaras@airbus.com*

[3]*Airbus Operations GmbH, Kreetslag 10, 21129 Hamburg, Germany,* *domenico.furfari@airbus.com*

*Residual Stresses* *Fatigue* *Crack Growth* *Numerical Analysis*

**Abstract** Surface technologies and mechanical processes to manage residual stresses, specifically as a means to salvage fatigue-critical "hot spots" and enhance structural integrity, are currently used in aerospace industry (e.g. shot peening, deep rolling, cold expansion). Fatigue and crack growth remain the primary degradation processes limiting the service life of metallic airframes. By implementing advanced methodologies like Laser Peening (LP), deep compressive residual stresses can be introduced into metallic components, significantly boosting their resistance to these degradation mechanisms.

This paper explores the dual role of residual stress management induced by LP for life extension & salvage of typical fatigue critical locations such as structural joints of aging fleet; and as design feature for Next-Generation aircraft integrating controlled residual stresses to achieve minimum weight and maximized maintenance intervals of inspections with compressive residual stress ahead of fatigue crack tip inducing crack closure to slow down propagation. The numerical simulation work presented in this paper is a key enabler to define LP strategies for both enhanced fatigue life and extending damage tolerance capability, being able to establish the surfaces of the fatigue critical airframes to be treated as well as the laser peening parameters to effectively delay the crack initiation and propagations. Aluminium alloy coupons, representing fatigue and damage tolerance critical locations of aircraft fuselage and wing structures, will be presented with both experimental results and numerical analysis to predict fatigue initiation and crack propagation based on Linear Elastic Fracture Mechanics (LEFM) approach. For structural joints, while cold expansion has been the industry standard for fatigue enhancement in the past decades, laser peening can be a game changer thanks to its ability to generate "engineered" residual stress fields capable to stop crack initiation from fastener holes even in presence of high secondary bending which induces crack initiation away from the hole surrounding. Tests supported with numerical simulations showed that managing the compressive residual stresses by LP at the fastener locations can delay the fatigue failure of the joints; the extension of the residual stresses and the intensity of laser peening can be predicted by advanced numerical simulations and crack propagation from Equivalent Initial Flaw Size (EIFS) up to final failure giving a large scope to optimize the fatigue life of the joints. Middle Tension (MT) coupons were tested to explore the capability of the compressive residual stress by LP ahead of crack tip, being able to induce crack closure and lowering effectively the Stress Intensity Factor (SIF) range directly retarding the crack propagation. Numerical simulations and crack growth calculations were used in this work to establish the locations of the residual stress patches in front of the crack tip, the extensions of the patch and the average compressive stress through the thickness as design features to maximize the crack growth life of the airframe.

# Size Effects and Subsurface Defects in the Fretting Fatigue Response of Additively Manufactured Ti-6Al-4V from Coupon-Scale Specimens to Dovetail Joint Connections

**Grzegorz Glodek[1], Tomáš Karas[1,2], Martin Nesládeka[2], Brecht Van Hooreweder[3], Reza Talemi[2]**

[1]*Department of Materials Engineering, KU Leuven, Leuven, 3001, Belgium*

[2]*Czech Technical University in Prague, Faculty of Mechanical Engineering, Technická 4, Czech Republic*

[3]*Department of Mechanical Engineering, KU Leuven, Leuven, 3001, Belgium*

*Fretting Fatigue* *Additive Manufacturing* *Subsurface Defects*

**Abstract** Fretting fatigue is a tribological damage mechanism that occurs at the interface of contacting surfaces and can severely reduce fatigue life of structural components. This study investigates the fretting fatigue response of additively manufactured (AM) Ti-6Al-4V across multiple length scales, ranging from coupon-scale specimens to dovetail joint connections. Three experimental configurations are employed, namely bridge-type [1], single-clamp, and dovetail joint setups [2], to assess size effects and the role of subsurface defects under fretting loading conditions. Particular attention is given to the interplay between specimen size, contact size, fretting-induced stress concentrations at the contact interface, and the spatial distribution of subsurface defects. Experimental results indicate that the fretting fatigue performance of AM Ti-6Al-4V is comparable to that of wrought material under similar loading conditions. However, size effects and internal defects inherent to the AM process, such as lack-of-fusion, can trigger premature failure outside the contact zone. Defects located near surface stress concentration regions are found to be especially detrimental, leading to a pronounced reduction in the fretting fatigue strength of AM components, as shown in Figure 1.

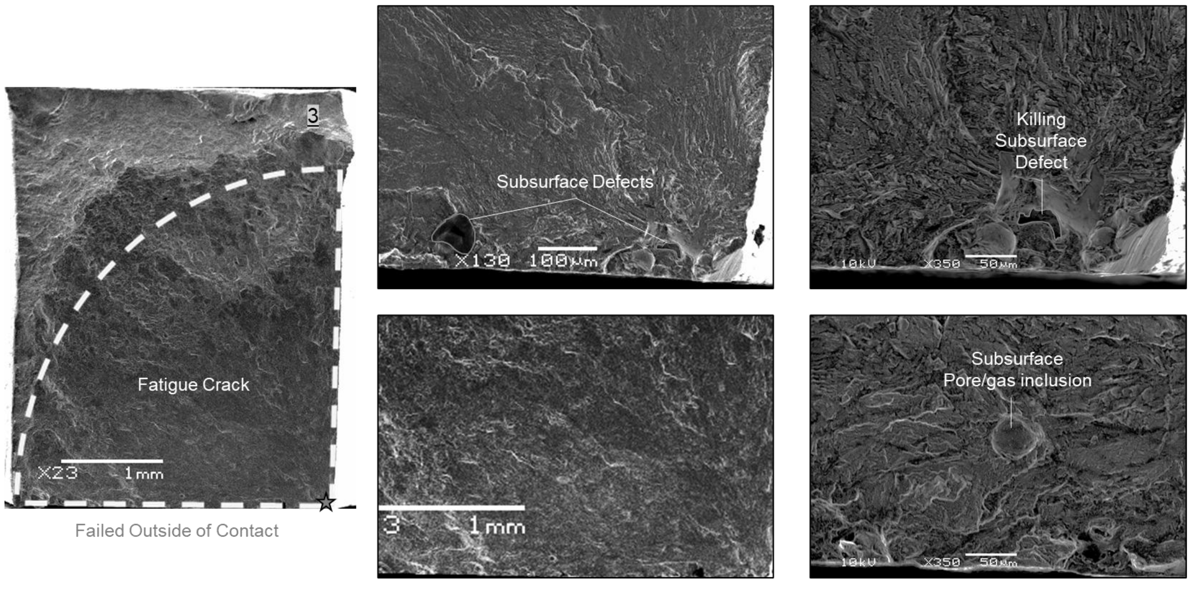


***Figure 1 -*** *Subsurface defects significantly reduce the fretting fatigue strength of AM components.*

## References

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# Multiaxial fatigue of C45 steel under constant amplitude and random loadings

**Łukasz Pejkowski[1], Adam Niesłony[2], Dariusz Skibicki[1]**

*[1]Bydgoszcz University of Science and Technology, Kaliskiego 7, 85-796 Bydgoszcz, Poland, lukasz.pejkowski@pbs.edu.pl*

*[2]Opole University of Technology, Prószkowska 76, 45-758 Opole, Poland*

*Multiaxial loading* *Random loading* *Fatigue life*

**Abstract** The study presents the results of multiaxial fatigue tests performed on cold-rolled C45 non-alloy steel. Cylindrical specimens were tested using an axial-torsional frame under stress control. First, uniaxial, torsional, in-phase, 60° out-of-phase, and 90° out-of-phase loadings were applied to determine the basic response of the material to multiaxial loading (Figure 1). Next, random loading histories were generated with controlling the Pearson's correlation coefficient, $\rho$, between normal and shear stress. $\rho$ was set to 1, 0.5, and 0, which correspond to cos(0°), cos(60°), and cos(90°). Comparison of the results should answer whether the phase shift in cyclic tests has the same effect as the correlation coefficient under random loading conditions.

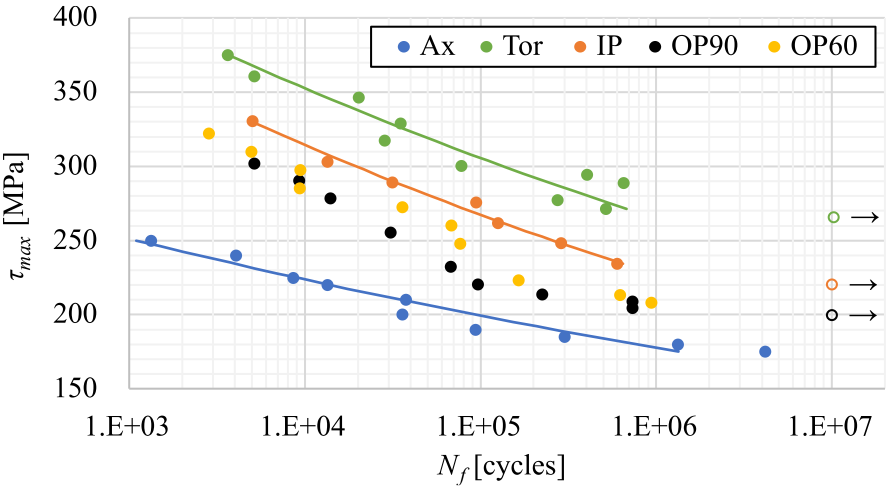


***Figure 1** – Maximum shear stress vs fatigue life of C45 steel for various cases of constant amplitude multiaxial loading*

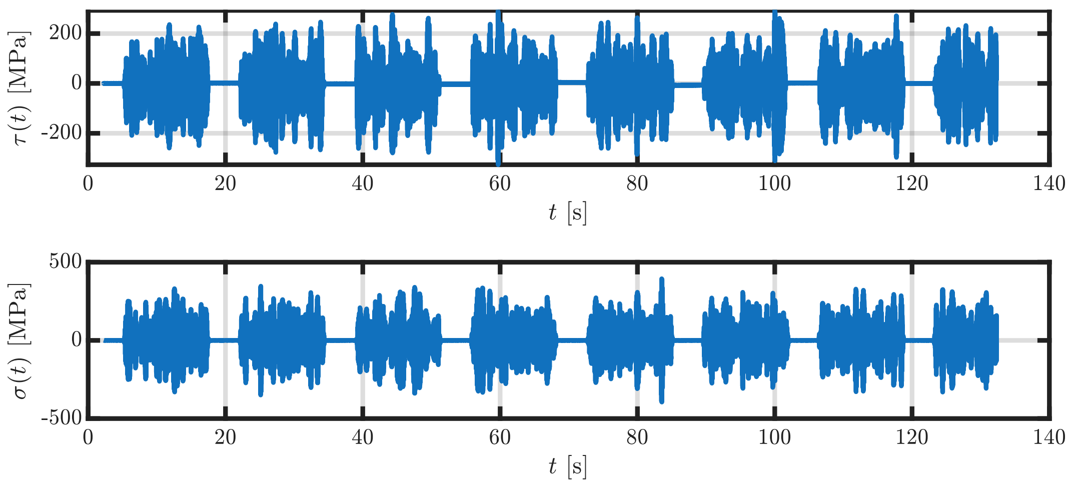


***Figure 2** – Fragment of multiaxial random loading history for $\rho$ = 0.5*

# Micro Scale Investigation of Fatigue in TiAl Alloys

**Pascale Kanoute, Anna Ask, Louise Toualbi**

*ONERA, Châtillon, France*
*pascale.kanoute@onera.fr*

*TiAl* *Crack initiation mechanisms* *Microstructure influence*

The pursuit of weight reduction in aeronautical structures and the operation of aircraft engines at increasingly high temperatures has intensified research on titanium-aluminide (TiAl) intermetallic alloys, leading to their recent implementation in advanced civil jet-engine designs. Owing to the strong dependence of TiAl mechanical behavior on thermal history due to the processing route of the alloy, identical chemical compositions can generate markedly different microstructures, thereby inducing a pronounced scatter in mechanical properties. To incorporate this intrinsic variability, a finite-element framework is presented that explicitly accounts for the microstructural state of TiAl components subjected to mechanical loading.

This contribution belongs to a multi-scale fatigue-life assessment methodology for TiAl intermetallics, with a particular focus on the IRIS TiAl. The primary objective is to elucidate the correlation between TiAl microstructures and their fatigue strength. Fatigue-indicator parameters (FIPs) are employed at the microstructural scale to quantify the driving force for fatigue-crack initiation. Two crack-formation mechanisms are considered: (i) volumetric trans-granular fatigue cracks and (ii) surface-initiated cracks. The FIPs are evaluated in a post-processing stage after a prescribed number of load cycles on a semi-periodic synthetic crystalline aggregate.

Computational efficiency is attained through a “structural-zoom” strategy, wherein selected sub-domains of a global model are refined to resolve the lamellar architecture of individual grains. For trans-granular crack propagation, we employ modified criteria that explicitly link crack orientation to the activated slip systems. Moreover, the evolution of surface roughness under cyclic loading is forecast by crystal-plasticity simulations taking into account the lamellar structure. The purpose is to provide both the magnitude and direction of intrusions and extrusions. The numerical predictions are analyzed through experimental characterizations of intrusion/extrusion phenomena obtained via scanning electron microscopy and quantified by atomic-force microscopy.

Overall, the proposed methodology furnishes a robust, scalable tool for predicting the fatigue life of TiAl components by directly integrating microstructural heterogeneity into finite-element analyses.

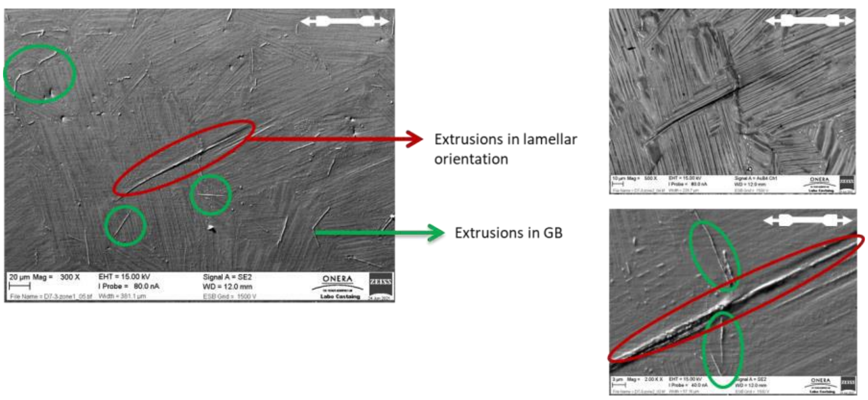


***Figure 1 -*** SEM intrusion and extrusion on a TiAl IRIS specimen subjected to cyclic loading at 750°C

# Improved predictability of near-threshold fatigue crack growth rate data by distinguishing crack closure mechanisms

**Tomáš Vojtek[1], Pavel Pokorný[1], Radek Kubíček[1], Michal Jambor[1], Pavel Hutař[1]**

[1]*Institute of Physics of Materials, Czech Academy of Sciences, Žižkova 513/22, 616 00 Brno, Czech Republic*

*Crack growth threshold* *Residual fatigue life* *Crack closure*

**Problem definition** Improvement of the accuracy of fatigue crack growth rate prediction in the near-threshold regime is crucial for structural integrity of components with high demands for long-term safe operation. Only slight changes in the threshold value may result in changes of the estimated residual fatigue life by orders of magnitude. The threshold is by far not a constant and it is often wrongly measured by standard methods. Various influencing factors of the procedure are related to crack closure mechanisms. Models based on continuum mechanics are not sufficient. Phenomena at microscale and nanoscale, such as discrete dislocation behaviour or oxide debris formation play a role. Respecting the physical mechanisms is required to describe correctly the load ratio effect and the loading history effects. The crack tip shielding effects are responsible for at least one half of the experimental threshold value, while the effects of material strength do not cause variation. A new methodology applicable easily to practical problems was developed. Relevant parameters are extracted from experimental data and used for residual fatigue life estimations.

**Methods and Results** The effect of load ratio on fatigue crack growth rate was investigated for several grades of steel. Data from humid air and from dry air enabled for the first time a complete quantitative decomposition of the applied $\Delta K$ into the effective component and the individual crack closure components. Differences in plasticity-induced crack closure (PICC) were revealed for different materials, which are not predicted by the commonly used models. The reason is that PICC should not be determined from the plastic stretch of material at the maximum load. Instead, it should be determined from both the forward plastic stretch and the plastic rebound during unloading. Material cyclic plastic properties influence this quantity. Fatigue crack growth rates and threshold were divided into two components. The first one is relevant as the material characteristic, which is obtained in dry air and it is freed from many problematic experimental influences. The second component is the difference between the data measured in humid air and in dry air, which is caused by the effect of oxide-induced crack closure. This component depends on various experimental influences, such as geometry of the crack and the specimen, loading frequency, loading history, air humidity etc. It is responsible for the typical large scatter of the data and for the discrepancies observed in data obtained by different laboratories. Moreover, it is responsible for non-conservativeness due to the parasitic influences occurring during testing but not in operation. On the other hand, the data from dry air are always conservative and they are fairly reproducible with a much smaller scatter. Roughness-induced crack closure was determined as the remaining part of the applied $\Delta K$. This is the only reliable way of its quantification, since no physical modelling gives reliable results. The methodology explained some observed phenomena that are inexplicable using other approaches. For example, residual fatigue life was longer when non-damaging cycles from the loading spectrum were applied in addition to the damaging cycles.

**Conclusions** The first methodology for quantitative crack closure separation was introduced. Fatigue crack growth rate data should be measured in dry air, especially the threshold. They have a much smaller scatter and they represent the material properties, freed from many parasitic experimental influences caused by oxide-induced crack closure. Data from standard tests in humid air are non-conservative, they can lead to dangerous predictions for components operated in winter climate or at loading frequencies $< 20$ Hz.

# The Effect of the Strain Rate on the Low Cycle Fatigue Behavior of a 10Cr-2W-Mo-3Co-NbV steel at room temperature

**Nadezhda Dudova[1], Wu Kaiming[2], Rustam Kaibyshev[3], Mishnev Roman[2]**

[1]*Belgorod State National Research University, Belgorod 308015, Russia*

dudova@bsuedu.ru

[2]*Wuhan University of Science and Technology, Wuhan 430081, China*

[3]*Belgorod State National Research University, Belgorod 308015, Russia*

*Low Cycle Fatigue* *Cyclic softening* *Microstructures*

**Abstract** The low cycle fatigue (LCF) behavior of a 10%Cr-2%W-0.7%Mo-3%Co-NbV steel with the high boron and low nitrogen contents was investigated at room temperature under the strain rates ranging from $\sim 10^{-3}$ to $\sim 10^{-5}$ $s^{-1}$ and strain amplitudes varied from ±0.25% to ±0.6%. The fatigue life slightly increased with decreasing the strain rate, in contrast to high-temperature LCF behavior, where the strain rate reduction significantly reduced lifetime. The Basquin-Manson-Coffin relationship effectively described fatigue life across all tested strain rates.

Cyclic softening and hardening behaviors were strain-rate-dependent only at low amplitudes. At the low strain amplitude (±0.25%), a decrease in the strain rate significantly prolongs the initial stage of weak softening from 200 to 2000 cycles. As a result, the stage of continuous cyclic softening started later, which was characterized by a higher softening coefficient $\Delta\sigma/\Delta \lg N = -24$ at $\sim 10^{-4}$ $s^{-1}$ compared to $-18$ at $\sim 10^{-3}$ $s^{-1}$. Fractography showed enhanced secondary cracking and multi-level crack propagation at lower strain rates, particularly along carbide-decorated boundaries.

Microstructural analysis of fatigue-failured steel revealed that at a low strain amplitude with predominant elastic strain (±0.25%) and a strain rate of $\sim 10^{-3}$ $s^{-1}$, the tempered martensite lath structure remained stable despite a decrease in dislocation density. At a lower strain rate of $\sim 10^{-4}$ $s^{-1}$, the cell dislocation structure was observed in the lath interiors. Formation of the low-energy dislocation configuration led to an increase in the back stress and transition to non-Masing behavior. At a high strain amplitude (±0.6%), the lath structure transformed into the subgrain structure. The dislocation density decreased by up to 60% independently of the strain rate. Strain rate had insignificant effect on this transformation due to the predominance of plastic deformation in the microstructural changes.

# Parasitic effects in cyclic testing of samples for fatigue damage accumulation

**Koščo, V.[1], Margetin, M.[1], Chmelko, V.[1]**

[1] *Slovak University of Technology, Faculty of Mechanical Engineering, Institute of applied mechanics and mechatronics, Námestie slobody 17, 812 31 Bratislava, Slovak republic, vladimir.chmelko@stuba.sk*

*fatigue testing* *uncertainty in cyclic tests* *S-N curves*

**Abstract** The concept of computational assessment of the fatigue life of a structure is based on the relationship between the cyclic properties of the material and the variable stress components in the operation of the structure. The most difficult task is to determine the stress fields at the most stressed point of the structure, which involve the greatest degree of uncertainty. Although cyclic tests are performed on test specimens of precise shape, the results of cyclic tests are often burdened by additional influences, such as

- additional bending due to inaccurate clamping of the test specimen in the jaws

- edge effect in specimens with a rectangular cross-section

the influence of test specimen manufacturing technology on the resulting fatigue life

This paper will analyze these uncertainties and inaccuracies in determining the cyclic properties of materials as additional factors entering into fatigue damage hypotheses.

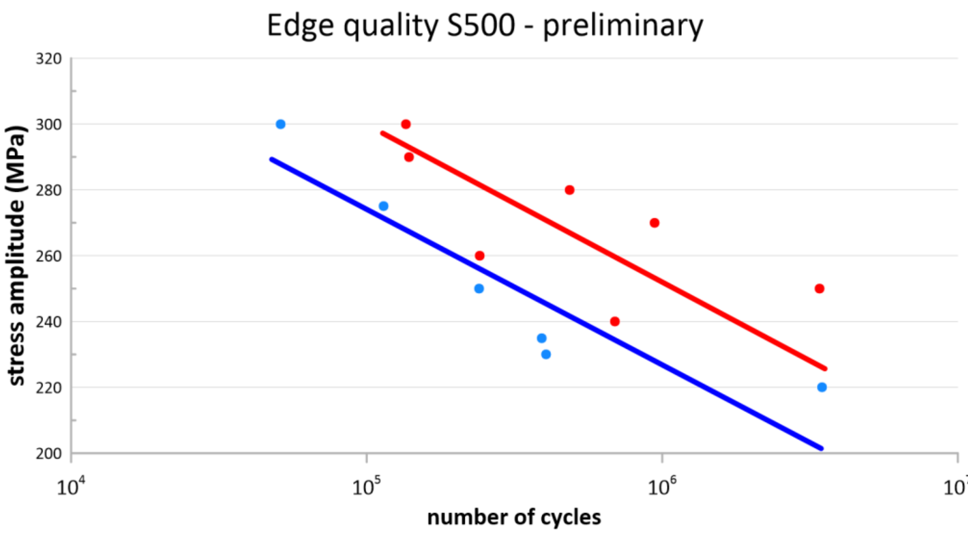


***Figure 1*** -N curves curves for two different technologies for producing test samples.

# Numerical fatigue strength investigation of wire and arc additive manufactured (WAAM) specimens based on 3D-scans and implicit gradient model

**Sulaiman Shojai[1], Hessam Moshayedi[2], Moritz Braun[1], Elyas Ghafoori[2]**

[1]*Sulaiman Shojai, Düneberger Straße 108 | 21502 Geesthacht – Germany, sulaiman.shojai@dlr.de.*

[2]*Institute for Steel Construction, Leibniz University Hannover, Germany*

*Additive Manufacturing* *3D-scans* *Implicit gradient model*

**Abstract** Components produced Wire and Arc Additive Manufacturing (WAAM) components can have high surface waviness and roughness, which leads to stress concentrations and reduction of the fatigue strength, also known as the notch effect.

The notch effect resulting from the waviness can be considered within the notch stress approach. A main issue in the notch stress approach is the consideration of micro-support effect, which is usually considered with a fictitious radius of $r_f$ = 1 mm. This procedure is limited to welded components because the potential crack locations are limited to the weld toe and weld root and thus only few locations have to be rounded. Alternative approaches for micro-support consideration such as the point- or line-method of the theory of critical distance (TCD) have similar limitations. Because of the great number of notches on WAAM specimens, the stress evaluation requires an enormous effort in post processing, as it has to be performed separately for all potential notches. This issue has to be faced, when the 1mm radius method or the TCD methods should be applied on WAAM components. One way to overcome this is by application of the implicit gradient model (IGM) approach, which allows the micro-support effect to be taken into account within the numerical analysis of the stress field. This enables the consideration of all notches of a WAAM component in a single numerical analysis, without rounding or post processing effort.

In this study, the IGM was applied to WAAM specimens that were tested on fatigue by Huang et al. (Huang et al. 2023). For this purpose, the specimens were scanned using 3D scanners before the fatigue tests and transferred to a numerical model using the reverse engineering process (Shojai et al. 2022). The comparison of the numerical stress hotspots with the crack initiation locations from the fatigue test showed good agreement for many specimens, showing the capability of the IGM-approach for fatigue analysis.

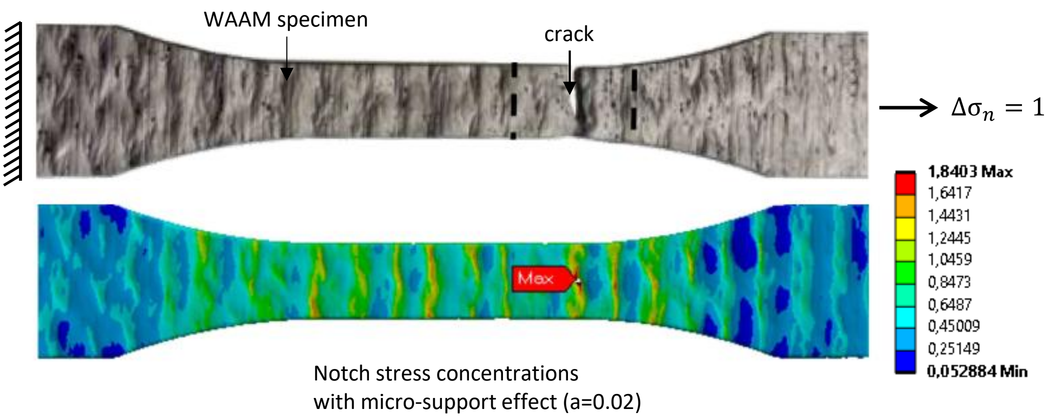


Figure 1: WAAM specimen with boundary conditions (upper plot) and notch stress concentrations after numerical analysis with consideration of the micro-support effect with IGM (lower plot).

# Coupling Size and Stress Gradient Effects in Notch Fatigue Assessment

**Jan Papuga[1], Petr Vaněk[1], Martin Nesládek[1], František Fojtík[2], Marius Müller[3], Alexander Hasse[3]**

[1]*FME, Czech Technical University in Prague, Technická 4, 166 07 Prague 6, Czechia; jan.papuga@cvut.cz*

[2]*FME, VSB-Technical University of Ostrava, 17.listopadu 2172/15, 708 33 Ostrava, Czechia*

[3]*TU Chemnitz, IKAT, Reichenhainer Str. 70, 09126 Chemnitz, Germany*

*Notch effect* *Size effect* *Stress gradient effect*

**Abstract:** Accounting for the notch effect is an essential component of fatigue life estimation. Modern computational approaches have largely abandoned the classical use of the stress concentration factor (SCF), replacing it with concepts such as the critical distance, critical volume, or the relative stress gradient. Historically, SCF-based approaches were refined over several generations of fatigue analysis through the introduction of correction factors to better match experimental fatigue strength. A comparable refinement is required for these modern notch-effect concepts. This need is reflected in the relatively recent update of the FKM Guideline (6th edition), which explicitly incorporates both the stress gradient effect and the critical surface area effect. The present study builds on the critical volume concept as a starting point. When applied to seven types of notched specimens from ČSN 41 1523 common structural steel (equivalent to S355J2) tested under push–pull, plane bending, and torsion modes of loading, the results indicate that the critical volume alone is insufficient to fully describe the fatigue response for the selected test set.

Therefore, this paper presents an extended approach in which the relationship between critical volume and fatigue strength is augmented by an additional variable: the relative stress gradient. The results, summarized in Fig. 1, demonstrate that all three parameters can be related by a single curve when using the Dang Van multiaxial fatigue criterion. In contrast, the Manson–McKnight criterion exhibits pronounced deviations under torsional loading for large critical volumes, which in this test set correspond to small relative stress gradients.

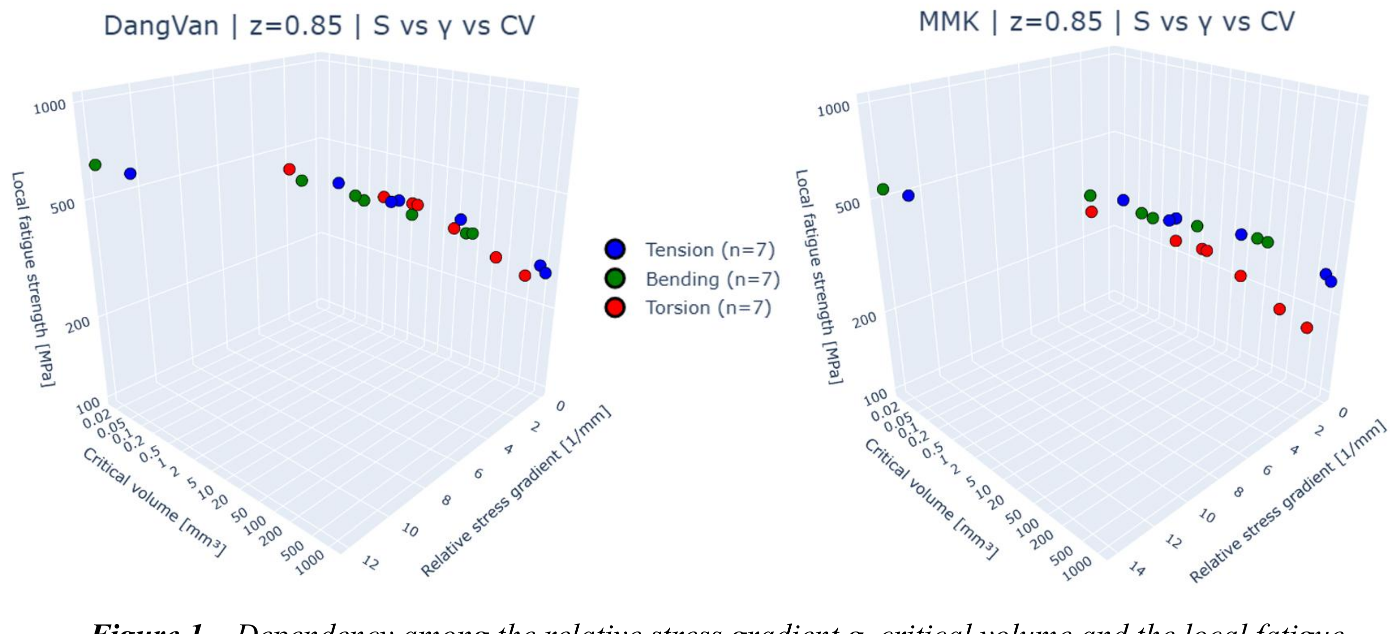


***Figure 1*** *– Dependency among the relative stress gradient g, critical volume and the local fatigue strength at 500,000 cycles for two calculation methods – Dang Van criterion on left, and Manson-McKnight criterion on right.*

# Benchmarking Fatigue Life Estimation: The FABER and FABEST Initiative

**Jan Papuga**[1]

[1]*FME, Czech Technical University in Prague, Technická 4, 166 07 Prague 6, Czechia; jan.papuga@cvut.cz*

*FABER* *Fatigue estimation* *FABEST*

**Abstract:** The FABER project was established with the aim of providing the fatigue community with clear insight into fatigue life estimation by enabling analysts to validate and verify fatigue models, routines, and solvers with a reasonable and well-defined effort. Despite rapid advances in computational methods and artificial intelligence, the quality of fatigue life predictions is still limited by the lack of sufficiently broad and publicly available experimental datasets. FABER therefore set its main objective as the construction of benchmark sets—curated datasets of experimental fatigue data—dedicated to the systematic investigation of individual high-cycle fatigue effects, such as notch effects, multiaxiality, size effects, and mean stress effects.

FABER has received funding for networking activities from the COST Association for the period 2024–2028. The action is permanently open to new participants, and at the time of writing comprises more than 260 members. To achieve its goals and ensure broad adoption within the community, FABER defined three additional objectives: (1) building a comprehensive database of experimental fatigue data as the basis for derived fatigue benchmarks, (2) developing FatPy, an open-source fatigue library in Python enabling independent validation of new research concepts and models, and (3) establishing the FABEST fatigue competition, organized in two volumes, aimed at identifying the best fatigue life estimates for well-defined tasks and highlighting the discrepancy between commonly achieved prediction quality and experimental reality.

The call for submitting estimates to the first volume of the FABEST competition is released at the 14th International Fatigue Congress in Madeira. The competition is open worldwide. To provide participants with the broadest possible input data, more than 50 S–N curves for a single batch of 42CrMo4 +QT steel have been generated, complemented by a limited number of strain-life curves. All datasets are made available to competition participants. Researchers are invited to join the competition and assess how their estimates compare with multiaxial fatigue experiments performed after the submission deadline. Beyond providing essential feedback to individual participants, all submitted results will contribute to a statistical evaluation that benefits the fatigue community as a whole.

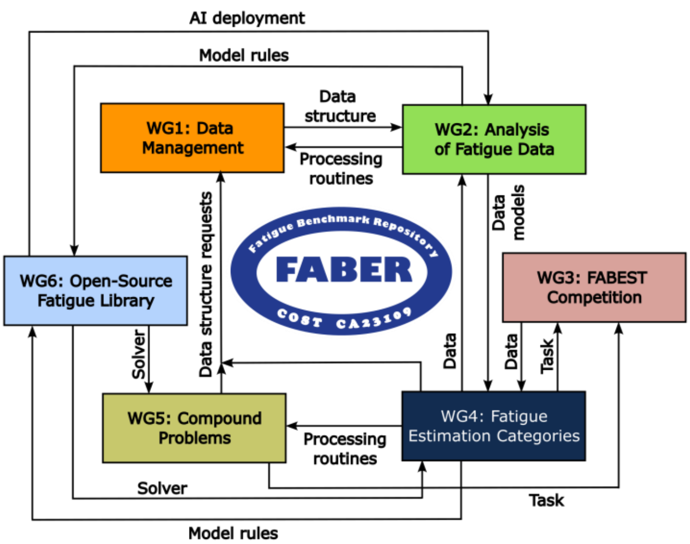


***Figure 1*** *– The scheme of the Working Groups and process flows in the FABER consortium.*

# Cold Spray Solid-State Deposition of AA7075 on Magnesium: Residual Stress and Fatigue Performance

**Hamid Jahed, Bahareh Marzbanrad, Sugrib Shaha, Siavash Borhan-Dayani, Jie Wang**

*Fatigue & Stress Analysis Laboratory, University of Waterloo, 200 University Ave W, Waterloo, Ontario N2L3G1, CANADA; hamid.jahed@uwaterloo.ca*

***Keywords:*** *Cold Spray Deposition* *Residual Stress* *Fatigue Performance*

**Abstract** Lightweight alloys with low melting temperatures, most notably aluminum and magnesium, form the backbone of modern transportation systems, where aggressive weight reduction is essential to meet ever-tightening efficiency, performance, and sustainability targets. Although fusion-based additive manufacturing (AM) has achieved notable success in processing some aluminum alloys, extending these technologies to a broader range of alloy compositions remains constrained by narrow thermal processing windows, susceptibility to solidification cracking, and inherent melt-pool instabilities that compromise build quality and reliability. In this context, solid-state AM emerges as a compelling alternative, offering layer-by-layer deposition below the melting point, high deposition rates reaching kilograms per hour, and scalability to large structural components. However, despite these advantages, limited understanding exists regarding the mechanical performance, particularly fatigue behavior, of dissimilar solid-state deposits such as AA7075 on magnesium alloys, motivating a systematic investigation into the fatigue performance and underlying structure-property relationships of such solid-state deposited systems.

Bridging the promise of lightweight alloy integration with the need for reliable manufacturing, cold spray (CS) has emerged as a viable solid-state metal deposition solution. This technology employs kinetic energy to deposit 15 µm -50 µm powder particles accelerated to supersonic velocities by high-pressure air, nitrogen, or helium at temperatures below their melting point, enabling strong mechanical and metallurgical bonding without the thermal penalties associated with fusion processes. Such attributes make CS uniquely suited for fabricating dissimilar lightweight alloy systems, such as aluminum on magnesium, while preserving microstructural integrity and unlocking new pathways for enhanced fatigue performance.

We utilized CS to deposit AA7075 aluminum powder onto AZ31B magnesium substrates. To investigate the impact of thermal energy (carrier gas heat, and impact-iduced heat), we manipulated heat balance by varying nozzle speeds and employing either water-cooled sunstrates or insulated fixtures to selectively induce compressive or tensile residual stress states. Comprehensive characterization was performed using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) for microstructural analysis and studying interface characteristics, while hole-drilling methods were used to quantify residual stress distributions. Durability was assessed via load-controlled fatigue testing in both round and flat samples in three- and four-point bending configurations, supported by digital image correlation (DIC) and computed tomography (CT) for in-situ crack initiation monitoring.

The interface is characterized by a nano-size interlayer consisting of a solid-state mixture of Al and Mg with fine crystalline grains, followed by columnar magnesium grains growing perpendicular to the boundary. Fatigue cracking mechanisms are highly dependent on the size of this interlayer, size of recrystallized grains, and induced residual stress state; tensile residual stresses at the interface promote interfacial delamination and intra-splat (transgranular) cracking, whereas compressive stresses shift crack initiation to the deposition surface via an inter-splat propagation path. Additionally, the deposition enhances durability by the presence of high-strength AA7075 at the surface. These factors lead to fatigue life enhancements, including a 40% improvement in fatigue strength at $10^5$ cycles for specimens with compressive interface stress and an overall 25% increase in fatigue strength at $10^7$ cycles for cast alloys.

# Thermomechanical and isothermal fatigue of 316L stainless steel with long hold periods in LWR environment

**Tomáš Babinský[1], Philippe Spätig[1], Hans-Peter Seifert[1]**

*[1]PSI Center for Nuclear Engineering and Sciences, Paul Scherrer Institute, Forschungsstrasse 111, 5232 Villigen PSI, Switzerland*

*Thermal Fatigue* *Nuclear engineering* *Light water reactor environment*

**Abstract** Environmentally assisted fatigue of austenitic stainless steels is a key degradation mechanism for structural components operating in light water reactor environments (LWR). In the present work, the influence of strain rate, long hold periods and thermomechanical loading on the fatigue life of annealed 316L stainless steel was investigated under representative PWR and BWR/HWC water conditions. Low-cycle fatigue tests were performed under total mechanical strain control at elevated temperature, covering both isothermal fatigue at 300 °C and in-phase thermomechanical fatigue (TMF) between 150 and 300 °C. Fast and slow strain rates were applied, and selected tests included long static hold periods (up to 48 h) at stresses exceeding the yield strength (up to 150 MPa), in order to assess possible fatigue–stress corrosion cracking interaction effects. The results show no detrimental effect of long hold periods on fatigue life in the investigated low-cycle fatigue regime. Fatigue lives are generally well described by the $F_{en}$-corrected NUREG/CR-6909 fatigue curve. While a reduction of fatigue life with decreasing strain rate is expected based on existing models, the experimental results exhibit noticeable scatter, including cases of longer fatigue life at lower strain rates. Post-test fractography reveals fatigue-dominated damage with striation-controlled crack growth and no clear evidence of stress corrosion cracking. Overall, the results indicate that, under the investigated conditions, long hold periods do not significantly promote environmentally assisted fatigue damage beyond what is captured by existing fatigue assessment approaches.

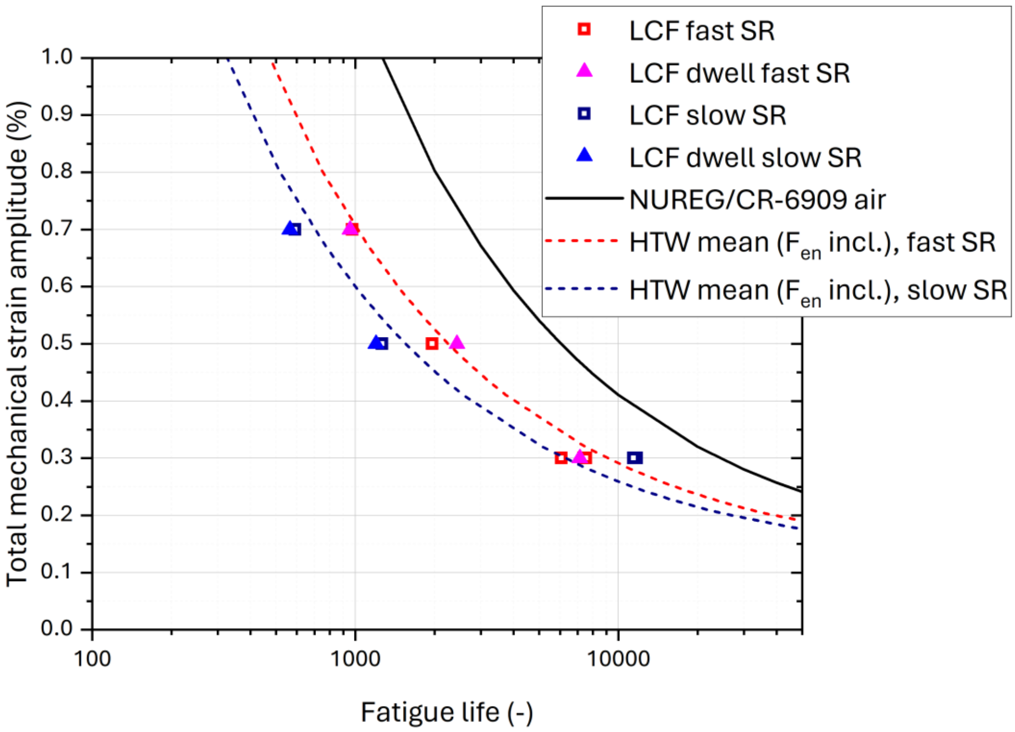


***Figure 1*** *– Comparison of experimental data with NUREG/CR-6906 curve corrected with environmental factor $F_{en}$.*

# What is Kitagawa-Takahashi diagram? Remaining anomalies and biases

**Joona Vaara[1], Miikka Väntänen[2], Kimmo Kärkkäinen[3], Jukka Kemppainen[4], Tero Frondelius[1,3]**

[1]*Wärtsilä, Teollisuuskatu 1, 65170 Vaasa, Finland*

[2]*Global Boiler Works Oy, Lumijoentie 8, 90400 Oulu, Finland*

[3]*Materials and Mechanical Engineering, University of Oulu, Pentti Kaiteran katu 1, 90014, Finland*

[4]*Applied and Computational Mathematics, University of Oulu, Pentti Kaiteran katu 1, 90014, Finland*

*Mechanisms* *Anomalies* *Biases*

**Abstract** Several models have been proposed to describe the Kitagawa-Takahashi (KT) diagram based on various hypotheses. Why do certain models work so well, and what are the limitations? A widespread consensus has not been reached either on the governing mechanisms or the most important parameters. In this talk, we will discuss the nature of different parts of KT diagram and propose a set of rules to distinguish certain underlying mechanisms. The most pressing remaining anomalies and open questions are highlighted and discussed. As a case study, an explanation to ultra-high strength steel fatigue behavior is proposed. Additionally, the statistical effect of competition with natural defects will be discussed together with the resulting biases.

The major takeaway from this analysis suggest that the microstructurally short cracks and associated crack initiation have a bigger role than anticipated before – especially for the harder materials. A larger meta-analysis of this subject would require researchers to report not only the lengths of non-propagating cracks but also the frequency of observing them.

# Multiaxial fatigue of polymeric pressure sheaths for oil and gas applications: a case study on polyvinylidene fluoride (PVDF) using the Fatemi–Socie criterion

**Tiago Lima Castro[1], Camila Alves Farias[1], Celio Albano da Costa[1]**

[1]*Department of Metallurgical and Materials Engineering, Federal University of Rio de Janeiro—UFRJ, Avenida Horácio Macedo, 2030, Rio de Janeiro 21941-598, RJ, Brazil; tiago.castro@metalmat.ufrj.br*

*Thermoplastic materials and time-dependent behaviour* | *Strain-based fatigue assessment* | *Combined axial-torsional loadings*

**Abstract** Among the components that constitute subsea oil and gas infrastructures, flexible pipes are an essential part of modern offshore rigs. Typically composed of helically wound armour strips with concentric layers of polymers, these structures are widely used to transport oil, gas, or multiphase mixtures from subsea wells to floating production facilities due to their ability to withstand dynamic loading. In this context, polyvinylidene fluoride (PVDF) is a thermoplastic polymer commonly employed as a pressure sheath in flexible pipes, which in service is subjected to significant deformations imposed by internal pressure cycling and environmental loads. The resulting multiaxial, time-varying states of strain and stress may therefore induce fatigue-related damage mechanisms, whose characterisation is considerably less established for polymers than for metallic materials. As such, the present work aims to characterise the multiaxial fatigue behaviour of PVDF using the Fatemi and Socie (F&S) criterion. Since polymers are susceptible to viscoelastic phenomena such as stress relaxation and stress-strain phase shift, the study includes a discussion of the experimental aspects and highlights the assumptions and adaptations required to apply the model to thermoplastic materials. From pure torsion tests, an experimental curve associated with the right-hand side of the F&S model was obtained, establishing the functional relation between the F&S parameter and fatigue life for PVDF. In addition, a systematic procedure to determine the material constant appearing in the F&S parameter was developed, and the predictive capability of the model was subsequently assessed under combined axial-torsional loading, revealing fair agreement between predicted fatigue lives and experimental results.

# Microstructure-Driven Variability in Probabilistic Fatigue Crack Growth Analysis of Welded Structural Steel Joints

**Kamal Harb[1, 2, 3, 4], Julien Baroth[2], Rafael Estevez[3], Arnaud Isaac[4], Vincent Michaud[4]**

[1] *Grenoble INP Foundation, Grenoble, F-38000, France*

[2] *Grenoble Alpes University, Grenoble INP, CNRS, 3SR Laboratory, Grenoble, F-38000, France*

[3] *Grenoble Alpes University, Grenoble INP, CNRS, SIMaP Laboratory, Grenoble, F-38000, France*

[4] *SPRETEC, Artelia Group, Échirolles, 38130, France*

kamal.harb@univ-grenoble-alpes.fr

*probabilistic fatigue-fracture analysis; welded steel structures; spatial stochastic variability*

**Abstract** The heterogeneous microstructure of metallic materials induces local variability in mechanical properties and, consequently, a non-uniform resistance to fatigue crack propagation. This variability is commonly evidenced by the scatter observed in S–N (Wöhler) curves and the associated cycles to failure, and it is similarly observed in fatigue crack growth behavior. Within the Paris law framework, the parameters $C$ and $m$ are typically obtained by fitting a linear relationship between crack-growth rate and stress-intensity-factor range through regression based on a series of experimental measurements. However, the noticeable dispersion in fatigue crack growth measurements suggests that $C$ and $m$ should be regarded as variable quantities rather than fixed constants. This observation naturally motivates the use of probabilistic fatigue-fracture approaches and, ultimately, raises reliability considerations for structural assessment.

In this paper, we propose a probabilistic framework to quantify the influence of variability in the Paris law parameters $C$ and $m$ on fatigue crack growth. The approach is demonstrated on a welded structural steel joint containing a pre-existing crack, corresponding to a manufacturing defect induced by the welding process.

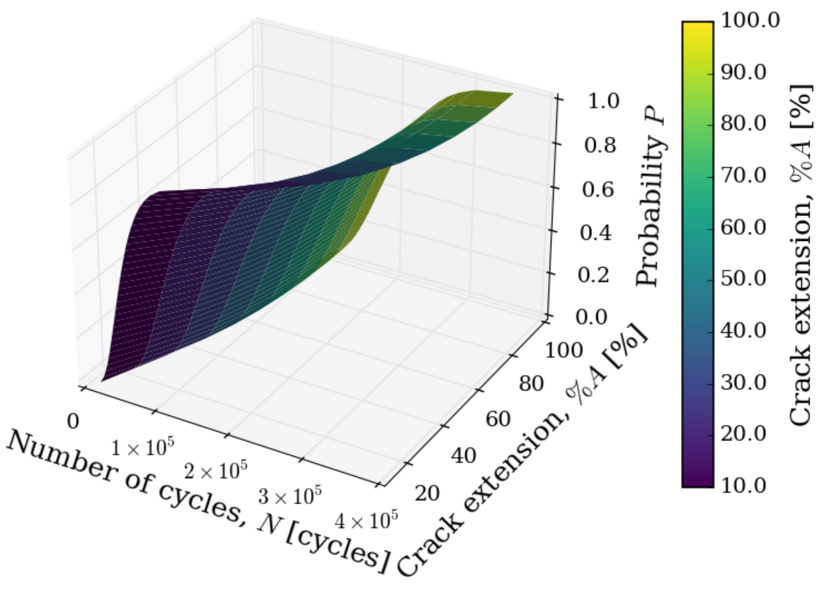


***Figure 1*** *– Probabilistic life response surface –* $\mathcal{Z} \in \{N,\ P_f\}$

# Effect of hydrogen concentration and pressurized hydrogen environment on the fatigue behavior of Inconel718 L-PBF at room and intermediate temperatures

**D. TADE[1,2], V. Bonnand[1], A. Marano[1], X. Feaugas[2], A. Oudriss[2], J. Bouhattate[2]**

[1]*DMAS, ONERA The French Aerospace Lab, Université Paris-Saclay, 92320, Châtillon, France*
[2]*La Rochelle Université, LaSIE, Allée de l'Océan, 17000 La Rochelle, France*
[3] *CETIM, 44300 Nantes, France*
[4]*DGAC, Direction Générale de l'Aviation civile, France*

*Hydrogen embrittlement* *Low Cycle Fatigue* *Additive manufacturing* *Crack initiation* *Crack propagation*

**Abstract:** In aerospace industry, engine manufacturers have turned to hydrogen as a new energy source for aircraft propulsion, resulting in the exposure of critical parts, such as turbojets injectors, to complex thermomechanical loading in the presence of high-pressure hydrogen gas. It is well known that long-term exposure to hydrogen can lead to a deterioration in the mechanical properties of metals and lead to their premature failure, a phenomenon known as hydrogen embrittlement. In this work, two approaches were considered to study the impact of gaseous hydrogen on the fatigue behavior and the reduction in service life of additive manufactured recrystallized and precipitation-hardened Inconel 718, a key alloy considered for designing complex turbojets parts. The first approach focuses on the effect of internal hydrogen concentration (through gaseous pre-charging of test specimens) while the second examines the effect of direct exposure to a gaseous hydrogen environment during mechanical testing (in-situ specimens). First results from fatigue testing at room temperature show a drastic reduction in fatigue life in the presence of hydrogen, with a much more severe effect for tests conducted under pressurized hydrogen environment (FIGURE 1). At room temperature, in the reference state, analyses of the fracture surfaces reveal that the microstructure promotes mixed crack propagation regime, combining long crack growth governed by Paris' law with marked cleavage of large grains. For the pre-charged specimens containing 57 ppm wt. of hydrogen, this long crack propagation regime is bypassed, giving way to an accelerated crack growth regime for high stress levels. Although the significant impact of the hydrogenated environment is already evident, its respective contribution to the crack initiation and propagation regime was quantified. Additional fatigue tests to intermediate temperatures (150°C, 300°C) have been conducted to accelerate in-situ diffusion and detrapping of hydrogen during mechanical loading and to evaluate their effect on the mechanical response and plastic deformation mechanisms. By integrating the metallurgical heterogeneity specific to the studied alloy, this experimental approach as a whole constitutes a critical step in ensuring the reliability of the injector under extreme operating conditions.

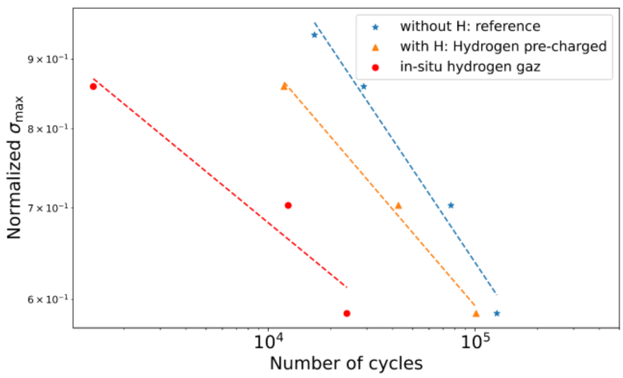


*Figure 1- S-N curve of Inconel 718 L-PBF at room temperature for reference, pre-charged hydrogen and in-situ tested samples*

# An Experimental Evaluation of Fatigue Life Models for Small Defects

**Roberto Azevedo da Costa[1], Fábio Comes de Castro[2]**

*Department of Mechanical Engineering, University of Brasilia, 70910-900, Brasilia, DF, Brazil,*
*[1] robertoac.enm@gmail.com, [2] fabiocastro@unb.br*

*Defect* *Fatigue life prediction* $\sqrt{area}$ *parameter*

**Abstract** Small defects inherent to the material or generated by external action act as microscopic stress concentrators and represent critical sites for the fatigue failure of engineering components. Significant progress has been made over the last decades in modeling the high-cycle fatigue life and the fatigue limit of defect-containing metals. The modeling approaches range from sophisticated microscale models that explicitly incorporate local microstructural attributes to engineering methods such as the $\sqrt{area}$ parameter model and the Theory of Critical Distances. In this contribution, these engineering models for fatigue life prediction of defect-containing metals are evaluated against experimental results obtained with cylindrical specimens of 1045 steel containing artificial surface defects. The experimental program covered the mean stress effect under multiaxial axial-torsional loadings and the influence of defect shape (cylindrical or oblong holes) under uniaxial conditions. The fatigue lives ranged from $10^5$ to $10^7$ cycles. The small cracks emanating from the defects were examined using a confocal laser microscope as illustrated in Fig. 1. These experimental observations served not only to identify the fatigue failure mode but also to determine critical plane angles to assess the models. Based on the experimental fatigue lives and the observed cracking angles, this study evaluates the predictive capability of the fatigue life models.

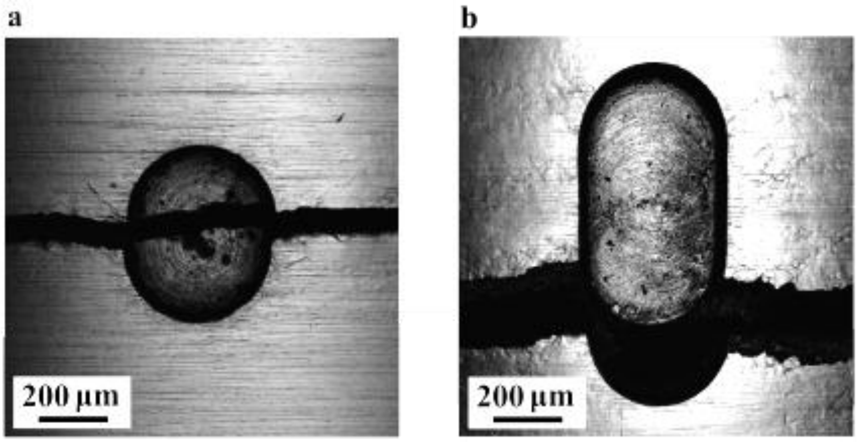


***Figure 1 -*** *Blind microholes with the same defect size ($\sqrt{area}$ = 400 µm) subjected to fully reversed tension-compression loading at a stress amplitude of $\sigma_a$ = 200 MPa: (a) cylindrical microhole, failed at $N_f$ = 4.5 × $10^5$ cycles; (b) oblong microhole, failed at $N_f$ = 1.8 × $10^6$ cycles.*

# Fatigue strength assessment of full-scale arc-welded steel booms for agricultural trailed sprayers using the Peak Stress Method

**Filippo Coppola[1], Davide Della Volpe[1], Andrea Ruffin[2] and Giovanni Meneghetti[1]**

[1]*Department of Industrial Engineering, University of Padova, Via Venezia 1, 35131, Padova, Italy*

[2]*Research and Development, Maschio Gaspardo S.p.A., Via Marcello 73, 35011, Padova, Italy*

*Fatigue of Weldments* *Full-scale fatigue tests* *Local Approaches*

**Abstract**

The present work deals with the fatigue strength assessment of full-scale arc-welded steel booms designed for agricultural trailed sprayers in crop protection applications. Besides the fatigue design approaches prescribed by Design Codes, complementary methods can be adopted. Here, a local approach based on Notch Stress Intensity Factors was investigated. The Peak Stress Method (PSM) enables a rapid estimation of the Notch Stress Intensity Factors (NSIFs) through finite element (FE) analyses with relatively coarse finite element mesh patterns. To be used as a fatigue design method, the PSM adopts the strain energy density averaged over a control volume surrounding the crack initiation point (the SED parameter), which can be analytically expressed as a function of the NSIFs and used as a fatigue damage parameter. To this end, load-controlled, constant amplitude tension–tension fatigue tests (load ratio, R = 0.05) were carried out on six full-scale components using a specifically designed servo-hydraulic fatigue test bench. To investigate technical crack initiation, strain-based monitoring using instrumented components and regular dye-penetrant inspections were adopted. A 3D FE model of the full-scale structure was created according to the PSM, by adopting ten-node tetrahedral finite elements with a minimum element size equal to one-third of the main plate thickness. Firstly, the FE model was validated through monotonic loading–unloading ramps carried out prior to fatigue testing on a boom instrumented with six strain gauges measuring nominal or structural stresses close to the crack initiation point. Then, the FE model was used to estimate the fatigue lifetime according to the Peak Stress Method. Finally, the theoretical estimations of the PSM were found to be in good agreement with the experimental fatigue test results.

# Estimating fatigue crack location, size, and shape in axially loaded cylindrical specimens using a multi-probe Direct Current Potential Drop method

**Vecchiato Luca[1], Campagnolo Alberto[1], Rollo Matteo[1] and Meneghetti Giovanni[1]**

[1]*Department of Industrial Engineering - DII, University of Padua, Italy. luca.vecchiato@unipd.it*

*non-destructive testing* *Direct Current Potential Drop* *Structural Health Monitoring*

**Abstract**

Crack initiation and subsequent propagation are crucial phenomena to investigate in both fatigue crack growth testing and structural health monitoring of real components. In this context, the size of a propagating crack must be estimated in real time using non-destructive experimental methods. Among these, the Direct Current Potential Drop (DCPD) technique exploits the densification of potential field lines in the cracked component resulting from an increase in the crack size. Typically, DCPD is applied in a single-probe configuration, where a single potential drop value is measured on the specimen. Owing to its operating principle, the single-probe configuration is an integral method, because it estimates the cracked area, but not the actual crack size, shape, and location. Therefore, single-probe DCPD is well suited to standard fracture-mechanics fatigue tests (e.g., CT, CCT, SENT, or SENB specimens), where the crack location, path, and shape are known a priori. However, single-probe DCPD cannot be effectively applied to specimens or real components with complex geometries, where the crack location, path, and shape are not known a priori.

To address the limitations of the single-probe DCPD, the present work proposes a multi-probe DCPD setup. In particular, cylindrical additively manufactured AlSi10Mg specimens containing simulated defects as crack starters were investigated under pure axial fatigue loading. Semi-elliptical internal and/or surface (edge) cracks were considered, with the aim of identifying the crack geometry (i.e., angular location, shape, and size) by means of a multi-probe potential-drop method employing up to seven potential-drop probes. A novel diagnostic algorithm for estimating crack location, size, and shape is introduced and discussed. The method leverages a database built from finite element analyses and experimental measurements to estimate crack geometry. The accuracy of the proposed approach was then validated against the experimental data.

# Mean Stress Effects in Multiaxial HCF Methods: Stress Measures and Calibration

**Luis Pallarés-Santasmartas**[1]

[1] *Ministry of Education, Vocational Training and Universities, Government of Cantabria (Spain). Calle Río de la Pila, 13 39003 – Santander. E-mail: luispallares.bilbao@gmail.com*

*Multiaxial methods* *Mean stress effect* *Verification and Validation*

**Abstract** Multiaxial high-cycle fatigue (HCF) criteria are widely applied; however, their agreement under mean stress remains highly dependent on both the material family and the load subset. From a verification and validation (V&V) perspective, this study investigates the effect of stress measures embedded in critical-plane and invariant-based formulations governing the mean-stress effect across different material families.

The database builds on Papuga's (2010) classical review, which comprised 407 tests. A literature review was conducted to identify additional tests of mean-stress effects. Records were screened for traceability and sufficient metadata; low-cycle fatigue results and notched-specimen tests were excluded. As a result, an additional 100 tests were added to the database, and mean-stress cases increased from 236 to 334. The analysed subsets include axial tensile and compressive mean stresses, mean torsional stress, and high mean-stress loading, defined by $R_{von\ Mises}$>0.05. The curated dataset spans 51 materials organised into 8 material families.

A representative set of critical-plane and invariant-based criteria is benchmarked, covering the stress measures governing mean-stress effects: $N_m$, $N_{max}$, $\sigma_{H,m}$, $\sigma_{H,max}$, $\sigma_{1,max}$, $C_m$, $\sqrt{J_{2,m}}$. Prediction indices of errors are stratified by load case and material family and summarised as median and interquartile range (IQR) in box charts with Tukey whiskers, together with conservative/non-conservative fractions. Calibration requirements are summarised for each criterion, including the number of fatigue and static tests required for adjustment.

The study shows that all methods exhibit inherent strengths and weaknesses that depend strongly on load cases and material groups, resulting in a number of outliers (***Figure 1a***). Criteria accounting for mean-stress effects solely via a hydrostatic mean-stress term are strongly non-conservative in mean torsion loading, as shown in ***Figure 1b*** for the Crossland method, indicating the need for mean-shear-related terms such as $\sqrt{J_{2,m}}$ or $C_m$ to capture mean torsion effects. The calibration method also has a significant impact on predictions: the fatigue limit ratio $\kappa = \sigma_{-1}/\tau_{-1}$, used in classic formulations, captures first-order trends but does not uniquely explain mean-stress sensitivities across families. Criteria that explicitly use repeated fatigue limits (R=0) as calibration inputs tend to reproduce the corresponding mean-stress response more closely; this should be interpreted in light of the additional calibration information rather than as a universally superior formulation.

Aligned with FABER V&V objectives, the study provides a curated dataset and a transparent benchmarking workflow to define domains of validity—by material family and by the stress measures driving mean-stress effects—supported by concise tracking of calibration inputs and parameter counts.

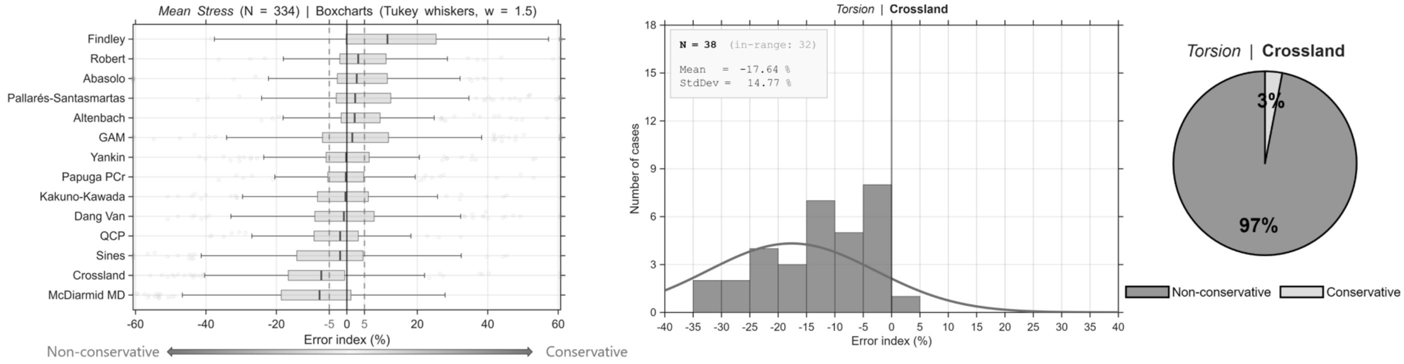


***Figure 1 – a)*** *Mean stress box charts* ***b)*** *Histogram of the Crossland method for torsional fatigue*

# Influence of Surface Treatments Fatigue Life of the Ni-Based Superalloy AD730®

**Henry Boyle[1], Zhe Chen[2], Rachid M´Saoubi[3,4], Jinming Zhou[3], Olle Widman[5], Ru Peng[1]**

[1]*Division of Engineering Materials, Department of Management and Engineering, Linköping University, Linköping, Sweden*

[2]*Siemens Energy, Finspång, Sweden*

[3]*Division of Production and Materials Engineering, Lund University, Lund, Sweden*

[4]*Materials and Technology Development, Seco Tools AB, Fagersta, Sweden*

[5]*Curtiss-Wright Surface Technologies AB, Arboga, Sweden*

*Machining* *Residual Stress* *4-Point Bending*

**Abstract** To develop and improve turbine efficiency, there is a need to develop Ni-based alloys that balance mechanical properties, microstructural stability, and cost. Cast and wrought alloys are significantly cheaper than powder metallurgy-based alloys and are therefore preferred for applications where ultimate performance is less critical. During component manufacture, machining is typically employed to achieve the desired shape and tolerance; however, this can alter surface properties, leading to variations in functional performance, particularly fatigue life.

Surface treatments such as shot peening and laser shock peening are commonly used to increase fatigue life by imparting compressive residual stresses at the surface, thereby retarding crack initiation and propagation. In this project, the effect of surface treatments on fatigue life was investigated for the advanced wrought Ni-based superalloy AD730®, developed as a successor to IN718, to establish which methods provide the greatest benefit.

Polished, as-milled, shot peened, and laser shock peened (no ablative layer) samples were compared by examining subsurface microstructural alterations. All peening was performed on as-milled samples. Residual stresses were measured using laboratory-based X-ray diffraction, while fatigue testing was conducted using a four-point bending rig. Fracture surfaces were subsequently examined using secondary electron SEM.

Shot peening imparted the greatest compressive residual stresses, followed by laser shock peening and then the as-milled condition. Although laser shock peening produced deep compressive residual stresses to depths of up to 1.8 mm, tensile residual stresses and porosity were observed within the top 5 μm due to the absence of an ablative layer. In contrast, near-surface residual stresses in the as-milled and shot peened samples were entirely compressive. EBSD analysis of cross-sections showed good correlation between deformation depth and residual stress profiles measured by XRD.

Fatigue testing showed that shot peening was the only treatment to provide a substantial improvement over the polished baseline across the entire range of stress levels tested. For the as-machined condition, an increase in fatigue life was observed only at lower stress levels, where crack initiation dominates the fatigue response. Laser shock peening without an ablative layer resulted in reduced fatigue life compared with the as-machined condition, despite the presence of deep compressive residual stresses, demonstrating that near-surface damage dominates fatigue crack initiation. Consequently, conventional shot peening is recommended for improving the fatigue life of as-milled AD730, while further work is required to assess laser shock peening with an ablative layer.

# Order-of-Magnitude Enhancement in VHCF Life of Bearing Steel Enabled by Tailored Deformation Compatibility

**Binxun Xu[a,b†], Tengyuan Liu[a†], Zhonghua Jiang[a], Pei Wang[a*], Dianzhong Li[a*]**

[a] *Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China*

[b] *School of Materials Science and Engineering, University of Science and Technology of China, Shenyang 110016, China*

*† These authors contributed equally to this work*

** Corresponding author. Tel. +86 24 8397 0106; Fax: +86 24 8397 0097*

*Very-high-cycle fatigue (VHCF)*　　*Multi-scale characterization*　　*Strain partitioning*

**Abstract** To overcome the technical and economic limitations of traditional strategies for enhancing very-high-cycle fatigue (VHCF) performance in bearing steels, this study proposes an innovative approach. Following inclusion refinement and rare-earth modification, we employ a multi-step phase transformation to introduce finely dispersed bainite sheaves into the martensitic matrix. Crucially, the scale of these sheaves is tailored to match the Fine Granular Area (FGA), ensuring the high-stress volume surrounding inclusions is effectively populated with strain-accommodating bainite and thereby mitigating local strain concentration. Under identical inclusion conditions, this designed microstructure elevates the $L_{10}$ fatigue life (10% failure probability) by 11-fold versus the fully martensitic counterpart. Fractography reveals an enlarged FGA, indicating retarded crack initiation. Multi-scale characterization and crystal plasticity simulations confirm that the spatially optimized bainite promotes compatible plastic deformation and suppresses strain localization in martensite. This work establishes a viable methodology for enhancing VHCF performance by prioritizing microstructural design within the damage-initiation zone—without altering inclusion characteristics or bulk composition.

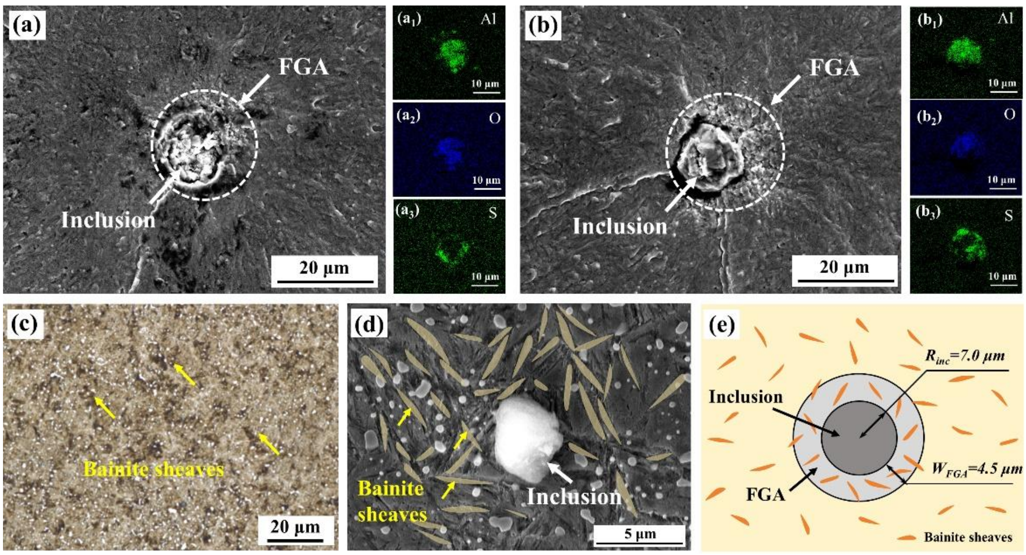


***Figure 1 -*** *SEM of fatigue damage origin in different samples and microstructure surrounding the inclusion in MBM sample.*

# Process–Structure–Fatigue Relationships in MIM 17-4PH: From Porosity to δ-Ferrite

**Tobias Hajeck[1], Christian Weck[2], Alexander Bezold[1], Christoph Broeckmann[1]**

*[1]Institute for Materials Applications in Mechanical Engineering IWM RWTH, Augustinerbach 4, 52052 Aachen, t.hajeck@iwm.rwth-aachen.de*

*[2] Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Bremen*

*17-4 PH* *metal injection molding (MIM)* *fatigue*

**Abstract** This study investigates how residual porosity and δ-ferrite jointly influence the fatigue strength of metal injection molded (MIM) 17-4PH stainless steel components. While extended sintering can increase densification, it may also promote the retention or formation of δ-ferrite, which does not fully transform to the strengthening martensitic matrix and can reduce the response to subsequent precipitation hardening. The work therefore addresses not only pore fraction, size, morphology, and spatial distribution, but also the δ-ferrite content as a microstructural design variable.

A controlled processing matrix is applied to vary sintering conditions and thereby decouple, as far as possible, densification from δ-ferrite evolution. Porosity is quantified using metallography and volumetric methods, complemented by statistical descriptors of defect population. The δ-ferrite fraction is determined by microstructure-sensitive techniques (e.g., EBSD and phase analysis), enabling correlations between processing, phase constitution, and mechanical performance. Fatigue behavior is evaluated under cyclic loading and linked to defect- and phase-controlled crack initiation mechanisms. Finally, a calculation concept is derived to support reliable fatigue design of MIM 17-4PH components, providing processing recommendations that balance densification against microstructural conditions favorable for precipitation hardening and cyclic durability.

# Multiaxial fatigue strength assessment of dissimilar GJS500-7 ductile iron-to-S355 steel arc-welded joints according to the Peak Stress Method

**S. Bolner[1], A. Campagnolo[1], A. Visentin[1], and G. Meneghetti[1]**

*[1]Department of Industrial Engineering, University of Padova, Via Venezia, 1, 35131 Padova, Italy*

*Email: simone.bolner@phd.unipd.it*

*Dissimilar welded joints* *Welding of ductile iron* *Peak Stress Method*

**Abstract** Many different industries benefit from using multiple materials or manufacturing methods within a single structure, allowing each component to be optimized for cost, weight and reliability based on specific structural and operational requirements. These components often need to be joined together, with traditional arc-welding being a widespread solution, and are often subjected to complex, multiaxial cyclic loading. However, current design Standards and Recommendations do not include fatigue strength categories for dissimilar joints.

In this study, the multiaxial fatigue strength of dissimilar arc-welded joints between EN-GJS-500-7C ductile iron and S355 structural steel was investigated. First, micro-hardness, residual stress measurements and metallographic analyses were conducted. Then, fatigue tests were performed on (i) flush-ground butt-welded joints under axial loading and (ii) pin-to-flange joints under pure bending, pure torsion and combined in-phase as well as out-of-phase bending-torsion loadings with R = 0.1. Crack initiation and propagation were monitored on pin-to-flange joints using dye penetrant inspections, complemented by fracture surface analyses. Fatigue strength categories in terms of nominal stresses were determined and compared with those available for similar steel welded joints in current International Standards.

Finally, the experimental results have been analysed according to the Peak Stress Method (PSM) approach. First, the material-dependent parameter involved in the method, namely the structural volume size $R_0$, was calibrated for GJS500-7 ductile iron-to-S355 structural steel dissimilar welded joints by equalling the high-cycle averaged Strain Energy Density (SED) of butt-welded flush-ground joints under axial load and pin-to-flange joints under bending loading. Then, all available multiaxial fatigue experimental results were summarized in a newly defined PSM-based fatigue design scatter band and discussed in view of future developments.

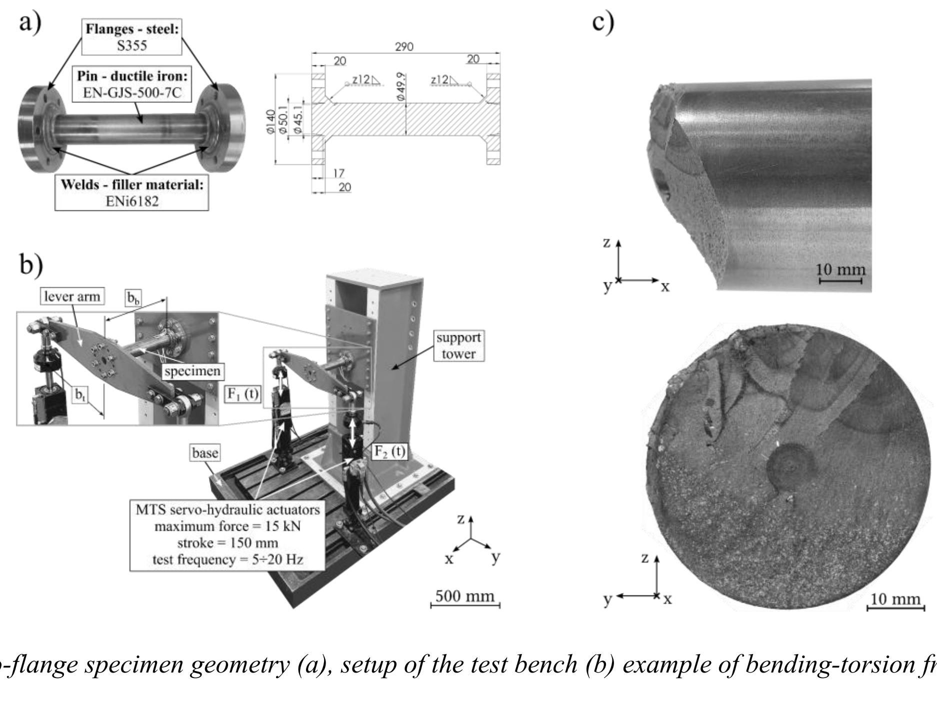


***Figure 1*** *– Pin-to-flange specimen geometry (a), setup of the test bench (b) example of bending-torsion fracture surface (c).*

# Structural Simulation of a Concrete-Based Floating Offshore Wind Platform under Hydrodynamic and Aerodynamic Loadings

**Luís Carrasco[1], Mário Vieira [3], Tiago Mota[3], Luís Reis [1,2]**

[1]*Instituto Superior Técnico, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal*
*luis.carrasco@tecnico.ulisboa.pt*

[2]*IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal*

[3]*WavEC Offshore Renewables, Lisbon, Portugal*

*Floating offshore wind turbines* | *Coupled aero–hydrodynamic simulation* | *Wind turbine control integration*

Floating offshore wind platforms are subjected to simultaneous wind, wave, and current loading, resulting in a strongly coupled aero–hydro–elastic response. Concrete floating platforms are an emerging solution for offshore wind, but their structural response under combined aerodynamic and hydrodynamic loading remains insufficiently understood, particularly when these effects are treated in a decoupled or sequential manner.

This work develops a fully coupled numerical model for the structural assessment of a concrete floating offshore wind platform under combined environmental loading within a single simulation environment. The methodology integrates hydrodynamic analysis in ANSYS AQWA, rigid-body motion in ANSYS Rigid Dynamics, and aerodynamic load computation using the AeroDyn module from OpenFAST, linked through ANSYS System Coupling. In this framework, the rigid-body dynamics solver determines the six-degree-of-freedom motion of the floating wind turbine system under the combined action of hydrodynamic and aerodynamic loads, enabling the direct transfer of structurally consistent loading conditions without the need for external load combination or sequential coupling approaches.

In addition to the existing co-simulation capabilities, this work addresses a current limitation of the ANSYS coupling framework by incorporating wind turbine control strategies. A generator torque control law is implemented to regulate rotor speed, while blade pitch control is introduced to adapt the aerodynamic response of the rotor to varying operating conditions, effectively adding a missing control layer to the coupled simulation environment.

A comparative study between hydrodynamic-only simulations and fully coupled aero–hydrodynamic simulations shows a clear increase in pressure levels and structural stresses when aerodynamic loads are included. These results demonstrate the non-negligible contribution of aerodynamic forces to the structural response of the floating platform and confirm that fully coupled aero–hydrodynamic simulations provide more realistic and structurally relevant loading conditions than hydrodynamic-only analyses.

# The Peak Stress Method applied to the fatigue characterization of dissimilar arc-welded AISI 316L joints made of additively manufactured and wrought plates

**L. Contiero[1], L. Vecchiato[1], A. Campagnolo[1],V.Babini[2], and G. Meneghetti[1]**

[1] *Department of Industrial Engineering, University of Padova, Via Venezia 1, 35131 Padova (Italy), e-mail: giovanni.meneghetti@unipd.it*

[2]*Antonio Zamperla S.p.a., Via Monte Grappa 15/17,36007, Altavilla Vicentina, Italy*

*Dissimilar joints* *Peak Stress Method* *Fatigue*

Additive manufacturing (AM), and specifically the laser powder bed fusion (L-PBF) process, is currently undergoing a rapid industrial expansion. Nevertheless, the production of large-scale components—as typically required in the amusement park industry—is still significantly hindered by the limited build volume achievable by current L-PBF systems. In this context, joining AM and conventionally manufactured components by arc-welding has emerged as a practical route to overcome such dimensional constraints.

However, the mechanical performance of welded AM parts is still poorly documented in the literature, particularly regarding fatigue strength. To address this, the present work investigates the fatigue behaviour of dissimilar arc-welded butt, transverse non-load-carrying and cruciform joints composed of additively manufactured (AM) and wrought (WR) AISI 316L stainless steel plates. Here, the term dissimilar refers specifically to the distinct microstructures of the two joined materials.

More in detail, the fatigue strength of the arc-welded joints was characterised experimentally under pure axial loading, considering both similar (WR/WR) and dissimilar (AM/WR) configurations. For comparison purposes, experimental fatigue results available in the literature for similar (WR/WR, AM/AM) and dissimilar (AM/WR) AISI 316L arc-welded joints were also collected.

After an initial analysis of the available data using the nominal stress approach, the results were re-evaluated by means of the Peak Stress Method (PSM). This local engineering approach, based on the Notch Stress Intensity Factors (NSIFs), enables a rapid estimation of the fatigue strength through linear-elastic finite element analyses employing coarse FE mesh patterns. According to the published literature, the PSM correlates the geometrical effects in fatigue for given class of materials therefore it will be applied separately to the dissimilar (AM/WR) and similar (WR/WR, AM/AM) experimental data. Additionally, the possibility to collapse all available experimental data into a single unified scatter band will be assessed.

# Fatigue Life Prediction Methodology for Welded Joints Considering Residual Stress Relaxation

**Xiaogang Liu, Qiang Hu, Jinhong Li**

*College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*

*Email: liuxg03@nuaa.edu.cn*

*Residual stress relaxation* *X-ray diffraction* *Fatigue life prediction* *Welded joints*

**Abstract** Surface residual stresses significantly influence the fatigue life of welded structures, yet their evolution under cyclic loading conditions poses challenges for accurate fatigue life assessment. In this study, focusing on GH4169 electron beam welded joints commonly used in aero-engine components, the evolution behavior of residual stresses in the joints under cyclic loading is analyzed, and a fatigue life prediction model incorporating the effects of residual stress is established. Firstly, X-ray diffraction (XRD) technique was employed to systematically measure and analyze the initial residual stress near the weld seam and its evolution during cyclic loading. The results indicate that residual stress on the specimen surface is partially released under cyclic loading. Significant relaxation occurs within the first few hundred cycles, after which the residual stress gradually stabilizes with increasing cycle count. Moreover, the relaxation behavior varies under different load levels: higher stress amplitudes lead to faster relaxation rates and ultimately lower stabilized residual stress values. Based on the experimental data, a residual stress relaxation model was developed to quantitatively describe the relationship between residual stress, number of cycles, and load level, thereby enabling the determination of stabilized residual stress after relaxation. By superimposing the stabilized residual stress with the externally applied load, a fatigue life prediction model for welded joints incorporating residual stress relaxation was finally established. Predictions from the proposed model show good agreement with experimental data, with all data points falling within a 1.5-fold scatter band, demonstrating high predictive accuracy. This work provides a reliable basis for the accurate fatigue life assessment of welded structures.

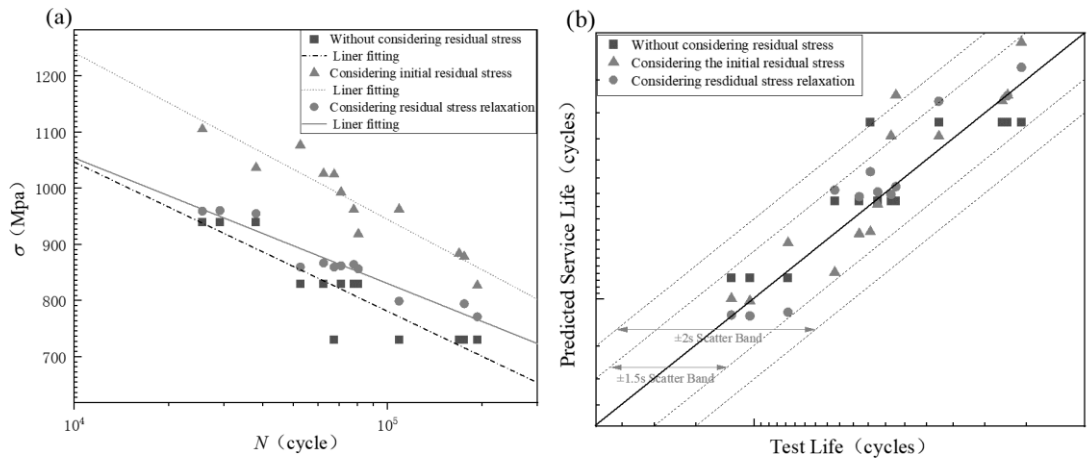


***Figure 1 -*** *Comparison of Predictive Results from Different Models: (a) S-N Curve; (b) Scatter Band*

# VHCF of QT steel in hot hydrogen

**M. Fitzka[1,2], B.M. Schönbauer[1,2,3], J. Vaara[4], T. Frondelius[3,4], H. Mayer[1]**

[1]*Institute of Physics and Materials Science, BOKU University, Peter-Jordan-Str. 82, 1190 Vienna, Austria, michael.fitzka@boku.ac.at*

[2]*Christian Doppler Laboratory for Defect Tolerance of Steels in the High and Very High Cycle Fatigue Regime, BOKU University, Peter-Jordan-Str. 82, 1190 Vienna, Austria*

[3]*Materials and Mechanical Engineering, University of Oulu, Pentti Kaiteran katu 1, 90014, Finland*

[4] *R&D and Engineering, Wärtsilä, P.O. Box 244, 65101, Vaasa, Finland*

*very high cycle fatigue* *hydrogen embrittlement* *experimental technique*

**Abstract** Hydrogen is known to diffuse into materials and cause hydrogen embrittlement through various mechanisms. The loss of cyclic strength during operation must be considered especially for materials subjected to high and very high numbers of cycles, where damaging mechanisms, e.g. hydrogen trapped at inclusions, are especially relevant.

Novel ultrasonic testing equipment for fatigue testing at high and very high numbers of load cycles in hot hydrogen gas at elevated pressure was developed. The BOKU ultrasonic system has been enhanced to include the capability to cycle samples in hydrogen gas, as well as inert gases and air, at temperatures up to 450 °C and pressures up to 3.5 MPa. As opposed to electrochemical charging of samples, soaking and subsequent testing in hot hydrogen gas enables testing at elevated temperatures while maintaining defined hydrogen concentrations in the testing material without further treatment of the specimen surface.

In the present investigation, low alloy CrMo QT steel samples with artificial defects (drill holes) are tested in hydrogen gas at 400°C and 20°C, along with reference measurements at the same temperatures in inert atmosphere and air. Lifetimes are presented, and mechanisms of crack initiation in the respective medium are discussed.

***Figure 1 -*** *Testing facility for VHCF test in hot hydrogen gas at elevated pressures at BOKU Vienna.*

# Automated implementation of the PSM combined with *shell* finite element models for the fatigue design of complex welded structures

**Alberto Visentin[1], Alberto Campagnolo[1], Vittorio Babini[2] and Giovanni Meneghetti[1]**

*[1]Department of Industrial Engineering, University of Padova, Via Venezia 1, 35131 Padova, Italy*

*[2]Antonio Zamperla S.p.a., Via Monte Grappa, 15/17 – 36007 Altavilla Vicentina, Italy*

*Welded structures* *Shell FE models* *Peak Stress Method*

**Abstract** In the framework of fatigue design of welded structures, the Peak Stress Method (PSM) stands as a FEA-based engineering local approach that leverages the linear-elastic local peak stresses calculated at the weld toe and weld root V-notch tips for rapidly evaluating the Notch Stress Intensity Factors (NSIFs). Owing to the combination with the averaged Strain Energy Density (SED) fatigue criterion, the PSM has been applied to the fatigue lifetime assessment of welded structures made of structural steel and aluminium alloys and subjected to both constant amplitude and variable amplitude uniaxial and multiaxial loadings [1]. Moreover, a dedicated fatigue analysis tool, the "PSM App", has been developed in Ansys® Mechanical to implement the analysis workflow of the PSM [2]. State-of-the-art PSM enables to exploit relatively coarse meshes of 2D four-node plane and 3D eight-node brick as well as four-node and ten-node tetrahedral *solid* finite elements. However, it is well known that the adoption of *shell* FE models significantly reduces the computational time required to assess large-scale structures if compared to *solid* FE models. In this work, a dedicated analysis routine has been developed and implemented in the "PSM App" which enables PSM application starting from a surface CAD model, subsequently meshed with *shell* finite elements. No explicit modelling of the welds is required, and the intersection lines of the *shell* mid-surfaces are used to automatically identify the welds in the model. Then, the analyst is requested to specify the weld type (e.g. butt-weld, T-joint weld, cruciform weld, etc.), the weld leg lengths and penetration of the actual welds represented by the *shell* junction lines. Afterwards, a three-steps automated procedure is carried out. Firstly, the stiffness contribution of the welds in the global *shell* FE model is implemented by locally increasing the thickness of the *shell* finite elements originating from junction lines by means of calibrated factors based on the local dimensions of the welds, e.g. weld leg lengths and *shell* sheets thickness. Then, a PSM-compliant FE mesh is generated by adopting six-node as well as eight-node *shell* finite elements. After solving the linear-elastic FE analysis, the PSM App maps the displacement fields of the global *shell* FE model to dedicated local *solid* models of the actual welds by means of a sub-modelling technique and retrieves the local peak stresses acting at the weld toes and weld roots. As an outcome, the fatigue lifetime estimated according to the PSM can be plotted along the weld lines over a wireframe view of the model. Eventually, the "PSM App" implementing the newly developed analysis procedure has been applied to the case study of large-scale steel amusement park structure subjected to multiaxial fatigue loads. Also, the mesh density and solution time required to apply the PSM combined with a *shell* FE model have been compared with those required by a ten-node tetrahedral model to highlight the advantages of adopting a *shell* finite element-based approach.

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# Effect of post-processing heat treatments on the fatigue crack growth resistance of an AlSi10Mg alloy produced by laser-based powder bed fusion

**Sidney Araújo[1,2], Geraldo Faria[1], Leonardo Godefroid[1], Ricardo Cláudio[3,4], Rodolfo L. Batalha[3,5,6]**

*[1]Federal University of Ouro Preto, Ouro Preto, MG, Brazil*
*[2]REDEMAT – Graduate Program on Materials Engineering, Escola de Minas, Universidade Federal de Ouro Preto, 35400-000 Ouro Preto, Minas Gerais, Brazil*
*[3]Escola Superior de Tecnologia de Setúbal, Instituto Politécnico de Setúbal, 2910-761 Setúbal, Portugal*
*[4]IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal*
*[5]ENIDH – Escola Náutica Infante D. Henrique, 2770-058 Paço de Arcos, Portugal*
*[6] Instituto de Soldadura e Qualidade, Av. Prof. Dr. Cavaco Silva, Porto Salvo, 2780-920, Portugal*

*Corresponding author: rlbatalha@isq.pt*

*AlSi10Mg      PBF-LB additive manufacturing      Heat treatments      Fatigue behavior*

Aluminum alloys and Additive Manufacturing (AM) have been an important combination to produce lightweight parts with complex geometries. Post-processing heat treatment is commonly applied to reduce residual stresses and modify the alloy's microstructure, thereby improving its mechanical properties. The present study examined the fatigue crack growth performance in the linear region of *da/dN vs. ΔK* diagram of an AlSi10Mg alloy obtained by PBF-LB. C(T) specimens were tested in the as-built (AB) condition and in three distinct post-processed heat treatments: standard peak aging (T6), optimized peak aging (OT6), and direct aging (DA). Two different orientations were adopted for load application and crack growth, as indicated in Figure 1. An X-Y-Z system was used: XY is the construction plane for each layer, and the Z is the stacking direction of the layers. In each specimen, the first letter corresponds to the load application, while the second letter indicates the crack propagation. Specimens were tested at a constant force range, at room temperature, under stress ratio R = 0.1 and a frequency of 30 Hz. A preliminary analysis of the tensile behavior indicated that conditions AB and DA achieved a mechanical strength superior to the traditionally processed material. Similarly, these two conditions provided the highest fracture toughness values using J-integral methodology. As shown in Figure 1, fatigue behavior does not follow the same trend. In this case, conditions T6 and OT6 performed better than condition DA. Microstructural homogenization, reduction of residual stresses, and plasticity-induced crack closure were responsible for this behavior. Finally, as also illustrated in Figure 1, it should be considered that the OT6 condition showed the smallest anisotropy among the samples studied.

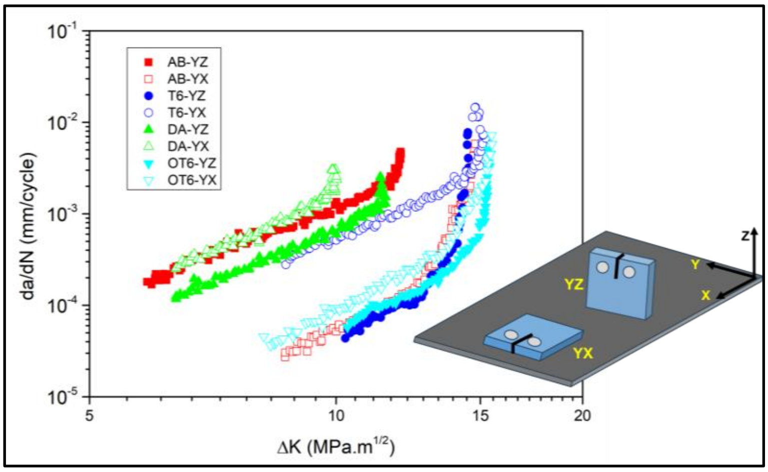



***Figure 1 -*** *Fatigue crack growth curves (region II and III) of the studied materials and corresponding compact tension C(T) specimens with designation as a function of both loading and notch directions.*

# Fatigue crack propagation mechanisms in ductile bulk metallic glasses and ductile polycrystalline metals: a comparison

**Reinhard Pippan[1], Simon Pillmeier[2], Anton Hohenwarter[2]**

[1] *Erich Schmid Institute of Materials Science, Austrian Academy of Sciences, Jahnstraße 12, 8700 Leoben, Austria*

[2] *Department of Materials Science, Montanuniversität Leoben, Jahnstraße 12, 8700 Leoben, Austria*

*Fatigue crack propagation* *BMG* *Metals*

**Abstract** Plastic deformation in ductile bulk metallic glasses, BMGs, and metals is quite different. In metals plasticity is mainly governed by dislocation motion, whereas BMGs deform plastically by localized shear bands. Despite the significant differences in the plastic deformation mechanism, the fatigue crack propagation behavior is quite similar. BMGs show a well-defined threshold of stress intensity factor range, with a drop of the fatigue crack growth rate, da/dN, at 0.1nm/cycle to zero. They exhibit a well pronounce Paris regime with a Paris exponent of about 2. Even the fractographs of BMG and ductile metals exhibit many similarities. Like many ductile metals BMGs exhibit striations, an example is presented in Figure1.

The goal of the paper is to show that the fatigue crack propagation in BMGs and ductile metals is quite similar. Blunting and resharpening are the intrinsic crack propagation mechanism. It will be shown that the threshold of stress intensity factor range, as well as the fractographic feature can be explained by the similarities of the effect of the stress field of dislocation bands in ductile metals and shear bands in BMGs and their effect on the cyclic and monotonic deformation during crack propagation. Beside the explanation of the fatigue crack propagation mechanism in BMGs, it will be shown that the fatigue crack propagation behavior of BMGs delivers a deeper understanding of the nucleation of shear bands and the plasticity of BMGs.

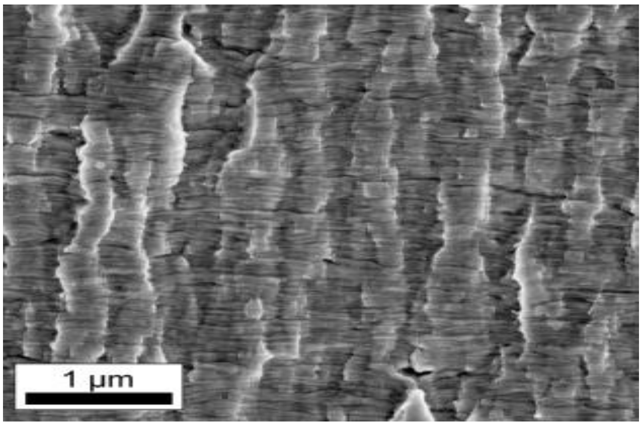



***Figure 1** – SEM micrograph of a fatigue fracture surface obtained near the threshold of stress intensity range (da/dN about 0.5 nm/cycle) in a bulk metallic glass, Vitreloy 105. The figure demonstrates the formation of an unnormal striation spacing in BMGs, which is also often observed in many ductile metals near the threshold of stress intensity range [1].*

[1] Simon Pillmeier et.al. Insights into the fracture and fatigue behavior of a selective laser melted Zr-based bulk metallic glass, submitted 2026.

# The limit notch radius in mixed mode I+III loadings and an effective stress for multiaxial fatigue design

**Pietro Foti[1], Michele Zappalorto[2], Filippo Berto[1]**

[1]*Department of Chemical, Material and Environmental Engineering (DICMA), La Sapienza University of Rome, Via Eudossiana 18, 00184 Rome (Italy)*

[2]*Department of Management and Engineering, University of Padova, Stradella San Nicola 3, 36100, Vicenza (Italy)*

*Fatigue Design* *Notch-mechanics* *Multiaxial fatigue behavior*

**Abstract** The design of mechanical components often involves geometrical discontinuities, known as notches, which induce stress-concentrations and steep stress gradients, ultimately reducing the structural reliability and fatigue strength. Conventional point-based approaches tend to markedly overestimate the detrimental influence of notches on fatigue behaviour, leading to a possible distinction between blunt and sharp notches. While the former can be reasonably assessed using point-based methods, sharp notches cannot be accurately designed through these approaches. Over the years, many studies have focused on identifying criteria capable of separating these two regimes and on developing methods suitable for both. Within this context, the averaged Strain Energy Density (SED) approach -a local energy-based method- has been extensively validated for its ability to handle both sharp and blunt notch behaviour. Building on this approach, a recent study by the present authors derived a limiting condition under pure Mode I loading, expressed in terms of a critical notch radius. In this work, the concept is extended and formalized to multiaxial fatigue conditions (I+III mode). By generalizing the definition of the limit condition, a corresponding limit radius is proven to exist for multiaxial fatigue. Moreover, this radius must lie within the bounds defined by the limiting notch radii associated with pure mode loadings. The theoretical framework and resulting formulations for fatigue assessment under mixed-mode loading are examined analytically and validated against a dedicated database of multiaxial fatigue data. Finally, an effective stress value is defined to derive a fatigue assessment methodology for notched components under multiaxial fatigue loadings.

# A phase-field numerical study on the effects of Thermal Growth Oxide thickness and composition on thermal fatigue failure of thermal barrier coatings

**Lang Gao[1], Jiewei Lin[1], Junhong Zhang[1,2], Lin Yu[1], Tianci Wang[1], Huwei Dai[1,*]**

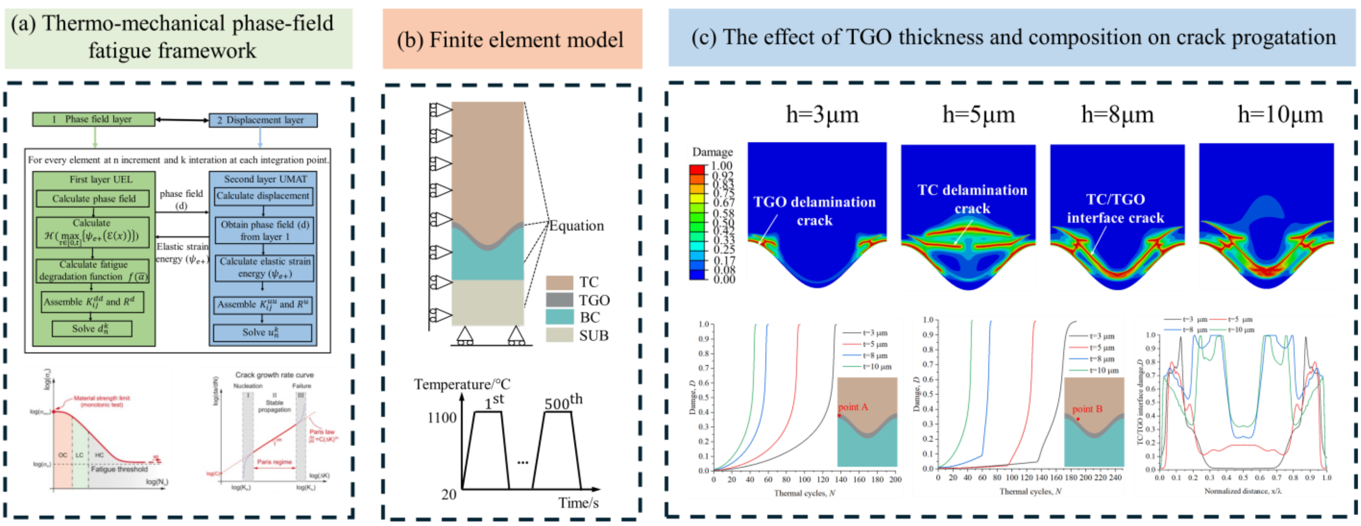
[1]*State Key Laboratory of Engines, Tianjin University, Tianjin 300354, China;*

[2]*Department of Mechanical Engineering, Tianjin Renai College, Tianjin 301636, China;*

* *Corresponding author, E-mail address: dhwmail@tju.edu.cn.*

*Phase-field fatigue* *Thermal barrier coatings* *Thermally grown oxide*

**Abstract** Thermal barrier coatings (TBCs) play a crucial role in the protection of aero-engine hot-end components; however, the evolution of thermally grown oxide (TGO) at elevated temperatures severely affects their reliability during service. The effects of TGO thickness have received lots of attention, while the effects of TGO composition evolution (from α-$Al_2O_3$ to (Ni, Co)Al2O4-based spinel-type mixed oxides) remain limited. A coupled thermo-mechanical phase-field model is proposed to quantify the impact of TGO thickness and composition on thermal fatigue crack propagation. The results indicate that during the initial oxidation stage dominated by α-$Al_2O_3$, an increase in TGO thickness significantly amplifies the tensile stress within the TBC system. An increase in TGO thickness from 3 μm to 5 μm elevates the residual tensile stress in the TGO peak region from 270.3 MPa to 324.8 Mpa. Consequently, the increase of tensile stress accelerates crack initiation, reducing the initiation time of crack from 133 to 92 thermal cycles. In the later stage of oxidation, the formation of mixed oxides further exacerbates damage accumulation, advancing crack initiation to 45 thermal cycles. Notably, the mismatch of thermal expansion coefficients between mixed oxides and α-$Al_2O_3$ induces complex crack evolution behaviors. This drives a transition in the dominant failure mode from conventional interlaminar cracking within the TC layer to interfacial delamination along the TC/TGO interface. This study quantitatively reveals the influence of TGO evolution on the thermal fatigue life of TBCs, providing a theoretical basis for the assessment of thermal fatigue life and durability.



# Dynamic response and life analysis of an reverse flow type pulse detonation combustor

**Jing Xin[1], Zheng Longxi[1]**

[1] *School of Power and Energy, Northwestern Polytechnical University, Xi'an, 710072, China;*

*jingxin@nwpu.edu.cn*

*Pulse detonation combustor*    *Dynamic response*    *Fatigue life analysis*

**Abstract** Pulse detonation is an approximately isochoric combustion mode, and the application of pulse detonation combustor (PDC) in aeroengines will significantly enhance their performance. However, the cyclic gas impact loads induced by pulse detonation lead to distinct characteristics in the structural response and service life of the combustor compared with those of traditional isobaric combustors. Although a considerable number of previous studies have focused on the deformation and fracture of cylindrical tubes under detonation loading, most of them addressed the large deformation failure of straight circular tubes subjected to a single severe impact. In contrast, pulse detonation is associated with cyclic loading at a relatively lower load, where the dominant structural strength issue is fatigue—specifically, fatigue failure under thermo-mechanical coupled cycles.

Specifically, the reverse flow type PDC investigated in this paper is an innovative design intended to reduce the axial length of the combustor—a tailored solution designed to comply with the axial dimensional constraints of aeroengines. Its structural response and failure behavior under cyclic detonation pulses are more complex than those of straight circular tubes. Therefore, this paper carries out experimental and numerical investigations on the structural response of this detonation chamber under pulse detonation loads, and conducts a comprehensive service life assessment for it. The results show that its structural response is characterized by steady-state thermal stress under different operating conditions (i.e., detonation frequencies) and transient responses induced by the transient pressure impact of pulse detonation. Notably, in contrast to the previously hypothesized continuous amplification of structural response induced by cyclic impact (a resonance-like phenomenon), the experimentally observed transient response exhibits a distinct upper bound. Owing to the damping effect, the dynamic response triggered by a single preceding impact attenuates rapidly and only exerts an influence on the subsequent several cycles, which is dependent on the detonation frequency. In comparison with the dynamic response under a single detonation impact, the incremental dynamic response induced by cyclic impact is limited. For this reverse flow type PDC, there are two primary fatigue-critical locations. First, the exit section experiences significant hoop stress induced by detonation loads (caused by pipeline breathing deformation); meanwhile, the maximum temperature at the exit section gives rise to high-low cycle fatigue issues, with the frequency up to 10~20kHz. Second, the bottom of the notch in the detonation-enhancing structures at the recirculating elbow suffers from stress concentration due to bending stress, where the high-cycle excitation frequency is relatively lower to 40~200Hz. Then, rainflow counting method are adopted to analyze the fatigue life of the combustor under a single operating condition. The results indicate that the operating frequency and wall thickness of the PDC exert a significant influence on its service life. Rig tests under multi-frequency operation were performed on the PDC with a 2 mm wall thickness fabricated from GH3625, which achieved a cumulative service life of 16 hours and thus demonstrated the excellent fatigue performance of the PDC.

# Assessing multiaxial fatigue thresholds of metals weakened by different stress raisers beyond the Kitagawa–Takahashi diagram

**Giovanni Meneghetti[1], Francesco Collini[1], Daniele Rigon[1], Nicolò Belè[1], Giuseppe De Marco[2], Simone Turani[3]**

[1] *Department of Industrial Engineering, University of Padova, Padova, 35131, Italy*
[2] *Kilometro Rosso S.p.A., via Stezzano 87 – 24126, Bergamo, Italy*
[3] *Brembo S.p.A, Via Brembo, 25 - 24035 Curno (BG), Italy*

*Fatigue Thresholds* *Multiaxial fatigue* *Notch and Fracture Mechanics*

**Abstract** A unified notch- and fracture-mechanics-based framework for estimating the constant-amplitude multiaxial fatigue threshold of metallic components weakened by defects, cracks, and sharp U- and V-notches was recently proposed [1]. The approach is based on the averaged strain energy density (SED) criterion, which assumes that fatigue behavior is to be governed by the SED averaged over a material-dependent structural volume in the vicinity of the stress raiser. By exploiting the definition of notch stress intensity factors (NSIFs) for different loading modes and calibrating mode- and material-dependent structural volume sizes, the approach reformulates the Atzori–Lazzarin–Meneghetti (ALM) diagram, originally developed to estimate the uniaxial fatigue limit of components weakened by defects, cracks, and sharp U- and V-notches to account for multiaxial loading conditions (Fig. 1). The resulting multiaxial model, was validated against a broad literature dataset, including 128 multiaxial fatigue limits for different metallic materials (including steels and Ti–6Al–4V alloy), containing sharp V-notches and artificial or crack-like defects. In addition, new original fatigue data have been included in the validation, consisting of net-shape additively manufactured Ti–6Al–4V specimens featuring sharp V-notches with different opening angles, which were tested under axial, torsional, and combined axial–torsional loading conditions, including both proportional (in-phase) and non-proportional (out-of-phase) load paths. Satisfactory theoretical estimations were obtained by comparing with experimental fatigue thresholds.

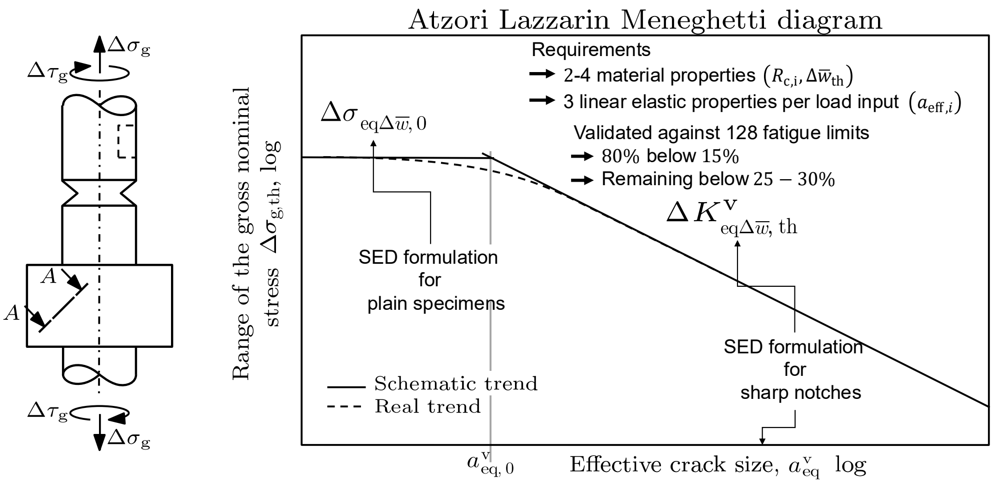



***Figure 1*** *– Schematic representation of the ALM diagram for estimating the fatigue thresholds of metallic components weakened by different stress raisers (defect, short cracks, sharp notches)*

# Using small crack growth to calculate high cycle fatigue life for different maximum stress and stress ratios

**E. Amsterdam**[1]

*[1]Royal NLR, Voorsterweg 31, Marknesse, The Netherlands, emiel.amsterdam@nlr.nl*

*Small cracks* *Mean stress effect* *probabilistics*

**Abstract** In 1972 Forman was one of the first to investigate the use of linear elastic fracture mechanics (LEFM) to calculate the number of cycles for fatigue crack initiation from flaws and concluded that most of the cyclic behavior was crack growth and only a small part was nucleation. A few years later Kitagawa and Takahashi showed that the fatigue crack growth rate threshold stress range as a function of the initial crack length becomes constant below a certain crack length, demonstrating that small cracks violate LEFM assumptions. Currently, there is still much debate on whether the high cycle fatigue life is dominated by crack nucleation or small crack growth. In this study quantitative fractography is used to measure the fatigue crack growth rate of small cracks in 7075-T7351. The results and constructed small crack growth rate model showed that the Kitagawa-Takahashi diagram can be physically explained by the probabilistics of small crack growth rates. The small crack growth model is subsequently used to compare the constant amplitude high cycle fatigue life (S-N) curve of smooth specimens with the fatigue crack growth life from the initial discontinuity sizes in aluminum alloy 7075-T7351 up to failure. The calculated small crack growth lives show good agreement with the experimental S-N curve and if crack nucleation was incorporated or long crack data was used, then the calculated fatigue lives were higher (less conservative) than the experimental results. Accurate long crack growth measurements on the same material have shown that a fatigue crack growth rate master curve can be created using different stress ratios when a new parameter of similitude is used that is based on the strain energy release rate, i.e. the original crack driving force in LEFM. Small variations in the threshold region of the long crack master curve with stress ratio show that crack growth in stage I is additionally influenced by the stress ratio through, for example, the influence of stress ratio on resharpening of the crack tip or the cyclic plastic zone size. Modelling of the additional stress ratio influence has been applied to model the stress ratio influence on the S-N curve for positive and negative stress ratios with the underlying idea that small crack growth dominates the fatigue life of these specimens and occurs mainly in region I and the beginning of the region II (Paris regime).

# A novel variable amplitude fatigue crack growth model applied to fatigue damage accumulation

**E. Amsterdam[1]**

*[1]Royal NLR, Voorsterweg 31, Marknesse, The Netherlands, emiel.amsterdam@nlr.nl*

*Fracture mechanics* *Damage accumulation* *Aluminium alloys*

**Abstract** It has been proven that the fatigue crack growth rate shows a power law relationship with the cyclic strain energy release rate over the maximum stress intensity factor. This new description for fatigue crack growth gives a physical explanation for the stress ratio/mean stress effect during constant amplitude loading and for crack growth retardation under variable amplitude (VA) loading. The method has been successfully applied to VA crack growth with spectra that are representative of different fatigue dominated aircraft locations. Additionally, quantitative fractography has shown that the constant amplitude high cycle fatigue life of smooth specimens made from aluminium alloy 7075-T7351 is dominated by small crack growth. Since small crack growth dominates the fatigue life (S-N) curve of smooth specimens the VA crack growth model has also been applied to model the fatigue damage accumulation under VA loading. The VA crack growth model includes automatically includes load interaction effects and does not require rainflow counting, but uses the amount of strain energy in actual spectrum to determine the severity of a spectrum. This is in contrast with Miner's rule where load interaction is not included and rainflow counting is typically used. Per definition, the severity of constant amplitude loading with R=0 is equal to one. It is shown that the number of VA cycles to failure times the spectrum severity is constant. The current methodology basically creates a single master S-N curve for constant and variable amplitude loading and has been successfully applied to 7XXX series aluminium alloys for smooth specimens with 30 µm deep artificial laser defects, long crack middle tension specimens (see Figure 1) and specimens with a hole ($K_t$=3) and naturally occurring fatigue cracks from pre-penetrant inspection etch pits.

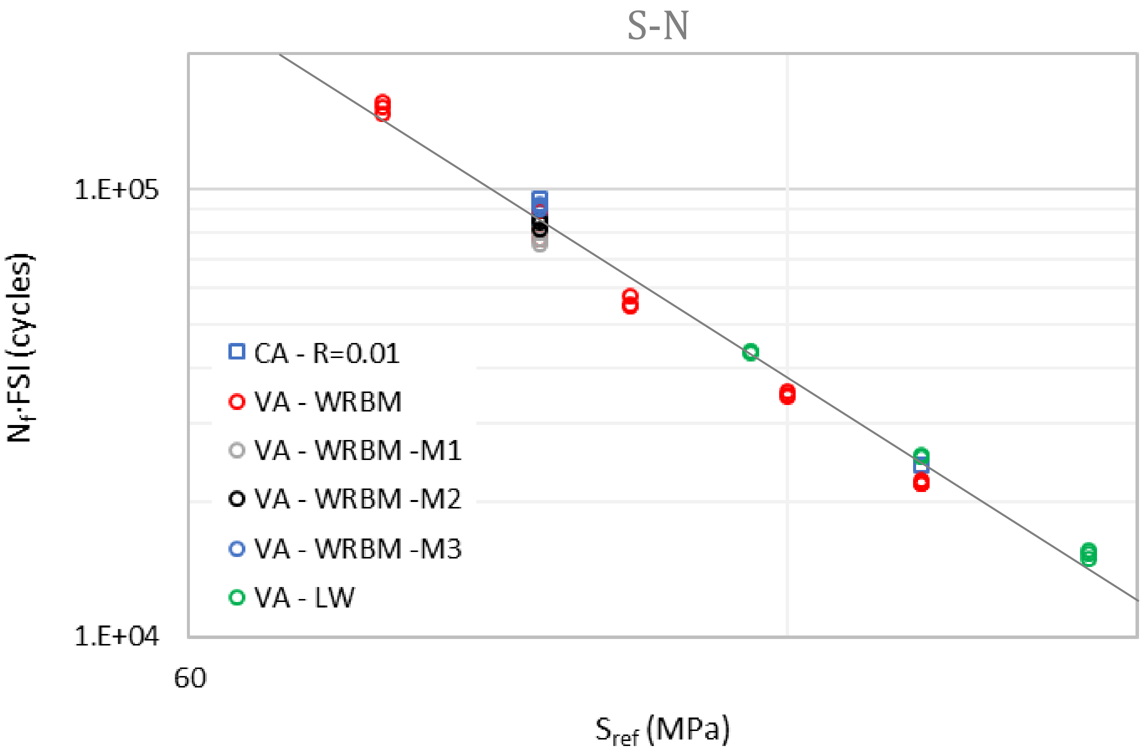



***Figure 1** – VA cycles to failure times the spectrum severity as a function of the reference stress for multiple spectra*

# Understanding the effect of skin removal on total fatigue life in LPBF AlSi10Mg parts for accurate life prediction

**Ninian Sing Kok Ho[1], Tong Liu[2], Yi Zhou[1], John Hock Lye Pang[1]**

*[1]Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, ninian.ho@ntu.edu.sg*

*[2]Singapore Institute of Manufacturing Technology (SIMTech), Agency for Science, Technology and Research (A*STAR), 5 Cleantech Loop #01-01, CleanTech Two Block B, Singapore 636732, Republic of Singapore*

*Laser Powder Bed Fusion* *X-ray Computed Tomography* *Finite Element Model*

**Abstract**

Laser Powder Bed Fusion (LPBF) is an Additive Manufacturing (AM) process that allows complex parts to be fabricated in a single piece, which is not always possible using conventional manufacturing routes. While it has the best geometrical accuracy and surface finishing, its surface features are the smallest among AM processes thus being the most challenging to analyze, and internal pores herein termed defects are inevitable. Both of them are known fatigue initiators. A wealth of information exists on the effects of these factors, showing large scatter in S-N characteristics across studies that have not been fully explained. This study comprehensively analyzes fatigue failure in LPBF AlSi10Mg with as-built and machined surfaces to understand the root cause, using detailed X-ray Computed Tomography, defect correlation via reverse engineering, and Finite Element Modelling, which is eventually validated as a predictive tool. A qualification baseplate of samples was printed in accordance with guidelines and requirements set out by major certification bodies. E466 fatigue samples were scanned by high resolution X-ray Computed Tomography across the baseplate to quantify and reconstruct internal pores and surface features. Defect distributions across and within the E466 samples were examined. Half were kept in the as-built condition while half were subjected to surface machining, i.e. skin removal, and both batches were tested under stress-controlled fatigue. Counterintuitively, no performance enhancement was found in skin removed samples. As-built samples contained hundreds of pores, yet none of them was observed to initiate the fatigue crack. Correlation of observed fatigue crack initiation sites on rough as-built surfaces to X-ray reconstructions showed that they can be predicted numerically and preemptively. For skin removed samples, cracks initiated at defects on the machined surface. Numerical crack propagation analyses of these samples using E647 crack growth experimental data were in agreement with experimental findings. The predictive techniques and experimental observations provide insight into the fatigue behaviour of LPBF parts which can accelerate industrial adoption.

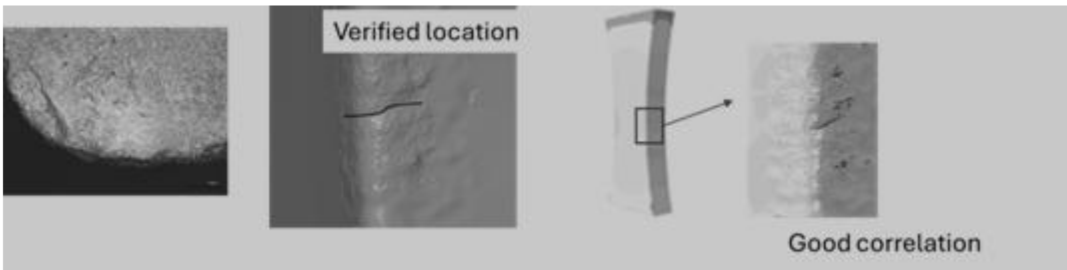



***Figure 1** – Crack initiation prediction on as-built LPBF sample surface for preventive surface treatment*

# Effect of Hold Time During Automated Ball Indentation Testing of Stainless Steel 304L(N) in Pristine and Post-Fatigue Cycling.

**Raghu V. Prakash[1], S. Vishal [1]**

[1]*Department of Mechanical Engineering, Indian Institute of Technology Madras*

*Chennai, India; raghuprakash@iitm.ac.in*

*Ball Indentation* *Fatigue damage* *Indentation dwell*

**Abstract** Tension, fatigue, fracture and creep response of in-service components serve as inputs for residual life prediction. Automated Ball Indentation test (ABI) using a spherical indenter is an effective, in-situ small specimen testing technique to characterize the true stress-plastic strain response and fracture properties of a material. Cyclic ABI test – a derivative of ABI test is used to estimate the fatigue life properties; indentation creep testing using flat indenters is used to assess the creep response of materials. Prior to field implementation, controlled experiments on a known material having a known history of damage is essential and it is carried out in a laboratory to better understand the complex in-service problems.

In the present work, controlled high cycle fatigue damage is introduced in a dog-bone sample made of a structural stainless steel SS 304L(N) from pristine state to 10000 cycles of constant amplitude (CA) fatigue, followed by additional 30000 cycles of CA fatigue; the post fatigue indentation response is investigated at room temperature using static ABI tests. During static ABI, multiple steps of loading-unloading are carried out to estimate the plastic strain response as a function of indentation depths (Ref. Fig 1). A novel test procedure of load hold at the peak compression load for a dwell time of 500 seconds at multiple load reversal points of ABI test was tried out to verify if the plastic strain exhibits a time-dependent response. ABI tests with dwell time revealed increased indentation depth during the dwell, similar to a typical creep strain vs. time response; the true stress decreased marginally as a function of hold time. The dwell period stress and strain response w.r.t time was modeled using a Norton-Bailey type creep law. This study provides an insight into material degradation due to CA fatigue cycling – both from the true stress-plastic strain response and time dependent plastic strain response – which can serve as an input for component life prediction.

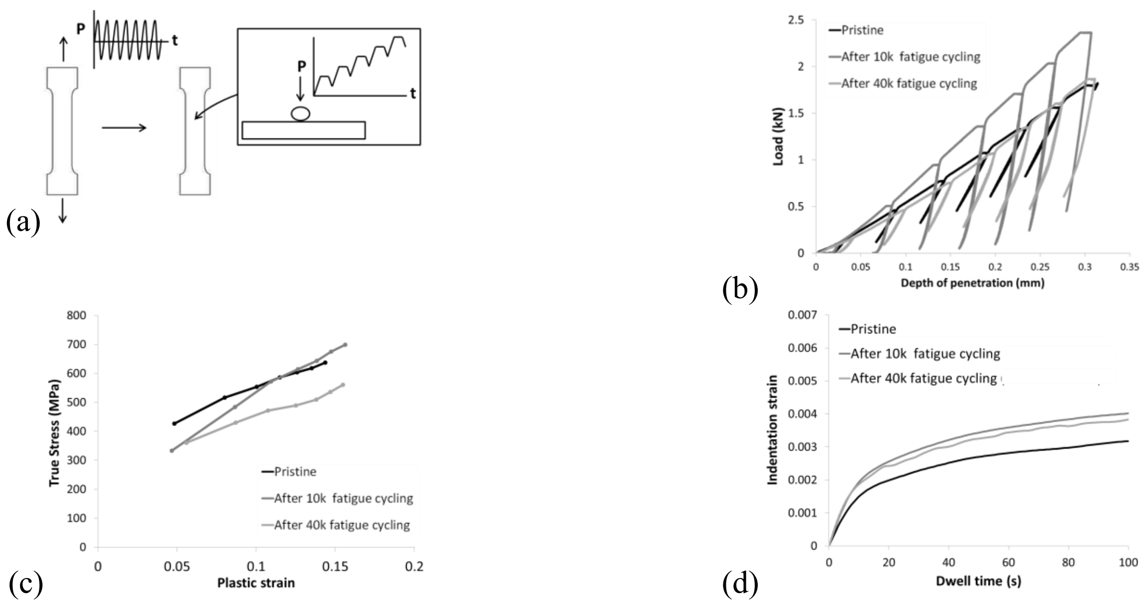



***Figure 1 – (a)** Schematic of ball indentation with dwell on fatigue-damaged specimen **(b)** load–displacement responses **(c)** True stress-plastic strain responses **(d)** dwell strain accumulation responses at different damage states.*

# Effective Crack Size and Fatigue Limit estimation of Ti–6Al–4V specimens produced by PBF-LB/M with different surface roughness condition

**Daniele Rigon[1], Filippo Mioli[1], Nicolò Bonato[2], Rachele Bertolini[1], Enrico Savio[1] and Giovanni Meneghetti[1]**

*[1]Department of Industrial Engineering, University of Padova, Via Venezia 1 35131, Padova, Italy*
*[2]Department of Management and Engineering, University of Padova, Stradella San Nicola 36100 - Vicenza Italy*

*Roughness* *Fatigue Thresholds* *Additive Manufacturing*

**Abstract.** The fatigue limit of series of Ti–6Al–4V alloy specimens produced by Laser Powder Bed Fusion of metals (PBF-LB/M) characterized by different surface conditions, namely as-built and chemically electropolished, is analysed by means of a fracture mechanics-based approach recently proposed [1]. The investigation focuses on a detailed characterization of an equivalent crack size accounting for the effect of surface roughness within a linear elastic fracture mechanics framework. Surface morphology was characterised by adopting two techniques, namely optical profilometry (OP) and X-ray Computed Tomography (CT). The former provides high spatial resolution of surface valleys, but neglects internal and re-entrant defects, whereas the latter allows for the detection of internal and subsurface features with a lower spatial resolution. For both surface conditions and measurement techniques, extreme value statistics (EVS) was applied to the roughness-related parameters $S_v$ to estimate the maximum defect size expected within the highly stressed volume of the specimens, starting from a limited number of measurements. Afterwards the statistically estimated maximum defect size was interpreted as an effective crack length ($a_{eff}$) and adopted in a fracture mechanics-based fatigue limit model. X-ray CT analysis also allowed to determine the critical size of subsurface and internal defects, which was subsequently compared with the critical surface defect population characterised by OP. Finally, the estimated fatigue thresholds were compared with the experimentally determined fatigue limit for each specimen series. The results show that the proposed approach captures the effect of surface roughness condition on the fatigue limit.

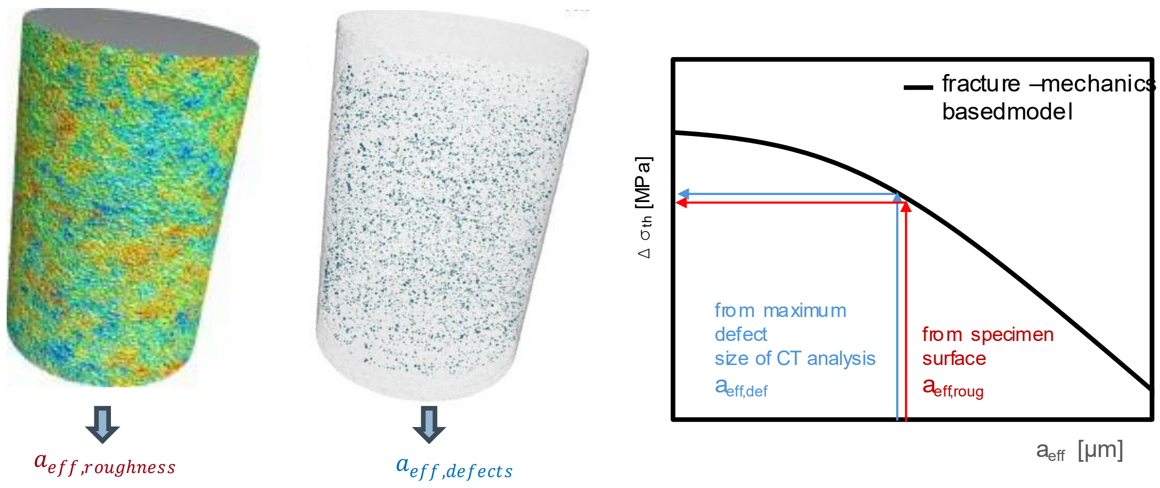



***Figure 1** – Schematic representation of the effect of roughness and internal defects throughout the fracture mechanics-based approach*

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# A new fatigue damage evaluation for multiaxial variable amplitude fatigue lifetime assessment of steel welded joints according to the Peak Stress Method

**Alberto Campagnolo[1], Alberto Visentin[1] and Giovanni Meneghetti[1]**

*[1]Department of Industrial Engineering, University of Padova, Via Venezia 1, 35131 Padova, Italy*
giovanni.meneghetti@unipd.it

*Welded structure* *Multiaxial fatigue* *Variable amplitude*

**Abstract** The fatigue life assessment of welded structures is a critical task of structural engineering, particularly under complex multiaxial variable amplitude (VA) loading. Among local approaches, the Peak Stress Method (PSM) [1] is an FE-oriented tool for estimating Notch Stress Intensity Factors (NSIFs). By modeling weld toes and roots as sharp V-notches ($\rho = 0$), the PSM enables the use of coarse FE meshes to calculate singular peak stresses, which are converted into NSIF-based parameters through calibrated coefficients. In a previous study [2], the PSM was extended from constant amplitude (CA) to variable amplitude (VA) uniaxial and multiaxial loadings. This formulation combined the PSM with the Palmgren-Miner linear damage rule (LDR) to account for cumulative damage. The procedure involved applying the Rainflow cycle counting algorithm to the time-histories of mode I, II, and III peak stresses to determine the stress spectra. These were then used to define equivalent constant amplitude peak stress histories, combined into a single multiaxial equivalent peak stress range $\Delta\sigma_{eq,peak}$. This parameter was compared against fatigue design curves selected based on the local biaxiality ratio $\lambda$. Although validated against approximately 900 experimental data points with good agreement for the majority of test series, the fatigue damage evaluation highlighted complexities in certain multiaxial loading situations. In the present work, a new formulation of the fatigue damage estimation is proposed to address these limitations. While still utilizing the Palmgren-Miner LDR to analyze individual loading modes, the new approach estimates the fatigue damage contributions from mode I ($D_I$), mode II ($D_{II}$), and mode III ($D_{III}$) local stresses independently and addressing the respective mode-specific design curves. The total damage is then evaluated as the sum of these components: $D_{tot} = D_I + D_{II} + D_{III}$, the critical damage being $D_{tot,critical} = 1$ for 50% survival probability. By adopting this mode-based damage summation approach, previous limitations could be fixed. The new fatigue evaluation has been validated against experimental fatigue data from the literature, demonstrating good accuracy and ease of implementation for complex industrial applications.

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# Impact of Heat Treatments on the Fatigue Behaviour of AlSi10Mg Processed by PBF-LB/M

**João Marques[1,2], Afonso Leite[1], Pedro Jesus[1,3], Carla M. Ferreira[1,4], José Simões[1], Maria J. Carmezim[1,5], Célio Pina[1,6], Rodolfo Batalha[1,6], Luís Reis[4], Ricardo Cláudio[1,4,7]**

[1]*ESTSetúbal, Instituto Politécnico de Setúbal, 2910-761 Setúbal, Portugal.*

[2]*Atlantica – Instituto Universitário, Fábrica da Pólvora de Barcarena, 2730-036 Barcarena, Portugal.*

[3]*LAUAK Portugal, Rua do Bairro da Estação, Grândola, 7570-205, Portugal.*

[4]*IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal.*

[5]*CQE, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, Lisboa, 1049-001, Portugal*

[6]*Instituto de Soldadura e Qualidade, Av. Prof. Dr. Cavaco Silva, Porto Salvo, 2780-920, Portugal.*

[7]*DICE Lab, Instituto Politécnico de Setúbal, Setúbal, Portugal.*

*PBF-LB/M* *Rotating-Bending Fatigue* *Heat Treatments* *X-Ray Computed Microtomography*

**Abstract**

Powder Bed Fusion of metals processed by Laser Beam (PBF-LB/M) is an Additive Manufacturing (AM) technique that uses a laser beam to selectively melt powder, layer by layer. When compared with traditional manufacturing processes, PBF-LB/M enables the creation of complex geometries with high buy-to-fly ratios, but it inherently generates surface roughness and defects like lack-of-fusion, keyhole or gas pores which can impair the mechanical performance of components, particularly under cyclic loading conditions. Fatigue is a critical consideration in demanding applications, such as critical components for aircrafts, where structural reliability and long-term performance are paramount. Post-processing heat treatments are widely applied to modify the microstructure, relieve residual stresses, and improve the mechanical performance of PBF-LB/M materials. Nevertheless, the influence of different thermal treatments on the high-cycle fatigue behaviour of additively manufactured AlSi10Mg remains insufficiently understood, especially when considering their interaction with inherent process-induced defects. In this study, AlSi10Mg fatigue specimens were produced via PBF-LB/M and divided into several batches to evaluate the influence of thermal post-processing in accordance with ASTM F3318 standard. A reference batch was tested in the as-built (AB) condition, while additional batches were subjected to different heat treatments, including T6, direct aging (DA), and a novel thermal treatment at 150 °C for 2 hours. High-cycle fatigue tests were performed under controlled rotating-bending loading conditions to assess the effect of each heat treatment on fatigue life. Important parameters such as surface roughness, geometry, location and nature of defects were assessed via X-ray Computed Microtomography (μCT) and analysed to investigate the influence of the defects on the fatigue life and behaviour of additively manufactured AlSi10Mg specimens. The results provide a comparative evaluation of the different heat treatment strategies and their impact on fatigue performance. This study highlights the critical role of thermal post-processing in tailoring the mechanical response of PBF-LB/M AlSi10Mg components. The findings provide practical guidance for selecting heat treatments for fatigue-critical applications, supporting safer and a more reliable use of additively manufactured aluminium alloys across several industries such as aerospace and automotive.

# A local approach to understanding the bimodal fatigue behavior of gear teeth made from case-hardened steel

**Aniclelson ALVES DE MOURA[1,2], Franck MOREL[1], Etienne PESSARD[1], Daniel BELLETT[1], Louis AUGUSTINS[2], Damien HERISSON[2]**

*[1]LAMPA, Arts et Métiers Institute of Technology, 2 Bd du Ronceray, 49035 Angers, France*
*aniclelson.alves_de_moura@ensam.eu*
*[2]Safran Tech, Materials and Processes Department, Rue des Jeunes Bois, Chateaufort, 78114 Magny-Les-Hameaux, France*

*HCF and VHCF* *Material property gradients* *Crack initiation*

**Abstract:** The gears used in aircraft engines are typically made from steel superficially reinforced by thermochemical treatments (TTCh). These treatments increase the local fatigue strength in the surface layers through microstructural modifications, enhancing the surface hardness and adding a compressive residual stress distribution. In some cases, the combination of the material, TTCh and the applied cyclic loads can lead to a bimodal behavior in terms of the fatigue life. This behavior occurs due to competition between different crack initiation mechanisms, characterized by very different crack initiation kinetics. The present work investigates the bimodal fatigue behavior of the case-hardened M50NiL steel and aims to identify and quantify the influence of the strength and applied stress distributions in the surface layer, with the objective of proposing an appropriate fatigue modeling approach. An extensive experimental fatigue campaign to investigate three TTCh treatments, was conducted: a carburizing treatment and two duplex treatments (carburizing followed by nitriding). Fatigue tests were performed on notched specimens loaded in plane bending and on gears using Single Tooth Bending Fatigue (STBF) tests. Given that the hardness, residual stresses, and the maximum applied stresses vary as a function of the distance from the notch tip, this implies that the stress ratio of the local cyclic stress is not constant along this distance. This has important consequences as failures in the HCF and VHCF domain often occur as internal fish-eye cracks. Consequently, an analysis based solely on the maximum surface stress and the applied load ratio is insufficient to describe the fatigue behavior. Within this framework, a short crack propagation model based on Murakami's local fatigue limit ($\sigma_w$) concept has been proposed to predict the bimodal fatigue life, incorporating different initiation mechanisms, the local material properties, and the defect size. This modeling approach makes it possible to estimate two distinct fatigue limits associated with surface and internal crack initiation mechanisms (Figure 1). Although these limits correspond to different defect size ranges, they may overlap. In which case, surface and internal defects can exhibit comparable fatigue strength due to the same stress level. This overlap defines a competition zone between crack the initiation mechanisms, leading to bimodal fatigue behavior, with the dominant mechanism governed by the local conditions.

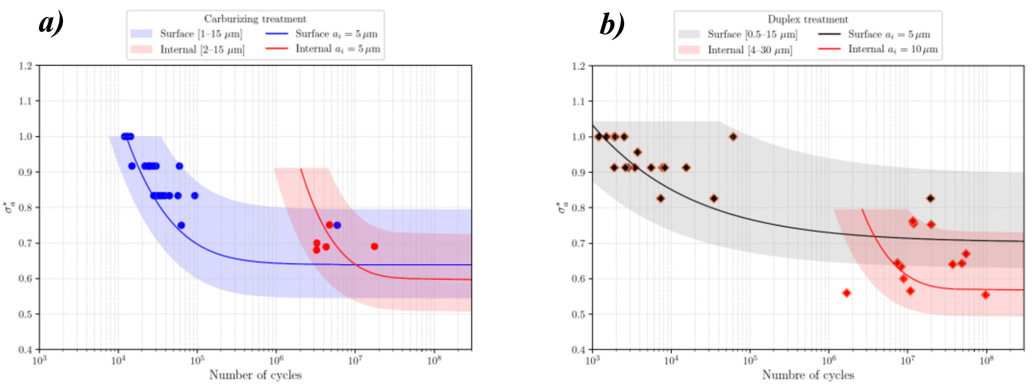



***Figure 1*** *– Normalized S–N curves for bimodal fatigue life prediction of TTCh steel, based on a local modeling approach using properties at the crack initiation site and the defect size distribution. (a) Carburized treatment; (b) duplex treatment.*

# Influence of microcracks on fatigue behaviour of welded joints

**Simon Sedmak[1], Mihajlo Aranđelović[1], Stefan Dikić[2], Lazar Jeremić[1], Milan Ostojin[3]**

[1]*Innovation Center of Faculty of Mechanical Engineering, Kraljice Marije 16, 11120 Belgrade, Serbia*

[2]*University of Belgrade, Faculty of Technology and Metallurgy, Karnegijeva 4, 11120 Belgrade, Serbia*

[3]*Naftagas - Tehnički servisi d.o.o., Pančevo, Serbia*

*Fatigue crack growth* *Welded joint* *Finite element method*

**Abstract** The goal of this research was to determine how the presence of microcracks in the welded joint root could affect its fatigue life. After the welded joint was made, non-destructive test methods were used to determine the presence of potential defects, and two microcracks, with lengths of 0.2 and 0.3 mm were detected in the weld root area. It was then determined numerically that these microcracks do not have significant influence of the integrity of the welded joint in the case of static loading, but the question still remained about what would happen if this welded joint was subjected to variable, cyclic loading. Numerical simulations of fatigue crack growth were performed using SMART crack option, with a model that included both cracks simultaneously (as opposed to previous analyses where only one crack could be defined at a time).

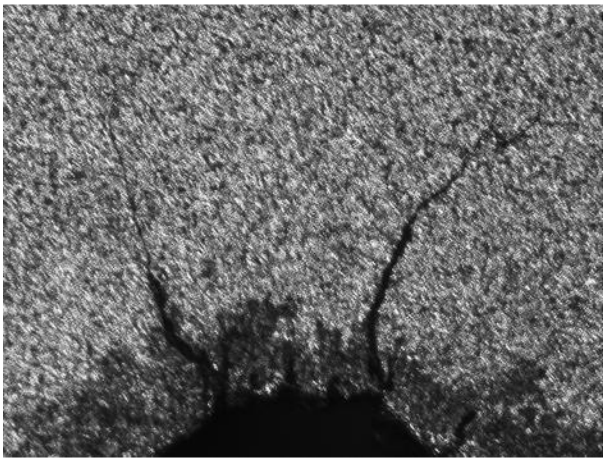


***Figure 1 -*** *Microcracks in the welded joint root*

# Non-uniform deformation and damage evolution of gradient nano-grained metals: A crystal plasticity simulation

**Jie Qu[1], Zhixin Zhan[1], Weiping Hu[1], Qingchun Meng[1]**

[1] *National Key Laboratory of Strength and Structural Integrity, School of Aeronautic Science and Engineering, Beihang University, Beijing 102206,*

*China*

*Gradient nano-grained metals* *Crystal plasticity* *Damage evolution*

**Abstract** The development of gradient nano-grained (GNG) metals represents an innovative design strategy for metallic materials to overcome the strength-ductility trade-off from the perspective of microstructural heterogeneity. However, despite their promising potential for engineering applications, the lack of in-depth understanding regarding microscopic damage mechanisms of GNG metals is a major constraint. In this work, to address this challenge, we develop a simulation framework for GNG metals based on the crystal plasticity finite element (CPFE) method. The continuous grain size gradient feature within the representative volume element (RVE) is achieved by introducing a spatially weighted Voronoi tessellation method to represent the spatial heterogeneity of the GNG structure. In addition, a crystal plasticity constitutive model coupled with a strain energy density (SED)-based damage criterion is established to investigate the failure mechanisms. After validating the model against existing experimental data, the discrepancies in damage evolution predictions between the SED-based and cumulative plastic strain criteria under various tensile strains are systematically analyzed. Simulation results show that the SED-based damage criterion outperforms the strain-based approach by identifying failure risks in high-stress fine grains, rather than erroneously predicting damage in coarse grains. This investigation provides critical insights into the damage evolution mechanism in gradient microstructures under non-uniform deformation, offering a vital basis towards understanding the low-cycle fatigue failure of GNG metals.

# Effect of heat treatment on very high cycle rotating bending fatigue properties of rail steel

**Noriyasu Oguma[1], Mitsuru Hosoda[2], Jun Mizutani[2], Tadashi Deshimaru[2]**

[1]*Faculty of engineering, University of Toyama, 3190 Gofuku, Toyama-city, Toyama 930-8555, Japan*
*e-mail: oguma@eng.u-toyama.ac.jp*

[2]*Track technology division, Railway Technical Research Institute, Japan*

*Rail steel* *Residual stress* *Crystal distortion*

**Abstract** The bottom of a railway rail is subjected to repeated bending stresses over long periods of time due to the movement of railway vehicles. Rails are required to be replaced at designated intervals to ensure safe operation. Because replacement is extremely costly, extending the replacement interval while maintaining the fatigue strength reliability of railway rails is essential. In this study, fatigue specimens were cut from the bottom of actual railway rails and their very high cycle rotating bending fatigue properties were evaluated. Railway rails were prepared using ordinary steel specified in JIS E1101 and heat-treated steel specified in JIS E1120. The heat-treated steel exhibited a hardness increase of approximately 30 to 80 HV, and residual stress varied depending on the cutting position from the rail, with significant heat treatment strain in the center. As shown in Fig. 1, the fatigue test results show that the heat-treated steel has a higher fatigue strength than ordinary rail steel. In particular, the fatigue strength of the specimens taken from the center (HT middle) where the heat treatment strain is larger, is higher than that of the specimens taken from the edge (HT side). Both steels exhibited a clear fatigue limit, and no specimens were observed to failure in the very high cycle regime. This suggests that the presence of inclusions or segregations that could serve as internal initiation sites is extremely unlikely. Furthermore, the fatigue limits in this experiment were higher than those estimated from Vickers hardness, and were in good agreement with those estimated from hardness calculated from crystal distortion using X-ray diffraction parameter.

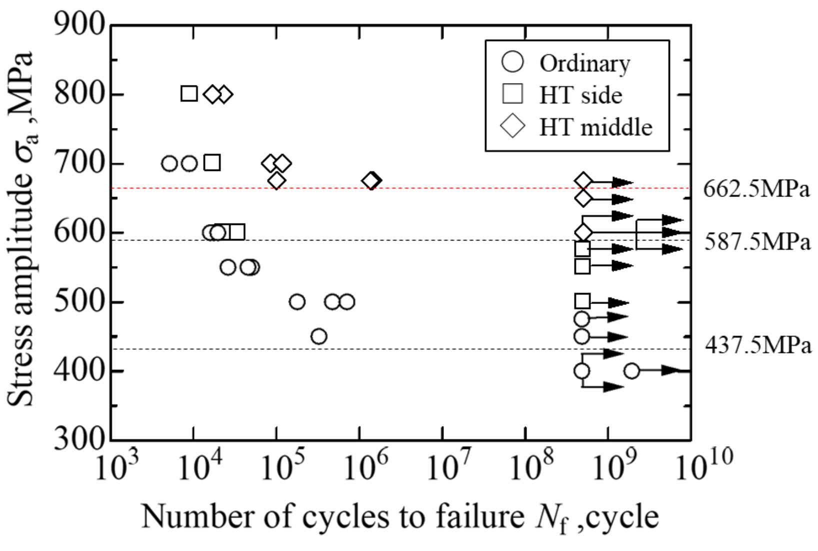



***Figure 1*** *– S-N properties of the ordinary rail steel and the heat-treated rail steel*

# Melt Pool Signatures as Indicators of Defects and their Impact on Rotating-Bending Fatigue Samples Produced by PBF-LB/M

**Carla M. Ferreira[1,2*], Afonso Leite[1], João Marques[1,3], José Simões[1],**

**Pedro Jesus[14], Rodolfo Batalha[1,5] Luís Reis[2], Ricardo Cláudio[1,2,6]**

[1]*ESTSetúbal, Instituto Politécnico de Setúbal, 2910-761 Setúbal, Portugal.*

[2]*IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal.*

[3]*Atlantica – Instituto Universitário, Fábrica da Pólvora de Barcarena, 2730-036 Barcarena, Portugal.*

[4]*LAUAK Portugal, Rua do Bairro da Estação, Grândola, 7570-205, Portugal.*

[5]*Instituto de Soldadura e Qualidade, Av. Prof. Dr. Cavaco Silva, Porto Salvo, 2780-920, Portugal.*

[6]*DICE Lab, Instituto Politécnico de Setúbal, Setúbal, Portugal.*

*PBF-LB/M*     *Rotating-Bending Fatigue*     *Melt Pool Monitoring*     X-ray computed microtomography

**Abstract**

Additive Manufacturing (AM) by Laser Powder Bed Fusion of Metals (PBF-LB/M) continues to expand into safety-critical applications, where fatigue performance is a dominant requirement. Process-induced defects like lack of fusion and keyhole porosity remain major drivers of fatigue uncertainty, especially when located near the surface of a component. Built upon previous works from the authors that explored the possibility of establishing correlations between melt pool emission signatures and defect morphology in static tensile specimens, this study extends the methodology to rotating-bending fatigue AlSi10Mg samples.

Fatigue specimens were produced with optimum printing parameters and Melt Pool Monitoring (MPM) data was investigated through histogram-based descriptors and spatial emission patterns. This information was subsequently correlated with defect morphology, size, type, and location obtained from high-resolution X-ray computed microtomography (µCT). Furthermore, fatigue testing under rotating-bending scenarios were performed to obtain the S–N curve and infer the influence of defects on fatigue life. Results suggest that defects located closer to the surface deteriorate the fatigue performance, and that specific MPM emission signatures may be associated with these critical flaws. The combined analysis demonstrates the potential of MPM not only as an in-situ defect detection tool, but also as a potential predictor of fatigue live based on defect morphology and location. This work contributes to the development of data-driven quality control strategies for PBF-LB/M while supporting real-time fatigue life prediction.

# Effect of Laser Peening on Residual stress and Fatigue properties of Metal Additive Manufacturing Materials

**Yoshio Mizuta[1], Satoshi Tamaki[1], Kiyotaka Masaki[2], Koichi Akita[3], Niroj Maharjan[4], Andrew Ang[4], Tomonao Hosokai[1], Yuji Sano[1,5,6]**

*[1]SANKEN, The University of Osaka, 8-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan*
*y.mizuta@sanken.osaka-u.ac.jp*

*[2] Saitama Institute of Technology*

*[3]Tokyo City University*

*[4]Swinburne University of Technology*

*[5]Nagoya Industrial Science Research Institute*

*[6]National Institutes of Natural Sciences*

*Laser peening* *Metal additive manufacturing* *Extending fatigue life*

**Abstract** Metal additive manufacturing (AM) is a fabrication technology in which metal powder is melted and solidified using a heat source such as a laser or an electron beam, and three-dimensional components are produced by stacking the material layer by layer. This technology enables the fabrication of complex geometries that are difficult to achieve using conventional subtractive manufacturing methods. In addition, because no mold is required, AM offers advantages in reducing mold storage costs and the time and effort needed for design modifications. The main applications of metal additive manufacturing span a wide range of fields, including aerospace, medical and dental applications, the automotive industry, and industrial machinery.

Despite its many attractive features and broad applicability, AM-fabricated materials have been reported to exhibit lower fatigue strength compared with materials produced by conventional manufacturing processes. To address this issue, we have focused on laser peening (LP) as one of the potential solutions and have been conducting research and development in this area.

Laser peening is a surface treatment technique that utilizes high-pressure plasma generated by laser irradiation, enabling the introduction of compressive residual stress from the material surface into the subsurface region. This compressive residual stress suppresses the initiation and propagation of cracks, thereby improving fatigue strength and extending the fatigue life of the material.

This presentation will report on the effectiveness of improving surface residual stress and the potential for enhancing fatigue properties in metal additive manufacturing materials using microchip lasers.

# Effect of Welding Pressure on Microstructure and Properties of Linear Friction Welded Joints of 7050-T7451 Aluminum Alloy

**Xinwei Wang[1], Chuanchen Zhang[1], Ju Li[1]**

[1] *Aeronautical Key Laboratory for Welding and Joining Technologies, AVIC Manufacturing Technology Institute, Beijing, People's Republic of China*

*Wang_xinwei@qq.com*

*Linear friction welding* *7050-T7451 aluminum alloy* *High cycle fatigue*

**Abstract** This study investigated the effect of welding pressure (60–240 MPa) on the microstructure and mechanical properties of linear friction welded (LFW) joints of 7050-T7451 aluminum alloy, with a focus on their high-cycle fatigue behavior and the fatigue and fracture mechanisms of weldments. Results indicated that welding pressure was a critical parameter governing joint integrity and performance. Insufficient pressure (60 MPa) led to low interfacial heat input, inadequate plastic flow, and extensive defects (voids, unwelded interfaces) within the weld zone (WZ), resulting in low tensile strength (415 MPa) and brittle fracture. When the pressure was optimized to 180 MPa, sufficient thermomechanical coupling promoted dynamic recrystallization, eliminated defects, and significantly refined WZ grains (average size decreased from 5.75 μm at 60 MPa to 2.37 μm at 180 MPa). Joints fabricated at this optimal pressure exhibited the best overall performance: a maximum ultimate tensile strength of 506 MPa (92.4% of the base material) with ductile fracture occurring in the thermo-mechanically affected zone (TMAZ), and a median fatigue limit of 230.8 MPa determined via the up-down method under a stress ratio (R) of 0.1, reaching 92.7% of the base material's fatigue limit (249 MPa). Fractographic analysis revealed that fatigue cracks initiated from stress concentration sites at the specimen corners. The crack propagation zone exhibited typical fatigue striations, and no welding defects were observed at the crack initiation site, confirming the high reliability of the joint. Excessive pressure (240 MPa) induced macroscopic cracks in the flash. This work demonstrates that optimizing welding pressure is key to producing high-integrity 7050 aluminum alloy LFW joints with superior static and high-cycle fatigue properties.

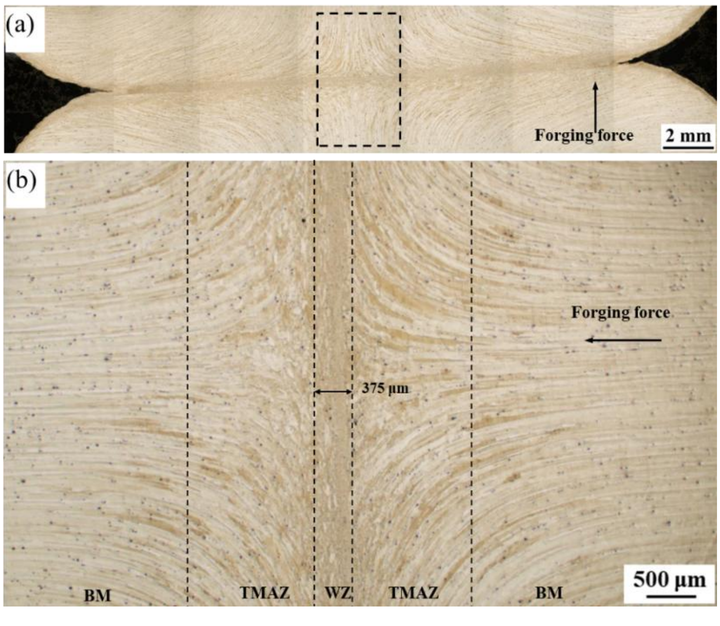



***Figure 1 -*** *Microstructure of LFW Joint*

# Application of a computationally efficient fretting wear-fatigue analytical model to submarine power cables

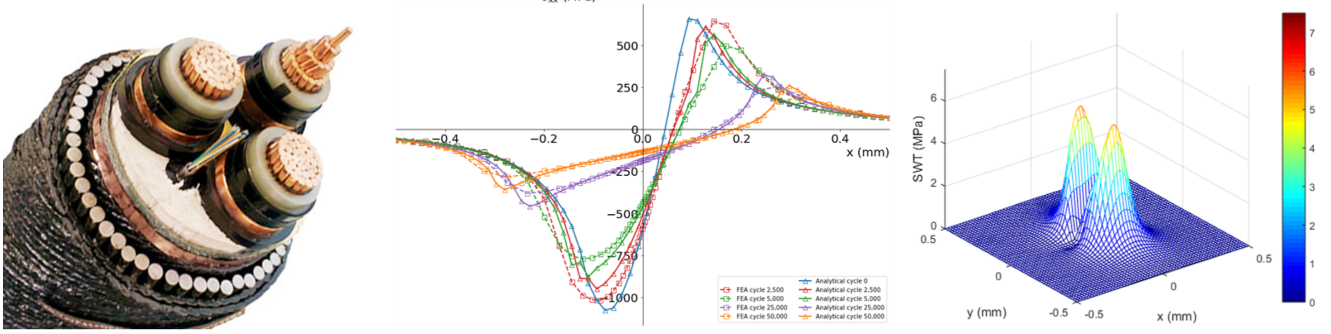
**S.M. Uí Mhurchadha [1], C. Poon[2, 3], S.B. Leen[2, 3, 4]**

*[1]Department of Science, School of Science and Computing, South East Technological University, Cork Rd Campus, Waterford X91 KOEK Ireland*
*[2]Mechanical Engineering, School of Engineering, College of Science and Engineering, University of Galway, University Road, Galway H91 HX31, Ireland*
*[3] MaREI SFI Research Centre for Energy, Climate and Marine, University of Galway, Ireland*
*[4] I-Form Advanced Manufacturing Research Centre, University of Galway, University Road, Galway H91 HX31, Ireland*

*Fretting wear* *Fatigue crack initiation* *Three-dimensional contacts*

**Abstract** This work presents the application of a computationally-efficient fretting wear-fatigue model to complex three-dimensional fretting contacts representative of submarine power cables. Modelling of three-dimensional contacts is not trivial and the computational cost of three-dimensional finite element models that include incremental wear simulation is often prohibitive across multiple load cases, as required for submarine dynamic structures. Submarine power cables consist of conductors with multiple helically-wound, inter-contacting wires (Figure 1 (a)) which experience micro-scale displacements due to dynamic global loading, with potential for wear and fatigue damage or cracks.

A validated finite element computationally-efficient analytical three-dimentional fretting wear-fatigue model is presented and applied to cylinder-on-cylinder contacts representative of helically-wound copper wires in submarine power cables. The analytical model is based on quadratic programming and has been shown to accurately predict wear-induced evolutions of contact pressure, subsurface stresses and multiaxial fatigue indicator parameter distributions, as well as numbers of fretting cycles to fatigue crack initiation in evolving fretting wear contacts, as shown in Figure 1. This work can be used to rapidly generate physically-based nueral networks for digital twin representation of such three-dimensional fretting wear-fatigue behaviour, leading to more accuract service life predicitons and perhaps design for dynamic offshore structures.




(a) (b) (c)

***Figure 1** – (a) An example of a submarine power cable (www.ssgcable.com), (b) subsurface stress evolution due to fretting wear, (b) multiaxial fatigue damage distribution.*

# Very-high-cycle fatigue (VHCF) predictions in the presence of mean stresses and non-metallic inclusions

**J.A. Araújo[1], M.V. Pereira[1]**

*[1]Pontifical Catholic University of Rio de Janeiro – PUC-Rio, Department of Chemical and Materials Engineering, Rua Marquês de São Vicente 225, Rio de Janeiro, Brazil. joaoaraujo667@gmail.com*

*Goodman model* *Murakami model* *Al 6351 T6 and DIN 34CrNiMo6*

**Abstract** With technological advancement, equipment in several areas of engineering experience large quantities of loading cycles within their service life. The need to understand fatigue behavior for lives beyond $10^7$cycles fostered the use of ultrasonic equipment capable of producing loadings at a frequency of 20 kHz. Although this new testing method brings benefits in generating information about fatigue life of materials in a short period of time, it is seen in the literature that several classical fatigue life prediction models require adjustments, since failure characteristics change when the VHCF regime is reached, such as the change in the initiation site, which migrates from the surface to metallurgical defects in the bulk of the specimen. In this context, this work proposed to evaluate classical fatigue life prediction models with the presence of mean stress using Murakami's approach under the effect of non-metallic inclusions. To achieve the scope, two metallic alloys were selected, Al 6351 T6 and DIN 34CrNiMo6 steel. Metallographic tests were conducted to evaluate the non-metallic inclusions. Subsequently, a hole with a depth equivalent to the √area of the projection of the largest inclusion in each material was machined in its critical region. Finally, both materials were tested in ultrasonic equipment for different load ratios ($R \neq -1$). Murakami's approach proved to be conservative for the DIN 34CrNiMo6 steel and non-conservative for the Al 6351 T6 alloy. In comparison with the classical models of Goodman, Gerber, and Soderberg, Goodman better assimilated Murakami's predictions for both alloys. The high hardness of the steel resulted in Murakami's equation high values of fatigue limit, making the Goodman and Soderberg models more conservative. On the other hand, the lower hardness of the aluminum brought the alloy closer to both the Goodman and Gerber models, making the Soderberg model extremely conservative.

# Advancing VHCF Characterization of Cantilevered Bending Specimens via Ultrasonic Fatigue Testing

**A. Oliveira[1], J. H. Lopes[1,4], P. Costa[2,3], R. Cláudio[5], R. Batalha[6], L. Reis[1,4]**

[1]*Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal*

[2]*Atlantica Instituto Universitário, Barcarena, Portugal*

[3]*Centre for Mechanical and Aerospace Science and Technologies (C-MAST), Covilhã, Portugal*

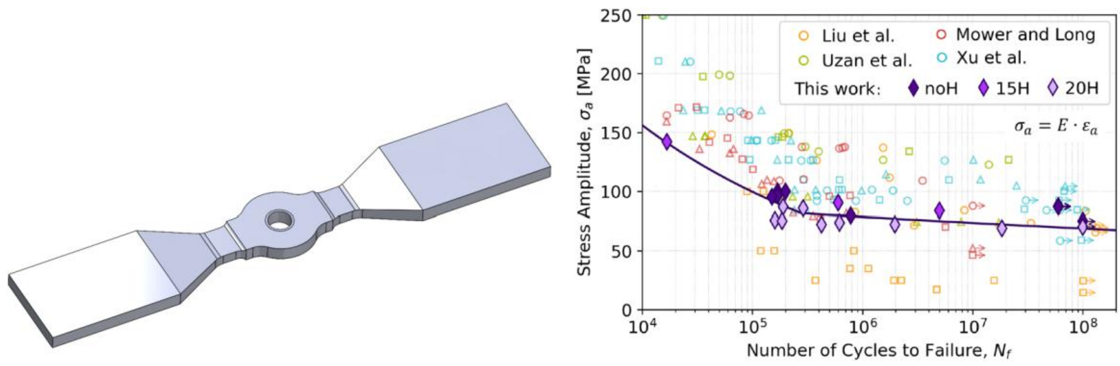
[4]*IDMEC, Instituto Superior Técnico, Lisbon, Portugal - luis.g.reis@tecnico.ulisboa.pt*

[5]*ESTSetúbal, Instituto Politécnico de Setúbal, 2910-761 Setúbal, Portugal*

[6]*Instituto de Soldadura e Qualidade, Taguspark-Oeiras, 2740-120 Porto Salvo, Portugal*

*Ultrasonic fatigue testing* *Plane bending specimen design* *Additive Manufacturing*

**Abstract** Many high-level industries, such as aerospace and naval, require components or parts subjected to complex loading conditions that withstand billions of cycles during their service life. Recent developments in Metal Additive Manufacturing (AM) have provided the conditions to fulfil the geometric requirements of Ultrasonic Fatigue Testing (UFT) under loading conditions different from the standard longitudinal uniaxial, thus bridging the gap between material and component testing. The present work introduces a design methodology to test the fatigue behaviour of the Laser Beam Powder Bed Fusion (LB-PBF) AlSi10Mg alloy under plane bending condition. Three different ultrasonic geometries were additively manufactured following a numerical analysis to ensure excitation in the bending stress ratio of R=-1 at the frequency of 20 kHz and an appropriate distribution of bending stresses across all designs. Experimental validation and fatigue testing were conducted through the ultrasonic setup developed at Instituto Superior Técnico (IST), Universidade de Lisboa using a control system of crack initiation detection through the monitoring of the specimens' displacement amplitude. The S-N curve shows similar behaviour to the literature data of this alloy for rotating bending under the same stress ratio, exhibiting a horizontal asymptote above $10^6$ cycles and crack initiation mainly at the surface.




a) b)

***Figure 1** – a) Ultrasonic bending fatigue geometry and b) S–N curve of AM AlSi10Mg*

# Accelerated Fatigue Test Comparison for Additively Manufactured Aluminum and Aluminum Matrix Composite

**Onome Scott-Emuakpor[1], Philip Johnson[2], Harshith Vadrevu[3], and Troy Krizak[4]**

[1]*Hyphen Innovations, 3250 Kettering Blvd, Moraine, OH 45439, onomese@hyphenmade.com*
[2]*Hyphen Innovations, 3250 Kettering Blvd, Moraine, OH 45439, philip@hyphenmade.com*
[3]*Hyphen Innovations, 3250 Kettering Blvd, Moraine, OH 45439, harshith@hyphenmade.com*
[4]*Hyphen Innovations, 3250 Kettering Blvd, Moraine, OH 45439, troy@hyphenmade.com*

*Fatigue* *Additive Manufacturing* *Vibration*

**Abstract:** Accelerated fatigue testing provides a method to gather data that cuts testing time, reduces total costs, and speeds up product launches into disruptive industries. The need for accelerated fatigue is based on the time and cost associated with standard test methods like ASTM E466 and ISO 1143. Specifically, standard tests like axial load-controlled (ASTM E466) and rotating bending fatigue (ISO 1143) gather data between 5-20 Hz, depending on the material. The accelerated fatigue test method gathers data as high as 6000 Hz.

Accelerated fatigue testing is a resonance based bending method that uses the natural frequency of a test specimen and an excitation source to generate a critical strain amplitude on the specimen. This method allows for fatigue data to be gathered at high frequencies controlled by excitation source and test setup capabilities. Accelerated fatigue testing differentiates from existing very high cycle fatigue test methods in three areas. First, the parts, equipment, and electricity needed for testing are more affordable than comparable standard approaches. Second, simple instrumentation and test setups are employed. Third, minimal test operator bias makes test-to- test comparisons more accurate.

The major results in this work compare the accelerated fatigue dataset to standard fatigue data for multiple materials. The materials of interest in these comparisons are manufactured with the laser powder bed fusion (LPBF) additive manufacturing process. Specifically, AlSi10Mg LPBF accelerated fatigue specimens operating at 1150 Hz are compared against rotating bending fatigue specimens tested at 60 Hz. Also, LPBF oxide dispersion strengthened (ODS) Aluminum 5083 (A5083 RAM5) produces specimens fatigue tested with accelerated fatigue at 5560 Hz and axial fatigue at 5 Hz. The results highlight the discrepancy in build orientation associated with LPBF AM. Also, the comparison of accelerated fatigue and standard axial and rotating bending fatigue data shows consistency. The S-N plot in Figure 1 shows the visual accuracy in comparing accelerated fatigue and standard rotating bending fatigue of AlSi10Mg, thus proving the new accelerated fatigue testing method as a viable approach for gathering data.

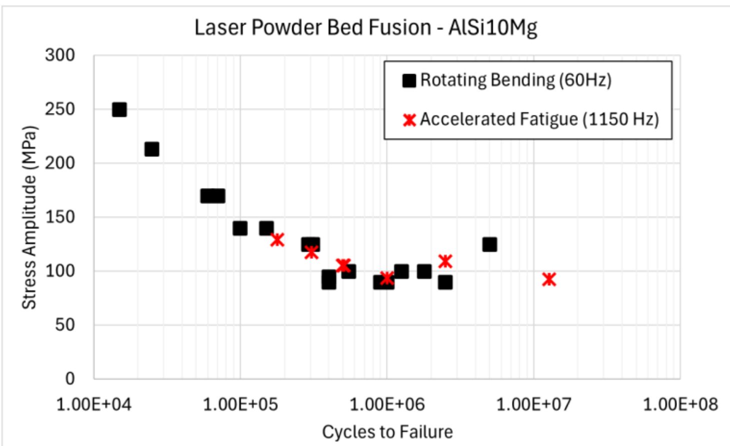



***Figure 1*** *– Comparison of accelerated fatigue and rotating bending fatigue for LPBF AlSi10Mg*

# Supporting the construction and wet-storage of concrete-manufactured platforms for floating offshore wind using advanced finite element simulations

**Arjun Janardhanan[1,*], Tiago Mota[1], Mário Vieira[1]**

*[1]WavEC Offshore Renewables, Edifício Diogo Cão, Doca de Alcântara Norte, 1350-352 Lisbon, Portugal*

*[*] arjun.janardhanan@wavec.org]*

*Floating offshore wind* *Prestressed reinforced concrete platform* *Hydrodynamic pressure mapping*

**Abstract** This study presents a computational workflow for evaluating stress distributions in reinforced and prestressed concrete floating platforms subjected to wave-induced loading during wet-storage conditions. The workflow is applied to a semi-submersible floating offshore wind platform at the construction stage, prior to tower and turbine installation, with particular focus on the simulation of post-tensioning sequences.

Hydrodynamic loads are computed in the frequency domain using ANSYS AQWA and transferred to a detailed finite element model developed in ANSYS Mechanical. Prestressing effects are introduced through the explicit simulation of post-tensioning sequences, allowing the stress state to evolve consistently with the construction process. Several structural configurations are investigated, including vertical and horizontal post-tensioning of columns and pontoons, as well as the inclusion of steel tie beams connecting the columns at the deck level.

The results show that reinforcement alone may lead to elevated tensile stress levels in localized regions under wave-induced loading. Horizontal and vertical post-tensioning affect distinct structural components, with horizontal post-tensioning primarily reducing stress levels in the pontoons and vertical post-tensioning improving the structural response of the columns. Combined post-tensioning configurations reduce global stress levels but may still result in localized stress concentrations. The inclusion of steel tie beams alters load redistribution patterns, emphasizing the importance of connection detailing at the beam-concrete interfaces.

Overall, the study highlights that the configuration and sequencing of post-tensioning, rather than prestress magnitude alone, play a key role in governing structural response during construction and wet-storage phases. The proposed workflow enables systematic identification of critical stress regions and supports informed refinement of reinforcement and post-tensioning strategies for concrete floating platforms.

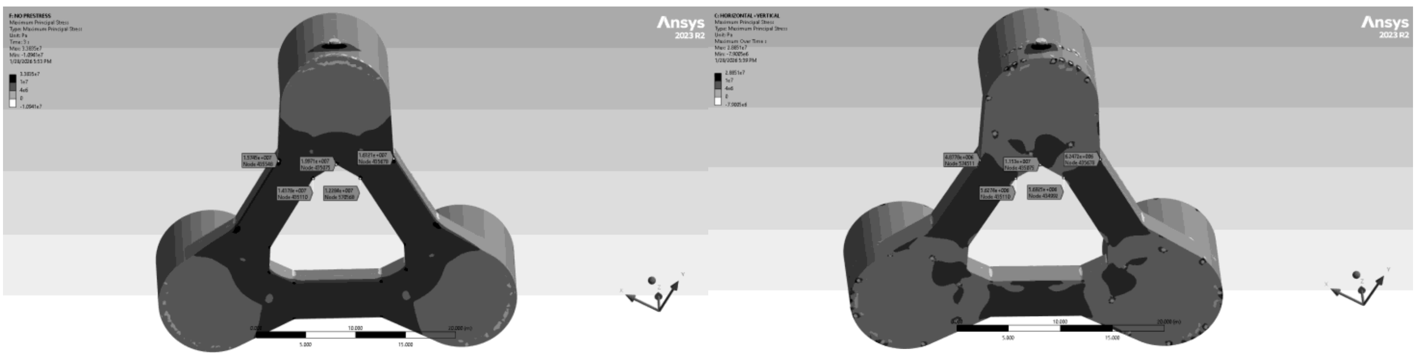



***Figure 1 – Maximum principal stress distribution in the concrete under hydrodynamic loading, comparing the platform without prestressing (left) and with prestressing (right).***

# Application of energy-based damage accumulation rule for fatigue monitoring of structure under variable amplitude loading

**Matus Margetin[1], Vladimir Chmelko[2], Jakub Hujavy[3]**

*[1]Slovak University of Technology, Faculty of Mechanical Engineering, Institute of applied mechanics and mechatronics, Námestie slobody 17, 812 31 Bratislava, Slovak republic, matus.margetin@stuba.sk*
*[2]Slovak University of Technology, Faculty of Mechanical Engineering, Institute of applied mechanics and mechatronics, vladimir.chmelko@stuba.sk*
*[3]Slovak University of Technology, Faculty of Mechanical Engineering, Institute of applied mechanics and mechatronics, jakub.hujavy@stuba.sk*

*Damage accumulation rule fatigue monitoring variable amplitude loading*

**Abstract** Fatigue lifetime estimation of engineering structures loaded by operational variable amplitude loading is usually based on accumulation of damage caused by loading cycles identified from loading process. While damage accumulation rule proposed by Palmgren and Miner is still wildly used, other rules leading to more accurate estimation have been proposed in last decades. The scope of this article is to provide methodology how to use energy-based damage accumulation rule proposed by Kliman (1985) in case of online lifetime monitoring system. Two possible application of damage accumulation rule are discussed: the system for estimation of remaining lifetime in probabilistic form and system for estimation of failure probability. In both case loading conditions are represented by block of harmonic cycles obtained from loading signal using standardized rainflow method modified for continual stress measurement.

# A Dynamic Bayesian Network Framework for Fatigue Life Prediction of Welded Connections

**Caroline Correa de Faria[1], Cláudio Carlos da Silva Horas[2], Túlio Nogueira Bittencourt[3]**

[1,3]*Department of Structural and Geotechnical Engineering, University of São Paulo, Av. Prof. Almeida Prado, São Paulo, 05508-900, Brazil – e-mail (CCF): carolinecorreaf@usp.br*

[2]*Faculty of Engineering, University of Porto, Portugal*

*Fatigue life prediction* *Dynamic Bayesian Network* *Welded connections*

**Abstract** Fatigue is a damage accumulation process caused by cyclic loading and is one of the main failure modes in welded structural components, including those found in steel railway bridges. Its assessment is affected by significant uncertainties in material and geometric properties, loading conditions, and damage models, which make probabilistic approaches suitable for fatigue life evaluation. Within this framework, Dynamic Bayesian Networks (DBNs) provide a consistent and flexible methodology for combining expert judgment with physical, numerical, empirical, and data-driven models. DBNs have three main components: representation, inference, and learning. Their structure enables modeling of systems that evolve over time (Figure 1). Inference procedures enable structural assessment under uncertainty, including prediction of remaining useful life with or without observational evidence. When evidence is available, predictions can be updated using data on model parameters or state variables obtained from inspections, structural health monitoring systems, or field measurements. In addition, DBNs support the discovery of relationships among variables based on experimental, synthetic, or numerical datasets. This work addresses the development and application of a Dynamic Bayesian Network for fatigue life assessment of welded connections, with emphasis on railway bridge applications. The capabilities and limitations of the DBN framework are evaluated through case studies involving fatigue tests on welded steel beam connections, considering both stress-based approaches and linear elastic fracture mechanics methods.

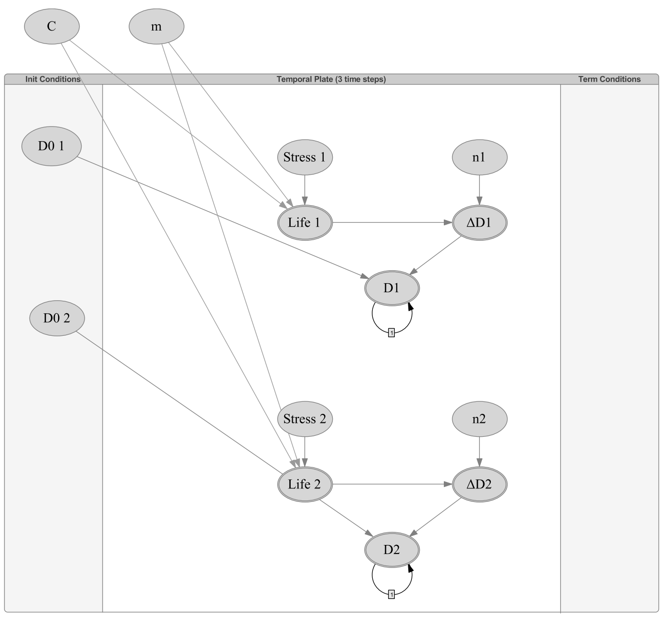



***Figure 1 –*** *DBN model for two welded components with similar material properties*

# The role of shot peening for a better fatigue behavior of additive manufactured materials and components

**Mario Guagliano[1], Erencan Oranli[1], Sara Bagherifard[1]**

*Politecnico di Milano, Dept. Mechanical Engineering, Via La Masa, 1 - 0156 Milan (Italy)*

*Shot peening* *Additive Manufacturing* *Fatigue*

**Abstract** Metal additive manufacturing (AM) is gaining increasing attention due to its unique ability to fabricate components with highly complex geometries, internal features, and customized designs that are difficult or impossible to achieve with conventional manufacturing routes. These advantages make AM particularly attractive for high-performance applications across aerospace, automotive, biomedical, and energy sectors. However, despite these benefits, the mechanical properties and fatigue performance of materials and components produced by AM processes are often inferior to those of conventionally manufactured parts. As a result, suitable post-processing treatments are generally required to enhance surface integrity and overall mechanical performance.

Among the available post-processing techniques, shot peening represents one of the most attractive solutions for improving fatigue strength, owing to its relatively low cost, high flexibility, industrial maturity, and reduced environmental impact compared to alternative surface treatments. Nevertheless, the distinctive surface condition of additively manufactured parts—characterized by high roughness, partially melted particles, and process-induced defects—means that the application of shot peening cannot be directly transferred from conventional materials and must instead be carefully designed and optimized.

In this presentation, after introducing the fundamentals of the shot peening process, its main effects, and the specific challenges associated with its application to additively manufactured components, the results of a comprehensive experimental campaign are presented and critically discussed. The analysis is carried out in the light of the three main effects induced by shot peening: the introduction of compressive residual stresses, surface work hardening and grain refinement, and modifications to surface roughness.

The role of each of these factors in determining the fatigue strength of AM parts is examined in detail, and their mutual interactions and dependence on the main process parameters are highlighted. Finally, the concept of hybrid surface treatments is introduced, focusing on the combined application of shot peening with other finishing processes, with the aim of further enhancing fatigue performance and tailoring surface properties to specific application requirements.

# Robotic 3D printing of continuous flax fibers composites

**Zouheyr Belouadah[1], Marcelo Tanglao[1], Ahmed Sarwar[1], Toubal Lotfi[2], Donatus Oguamanam[1], Habiba Bougherara[1]**

[1]*Department of Mechanical, Industrial, and Mechatronics Engineering, Toronto Metropolitan University, 350 Victoria Street, Toronto, ON M5B2K3, Canada, zouheyr.belouadah@torontomu.ca*

[2]*Innovations Institute in Ecomaterials, Ecoproducts and Ecoenergy (I2E3), Université du Quebec à Trois-Rivières, 3351 boul. des Forges, Trois Rivières, G9A 5H7, Canada*

*In-situ Robotic printing* *Continuous Natural fibers* *Step loading fatigue*

## Abstract

This research explores a new frontier in sustainable manufacturing by developing a proof of concept for 3D printing continuous flax fiber-reinforced polymer composites using a 6-DoF robotic arm. While traditional Fused Filament Fabrication (FFF) has long been the industry standard, its rigid 3-axis movement often limits the potential of natural fibers. By leveraging a robotic platform, this work will offer a foundation to non-planar printing.

To validate this proof of concept, we benchmarked the robotic platform directly against conventional FFF using a Raise3D Pro2 Plus printer. Uniaxial tensile and cyclic loading combined with Infrared (IR) Thermography were used to analyze the damage evolution and determine the high cyclic fatigue strength. Optical and scanning electron microscopy (SEM) were used to examine the failure mechanisms of the fractured surfaces.

The experimental tests demonstrate that robotic continuous fiber printing achieves a manufacturing quality and mechanical properties comparable to standard FFF printers, while successfully overcoming the geometric limitations of 3-axis systems. These findings validate the potential of robotic-based 3D printing for the fabrication of high-performance, sustainable natural fiber composites, offering a scalable pathway for non-planar structural applications in various engineering applications.

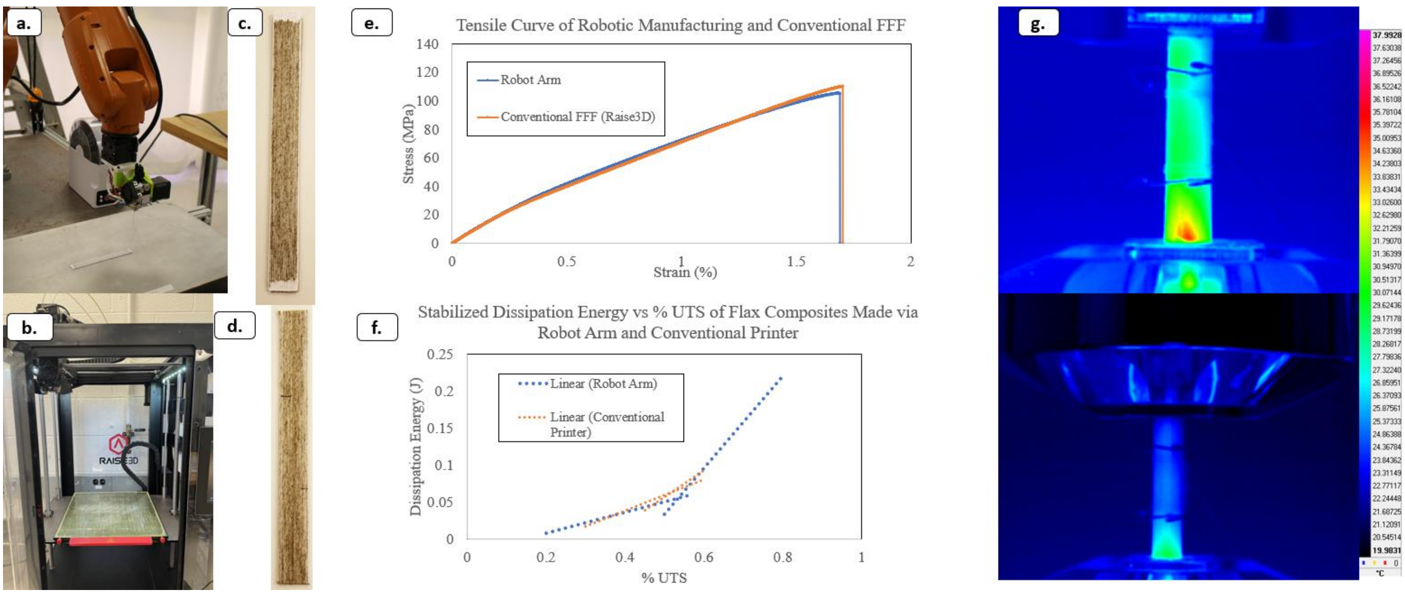



***Figure 1*** *– Summary of Study: (a.) 6-DoF Robot Arm, (b.) Raise3D printer, (c.) Robot Arm Specimen, (d.) Raise3D Specimen, (e.) Tensile Curves, (f.) Standardized Dissipation Energy vs % UTS, (g.) Infrared Thermography of Specimens*

# Meso-aggregate Model Relating Local and Global Material Properties for Fatigue Analysis

**Juan Julio Gonzalez-Frias[1], Jinseok Kim[1], Daniel Kujawski[1]**

[1] *Western Michigan University, 1903 W. Michigan Avenue, Kalamazoo, MI, United States of America*

*Emails: juanjulio.gonzalezfrias@wmich.edu, jinseok.kim@wmich.edu, daniel.kujawski@wmich.edu*

*Fatigue finite element model* *AA7075* *Microstructure modeling*

**Abstract.**

Microstructure plays a critical role in governing cyclic deformation heterogeneity and the development of fatigue-relevant local response, yet quantitative links between global loading conditions and local microstructure remain insufficiently understood. In this work, a microstructure-resolved finite element framework is developed to investigate cyclic stress and plastic strain localization in AA7075 under strain-controlled loading.

Two-dimensional finite element models are generated using statistically defined phase distributions with elastic-perfectly plastic behavior. In this framework, first material properties are calibrated to reproduce experimentally measured cyclic stress–strain response at the global scale. Local response is then quantified using a set of fixed regions of interest (ROIs) distributed along opposing boundaries of the domain. For each ROI, local phase volume fractions, average stress, and average plastic strain are extracted and compared against global quantities.

Results demonstrate pronounced spatial heterogeneity in cyclic plastic response despite identical global loading conditions, with localized regions exhibiting stress and plastic strain levels that deviate substantially from the global behavior.

One of the goals of the study is to determine the correlation between the magnitude of this heterogeneity and local phase composition, which would highlight the influence of microstructural variability on cyclic response. Also, exploring different strain R-ratios reveals non-uniform translation from imposed strain ratios to local stress ratios across the domain and the ROIs.

The proposed ROI-based methodology provides a systematic approach for characterizing microstructure-driven cyclic plasticity localization and establishes a foundation for the future development of fatigue initiation indicators based on the microstructure of material systems.

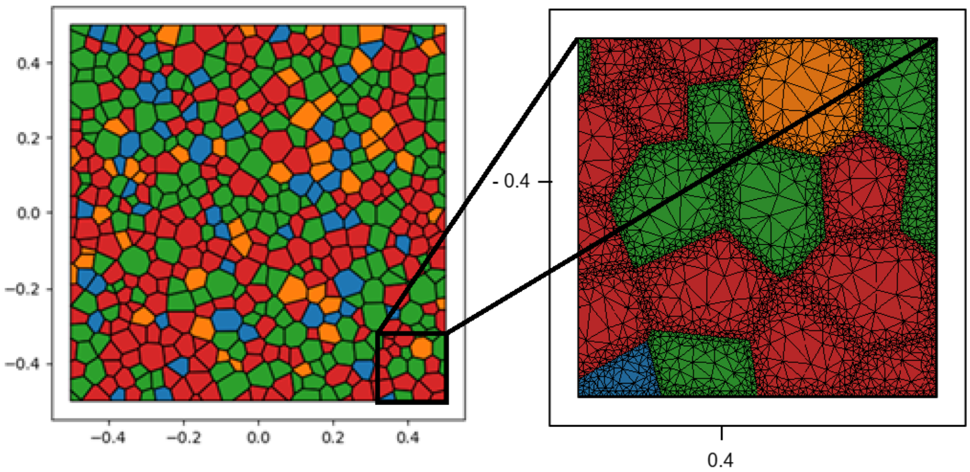



***Figure 1*** *–Meso-structure polygonal mesh (left) and close-up of triangular mesh (right)*

# In-situ optical tomography and fatigue of PBF-LB IN718

**Jinghao Xu[1,*], Arda Baytaroglu[2], Dmitri Riabov[3], Emmy Cao[3], Mattias Calmunger[1], Mats Delin[2], Lars Nyborg[3]**

[1] *Linköping University, Linköping SE-58183, Sweden*
[2] *GKN Aerospace Sweden AB, Trollhättan SE-46138, Sweden*
[3] *Chalmers University of Technology, Göteborg SE-41296, Sweden, lars.nyborg@chalmers.se*

*Optical tomography* *Defect detection* *Fatigue life*

## Abstract

In powder bed fusion-laser beam (PBF-LB), stochastic defect formation remains a critical challenge for achieving reliable fatigue performance in safety-critical components. This study investigates the capability of in-situ optical tomography (OT) to detect incorporated spatter particles that can give rise to lack-of fusion defects and to establish quantitative correlations with post-build mechanical and fatigue properties in PBF-LB-fabricated IN718. An OT system operating in the near-infrared range was used to monitor the build process, generating layer-wise maps of maximum and integrated thermal intensity. A intentionally designed build layout was employed to deliberately induce different levels of spatter activity, resulting in four processing conditions with systematically varying tentative defect populations. The OT detections were ranked and compared with ex-situ X-ray computed tomography (XCT), tensile testing, axial stress-controlled fatigue testing, and detailed fractographic analysis.

The results demonstrate a strong correlation between local OT intensity and defect statistics obtained from XCT, confirming the geographical reliability of the monitoring system. Specimens with higher OT detections exhibited reduced ductility and significantly degraded fatigue life. Stress–life behaviour revealed distinct slopes for hot isostatically pressed (HIP) and heat-treated (HT) conditions, with HIP being particularly beneficial for specimens originating from defect-rich builds. Furthermore, OT detection peaks were shown to correlate with the build height at which fatigue fracture initiated, providing a direct link between in-situ signals and failure locations.

Fractography confirmed that fatigue cracks in defect-rich samples predominantly initiated at lack-of-fusion connected to incorporation of spatter, while defect-lean samples showed subsurface or microstructurally controlled crack initiation. Overall, the study demonstrates that optical tomography can serve as a physically meaningful in-situ indicator of spatter-induced defect formation and fatigue-critical regions, offering a pathway towards data-driven quality assurance and reliability assessment in metal additive manufacturing.

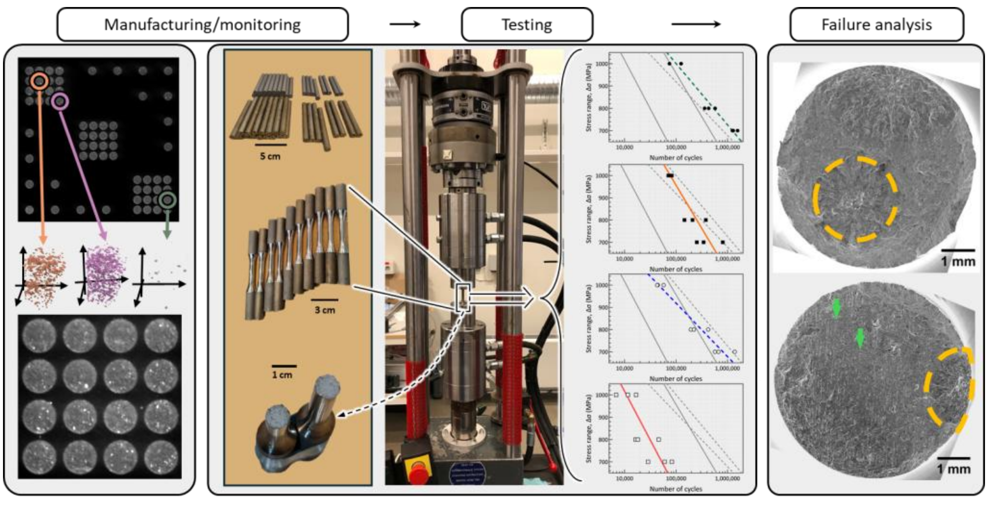



***Figure 1 -*** *Correlation framework between in-situ optical tomography during LPBF of IN718 and defect formation, mechanical response, fatigue life, and fracture.*

# Rapid estimation of fatigue limit in metallic materials using thermographically instrumented cyclic tensile tests: experimental framework and perspective

**Lydia SADEG[1], Arnaud DUCHOSAL[2], Guillaume ALTMEYER[3]**

[1]*University of Orléans · E.A. 7494 Laboratoire de Mécanique Gabriel Lamé (LaMé), 16 rue d'Issoudun 45067 Orléans CEDEX 2 lydia.sairi@univ-orleans.fr*

[2-3]*University of Tours · E.A. 7494 Laboratoire de Mécanique Gabriel Lamé (LaMé)*

*Fatigue* *Experimental methods* *Energy based approach*

**Abstract**

The determination of fatigue limits in metallic materials traditionally relies on long and costly high-cycle fatigue tests, which limits their applicability in rapid material qualification and design stages. Alternative approaches based on energy dissipation and self-heating measurements have been proposed as promising solutions to overcome these limitations.

This work presents an experimental framework for the rapid estimation of fatigue endurance using thermographically instrumented cyclic tensile tests. A dedicated experimental setup has been developed, combining cyclic tensile loading with infrared thermography to monitor temperature evolution induced by internal energy dissipation. Preliminary investigations were carried out on metallic materials such as aluminum alloys and mild steels, using loading protocols inspired by Risitano and Luong methodologies.

The experimental results highlight both the potential and the limitations of the ΔT-based approach, particularly regarding thermal stabilization, environmental sensitivity, and material-dependent dissipation behavior. While preliminary fatigue limit estimations were obtained, deviations from conventional fatigue data underline the importance of controlled experimental conditions and robust data interpretation.

Building upon these initial results, the ongoing work aims to consolidate the methodology through extended experimental campaigns and the calibration of a thermomechanical finite element model. The objective is to establish a quantitative correlation between measured self-heating and simulated energy dissipation, enabling a more reliable and predictive fatigue assessment framework.

This contribution emphasizes the methodological aspects, experimental challenges, and future perspectives of thermography-based fatigue evaluation, paving the way toward faster and more cost-effective fatigue characterization strategies.

# Real-Time Structural Performance Estimation of Concrete-Based Floating Offshore Wind Platforms Using Inertial Loads in Finite Element Analysis

**Ricardo Pinto[1], Mário Vieira[2], Tiago Mota[2], Luís Reis[1,3]**

[1]*Instituto Superior Técnico, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal*
*ricardo.jorge.pinto@tecnico.ulisboa.pt*

[2]*WavEC Offshore Renewables, Lisbon, Portugal*

[3]*IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal*

*Floating offshore wind energy*    *Concrete-based platforms*    *Finite element structural simulation*

The increasing deployment of floating offshore wind turbines has raised new challenges regarding the structural assessment of their floating platforms. Particularly during non-operational phases such as wet storage, where the platform is fully exposed to environmental loads while missing the eventual damping and mass contributions of the soon to be installed wind turbine, making structural response more sensitive to metocean excitation. Concrete-based floating platforms have emerged as a competitive alternative to traditional steel structures, offering advantages in terms of durability, corrosion resistance, and availability of locally sourced materials. Guaranteeing reliable structural performance evaluation during the life cycle of floating platforms is, therefore, essential for their safe deployment and long-term operation.

This research proposes a quasi-real-time approach to estimate structural loads in concrete-based floating offshore wind platforms from the inertial response of the structure, obtained by coupling hydrodynamic simulations and finite element analysis under metocean inputs. The study focuses on a semi-submersible concrete platform under wet storage conditions in the Sado estuary, Portugal, within the scope of the PRR ATE project. The analysis follows a sequential workflow in which frequency-domain hydrodynamic coefficients are obtained with OrcaWave and time-domain rigid-body motions are computed using OrcaFlex. As the physical platform has not yet been constructed, these motions, in the form of linear accelerations and rotational velocities, are numerically generated through the Orcina software suite, mirroring measurements from the intended onboard inertial measurement unit (IMU). The generated time-dependent data is processed to serve as dynamic inputs for a thorough frequency-domain finite element model developed in ANSYS Mechanical, incorporating concrete solid elements, steel reinforcement bars, prestressing tendons, gravity, hydrostatic pressure, and added mass ocean effects.

The frequency-domain formulation adopted for the finite element analysis allows for a more computationally efficient representation of the platform's dynamic response while remaining fully consistent with the hydrodynamic previous modeling. Transforming time dependent motion data into the frequency domain using the Fast Fourier Transform (FFT) allows loads to be applied through the harmonic response analysis in ANSYS, capturing dominant excitation frequencies and potential resonance effects with less computational cost, which is essential for quasi-real-time structural assessment.

The proposed methodology will make the evaluation of global structural displacements and stress distributions in both concrete and steel components under realistic ocean-induced loading conditions viable. Validation is carried out through comparison between displacements obtained from OrcaFlex and structural displacements computed with the finite element model in ANSYS, demonstrating consistent dynamic behaviour and good agreement between the two phases. The results confirm the ability of the proposed framework to reproduce the structural response of concrete-based floating platforms and establish a scalable basis for future integration of in situ monitoring data, supporting structural assessment and, therefore, enhanced safety during early life cycle phases.

# Defect tolerance of thick high-strength steels for truck chassis assessed by fatigue notch sensitivity and fracture toughness

**Sergi Parareda[1,2], David Frometa[1], Daniel Casellas[1,3], Henrik Sieurin[4,5]**

*[1]Eurecat, Centre Tecnològic de Catalunya, 08243 Manresa, Spain and* sergi.parareda@eurecat.org

*[2]Mechatronics and Modelling Applied on Technology of Materials (MECAMAT) group. Universitat de Vic-Universitat Central de Catalunya (UVic-UCC), 08500 Vic, Spain*

*[3]Luleå University of Technology, Division of Mechanics of Solid Materials, 97187 Luleå, Sweden.*

*[4]Scania CV AB, Materials Technology, Södertälje, SE-151 87, Sweden*

*[5]KTH Royal Institute of Technology, Department of Materials Science and Engineering, Stockholm, SE-100 44, Sweden*

*Damage tolerance* *Fatigue* *Fracture toughness*

**Abstract** Heavy-duty vehicles (HDVs) face increasingly stringent $CO_2$ emission targets, which drive the demand for lightweight structural solutions that maintain durability under severe cyclic loading. Chassis components represent a major opportunity for weight reduction. Their application is, however, constrained by high load levels, large thicknesses required to maintain component stiffness, and the sensitivity of high-strength steels to surface defects introduced during manufacturing or service. As a result, lightweighting approaches developed for body-in-white components cannot be directly transferred to HDV chassis parts, making fatigue-oriented material selection a critical issue. This work presents a material selection framework for thick high-strength steels with a thickness of 8 mm used in fatigue-critical HDV chassis components. The framework combines rapid fatigue testing with fracture toughness-based notch sensitivity assessment. Fracture toughness is evaluated using the essential work of fracture (EWF) methodology applied to thick steel sheets tested with single-edge notched bending (SENB) specimens. Fatigue behaviour is characterised using an accelerated testing approach known as the stiffness method, which enables the determination of fatigue resistance under both unnotched and notched conditions within a reduced testing time. By correlating fracture toughness parameters with fatigue notch sensitivity, the proposed approach provides a physically grounded measure of material tolerance to surface defects introduced during manufacturing processes such as punching and cutting, as well as during the service life of the component. The methodology is applied to a range of high-strength low-alloy steels with yield strengths from 500 MPa and complex-phase steels with yield strengths up to 1000 MPa that are relevant to HDV chassis applications. The results show a consistent relationship between EWF parameters and the experimentally determined fatigue notch factor. The proposed framework offers a practical and time-efficient tool for material screening. It allows designers to focus conventional fatigue testing on the most promising material candidates and supports the development of lighter and more efficient HDV chassis structures.

# Application of the DCPD technique to monitor crack propagation from volumetric CAD-seeded defects in PBF-LB Scalmalloy®

**Luca Mariotti[1], Andrea Zanon[2], Stefano Beretta[2,3], Luca Patriarca[2]**

[1]*Politecnico di Milano, Mechanical Engineering Department, Via La Masa 1, 20156 Milano, Italy,* *mariotti.luca@polimi.it*

[2]*Politecnico di Milano, Mechanical Engineering Department*

[3]*Auburn University, National Center for Additive Manufacturing Excellence (NCAME)*

*Direct current potential drop* *Internal fatigue crack growth rate* *PBF-LB Scalmalloy®*

**Abstract:**

Additive Manufacturing (AM) of aluminium alloys, especially with Powder Bed Fusion Laser Based (PBF-LB) method, is increasingly adopted in aerospace and space applications due to its design flexibility, material efficiency, and high mechanical performance. However, the presence of intrinsic manufacturing defects such as gas porosities, lacks of fusion, and keyholes remains a critical issue for the fatigue behaviour and certification of safety-critical components. A different crack growth behaviour between volumetric and superficial defects has been observed in literature. These preliminary studies have shown that cracks initiated from volumetric defects, which are not exposed to the atmosphere, has shown a slower fatigue crack propagation rates and different threshold stress intensity factors compare to surface fractures, resulting in significantly longer fatigue lives. However, a robust experimental characterization of crack propagation of internal defects is still missing.

This work investigates the fatigue behaviour of internally-initiated fractures in AM Scalmalloy® produced by the PBF-LB process. The Direct Current Potential Drop (DCPD) technique is proposed and applied as an innovative method for the in-situ measurement of growth rates of internal fatigue cracks. Traditionally used for surface crack monitoring, the DCPD methodology is here applied to crack monitoring in specimens containing artificial CAD-seeded internal flaws. The evolution of the electrical potential drop across the crack is correlated to crack advancement by means of both finite elements analyses and experimental measurements. DCPD enables continuous and high-resolution monitoring of internal crack propagation during fatigue loading without the need for complex specimen geometries or advanced in-situ facilities (e.g. synchrotron X-ray tomography).

The experimental results demonstrate the capability of the DCPD technique to reliably track the growth of internal cracks in Scalmalloy®. The measurements show a clear reduction in crack growth rate for internally-initiated fractures compared to surface cracks, as shown in Figure 1. The identified trend is in agreement with previous literature studies, confirming the existence of a distinct internal crack propagation behaviour. The proposed approach represents a practical and versatile tool for the experimental characterization of internal crack growth, providing a promising route towards the standardization of internal fatigue testing procedures.

# Non-destructive Material Property Measurements for Meso-aggregate Fatigue Model

**Isaiah Zebrowski[1], Juan Julio Gonzalez-Frias[1], Jinseok Kim[1], Daniel Kujawski[1]**

[1]*Department of Mechanical and Aerospace Engineering, Western Michigan University, Kalamazoo Michigan, 49008, USA*

isaiah.j.zebrowskia@wmich.edu, juanjulio.gonzalezfrias@wmich.edu, jinseok.kim@wmich.edu, daniel.kujawski@wmich.edu

*Meso-aggregate Fatigue Model     Non-destructive measurement     Phase Characterization*

A new meso-aggregate finite-element (FE) model was developed for fatigue analysis with randomly distributed phases. Each phase is assumed to exhibit elastic perfectly plastic stress–strain behavior. The yield strength and volume-fraction parameters in the meso-aggregate model are not known a priori and must be selected such that the overall monotonic and cyclic stress–strain responses are accurately reproduced. The selection of these meso-aggregate parameters is time-consuming, as no clear guidance exists for their determination. To utilize the fatigue model, it is essential to develop a systematic way to measure phase distribution and material properties for each phase.

In this research, non-destructive microhardness measurements are used to facilitate the selection of meso-aggregate parameters by linking them to the actual microhardness distributions within the alloy of interest. Micro-indentation provides valuable information on regional variations and their statistical distributions. To properly relate the microhardness data to the meso-aggregate model, the measurements are sorted into the same number of bins as the number of phases in the model. Statistical characteristics of each bin are then examined to assess whether systematic patterns emerge.

The goal of this study is to develop a methodology for determining yield-strength distributions that assist in the implementation and performance of the meso-aggregate fatigue model. To account for directional variations in grain elongation caused by manufacturing processes, the methodology is demonstrated through the analysis of extruded rods. Extrusion process significantly influences the mesostructure by elongating grains along the extrusion direction. Accordingly, specimens for microhardness testing are taken both parallel and transverse to the extrusion direction for analysis to establish relationships with the elastic perfectly plastic material parameters. The approach is demonstrated using AA2024 and AA7075 aluminum alloys as initial case studies. Figure 1 illustrates the frequency versus hardness tests done on AA7075 samples in both the longitudinal and transversal directions.

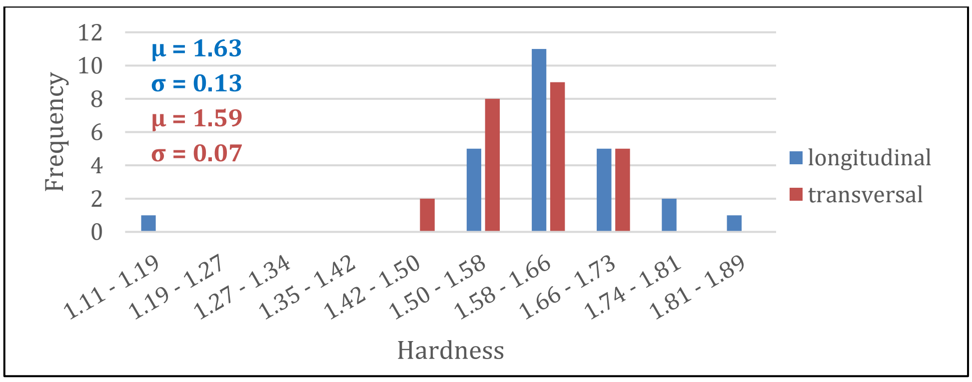



***Figure 1** – Martens hardness values of AA7075 in kN/mm$^2$*

# Effect of Environment on Fatigue Crack Growth in High Strength Steels

**Monisha Manjunatha*, Tugrul Comlekci, Yevgen Gorash & Donald Mackenzie**

*University of Strathclyde, Mechanical and Aerospace Engineering Department, 75 Montrose Street, Glasgow, G1 XJ,UK. monisha.manjunatha@strath.ac.uk*

*Fatigue* *Corrosion* *Temperature*

## Abstract

High Strength Steel (HSS) are widely used in critical structural applications where fatigue performance under aggressive service conditions is of significant importance. This study investigates the influence of environmental conditions on fatigue crack growth rate (FCGR) performance in selected HSS grades, with particular emphasis on corrosive environments and low-temperature exposure. Experimental FCGR tests were conducted according to ASTME647 standard under ambient room temperature, corrosive environments, and reduced temperature conditions to quantify their effects on crack propagation behaviour. The experimentally determined Paris Law coefficients, *m* and *C*, for each steel grade were obtained from the test data and subsequently implemented into a finite element analysis (FEA) framework using the ANSYS SMART crack growth tool to simulate fatigue crack propagation under environmental conditions.

Fractographic investigations were performed using SEM to identify dominant crack growth mechanisms and to correlate fracture features with the observed fatigue performance under different operating environments. The results demonstrate that both corrosive environments and low temperatures influence fatigue crack growth rates compared to ambient room temperature conditions, with notable variations among the tested steel grades. The combined experimental, numerical, and fractographic approach provides improved insight into environment-assisted fatigue mechanisms and supports more reliable life prediction of HSS components operating under adverse service conditions.

a) b)

***Figure 1-*** *Fatigue Crack growth setup:(a) Low temperature testing, (b) Post corrosion test*

# Correlating In-situ Monitoring with Defect Formation in SLM: A Comparative Study of EOSTATE Optical Tomography Outputs and Unprocessed Monitoring Data

**Yusuf Bakir, I. Zetková, Adam Polansky**

*Regional Technological Institute, Faculty of Mechanical Engineering, University of West Bohemia, Univerzitní 8, 306 14 Pilsen, Czech Republic*

*Selective Laser Melting* *In-situ Monitoring* *Quality Assurance*

**Abstract** Selective Laser Melting (SLM) has transitioned from a prototyping tool to a primary manufacturing method for mission-critical components. However, the stochastic nature of the melt pool and costly destructive testing are hindering quality assurance. This research investigates the efficacy of in situ monitoring using the EOSTATE Optical Tomography (OT) system as nondestructive quality assurance method, and comparing unprocessed OT data compared to standard processed outputs. By utilizing a methodology centered on the exposure of singular melting tracks and singular layers, this study isolates the thermophysical variables that contribute to volumetric defects.

A primary focus of this work is the correlation between the laser scanning path angle and the inert gas flow vector within the build chamber. In the SLM process, the interaction between the high-energy laser beam and the powder bed generates a significant plume of metallic vapor and spatters that are ejected molten material. The research demonstrates that the direction of these ejections, relative to the gas flow, significantly modulates the heat input received by the powder bed. When the scanning path results in spatter or smoke overlap with the path of the laser beam, OT sensors capture the difference between a healthy process and abnormalities that might lead to defects in parts.

Through the analysis of raw OT data, this study identifies the durability and stability of the melt pool with higher temporal resolution than standard software allows by enabling frame by frame observation with significantly lowered visual noise. The raw data stream is utilized to detect defects in the parts such as balling effects, lack of fusion, and gas entrapment.

Finally, the study connects the in-situ signal detection and mechanical performance. While considering the re-melting or curing of defects during printing of full volume parts, the results indicate correlation between melting pool instabilities and spatter-induced defects identified in the raw OT stream and a reduction in fatigue cycles to failure.

# Numerical Investigation of the Fatigue Behaviour of TPMS Structures

**Žiga Žnidarič[1], Branko Nečemer[1], Srečko Glodež[1]**

[1] *University of Maribor, Faculty of Mechanical Engineering, Smetanova ulica 17, 2000 Maribor*
*ziga.znidaric@um.si*

*Fatigue behaviour* *TPMS structures* *Numerical simulation*

**Abstract** Triply Periodic Minimal Surface (TPMS) structures have attracted increasing interest in applications where fatigue resistance is critical because of their smooth topology and favourable stress distribution when compared to strut-based cellular materials. However, reliable fatigue assessments of such geometries remain a challenge, particularly when accounting for manufacturing conditions, base material behaviour, and complex geometry.

This contribution presents an ongoing numerical-experimental study focused on predicting the fatigue behaviour of additively manufactured TPMS structures. This work is divided into two stages. In the first stage, the cyclic mechanical behaviour of the base material is characterised using available experimental data and relevant material parameters reported in literature for as-built and heat-treated conditions. The data is used to characterise the post-treatment influence on the material and to calibrate the constitutive and fatigue parameters for numerical modelling.

In the second stage, the material models are applied in finite element simulations of TPMS structures (Figure 1). The numerical analyses focus on stress-strain localisation within the TPMS structure and how global loading conditions translate into local stress and strain levels relevant for fatigue resistance. The adopted methodology builds on a previously validated approach. The results demonstrate the proposed framework's ability to capture the interaction between base material behaviour and structural geometry and providing insight into fatigue-critical locations and expected failure mechanisms. The presented approach represents a step towards efficient fatigue-oriented design of TPMS structures, reducing experimental effort while improving understanding of their fatigue performance.

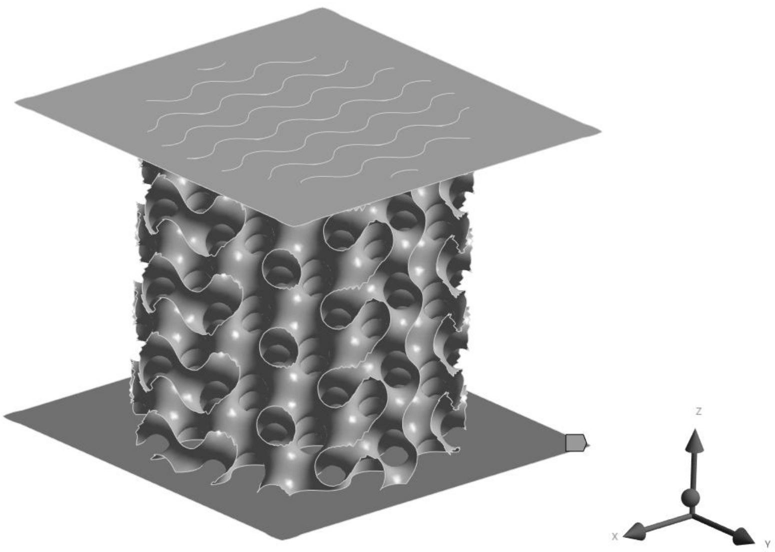


***Figure 1 –*** *Numerical model of TPMS structures*

# Assessment of crack closure during fatigue crack growth under large scale yielding and negative strain ratio

**Théotime Asselin[1, 2], Olivier Ancelet[2], Valery Valle[1], Florence Hamon[1], Guillaume Benoit[1], Gilbert Hénaff[1]**

[1]*Institut Prime, UPR 33646 CNRS ENSMA Université de Poitiers, France*

[2]*Framatome, France*

*Finite element analysis* *Crack driving force* *Nuclear energy industry*

**Abstract** Components of the primary circuit of a nuclear power plant endure during their lifetime numerous pressure and temperature transients, that respectively induce stress-controlled and strain-controlled loadings. Some specific transients may initiate and propagate a fatigue crack at negative load ratios in the LCF regime. The present study was undertaken in close collaboration between Institut Pprime and Framatome in an attempt to improve the prediction of the fatigue life of a component under such loadings. With this aim, uniaxial fatigue tests were first performed under strain-control at R=-1 at various strain amplitudes, on two different grades, namely a low alloy 18MND5 pressure vessel steel and a 304L austenitic stainless steel, using rectangular section area samples containing an EDM micro-notch as a crack starter on one face. The crack initiation and propagation stages were monitored using DCPD technique, while the crack opening and closure strains were determined using both DCPD and an innovative discontinuous DIC method. Meanwhile, standard fatigue crack growth tests were conducted on CT specimens at positive load ratios. It was shown that, for the two materials studied, values of crack opening strain vary as a function of the level of stress applied, the load ratio and, to a lesser extent the crack depth.

The experimental results were thereafter analysed by considering various driving force parameters, such as the strain intensity range $\Delta K_\varepsilon$ or the range of J integral $\Delta J$, as evaluated on the basis of FEA modelling. A new method for the calculation of the driving force parameter $\Delta J_{eff}$ is proposed and offers promising results to account for both crack closure and large-scale yielding effects.

# Towards Unravelling the Multiscale Nature of Fatigue in Additively Manufactured Metals: Assessing Defects, Residual Stress, and Microstructural Scatter

**Enrico Salvati, Alessandro Tognan, Marco Pelegatti, Emanuele Avoledo, Jasen Zenzerovic**

*Polytechnic Department of Engineering and Architecture (DPIA), University of Udine. Via delle Scienze 206, 33100 Udine (Italy)*

*Defects* *Residual stress* *Microstructure*

**Abstract** The integrity of metallic components under cyclic loading is governed by a complex interplay of microstructural heterogeneities, manufacturing-induced defects, and residual stress fields. This presentation provides a comprehensive overview of the factors influencing fatigue damage, emphasising how localised microstructural phenomena affect macroscopic structural integrity. Recent developments in the characterisation of these features are presented and, where possible, their implementation in innovative fatigue predictive tools is showcased.

A primary factor influencing fatigue is the presence of defects. Here, modern techniques can effectively reveal these defects, and rigorous uncertainty analyses can assess their impact in a rigorous manner. Residual stress likewise requires sophisticated strategies for quantification, particularly as characterisation moves toward smaller length scales. Furthermore, intrinsic material properties often exhibit high inhomogeneity at finer scales, resulting in scattered fatigue performance, especially for a high cycle fatigue regimes. As direct measurement at the micron scale is often prohibitive, alternative experimental characterisation strategies are required. This integrated perspective, which incorporates machine learning approaches, aims to provide researchers and engineers with novel approaches for managing fatigue in the next generation of evaluation and design criteria.

# Artificial Neural Networks in Fatigue Modeling:

# Challenges in Validation and Engineering Interpretation

**Marohnić Tea[1], Basan Robert[2], Cernescu Anghel-Vasile[3]**

[1] *University of Rijeka, Faculty of Engineering, Vukovarska 58, 51000 Rijeka, Croatia, tmarohnic@riteh.uniri.hr*

[2] *University of Rijeka, Faculty of Engineering*

[3] *Politehnica University Timișoara, Department of Mechanics and Strength of Materials*

*fatigue life prediction* *machine learning* *model validation*

**Abstract** The use of artificial neural networks (ANNs) for estimating fatigue-related material behavior has increased rapidly in recent years, driven by the growing availability of experimental data and the limitations of traditional empirical approaches. However, reported improvements in predictive accuracy are often difficult to interpret and compare, and their relevance for engineering fatigue assessment remains uncertain.

This contribution critically examines common practices in ANN-based fatigue modeling, with emphasis on recurring methodological shortcomings rather than isolated case studies. Key issues include the treatment of small and heterogeneous fatigue datasets, insufficient separation between training and validation data, neglect of regime-dependent behavior, and the widespread use of performance metrics that do not adequately reflect fatigue life scatter.

The presentation discusses the implications of these limitations for model generalization and engineering decision-making, and outlines methodological requirements for the meaningful evaluation of machine-learning-based fatigue predictions. The aim is not to replace established fatigue concepts, but to clarify the conditions under which data-driven models can provide reliable and physically consistent support to fatigue analysis.

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# Statistical average strain energy density method applied to a computational efficient finite element framework to estimate lattice structure fatigue resistance

**Raffaele De Biasi[1,2], Simone Murchio[1,2], Matteo Benedetti[2], Filippo Berto[1]**

[1] *Department of Chemical Engineering Materials Environment. La Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy*

[2] *Department of Industrial Engineering, University of Trento, Via Sommarive 9, 38123 Trento, Italy*

*Fatigue estimation* *Lattice structures* *Finite element*

**Abstract** The structural application of lattice components represents a key frontier for the integration of additive manufacturing (AM) benefits into industrial products. The widespread adoption of lattice structures enables tunable mechanical properties, weight reduction, and multiphysics functionalities in industrially relevant components, potentially to change of paradigms in fields such as biomedical and aerospace. However, their large-scale integration is currently hindered by the lack of robust qualification and validation procedures for AM components and, in particular, by the absence of accurate and computationally efficient methods for fatigue life estimation. To address this limitation, this work presents a procedure for estimating the fatigue resistance of lattice components based on a multiscale approach. The global loading conditions of the metamaterial are simulated using a computationally efficient finite element model capable of capturing the overall structural response and identifying critical regions prone to fatigue failure. A second, local model is then derived from the global analysis to resolve the geometric details of the lattice architecture and to identify sub-millimetric features responsible for fatigue crack initiation. The local model incorporates the as-built surface morphology of the component, thereby accounting for geometric deviations induced by the AM process. Fatigue life estimation is performed through a statistical implementation of the Average Strain Energy Density (ASED) method, where fatigue hot spots are identified by comparing the finite element results with a material-specific reference curve. The proposed workflow thus enables a two-step, computationally efficient analysis providing fatigue life predictions of lattice components informed by as-built geometries. The methodology is validated through three-point bending fatigue tests performed on L-PBF lattice specimens.

# Study on the mechanics of fretting crack initiation for flat-on-flat contacts

**Denny Knabner[1], Marius Matthias Müller[1], Alexander Hasse[1]**

*[1]Technische Universität Chemnitz, Reichenhainer Straße 70, 09126 Chemnitz, Germany*
*Institute of Design Engineering and Drive Technology*
*denny.knabner@mb.tu-chemnitz.de*

*Fretting Fatigue* *Adhesion* *Crack initiation*

**Abstract** This work investigates the crack-initiation-mechanism under fretting conditions. For this purpose, experimental and numerical investigations were carried out on a fretting pad model with flat-on-flat contact conditions using the steel 34CrNiMo6+QT. These investigations are divided into two series of experiments - one under fretting fatigue loading and one under plain fretting loading. All experiments were carried out with the tribological parameters contact pressure (nominal) $p = 40$ MPa and slip amplitude $s_a = 5$ µm, whereby the slip amplitude was measured and controlled in real time from the fretting loops using a new method. In the fretting fatigue tests, the fretting fatigue limit was determined first. Subsequently, various fretting fatigue tests (slightly above the fretting fatigue limit level) and plain fretting tests were stopped after certain numbers of load cycles. The specimens were examined metallographically with the aim of determining the crack initiation lifetimes and the crack growth behavior. It was found that the crack initiation lifetimes barely differed in the two test series and were around 10,000 load cycles. The crack lengths also differed little for short cracks at the various load cycles. In all cases, the location of the crack was near the center of the contact and not at the contact edges, where the highest stresses are located when a frictional contact according to Coulomb is assumed. Three effects were then evaluated in the numerical simulations to determine the crack-initiation-behavior: pure frictional contact according to Coulomb, local form fit and local material bonding due to adhesion. The assumption of the two latter effects resulted from the microscopic analysis of the fretting scars, which indicated striking spots in the area of crack initiation. The predominant effect at the time of crack initiation was assessed based on the indicators: crack initiation position, crack initiation lifetime, crack initiation angle, and shape of the fretting loop. The parameters SWT, FS, and tools of linear elastic fracture mechanics were used. It was found that most indicators point to the local adhesion spot as the predominant effect.

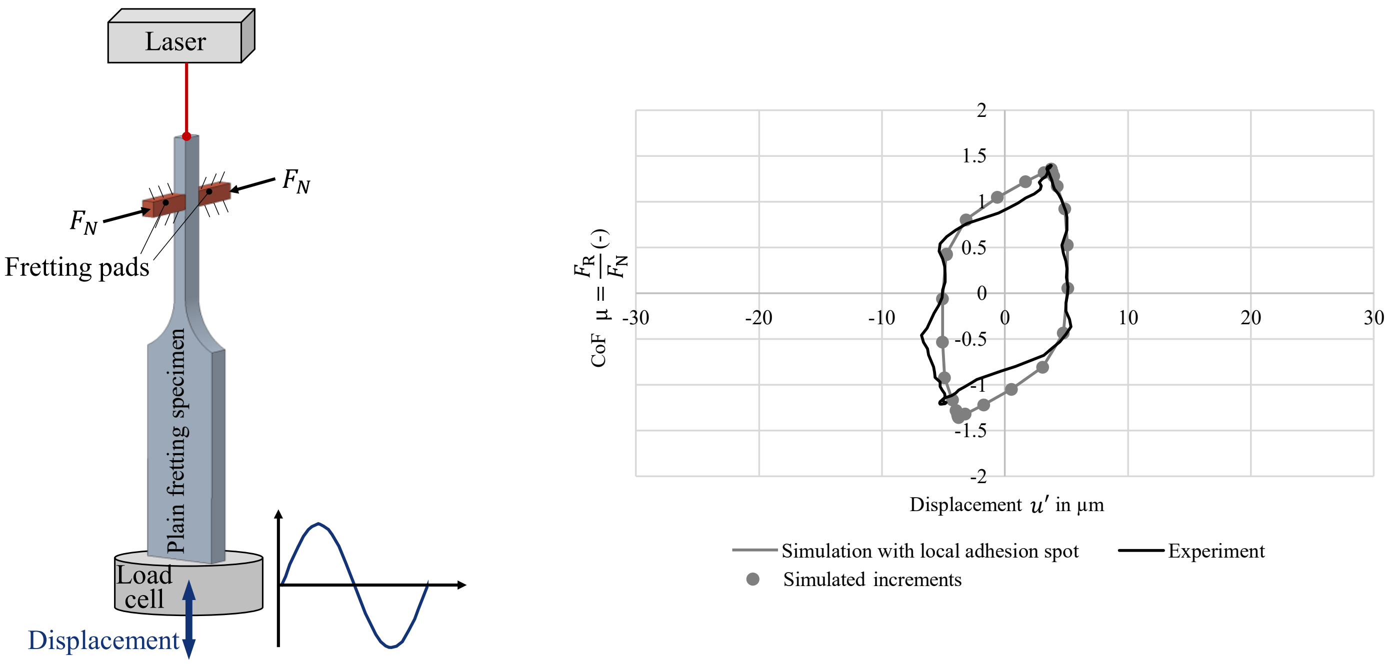


***Figure 1** – Test principle, experimental and simulated fretting loop*

# Mitigation of fretting fatigue: Effects of case-hardening on the durability and failure modes

**Marius Müller[1], Denny Knabner[1], Jiří Čapek[2], Karel Trojan[2], Alexander Hasse[1]**

[1] *Institute of Design Engineering and Drive Technology, Reichenhainer Str. 70, 09126 Chemnitz, Germany, marius.mueller@mb.tu-chemnitz.de*

[2] *Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Trojanova 13, Praha, 120 00, Czech Republic*

*Fretting fatigue* *Case-hardening* *Mitigation*

**Abstract** Fretting fatigue significantly reduces the fatigue limit of components in contact due to oscillating micro-movements between at the interfaces. Contrary to the trend observed for tensile strength, the fretting fatigue limit shows only minor differences between low- and high-strength steels. This is in conflict with the common use of high-strength steels to improve durability at free surfaces creating the need for components that exhibit both, increased fatigue strength in contact regions and at free surfaces.

The early failure under fretting fatigue is mainly due to accelerated crack initiation and propagation. These cracks were found in an arrested state even in components loaded below their fretting fatigue strength. Therefore, mitigation strategies for fretting fatigue should target both, crack initiation and propagation. On the one hand, this could be achieved with a hardened surface potentially leading to reduced surface damage represented by a smaller coefficient of friction [1]. On the other hand, an introduced compressive residual stress field can markedly enhance the crack arrest, which is proven at free surfaces and also for roller-burnished or laser quenched surfaces tested under fretting fatigue [1,2]. However, these surface treatment processes are barely applicable to bearing seats or shaft-hub connections. Instead, case hardening offers a flexible and economical heat-treatment route to generate a hard surface combined with a compressive residual stress field and a ductile core.

In this study, the effect of case hardening on the fretting fatigue is investigated experimentally using specimens made of 18CrNiMo7-6 (AISI 4820). Fretting fatigue tests are performed using an established flat-on-flat laboratory model with oscillating fretting pads made of 34CrNiMo6+QT (AISI 4340) [3]. Two specimen conditions are examined: case-hardened specimens with a hardness of 550 HV at a depth of 0.5 mm (660 HV at surface) and blind-hardened specimens representing the core material condition. Both series are ground to achieve comparable surface topographies. The fretting fatigue limit is determined using the staircase method. In addition, it is compared to the limit of the high-strength steel 34CrNiMo6+QT having a smaller depth of compressive residual stress profile.

The case-hardened specimens exhibit an increase in fretting fatigue limit of up to 30 %. Post-test analyses reveal an enhanced crack arrest within the hardened layer while the overall crack character is similar to the blind-hardened case. The crack initiation angle and initial crack path, governed by contact stresses, differ within the test series, indicating a persistent influence of surface damage. Furthermore, the applicability of hardening factors from strength assessment methods is investigated using fretting fatigue simulations based on the measured residual stress field.

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# Influence of ultrasonic-assisted milling on surface integrity and fatigue strength of a low alloy steel

**Lorenz Engelking[1], Mauro Madia[1], Dirk Schroepfer[1], Romeo Saliwan Neumann[1], Thomas Kannengießer[1]**

[1]*Bundesanstalt für Materialforschung und -prüfung (BAM), 12205 Berlin, Germany*

*Ultrasonic-assisted milling* *Surface integrity* *Fatigue strength*

**Abstract** The milling process significantly influences the surface integrity of metallic components through machining induced near-surface residual stresses. Modern hybrid machining processes, such as ultrasonic-assisted milling (USAM), offer the potential to induce beneficial near-surface compressive residual stresses compared to the near-surface tensile residual stresses typically resulting from conventional milling (CM). This study investigates the effects of USAM compared to CM on the near-surface residual stress state and fatigue performance of a S355J2C low-alloy steel. Milling experiments and subsequent rotating bending tests revealed that USAM significantly reduces cutting force by approximately 45% and induces near-surface compressive residual stresses as low as -733 MPa. This leads to a significant improvement in fatigue strength estimated in approximately 34% compared to polished specimens and 11% compared to the CM, cf. Figure 1. These findings highlight the potential of USAM to enhance the fatigue performance of components made of steel.

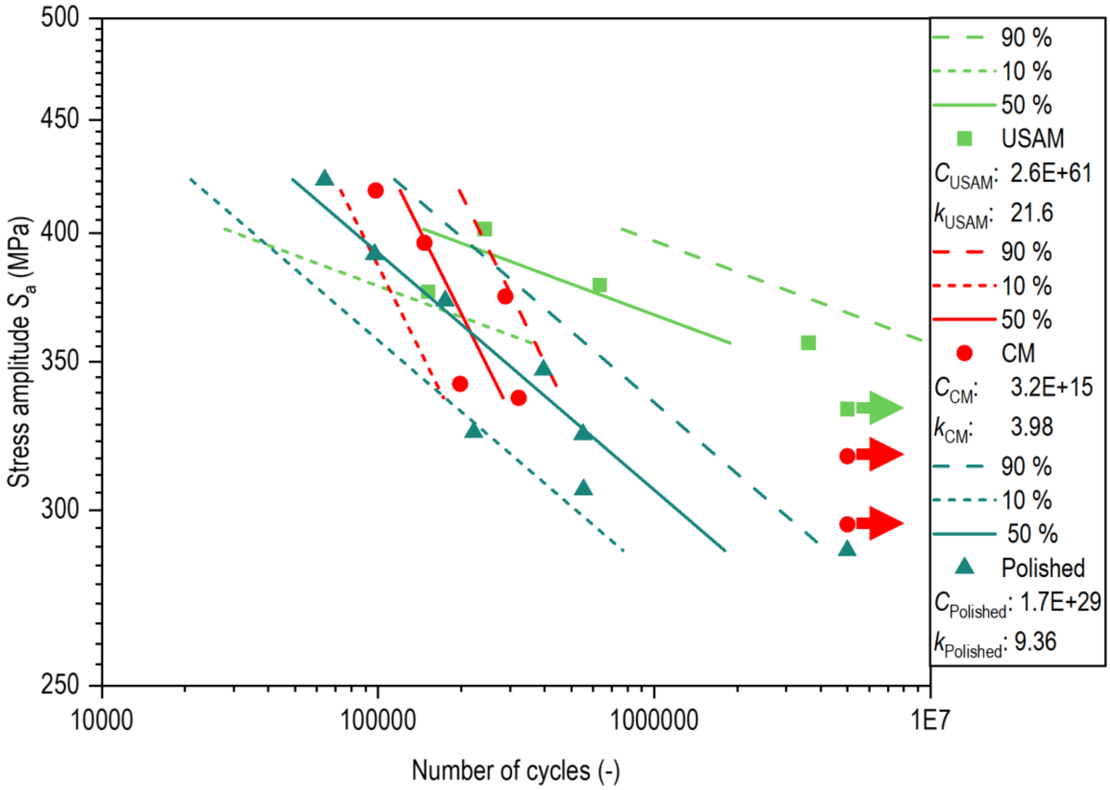


***Figure 1 -*** *Results of the rotating bending tests: S-N curves, including the curves for 10 % and 90 % failure probability, and the value of the parameters of the Basquin's law.*

# Microstructural evolution of coated Ni-based single crystal superalloy under thermal mechanical fatigue loadings

**Wenqi Hao[1], Duoqi Shi[2], Changqi Liu[2], Xiaoguang Yang[2]**

[1]*School of Energy and Power Engineering, Beihang University, Beijing 102206, China,*
*E-mail address: haowq2023@buaa.edu.cn*

[2] *School of Energy and Power Engineering, Beihang University*

*Thermo-mechanical fatigue* *Microstructural evolution* *Oxidation-resistant coating*

**Abstract** Coated single-crystal (SC) turbine blades are exposed to typical thermo-mechanical fatigue (TMF) loading, with the coating-substrate system exhibiting the complex microstructural evolution and damage mechanism. The present study is aimed at the microstructural evolution behaviour of SC substrate and polycrystalline coating under TMF loading with different phase angles, including the IP, OP, -90° and -135° phases. Phase angle-dependent microstructural evolution and cracking characteristics are systematically investigated using quasi-in-situ X-CT scanning and ex-situ SEM and EBSD analysis. The results show that the SC substrate exhibits distinct rafting evolution morphology during TMF tests. Under the IP-TMF loading, the $\gamma/\gamma'$ two-phase is governed by N-type rafting, whereas it tends toward P-type rafting microstructure at -135° and under OP conditions. The type and degree of rafting are controlled by the phase angle and high-temperature exposure time, respectively. Moreover, grain growth and phase transition within the coating are captured based on EBSD characterisation. The geometrically necessary dislocations during TMF cycling are redistributed from the grain boundary to the grain interior, suggesting aggravated deformation incompatibility within individual grains. The crack behaviour of coated alloys is further revealed through X-CT scans performed under specified cycles. Cracks under -135°and OP-TMF conditions are sourced from the valley of surface rumplings at approximately 20% of the lifespan. The crack then propagates into the internal substrate after more TMF cycles. In contrast, the first internal crack is observed at 50% lifespan under IP conditions, dominated by a creep-fatigue damage mechanism. Notably, almost no coating cracks are detected over the entire lifetime, except when internal cracks penetrate the coating. The crack density evolution curves at various TMF phases confirm the more detrimental effect of the coating at (near) OP-TMF. The quantification of microstructural characterisation and damage evolution is the focus for future life modelling.

# Mechanical Characterisation and Fatigue Testing of Material from a Historical Metallic Railway Bridge

**Patrícia Freitas [1,2*], José Oliveira Pedro [1,2], João Pedro Martins [3], Luís Reis [4], Ricardo Branco [5]**

[1] *CERIS, Instituto Superior Técnico, Universidade de Lisboa, Portugal*

[2] *GRID INTERNATIONAL Consulting Engineers, Portugal*

[3] *ISISE, Departamento de Engenharia Civil, Universidade de Coimbra, Portugal*

[4] *IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Portugal*

[5] *CEMMPRE, Departamento de Engenharia Mecânica, Universidade de Coimbra, Portugal*

[*] E-mail: patricia.freitas@tecnico.ulisboa.pt

*Fatigue behaviour*    *Historical steel bridges*    *Mechanical characterization*

**Abstract** Many metallic railway bridges built in the late nineteenth century remain in service despite significant increases in traffic loads and the absence of explicit fatigue considerations in their original design. The evaluation of the mechanical and fatigue behaviour of the original structural materials is therefore essential for assessing their remaining service life and potential reuse.

This paper presents an experimental investigation on metal extracted from a historical railway bridge located on the Beira Baixa railway line in Portugal. The experimental program includes mechanical characterisation and uniaxial fatigue testing performed on specimens extracted from original bridge elements, namely plates and angle sections. Fatigue tests are carried out on specimens without geometric discontinuities as well as on specimens containing drilled holes, representative of riveted connections and structural details.

The experimental program includes mechanical testing and fatigue experiments performed at the Departments of Mechanical Engineering of Instituto Superior Técnico and the University of Coimbra. In addition, microstructural and chemical analyses are carried out using scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS), providing complementary insight into the material characteristics and fracture mechanisms.

The experimental results are analysed in terms of stress–life (S–N) behaviour, and the influence of geometric discontinuities on fatigue performance is discussed. Furthermore, crack initiation and propagation in notched specimens are monitored using digital image correlation techniques. Fracture surface analyses are also performed to support the interpretation of the fatigue mechanisms observed.

The results contribute to a better understanding of the fatigue behaviour of historical bridges and provide experimental data relevant for the structural assessment and life extension of existing metallic railway bridges.

# Low-Cycle Fatigue Assessment of thin plates extracted from aluminium sheets and from Mega-castings

**Maria Margarita Mitsi[1], Yu Cao[1], Johan Ahlström[2]**

[1]*Department of Mechanical Engineering, Division of Materials and Manufacture, Chalmers University of Technology, Gothenburg, Sweden, mitsi@chalmers.se*

[2]*Department of Mechanical Engineering, Division of Computational Mechanics and Materials Engineering, Chalmers University of Technology, Gothenburg, Sweden*

***High Pressure Die Casting*** ***Low-Cycle Fatigue*** ***Al-Si Alloy*** ***Adhesively Bonded***

Al-Si alloys are increasingly employed in large-scale high-pressure die castings (HPDC), called Mega- or Giga-castings, where large vehicle sections can be produced replacing welded steel structures. These components provide reduced weight, high mechanical efficiency, and enable battery pack integration, offering a more sustainable and cost-efficient solution. During service, they experience cyclic thermal and mechanical loading, making characterization of cyclic plasticity and low-cycle fatigue (LCF) behavior essential for reliable design and life assessment.

Experimental investigation of LCF in thin or sub-scale aluminium specimens is challenging due to elastic buckling under fully reversed strain-controlled loading. To address this, a laminated-specimen approach was developed, where thin sheets are stacked and bonded to increase thickness and improve stability, potentially achieving a quadratic cross section for maximum buckling resistance.

This method has been successfully applied to rolled aluminium sheets using epoxy-bonded laminates. Fully reversed strain-controlled tests (up to 0.2% strain amplitude) showed stable cyclic behavior, with minor variations in plastic strain but similar stress responses in early fatigue stages. At higher cycle counts, differences increased due to damage evolution. Fractography revealed non-planar crack paths across layers with distinct fatigue and final fracture regions, confirming that the approach captures relevant fatigue mechanisms, although decohesion may occur at higher strains.

This study extends the laminated-specimen methodology to HPDC Al–Si alloys used in Mega-cast components. The focus is on cyclic stress–strain behavior, fatigue life, and fracture response under fully reversed strain-controlled loading. By transferring this approach, the work aims to establish a reliable framework for LCF assessment and improved fatigue life prediction of Mega-cast components and to support improved fatigue life prediction in industrial applications.

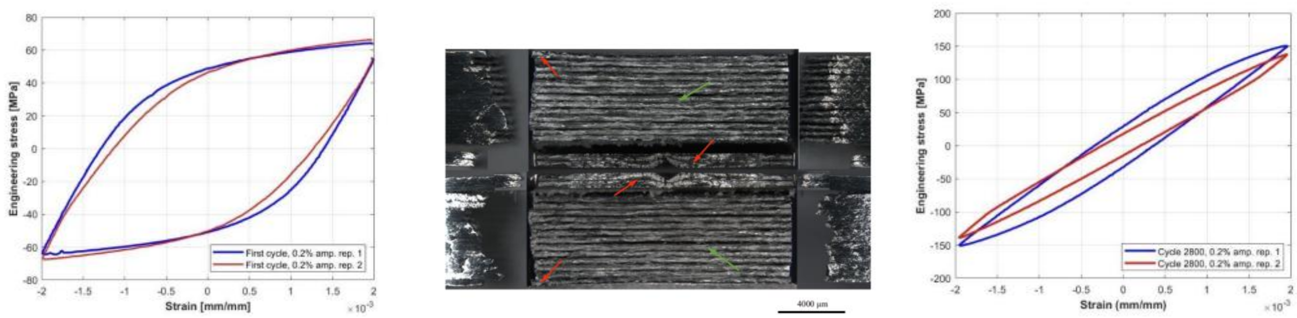


***Figure 1.*** *Representative cyclic stress–strain hysteresis loops obtained from adhesively bonded laminated thin aluminium sheet specimens tested at a total strain amplitude of 0.2%, together with corresponding fracture surface features showing fatigue crack growth patterns.*

# From the surface defect population to an efficient fatigue life prediction: effects of defect geometrical characteristics and material variability

**David Mellé[1], Etienne Pessard[2], Franck Morel[2], Daniel Bellett[2]**

[1]*Safran Tech M&P Department, Rue des jeunes Bois, 78772 Magny les Hameaux, France*

*david.melle@safrangroup.com*

[2]*LAMPA, Arts et Métiers Institute of Technology, 2 Bd du Ronceray, 49035 Angers, France*

*Additive Manufacturing* *Fatigue design* *Ti-6Al-4V*

**Abstract** Additive manufacturing notoriously produces components with complex shapes that are interesting, especially in the aerospace industry, for the possible gains in terms of mass but with surface states that may be challenging for components subjected to fatigue loads. This is why very few highly loaded, critical parts, subjected to fatigue loads, are currently used.

In order to safely design such components, understanding the link between the material, the defect population, and the fatigue performance is compulsory. In this work, the Ti-6Al-4V titanium alloy and laser powder bed fusion process are investigated. Flat specimens were produced in order to extract the total surface defect population using optical profilometry. Several chemical etching times were applied to achieve different surface defects populations characteristics. These specimens were subjected to bending fatigue loads to determine their fatigue performance and to identify the critical surface defect in the population. Analyses of the different specimens populations are then conducted and several indicators based on the geometrical characteristics of the defects are discussed.

This work showed that criticality indicators based on linear elastic fracture mechanics are the most efficient but also that material variability makes the geometrical characteristics of the defects insufficient to accurately predict the critical defect from the specimen population. In addition, from comparison between the different specimen populations, it appears that the specimen surface is too small to be representative of the "global defect population" particularly in terms of the larges most rare defects. These findings make classical deterministic fatigue-life approaches too conservative for many components. Probabilistic or even fiabilistic approaches may be a solution to design and validate critical highly loaded parts subjected to fatigue loadings.

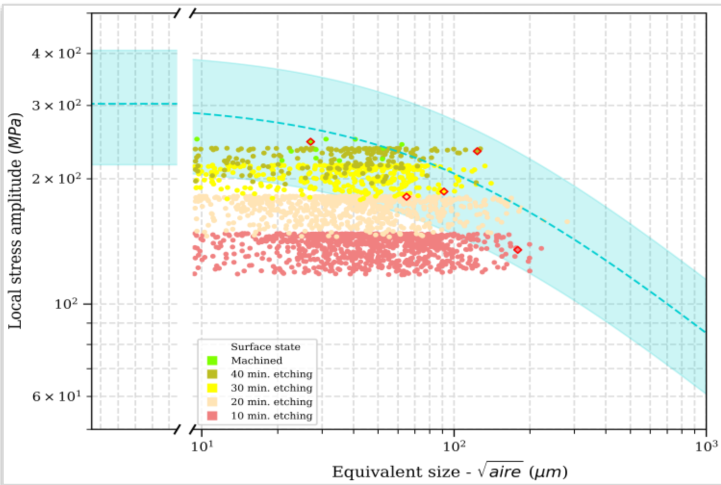


***Figure 1 -*** *Example of the full surface defect population on some specimens from all surface states – Identification of the defect present in the critical area (blue zone) and of the defect responsible of the fatigue failure (red diamonds), from these populations*

# Predicting fatigue lifetimes of additively manufactured metallic parts with few experiment data: A multi-fidelity machine learning model

**Shiyi MAO[1], Binchao LIU[2], Rui BAO[1]**

[1] *School of Aeronautic Science and Engineering, Beihang University (BUAA), Beijing, China*

[2] *Hangzhou International Innovation Institute, Beihang University (BUAA), Hangzhou, China*

*Fatigue life prediction* *Multi-fidelity machine learning* *Additive manufacturing*

**Abstract**

Fatigue lifetimes of additively manufactured (AM) metallic parts exhibit extraordinarily large scatter, which makes it difficult to obtain acceptable fatigue lifetime conclusion with high reliability and thus impedes the large-scale application of metal AM to fatigue-critical components. Despite it has been revealed that killer defect characteristics are of great importance to fatigue lifetimes of AM metallic parts, revealing the impacts of killer defect on fatigue lifetimes comes at a high cost, again due to the extraordinarily large scatter of fatigue lifetime data. Therefore, developing a method which is capable of predicting fatigue lifetimes with few experiment data is of great significance.

For this purpose, this work proposes a multi-fidelity machine learning model, which fuses the data of few experiment data and plentiful simulation data to achieve accurate prediction. The simulation data is provided by peridynamic simulations, which represents a mechanical perspective of impacts by killer defect sizes and locations. The experiment data includes fatigue lifetime data obtained by fatigue tests and killer defect characteristics by fractographic analysis. The multi-fidelity model works by a two-network architecture, as shown in Figure 1. The first network is low-fidelity network, whose duty is capturing the semi-quantitative correlations between killer defect characteristics and fatigue lifetimes by plentiful simulation data. The second network is high-fidelity network, whose duty is transferring the above virtual-space correlations to real-space ones by guide of few experiment data.

The proposed model achieves fatigue lifetime prediction of ±2 error band, which fully demonstrates its capability that few experiment data guides semi-quantitative correlations in virtual space to transfer to quantitative correlations in real space. Based on above, we furthermore discuss the generalization as well as interpretability of the multi-fidelity machine learning model, and find that such method is also applicable to other materials and other AM techniques. Therefore, the proposed model in this work offers an economical and practical way to evaluate fatigue properties of AM metallic parts.

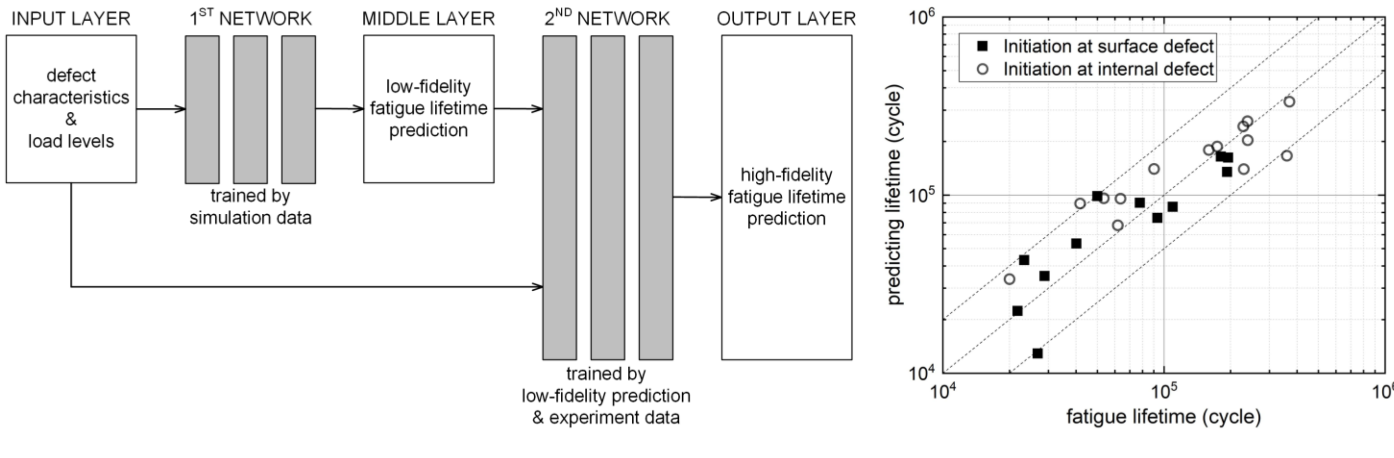


*Figure 1-Modeling Approach and Prediction Results*

# Can oxidation damage be beneficial to cracking resistance under long-dwell fatigue loading at elevated temperature?

**Binchao LIU[1], Qiuyi WANG[2], Rui BAO[2]**

[1] *Hangzhou International Innovation Institute, Beihang University (BUAA), Hangzhou, China*

[2] *School of Aeronautic Science and Engineering, Beihang University (BUAA), Beijing, China*

*Cracking resistance* *Dwell fatigue loading* *Oxidation damage*

**Abstract**

Oxidation damage is commonly considered as detrimental to service performances under long-dwell fatigue loading at elevated temperature, as the fatigue damage and creep damage do. This work, however, reports that oxidation damage can be beneficial to cracking resistance if grain boundary (GB) network is well tailored.

Cracking behaviors under long-dwell fatigue loading (hold time being 2160 s) at 650 °C are investigated in two typical GB networks, i.e. columnar grains in horizonal direction (CG-H) and vertical direction (CG-V), while equiaxed-grain (EG) GB network is taken as baseline reference. It has been revealed that oxidation damage dominated the cracking behaviors, making cracks for all three GB networks strongly intergranular. Due to distinctive topology of GB network, however, the test of EG network lasted for 17 hours (less than 1 day), while the test of CG-H network lasted for 14 days due to the surprisingly declined crack growth rates by one order of magnitude, and severe crack deflection/branching led to total propagation of only 0.45 mm during 21 days in CG-V network. Such significantly different cracking resistance is attributed to the preferential oxygen diffusion along GB networks and the GB susceptibility to oxidation damage. CG-H network enhances the cracking resistance via depressing oxygen diffusion by sparser GB network and less GB triple junctions, which can be well explained by theory of network topology; CG-V network enhances the cracking resistance by utilizing oxidation damage to guide crack deflection/branching, which drastically declines the crack driving force.

It is fully demonstrated that oxidation damage (commonly detrimental) can be utilized to enhance cracking resistance (undoubtedly beneficial) against long-dwell fatigue loading via proper GB network tailoring. This innovative strategy provides significant guidance for improving damage tolerance performances of elevated-temperature components.

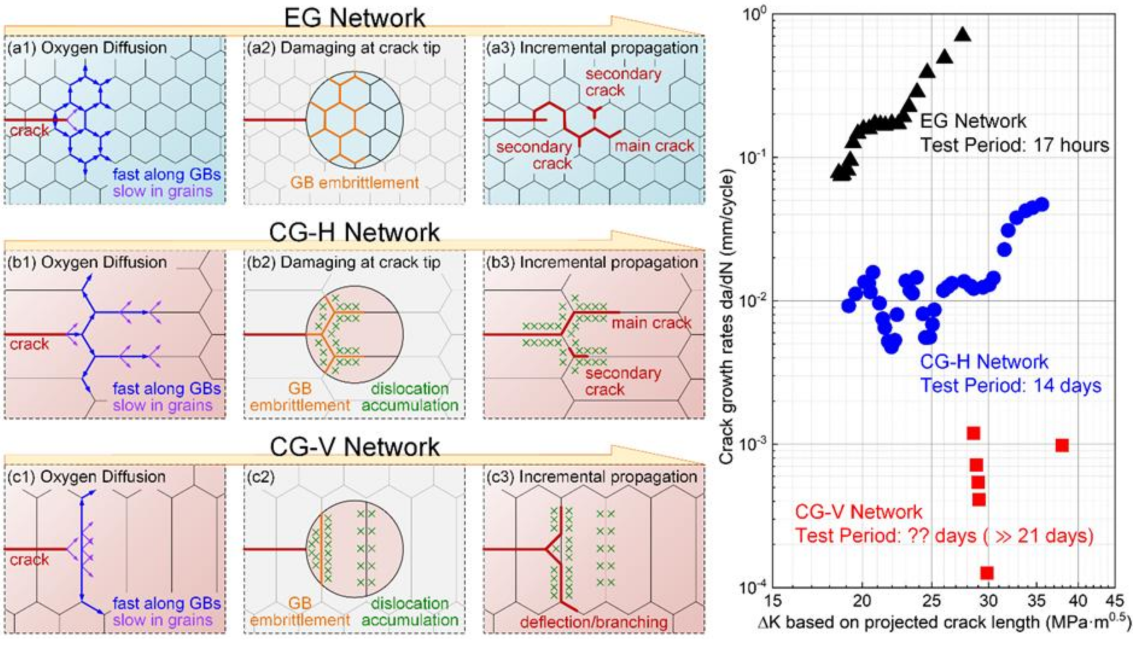


*Figure 1 - Oxidation damage, cracking behaviors and crack growth rates.*

# On the use of Thermoelastic Stress Analysis for fatigue crack growth modelling

**Lorenzo Bercelli[1], Bruno Levieil[1], Cédric Doudard[1], Sylvain Calloch[1], Florent Bridier[2]**

[1]*ENSTA, IRDL – UMR CNRS 6027, 29200 Brest, France*

[2]*Naval Group, Technocampus Océan, 44340 Bouguenais,France*

*High cycle fatigue* *Infrared thermography* *Structure testing*

**Abstract** Propagation of fatigue cracks drives the in-service life of many structural components, especially for welded-joints and parts processed via additive manufacturing in the as-built condition. In such configurations, crack growth depends on both the material and the fabrication process, via the microstructure, the local geometry (e.g. roughness) and the residual stresses. The consideration of these parameters through modelling requires experimental data of reference captured directly from the structure of interest.

This study focuses on the use of Thermoelastic Stress Analysis (TSA) as a tool for data acquisition useful to the modelling of fatigue crack growth in structures with consideration of process induced residual stresses. TSA relies on the monitoring via infrared thermography of the temperature of an object submitted to cyclic loading. Within the right theoretical framework, one can relate the measured temperature to the thermoelastic coupling and, hence, to stress at the surface of observation. As a result, the presence of surface cracks and their propagation can be monitored using an infrared camera, and all of this in a wide field of view, with no a-priori knowledge of the initiation locations. A more thorough analysis of the temperature signal also provides quantitative information as to crack-closure phenomena, linked to the presence of residual stresses and/or to the applied loading.

First, the theoretical framework is detailed in the simple case of a 2D through crack loaded in Mode I for many stress ratios. Second, application of the method is then illustrated on two different real-world case scenarios: a naval-grade welded-joint and wire and arc additive manufactured samples with different surface treatments.

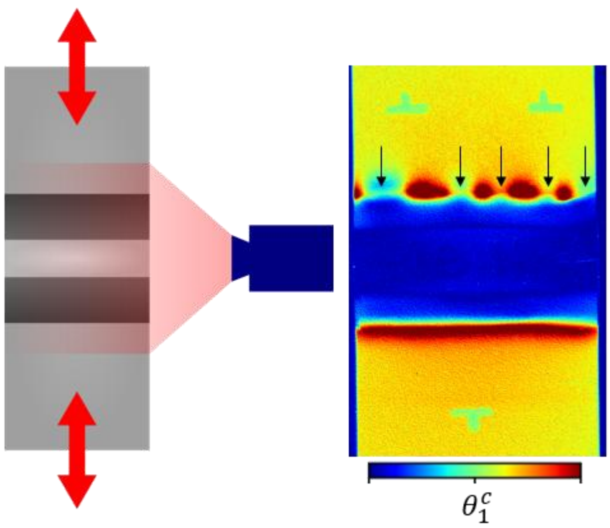


***Figure 1** – Illustration of TSA results for the case of a naval-grade welded-joint – five cracks are detected on the upper weld toe in the image of the temperature first harmonic $\theta_1^c$*

# High-Cycle Fatigue of LPBF CuCrZr for Nuclear Fusion Components

**L. Salvò[1,2], A. Pepato[2], M. Benedetti[1]**

[1] *Department of Industrial Engineering, University of Trento, Via Sommarive 9, Trento, 38123, Italy*

[2] *National Institute for Nuclear Physics (INFN) – Padua Division, via Marzolo 8, Padova, 35131, Italy*

*Laser Powder Bed Fusion* *Process-Induced Defects* *Defect-Tolerant Design*

**Abstract** The Neutral Beam Injector (NBI) of the Divertor Tokamak Test (DTT) facility relies on copper-based grids featuring complex openings and internal cooling channels, for which Laser Powder Bed Fusion (LPBF) is being pursued to enable design freedom and manufacturing integration. CuCrZr is a key candidate alloy; however, its fatigue performance remains strongly affected by LPBF defect populations and post-processing routes. This work provides a comparative High-Cycle Fatigue (HCF) and defect sensitivity assessment of five LPBF conditions (four CuCrZr, one industrial SoA LPBF Cu-CP as reference) aimed at qualification-oriented selection of process/heat-treatment conditions for fusion-relevant grid components.

Five LPBF conditions were investigated: P1 (80 µm, 1 kW, SHT/FC+AA), P2 (80 µm, 1 kW, DAH), F1 (60 µm, 1 kW, SA+AA), DIAM (30 µm, 400 W, DAH), and pure copper Cu-CP (40 µm, 1 kW, AN) produced by an european market leading company using industrial parameters. HCF tests were conducted at room temperature under fully reversed loading (R = −1) up to $10^7$ cycles; notched specimens were used to apply the Benedetti–Santus KT framework, which fits smooth and notched data simultaneously by accounting for local stress gradients and defect size (√area) at the crack origin. Fatigue data were fitted using Basquin-type relationships and complemented by SEM fractography to identify crack-initiating defects and quantify their characteristic size via $\sqrt{area}$ measurements.

The optimized CuCrZr conditions achieved the highest fatigue limits at $10^7$ cycles: EOS Finland (SA+AA) reached $\sigma_w^{10^7} \approx$ 138 MPa, and AMCM P2 (DAH) $\sigma_w^{10^7} \approx$ 133 MPa, confirming that optimized processing and suitable ageing routes deliver the best HCF resistance. The DIAM 30 µm batch (DAH, 400 W) showed a lower fatigue limit ($\sigma_w^{10^7} \approx$ 114 MPa), consistent with the documented sensitivity of defect incidence to the combined effect of layer thickness and available laser power. As an LPBF reference material, Cu-CP exhibited $\sigma_w^{10^7} \approx$ 99 MPa in the annealed condition. The suboptimal AMCM P1 batch displayed the lowest endurance, with an endurance limit near 67 MPa. For the KT identification methodology, the Benedetti–Santus approach (already demonstrated on P1) yields a single Kitagawa-Takahashi (KT) diagram calibrated using both smooth and notched results; in the P1 study, the procedure converged to $\Delta K_{th} \approx 4.4$ MPa$\sqrt{m}$ and an intrinsic length $a_0 \approx$ 117 µm. The same workflow is applied across all LPBF conditions in this comparative campaign to extract condition-dependent KT boundaries and quantify how process/heat-treatment routes reposition the safe/unsafe domain for defect-controlled fatigue.

A key outcome for fusion-relevant LPBF component manufacturing is that Direct Age Hardening (DAH) further enhances fatigue performance by increasing material strength without promoting grain coarsening, thereby enabling high-strength conditions while avoiding the distortion risks associated with water quenching in large, thin-walled grid structures. Overall, the dataset establishes a process- and heat-treatment-informed ranking of LPBF copper alloys for NBI grid applications and provides fatigue parameters suitable for defining design allowables and supporting subsequent defect-tolerant assessments.

# Fatigue Crack Characteristics in Gradient Predeformed Pearlitic Steel under Multiaxial Loading

**Daniel Gren[1,2], Johan Ahlström[1*], Magnus Ekh[1]**

[1]*Chalmers University of Technology, Computational Mechanics and Materials Engineering, Mechanical Engineering*
[2]*now at GKN Aerospace, Sweden AB, Trollhättan, Sweden*

*Email: johan.ahlstrom@chalmers.se

*Fatigue Crack Propagation* *Predeformed pearlitic steel* *Multiaxial fatigue*

Rolling contact fatigue of railway rails not only severely deforms the surface material near the rail head, but also induces an anisotropy in the mechanical behavior due to work hardening and alignment of the microstructure along the shear direction. Cracks typically initiate in this region and propagate along the aligned microstructure. The fatigue behavior of rails is normally evaluated under uniaxial loading in the undeformed material state. However, this is not representative of the contact loading condition and material performance after years of service. Herein, the nonproportional multiaxial fatigue crack propagation of as-received and biaxially predeformed pearlitic rail steel R260 is investigated. Four material states are investigated, corresponding to the microstructure found at different depths from the severely deformed surface material at the rail head. A starting notch is machined by electrical discharge machining to control crack initiation and allow for comparable surface crack propagation measurements. The crack path is found to be strongly influenced by the degree of predeformation while the early surface crack propagation rate is found to be similar for all material states.

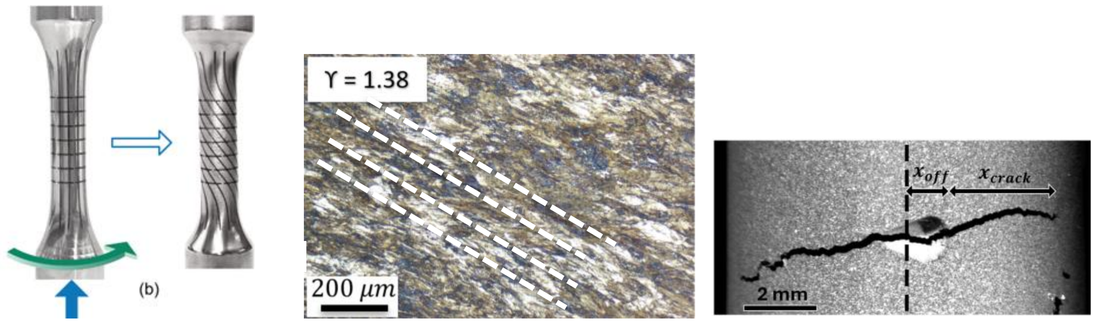


***Figure 1*** *– Predeformation method: (a) Shear deformation from twisting and compressing the test bar; (b) Microstructure alignment with drawn flow lines after predeformation (c) drop-shaped notch geometry and photo of test bar surface, showing crack direction.*

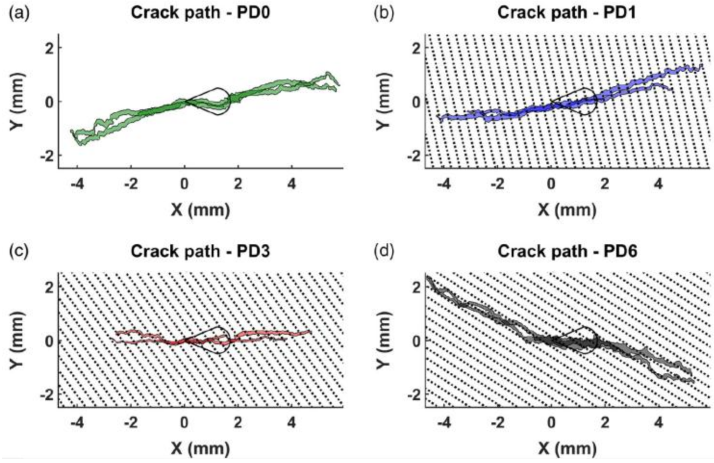


***Figure 2*** *Surface crack path for the lowest (a, PD0) to highest (d, PD6) pre-deformation state.*

*The effect of anisotropy is clearly seen by the change in direction. The dashed lines indicate the increasing level of predeformation (cf Fig 1b).*

# Corrosion-Fatigue Behavior of L-PBF Ti-6Al-4V Lattice Struts in Physiological Media

**Simone Murchio[a,b], Farnoosh Farhad[c], Melika Babaei[b], Alessandro Albertini[b], Devid Maniglio[b], Filippo Berto[a], Matteo Benedetti[b]**

*a Department of Chemical Engineering Materials Environment – La Sapienza University of Rome, Italy*

*b Department of Industrial Engineering – DII, University of Trento, Trento, Italy*

*c School of Engineering, Physics and Mathematics, Northumbria University, Newcastle upon Tyne, UK*

**Corresponding authors:* **simone.murchio@uniroma1.it**

*Corrosion-Fatigue* *Additive Manufacturing* *Lattice Structures*

**Abstract** Metallic lattice-based components fabricated via laser powder bed fusion (L-PBF) represent a promising solution for next-generation orthopedic implants, offering tailorable mechanical properties that mitigate stress-shielding effects while promoting bone ingrowth through optimized porosity. Among candidate alloys, Ti-6Al-4V remains the clinical gold standard owing to its biocompatibility, corrosion resistance, and favorable strength-to-weight ratio. However, the long-term structural integrity of these architectures under cyclic loading in the human body remains a critical concern. While extensive research has characterized the fatigue behavior of additively manufactured components under laboratory conditions, the synergistic effects of mechanical cycling and electrochemical degradation in physiological environments are often overlooked, particularly for AM-architected cellular materials. Given that implants experience concurrent exposure to body fluids and repetitive loading over decades of service, understanding corrosion-fatigue interactions is essential for safe clinical translation. Moreover, unlike subtractive manufacturing, L-PBF inherently produces pronounced geometric irregularities and surface defects that may serve as preferential sites for both mechanical crack initiation and localized corrosion.

This investigation examines the corrosion-fatigue performance of L-PBF Ti-6Al-4V lattice struts using miniaturized specimens manufactured at 60° build orientation and tested under tension-tension loading ($R = 0.1$) in both laboratory air and phosphate-buffered saline (PBS) at physiological temperature. Micro-computed tomography enabled comprehensive characterization of surface topology, dimensional deviations, and subsurface defect distributions, establishing a framework for defect-based failure prediction methodologies. The experimental results demonstrate that fatigue life is highly sensitive to manufacturing-induced imperfections, with physiological media causing substantial reductions in the high-cycle fatigue regime. Fractographic analyses reveal that surface morphology dictates crack nucleation sites, while environmental exposure predominantly accelerates propagation kinetics through corrosion-assisted mechanisms.

# Ultrasonic fatigue testing of single-phase materials with elastic-plastic and metastable materials behavior in the VHCF regime

**Marek Smaga, Elen Regitz, Tilmann Beck**

*Institute of Materials Science and Engineering (WKK) at RPTU in Kaiserslautern, Germany*

*ultrasonic fatigue* *elastic-plastic* *metastability*

Ultrasonic fatigue testing is a common method for achieving a very high number of cycles to failure ($10^9$-$10^{11}$) within a limited experimental runtime. To excite the specimen in its eigenmode at loading frequencies in the kHz range (typically around 20 kHz), macroscopic elastic specimen behavior is usually assumed. However, for face-centered cubic (fcc) Fe-based materials such as austenitic stainless steels (ASSs), elastic–plastic behavior can occur even at stress amplitudes within the in the very-high-cycle fatigue (VHCF) regime. This leads to a pronounced increase in specimen temperature and, in some cases, can prevent stable oscillation. Since the fcc austenitic phase is often metastable in ASSs, a phase transformation from fcc austenite to body-centered cubic (bcc) alpha′-martensite may occur during cyclic loading. In this talk, the VHCF behavior of different ASSs will be discussed, including:

- AISI 347 and AISI 304L tested at ambient temperature and at 300 °C
- Weld metal ER347 tested parallel and perpendicular to the welding direction
- Heat-affected zone material in AISI 347
- Powder laser bed fusion additively manufactured AISI 316L

The cyclic deformation behavior is characterized using representative stress–strain hysteresis measurements at defined fatigue states obtained with servo-hydraulic testing. In addition, magnetic non-destructive measurements enable analysis of the evolution of ferromagnetic α′-martensite within paramagnetic austenite during cyclic loading. Furthermore, the consequences of elastic–plastic material behavior and the phase transformation under ultrasonic cyclic loading will be introduced and discussed. In summary, the fatigue lives of the above-mentioned materials, as well as concepts for determining total-strain-based fatigue life curves derived from ultrasonic fatigue testing, will be presented.

# Experimental study and modeling of SMAT-treated Inconel 718 fatigue behavior

**Anna Garambois[1,2], Pascale Kanouté[1], Louise Toualbi[1], Delphine Retraint[2]**

*[1]ONERA, Châtillon, France*
*anna.garambois@onera.fr*
*pascale.kanoute@onera.fr*
*louise.toualbi@onera.fr*

*[2]LASMIS, University of Technology of Troyes, France*
*delphine.retraint@utt.fr*

*SMAT* *Ni-based alloys* *Residual stress*

Fatigue damage was identified as the primary failure mechanism of turbine disks, with crack initiation mainly occurring at the surface. To delay crack initiation, mechanical surface treatments such as shot-peening are widely used in the aeronautical industry. Surface Mechanical Attrition Treatment (SMAT), derived from conventional shot-peening, additionally produces a nanocrystalline surface layer along with compressive residual stresses and work hardening. While SMAT has been shown to significantly improve fatigue life, it remains difficult to distinguish the respective roles of these mechanisms, as well as the effect of residual stress relaxation.

This study investigates the fatigue behavior of SMAT-treated Inconel 718 using a multiscale approach that accounts for the induced property gradient and its thermal and mechanical relaxation. Strain-controlled fatigue tests were performed on SMAT-treated specimens at room temperature and 450°C and compared with conventionally shot-peened and untreated references. SMAT led to a significant increase in fatigue life over the full range of strain amplitudes, compared to both untreated and shot-peened conditions.

Microstructural and mechanical gradients were characterized using transmission electron microscopy (TEM), electron backscatter diffraction (EBSD), microhardness measurements, and X-ray diffraction (XRD). A nanocrystalline surface layer with grain sizes around 100 nm was observed within the first few micrometers. Additionally, pronounced work hardening and high compressive residual stresses up to -1000 MPa were evaluated through several hundred micrometers below the surface. The relaxation of these residual stresses under thermal and mechanical loading was specifically investigated. *In situ* four-point bending tests were performed in a scanning electron microscope (SEM) and combined with digital image correlation and EBSD. This approach provided access to local strain fields and deformation mechanisms at multiple scales to support constitutive modeling. Finite element simulations incorporating experimentally measured and relaxed residual stress profiles were used to evaluate the respective contributions of residual stresses, work hardening, and microstructural refinement, enabling the development of a cyclic constitutive model for fatigue life prediction.

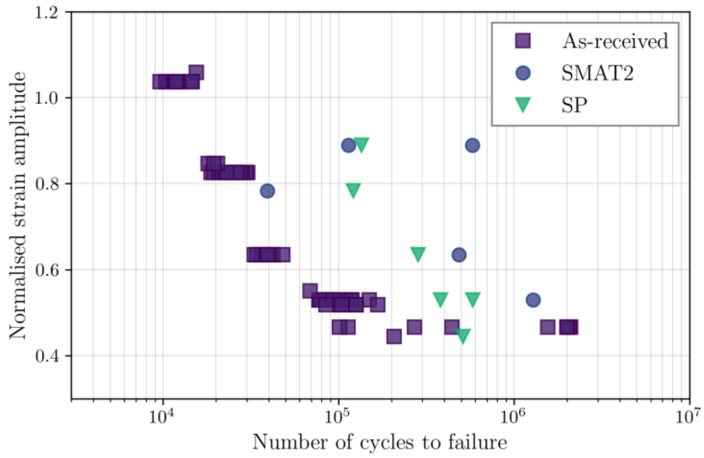


***Figure 1*** – Strain amplitude vs the number of cycles to failure for Inconel 718 subjected to different surface conditions.

# From cyclic deformation to fatigue crack nucleation at basal twist grain boundaries in the Ti-6Al-4V titanium alloy

**T. Yvinec[1], V. Valle[1], F. Hamon[1], D. Iabadden[2], J. Guénolé[2], S. Hémery[1]**

[1] *Institut Pprime, ISAE-ENSMA, Université de Poitiers, CNRS UPR 3346, Téléport 2, 1 avenue Clément Ader, BP 40109, Futuroscope-Chasseneuil Cedex, 86961 France*

[2] *CNRS, Université de Lorraine, Arts et Métiers Institute of Technology, LEM3, F-57000, Metz, France*

*Crack initiation* *Titanium alloys* *Grain boundaries*

**Abstract** Titanium alloys are widely employed in aerospace applications owing to their outstanding combination of properties. As components often experience cyclic mechanical loadings during service, accurate predictions of fatigue lifetimes are a key milestone for safe and lightweight aircrafts, but require a mechanistic modeling of underlying processes. Recent studies revealed the nucleation of fatigue cracks at basal twist grain boundaries (BTGBs) in α+β titanium alloys. The presentation will focus on recent progress in clarifying the deformation and fracture mechanisms operating in these microstructural configurations. In particular, a combination of experimental and simulation techniques, including HR-DIC, EBSD, in-situ mechanical testing, and molecular dynamics simulations, was leveraged to characterize the mechanical behavior at BTGBs in titanium alloys subjected to monotonic and cyclic loadings. The origin of preferential cracking at these microstructure configurations will finally be discussed and clarified.

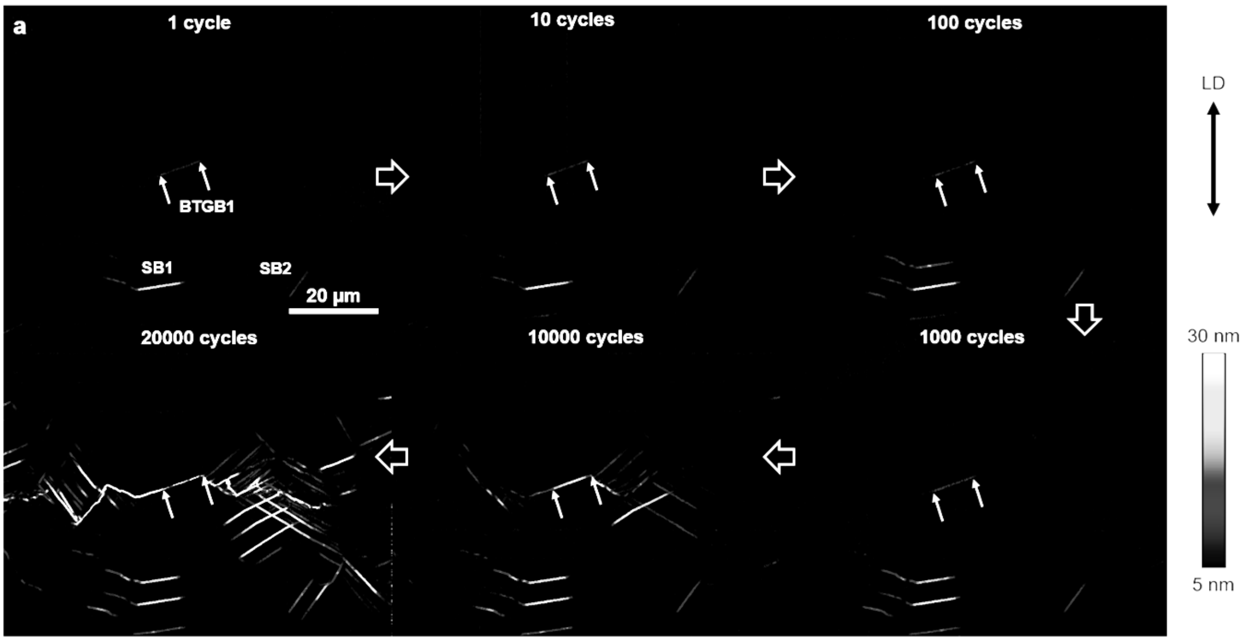


***Figure 1** – In-plane slip displacements measured during interrupted fatigue tests in a Ti-6Al-4V specimen*

# Thermomechanical Fatigue: Early Irreversible Deformation and Its Impact on Lifetime

**Stefan Guth[1], Jan Lars Riedel[1], Dhruv Anjaria[2], Mathieu Calvat[2], Jean-Charles Stinville[2]**

[1]*Karlsruhe Institute of Technology, Engelbert-Arnold-Str. 4, 76135 Karlsruhe, Germany, Stefan.guth@kit.edu*

[2]*University of Illinois Urbana-Champaign, IL, USA*

*Thermomechanical Fatigue* *High-Resolution Digital Image Correlation* *Damage Evolution*

**Abstract**

Thermomechanical fatigue (TMF) often governs the lifetime of high-temperature structural components. In many high-temperature alloys, the evolution of crack damage during the later stages of TMF life has been well characterized, leading to the development of accurate lifetime prediction models. By contrast, early TMF deformation and damage mechanisms, such as slip irreversibility and its transition to crack initiation, and their impact on TMF lifetime remain poorly understood. This study examines incipient deformation and slip irreversibility during early TMF cycling, in relation to reference macroscopic push–pull TMF tests on solid round Inconel 718 specimens subjected to continuous temperature cycling between 300 and 650 °C under in-phase (IP) and out-of-phase (OP) conditions. To characterize early slip localization under TMF conditions, we performed high-resolution digital image correlation (HR-DIC) measurements in the first cycles (tension and compression) of the push-pull TMF tests on flat bending specimens at room temperature (as a reference), 300 °C, and 650 °C. To represent IP loading, tensile straining followed by unloading was performed at 650 °C, while compressive straining and unloading occurred at 300 °C. For OP loading, the test conditions were reversed. Slip irreversibility on the bending specimen surfaces was characterized to elucidate the effect of the TMF loading condition. For a given phase relation, the intensity of slip irreversibility in the initial cycles is observed to correlate with the TMF lifetime obtained from conventional TMF testing. Based on these results, we discuss the potential of HR-DIC measurements as a rapid life prediction method for TMF loading.

# Fatigue Performance of the New Leaf Spring Steel 45SiCrV9Ni for Applications in Battery Electric Vehicles

**Niki Nouri[1], Christos Gakias[2], Borja Escauriaza[3], Javier Isach[4], Roberto Elvira[3], Georgios Savaidis[2], Stefan Dietrich[1], Volker Schulze[1]**

[1] *Institute for Applied Materials - Materials Science and Engineering (IAM-WK), Karlsruhe Institute of Technology (KIT), Engelbert-Arnold-Str. 4, 76131 Karlsruhe, Germany; niki.nouri@kit.edu*

[2] *Laboratory of Machine Elements and Machine Design, Mechanical Engineering Department, Aristotle University of Thessaloniki, Egnatia & 3rd September Str. Crossing, 546 24 Thessaloniki, Greece*

[3] *Sidenor I+D, Barrio Ugarte s/n, 48970 Basauri, Spain*

[4] *Muelles y Ballestas Hispano Alemanas (MBHA) Projects, S.L., Camino Viejo de Castellón a Onda s/n, 12540 Villarreal, Spain*

*Leaf Spring Steels* *Fatigue Behaviour* *Shot Peening*

**Abstract** The continuously increasing load levels in suspension systems of commercial battery electric vehicles (BEVs) require the use of structural materials with enhanced strength and fatigue resistance. A recently developed high-strength spring steel, 45SiCrV9Ni, has shown advantageous processing-related properties and represents a potential alternative to the established 51CrV4 grade used in leaf spring applications. The present study systematically investigates the fatigue performance of 45SiCrV9Ni in two different heat-treatment conditions to assess its suitability for demanding service conditions. Fatigue behaviour is first examined on laboratory-scale specimens subjected to axial tension–compression loading, while rotating bending fatigue tests are conducted on shot-peened specimens. The mechanical results are supported by fractographic investigations to elucidate dominant damage and crack initiation mechanisms. In a second step, the fatigue performance is evaluated at component level using downscaled monoleaves tested under cyclic loading in a dedicated test setup. Complementary microstructural and mechanical characterisation of the monoleaves is performed to establish structure–property–performance relationships. The results indicate that lower tempering temperatures provide superior fatigue resistance compared to higher tempering temperatures and to the reference steel. Rotating bending fatigue testing reveals a pronounced beneficial effect of shot peening, particularly for 45SiCrV9Ni, where the elevated base strength enables the generation of higher and more stable compressive residual stress states. Crack initiation behaviour is strongly dependent on the applied stress amplitude, with surface-initiated fatigue cracks prevailing at high stress levels, while subsurface crack initiation dominates at lower stress amplitudes, typically within the depth range influenced by shot peening. Furthermore, decarburization is identified as a critical manufacturing-related issue, especially for 45SiCrV9Ni, which exhibits an increased and more pronounced decarburized surface layer after reheating. This highlights the necessity for strict control of furnace atmosphere, temperature, and holding time during thermal processing. Overall, the findings demonstrate that 45SiCrV9Ni exhibits markedly improved fatigue performance relative to 51CrV4 across all investigated loading conditions, confirming its potential for use in high-load suspension components for commercial BEVs.

# Influence and Handling of Process Interruptions in PBF-LB/M

**Martin Moser, Vesna Nedeljkovic-Groha**

*University of the Bundeswehr Munich, Department of Mechanical Engineering*

*Werner-Heisenberg-Weg 39, 85577 Neubiberg, martin.moser@unibw.de*

*Additive Manufacturing* *Process interruptions* *Mechanical properties*

**Abstract:** In recent years, additive manufacturing has become an important production technology for various industries, with laser-based powder bed fusion of metals (PBF-LB/M) being the most widely used process for manufacturing metal components. However, build jobs may be interrupted for various reasons. While the process can often be continued, a reduction in component quality - particularly in terms of fatigue performance - must be expected. Previous studies have shown that cooling of the system and components during downtime leads to various types of defects. For example, an inappropriate restart procedure may cause increased pore formation at the interruption plane. However, more critical are the formed interruption marks, which represent not only an optical flaw but also a geometric notch. If the components are not machined and the layer shift is therefore not removed, the fatigue properties are often severely impaired even for short standstill times. Since complex geometries often cannot be machined spontaneously with conventional methods to remove these marks, this study investigates three alternative post-processing methods to address this challenge: blasting, vibratory finishing, and manual grinding. These methods can be applied flexibly and with comparatively low effort. Their influence on surface condition, interruption mark geometry, and residual stresses was analyzed. Fatigue tests and fracture surface analysis were conducted to evaluate the capability of the investigated methods to mitigate the negative effects of process interruptions. The results demonstrate that the post-processing methods affect component properties and fatigue strength in different ways. Overall, all three approaches were able to significantly reduce the negative influence of interruption marks, thereby lowering the scrap rate associated with process interruptions in PBF-LB/M.

# A Spectral Framework for Multiaxial Random Fatigue Based on the Fatemi–Socie Critical-Plane Criterion

**Michele Sgamma[1,2], Andrea Chiocca[1], Francesco Bucchi[1], Francesco Frendo[1]**

*[1]Department of Civil and Industrial Engineering, University of Pisa, MS: michele.sgamma@cisup.unipi.it, AC: andrea.chiocca@unipi.it, FB: Francesco.bucchi@unipi.it, FF: francesco.frendo@unipi.it*

*[2]Center for Instrument Sharing of the University of Pisa (CISUP), University of Pisa*

*multiaxial fatigue* *frequency-domain* *critical plane*

**Abstract:** Mechanical components in transportation, energy and industrial systems are often subjected to multiaxial random loadings with broadband frequency content and significant non-proportionality. In these conditions, fatigue assessment based on time-domain stress/strain histories becomes computationally demanding, especially when long recordings, multiple operating scenarios and iterative design loops are involved. At the same time, widely used critical-plane criteria—such as the Fatemi–Socie—require the identification of the damaging plane and the evaluation of coupled shear and normal stress effects, which are typically performed through cycle-by-cycle processing in the time domain. This contribution addresses these limitations by presenting a frequency-domain methodology aimed at estimating Fatemi–Socie fatigue damage under stationary multiaxial random loading by exploiting spectral representations of the stress/strain tensor. The approach uses power and cross-spectral densities to reconstruct the second-order statistics of shear strain and normal stress components on candidate material planes, enabling an efficient plane search driven by covariance-based indicators rather than exhaustive time-domain transformations. A probabilistic description of cycle amplitudes is then obtained from spectral moments, allowing the Fatemi–Socie damage parameter to be evaluated efficiently through established spectral cycle distribution models. The methodology is intended to provide a fast yet accurate alternative for engineering applications where large datasets, multiple load cases, or optimization loops make time-domain processing impractical. The contibution will illustrate the workflow of the method and discuss its applicability through a representative case study, with validation against established reference procedures when available.

# Influence of the Surface Hardening Depth on the Tooth Root Fatigue Strength of Induction Hardened Sintered Steel Gears

**Moritz Klug[1], Stefan Dietrich[1] and Volker Schulze[1]**

[1]*Institute for Applied Materials – Materials Science and Engineering (IAM-WK) / Karlsruhe Institute of Technology (KIT), Engelbert-Arnold-Str. 4, 76131 Karlsruhe, Germany, moritz.klug@kit.edu*

*Sintered Steel* *Induction Hardening* *Tooth Root Fatigue Strength*

**Abstract** Sintered steel components allow for economic near-net-shape manufacturing of complex-shaped parts such as gears used in automotive drivetrains. The inherent porosity of sintered steel components typically results in reduced load-bearing capabilities compared to components manufactured from conventional steels. To enhance fatigue performance, post-sintering heat treatment processes are required. Among these, induction surface hardening is particularly beneficial, as it allows for close-to-contour hardening profiles on complex-shaped parts with minimal distortion.

The relationship between surface hardening depth and tooth root fatigue strength is well documented for gears manufactured from conventional steels. In particular, an optimum surface hardening depth from approximately 10% to 20% of the gear's module is commonly cited. For sintered steel gears, the presence of porosity significantly influences local stresses, crack initiation behaviour and fatigue performance. Consequently, the applicability of existing hardening recommendations to sintered steel gears remains unclear.

In this study, the influence of the surface hardening depth on the fatigue performance of induction hardened gears manufactured from the sintered steel Astaloy CrA (Fe-1.8%Cr-0.6%C) is investigated. First, the gears were induction hardened and subsequently tempered to achieve a surface hardness of approximately 700 HV. To allow for a close-to-contour hardening pattern, a dual-frequency heating system was used. Different surface hardening depths were achieved by varying the heating time as well as the relative power contributions from the high- and mid-frequency circuit of the induction hardening machine. Subsequently, tooth root fatigue tests were performed using a resonance-pulsator at a constant load ratio of R=0.1. Additionally, the results for different surface hardening depths were compared to a through-hardened gear as well as a gear in the as-sintered condition. To allow for the derivation of the corresponding S-N curves, the local stress state at the tooth root was analysed using finite element simulations. Material parameters for the simulation were obtained from tensile tests conducted on the material.

The results confirm a beneficial effect of induction hardening on the tooth root fatigue strength compared to the as-sintered condition. At the same time, the fatigue behavior is influenced by the surface hardening depth as well as the material's porosity, emphasizing the complexity of the mechanisms relevant to fatigue in sintered steel components.

The findings of this study contribute to an improved understanding of the fatigue behavior of induction-hardened sintered steel gears subjected to cyclic loading. The results provide a foundation for heat treatment strategies for fatigue-critical applications of sintered steel components, providing the basis for further industrial application.

# Application of the Effective Critical Plane approach to welded joints

**Andrea Chiocca, Michele Sgamma, Francesco Frendo**

*Department of Civil and Industrial Engineering, University of Pisa, AC: andrea.chiocca@unipi.it, MS: michele.sgamma@cisup.unipi.it, FF: francesco.frendo@unipi.it*

*multiaxial loading* *critical plane* *local approaches*

**Abstract** Welded joints are frequently the most fatigue-sensitive regions of structures, as local stress concentrations, microstructural modifications, residual stresses and complex multiaxial loading conditions can promote early crack initiation. While current design procedures are effective for many practical cases, their accuracy may reduce for complex load histories (multiaxial and non-proportional), or their application may result critical for geometric details not covered by the standards. This contribution presents an application of the Effective Critical Plane (ECP) approach, a local approach already proposed by the authors, to the fatigue assessment of welded joints. The method evaluates a critical-plane damage parameter starting from a locally averaged stress/strain field around the hotspot, to get an "effective" CP parameter (thus embedding the micro support theory of Neuber). This strategy aims to incorporate both the multiaxial nature of loading and the severe stress gradients typical of connection details, while remaining compatible with linear-elastic finite element analyses. The work discusses practical modelling aspects, calibration needs, and how the approach can be implemented for common connection geometries and load combinations. The goal is, overall, to evaluate the ECP capabilities as a reliable engineering tool for the fatigue life assessment of structural joints, especially in case of complex geometries and loading histories.

# Fatigue of metallic glasses: In-situ investigations in the SEM

**M. Marx[1], R. Busch[2], C. Motz[1]**

*[1] Saarland University, Materials Science and Methods, Campus C5 3, Saarbruecken, Germany*

*[2] Saarland University, Metallic Materials, Campus C6 3, Saarbruecken, Germany*

*metallic glass* *CTOD* *plastic zone*

The ductile deformation behavior in bulk metallic glasses (BMGs) differs from that of crystalline metals due to different mechanisms: BMG plasticity is induced by shear bands instead of dislocations. However, the fracture surfaces after fatigue crack growth and final fracture look quite similar to typical fatigue fracture surfaces with striations in the fatigued part and dimple structure in the residual fracture. Even after an overload, a similar behavior of arresting cracks arrest is described in literature, hereby crack branching induced crack closure was found. This might also influence the fatigue behavior at variable load spectra. However, comprehensive investigation for this class of material is missing.

In this work, the effect of a different load levels on the crack opening behaviour, the “plastic zone” and the crack propagation rate is investigated in situ in the SEM. Mini-CT specimens were prefatigued during an ex-situ fatigue test while the crack propagation rate was measured. After that, the specimens were fatigued for a few cycles in situ in the SEM. Thereby perfectly closing cracks were found during normal fatigue. Only at high loads, shear bands could be found surrounding the crack tip and indicating the plastically deformed region. After overloads, in contrast to literature, no crack deceleration was found. However, the behavior differs for very pure BMGs which induce a relatively high ductility and industrial grade BMGs which preferentially show a brittle behavior.

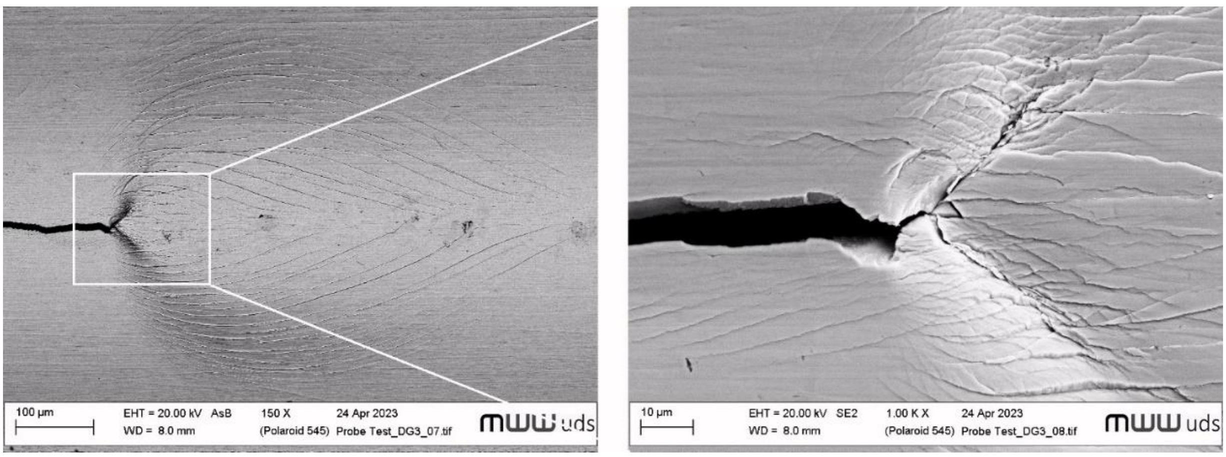


***Figure 1 -*** *Fatigue crack with plastic zone after an overload and additional 1000 cycles (left) and enlarged view of the crack tip (right).*

# Integrated Cellular Automaton and Progressive Damage Analysis for Corrosion Fatigue Life Prediction in Marine Environment

**Rui Deng[1], Xuejiao Chen[1],Yifei Deng[1],Chi Hou[1], Meiying Zhao[1]**

[1]*School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, China.*
*dengruii@mail.nwpu.edu.cn*

[2]*School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, China.*

*Life prediction* *Corrosion fatigue* *Multi-scale simulation*

**Abstract** The assessment of environmental corrosion damage effects on structural integrity and corrosion fatigue life is critical for ensuring the operational safety and durability of marine engineering structures. Traditional experimental methods for post-corrosion fatigue life assessment suffer from drawbacks of long test cycles and high costs, which limit their large-scale application in engineering practice. Moreover, these methods typically provide only macroscopic fatigue data without elucidating the underlying mechanisms through which corrosion morphology—such as pit geometry and distribution—influences corrosion fatigue behavior, thus offering limited theoretical support for structural design optimization and corrosion mitigation. To address these challenges, this study develops a novel multi-scale simulation framework that integrates a Cellular Automaton (CA) model with progressive damage analysis (PDA) for high- precision life prediction of marine structures subjected to corrosion and fatigue. The core of this methodology lies in bridging mesoscale corrosion evolution with macroscale fatigue damage propagation, enabling a comprehensive simulation of the entire corrosion-fatigue process. Firstly, a three-dimensional CA method-based simulation model and technical framework were established to simulate the evolution of structural corrosion damage in marine environments. This model fully considers the randomness of corrosion pit nucleation and through systematic numerical simulation, key corrosion damage parameters (including pit depth, corrosion area, and pit distribution density) that are statistically consistent with the results of three-dimensional morphology observation experiments were obtained. Secondly, via the equivalent ellipsoid model characterizing pit geometric features, a quantitative correlation was established between critical corrosion damage parameters and stress concentration factors. The derived correlation was then applied to quantify the residual structural strength, providing reliable mechanical input for subsequent fatigue analysis. Furthermore, by incorporating the dual effects of stress concentration and strength degradation into the Lemaitre fatigue damage constitutive model, a modified failure criterion and fatigue threshold correction method were established for corrosive service conditions. On this basis, progressive corrosion fatigue damage propagation analysis of post-corrosion structures was performed via the finite element method, enabling high-precision fatigue life prediction and ultimately forming a micro-macro coupling multi-scale simulation analysis method. To validate the proposed integrated method, systematic experiments and simulations were carried out on LY21 aluminum alloy specimens with different pre-corrosion periods, including corrosion morphology observation, numerical simulation, corrosion fatigue life testing, and prediction. The results demonstrate that the constructed CA model can accurately characterize the randomness and spatial distribution characteristics of corrosion initiation and propagation. The average relative error between simulated morphology parameters and experimental measurements is less than 5%, and the simulated corrosion damage evolution law is highly consistent with the actual corrosion behavior in marine environments. Additionally, the relative error between predicted and experimentally measured corrosion fatigue life is within 6%, which verifies the high prediction accuracy and engineering applicability of the developed integrated multi-scale simulation method.

# Fatigue characterization of tread braked railway wheels by experimental and numerical analysis

**G. Megna[1], A. Bracciali[2], A. Francesconi[2], A. Lanzutti[3], F. Sordetti[3]**

[1] *Department of Industrial and Civil Engineering, University of Pisa, Italy, gianluca.megna@ing.unipi.it*

[2] *Department of Industrial Engineering, University of Florence, Italy*

[3] *Department Polytechnic of Engineering and Architecture, University of Udine, Italy*

*Railway wheels* *Experimental analysis* *Fatigue life prediction*

**Abstract** Fatigue life of tread braked railway wheels is a crucial issue to be addressed by railway companies operating in freight transport. The use of low-noise composite brake blocks results in higher thermal loads that change the mechanical strength of wheel materials promoting cracks from the wheel rim or the wheel web that may lead to wheel failure and severe accidents. The effect of the combined action of thermal loads, mechanical loads and residual stresses on the fatigue behavior of in-service wheels is still a subject to be deeply studied.

The paper describes the experimental analysis performed after specific braking tests that were performed to induce high thermal loads within the wheels of a freight wagon, in which the actual wheel tread temperature was measured by a moving spot pyrometer. After the test the wheels were removed from the wagon to investigate the state of the material in terms of microstructural and mechanical properties such as residual stresses, hardness and tensile strength. The results of these tests were then used to set up a Finite Element thermomechanical model to simulate the stresses occurring at the wheel-rail contact and the related damage in different operating conditions. Several damage accumulation models were evaluated considering the specific application.

The results proved what experienced in real life, where Rolling Contact Fatigue damages distributed along the whole circumference of the wheel tread (named THRING, i.e. Thermal Ring) were found during wheels' inspections, showing that major damages can occur due to relevant mechanical strength reduction after thermal loads and the combined application of maximum loads at the wheel-rail contact. Compressive residual stresses on the wheel rim may reduce the probability of crack growth but measurements should be carefully carried out during the whole service life of the wheel.

***Figure 1*** *– Severe Rolling Contact Fatigue damage on the wheel tread induced by the combination of thermal loads and mechanical loads.*

# Behaviour of an Aeronautical Component Produced by PBF-LB/M

**Ricardo Cláudio[1,2,3], Tiago Alves[1], Pedro Pêcego[4], Rodolfo L. Batalha[1,6], Paulo Moita[1,2,6], Pedro Rendas[1], Susana Cravo[1], Ana Ferramacho[7], Carla Ferreira[1,3], Luís Reis[3], Aníbal Valido[1,2,6]**

[1]*ESTSetúbal, Instituto Politécnico de Setúbal, 2910-761 Setúbal, Portugal.*

[2]*DICE Lab, Instituto Politécnico de Setúbal, Setúbal, Portugal.*

[3]*IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal.*

[4]*Tekever UAS, Rua das Minas nº2 1, Estrada da Foz Do Arelho, Zona Industrial, Caldas da Rainha, 2500-750, Portugal*

[5]*Instituto de Soldadura e Qualidade, Av. Prof. Dr. Cavaco Silva, Porto Salvo, 2780-920, Portugal*

[6]*CENTEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal*

[7]*LAUAK Portugal, Rua do Bairro da Estação, Grândola, 7570-205, Portugal.*

[9]*Instituto de Soldadura e Qualidade, Av. Prof. Dr. Cavaco Silva, Porto Salvo, 2780-920, Portugal*

*PBF-LB/M* *Full Scale Testing* *Failure Analysis*

## Abstract

Additive Manufacturing (AM) has become a key enabler for next-generation aerospace structures, offering unprecedented geometric freedom, reduced part count, and the ability to produce highly optimized lightweight components. Among metal AM processes, Laser Powder Bed Fusion (PBF-LB/M) stands out for its capability to fabricate intricate load-bearing parts with fine feature resolution and high material utilization, attributes that are particularly attractive for aerospace applications where performance, weight, and reliability are critical.

Understanding the static and fatigue behaviour of components produced by PBF-LB/M becomes essential. While standardized test coupons provide baseline mechanical properties, they do not fully capture the complex interaction of residual stresses, microstructural heterogeneity, geometric effects, and process-induced defects inherent to additively manufactured structures. These factors can significantly influence both the ultimate load-carrying capacity and the fatigue performance of the final component, properties that are especially important in aerospace environments characterized by cyclic loading, and stringent safety margins.

In this context, the present work investigates the structural response of a PBF-LB/M manufactured support structure through a dedicated set of tests which include non-destructive tests, specimen level and destructive static tensile test and fatigue to the component. The study focuses on verifying elastic behaviour under elevated loading levels, identifying the transition to instability/plasticity, and characterizing the ultimate load capacity and failure mechanisms. Although the primary scope of this contribution is static performance, the work also provides fatigue assessment by full testing the component. These results contribute to ongoing efforts to integrate AM components into aerospace systems with confidence, supporting the broader objective of developing reliable, experimentally validated pathways for the static and fatigue qualification of additively manufactured parts.

# An impact fatigue model for TC18 titanium alloy considering stress gradient and load dynamic effects

**Xulong Chen[1], Xiongfei Li[1], Yupei Guo[2], Qiang Yang[2], Weiping Hu[1], Zhixin Zhan[1], Qingchun Meng[1]**

[1]*National Key Laboratory of Strength and Structural Integrity, School of Aeronautic Science and Engineering, Room 534, No. 2 Building, 9 Nansan Street, Beihang University, Beijing 102206, China. by2505107@buaa.edu.cn*

[2]*National Key Laboratory of Strength and Structural Integrity, Aircraft Strength Research Institute of China, Xi'an, Shaanxi, 710065, China*

*Equivalent fatigue damage model*   *Impact loading*   *TC18 titanium alloy*

**Abstract** Fatigue life assessment of notched components under impact loading requires simultaneous consideration of the effects of the stress gradient and the material dynamic response on damage evolution. To address this engineering requirement, this study takes TC18 titanium alloy as the research object and, within the framework of the Xiao damage evolution model, establishes a life prediction method for notched components under impact fatigue conditions.

First, considering the geometric discontinuity characteristics of notched components, the Xiao damage evolution equation is modified by introducing a stress gradient effect function to describe the influence of local stress non-uniformity on damage evolution. This function is jointly characterized by a stress triaxiality factor and the critical plane method, comprehensively reflecting the dominant damage mechanism at the notch root under multiaxial stress states. The model is validated using the fatigue test data from handbook, and the results indicate that the established equivalent fatigue damage model modified by the stress gradient effect can reasonably describe the influence of the notch effect on fatigue damage evolution and fatigue life of the material.

Furthermore, the influences of material strain-rate sensitivity and strain hardening behavior under impact loading on fatigue damage evolution are further considered, and the Xiao model is modified accordingly to enhance its applicability to impact fatigue conditions. The corresponding modifications are validated using impact fatigue test data of smooth specimens, and the results show that the established equivalent fatigue damage model modified by strain-rate and strain hardening effects can reasonably reflect the influence of load dynamic effects on fatigue damage evolution and fatigue life of the material.

On this basis, the stress gradient effect, strain hardening, and strain-rate effect are unified and coupled to establish a comprehensive damage model applicable to impact fatigue life prediction of notched components. Impact fatigue tests are conducted on TC18 titanium alloy notched specimens, and the predicted results are compared with the experimental data. The results indicate that the predicted lives show good agreement with the experimental data and can reasonably reflect the variation trend of impact fatigue life of notched components under different stress concentration conditions.

The method proposed in this paper enables direct prediction of impact fatigue life of notched components. It requires only a single-impact response analysis of the test specimen and uses the analytical integral form of the damage evolution equation, thereby avoiding the high computational cost of iterative numerical simulation of the damage evolution process. It provides both a theoretical model and an application method for fatigue life assessment of impact-loaded notched components in engineering practice.

# Strain-Rate-Dependent Continuum Damage Model and Damage Evolution Calculation Method for Low-Velocity Impact Fatigue of Metals

**Xia Qianyu[1], Weiping Hu[1], Zhixin Zhan[1], Yupei Guo[2], Qiang Yang[2], Qingchun Meng[1]**

[1]*National Key Laboratory of Strength and Structural Integrity, School of Aeronautic Science and Engineering, Room 534, No. 2 Building, 9 Nansan Street, Beihang University, Beijing 102206, China.* by2405218@buaa.edu.cn

[2]*National Key Laboratory of Strength and Structural Integrity, Aircraft Strength Research Institute of China, Xi'an, Shaanxi, 710065, China*

*Impact fatigue* *Continuum damage mechanics* *Strain-rate effect*

**Abstract** Impact fatigue commonly occurs in aerospace applications during stages such as landing and separation of flight vehicles. Owing to its relatively short loading duration, the impact loading can induce non-negligible transient dynamic responses. Meanwhile, the loading-unloading cycles inherent in repeated impacts, together with high strain-rate effects, lead to local stress/strain evolution and damage accumulation mechanisms that are markedly different from those in conventional fatigue. Therefore, it is necessary to develop damage analysis and life prediction methods for metallic materials subjected to repeated impact conditions. To achieve the life prediction of low-cycle impact fatigue for metallic materials subjected to repeated low-velocity tension-tension impact loading, a continuum damage model for impact fatigue incorporating strain-rate effects, together with an impact fatigue life prediction approach, is proposed based on the frameworks of continuum damage mechanics and irreversible thermodynamics. Under thermodynamic consistency constraints, the strain-rate effect is coupled into the damage evolution law, and the degradation of material load-carrying capacity induced by damage is described using the effective stress concept. Based on the ABAQUS/Explicit platform, a numerical implementation of the proposed constitutive and damage evolution model is developed to compute the time-history evolution of the damage variable during repeated impact loading, which is further combined with a damage-threshold-based failure criterion to achieve impact fatigue initiation life prediction. Model parameters are calibrated and validated using tension–tension impact fatigue experiments conducted on rod-shaped metallic specimens. The results indicate that the proposed improved damage evolution model can effectively describe the damage accumulation process, thereby providing a reliable numerical approach for predicting low-cycle impact-fatigue life.

# Measuring Fatigue-driven Degradation of Mode I Traction-separation Relation in Adhesively Bonded Joints using Fiber Sensors

**Wandong WANG[1,2], Jiacheng LIU[1]**

[1]*School of Aeronautics, Northwestern Polytechnical University, Xi'an, Shaanxi, 710072, China and w.wang@nwpu.edu.cn*

[2]*National Key Laboratory of Strength and Structure Integrity, Xi'an, Shaanxi, 710072, China*

*Adhesive joints* *Traction-separation relation* *Fatigue degradation*

Accurate traction–separation relations (TSRs) are essential for modeling adhesive joint failure, yet direct experimental methods are scarce, especially under fatigue. This study introduces a backface strain method to determine Mode I TSRs without prior assumption of their form. Using fiber-optic sensors on adhesively bonded titanium DCB specimens, the strain distribution along the substrate outer surface is measured during quasi-static and fatigue tests. The TSR and fracture parameters are derived analytically from the strain profile. Validation against digital image correlation shows close agreement in quasi-static TSR shape and fracture toughness. Under fatigue loading, the progressive degradation and spatial damage heterogeneity of the adhesive interface in the fracture process zone are observed, as shown in Figure 1. The fatigue crack length can also be extracted from the measured strain distributions. Most importantly, this method provides a novel yet pragmatic in-situ measurement approach for TSR degradation.

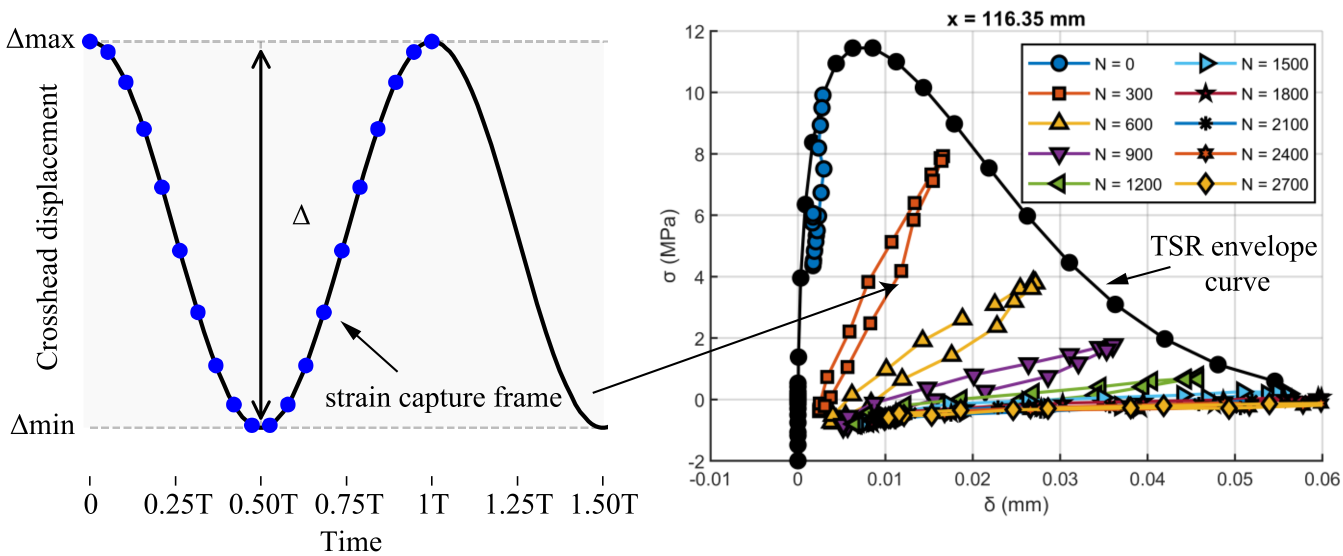


***Figure 1*** *- Strain capture frame (left) and fatigue degradation of TSRs(right)*

This method provides direct experimental insight into cohesive degradation and supports the development of reliable prediction models for fatigue damage in bonded joints with ductile adhesives.

# Force–Heat Equivalence Energy Density Principle and Its Application to the Characterization of Material Fatigue and Fracture under Extreme Conditions

**Weiguo Li [1]**

[1] *College of Aerospace Engineering, Chongqing University, China,* wgli@cqu.edu.cn

*Force-Heat Equivalence Energy Density Principle* *Material fatigue and fracture* *Extreme conditions*

**Abstract** With the rapid development of modern science and technology, the demand for expanding the service conditions of materials has become increasingly intense. The mechanical/physical properties of materials under diverse and wide-range extreme conditions have become a core issue of concern in various fields, and there is an urgent need to establish the ability to predict the performance of materials under such conditions. Focusing on the major needs of the country, aiming at the advanced materials and structures that have a wide application prospect in national strategic equipment, focusing on their mechanical behaviors, strength theory and characterization methods under diverse and wide-range extreme conditions, the author originally proposed a method that could quantitatively characterize the effect of temperature on the mechanical/physical properties of materials - the Force-Heat Equivalence Energy Density Principle (Li's principle of energy equivalence). Based on this principle, for the first time, established a series of theoretical quantitative characterization models for the mechanical/physical properties (fracture strength, yield strength, ultimate strength, fatigue strength, creep life, buckling strength, hardness, melting point, band gap width, electrical breakdown strength, and exciton energy, etc.) of various material systems, including inorganic non-metallic, metallic, polymeric, and composite materials, without any fitting parameters.

# Probabilistic approach for the fatigue forecast of structures with process induced defects

**Baptiste Lamothe[1,2], Lorenzo Bercelli[1], Cédric Doudard[1], Romain Jacquelin[2], Julien Louge[3], Sylvain Calloch[1]**

*[1]ENSTA, Campus de Brest, IRDL – UMR CNRS 6027, 2 rue François Verny 29806 Brest Cedex, baptiste.lamothe@ensta.fr*
*[2]Direction Générale de l'Armement, 47 rue Saint-Jean 31131 BALMA Cedex*
*[3]Naval Group, Technocampus Océan, 5 rue de l'Halbrane 44340 Bouguenais*

*High cycle fatigue* *Defects* *Probabilistic fatigue modelling*

High-cycle fatigue of metallic materials is an insidious phenomenon, and therefore particularly critical for the structural integrity of components in service. To allow for predictive modelling and prevent in-service failure, the fatigue properties of constitutive materials must be determined. However, conventional fatigue testing is costly and time-consuming. An alternative is the so-called self-heating approach. This method relies on the measurement of the temperature of a sample under cyclic loading. This temperature can be linked to the material's intrinsic dissipation, attributed to fatigue damage. Using an ad-hoc multi-scale model, the complete S-N curve and relative scatter can be derived from the self-heating behaviour of a single specimen [1].

More specifically, the use of the self-heating method yields interesting results for materials containing process-induced defects. Indeed, depending on the number of defects per unit of volume, the temperature signal of a specimen under cyclic loading can be significantly affected, and hence the derived fatigue predictions. Such is the case of a casted copper-aluminium containing many defects [2]. On the contrary, rare defects can be responsible for fatigue failure, while having no measurable thermal signature under cyclic loading. Then, the derived fatigue model corresponds to a virtually defect free material. Such is the case of a wire-arc additively manufactured copper-aluminium [3].

The present study proposes the use of the self-heating method applied to materials with process-induced defects. Thermometry is used to measure and model the effect of voids on the fatigue behaviour. The fatigue sample is considered as a structure, voids being its geometric features. Through extensive modelling and the use of thermometry, a difference is made between the constitutive material dissipative behaviour and the influence of defects. Then, by taking advantage of the multi-scale model, that naturally considers volume effects [2], the influence of defects on fatigue life and relative scatter can be determined via simulation. First, the self-heating method and the derived multi-scale approach are presented. Second, experimental thermometry results of an as-casted copper-aluminium specimen under cyclic loading are detailed. Finally, a link towards fatigue life prediction considering the effect of process-induced defects is proposed.

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# Fatigue damage evolution in copper: linking NDT-based indicators to microstructural mechanisms

**Jan-Erik Nebel[1], Janina Koziol[1,2], Peter Starke[1,2]**

[1] *Department of Materials Science and Materials Testing (WWHK), Institute QM³, University of Applied Sciences Kaiserslautern, Schoenstr. 11, 67659 Kaiserslautern, Germany*

[2] *Faculty of Natural Sciences and Technology, Saarland University, 66123 Saarbrücken, Germany*

*Fatigue characterization* *Microstructural evolution* *Copper*

**Abstract** The understanding of fatigue processes in metallic materials requires linking the macroscopic material response to the underlying microstructural mechanisms determining the early damage evolution and crack initiation. Modern non-destructive testing (NDT) methods are based on physical processes that describe the interaction between different forms of energy and the materials' microstructure or its evolution, respectively. Understanding the microstructural evolution under quasi-static and cyclic loading is essential for linking deformation and damage mechanisms with experimentally observed signals. This work aims to establish a correlation between NDT-based signals and fatigue-induced microstructural changes in metallic materials, thereby enabling the development of microstructure-informed simulation models.

In this study, technically pure copper (CW021A) is used as a model material to systematically correlate mechanical fatigue data and fatigue-induced microstructural changes with NDT signals based on stress-temperature- (Figure 1) and stress-strain-hysteresis as well as electrical resistance measurements. During cyclic loading, these signals are continuously recorded and used to identify characteristic fatigue states, enabling a mechanism-based definition of damage stages rather than purely lifetime-based criteria. Selected specimens at defined fatigue stages are then transferred to a scanning electron microscope equipped with an in-situ tensile-compression module. In-situ investigations combining electron backscatter diffraction and high-resolution digital image correlation are performed to resolve the underlying microstructural evolution in terms of local deformation and grain misorientation under cyclic loading to link these mechanisms directly to the previously recorded NDT signals.

The presented approach provides a mechanistic framework for interpreting NDT-signals on the basis of microstructural evidence and offers a transferable methodology for mechanism-based fatigue assessment beyond phenomenological S-N characterization.

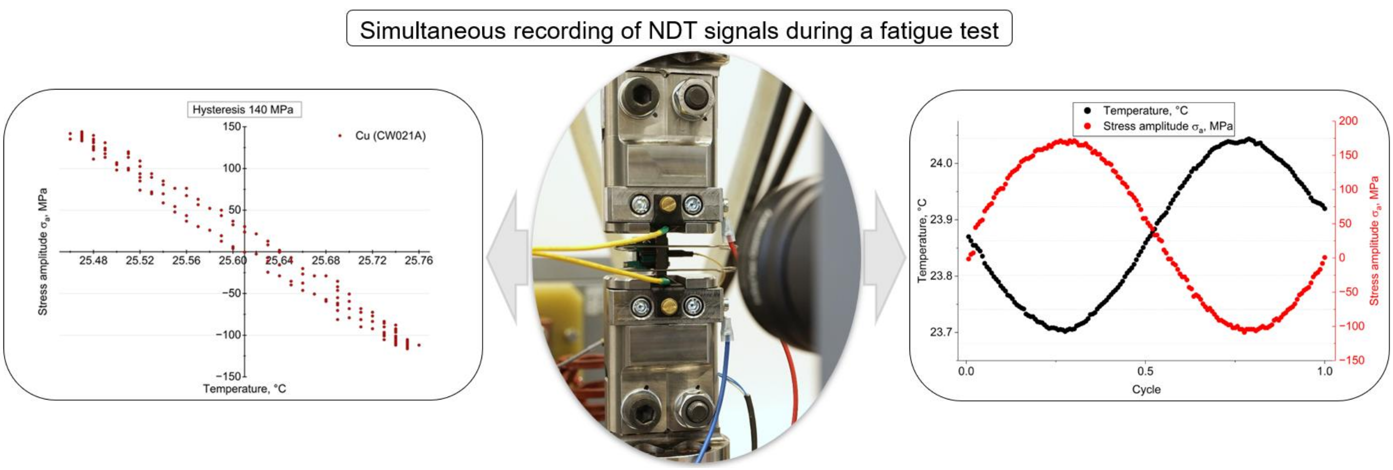


***Figure 1*** *– Integrated measurement technology and recording of hysteresis measurements during fatigue loading*

# LEFM prediction and atomic-scale K-field simulation of crack-tip behaviors/mechanisms in titanium

**Jiaping Ma[1, 2], Yu E. Ma[1, 2]**

[1] *School of Aeronautics, Northwestern Polytechnical University, Xi'an, 710072, Shaanxi, China*

[2] *National Key Laboratory of Strength and Structural Integrity, Xi'an, 710072, Shaanxi, China*

*Titanium; Crack; Temperature; Linear elastic fracture mechanics prediction; K-field simulation*

**Abstract** Fracture is a material separation process at the atomic scale, and the fracture toughness of materials is associated with the atomic-scale crack-tip behaviors/mechanisms. Atomic thermal oscillation increases with increasing temperature, which may affect/alter the crack tip behaviors. This work investigates the effects of temperature on crack-tip behaviors in titanium by using anisotropic linear elastic fracture mechanics (LEFM) prediction and atomic-scale K-field simulation. The parameters for LEFM prediction are obtained via density functional perturbation theory calculation. The results show that $K_{Ic}$ decreases with increasing temperature, and changes in the stress distribution initiate a brittle-ductile transition in crack-tip behavior. The ductile crack tip can be blunted by continuous crack-tip dislocations nucleation/slip and twins nucleation/growth, and the evolution of the ductile crack tip geometry from sharp to semicircular structure significantly decreases the crack tip stress concentration. A new criterion of the crack-tip dislocation slip vector is established, which reasonably explains the geometrical evolution of the ductile crack tip where the angle $\theta$ between the crack plane and the slip plane is $0^{\circ}<\theta\leq 90^{\circ}$. his work expands the atomic-scale crack-tip behaviors/mechanisms of titanium, which provides a reference for crack-tip behavior analysis in engineering research.

# Effect of wall thickness on the multiaxial fatigue of additively obtained tubular IN718 specimens

**B. Bouzid Souihli[1,2], N. Saintier[1], O. Ciobanu[2]**

[1]*I2M-Bordeaux, Arts et Métiers ParisTech – CNRS UMR5295, Université de Bordeaux, Bordeaux INP, badr.bouzid_souihli@ensam.eu*

[2]*Safran Additive Manufacturing Campus*

*Multiaxial fatigue* *Additive manufacturing* *Architected materials*

**Abstract**

In order to achieve the challenging goal of zero carbon emissions in 2050, the aeronautical industry research focuses on the latest fabrication processes to produce new materials and reduced weight parts. Our aim is to show that metallic, LPBF manufactured, triply periodic minimal surface structures (TPMS) can be used to reduce the weight of critical mechanical aeronautical components and optimize their performance, achieving a better weight-to-resistance ratio.

TPMS structures, made of thin walls, allow to reach high specific properties, but have complex microstructures due to the LPBF process. Texture and grain structure that are strongly linked with the LPBF process impact the mechanical properties at both the meso and macro scale. In addition, the complex TPMS architecture generates strong stress gradients and heterogeneous surface roughness that drive the overall fatigue strength.

This work describes the microstructure and mechanical behavior of thin-walled structures, between 1000 and 200 microns of width. The effect of building direction is evaluated to map the behavior at various locations within the TPMS geometry

Microstructural analysis aligns with findings reported in literature [1]. Columnar grains along the building direction are observed even after heat treatment. EBSD maps reveal elongated grains and a significant degree of texture. We show that surface topology in the as-built state is heavily dependent on building orientation and remains a primary factor influencing fatigue life. Moreover, adhered powder on surfaces can create small notches in material and serve as potential crack initiation sites.

Given that surface topology is a critical factor for fatigue behavior, optical and tomographic measurements were used to characterize it, before performing axial, torsional and combined cyclic loading. Furthermore, we show how factors like width, high-stress concentrations, coupled with adhered powder notches and gaseous pores lead to a decrease in fatigue life.

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[3] M. Pirotais, « Étude du comportement en fatigue de parois minces et structures lattices obtenues par fabrication additive du titane Ta6V », PhD thesis, 2023.

[4] E. Fessler, « Etude des interactions fatigue-fluage-environnement lors de la propagation de fissure dans l'Inconel 718 DA », These de doctorat, Toulouse, INPT, 2017. Consulté le: 14 mars 2024. [En ligne]. Disponible sur: https://www.theses.fr/2017INPT0141

# Surface Modification and Crack Formation Studies on Medium-Carbon Steel due to Microstructure Evolution during Contact Fatigue Testing

**Phanuphak Seensattayawong[1], Gerhard Stelzer[2], Jörg Seewig[2] and Eberhard Kerscher[1]**

[1]*Materials Testing (AWP), RPTU University Kaiserslautern-Landau, D-67663 Kaiserslautern, Germany, p.seensattayawong@rptu.de, e.kerscher@rptu.de*

[2]*Institute for Measurement and Sensor Technology (MTS), RPTU University Kaiserslautern-Landau, D-67663 Kaiserslautern, Germany*

*Surface modification* *Microstructure refinement and evolution* *Contact fatigue testing*

**Abstract** Contact fatigue loading is encountered in the applications of bearings as well as in the rail-wheel contact of railways. Therefore, this study aims to investigate surface texture modification and microstructure evolution of medium-carbon steel (C45E) after contact fatigue testing. The tests were carried out on a push-pull servo hydraulic testing machine (Instron-MTS with 15kN) in atmospheric conditions with point contact pressure ($p_{max}$) of 2 GPa, stress ratio ($R$) of 0.1, frequency ($f$) of 10 Hz, and the ultimate number of cycles ($N_u$) are $1 \times 10^6$ and $5 \times 10^6$. The roughness measurement was carried out by a confocal microscope. Microstructure and crack observations were conducted by a stereomicroscope and a scanning electron microscope (SEM). As a result, a ring-like pattern is identified on the contact surface, which consists of contact, contact-separation, and deformed zones. The highest asperities on the contact-separation zone were observed, which was encouraged by microstructure evolution beneath the contact area and in its direct vicinity. The cracks were possibly initiated at newly induced and refined microstructures. As a result, the zone of contact-separation on the specimens reveals significantly developed roughness in Sp (maximum peak height), Sv (maximum valley depth), and Sz (maximum height) parameters. Furthermore, the deformed zone was observed only on the specimen with $5 \times 10^6$ cycles, which has less surface alteration than the contact-separation zone. The asperity in the contact-separation zone is possibly caused by the microstructure refinement during cyclic loading, an increase in the friction coefficient, and a tangential force due to the adhesion processes and repeating direct metal-metal contact. Especially, the cracks and voids could be potentially formed in the microstructure refinement area.

# Fatigue analysis and prediction with applied work energies

**Hyung-Jun CHANG[1], Flavien GHIGLIONE[1]**

*[1]SafranTech, Rue des jeunes bois Châteaufort CS80112, 78772 Magny-les-Hameaux France, Hyung-jun.chang@safrangroup.com*

*Fatigue* *Work-energy* *Anelasticity*

**Abstract** The general fatigue behavior of metallic materials from low cycle fatigue (LCF) to very high cycle fatigue (VHCF) was analyzed based on three possible work energies which could affect fatigue behavior. It is well known that the fatigue crack initiation and propagation in metals are essentially influenced by the accumulation of microscale material behaviors, such as irreversible deformations by the dislocation motions. However, a reasonable prediction of the fatigue behaviors covering both the LCF and the VHCF has been unattainable so far even with recent advanced theoretical models. Most of current theories for fatigue life are focused on the significance of plastic deformations and related plastic work energy accumulation. Whereas these theories cannot be directly applied to VHCF under fully elastic loading cycles. In addition, current theories cannot explain the wide variation of fatigue life in S-N curves especially for the VHCF case without introducing the uncertain heterogeneity of the target material.

In this work, in addition to the plastic work energy as a representative origin affecting fatigue behavior especially for LCF scenario, two more possible work energy sources based on anelasticity [1] were introduced to explain the distinctive fatigue behavior observed particularly for VHCF condition. The consideration of the three possible work energies may explain the difference between LCF and VHCF behaviors regarding the position of crack initiation (surface for LCF and internal for VHCF), the deviation of S-N curves (relatively small during LCF and very large during VHCF), and the effect of pre-deformation (weak for LCF, significant for VHCF [2]. Finally, new applied energy-based fatigue experiments are proposed for better fatigue analysis and prediction.

[1] Li D., Wagoner R.H., The nature of yielding and anelasticity in metals, Acta Materialia, Vol. 206, 116625, 2021.

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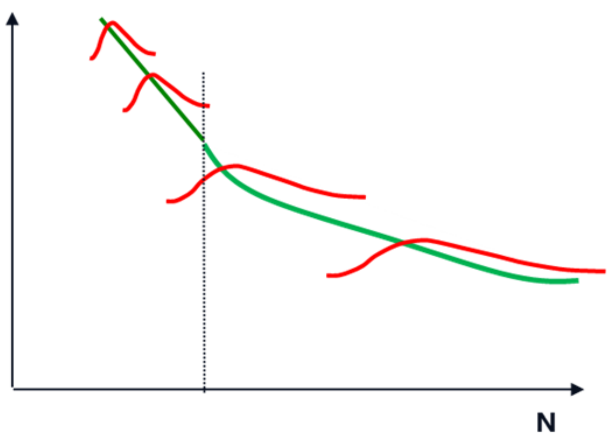


***Figure 1** – The variation of fatigue life is not clearly understood yet, where new energy-based fatigue experiments may reduce deviations in predicted fatigue life.*

# Effect of Hydrogen Pressure and Loading Frequency on Fatigue Crack Growth in Nickel Alloy 625

**Pierre Osmond[1], Marie Lemaitre[2], Thomas Landron[2], Théo Larue[2], Daniella Guedes Sales[2], Ayoub El Moutaouakkil[2], Anthony Nakhoul[2]**

[1]*Cetim, 52 avenue Felix Louat, 60300 Senlis, France*

[2]*Cetim, 52 avenue Felix Louat, 60300 Senlis, France*

*Nickel based alloy* *Fatigue crack growth* *Gaseous hydrogen*

**Abstract :**

Nickel alloys are widely used in oil and gas, aerospace, and aeronautical applications owing to their good mechanical properties-particularly at elevated temperatures-and their high resistance to corrosive environments. However, this class of materials can exhibit significant sensitivity to hydrogen embrittlement, which increases the risk of premature failure for components operating in hydrogen-containing environments.

In this context, significant efforts have been devoted to assessing the impact of hydrogen on the mechanical properties of nickel based alloys, with most studies focusing on alloy 718. Yet few studies address hydrogen effects on fatigue properties, particularly fatigue crack growth behavior.

This work aims to characterize fatigue crack growth properties in nickel alloy 625 exposed to gaseous hydrogen, a material for which hydrogen sensitivity remains sparsely documented in the literature. Tests were performed at room temperature under a load ratio of 0.1, for hydrogen pressures ranging from 2.5 to 250 bar and frequencies conditions from 0.01 to 10 Hz. Gaseous hydrogen markedly affects crack growth, as evidenced by: (i) an increase in crack growth rate above a threshold hydrogen pressure of 25 bar, (ii) a particularly strong effect at low $\Delta K$ levels, and (iii) an increase in crack growth rate as the loading frequency decreases in hydrogen. In contrast to alloy 718, exposure to gaseous hydrogen does not modify the crack propagation mode in alloy 625, which remains transgranular. This behavior is promoted by the low amount of intergranular precipitates, which limits hydrogen transport along grain boundaries. Additionally, hydrogen tends to enhance the crystallographic character of crack propagation, suggesting localized plasticity effects consistent with hydrogen-enhanced localized plasticity (HELP) mechanisms.

# Influence of the Load Type on the Fatigue Behavior of Additively Manufactured AISI 316L

**Paula Rahm[1], Andreas Warth[2], Roman Teutsch[2], Tilmann Beck[1], Bastian Blinn[1]**

[1]*Institute of Materials Science and Engineering, RPTU Kaiserslautern-Landau, Gottlieb-Daimler-Straße 44, 67663 Kaiserslautern, p.rahm@mv.rptu.de*

[2]*Institute for Mechanical and Automotive Design, RPTU Kaiserslautern-Landau*

*Additive manufacturing* *Austenitic stainless steel* *Varying load types*

**Abstract** Additive manufacturing enables the fabrication of parts with intricate geometries such as topology-optimized structures. Due to these elaborate geometries, complex loading conditions, consisting of superimposed tension, bending, and torsion, occur in the respective lightweight components. Since the different loading types have an impact on the failure mechanisms, their interrelation and its influence on the fatigue behavior must be analyzed. However, in most research works only one load type tends to be investigated. Furthermore, the specific characteristics of additively manufactured materials, i.e., process-induced microstructural defects, the rough "as-built" surface and residual stresses must be considered, since they are crucial for the fatigue strength and their impact might be influenced by the applied loading type.

Therefore, the objective of the presented work is to analyze the influence of the load type on the fatigue behavior of the austenitic stainless steel AISI 316L produced via laser-powder bed fusion (PBF-LB/M). For this, fatigue specimens with a turned and subsequently polished gauge length were investigated, leading to a removal of the "as-built" surface layer as well as the process-related residual stresses and thus, excluding these influencing factors. To establish a sound base for the analysis of the interrelation of the different loading types, each type was analyzed separately first. Therefore, fatigue tests with uniaxial tension/compression (TC), rotating bending (RB) and torsional loading (TO) were carried out. Then, biaxial fatigue tests with a superposition of TC and TO were performed using the conventional and symmetric fatigue specimens to simulate a load combination. Further, specimens with more complex geometries were loaded in fatigue tests, where the specimens' eccentric gauge section induced superimpositions of bending (B), TO and TC loading.

The generated *S*-*N* curves of the individual load types show that TC results in the lowest numbers of cycles to failure $N_f$, while TO leads to the highest $N_f$ at similar equivalent stresses (von Mises $\sigma_{vM}$). The fracture surfaces of the specimens loaded by TC and RB reveal predominantly defect-based failure, whereas after TO loading, no defects were observed as crack initiation sites. This indicates a change in the dominant failure mechanism between loading conditions governed by normal stresses and those dominated by shear stresses. Correspondingly, superimposed TC and TO loading with a proportion of 1/1 applied to the symmetric specimen geometry led to defect-free failure and higher fatigue life than sole TC loading, but lower $N_f$ in relation to pure TO loading, whereas the 2.83/1 proportion yielded fatigue lives closer to individual TC loading. The fatigue tests with the geometry-induced superimposed loading with proportions of 1/1 and 2.83/1 also reveal fatigue lives in the range between TC (or RB) and TO loading, but with higher $N_f$ than those achieved in the fatigue tests performed using the symmetric fatigue specimens with superimposed TC and TO, see Figure 1. Notably, defects were observed at the crack initiation sites of these eccentric specimens.

Overall, these results demonstrate that the failure mechanisms and the resulting fatigue life are strongly influenced by the load type applied. Moreover, the geometry and its influence on the stress state have a pronounced influence on failure mechanisms and fatigue life.

# Notch effects on the dwell-fatigue behavior of the Ti-6Al-4V alloy

**Julie Bouillon[1], Samuel Hémery[2], Patrick Villechaise[3], Benjamin Dod[4]**

*[1]Endommagement et durabilité [Institut Pprime] Département Physique et Mécanique des Matériaux [Institut Pprime], CNRS-ENSMA, U. Poitiers, Futuroscope, France, julie.bouillon@ensma.fr*

*[2,3] Département Physique et Mécanique des Matériaux [Institut Pprime],*

*[4] AIRBUS.*

*Ti-6Al-4V* *Stress concentrators* *Dwell-fatigue*

## Abstract

The fatigue behavior of the Ti-6Al-4V alloy is strongly affected by stress concentrators and dwell periods, which can drastically shorten component life in aerospace applications. Understanding their combined influence is therefore essential for reliable design. In this study, smooth and notched specimens with identical microstructures were tested using conventional fatigue and dwell-fatigue loadings. The heterogeneous strain distribution was characterized using Digital Image Correlation (DIC) for different notch characteristics and loading conditions. Complementary simulations of the stress and strain fields were achieved using an elastic-viscoplastic constitutive model. Experiments highlighted the strong dwell-time sensitivity of the mechanical response of smooth specimens, which exhibited a marked reduction in fatigue life upon the introduction of 120 s hold time at peak stress. In agreement with prior studies, increasing the stress concentration factor ($K_t$) significantly decreased the conventional fatigue lives. However, dwell-fatigue lifetime debits (DFD) were significantly reduced, or vanished, depending on the notch characteristics and tests conditions. Unexpectedly, internal cracking events including smooth nucleation facets and terrace-like faceted growth, typical of dwell-fatigue failures, were found despite minimal lifetime debits. Additional fractographic analyses and microstructural characterization were carried out to clarify the prevalence of different crack initiation mechanisms in relation to the local stress states and time-dependent plastic strain accumulation. Factors determining the alleviation of dwell fatigue lifetime debits in notched Ti-6Al-4V specimens are finally discussed.

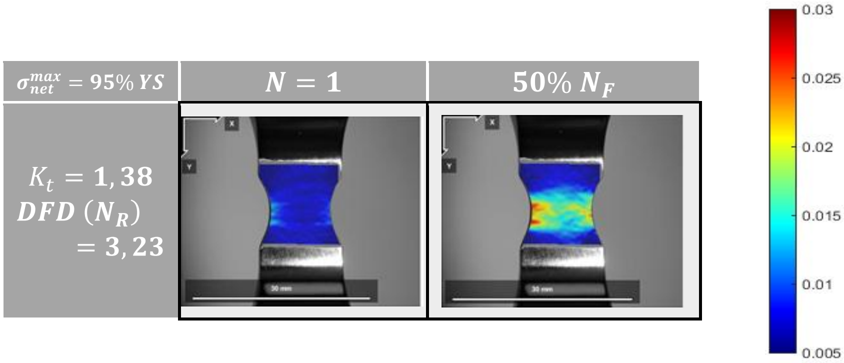


*Figure 11 : DIC monitoring showing total strain field for different Kt and different $\sigma_{net}^{max}$ at various stages of their lifetime.*

# Investigating the correlation between wear and fatigue properties of cryogenically treated tool steel Vanadis 4E using cyclic indentation testing

**F. Tadross[1], R. Walther[2], J. Heidrich[2], S. Winter[2], M. Smaga[1], T. Beck[1], B. Blinn[1]**

*[1] Institute of Materials Science and Engineering, RPTU Kaiserslautern-Landau, Gottlieb-Daimler Straße 44, 67663 Kaiserslautern, Germany, f.tadross@mv.rptu.de*

*[2] Fraunhofer Institute for Machine Tools and Forming Technology (IWU), Chemnitz, Germany*

*Fatigue behavior* *Cryogenic treatment* *Cyclic indentation testing*

**Abstract** Tool steel applications typically require a compromise between high hardness and high toughness, commonly achieved via quenching and tempering. However, in high-carbon steels, this often results in significant amounts of undesirable retained austenite (RA), reducing hardness and dimensional stability. Deep cryogenic treatments (DCT) conducted between -160 °C and -196 °C can reduce the RA fraction and, when combined with tempering, promote refined carbide precipitation and reduced martensitic distortion. To optimize the DCT parameters, highly time-consuming experimental efforts are required, since the effect of DCT on the mechanical properties is mainly shown under cyclic loading. In this context, the PhyBaL$_{CHT}$ method [1] offers an efficient approach to assess the cyclic deformation behavior by using instrumented cyclic indentation testing (CIT). Accordingly, a correlation between the properties obtained in CIT and the performance of cryogenically treated Vanadis 4E blanking tools was shown in previous work [2]. In the present work, the applicability of PhyBaL$_{CHT}$ for an assessment of cryogenically treated Vanadis 4E was evaluated by analyzing a broad range of different cryogenically treated conditions. As shown in Figure 1, the cyclic deformation behavior obtained in CIT correlates well with the results from uniaxial fatigue tests. SEM and XRD analyses revealed a lower RA content, reduced martensitic distortion, and refined carbides in the cryogenically treated conditions. These microstructural changes directly correlate with the mechanical results, validating CIT for the evaluation of cryogenic treatments.

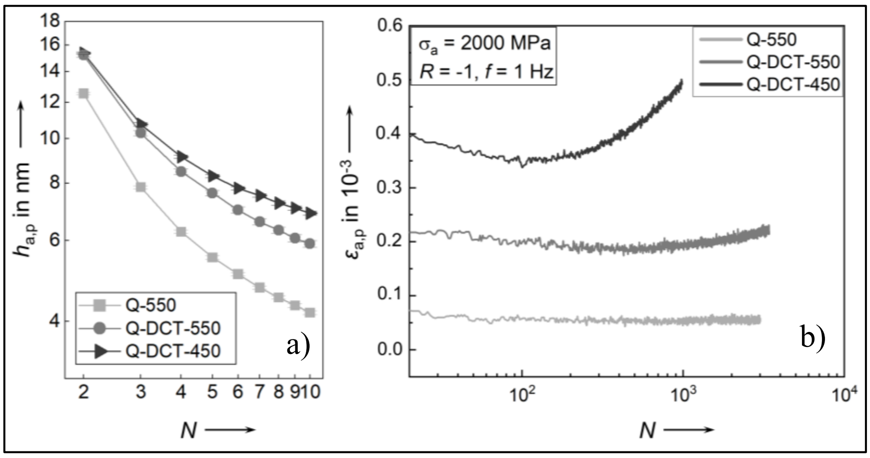


***Figure 1 -*** *Evolution in a) plastic indentation depth amplitude $h_{a,p}$ obtained in CIT and b) plastic strain amplitude $\varepsilon_{a,p}$ obtained in uniaxial fatigue tests during load cycles N for differently heat-treated Vanadis 4E (Q – quenching; DCT – deep cryogenic treatment; Number – tempering temperature in °C).*

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[2] Blinn et al., https://doi.org/10.1016/j.msea.2021.141846


Information classification: Internal

# Effects of Porosity Defects on the Fatigue Behavior of Al-Si Alloy Castings by Conventional and Ultrasonic Fatigue Testing

**I.S Cho[1], S.I Yun[2], J.S Choi[2], H.S Song[2], J.S Park[3], Y.R Cho[4], J.Y Lee[4], H.S Kang[4], A. Amanov[5]**

*[1]Sun Moon University, 70, Sunmoon-ro 221beon-gil, Asan-si, Chungcheongnam-do, 31460, Rep. Korea* *mbrosia1018@naver.com*

*[2]Samkee Corp. 263-29 Mujangsaneop-ro Jigok-myeon Seosan-si, Chungcheongnam-do, 31919, Rep. Korea*

*yoonsang1@samkee.com, jchoi345@samkee.com, hsong1923@samkee.com*

*[3]Korea Casting Industry Co., Ltd. 367 Bodeok-ro, Eumseong-gun, Chungcheongbuk-do, 27723, Rep. Korea*

*pars2001@hanmail.net*

*[4]Hyundai-Kia Namyang R&D Center, 93-20, Hyundaiyeonguso-ro, Namyang-eup, Hwaseong-si, Gyeonggi-do, 18278 Rep. Korea*

*youngrae90@hyundai.com, jiyong.lee@hyundai.com, 5510283@hyundai.com*

*[5]Tampere University, Korkeakoulunkatu 6, Tampere 33720, Finland, auezhan.amanov@tuni.fi*

*Porosity defects* *Cast Al-Si alloy* *Frequency effects*

**Abstract**

Porosity defects are a primary factor governing the fatigue performance of Al-Si alloy castings across high-cycle (HCF) and very-high-cycle fatigue (VHCF) regimes. In this study, the influence of porosity defects on the fatigue behavior of Al-Si alloy castings was investigated using conventional fatigue testing at 20 Hz and ultrasonic fatigue testing at 20 kHz under fully reversed loading conditions *(R = -1)* up to $10^8$ cycles. The combined approach enabled direct comparison of fatigue response from the HCF to the VHCF fatigue regime. Stress-life (S-N) results obtained at 20 Hz and 20 kHz show comparable trends when the temperature rise during ultrasonic testing is controlled, indicating limited frequency influence on fatigue strength. Fractographic analysis revealed that fatigue crack initiation in both testing methods was governed by casting porosity, with a transition from surface-initiated to subsurface-initiated cracking as fatigue life increased. The depth of crack initiation sites increased in the VHCF regime, consistent with reduced stress amplitudes. A strong correlation between fatigue life and defect size was observed using the √area parameter, providing a unified description of fatigue behavior across both testing frequencies. The results demonstrate that fatigue performance of porosity-containing Al-Si alloy castings is primarily defect-controlled rather than frequency-controlled, provided that thermal effects in ultrasonic testing are properly managed. These findings support the combined use of conventional and ultrasonic fatigue testing for reliable fatigue life assessment of cast aluminum components subjected to long-life cyclic loading.

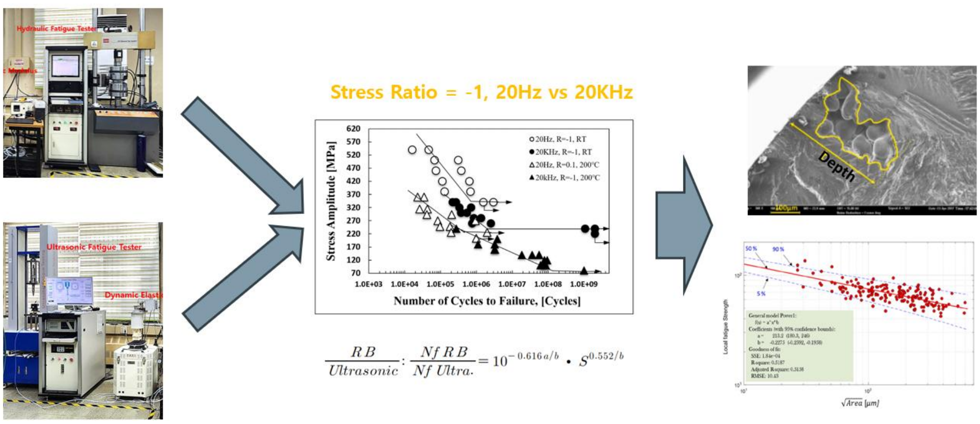


***Figure 1** – Comparison of fatigue behavior of an Al-Si alloy casting obtained from conventional and ultrasonic fatigue testing.*

# Geometrical Considerations for Fatigue of Laser-Based Powder Bed Fusion Metal Components

**Aloysius Tay[1,2], Ninian Sing Kok Ho[1], Yi Zhou[1], Zhen Lu[1,2], Alexander ZhongHong Liu[2], Mohsen Seifi[2], John Hock Lye Pang[1]**

[1] *School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, aloy0061@e.ntu.edu.sg*

[2] *ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959. United States*

*Additive Manufacturing* *Fatigue Design* *AlSi10Mg*

**Abstract** Laser-Based Powder Bed Fusion of Metals (PBF-LB/M) is a key additive manufacturing (AM) process that enables greater performance and geometrical complexity of metal parts. However, the increase in geometrical complexity presents localised differences in the manufacturing process, such as the application of different process parameters resulting in localised differences in defect distributions and microstructures impacting fatigue performance. This has presented significant challenges in manufacturing process qualification for AM due to the limited applicability of fatigue properties established in material property suites to different geometrical elements within the same component design.

In this comparative study, PBF-LB/M AlSi10Mg samples were fabricated in 15 different configurations – as-built or machined and polished, at 5 different orientations with unsupported overhang surfaces angled as low as 30° between the build platform and the unsupported surface, and at 2 geometrical scales for the as-built condition. Uniaxial force-controlled fatigue testing is conducted, and the fatigue performance of different geometrical elements, such as unsupported overhanging surfaces, and effects of component scale, are investigated to establish more robust geometry-process-structure-property relationships that can better inform component design for fatigue-critical applications. Trade-offs between manufacturability in the PBF-LB/M process and fatigue performance are also investigated to shed light on current limitations of the manufacturing process. Comparative analysis of fatigue performamce, surface condition, and fractography between all 15 fabricated geometrical conditions are conducted to establish critical geometrical considerations for fatigue-critical design for AM, linking back to the geometry's influence on the AM process resulting in fatigue properties established through testing.

# Hybrid Laser Shock Peening

**Jan Kaufman[1*], Jan Šmaus[1], Filip Čáp[1], MarianJeško[1], Petr Hauschwitz[1]**

[1]*HiLASE Centre, Institute of Physics of the Czech Academy of Sciences, Dolni Břežany, Za Radnicí 828, Czech Republic*

**corresponding author: jan.kaufman@hilase.cz*

*Hybrid laser processing* *Laser shock peening* *Advanced manufacturing*

## Abstract

Laser Shock Peening (LSP) is an advanced residual stress engineering method capable of improving crack resistance and fatigue performance of metallic components. Hybrid LSP is defined as the intentional combination of LSP with other laser technologies to achieve multi-functional improvements. First, we look at LSP combined with Laser Micromachining developed along two application paths. The first targets both regular and custom-made biomedical implants to create fatigue resistant structures combined with advanced antibacterial properties. The second path addresses impellers and propellers cavitation damage with blades strengthened by LSP and laser created periodic surface structures to affect the water flow. Next, we focus on LSP + Laser Hardening targeting components such as selected tools that require both high hardness and crack resistance. And finally, LSP combined with Wire Arc Additive Manufacturing (WAAM) is discussed, including conventional post-process peening and the promising approach of inter-layer LSP during WAAM, enabling in-situ control of residual stress accumulation and unique microstructure within the part.

# Crystal plasticity modelling of defect effects on fretting fatigue in laser powder bed fusion of Ti6Al4V

**Sunil Kumar Yadav[1,2,3], Majid Kavousi[1,2], Sean Leen[1,2,4], Reza Talemi[3]**

[1]*Mechanical Engineering, School of Engineering, University of Galway, Galway, Ireland*

[2]*I-Form Advanced Manufacturing Research Centre, Dublin, Ireland*

[3]*Department of Materials Engineering, KU Leuven, 3001 Leuven, Belgium*

[4]*Ryan Institute of Marine, Energy and Environment, University of Galway, Galway, Ireland*

*Crystal plasticity modelling, fretting fatigue, Ti-6Al-4V*

**Abstract** Titanium alloys are widely employed in aerospace and medical industries due to their exceptional mechanical and thermal characteristics. Laser powder bed fusion (LB-PBF) offers the fabrication of complex components with reduced material waste. However, the performance of such parts is driven by the LB-PBF process parameters which can introduce process induced defects. Despite advancements in crack detection and material technology, fretting fatigue is still critical for LB-PBF components. Under fretting conditions, the microscale interaction between defects and frictional contact can lead to early damage of the component[1]. As fretting is a localized phenomenon, crystal plasticity finite element (CPFE) models enable a precise evaluation of the fretting fatigue response as it considers the impact of material microstructure on macroscopic material properties. McCarthy et al[2] developed a CPFE model for fretting fatigue of dual phase Ti6Al4V alloy to capture phase boundary effects, predicting crack lengths shorter than those observed in experiments Cao et al[3] inserted defects in the CPFE model and used strain energy density-based fatigue indicator parameter (FIP) to identify the crack nucleation life and demonstrated preferred nucleation site.

The present work is focused on investigating the influence of microstructural inhomogeneity and defects on the fretting life of Ti6Al4V parts. Microstructural features are mapped from electron backscatter diffraction (EBSD) image to generate a realistic CPFE model with a microstructure sensitive FIP based on strain energy dissipation to predict crack initiation[4]. Additionally, internal defects measured from scanning electron microscopy (SEM) images[1] are incorporated into the micromechanical model. The realistic CPFE models are calibrated against monotonic tensile experimental data and stabilised cyclic loops and further implemented for models with defects. Similarly, FIP is calibrated for defect free models and used for micromechanical models with defects. Embedding defects into the CPFE models provides a transition from an ideal micromechanical model to a realistic representative model. Moreover, it creates direct linkage among process-structure-property-performance relationships by incorporating LB-PBF process induced defects and improves the prediction capabilities of microstructure based CPFE models.

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# Automated Cyclic Resistance Curve Testing for Defect-Initiated Cracks

**Miikka Väntänen[1], Joona Vaara[2], Kimmo Kärkkäinen[3] , Tero Frondelius[2,3]**

[1]*Global Boiler Works Oy, Lumijoentie 8, 90400 Oulu, Finland*

[2]*Wärtsilä, Teollisuuskatu 1, 65170 Vaasa, Finland*

[3]*Materials and Mechanical Engineering, University of Oulu, Pentti Kaiteran katu 1, 90014, Finland*

*Cyclic resistance curve* *Machine vision* *Accelerated testing*

**Abstract** Fatigue limit is commonly regarded as the loading limit below which cracks do not propagate to failure. Despite the straightforward definition, the limit is controlled by two observationally distinct mechanisms: crack initiation and crack non-propagation. To construct a Kitagawa-Takahashi (KT) diagram for a given defect morphology it is essential to understand both mechanisms and how they influence the fatigue limit in different regions of the KT diagram. The cyclic resistance curve describes the crack resistance to crack growth, but a statistical approach is required to account for the variance caused by microstructure with microstructurally short crack front lengths.

To capture the cyclic resistance curve, constant amplitude testing is inefficient and incapable of describing anything but the early crack growth. To address the limitation, a constant or decreasing $\Delta K$ load scheme is commonly utilised and the $\Delta K$ is increased only after a crack arrest is observed. Here, a novel testing method is presented that combines a constant $\Delta K$ load scheme with real-time automated crack monitoring for defect-initiated cracks.

The approach utilises an ultrasonic fatigue (USF) test machine, capable of fatigue testing at 20 kHz cyclic load frequency. The high loading frequency allows for rapid testing and longer cycle limits for crack non-propagation determination. The machine is equipped with a high magnification camera for crack detection. A trained, high-accuracy machine vision model is used for automated crack detection and length measurement. Crack lengths obtained in-situ are used to control the loading applied by the USF test machine to maintain the desired $\Delta K$ value.

Albeit the presented testing method focuses on measuring the cyclic resistance curve of a defect-initiated crack, pre-cracking is not utilised. Without pre-cracking, data on the initiation threshold stress can also be obtained. In terms of constructing the KT diagram, it is critical to quantify both mechanisms. By taking advantage of the high loading frequency and automated in-situ crack detection, the testing method serves as a rapid and efficient tool for comprehensive KT diagram determination.

# Heat dissipation and entropy accumulation in a polymer matrix composite under cyclic three-point bending at low and ultrasonic frequencies

**Aravind Premanand[1]**, **Hanna Schimmelpfeng[1]**, **Frank Balle [1,2,3]**

[1]*Department for Sustainable Systems Engineering (INATECH), Faculty of Engineering, University of Freiburg, 79110 Freiburg, Germany*

[2]*Freiburg Materials Research Center (FMF), 79104 Freiburg, Germany*

[3]*Fraunhofer Institute for High-Speed Dynamics, Ernst Mach Institute (EMI), 79104 Freiburg, Germany]*

*Ultrasonic fatigue testing*     *Very high cycle fatigue*     *Polymer matrix composites*

**Abstract** This study investigates the heat dissipation mechanisms and the entropy accumulation in a carbon-fiber-reinforced poly-ether-ketone-ketone (CF-PEKK) composite subjected to cyclic three-point bending loading conditions at low and ultrasonic frequencies. The heat dissipation rates of the fatigue experiments were compared with the results of finite element analysis (FEA) to identify the dominant dissipation mechanisms under different testing conditions. Conduction was found to be the main heat dissipation mechanism at low frequencies, while forced convection dominated at ultrasonic frequencies. Increasing-amplitude fatigue experiments showed that the load level and the loading frequency have a clear influence on the total heat dissipation rate, as well as the heat dissipation rates due to damage. Therefore, a pulse-pause sequence was used to capture the change in heat dissipation rate under constant-amplitude fatigue (CAF) experiments until failure. The CAF experiments showed that the heat dissipation rate increases in the presence of damage, and the heat dissipation rate in the event of failure was comparable between the low and ultrasonic frequencies. Finally, the total accumulated entropy at failure, also known as fracture fatigue entropy (FFE), increased from high-cycle fatigue to the very high-cycle fatigue regime for the CF-PEKK composite and was independent of the loading frequency. Therefore, this work encourages the use of entropy-based fatigue damage assessment in polymer matrix composites across a wide range of cyclic frequencies.

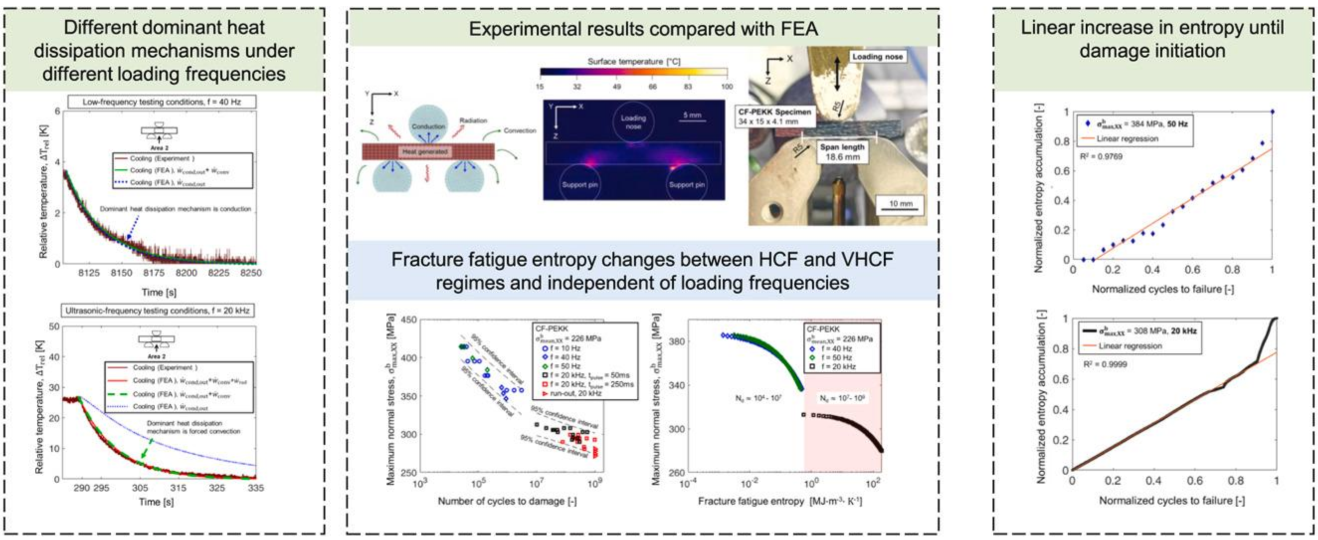


***Figure 1*** *– Figure showing linear accumulation of entropy for a CF-PEKK composite until damage initiation at low and ultrasonic frequencies [https://doi.org/10.1016/j.ijmecsci.2025.110530].*

# Challenges in specimen and experimental design for on- and off-axis fatigue testing of a polymer matrix composite at low and ultrasonic frequencies [size 14, centered, bold, times]

**Aravind Premanand[1], Hanna Schimmelpfeng[1], Frank Balle[1,2,3]**

*[1]Department for Sustainable Systems Engineering (INATECH), Faculty of Engineering, University of Freiburg, 79110 Freiburg, Germany*

*[2]Freiburg Materials Research Center (FMF), 79104 Freiburg, Germany*

*[3]Fraunhofer Institute for High-Speed Dynamics, Ernst Mach Institute (EMI), 79104 Freiburg, Germany]*

*Ultrasonic fatigue testing* *Polymer matrix composites* *Uni-axial loading*

**Abstract** This work investigates the fatigue behavior of a polymer matrix composite (PMC) under low (20 Hz) and ultrasonic (20 kHz) testing frequencies using identical specimen geometries. Specimen designs across all orientations were based on modal, harmonic, static-structural, and buckling analyses to ensure comparable results. This design enables uniaxial tension–compression loading PMCs to fail in the gauge section without global buckling and ensures overlapping stress amplitudes between the two test systems. The maximum possible stress amplitudes of ultrasonic fatigue testing (UFT) are higher than the lowest stress amplitudes that cause failure in the conventional servo-hydraulic (SH) system. By using the anisotropy of composite laminates, this design was validated through tension–compression experiments on dogbone-shaped specimens with four fiber orientations: 0°, 15°, 30°, and 45°, using SH and UFT systems. Results comparing high-cycle fatigue (HCF) and very high-cycle fatigue (VHCF) behavior of angle-ply laminates indicate a strong dependence on fiber orientation. A comparison of self-heating and microscopic analysis between the two systems demonstrates the applicability of UFT for off-axis VHCF characterization of woven composites. Finally, shear stress-induced damage initiation in 0°fiber-oriented dog-bone-shaped specimens, as observed in this work and reported in the literature, is addressed as a multi-axial stress state problem by incorporating the resultant normal, transverse, and shear stresses into the Tsai–Wu formulation.

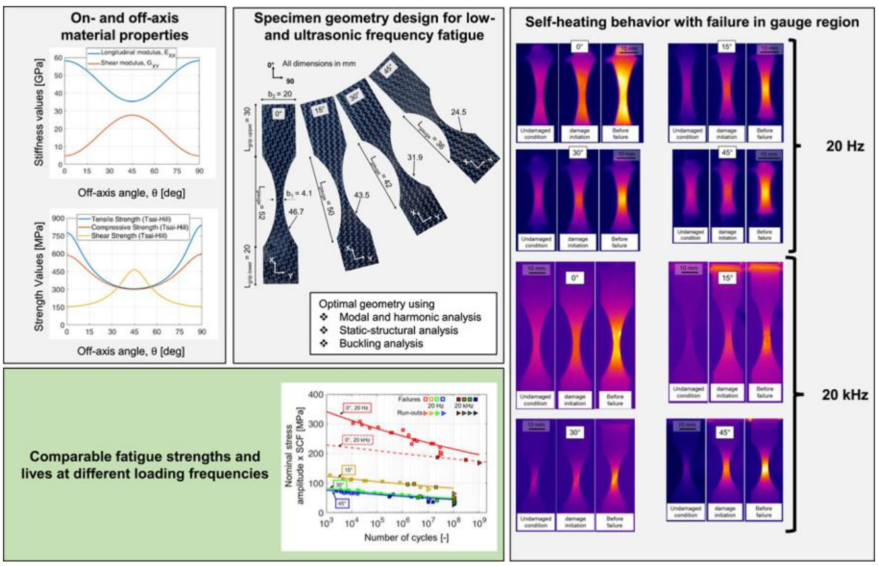


***Figure 1*** *– Specimen and experimental design to realize HCF and VHCF life of PMCs under uni-axial tension-compression loading conditions [https://doi.org/10.1016/j.compositesb.2025.112183].*

# Environmentally Assisted Fatigue of austenitic Weld Material

**Petr Gál[1], Ivana Schnablová[2], Radek Novotný[3], Miroslav Pejša[4], Radim Kopřiva**

[1] *Expert of structural and lifetime assessment, ÚJV Řež, a. s., Czech Republic, petr.gal@ujv.cz*

[2] *Head of Mechanical and Corrosion Testing Department, ÚJV Řež, a. s., Czech Republic*

[3] *Laboratory EMMA – AMALIA, JRC Petten, Netherland*

[4] *Team Leader of Corrosion Testing Group, ÚJV Řež, a. s., Czech Republic*

[5] *Expert of mechanical and corrosion Testing, ÚJV Řež, a. s., Czech Republic*

*Fatigue* *Environment* *Austenitic steel*

Components of nuclear power plants (NPP), including pressure vessels protected by austenitic cladding weld layers, are routinely subjected to fluctuating thermal stresses and pressure variations arising from plant start-ups, shut-downs and operational thermal transients. Such loading conditions can induce low cycle fatigue (LCF) damage, particularly in thicker component sections. A thorough understanding of the LCF behaviour of cladding weld metals is therefore essential for ensuring safe and reliable plant operation. ÚJV Řež, a. s., focuses on testing cladding weld materials used in WWER reactors, with a specific objective to increase confidence in its data through collaborative testing at the JRC on widely used cladding weld metals for reactor pressure vessels (RPVs) and other primary circuit components.

Within the joint UJV–JRC inter-laboratory programme aimed at examining cladding weld materials under conditions representative of Water–Water Energetic Reactor (WWER) operation, the project will investigate how exposure to primary coolant affects the fatigue life of austenitic materials. This will be accomplished using strain-controlled fatigue tests carried out in a simulated WWER primary water environment. The testing of selected materials was carried out using autoclave equipment. The generated data will enable direct comparison of results between the ÚJV and JRC laboratories for the same cladding weld metal.

The ENAFCLAD (Environmentally Assisted Fatigue of Cladding Weld Materials) project seeks not only to expand the database of low cycle fatigue results for the austenitic cladding weld metal Sv04Ch20N10G2B used in the primary circuit of WWER-1000 reactors, but also to evaluate the consistency of results obtained from specimens of identical geometry and material tested on two different facilities: Pluto 6 autoclave at ÚJV Řež, a. s., and Autoclave 1 at JRC Petten (EMMA–AMALIA laboratory). The outcomes will strengthen the reliability and comparability of experimental procedures and evaluated datasets.

This article presents a summary of low cycle fatigue tests performed on Sv04Ch20N10G2B specimens in an environment simulating the primary water of WWER-1000 reactors, conducted within the Open Access Joint Research Centre programme of the European Commission.

# Ultra-high fatigue strength steel enabled by coherent nanoprecipitates and Mo-enriched grain boundaries

**Suihe Jiang[1], Yuewu Li[1], Zhaoping Lu[1*]**

*State Key Laboratory for Advanced Metals and Materials, University of Science and Technology Beijing, Beijing 100083, China*

*Ultra-high fatigue strength* *Coherent nanoprecipitates* *Mo-enriched grain boundaries*

**Abstract** Coherent nanoprecipitation strengthening strategies featuring low-misfit interfaces are widely employed in high-performance alloys such as nickel-based superalloys, aluminum alloys and ultra-high-strength steels. However, the severe slip localization induced by this mechanism significantly increases the irreversibility of cyclic deformation, which often leads to early fatigue nucleation cracks. In this study, focusing on a coherent nanoprecipitate-strengthened maraging steel, we achieved a major breakthrough in fatigue performance through the synergistic regulation of nanoprecipitate configuration and grain boundary engineering. Our research demonstrates that the high shearing stress introduced by low-misfit B2-ordered Ni(Al, Fe) precipitates not only drives dislocations to traverse the high-dislocation-density martensitic matrix in a planar slip mode—thereby significantly extending the mean free path of dislocations—but also effectively compensates for the local softening induced by particle shearing via intense interactions between planar slip bands and pre-existing dislocations. This dynamic stress recovery mechanism minimizes slip concentration and the storage of coplanar dislocations within slip bands, thereby overcoming the inherent drawback of aggravated slip localization in traditional coherent strengthened alloys and significantly improving fatigue strength of the matrix. To mitigate the failure induced by the pile-up of same-sign dislocations at grain boundaries, we further optimized the heat treatment process to induce Mo segregation at grain boundaries. This significantly enhanced the tolerance of grain boundaries to dislocation pile-ups and associated stress concentrations. This grain boundary strengthening strategy promotes a transition in the fatigue failure mode from brittle intergranular cracking to local dynamic recrystallization, effectively reducing dislocation density accumulation at interfaces. In summary, through the synergistic effect of "intragranular homogeneous slip"and "grain boundary strengthening via Mo segregation", the fatigue strength of the material has been substantially elevated.

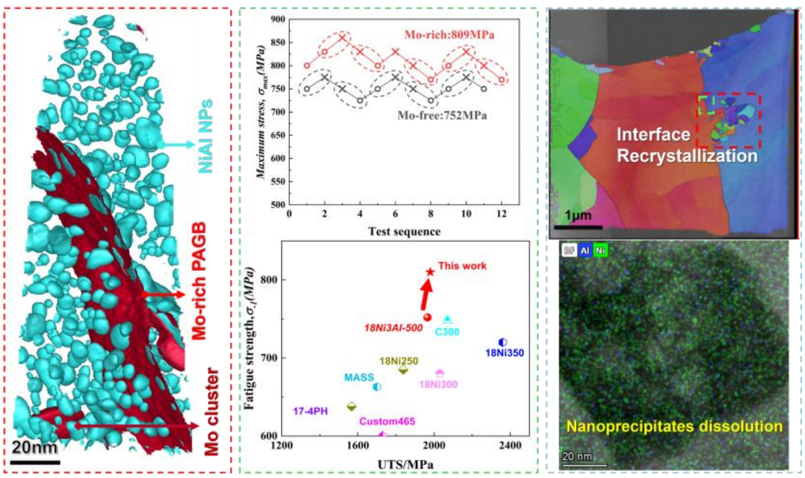


***Figure 1 -*** *Microstructural architecture of coherent NiAl nanoprecipitates and Mo-enriched grain boundaries that synergistically enable ultra-high fatigue strength via interface dynamic recrystallization*

# Data-Driven Life Prediction for Thermomechanical Fatigue: From Material Specimens to Industrial Structures

**Fabien SZMYTKA[1*], Baris TELMEN[1], Agathe FORRÉ[2]**

*[1]ENSTA, Institut Polytechnique de Paris, 91120 Palaiseau, France*
** Corresponding author: fabien.szmytka@ensta.fr*

*[2]Stellantis,78300 Poissy, France*

*Thermomechanical Fatigue* *Machine Learning* *Lifetime prediction*

**Abstract:** Thermomechanical fatigue (TMF) is a critical degradation mechanism under combined mechanical and thermal loading, particularly in the presence of temperature gradients typical of automotive components. While classical energy-based and strain–life approaches perform well in isothermal conditions, their extension to non-isothermal TMF remains limited due to temperature-dependent calibration needs and the difficulty of representing transient thermal effects.

A large GS-SiMo cast iron database (LCF and TMF), built through long-term industrial collaboration, is leveraged together with consistent simulation-derived inputs from an elasto-viscoplastic constitutive model implemented in Zset and Abaqus. Features include elastic/inelastic strain energy densities, inelastic strain amplitudes, temperature, hydrostatic pressure, and related quantities, combined with normalization, regularization, grid search, and K-fold cross-validation.

Random Forest and Gradient Boosting achieve excellent accuracy for isothermal data but tend to overestimate TMF lives, highlighting limited sensitivity to temperature effects. Artificial neural networks provide improved global correlations—especially for TMF—though with occasional underestimation and reduced interpretability. Transfer to structural thermal fatigue cases emphasizes remaining generalization gaps from homogeneous specimens to complex geometries, motivating further advances in feature design and physically informed interpretability.

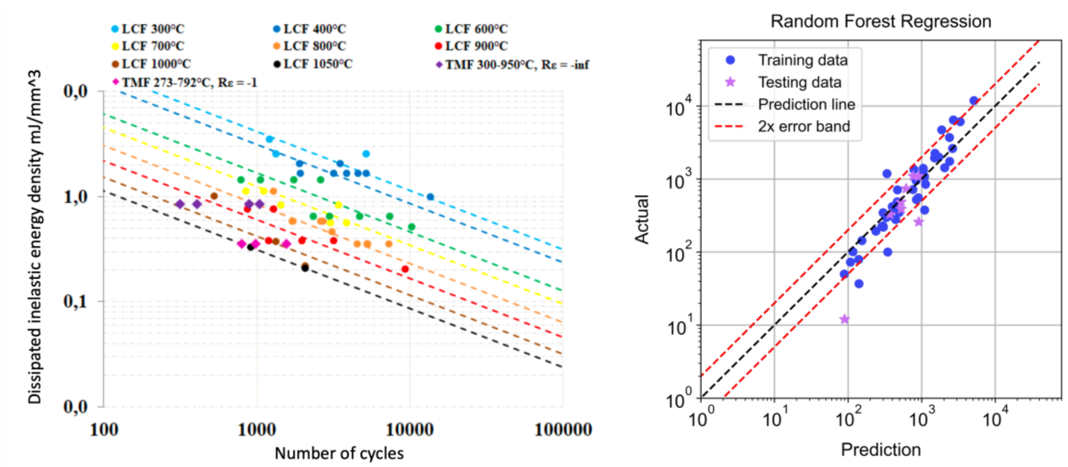


***Figure 1 - (Left)** Experimental fatigue trends for GS-SiMo cast iron, plotting the number of cycles to failure against dissipated energy density across different temperature levels. **(Right)** Performance of the Random Forest regression model, comparing predicted lifetimes versus experimental results for the complete dataset (combining isothermal and an-isothermal LCF cases). The diagonal line represents perfect correlation.*

# Fatigue crack initiation mechanisms in 7XXX Aluminum Alloys in representative aircraft environment (temperature, humidity)

**F. MAZEROLLE[1,3], G. HÉNAFF[2], J. ROUSSET[3]**

[1]*Institut Pprime UPR 3346 CNRS*

*ENSMA-ISAE Téléport 2, 1 Avenue clément Ader – 86360 Chasseneuil-du-Poitou*

*florian.mazerolle@ensma.fr*

[2]*Institut Pprime UPR 3346 CNRS*

[3]*Airbus Operations SAS*

*Fatigue* *Initiation* *Humid Environment*

**Abstract**

In the aircraft industry, fatigue and damage tolerance is an important sizing criterion for several components subjected to fatigue loading. While the damage tolerance methodology ensures the detectability of damages to be found and repaired through a crack growth approach, the fatigue crack initiation is used to determine the effective in-service lifetime, by application of a fatigue criterion. Therefore, the definition of initiation to distinguish fatigue phase from crack growth phase is important. Besides, airframe components are exposed to varying exposure conditions (humidity, temperature during the successive flights). Again, while the influence of a moist environment on fatigue crack propagation is relatively exhaustively addressed in literature, the impact on crack initiation is much less documented. As a consequence, such potential environmental effects are rarely considered in predictive models, which can account for some discrepancies between the design life and the actual in-service fatigue crack initiation lifetime.

The present study was undertaken in an attempt to fill this gap, in particular as regards fatigue crack initiation kinetics and mechanisms under these conditions. The goal is initially to characterize fatigue crack initiation life in varying exposure conditions, and ultimately to implement the effects in life prediction models. A special attention will be paid to low-frequency fatigue loadings, which are more representative of a ground-air-ground cycle.

The material under study is a 7175 T7351 rolled plate, widely used in the aeronautic industry for its high mechanical performance combined with a low density. To assess fatigue crack initiation kinetics, a detection method using the Direct Current Potential Drop (DCPD) technique on smooth samples was implemented. This technique allows for the monitoring of crack initiation without interrupting the environmental exposure of the specimen. Fatigue tests were conducted in representative environments, characterized by an Exposure Rate Parameter (ERP). An environmental effect was observed, particularly at extreme ERP conditions, impacting both initiation kinetics and total lifetime.

Additionally, a non-local Chaboche damage model was implemented and coupled with the microstructure, as the weak points regarding fatigue crack initiation were identified. As a consequence, a numerical strategy was developed to localize damage appearance and initiation on the specimen surface, so as to develop an accurate model to predict fatigue crack initiation as a function of various environmental exposure conditions.

# Crack initiation and propagation characterisation in Inconel 718 at high temperature

**Julien Lasgorceux[a,B,C], Pascale Kanoute[a], Charles Bianchetti[a], Vincent Bonnand[a], *Emmanuel Fessler[b]*, *Franck Morel[c]***

***a :*** *DMAS, Onera, Université Paris-Saclay, 92320, Châtillon, France, julien.lasgorceux@onera.fr*
***b :*** *Safran Aircraft Engines, 77550, Villaroche, France*
***c :*** *LAMPA, Ecole Nationale Supérieur des Arts et Métiers, 49035, Angers, France*

*Inconel 718* *Crack initiation* *Crack propagation*

Fatigue life distributions in metallic materials may exhibit complex statistical features. Fatigue bimodality is defined by the occurrence of two distinct fatigue life peaks at a given strain amplitude, often indicating the coexistence of competing crack initiation mechanisms. Such behaviour has been reported in Inconel 718 at 450 °C for several strain amplitudes *(Fouchereau, 2014)*. Bimodality was related to different crack initiation mechanisms and divided Wöhler curves into two distinct populations *(Jha, 2009)*. In direct aged (DA) Inconel 718, "population 1" associated with the shortest fatigue lives was considered as belonging to the low cycle fatigue regime (LCF) and was characterised by surface crack initiation on inclusions over the temperature range from 20°C to 600°C *(Alexandre, 2004; Zerrouki 2000; Abikchi, 2014; Texier, 2016)*. This behaviour derived from the comparable sizes of grains and inclusions and the local strain concentrations at the matrix/inclusion interface. This crack initiation mechanism was considered quasi-instantaneous in the LCF regime *(Alexandre, 2004; Bathias, 2013)*. A second population, associated to higher fatigue lives (100.000 and higher) and a large scatter, also called HCF regime, was mainly associated to internal crack initiation on grains or inclusions from 20°C to 600°C *(Alexandre, 2004; Zerrouki 2000; Abikchi, 2014; Texier, 2016)*. Using a fatigue database, this study investigated the temperature dependence on bimodality and crack initiation mechanisms in DA Inconel 718. The relative contribution of crack initiation and propagation of the total fatigue life is evaluated at 450°C in the so-called "population 1" regime, and long crack growth approach is evaluated for predicting fatigue lives in this regime.

A database of 5500 strain-controlled fatigue tests was analysed. The fatigue life bimodality and associated crack initiation mechanisms were analysed at 6 temperatures ranging from 20°C to 650°C. Additional fatigue tests were conducted at 450°C, at high applied strain amplitude to ensure surface crack initiation at inclusions. During tests, heat-tints were applied at given number of cycles early in the expected fatigue life in order to characterise to what extent a crack initiates early in the fatigue life.

Statistical bimodality was observed between 200°C and 550°C whereas no bimodality was observed at 20°C or 650°C. Population 1 was consistently associated with surface crack initiation on inclusions, regardless of temperature as observed in the literature *(Alexandre, 2004; Zerrouki 2000; Abikchi, 2014; Texier, 2016)*. In this regime, applied heat-tints revealed initiated cracks of roughly 20µm as early as 750 cycles (less than a tenth of expected total life), suggesting that, for tested loading conditions, crack propagation is a key factor of the total fatigue life. A Paris law formulation *(Paris, 1963)* with parameters identified using the Shiozawa approach *(Shiozawa, 2002* successfully predicted both the crack length at the marking cycle and the total fatigue life. These results suggested that long crack propagation contributed predominantly to the fatigue life. In contrast, population 2 exhibited a clear temperature dependence, with crack initiation competition between internal/surface grains and internal inclusions.

# Development of Industrial Coaxial Laser Shock Processing

**Nicholas Stiekema[1,2], Claudia Polese[1,3], Mark Newby[4]**

[1]*School of Mechanical, Industrial and Aeronautical Engineering, University of the Witwatersrand, Johannesburg 2000, South Africa, Nicholas.Stiekema@students.wits.ac.za*
[2]*Council for Scientific and Industrial Research, Pretoria 0001, South Africa*
[3]*ARUA Centre of Excellence in Materials, Energy and Nanotechnology (CoE-MEN), University of the Witwatersrand, Johannesburg 2000, South Africa*
[4] *eNtsa, Nelson Mandela University, Gqeberha 6001, South Africa*

*Residual Stress* *Coaxial LSP* *Root Serrations*

## Abstract

Steam powered turbines remain the leading means of electricity production globally. The last stage, low pressure (LP) steam turbine blades suffer the most frequent occurrences of cracks and fatigue damage, due to both high and low cycle loading [1,2], shortening the plant maintenance cycles and increasing the cost of risk mitigation. High intensity Shot Peening (with more than 100% coverage) is currently used to induce beneficial compressive residual stresses that prevent and delay crack growth on the fir-tree root serrations of LP blades within South Africa [3]. The occurrences of cracks that form on highly stressed portions of the roots are, however, ongoing. While thin water layer Laser Shock Processing (LSP) remains the popular alternative method for inducing beneficial stresses for planar industry applications, LSP using a coaxial system can deliver both the laser energy deposition and thick water tamping layer to more complex geometries. Treatment consistency, automation of both the water and laser beam path and part articulation, is discussed. The successes and challenges in building, fine tuning and implementing consistent application of coaxial LSP are highlighted. To assess process efficacy, complementary residual stress analysis methods, such as Incremental Hole Drilling, X-ray Diffraction, and Neutron Diffraction, are employed, together with fatigue testing.

***Figure 1*** *– Coaxial Laser Shock Processing accurately implemented on turbine blade coupons*

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# Simulation of Hybrid Selective Laser Melting and Plasma Shock Peening

**Angel Prado[1], Tomáš Hlavatý[1], Pavel Gruber[1], Jiří Šonský[1], Dušan Gabriel[1], Martin Isoz[1]**

[1]*Institute of Thermomechanics CAS, Dolejskova 1402/5, 182 00, Prague, Czechia*

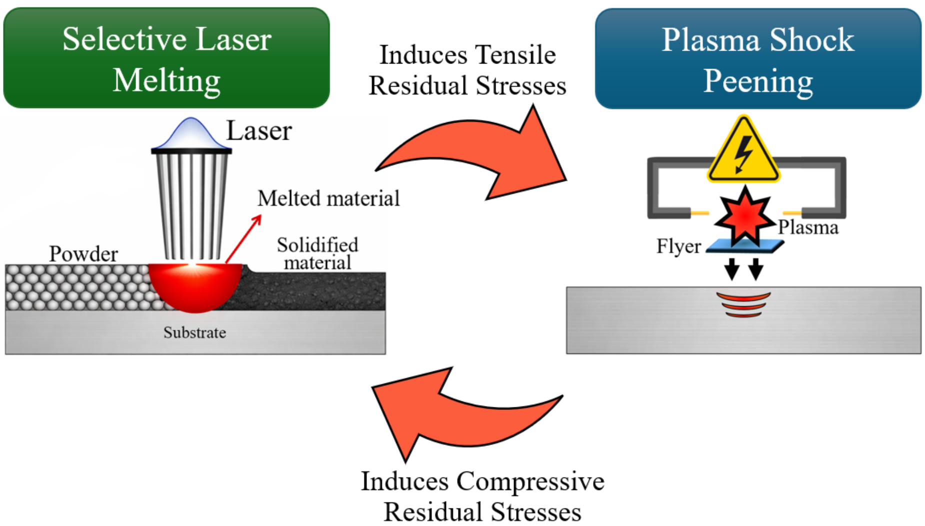
*Plasma Shock Peening* *Selective Laser Melting* *Numerical Simulation*

**Abstract**

Additive Manufacturing through Selective Laser Melting (SLM) has emerged as an advanced technology for producing metallic parts with high precision and design flexibility. This layer-wise powder fusion process enables the fabrication of complex geometries, making it particularly suitable for aerospace, medical, and high-performance engineering applications. However, parts produced by SLM often develop significant tensile residual stresses (TRS) during fabrication, which can negatively affect mechanical performance, reduce fatigue life, and, in some cases, start cracks or even lead to part failure. Strategies such as substrate preheating can partially mitigate the TRS generated by reducing thermal gradients during the layer-wise build, but residual stresses often remain a critical challenge.

Plasma Shock Peening (PSP) is a high-strain-rate surface treatment in which a plasma-generated pressure accelerates a flyer plate to impact the material surface, plastically deforming it and converting detrimental TRS into beneficial compressive residual stresses (CRS), thereby enhancing surface integrity and fatigue resistance. In this regard, PSP is conceptually similar to other high-strain-rate surface treatments, such as Laser Shock Peening.

This work provides a preliminary investigation of the hybrid SLM-PSP process, where PSP is applied periodically after a predetermined number of SLM layers, followed by continuation of the SLM build in a cyclic manner. A first approximation finite-volume-based simulation framework is developed to investigate the mechanical response associated with cyclic PSP application, incorporating temperature-dependent material behavior and thermal relaxation effects. The framework is used to assess the influence of periodic PSP on the evolution of CRS under idealized SLM stress states. The simulations provide insight into how hybrid SLM-PSP affects the magnitude, distribution, and depth of compressive stresses introduced by PSP, highlighting the potential of periodic PSP as a residual stress management strategy for SLM components.



# Laser Peen Forming for Deformation Correction in Aeronautical Structures

**Carina Lopes[1], Claudia Polese[1,2], Francesco Pietra[1]**

[1]*School of Mechanical, Industrial and Aeronautical Engineering, University of the Witwatersrand, 1 Jan Smuts Avenue, Johannesburg, South Africa, 2435625@students.wits.ac.za*

[2]*ARUA Centre of Excellence in Materials, Energy and Nanotechnology (CoE-MEN), University of the Witwatersrand, 1 Jan Smuts Avenue, Johannesburg, South Africa*

*Laser Peen Forming*    *Deformation Correction*    *3D Scanning*

Incorrect forming and post-machining distortion are common challenges encountered in the manufacture of metal airframe structures. When thin components fail to meet geometric tolerance specifications, they are typically scrapped, leading to significant financial losses and production delays. Laser Peen Forming (LPF) has emerged as an attractive alternative to conventional forming techniques due to its precision, controllability, and flexibility. This research explores alternative applications for LPF and investigates the feasibility and economic viability of using LPF-induced residual deformations to accurately correct distorted aluminium fuselage panels, bringing them within tolerance limits and rendering them suitable for industrial application. The project is conducted within a research collaboration involving the Airbus Manufacturing Engineering R&T Department, Hamburg, Germany, and the University of Naples Federico II, Italy, and is structured around three key objectives: (1) to conduct LPF experimental tests and establish correlations between process parameters and arc height such that a comprehensive database is developed for aeronautical aluminium alloy 2024 across a range of thicknesses, (2) to develop 3D scanning procedures to quantify geometric deviation and LPF induced corrective deformation, and (3) to create benchmarked numerical simulation and optimisation tools for LPF direct integration into assembly lines. Preliminary analysis using a correlation matrix and a trained radial-basis function response surface methodology in modeFRONTIER, a multi-objective optimisation platform, revealed a strong interdependence of LPF parameters. Observed key trends include maximising power intensity and coverage, up to a threshold value, minimising peening angle, and using a confinement layer to achieve the highest corrective deformation. With in-assembly LPF and post-processing as the long term-objective, the current experimental campaign investigated the effect of boundary conditions and clamping configurations on the induced corrective deformation. Under the same set of processing parameters, the single-clamped configurations experienced significantly greater magnitudes of induced deformation compared to the double-clamped configuration. To better understand these significant disparities and to determine how the differing boundary conditions influence the residual stress profiles, complementary Finite Element and Incremental Hole Drilling analyses will be conducted. All tests conducted thus far utilised small AA2024-T351 Almen-like samples. After which, the samples will progress to larger geometries and scenarios that better represent industrial applications. Variables under investigation include peened area placement relative to edges and clamped regions, and sample size scaling. The Kreon Ace 3D scanner, a seven-axis measuring arm and laser scan system, will be used to capture the distorted geometry such that a detailed deformation map is developed to measure the arc height. Subsequently, the analysis of collected data, through modeFRONTIER correlation matrices and RSM models will proceed to enable process optimisation and establish robust corrective strategies for industrial implementation.

# SHORT CRACK GROWTH FROM DEEP AND SHALLOW NOTCHES IN A MULTI-PHASE HIGH-STRENGTH STEEL

**Lukas Walch[1,2*], Thomas Klünsner[1], Bernhard Sartory[1], Stefan Marsoner[1], Larissa Egger[1], Anton Hohenwarter[3], Harald Leitner[4], Reinhard Pippan[5], Gerald Ressel[1]**

*1 Materials Center Leoben Forschung GmbH (MCL), Roseggerstraße 12, A-8700, Leoben, Austria*

*[2] Christian Doppler Laboratory for digital material design guidelines for mitigation of alloy embrittlement, Materials Center Leoben ForschungGmbH, Vordernberger Straße 12, Leoben, 8700, Austria*

*[3] Chair of Materials Physics, Technical University of Leoben, Jahnstraße 12, A-8700 Leoben, Austria*

*4 voestalpine BÖHLER Edelstahl GmbH & Co KG, Mariazeller-Straße 25, A-8605, Kapfenberg, Austria*

*5 Erich Schmid Institute of Materials Science, Austrian Academy of Sciences, 8700 Leoben, Austria*

** corresponding author e-mail: lukas.walch@mcl.at*

*Short cracks* *Small cracks* *High-speed steel*

**Abstract** Often, fatigue crack propagation is studied on cracks emanating from large, through-specimen-thickness notches that average a large number of microstructural features along the crack front. Such a deep and wide crack, however, does not accurately represent reality in most applications. In most metalworking tools, for example, cracks emanate from shallow notches, scratches, or small microstructural defects such as fractured carbides. To determine whether conventionally obtained fatigue data are representative of the behavior of application-relevant microstructurally small and shallow cracks, the propagation behavior of such cracks must first be reliably observed. The present work addresses this question by employing a novel method to monitor the propagation of application-relevant microstructurally short (and small) cracks. The technique enables in situ measurement of cracks emanating from an artificial defect introduced via focused ion-beam milling of an application-relevant size, using the alternating-current potential-drop method. Thus, the propagation of microstructurally short cracks emanating from shallow semi-elliptical notches, only 10 microns deep, was monitored. The results demonstrate similar behavior for cracks originating from physically short but macroscopically deep notches and microstructurally short, shallow notches in a multi-phase high-strength steel.

# Effects of Surface Treatment on Microstructure, Residual Stress Relaxation, and High-Temperature Creep Behavior of Powder Metallurgy René 95

**Dong Jun Lee[1], Yunji Cho[1], Eun Yoo Yoon[1], Hyunsung Choi[1], Hyeonil Park[1], Moo-Young Seok[1], Young Nam Kwon[1], Yuji Sano[2,3], Yoshio Mizuta[2], Satoshi Tamaki[2]**

[1]*Korea Institute of Materials Science, Korea, Republic of (South Korea)*
*djlee@kims.re.kr*

[2]*The University of Osaka*

[3]*Nagoya Industrial Science Research Institute*

*Shot peening* *Residual Stress Relaxation* *Creep Behavior*

**Abstract** This study investigated the effects of shot peening on the microstructure and high temperature creep property of a René 95 nickel-based superalloy produced by powder metallurgy. The alloy was processed by hot isostatic pressing followed by solution treatment at elevated temperatures and subsequent two stage aging. Following shot peening treatment a high compressive residual stress of approximately 1200MPa was induced near the surface and local plastic deformation together with grain refinement was observed. Heat treatment in the range of 400 ℃ to 800 ℃ revealed that, although no significant changes were observed in the average grain size and local misorientation based on EBSD analysis, compressive residual stresses were rapidly relaxed at temperatures above 700 ℃. This stress relaxation may be attributed to the dissolution of the fine tertiary γ' precipitates near 700 ℃, which can alter dislocation behavior and compromise microstructural stability. Tensile tests over a range of temperatures indicated that both yield strength and ultimate tensile strength were maintained up to 650 ℃, but decreased significantly above 700 ℃. In parallel, high-temperature creep tests conducted at 650 under a stress of 1034MPa revealed that the shot-peened specimens exhibited an approximately 82% longer creep life than the base material. These results suggest that the compressive residual stresses induced by shot peening can partly offset deleterious high temperature effects such as phase transformations, thereby enhancing the mechanical properties of René 95 in high temperature applications.

# Effect of Surface Treatment on Residual Stress Distribution and High-cycle Fatigue Properties of Lap-welded DP600 Steel Joints

**Yunji Cho[1], Hyunsung Choi[1], Hyeonil Park[1], Moo-Young Seok[1], Yong Nam Kwon[1], Dong Jun Lee[1]**

**Yuji Sano[2,3], Yoshio Mizuta[2], Satoshi Tamaki[2]**

*[1]Korea Institute of Materials Science, Korea, Republic of (South Korea)*
*yun4666@kims.re.kr*
*[2]The University of Osaka*
*[3]Nagoya Industrial Science Research Institute*

*Laser peening* *High-cycle fatigue* *Weld residual stress*

**Abstract** Lap-welded joints of advanced high-strength steels are widely used in automotive structures; however, premature fatigue failure frequently occurs in the high-cycle regime due to severe stress concentration and tensile residual stresses at the weld toe. Although peening-based surface treatment techniques have been proposed as effective post-weld solutions, most previous studies have been limited to simplified specimens or restricted joint geometries. Consequently, the effectiveness and underlying mechanisms of surface treatments under realistic lap-welded plate conditions remain insufficiently understood.

In this study, laser peening (LP) and ultrasonic nanocrystal surface modification (UNSM) were selectively applied to the weld toe of lap-welded DP600 steel joints to comparatively investigate their effects on residual stress distribution, microstructural evolution, and high-cycle fatigue behavior. Lap-welded specimens with plate thicknesses of 1.4, 1.6, and 2.0 mm were fabricated using metal inert gas (MIG) welding, and surface treatments were applied directly to the weld toe, where fatigue cracks preferentially initiate. Microstructural characteristics near the surface and along the depth direction were analyzed using optical microscopy and electron backscatter diffraction (EBSD), while residual stress distributions were measured by X-ray diffraction employing the $\sin^2\psi$ method. High-cycle fatigue tests were conducted under identical loading conditions with a stress ratio of R = 0.1.

The results indicate that both surface treatment processes contribute to improving the fatigue performance of lap-welded joints by modifying the stress state at the weld toe. However, clear differences were observed in the magnitude and penetration depth of compressive residual stress as well as in surface-related plastic deformation characteristics, leading to distinct fatigue life improvement trends in the high-cycle regime. These findings suggest that the effectiveness of post-weld surface treatment is strongly governed by the characteristics of compressive residual stress introduced at the weld toe.

This study provides a comparative understanding of LP and UNSM under realistic lap-welded plate conditions and offers practical insight into the selection of surface treatment processes for enhancing the fatigue performance of welded automotive steel structures.

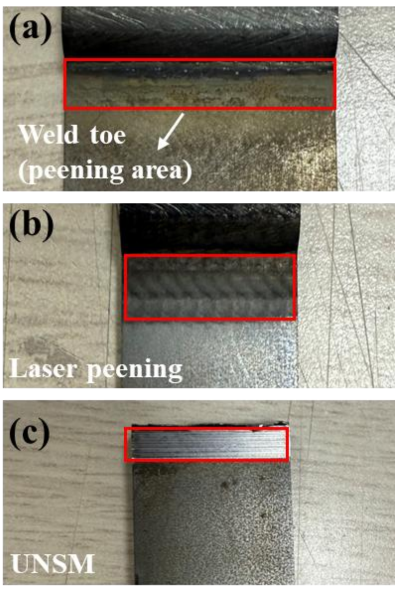



*Figure 1 -. Images of the weld toe region of lap-welded DP600 joints: (a) as-welded, (b) laser peened, and (c) UNSM-treated conditions*

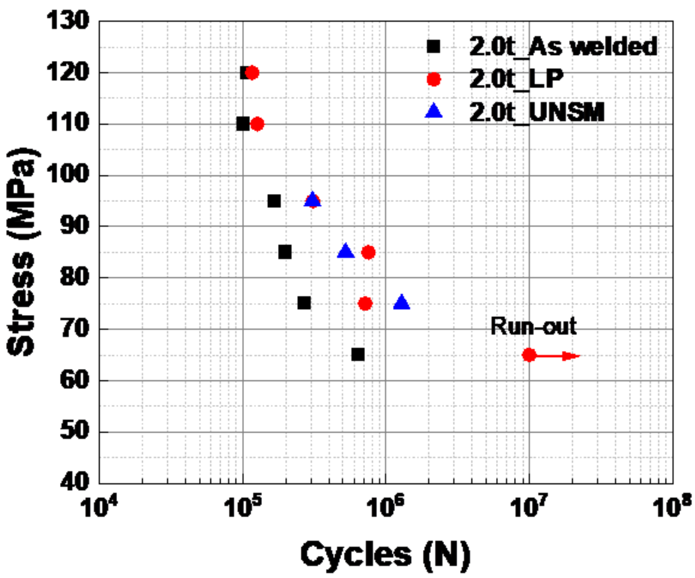



*Figure 2 -. S–N curve of lap-welded DP600 joints in the as-welded, laser-peened, and UNSM-treated conditions.*

# Title A Hybrid Structural Mechanics and Genetic Algorithm Method for Analyzing Local Stresses in Cracked Welded Plate Joints

**Liuyang Feng[1,2], Tao Suo[1,2], Xudong Qian[3]**

[1]*School of Aeronautics, Northwestern Polytechnical University, Xi' an, China, 710072*

[2]*National Key Laboratory of Strength and Structural Integrity, Xi'an, China, 710072*

[3]*Department of Civil and Environmental Engineering, Centre for Offshore Research and Engineering, National University of Singapore, Singapore 117576*

*Stress intensity factor* *Local stress field* *Genetic algorithm*

**Abstract** The paper proposes a hybrid method for determining the local stress field of welded plate joints by integrating analytical structural mechanics with the genetic algorithm. The nonlinear region of the notch stress intensity factor in welded plate joints under bending loads is determined solely by the equilibrium of total moment and total force through a genetic optimization approach. The line-averaged stress along the thickness direction of welded plate joints is compared with the numerical results obtained from the conventional finite element methodology. The local stress intensity factor of various crack patterns is derived using the proposed hybrid approach and validated against numerical results. The proposed approach eliminates the need for computationally intensive procedures to trace the evolving stress intensity factors of growing cracks, making it well-suited for real-time updating in online monitoring and assessment applications.

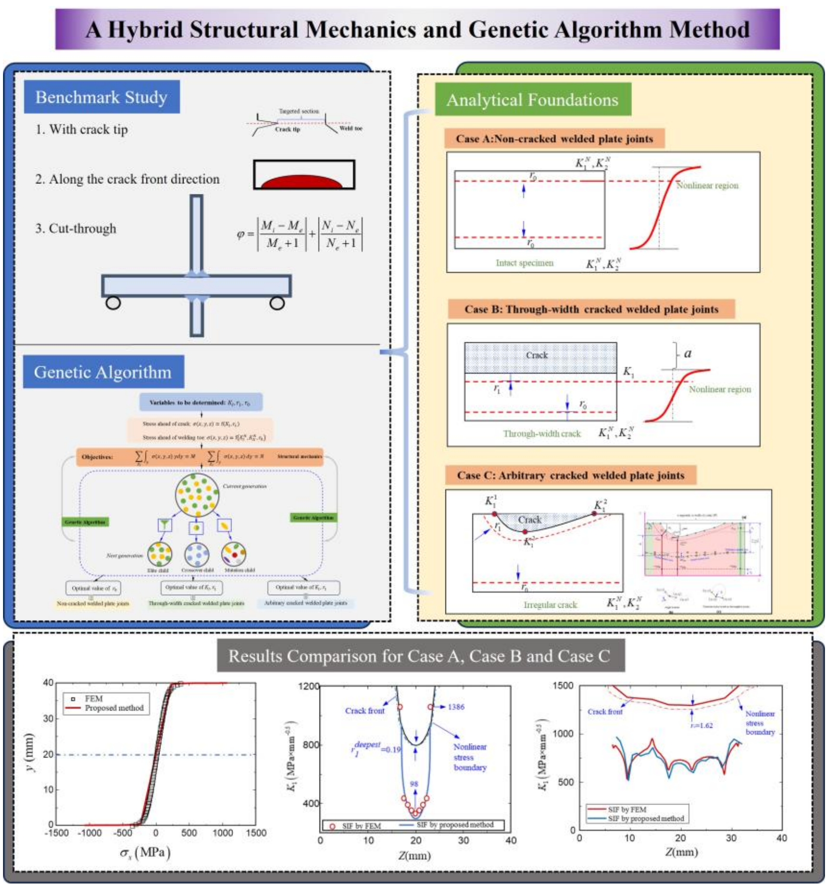



***Figure 1** – Graph Abstract of the stress intensity factor determination procedure*

# Theory of Critical Distances for Fatigue Life Prediction of Notched ZK60 Magnesium Alloy: Insights from X-Ray Tomography

**Jafar Albinmousa[1,2], Syed Haris Iftikhar[3], Aamir Farooq[1], Mumina Ahmed[1], Alaa Ahmed[1]**

*[1]Mechanical Engineering Department, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia; binmousa@kfupm.edu.sa*

*[2] Interdisciplinary Research Center – Intelligent Manufacturing and Robotics, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia*

*[3] Interdisciplinary Research Center– Advanced Materials, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia*

*Theory of Critical Distances* *ZK60 Magnesium Alloy* *X-Ray Tomography*

**Abstract** The lightweight properties of magnesium alloys make them attractive for aerospace and automotive applications, yet their fatigue behavior in the presence of notches remains insufficiently understood for reliable structural design. This work applies to the Theory of Critical Distances (TCD) to predict fatigue lifetime of notched ZK60-T5 magnesium extrusion. Experimental data from both U-notched (blunted, $\rho = 1.5$ mm) and V-notched (sharp, $\rho = 0.8$ mm, 60° opening angle) specimens tested under completely reversed stress-controlled loading ($R = -1$) are analyzed (Figure 1). Predictions will be compared with the Strain Energy Density (SED) approach previously applied to this material. A unique aspect of this investigation involves the use of X-ray computed tomography (CT) data collected during interrupted fatigue testing of a V-notched specimen. The crack surface area evolution, characterized by an exponential relationship $A_p = \kappa e^{\eta N}$ provides direct physical evidence to examine the mechanistic basis of the critical distance concept in wrought magnesium alloys. This study aims to explore how crack growth observations from X-ray CT can validate the physical interpretation of the material characteristic length.

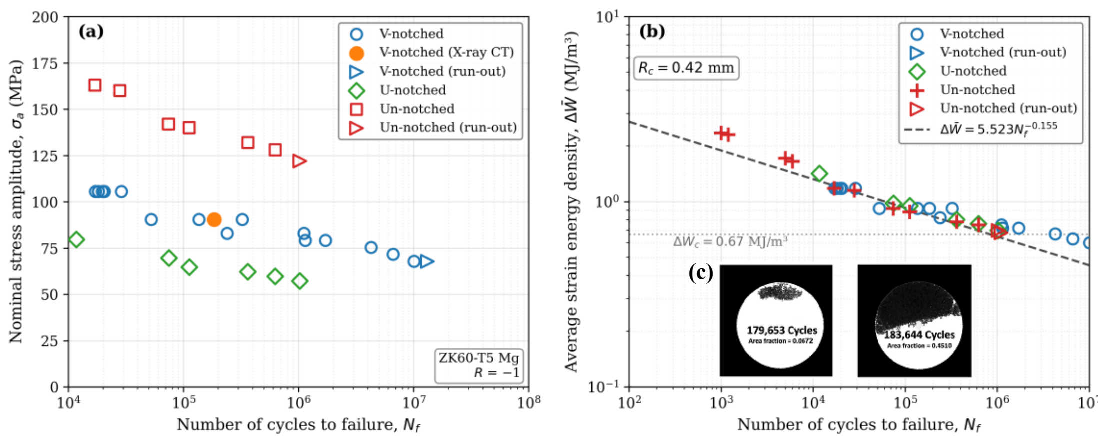



***Figure 1** – Fatigue analysis of ZK60-T5. (a) Stress-life curve, (b) Energy-life curve, (c) Area fraction of projected crack surface.*

# Temperature Dependence on Monotonic and Cyclic Damage for Extruded and Electrical Beam Additively Manufactured Ti-6Al-4V Alloy and Implications for the MultiStage Fatigue Model

**Dr. Mark Horstemeyer, Jared Darius, Dr. Marcos Lugo**

*Liberty University*

**Abstract.** The MultiStage Fatigue (MSF) model will be presented for the first time including temperature dependence. The MultiStage Fatigue (MSF) originally developed by McDowell *et al.* (2003) focused on a cast A356 aluminum alloy. The origination of the MultiStage Fatigue (MSF) model started with an application of a cast A356 aluminum alloy in which McDowell *et al*. [2003] developed the model for analysis of a Cadillac control arm [Horstemeyer 2012]. The MSF model extended into a more accurate incubation law by including more microstructural features when examining wrought aluminum alloys [Xue *et al*., 2007a,b]. Later, Jordan *et al*. [2010] added the effects of grain size and nearest neighbor distance to the defect size to garner more accurate structure-property relationships for the Microstructurally Small Crack (MSC) law. Jordon *et al*. (2011) later employed the MSF model using the crystal orientation (texture) part of the MSF model for MSC growth to capture the anisotropic behavior of the extruded magnesium alloy. Bernard *et al.* [2013] then correlated the experimental crack growth fatigue striations using the repliset method observed on the fracture surfaces to validate the MSC crack growth law for the MSF model. In the same year, Lugo *et al*. [2013] demonstrated that the MSF model could have the same material constants for a magnesium alloy although different processing methods (rolling, extrusion, and casting) produced different microstructures. The difference in the material's fatigue behavior arose from the different microstructural features that came from the diverse processing methods, but the MSF model admitted the effect of different processing methods by considering the grain size and crystal orientation (texture). Although Lugo *et al*. [2013] showed that one set of material constants could be used for a particular alloy that experienced different processing methods, it was not until Horstemeyer *et al*. (2020) put together a single set of MSF material constants could be applied to different aluminum alloys (17 in total) based upon their materials processing methods. As such, the differentiation between the alloys arose from the processing method (cast, rolled plate, rolled sheet, and extrusion) and the associated microstructural features (grain size, particle size, pore size, pore neighbor distance, and porosity), the grain orientations (texture), and the grain misorientations could be captured with the MSF model. However, no temperature dependence had been included to date.

In the context of the MSF model, this study investigates the temperature-dependent monotonic and cyclic behavior of extruded and electron beam method (EBM) additively manufactured Ti-6Al-4V alloy. The temperature ranged from 23°C to 550°C, and the structure-property relations were quantified using optical and scanning electron microscopy. Analysis of the fracture surfaces reveals a clear evolution in the mechanisms of void nucleation, growth, and coalescence . These findings serve as critical inputs for calibrating the damage parameters within the MSF model. Thus the application of MSF model can now be used for different titanium alloys with respect to their different materials processing method.

# Shot peening on high-strength steels: A computational study

**Christos Gakias[1], Niki Nouri[2], Stefan Dietrich[2], Phlipp Reeh[3] Paschalis Adamidis[1], Volker Schulze[2], Georgios Savaidis[1]**

*[1]Laboratory of Machine Elements and Machine Design, Mechanical Engineering Department, Aristotle University of Thessaloniki, 546 24 Thessaloniki, Greece, clgakias@auth.gr*

*[2]Institute for Applied Materials – Materials Science and Engineering, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany*

*[3]Stresstech GmbH, 56477 Rennerod, Germany*

*Stress shot peening* *Finite Element Method* *High-strength steel*

**Abstract** To enhance the durability of parabolic leaf springs, stress shot peening—peening under pre-tension—serves as a critical surface enhancement technique for improved fatigue life. This study conducts a comparative analysis of two high-strength spring steels, 51CrV4 and 45SiCrV9Ni, applicable to automotive suspension components, e.g. coil springs, leaf springs etc. The research establishes a foundation by experimentally characterizing the elastic-plastic and Low-Cycle Fatigue (LCF) behavior of both alloys. These experimental material laws are subsequently integrated into an advanced finite element framework designed to simulate the stress peening operation. Distinct from conventional models, this simulation accounts for stochastic shot impact, realistic boundary conditions, and surface degradation caused by decarburization. The findings demonstrate a superior residual stress development for the recently developed 45SiCrV9Ni steel alloy and therefore, potentially enhanced fatigue life. Ultimately, this validated model provides a computationally efficient surrogate for physical testing in process optimization.

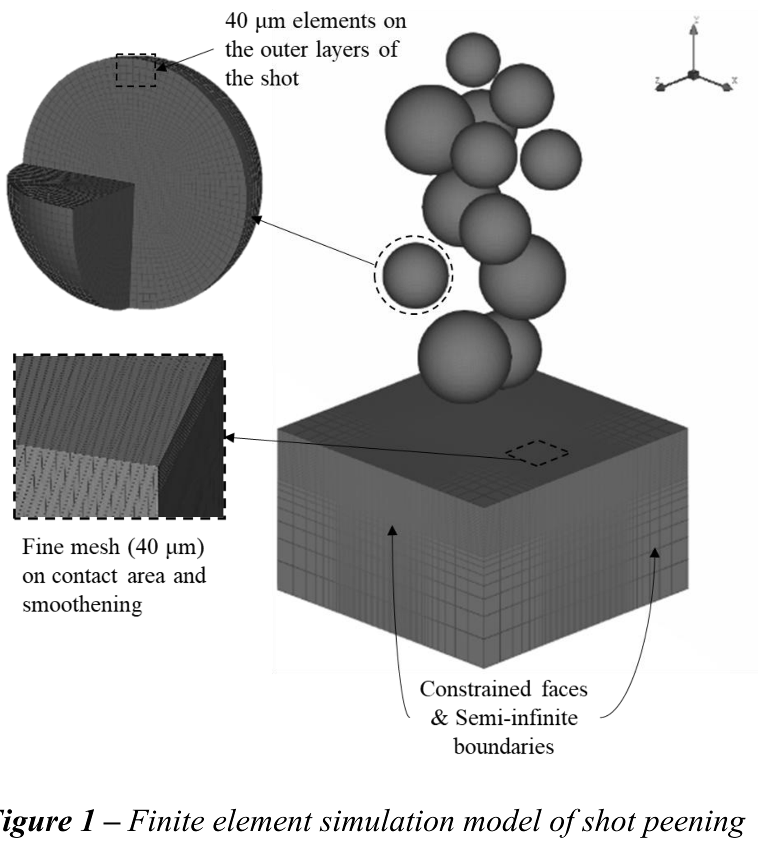



***Figure 1** – Finite element simulation model of shot peening*

# Laser shock peening effect on mechanical response of a superelastic NiTi alloy

**Klemen Pregeljc[1], Laurent Berthe[2], Črtomir Donik[3], Damjan Klobčar[1], Žiga Ahčin[1], Jonas Trojer[1], Miha Brojan[1], Jaka Tušek[1], Uroš Trdan[1,*]**

[1]*Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva cesta 6, 1000 Ljubljana, (corresponding author: uros.trdan@fs.uni-lj.si)*

[2]*PIMM, ENSAM, UMR8006 ENSAM, CNRS, CNAM, 151 Boulevard de l'Hôpital, 75013 Paris, France*

[3]*The Institute of Metals and Technology, University of Ljubljana, Lepi pot 11, 1000 Ljubljana*

*Superelastic NiTi alloy      Laser Shock Peening (LSP)      Mechanical response*

**Abstract** Superelastic NiTi alloys exhibit functional properties such as stress induced phase transformation and a pronounced elastocaloric effect. However, their application is limited by fatigue sensitivity and strong dependence of mechanical response on surface condition. This work investigates the effect of nanosecond laser shock peening (LSP) on the mechanical behaviour of a superelastic NiTi alloy, with emphasis on isothermal cyclic training and adiabatic loading.

The material was an ASTM F2063 NiTi 1mm thick plate with an austenite finish temperature of about 5 °C. Both sides were treated to ensure a balanced stress field. Peening was performed using a frequency doubled Nd:YAG laser, operating at 532 nm, using laser pulses of 10 ns and 3 mm spot size diameter, corresponding to laser power densities of 3, 4, 5 and 6 GW/cm$^2$. A water confinement and Al ablative layer was used, with 50 % overlapping rate.

The results confirmed beneficial effect after LSP treatment in the surface and near surface layers of the NiTi alloy, with grain refinement, changes in microhardness distribution and shifts in residual stress. At the highest power density (6 GW/cm$^2$), the surface grain size was reduced by 57 % and the subsurface hardness increased, indicating localized strengthening. Consequently, in isothermal tensile loading (strain rate = 0.00015 1/s), transformation stresses increased from ≈330 MPa to 350 – 386 MPa. Although the transformation plateau and the overall residual strain reduced, the maximum stress rose from around 704 MPa in the reference to approximately 782 MPa after treatment with 4 GW/cm$^2$. At cyclic training (strain rate = 0.0025 1/s) LSP treated samples exhibited lower permanent strain compared to base material (~0.25% - 40% *vs.* ~1%) . Under adiabatic loading (strain rate = 0.07 1/s), the untreated material showed a strong elastocaloric temperature change, with an increase of about +18.8 °C / -14.5 °C. In contrast, LSP treated regions exhibited significantly reduced temperature changes, limited to approximately 4.0 – 6.7 °C across all peened samples. Due to highest strain hardening effect, the samples treated with higher power density depicted the weakest elastocaloric response.

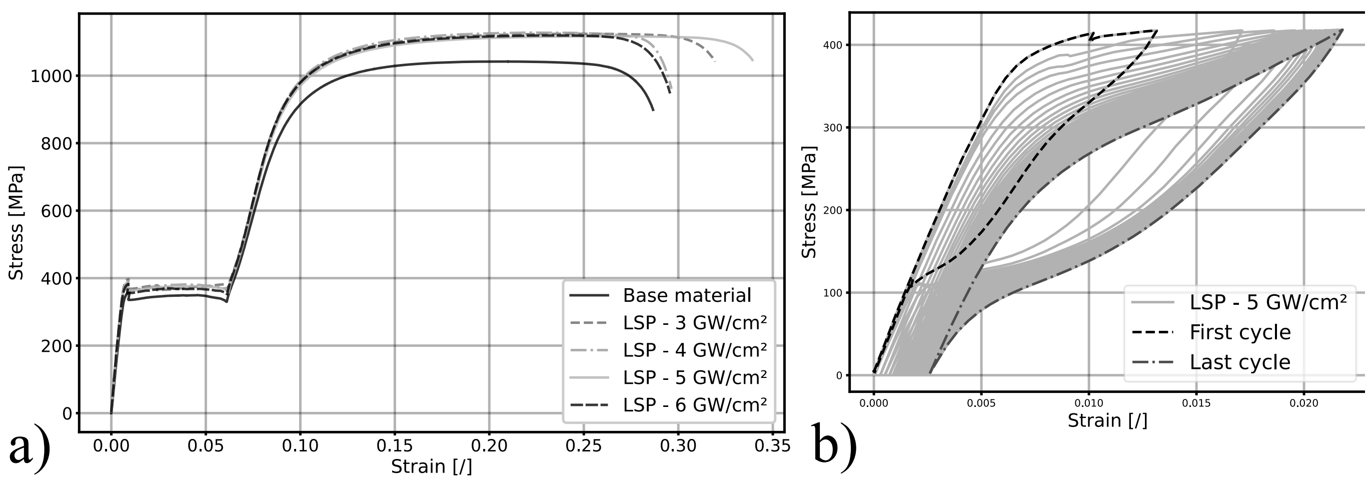



**Figure 1 –** a) Full tensile test to failure, b) Cyclic training for LSP 5 GW/cm$^2$ processed material

# Dislocation Glide Theories (CRSS) Relevant to Fatigue

**H. SEHITOGLU**

University of Illinois at Urbana- Champaign, Urbana, Illinois 61801, USA

*Critical Resolved Shear Stress* *Cross-slip* *Titanium Alloys*

**Abstract** Despite many years of research, the fundamental quantities that govern dislocation glide in metallic materials, such as the critical resolved shear stress (CRSS), remain poorly understood[1-7]. Theoretical predictions of critical stress far exceed experimental values because early theories neglect elastic strain energy, lattice type, dislocation character, and other factors. The variability of the critical stress is essential because slip planes exhibit compositional variations, and such variability may arise from spatial variations in short-range order in alloys. Because there are myriad arrangements of atoms at the lattice scale, artificial neural network methodologies have been developed to capture the variability in CRSS. This issue is exacerbated in complex compositions and spatial variations in composition, as observed in additively manufactured alloys. These results could potentially explain the wide variation in fatigue limits even for the same material. For example, when fatigue limits are normalized by nominal CRSS the variability is large, this is partly because there is a wide distribution of local CRSS. The determination of critical stress is also relevant to crystal plasticity models, which are widely used in fatigue. In this presentation, I will show examples of the determination of critical stress for a wide range of metallic materials, highlighting crystal orientation (non-Schmid) behavior, tension-compression asymmetry effects, the role of cross-slip, and the role of different slip systems, such as prismatic/pyramidal, in the case of titanium.

The work is supported by the National Science Foundation (high entropy alloys) and Department of Energy-BES (titanium).

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# Effects of microstructural characteristics on the fatigue behavior of un- and low alloyed steel

**Janina Koziol[1,2], Fabian Weber[1], Peter Starke[1,2]**

[1] *Department of Materials Science and Testing (WWHK), Institute QM³, University of Applied Sciences Kaiserslautern, Schoenstr. 11, 67659 Kaiserslautern, Germany*

[2] *Faculty of Natural Sciences and Technology, Saarland University, 66123 Saarbrücken, Germany*

*Microstructure* *Fatigue* *Damage evolution*

**Abstract** The fatigue behavior of metallic materials is a highly material-specific phenomenon influenced by the interaction of a variety of damage-relevant parameters. Besides non-inherent influencing factors such as variable loading conditions (e. g. increased testing frequency or temperature), material-inherent characteristics lead to substantial differences in the fatigue behavior. These may vary significantly due to alloying concepts, heat treatment, or processing parameters or routes. For a reliable and transferable interpretation of cyclic deformation and fatigue behavior, advanced damage evolution approaches combining non-destructive testing (NDT)-based degradation assessment and microstructural analyses are therefore essential to quantify damage-relevant features and process-induced variations.

This contribution presents a characterization strategy based on scanning electron microscopy combined with electron backscatter diffraction and an evaluation of sensor signals based on NDT methods to link microstructural signatures to the fatigue behavior. In addition to investigating the effects of alloying elements and different heat treatment conditions, the study also considers varying machining parameters leading to grain refinement and near-surface gradients as well as different surface roughness. The approach complements mechanical testing by providing quantitative information on microstructural heterogeneity, enabling a more robust comparison of specimens and conditions than purely global material parameters, and integrates this information into accelerated lifetime prediction concepts, such as MiDAcLife. The presented strategy supports the systematic evaluation of microstructure-property relationships and helps develop processing guidelines aimed at controlled microstructural states and improved fatigue reliability.

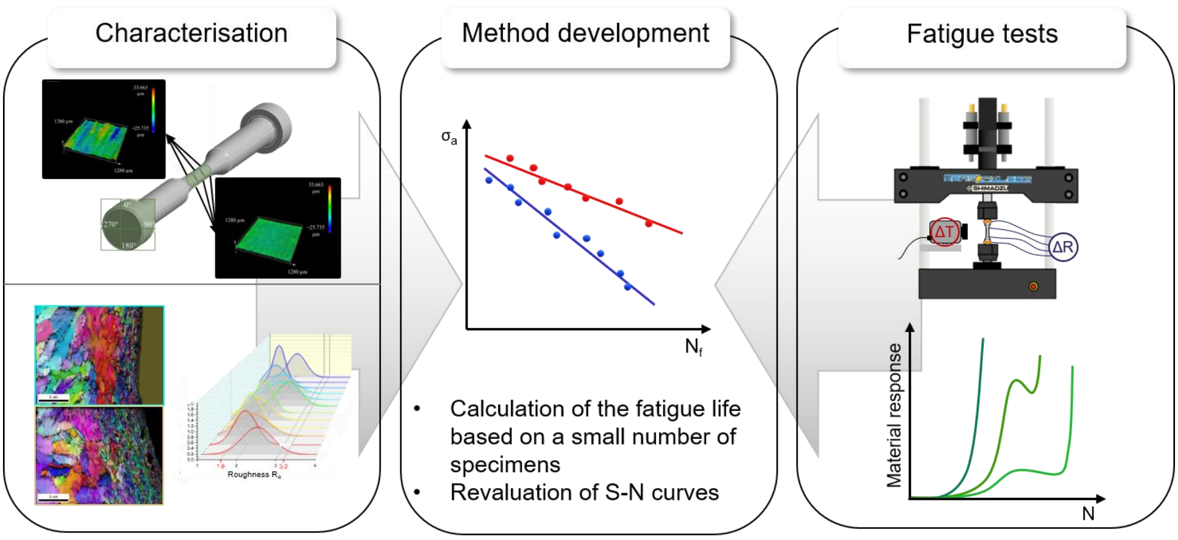


***Figure 1*** *– Integration of microstructural and NDT-based data into lifetime prediction methods.*

# Slip band influence on grain size effect in Inconel 718

**Tom L'hermite[1,2], Flavien Ghiglione[1], Jean-Michel Scherer[2], Henry Proudhon[2]**

[1] *Safran Tech, Digital Sciences & Technologies Department, Rue des Jeunes Bois, Châteaufort, 78114 Magny-Les-Hameaux, France, tom.lhermite@safrangroup.com*

[2] *Mines Paris, PSL University, Centre des Matériaux (MAT), UMR7633 CNRS, 21 Allée des Marronniers, 78000 Versailles, France*

*Grain size effect* *Crystal plasticity* *Slip bands*

**Abstract** Studying material microstructures is key to understanding their macroscopic behavior. In particular, the lifespan of the material and its grain size are strongly related. This work aims to build a methodology to consider plastic localisation induced by slip bands in finite element calculations to account for grain size effect on the cyclic behavior of Inconel 718, used in the aerospace industry.

In previous work by Lionel Gélébart [1], slip bands (parallel to the slip plane) within the grains have ben modelled using Fast Fourrier Transforms (FFT). This work adapts his approach to finite element models, in order to split grains into several slip bands with a given thickness, and to allocate a specific critical resolved shear stress (CRSS) to each band. Precisely, a CRSS value is first calculated for each integration point using a Weibull distribution. Then, the integration points are packed into separate groups, splitting the grains into several slip bands. Finally, for each band, the minimum CRSS value from integration points of the band is allocated to all the integration points within the band.

In order to analyse the grain size effect, several simulations using the Méric-Cailletaud crystal plasticity model [2] with a space-dependent CRSS within each grain have been performed on various mesh homotheties respecting usual grain sizes found in the Inconel 718 alloy. The Hall-Petch law, which states that the macroscopic yield stress scales with the inverse of the square root of the mean grain size, is recovered without introducing any explicit dependence of the behavior law on the grain size. In addition, cyclic behavior has also been tested. The result is consistent with prior statements: the bigger the grain size, the earlier the yielding in the cyclic curve, and the bigger the plastic loop grows.

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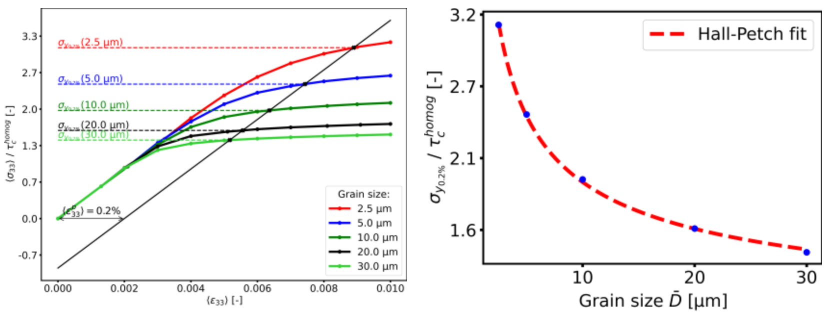



***Figure 1*** *– Grain size effect on yield curves and Hall-Petch effect*

# Fatigue damage tolerance and defect-based lifetime of additively manufactured metals

**S. Stammkoetter[1], P. Karentzopoulos[1], S. Mrzljak[1], F. Walther[1, *]**

*[1]Chair of Materials Test Engineering (WPT), TU Dortmund University, Baroper Str. 303, 44227 Dortmund, Germany, *frank.walther@tu-dortmund.de*

*Fatigue damage* *Defect-based lifetime* *Additive manufacturing*

**Abstract** The microstructure, process-related defects and surface roughness of additively manufactured metals determine the fatigue behavior in technical applications such as aircraft turbines and medical implants. Suitable testing strategies and measurement methods enable precise monitoring of process influences on the fatigue behavior and lifetime. Intermittent fatigue testing can be used to investigate the interaction between microstructure, defects like porosity, and crack initiation and propagation up to very high cycle fatigue (VHCF) region. Steel 316L and metal alloys AlSi10Mg, Ti6Al4V, TNM (TiAl), and IN718 were evaluated with regard to the effect of defects (EoF), build orientation, and stress conditions on the fatigue strength, which was correlated using the concepts of Murakami and Shiozawa. The investigations demonstrate the potential for improving damage tolerance and fatigue life based on fundamental process-structure-property-damage relationships that are integrated into unified approaches.

In addition, crack initiation and propagation tests have been carried out for selected titanium aluminide (TiAl) conditions in order to evaluate the fatigue-critical short crack behavior for integration into the damage tolerance approaches. The findings are used for transfer to complex lattice (TPMS Gyroid) structures. By using lattice structures only be producible by additive manufacturing, their stiffness can be reduced and adapted to requirements of respective applications. With the help of innovative, combined testing and measurement strategies consisting of µ-computed tomography (µCT), digital image correlation (DIC), and potential drop measurement (PD), fatigue failures were localized, and an understanding of the complex damage evolution of lattice structures was gained. Various approaches have been considered for predicting the service life of complex structures, which enable the standardization almost independently of local porosity.

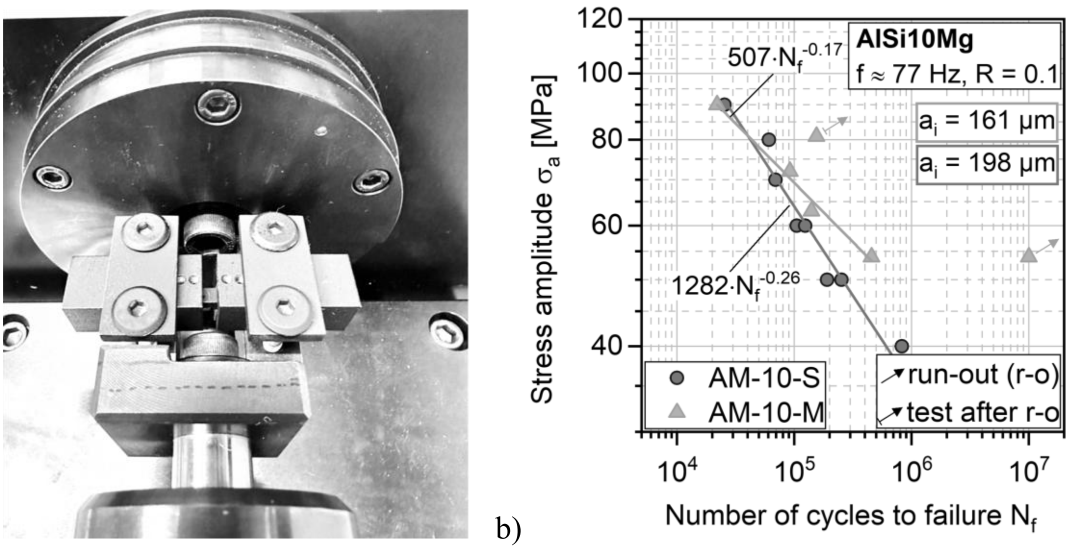
a)  b)


***Figure 1 -*** *a) Multiaxial alternating bending loading setup, b) Woehler (S-N) curves of standardized (S) and minimized (M) bending specimen geometries*

# Strut-dependent fatigue behavior of PBF-LB/M 316L steel with regard to lattice structure properties

**P. Karentzopoulos[1,*], G. Mao[2], S. Stammkötter[1], S. Mrzljak[1], S. Münstermann[2], F. Walther[1]**

[1]*Chair of Materials Test Engineering (WPT), TU Dortmund University, Baroper Str. 303, 44227 Dortmund, Germany, *peter.karentzopoulos@tu-dortmund.de*

[2]*Institute of Metal Forming (IBF), RWTH Aachen University*

*PBF-LB/M process* *Steel 316L* *Strut diameter*

**Abstract** Additive manufacturing using powder bed fusion of metal with a laser beam (PBF-LB/M) enables unprecedented design freedom for lightweight structures, particularly lattice geometries with tailored mechanical performance capability. For a given relative density, lattice structures can be realized either by a few unit cells with large strut diameters or by many unit cells with thinner struts, resulting in different surface-to-volume ratios and defect sensitivities. These geometric effects strongly influence the mechanical behavior of the diameter-dependent specimens.

In this work, the influence of the strut diameter on simplified solid PBF-LB/M-specimens with designated diameters made of AISI 316L steel (Fig. 1a) is systematically investigated to decouple geometric size effects from the lattice topology. X-ray computed tomography (CT) is performed to quantify the pore size distribution, defect morphology, and the deviation of the strut diameter and thus the cross-sectional area between the target and actual values. The results show pronounced diameter-dependent fluctuations, particularly in terms of geometric accuracy, with thinner diameters exhibiting a smaller deviation in cross-sectional area in absolute terms, but deviating more from the design diameter in relative terms. The mechanical characterization includes tensile, compression, and cyclic loading. The results from tensile tests underline a strut diameter size effect, with a larger strut diameter leading to higher tensile strength and, at the same time, increased elongation at break (Fig. 1b). This behavior is attributed to the surface-to-volume ratio and thus the increasing influence of roughness on the failure behavior at thinner strut diameters. Strain-controlled fatigue tests are introduced to investigate deformation-induced damage mechanisms and cyclic plasticity behavior. These strain-based fatigue tests underline the increased role of surface and microstructure heterogeneities under cyclic strain loading, especially at small strut diameters.

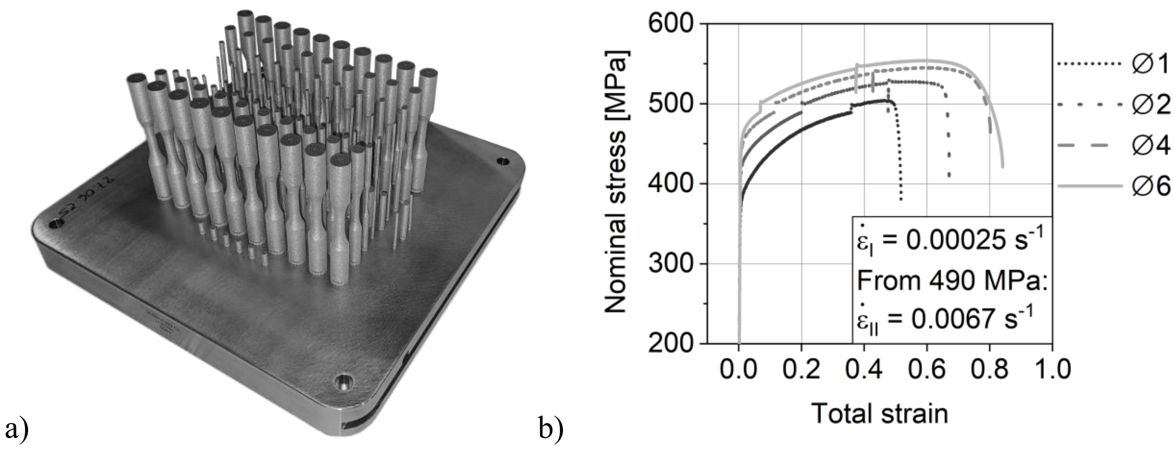



***Figure 1 -*** *a) PBF-LB/M-specimens with varying diameters, b) representative nominal stress-total strain curves for varying strut diameters*

# In-situ Crack Propagation of Pearlitic Rail Steel Subjected to Large Shear Deformation

**Tsering Wangmo[1*], Daniel Gren[2], Anton Hohenwarter[3], Ehsan Ghassemali[4], Christer Persson[1], Johan Ahlström[1]**

[1]*Chalmers University of Technology, Dept of Mechanical Engineering, Division of Computational Mechanics and Materials Engineering; *email: tsering@chalmers.se*

[2]*GKN Aerospace, Sweden AB, Trollhättan, Sweden*

[3]*Montanuniversität Leoben, Department of Materials Science*

[4]*Jönköping University, School of Engineering, Materials and Manufacturing*

*Fatigue Crack Propagation* *Pearlitic steel* *In-Situ SEM*

**Abstract** Rail heads operate under repeated rolling contact loading where axle loads are transmitted through a very small contact patch, leading to very high contact stresses. Traction and cornering also create strong shear stresses close to the surface. When frictional loading is largely unidirectional, repeated cycles lead to progressive accumulation of plastic shear strain (ratcheting) and extensive surface deformation[1,2]. This deformation drives work hardening and microstructural alignment, thereby modifying the material's properties and mechanical behaviour.

The severely deformed surface of the rail steel is replicated in the laboratory by twisting solid cylindrical test bars under a constant compressive force[3]. Based on previous work, a methodology to extract radial Single-Edge Notched Tension (SENT) specimens from predeformed bars (PD6) was developed, Fig 1a. These specimens are then tested using in-situ fatigue crack propagation experiments inside a scanning electron microscope. To prevent buckling, the load ratio was set to R = 0.1. The maximum stress was 125% of the undeformed 0.2% offset yield strength (668 MPa) to intentionally shorten fatigue life, since in-situ testing is time intensive. A displacement rate of 8 µm/s (≈0.03 Hz) was used. The surface crack length was measured perpendicular to the notch (Fig 1b).

The applied load caused extensive plastic deformation ahead of the main crack in the predeformed material, and the notch was too blunt for appropriate studies of the inital crack propagation. To overcome these limitations, a sharper notch was introduced. The notch is machined in two steps: first, a small groove is made by EDM, and then a sharp notch of about 200 µm in length is produced using a razor blade with diamond paste, see Figure 1c. The new notch geometry yields higher stress intensity, effectively reducing the nominal load required to propagate the crack. With the new notch, the crack will initiate at a more well-defined location, enabling comparative crack measurements. The reduced nominal load will also allow for longer crack propagation prior to fracture, allowing characterization of the fatigue zone at the fracture surface.

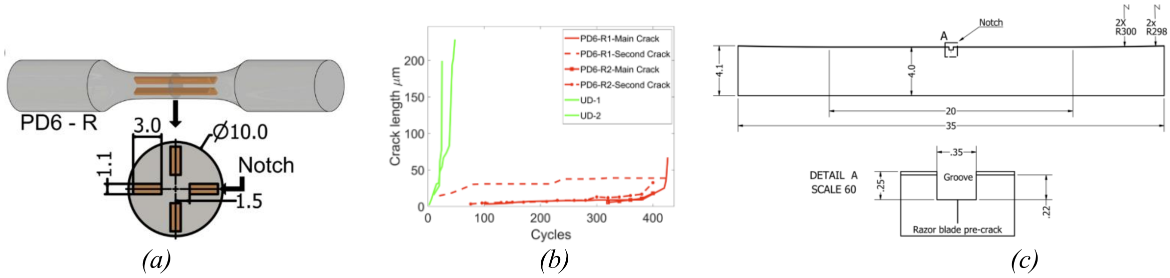



***Figure 1** – (a) SENT specimens (b) Surface crack length measurements of SENT predeformed specimens (PD6) and undeformed specimens (UD) (c) SENT specimen with a pre-crack made by a razor blade with diamond paste.*

[1] D. I. Fletcher, F. J. Franklin, and A. Kapoor, "Rail surface fatigue and wear," Wheel-Rail Interface Handbook, pp. 280–310, Jan. 2009, doi: 10.1533/9781845696788.1.280.

[2] U. Zerbst, K. Mädler, and H. Hintze, "Fracture mechanics in railway applications—an overview," Eng. Fract. Mech., vol. 72, no. 2, pp. 163–194, Jan. 2005, doi: 10.1016/J.ENGFRACMECH.2003.11.010.

[3] K. A. Meyer, D. Nikas, and J. Ahlström, "Microstructure and mechanical properties of the running band in a pearlitic rail steel: Comparison between biaxially deformed steel and field samples," Wear, vol. 396–397, pp. 12–21, Feb. 2018, doi: 10.1016/J.WEAR.2017.11.003.

# Revealing and Predicting Fatigue Crack Nucleation in Textured Zircaloy-4 via Full-Field Experiments and Physics-Informed Machine Learning

**Weifeng Wan[1], Fionn Dunne[2]**

[1] *School of Energy and Power Engineering, Beihang University, China*

[2] *Department of Materials, Imperial College London, United Kingdom*

*Long short-term memory* *Crack nucleation* *Zirconium*

**Abstract:** Fatigue crack nucleation in hexagonal close-packed zirconium alloys is strongly influenced by crystallographic texture, while quantitatively predicting its early evolution remains challenging due to pronounced strain localisation and microstructural heterogeneity. Bridging high-resolution experimental observations with predictive models that can capture spatiotemporal deformation fields is therefore of significant interest.

In this study, the texture-dependent fatigue crack nucleation behaviour of Zircaloy-4 is investigated by combining in situ digital image correlation (DIC), crystal plasticity finite element (CPFE) modelling, and a physics-informed long short-term memory (LSTM) framework. Three-point bending fatigue tests were performed on edge-notched specimens with orthogonal c-axis orientations. Experiments show that Z-type specimens, with c-axes oriented out of plane, nucleate short cracks in significantly fewer cycles than Y-type specimens. Full-field DIC reveals distinct strain-localisation morphologies, characterised by strong wing-shaped bands in Z-type samples and weaker, claw-like patterns in Y-type samples. These trends are captured by CPFE simulations, which indicate that texture-controlled slip activity governs early plastic strain accumulation. Incorporating strain-gradient hardening through geometrically necessary dislocations substantially improves the agreement with experiments.

Building on the experimentally resolved strain fields, a physics-informed LSTM model is developed to predict the spatiotemporal evolution of strain preceding crack nucleation. Trained directly on full-field DIC sequences, the model achieves high-fidelity strain-field prediction, while the inclusion of strain-gradient descriptors significantly enhances long-horizon accuracy, spatial resolution, and numerical stability. This work demonstrates that physics-informed recurrent learning provides a powerful and interpretable tool for predicting texture-sensitive fatigue damage in structural alloys.

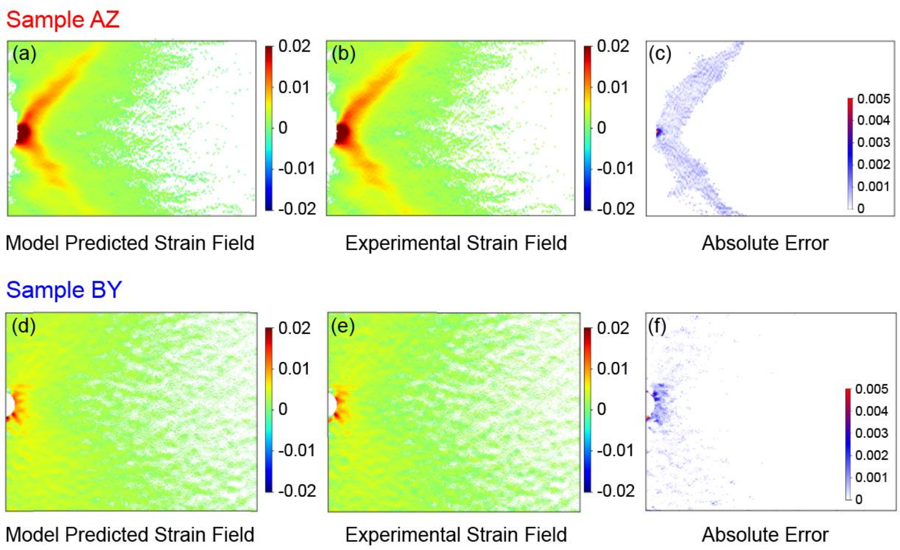



***Figure 1** – Physics-informed LSTM modelling for fatigue strain-field prediction in textured Zircaloy-4 with orthogonal basal textures (Y and Z)*

# Influence of Cyclic Hardening Behavior on Fatigue Performance

**Danton Buticosihz Müller[1], Pierre Osmond[2], Daniel Irmer[2], Pierre Mérot[3], Yves Nadot[4], Franck Morel[3]**

*[1]LAMPA, Arts et Métiers Institute of Technology, 2 Bd du Roncerray, 49035 Angers, France, danton.buticosihz_muller@ensam.eu*

*[2]CETIM, [3]LAMPA, Arts et Métiers Institute of Technology, [4]Pprime Institute, ISAE-ENSMA*

*Cyclic Hardening* *Defect Sensitivity* *Cast aluminum alloy*

**Abstract** The presence of defects (pores, inclusions, oxides) significantly reduces fatigue resistance in metallic materials. While numerous studies have analyzed the individual effects of defect size, location, and shape on fatigue performance, the impact of cyclic hardening behavior on defect sensitivity remains poorly understood. This knowledge gap limits accurate prediction of fatigue life in cast aluminum alloys where both defects and variable cyclic hardening behaviors coexist. This research uses a combined numerical and experimental approach with an AlSi7Cu0.5Mg0.3 cast aluminum alloy as model material. Different heat treatment conditions were selected to generate diverse cyclic hardening behaviors while maintaining controlled microstructure. Specimens underwent hot isostatic pressing (HIP) to establish a "defect-free" baseline state. Monotonic and cyclic characterization tests evaluated mechanical behavior evolution under different aging conditions. First, fatigue testing on HIP-treated specimens established baseline S-N curves. Mechanical characterization revealed that despite different initial monotonic properties, under-aged conditions (UA) evolve toward saturated cyclic hardening behavior similar to peak-aged (PA) material. Fatigue testing on defect-free specimens demonstrated that this convergence produces comparable fatigue resistance between UA and PA states. In contrast, over-aged (OA) treatments exhibited stable cyclic behavior with inferior fatigue performance (Figure 1). Future fatigue tests with artificial defects and numerical simulations analyzing stress fields around the defects will help understand how cyclic hardening properties govern defect sensitivity on fatigue life. While this study focuses on one type of alloy, the findings can provide fundamental insights into the interplay between defects and cyclic hardening that should facilitate understanding of fatigue behavior across other metallic alloy systems.

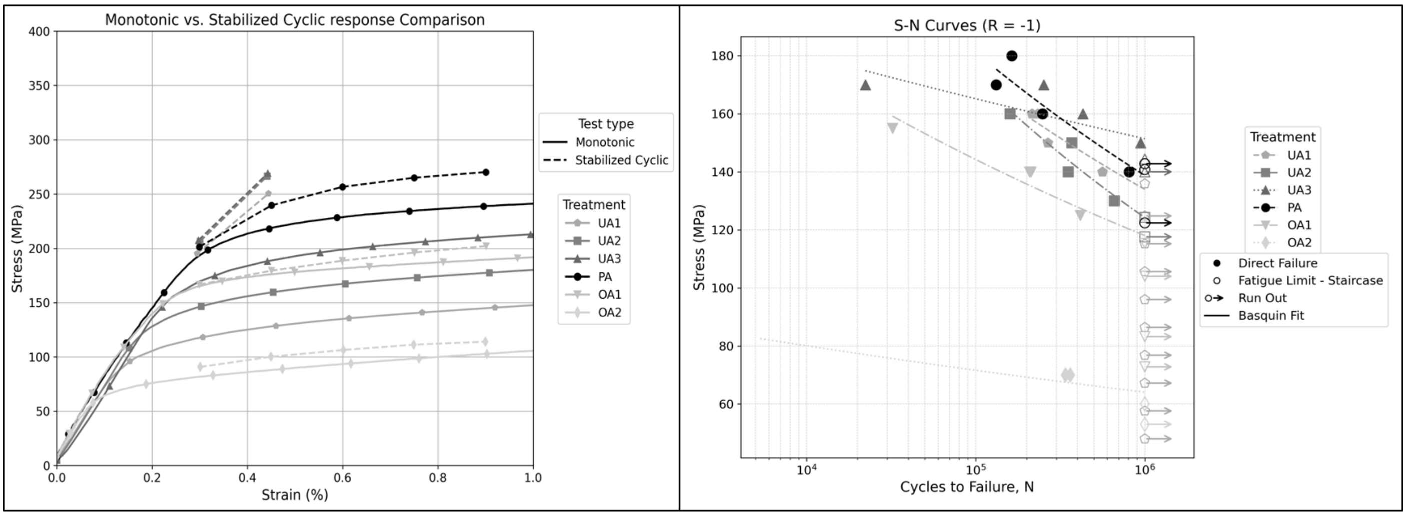



***Figure 1 -*** *Mechanical behavior (left) and fatigue performance, axial tension-compression; R = -1 (right) of AlSi7Cu0.5Mg0.3 cast aluminum alloy under different heat treatment conditions.*

# Combining Modal Decomposition and Gaussian Approximation for Fatigue Analysis of Non-Stationary Multi-Channel Random Vibration using Multivariate Moments

**Josef Weber[1], Arvid Trapp[2], Peter Wolfsteiner[2]**

*[1]Munich University of Applied Sciences, Dept. of Mechanical, Automotive and Aeronautical Engineering, Dachauer Str. 98b, 80335 München, Germany, josef.weber@hm.edu*

*[2]Munich University of Applied Sciences, Dept. of Mechanical, Automotive and Aeronautical Engineering*

*Random Vibration* *Non-Stationarity* *Fatigue Assessment*

**Abstract** Throughout their service life, many mechanical components are subjected to random vibration loading. Therefore, reliable fatigue life assessment is essential to ensure structural integrity.

In general, two different approaches are available for this purpose: PSD-based frequency-domain methods, such as the Dirlik or Tovo–Benasciutti methods, and time-domain methods, such as rainflow counting. While the former provide a computationally efficient option through an effective estimation of the load cycle distribution, their validity is limited to stationary Gaussian processes. The latter do not suffer from these restrictions; however, their computational cost becomes prohibitively high, particularly for large finite element models and long time series.

To address these challenges, a novel method is presented that combines the advantages of both approaches. Its core element is a modal decomposition into stationary components (MDGP). First, the modal degrees of freedom of the steady-state response are computed for a given non-stationary random load. Subsequently, the response is decomposed into quasi-stationary components while consistently accounting for higher-order multivariate statistical moments. By transforming the individual components back to the nodal coordinates, fatigue life evaluation is then performed using established PSD-based methods.

The advantages of the proposed method arise from the modal decomposition, which enables a substantial reduction of system size through modal truncation and provides inherent frequency selectivity, thereby eliminating the need for manual band-pass filtering. Moreover, the method is independent of the number of excitation channels. In addition, the back-transformation of the spectral moments allows for an efficient and direct damage assessment.

Based on an illustrative finite element model, the results of the proposed method are compared with those obtained from a purely time-domain analysis using rainflow counting and from a purely PSD-based analysis followed by damage evaluation using the Dirlik method. The high accuracy achieved alongside a significant reduction in computational effort highlights the practical relevance of the proposed approach.

# Tracking Fatigue Damage Evolution in AISI 4140 Using Magnetic Barkhausen Noise for Non-Destructive Machine Learning–Based Remaining Useful Life Estimation

**Mehdi Khabou[1], Volker Schulze[1], Stefan Dietrich[1]**

[1]*Institute for Applied Materials - Materials Science and Engineering (IAM-WK), Karlsruhe Institute of Technology (KIT), Karlsruhe, 76131, Germany*

*Magnetic Barkhausen Noise* *Machine Learning* *Remaining Useful Life*

**Abstract** Fatigue assessment of steels remains a major challenge when non-destructive, in-service evaluation of the material state is required. Tracking fatigue damage evolution and directly using it for remaining useful life (RUL) estimation is not yet established for magnetic Barkhausen noise (MBN) measurements. This gap limits the integration of micromagnetic methods into structural health monitoring and circular manufacturing strategies, where reliable decisions on component reuse are essential. This study investigates the evolution of the MBN response during rotating bending fatigue loading of quenched and tempered AISI 4140 steel with the objective of developing a non-destructive fatigue state estimator. Fatigue tests were performed at three load levels in the low-cycle fatigue (LCF) regime. MBN measurements were conducted intermittently at 10% intervals of the individual fatigue life. Characteristic MBN features were extracted in both time and frequency domains. These descriptors were related to the fatigue damage state using analytical correlation analysis and data-driven approaches. Supervised machine learning models, specifically multi-layer perceptron neural networks, were trained to predict fatigue life fraction and remaining useful life based solely on MBN features. The experimental dataset thus links cyclic load history, fatigue damage progression, and micromagnetic signal evolution. The results show a systematic evolution of the MBN signal with increasing cycle number. Pronounced changes occur during the early fatigue stage and immediately prior to failure, while an intermediate plateau region is observed. The extracted MBN features exhibit consistent trends with fatigue life fraction, enabling regression models to learn damage progression from non-destructive measurements. The study demonstrates that MBN can serve as a physically sensitive and data-driven compatible indicator of fatigue state in AISI 4140. This provides the basis for a non-destructive fatigue condition and RUL estimator, supporting condition-based reuse decisions and more efficient fatigue assessment in circular manufacturing systems.

# Machine learning-based fatigue crack path evaluation in high-speed steel

**J. Zitz[1], L. Walch[1], T. Klünsner[1,*], G. Ressel[1], A. Hohenwarter[2], S. Marsoner[1],**

**M.J. Cordill[3], A. Hackl[4], R. Pippan[3], C.O.W. Trost[3]**

*[1]Materials Center Leoben Forschung GmbH (MCL), Vordernberger Straße 12, 8700 Leoben, Austria,*
**thomas.kluensner@mcl.at*
*[2] Chair of Materials Physics, Technical University Leoben, 8700 Leoben, Austria*
*[3] Erich Schmid Institute of Materials Science, Austrian Academy of Sciences, 8700 Leoben, Austria*
*[4] voestalpine BÖHLER Edelstahl GmbH & Co KG, 8605, Kapfenberg, Austria*

*High-speed steel* *Carbide fracture* *Machine learning*

**Abstract** The improvement of the fatigue properties of high-speed steels (HSS) is important to enhance the performance of metalworking tools made of these composite materials. Due to restrictions in data evaluation techniques for large numbers of features on fracture surfaces, such as carbide phases, the influence of the fracture path within an HSS' microstructure on its fatigue crack growth resistance so far remained largely unexplored. A longstanding question in this regard is to what extent changes in the size of, and spacing between, primary carbides influence the fatigue crack path within the HSS' metallic matrix and ceramic carbides. The current work taps the potential of machine learning-based fracture surface evaluation to answer such questions on a statistically sound basis, as it facilitates the evaluation of much larger fracture surface areas than feasible with human interpretation alone. The investigated specimens were of single edge notched bending geometry made of two high-speed steel materials of equal chemical composition but distinctively different primary carbide size and spacing adjusted by heat treatment design. The specimens were tested in an eight-point bending test setup under cyclic stress ratios of $R = \sigma_{min} / \sigma_{max}$ = 0.1, -1, and -5. Human interpretation of scanning electron microscopy (SEM) images of fracture surface features served to establish a statistically meaningful dataset necessary to train and validate a YOLOv8-based object detection model capable of automated, large-scale evaluation of the fracture surface. This was done for SEM images attained at locations close to the threshold of stress intensity for long crack propagation and the fracture toughness $K_{IC}$. Particular emphasis was placed on the quantitative evaluation of the frequencies of fracture surface features such as circumvented and cleaved carbides with a distinction between carbides fractured parallel and oblique to the crack propagation plane as a function of mean stress and material microstructure. The results indicate that fatigue cracks circumvent a higher fraction of carbides in the material with lower carbide size and lower carbide spacing. Also, a higher area fraction of the fatigue crack propagates within the matrix under increasing compressive cyclic mean stress. The presented results demonstrate that machine learning-based fractography evaluation facilitates the statistically sound quantification of the fatigue crack growth path's area fractions in individual phases of two-phase microstructures, which are practically inaccessible without its application.

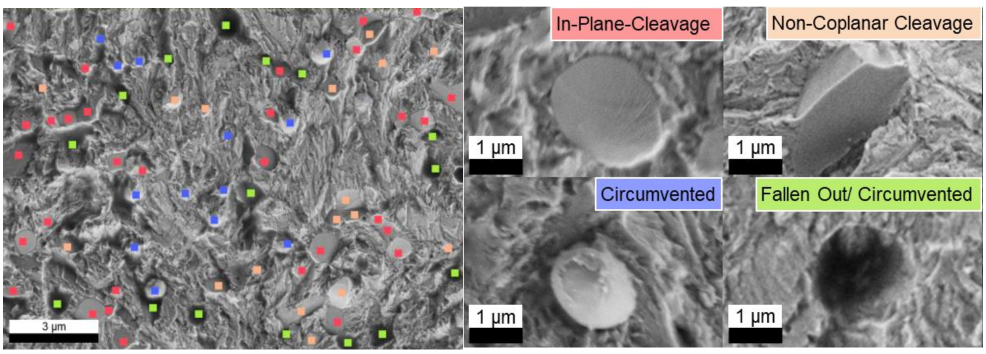



***Figure 1*** *– Machine learning-based evaluation of fatigue fracture surface features on SEM micrographs.*

# An Experimental Investigation on Small Fatigue Crack Growth Behavior and Mechanism in Al 2024-T3

**Mi Wang[1], Lindong Chai[1], Yihai He[1], Jing Lin[1], Wei Zhang[1,*]**

[1]*School of Reliability and Systems Engineering, Beihang University, Beijing 100191, China*

*Small crack growth* *Small crack mechanism* *Transition crack length* *Crack tip opening displacement*

**Abstract** The fatigue small crack growth behavior and mechanisms of 2024-T3 aluminum alloy under different stress ratios are systematically investigated in this study. Fatigue tests on physically small cracks (PSCs) are conducted under various stress levels and stress ratios, and high-resolution digital image correlation (DIC) is employed to characterize the evolution of crack closure during crack propagation. The growth behaviors of small and long cracks (LCs) under identical stress ratios are compared, enabling the determination of the transition crack length from PSCs to LCs. The experimental results demonstrate that the small crack effect is significant under all investigated conditions. At the same nominal stress intensity factor range, PSCs exhibit considerably higher growth rates than LCs. For a given stress ratio, the transition crack length decreases with increasing stress level. As crack growth proceeds, the crack closure level of PSCs gradually increases and approaches that of LCs. And the observed crack closure behavior alone cannot fully account for the pronounced small crack effect. Furthermore, a unified crack growth model driven by crack tip opening displacement (CTOD) is proposed for both PSCs and LCs, incorporating the effects of crack closure modification and microstructural dissimilitude. In addition, a transition criterion from PSCs to LCs is also established.

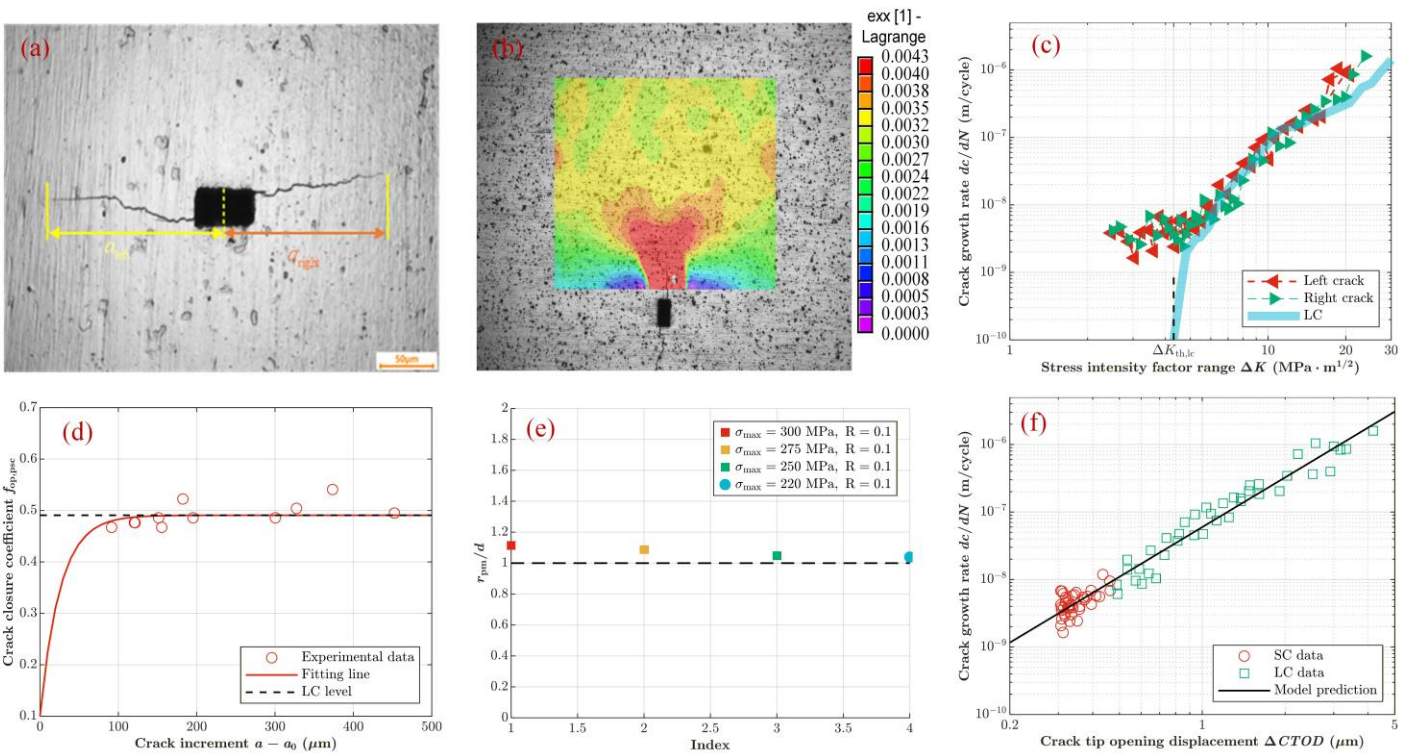



Figure 1 (a): Illustration of crack length measurement; (b): Small crack tip strain contour;(c): *da/dN* versus $\Delta K$; (d): Crack closure evolution; (e): Relationship between crack tip monotonic crack tip plasticity size and grain size for different stress levels; (f) *da/dN* versus $\Delta CTOD$

# Residual stress engineering for fatigue crack retardation by laser shock peening in additively manufactured aluminum

**Dominik Pöltl[1,*], Moritz Bolsinger[2], Volker Ventzke[2], Falk Dorn[2], Nikolai Kashaev[2], Benjamin Klusemann[1,2]**

*[1] Leuphana University of Lüneburg, Institute for Production Technology and Systems*
*[2] Helmholtz-Zentrum Hereon, Institute of Material and Process Design*

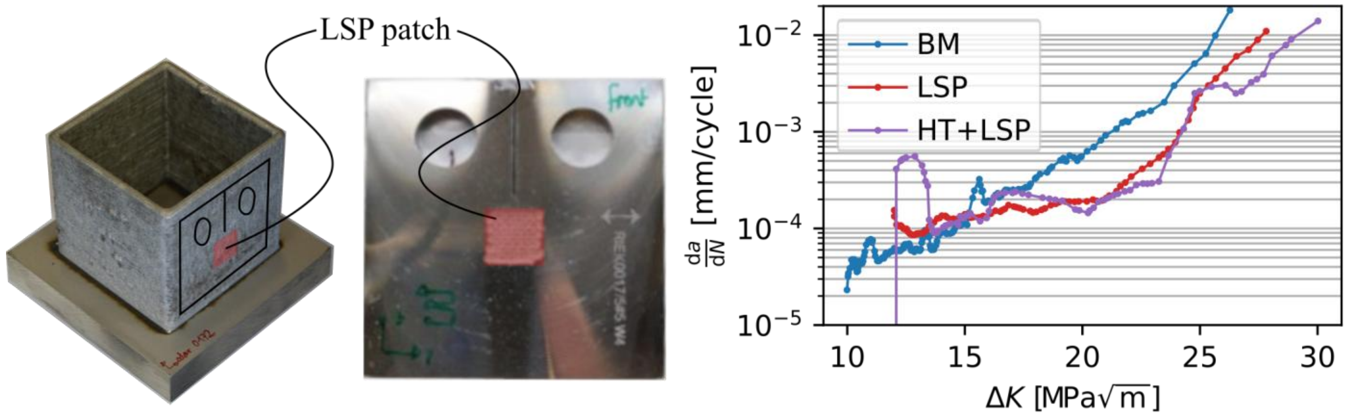
*[*]E-mail: dominik.poeltl@leuphana.de*

*Laser-based directed energy deposition with wire* *Residual stress* *Laser shock peening*

**Abstract** Laser-based directed energy deposition with wire (DED-LB-w) enables the additive manufacturing of near-net-shape structures. However, compared to conventional subtractive manufacturing processes, such structures exhibit inferior properties owing to residual stress field (RSF). Laser shock peening beneficially changes the RSF by inducing near-surface compressive stresses. This gives leverage on drivers of fatigue crack propagation (FCP) such as hot cracks and pores after manufacturing. Deepening the understanding of RSF generation, post-weld RSF manipulation and FCP supports establishing additively manufactured parts in critical components in the aerospace industry.

In this study, hollow cubes of the aluminum allow AA-5087, shown in Figure 1 (a), are additively manufactured by DED-LB-w. C(T) 50 specimen are extracted by conventional milling. The design of experiment categorizes the C(T) specimen based on as-received defects along the future crack path. For each category, three subsets of specimens – base material, LSP treated specimens (see Figure 1 (b)) and annealed-then-LSP-treated specimens – are compared w.r.t. their FCP behavior, see Figure 1 (c). The results underline that residual stress engineering by LSP is a mean to counter anisotropy, macroscopic defects and other negative influences of fatigue performance. The mechanisms are supported by findings via the numerical counterpart to these experiments.

Finally, the influence of RSF compared to the influence of AM-determined microstructure is investigated through fatigue tests that mimick the RSF after LSP by load force variation, determined from the numerical model, on the base material.




(a) (b) (c)

***Figure 1****- a) hollow cube with position of C(T) geometry outlined, b) C(T)50 specimen with laser peened patch, c)da/dN over stress intensity factor for categories of specimen*

# Use of multi-material additive manufacturing to produce complex dual steel parts with superior fatigue properties

**Lucy Farquhar[1], Jürgen Bär[1], Eric A. Jägle[1]**

*[1]Institute of Materials Science, Universität der Bundeswehr München, D-85579 Neubiberg, Germany*
*E-Mail: lucy.farquhar@unibw.de*

*Multi-Material Additive Manufacturing* *Steel Microstructures* *Fractography*

**Abstract** Multi-material additive manufacturing is a technique gaining popularity to produce parts, optimised through the use of multiple materials, to create very specific properties. It offers dimensional freedom to create complex geometries, between the different alloys, that were previously impossible to manufacture by any other method. This can lead to properties which are not achievable in conventional single alloy parts, through manipulation of alloy placement. In this case, manufacture of parts such as this is achieved using a selective powder deposition device, produced by Aerosint. The powders are adhered to drums through a negative pressure and then selectively deposited using an ejection of Argon gas. The resulting geometries manufactured are therefore limited by the resolution of the recoater, the alignment between the powders, and alignment of the powders with the laser.

In this work, 316L and 17-4PH stainless steels are used to create multi-material parts with differing internal geometries between the alloys. The aim is to enhance strength, ductility, and toughness, through production of metal 'composite' structures, containing material layers or fibres. The geometries are designed, such that material features are as fine as possible, within the available resolution of the recoater. This also allows for maximising the number of repeated patterns within the samples, which are small enough to be manufactured within a continuous build job. The resulting microstructure for each geometry is then analysed after subsequent heat treatment, to assess the accuracy of the interfaces produced, as well as to see the impact of the geometries on grain growth and phase formation. It is found that tailoring of the amount of austenite and martensite within the samples is possible, via varying the placement of the different materials, as well as hindering the columnar grain growth seen in single material samples.

The samples are then subjected to both tensile testing and fatigue testing and compared to their single-material counterparts. The influence of varying material geometry on tensile strength and fatigue behaviour is then discussed, along with the corresponding fractography. The yield strength of the multi material samples lies between that of the single materials, but with differing hardening behaviour. The fatigue strength of the resulting multi-material samples is shown to be higher than both the 316L and 17-4PH single material samples alone. Therefore, demonstrating that the creation of macro-scale metal composites through multi-material additive manufacturing can result in improved fatigue properties when compared with single material additively manufactured samples.

# Ultra-High Cyclic Fatigue of Nanobainitic Steels

**Bali Nagya Regmi[1], Eberhard Kerscher[1]**

[1]*Materials Testing (AWP), RPTU University Kaiserslautern-Landau, Gottlieb-Daimler-Str. 49, 67663 Kaiserslautern, Germany, b.regmi@rptu.de, e.kerscher@rptu.de*

*Very High Cycle Fatigue (VHCF)* *Nanobainitic steel* *Fine Granular Area (FGA)*

**Abstract** VHCF behaviour of conventional high-strength martensitic/bainitic steels, containing coarse carbides and minor retained austenite content beside martensitic/bainitic needles, has already been studied in several investigations. In these conventional steels, under VHCF loading, crack initiation has been specifically attributed to the presence of subsurface inclusions. Around these inclusions, a formation of a ring-like fracture surface appears, which is termed a "fisheye." Additionally, a characteristic fine granular area (FGA) within the fisheye can be found adjacent to the subsurface inclusion. It consists of a structure with significantly reduced grain size (smaller than 100 nm) compared to the martensitic/bainitic structure. In the presentation, we will show the microstructure of steels called nanostructured bainitic steels (0.6C1.5Si) that are achieved by making use of simple chemical compositions and an isothermal treatment at relatively low temperatures. The resulting microstructure, essentially free of carbides, consists of bainitic ferrite plates with a typical thickness of about 20 nm and heterogeneous carbon-enriched retained austenite features. We followed the hypothesis that this fine structure might be stable during VHCF loadings. Therefore, we investigated the fatigue behaviour of different nanobainitic microstructures, produced by isothermal bainitic transformation at slightly different temperatures, up to 10^9 load cycles. Results of the VHCF test, microstructural analysis, and fracture surface analysis will show the appearance of FGA in these steel states. Furthermore, resulting stress intensity factors of the crack-initiating inclusions, the FGAs, and the fisheyes will be derived and compared with those of conventional high-strength steels.

# Comparison of Room and High Temperature Fatigue Behavior of the New Ni-based Superalloy VDM 780 Fabricated by Laser Powder Bed Fusion

**Louis Hébrard** [1] *(louis.hebrard@bam.de)*, **Mauro Madia**[1], **Itziar Serrano-Munoz**[1], **Hans Jordan**[1], **Birgit Rehmer**[1], **Juri Munk**[2], **Joachim Gussone**[2], **Jan Haubrich**[2]

[1] *Bundesanstalt für Materialforschung und -prüfung (BAM) 12205 Berlin, Germany*

[2] *Institute of Materials Research, German Aerospace Center (DLR), Linder Höhe, 51147 Cologne, Germany*

*Ni-based superalloy* *Laser Powder Bed Fusion* *Fatigue* *High Temperature*

**Abstract**

The actual environmental challenges require a huge effort from all industrial sectors to reduce their emissions of greenhouse gases and pollutants. Aeronautics is one of the most emissions-intensive industrial sectors. In that context, two main lines of research should be tackled: (i) new and more energy-efficient processes, such as additive manufacturing, could be used for topology optimized part production; and (ii) the engine efficiency of airplanes should be significantly improved to reduce gas emissions. The latter can be achieved by increasing the engine thermal efficiency, *i.e.*, increasing the turbine inlet temperature. However, only single-crystalline cast materials are currently available for use in the parts of the gas turbine engine that are subject to the highest thermal loads. And these materials - which rely on a special casting technology - lose these original material performances when additive manufactured. In addition, current materials suitable for metal additive manufacturing have a limited range of temperature applications.

Therefore, the focus is on the development of new materials targeting higher in-service operation temperatures and durability. Recently, a new Ni-based superalloy (VDM 780) has been developed to ensure microstructural stability up to 750 °C and to be suitable for additive manufacturing like the classic Inconel 718 alloy (extensively used for aerospace applications but with a maximum in-operation temperature limited at 650°C). However, literature currently lacks characterization of the mechanical properties of VDM 780 processed by additive manufacturing.

Hence, the goal of this work is to provide a deeper understanding of the high-temperature fatigue properties of this alloy. For that purpose, a comparison of the mechanical properties, fatigue lives, and fatigue crack initiation mechanisms at room temperature, 300°C, 650°C, and 750°C has been conducted. This approach enabled the determination of the fatigue behavior of VDM 780 at elevated temperature.

Fractographic analyses revealed fatigue crack initiation at manufacturing defects. Therefore, Hot Isostatic Pressing (HIP) was applied to reduce the amount of porosity. As expected, early results pointed out a trend towards increasing fatigue lives.

# High-Energy, High-Repetition-Rate Laser Shock Peening Enabled by Optical Fiber Delivery

**Fahem Boudries [1], Camille Godel[1], Nicolas Boessinger[1], Samuel Bucourt[2], Donato Gallitelli[3]**

[1]*Shocklite, Ile de France, Orsay, France.*

[2]*Imagine-optic, Ile de France, Orsay, France.*

[3]*Europe technologies, 44475 Carquefou cedex, France.*

*Keyword 1 : Laser Shock peening* *Keyword 2 : Fiber-Delivered laser* *Keyword 3 : Residual stress, industrial integration*

**Abstract :**

Laser Shock Peening (LSP) is a well-established surface treatment process known for significantly improving the fatigue strength and damage tolerance of critical components, particularly in aerospace and other high-performance industries. Despite its proven benefits, conventional high-energy LSP systems remain difficult to deploy in industrial environments due to their large footprint, high cost, and limited flexibility.

This work presents a novel fiber-delivered Laser Shock Peening approach developed by Shocklite, aimed at overcoming the integration challenges of traditional LSP systems. By enabling the transmission of high laser energy through optical fibers, the proposed solution allows for compact system architecture, robotic compatibility, and enhanced accessibility to complex geometries, while maintaining the shock pressures required for effective peening.

In 2025, experimental investigations focused on high-energy, high-repetition-rate LSP via optical fiber delivery. First trials were conducted on aluminum alloys to assess process feasibility and mechanical impact. The results demonstrate successful laser-induced shock generation through fiber delivery, leading to the introduction of compressive residual stresses within the treated material. These preliminary findings confirm the strong potential of fiber-based LSP as a flexible and industrially viable alternative to conventional high-energy LSP systems.

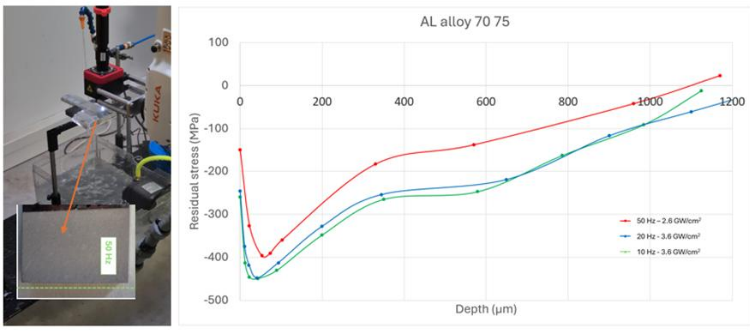



***Figure 1 -*** *Residuel stress measurements on 7075 T6 Aluminium*

# Design-for-Inspection of a Topology-Optimized PBF-LB/M Nose Landing Gear Fork and Component-Level Fatigue Life Validation

**Felix Scholz[1*], Lea Strauß[2], Günther Löwisch[2], Isabel Bayerdörfer[1]**

*[1]University of the Bundeswehr Munich, Institute for Aeronautical Engineering, Werner-Heisenberg-Weg 39, 85577 Neubiberg*

**f.scholz@unibw.de*

*[2]University of the Bundeswehr Munich, Institute for Materials Science, Werner-Heisenberg-Weg 39, 85577 Neubiberg*

*PBF LB/M* *fatigue life prediction* *design for inspection*

**Abstract** Laser powder bed fusion of metals (PBF LB/M) enables topology optimized replacement parts for legacy aircraft, yet fatigue performance remains strongly influenced by process induced features such as surface roughness and residual stress. For safety critical components, practical airworthiness requirements add an additional constraint: fatigue critical regions should be accessible for routine inspection, ideally by visual checks.

This paper presents an inspectability driven design evolution of a topology optimized AlSi10Mg nose landing gear fork for the *Gyroflug Speed Canard* and an ongoing component level fatigue validation campaign on scaled landing gear forks. A total of ten forks are being tested on a servo hydraulic INSTRON system under constant amplitude cyclic loading representative of landing gear service conditions. Prior to testing, surface roughness and residual stress are quantified at predefined candidate hotspot regions to capture part to part variability and to enable process aware fatigue assessment.

A Murakami based, process aware fatigue life model -previously showing good agreement on specimen level- is benchmarked on component level [1,2]. Local stress quantities are derived from static finite element load cases representing the experimental boundary conditions and are subsequently post processed together with the measured roughness and residual stress inputs to obtain predicted life and hotspot maps. Experimental outcomes are evaluated with respect to both cycles to failure and crack initiation location. In addition, the sensitivity of hotspot prediction to finite element modelling choices (e.g., clamping/contact representation and load introduction) is investigated. This analysis is motivated by prior observations where static FE predictions did not match early failure locations in small scale tests, while full scale multi axis testing showed failure at the predicted hotspot.

The contribution of this work is twofold: (1) an inspectability-driven design evolution that relocates fatigue-critical regions to inspection-friendly locations, and (2) a component-level validation study based on constant-amplitude fatigue tests (n=10) that assesses the transferability of specimen-validated, process-aware fatigue models to complex AM components via FE-based stress extraction and post-processing.

[1] Strauß, L., Pang G.A., Löwisch G. Fatigue life prediction of additively manufactured AlSi10Mg based on surface roughness and residual stress. Fatigue Fract Eng Mater Struct (2024). 2024;1 - 13. https://doi.org/10.1111/ffe.14441

[2] Strauß, L., Duarte, L., Kruse, J. et al. An equivalent stress approach for predicting fatigue behavior of additively manufactured AlSi10Mg. Prog Addit Manuf (2025). https://doi.org/10.1007/s40964-025-00974-0

# A universal effect of defect model for various engineering alloys made with additive manufacturing

**E. Amsterdam[1], W.W. Wits[2]**

[1]*Royal NLR, Voorsterweg 31, Marknesse, The Netherlands, emiel.amsterdam@nlr.nl*

[2]*Royal NLR, Voorsterweg 31, Marknesse, The Netherlands, wessel.wits@nlr.nl*

*Additive manufacturing* *Effect of defect* *Fracture mechanics*

**Abstract** Knowing the effect of defects on the fatigue life of additively manufactured (AM) components is crucial for the uptake of AM for safety-critical applications in many industries. The size of typical AM defects is such that long fatigue crack growth rate data with fracture mechanics modelling is not valid and small crack growth data and models are necessary to yield accurate predictions. The current study employs the elastic strain energy release rate as a fracture mechanics parameter to derive an empirical relationship between the initial defect size, the applied stress and the fatigue life. For that purpose round specimens of AlSi10Mg, Ti-6Al-4V and Corrax are printed with laser-powder bed fusion (L-PBF) and machined & polished to obtain the bulk material fatigue lives and exclude influences from surface roughness or porosity between the hatch and the contour lines. Tensile and fatigue specimens are printed with different settings, because the mechanical properties and defect distribution can vary with build parameters, location & orientation and post processing. Fractography was performed on all specimens and fracture mechanics was used to derive a single metric for the size of the nucleating defect. The results show that 1) the fatigue life vs stress (S-N curve) shows a power law relationship up to the ultimate tensile strength (UTS) for load-controlled testing at maximum stresses beyond the yield stress of the material and 2) the slope of the S-N curve is related to the defect size. The derived relationship between the size of surface defects, the applied stress and fatigue life only contains one fit parameter with a clear physical meaning and optimization of the parameter with experimental data gives a proportional relationship between the measured and predicted fatigue lives with a proportionality constant of less than 1.01 for all materials (see Figure 1). The model can be extended to also account for surface roughness and has been validated using corrosion pits in aluminum alloy 7075-T7351 plate material. Hence, the model captures the physics involved in fatigue crack growth from various surface defects in engineering alloys manufactured by different processing routes and can therefore be regarded as a universal model.

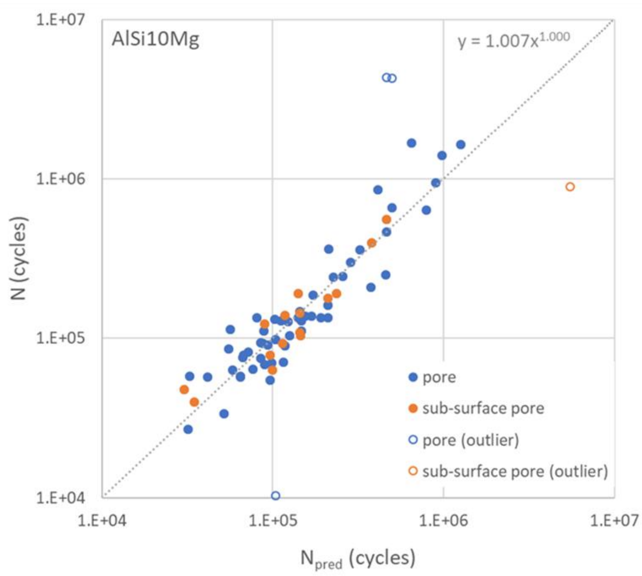



***Figure 1** – Experimental fatigue life as a function of the predicted fatigue life based on the defect size and the applied stress*

# Assessment of a Cast Iron Valve Under Ultra-High Cycle Fatigue

**Edwin Lopez[1] , Frederic Novelo[2], Tom Adam[3]**

*[1]Centre de Recherches Métallurgiques, Technologiepark zone A1b, 48 9052 Zwijnaarde, edwin.lopez@crmgroup.be; [2] Centre de Recherches Métallurgique; [3]VIVACUA*

***Cast Iron*** ***Flake Graphite*** ***Ultra-High Cycle Fatigue***

**Abstract** A flake graphite cast iron valve, in service since the 1970s, failed suddenly under nominal operating conditions. The DN600 butterfly valve was used in a public water supply network and macroscopically presented a fracture in the valve body, near the operating mechanism region, at the thinner section of a case stiffener. More precisely, the crack initiated at the handwheel side and propagated along the radial direction. The initial fracture surface examination showed extensive oxidation but no clear evidence of fatigue. Even after cleaning, neither brittle nor fatigue or brittle marks were observed, suggesting repetitive mechanical degradation of the fracture surface. Metallographic cross-sections revealed secondary cracks and microcracks initiating at flake graphite tips, as well as casting-related voids locally concentrated near the crack initiation region. It is proposed that in addition to radial and axial stresses, the valve was subjected to: (1) static tensile stress due to misalignment, (2) bending induced by flow momentum changes, (3) tensile stresses resulting from partial flow obstruction at the valve disc, and (4) vibration-induced dynamic loading associated with local turbulent flow. The combined action of these loads generated localized static tensile stresses with superimposed cyclic loading. It is concluded that the crack initiated at flake graphite tip particles and propagated under combined static and dynamic loads leading to approximately 70 years of crack growth under an ultra-high-cycle fatigue regime.

# A Fatigue Crack Growth Analysis Accounting for R-ratio Effects

**Daniel Kujawski**

*Mechanical and Aerospace Engineering*

*Western Michigan University*

*Kalamazoo, MI 49008, USA*

*daniel.kujawski@wmich.edu*

*Fatigue crack growth* *Paris & threshold regions* *Accounting for R-ratios*

**Abstract** A new approach for analyzing fatigue crack growth (FCG) behavior that accounts for R-ratio effects in both the Paris regime and the near-threshold region is proposed. Grounded in fundamental principles of fracture mechanics, the approach is supplemented by a comparative analysis of R-ratio and mean stress effects in both FCG and S–N analyses. By considering equivalency of mechanical energies at the same FCG rate during the fatigue loading cycle, an R-dependent scaling factor is derived. Unlike crack-closure models, the present method transforms the applied stress intensity factor range, ΔK, at a given R-ratio into an equivalent crack-driving force, $\Delta K_{0,eq}$, corresponding to R = 0. As an illustration, Fig. 1 shows this transformation for a 7075-aluminum alloy. Validation against experimental data taken from the literature for several engineering alloys demonstrates the capability of the proposed approach. In addition, important challenges particularly related to very high R-ratios and FCG regimes where different crack-growth mechanisms operate are also highlighted.

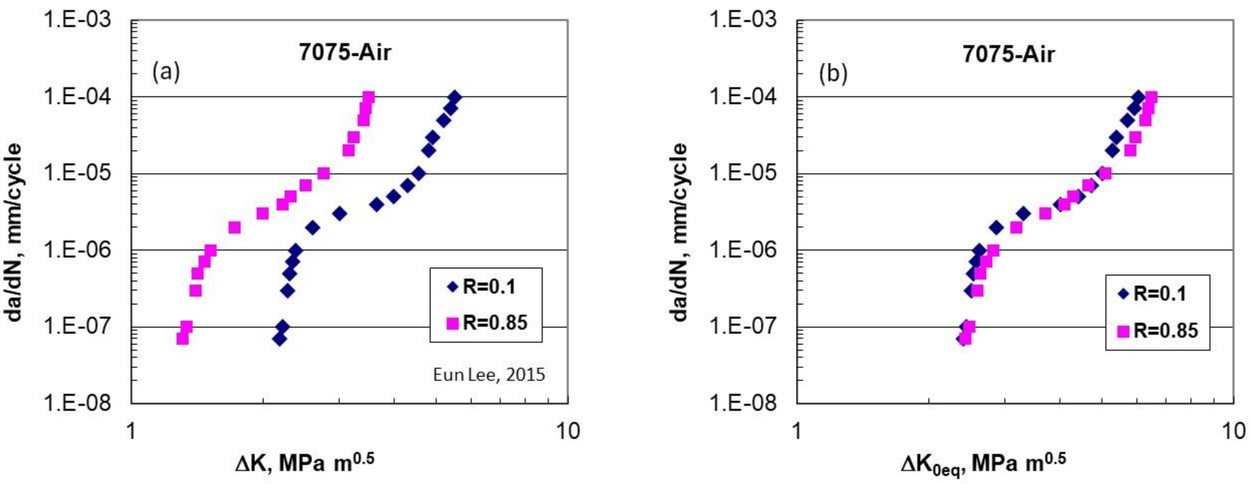



**Figure 1** *FCG data for 7075 Al alloy (a) in terms of ΔK, and (b) correlated with $\Delta K_{0eq}$.*

# Influence of Deposition Sequence on the Fatigue Performance of WAAM SS309L–IN625 Bimetallic Materials

**Ozan Can Ozaner[1], Abhay Sharma[2], Tegoeh Tjahjowidodo[3], Reza Talemi[4]**

[1]*Faculty of Engineering Technology, Department of Materials Engineering, KU Leuven, Campus De Nayer, 2860 Sint-Katelijne Waver, Belgium*

[2]*Department of Mechanical Engineering, Indian Institute of Technology Jammu, Jagti, NH-44, PO Nagrota, Jammu - 181 221 J&K, India*

[3]*Department of Mechanical Engineering, KU Leuven, Jan Pieter de Nayerlaan 5, 2860 Sint Katelijne Waver, Belgium*

[4]*Department of Materials Engineering, KU Leuven, Leuven, 3001, Belgium*

*Fatigue* *WAAM* *Bimetallic Materials*

**Abstract** Multi-material Wire Arc Additive Manufacturing (WAAM) enables advanced structural design, yet the fatigue behaviour of dissimilar metal interfaces remains poorly understood. This study examines the fatigue response of WAAM-fabricated SS309L–Inconel 625 (IN625) bimetallic walls produced using two deposition sequences, alongside single-material reference builds. Thermal histories were recorded by infrared thermography, volumetric defects were evaluated using X-ray computed tomography, and crack-initiation sites were identified by SEM/EDS through Mo and Nb signatures to trace IN625 dilution within SS309L. The results show that fatigue performance is primarily governed by the length of the interfacial elemental transition, which controls crack-initiation location and life scatter. Extended Fe–Ni transition zones promote crack initiation within chemically mixed regions, resulting in reduced fatigue life and pronounced scatter. When the transition is confined to a few layers, crack initiation shifts to near-pure SS309L, leading to higher and more repeatable fatigue behaviour. The SS309L-first deposition sequence exhibits the most stable response, achieving approximately twice the fatigue strength of monolithic SS309L, whereas the IN625-first sequence shows highly variable performance depending on transition length. Overall, the interfacial elemental transition is identified as the dominant factor controlling fatigue behaviour in WAAM SS309L–IN625 structures. Since deposition order directly determines transition length, it should be treated as a key process parameter for fatigue-critical multi-material WAAM components.

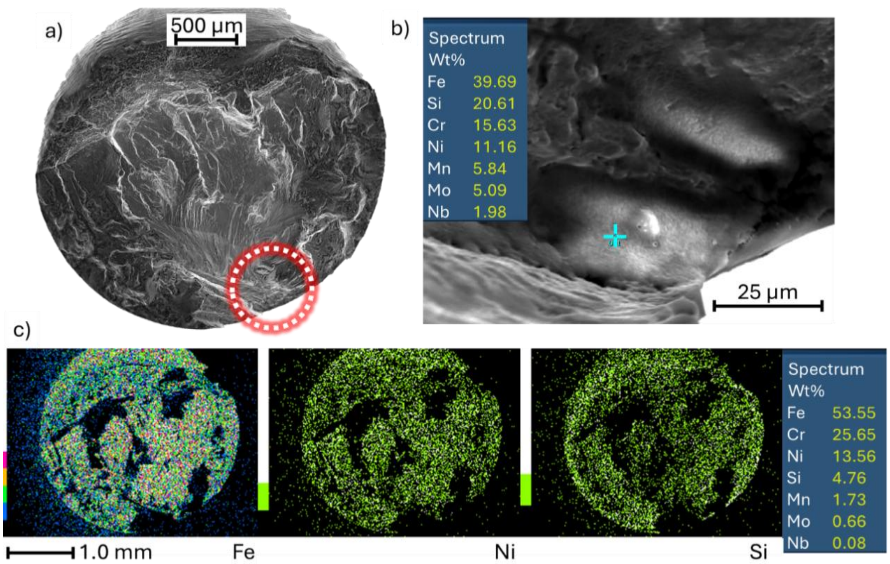



***Figure 1 -*** *IN625–SS309L crack initiation: (a) SEM overview, (b) EDS spot analysis, and (c) elemental maps revealing a Si-enriched inclusion linked to premature cracking.*

# A rapid assessment of the fatigue strength of specimens and components through damage evolution monitoring in stepwise loading tests

**Sergi Parareda[1,2], Milad Bemani[1], Marc Marés, David[1], David Fróemta[1] , Daniel Casellas [1,3]**

*[1] Eurecat, Centre Tecnològic de Catalunya, 08243 Manresa, Spain daniel.casellas@eurecat.org*

*[2]Mechatronics and Modelling Applied on Technology of Materials (MECAMAT) group. Universitat de Vic-Universitat Central de Catalunya (UVic-UCC), 08500 Vic, Spain*

*[3] Luleå University of Technology, Division of Mechanics of Solid Materials, 97187 Luleå, Sweden*

*Fatigue limit* *Fast method* *Damage*

**Abstract** Determining the fatigue behavior of metallic materials using standardized testing methods is costly, time-consuming, and requires many specimens. Consequently, several methods have been proposed to reduce testing time and enhance the optimization of fatigue performance in materials and components. This work introduces a novel fatigue testing approach based on a stepwise loading test. The method, referred to as the stiffness method, monitors inelastic strains as an indicator of fatigue damage evolution. Strain measurements were performed using digital image correlation techniques, which proved to be effective in tracking damage progression during fatigue tests. The evolution of fatigue damage at increasing load levels enables identification of the stress level where damage develops and becomes a propagating defect. This threshold is recognized as the fatigue limit. The method has been applied to a wide range of metallic alloys, including thin sheets of high-strength steels and aluminum alloys, as well as certain alloys produced by additive manufacturing. The approach was also extended to components, monitoring fatigue damage in the most highly stressed areas.

The estimated fatigue limit for specimens was compared with values obtained from standardized tests, demonstrating excellent agreement. For components, the fatigue strength was compared to values calculated using finite element modelling, again showing good concordance. Fractographic inspection confirmed that the fatigue mechanism is not altered by the stepwise loading, and fatigue origins are consistent with those observed in conventional methods. Furthermore, the results regarding the evolution of damage were more straightforward to obtain and interpret than those from other monitoring techniques, such as infrared cameras or acoustic emission sensors. Therefore, this work presents the stiffness method as an efficient and effective approach for rapidly determining the fatigue behaviour of metallic materials, in less than three hours per material or component.

# A unified non local approach to interpret defect's size and shape effects on fatigue crack initiation

**Pierre Merot[1], Franck Morel[1], Camille Burton[1], Etienne Pessard[1], Linamaria Gallegos Mayorga[1]**

*[1]LAMPA, Arts et Métiers, Angers, France*

*Corresponding author: 2 boulevard du Ronceray 49100 Angers France, pierre.merot@ensam.eu*

*Non-local approach Multiaxial fatigue criteria Defects*

**Abstract** Process-inherent defects in metallic alloys are often considered to be at the origin of cracks for parts subjected to High Cycle Fatigue (HCF) loading. Particularly, the literature reports the higher criticality of surface defects compared to internal ones. The detrimental effect of defect's size is also well documented. On the other hand, the effect of the defect shape is more controversial and seems dependent on the material. For fatigue strength prediction, the simplest approaches are based on linear elastic fracture mechanics. These empirical analytical models lead to a relation between the fatigue strength and the defect size and location. These formulations do not take into account the defect shape, since the defect is assimilated to a crack. Another way of dealing with this problem is using Finite Element Analysis (FEA), which, coupled with a fatigue criterion, could be used to infer the fatigue strength and the location of the hot spot within the geometry. Such approaches are only dependent on the defect shape via the stress concentration estimation and do not take into account its size, which leads to poor results most of the time.

In this work, a numerical case study is implemented, varying both defect size and shape in a FEA framework. The defect is approximated to a semi-ellipsoid, whose shape is controlled through different radii ratios, and whose size is set through Murakami's √area parameter, achieving 120 different defects. Pure elastic and elastoplastic material behaviours are also discussed. FEA are then post-treated using a Dang Van multiaxial fatigue criteria. Finally, a non-local approach is used, applying a mean of the fatigue criteria over a sphere of radius R* for each element of the FEA, with 21 different R*. A relative defect size √area/R* is then introduced, leading to a numerical normalized Kitagawa-Takahashi diagram. Comparing the effect of defect's shape within this representation highlights the competition between the effect defect size increasing the highly stressed volume and the defect shape affecting the stress concentration (i.e. the stress gradient near the defect). 316L L-PBF experimental data are in good agreement with numerical results.

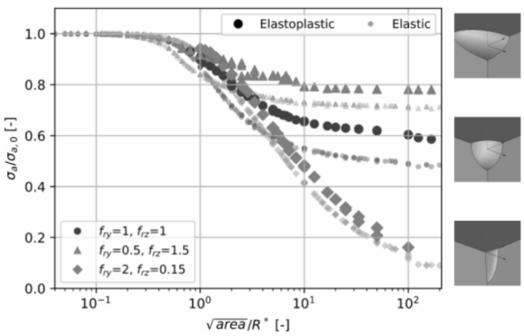



***Figure 1*** *– Normalized Kitagawa-Takahashi for different defects' shape and relative size.*

# Defect generation based on X-ray micro-computed tomography and generative neural networks

**Marcos Vitouley[1,2], Camille Burton[2], Laurent Dolle[1], Linamaria Gallegos Mayorga[2], Pierre Merot[2] and Franck Morel[2]**

*[1] CEA Pays de la Loire, Bouguenais, France*

*[2] LAMPA, Arts et Métiers, Angers, France*

*Corresponding author: 2 boulevard du Ronceray 49100 Angers France, pierre.merot@ensam.eu*

*Generative neural network* *X-ray tomography* *Defect generation*

**Abstract** High cycle fatigue behavior of metallic alloys containing defects is strongly related to the defect population within the material. More specifically, fatigue crack initiation is usually located in the vicinity of the most critical defect. This so-called *killer defect* is therefore a first-order parameter for fatigue strength prediction, either through Linear Elastic Fracture Mechanics approaches or by applying fatigue criteria based on Finite Element Analysis. The defect population can be identified using non-destructive control techniques, among which X-ray micro-computed tomography (μCT) is one of the most relevant, as it enables capturing volumetric defects with high geometrical resolution. Since the defect population depends on both the manufacturing process and the geometry of the mechanical part, the conventional fatigue design workflow consists in producing a prototype, characterizing the defect population using μCT, and assessing the fatigue strength with respect to the targeted application. If the fatigue strength is unacceptable, a new development iteration must be performed.

To accelerate fatigue design and reduce associated costs, a method aiming at generating realistic μCT images from process (temperature, material, etc.) and geometrical (CAD model) inputs is proposed. μCT images are generated using diffusion models. Different image structures (2D, 2.5D, 3D) and types (binary, grayscale, RGB) are used for model training. Both conditional and unconditional models are implemented, the former accounting for image context (process, geometrical or material parameters). Model performances are compared, highlighting the most effective strategy to generate realistic defect populations for fatigue strength prediction.

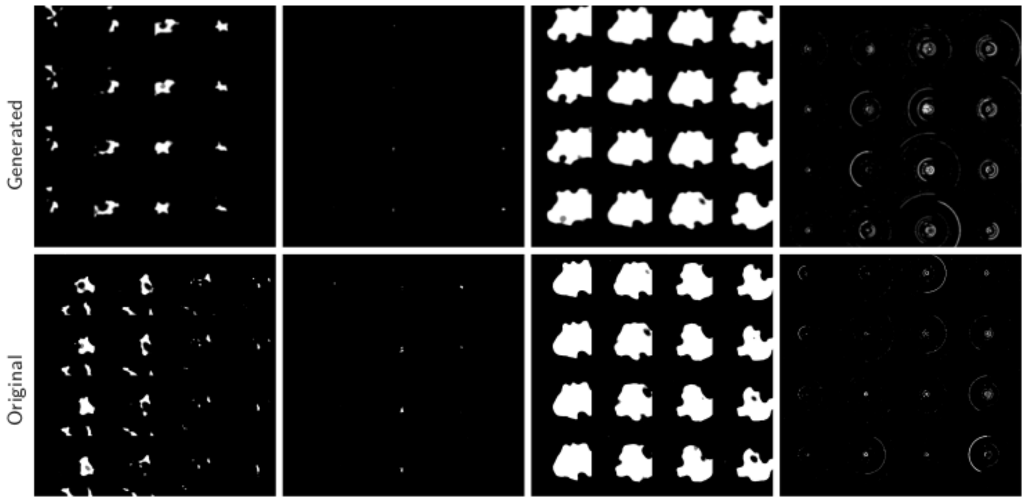



***Figure 1** – Original vs generated images through 2.5D binary unconditional diffusion model for a casted aluminum alloy (RGB is here converted to grayscale)*

# Fatigue behaviour of 17-4PH martensitic stainless steel additively manufactured by Metal Binder Jetting

**Pierre Merot[1], Benoit Roman[2], Hugo Roirand[3], Denis Vincent[4], Vincent Bonnefoy[4], Thomas Landron[3], Franck Morel[1]**

*[1]LAMPA, Arts et Métiers, Angers, France, [2]CEA Pays de la Loire, Bouguenais, France, [3]CETIM, Senlis, France, [4]CEA-LITEN, Univ.Grenoble Alpes, Grenoble, France. Corresponding author: 2 boulevard du Ronceray 49100 Angers France, pierre.merot@ensam.eu*

*17-4PH stainless steel* *Fatigue Behaviour* *Metal Binder Jetting (MBJ)*

**Abstract** Metal Binder Jetting (MBJ) is an emerging additive manufacturing process with: higher production rate, comparable geometrical resolution and lower energy cost compared to the well known Laser Powder Bed Fusion (L-PBF) technique. MBJ is an indirect method, passing through printing, binder-curing, depowdering, debinding and finally sintering to obtain the final product. The obtained material has typical sintered-material microstructural properties, making MBJ prone to ramp-up to Metal Injection Moulding (MIM), adapted for large serie production. However, such multi-step route leads to final parts with significant dimensional deviations, related to the high porosity within the as-sintered material (≈5%). This high porosity can also be detrimental in terms of durability, particularly for applications involving fatigue loading.

In this study, the focus is made on the 17-4PH stainless steel manufactured by MBJ. To address the question of maturity of this process, three batches of material are produced using three different raw-material manufacturing technologies, including: MBJ machine and sintering facilities. Powder and binder are the one provided by the machine supplier. Then, Hot Isostatic Pressing (HIP), H1025 heat-treatment and machining are performed to obtain final fatigue specimens. High cycle fatigue behaviour is investigated. Crack initiation mechanisms are observed and compared regarding the fatigue strength evaluated for each specimens. The three batches exhibit different fatigue strength, associated to different initiation mechanisms (matrix, oxides and mixed matrix-oxides). No cracks initiated on gas pores, despite the high porosity of the material.

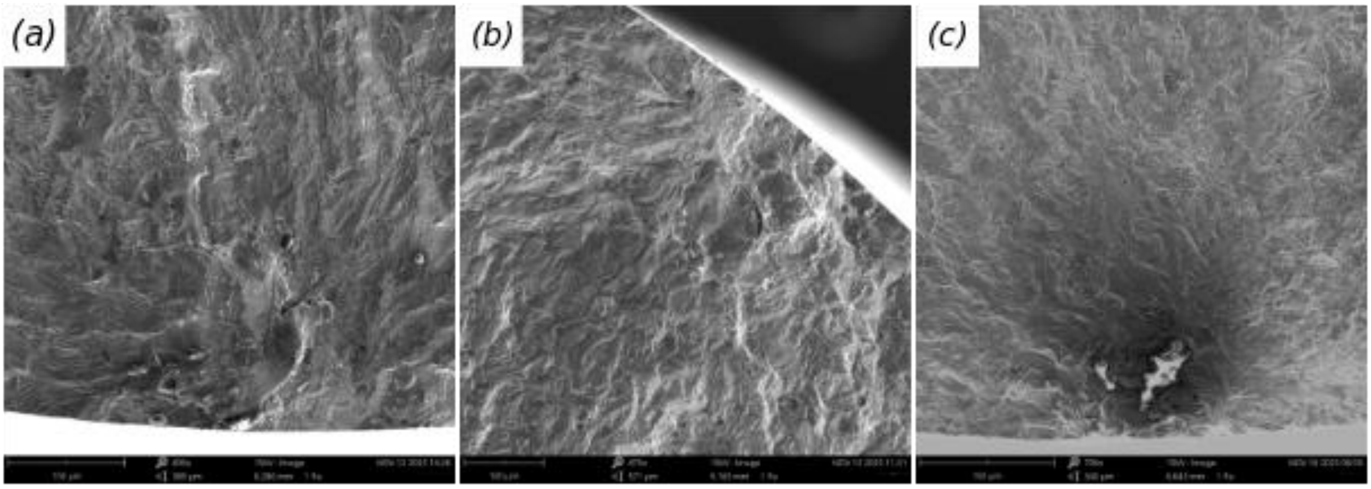



***Figure 1** – Crack initiation on (a) mixed matrix-oxide, (b) matrix and (c) oxide*

# Intergranular Cracking during Dwell-Time Fatigue of Nickel-Based Superalloys at Elevated Temperatures – The Dynamic Embrittlement Mechanism

**Ulrich Krupp[1], Lars Bähren[1], Charleen Baumann[2], Thomas Seifert[2], Hans-Jürgen Christ[3], Ken Wackermann[4], Aljoscha F. Baumann[4], Daniel Urban[4]**

[1]*IEHK Steel Institute, RWTH Aachen University, Aachen, 52072, Germany.*

[2]*Inst. for Digital Engng and Prod. (IDEeP),University of Applied Sciences Offenburg, Offenburg, 77652, Germany.*

[3]*Inst. Materials Engineering and Testing, University of Siegen, Siegen, 57076, Germany.*

[4]*Fraunhofer Institute for Mechanics of Materials IWM, Freiburg, 79108, Germany.*

*Intergranular Cracking* *Dwell-Time Fatigue* *Dynamic Embrittlement*

**Abstract** Polycrystalline nickel-based superalloys are designed for applications that require superior fatigue strength at elevated temperatures, e.g., gas-turbine discs. In analogy to "stress corrosion cracking", these alloys may fail by intergranular crack propagation that is driven by stress-assisted grain-boundary diffusion of oxygen; a mechanism that has been termed "dynamic embrittlement". Load relaxation, low cycle fatigue (LCF) and instrumented crack-propagation experiments were carried out on Alloy 718 and AD730 in vacuum and ambient air atmosphere at 650°C. It was shown that the combination of sustained tensile stress, load reversal and oxidizing atmosphere leads to a substantial increase in the crack-propagation rate. By combining the mechanical testing with extensive electron microscopy and an ab-initio-informed finite-element simulation scheme, the embrittling effect was attributed to stress-induced oxygen diffusion ahead of the intergranular crack tip lowering the cohesive forces, eventually leading to separation in a nanometer scale. The simulation has been supplemented by bicrystalline bending experiments on small microbeams (prepared by focused ion beam milling in the SEM) and SENB samples that revealed the relationship between grain-boundary character/misorientation and the resistance to intergranular cracking. The findings are discussed in terms to design grain size and misorientation distribution (grain-boundary-engineering-type processing).

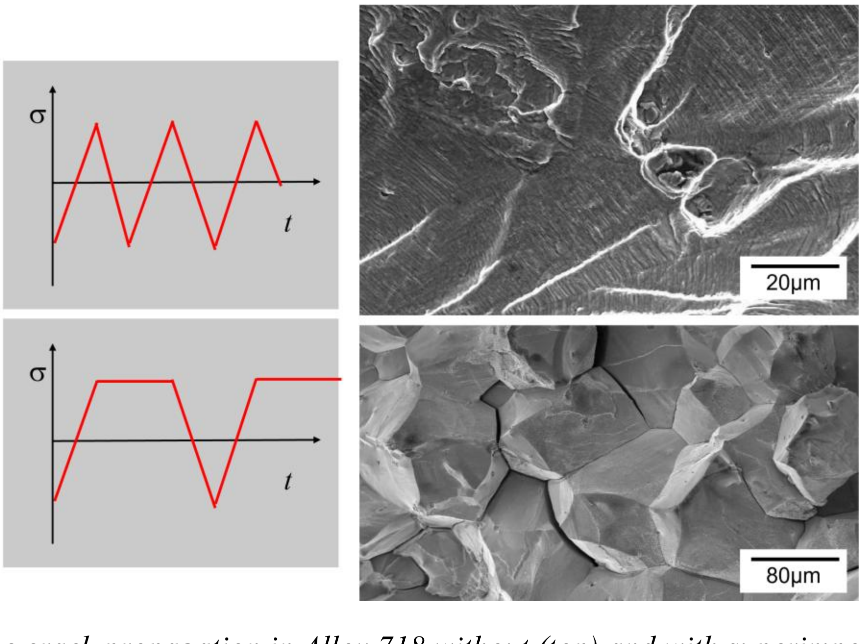



***Figure 1*** *– Fatigue crack propagation in Alloy 718 without (top) and with superimposed dwell-time at maximum tensile load (bottom). The fracture surfaces show exemplary the transition from transgranular cycle-dependent to time and cycle-dependent intergranular crack propagation governed by the dynamic embrittlement mechanism (bottom).*

# A High-Fidelity 3D Modeling and Life Prediction Framework for Fretting Fatigue–Wear Interaction

**Samira Ghadar[1], Jim Lua[2], Ali Fatemi[3]**

[1,3]*Department of Mechanical Engineering, University of Memphis, Memphis, TN, USA, afatemi@memphis.edu, sghadar@memphis.edu*

[2]*Global Engineering & Materials, Inc., Princeton, NJ 08540, USA*

*Fretting Fatigue–Wear Interaction* *Life Prediction* *Critical Plane Approach*

**Abstract** Fretting fatigue and fretting wear rarely operate in isolation in engineering contacts; instead, they evolve concurrently and interact through wear-driven changes in conformity that redistribute contact tractions and near-surface stress/strain fields, thereby shifting crack-initiation "hot spots" and altering durability. While many fretting-fatigue life assessments evaluate fatigue indicators on an initial (unworn) geometry, such an approach can miss the history-dependent evolution of slip regime and stress gradients that emerges as wear develops.

This work presents a mechanics-based, initiation-focused framework to predict fretting durability under coupled wear–fatigue conditions, targeting nonlinear and cycle-dependent contact response. The approach integrates: (i) a three-dimensional finite element (3D FE) model for fretting contact to predict local pressures, shear tractions, and multiaxial subsurface stress/strain histories under representative loading; (ii) wear-damage quantification consistent with evolving contact conditions; and (iii) a multiaxial, critical-plane-based fatigue assessment with an accumulation scheme suitable for fretting, allowing fatigue indicators to be evaluated on evolving stress–strain fields as the contact response changes with cycles. The framework is designed to support both single-cycle response prediction and multi-cycle-dependent response evolution, and to clarify the advantages of a 3D treatment relative to common 2D idealizations for capturing spatial variations and redistribution mechanisms relevant to fretting-fatigue crack initiation.

The contribution of the presentation is twofold: (1) a unified 3D modeling workflow that explicitly targets the coupled wear–fatigue problem (rather than evaluating fatigue on a fixed, unworn geometry), and (2) a practical pathway to initiation-life prediction that remains consistent with the strong stress/strain gradients and slip-regime transitions observed in fretting contacts. The framework is being demonstrated on a representative experimental dataset, and the role of key sensitivities—particularly friction evolution, wear-law calibration, and stress-gradient effects, is assessed to identify dominant sources of discrepancy and priorities for model refinement.

# Weld Metal Axial and Torsion Deformation and Fatigue Properties and Predictions for Durability Analysis of Weldments

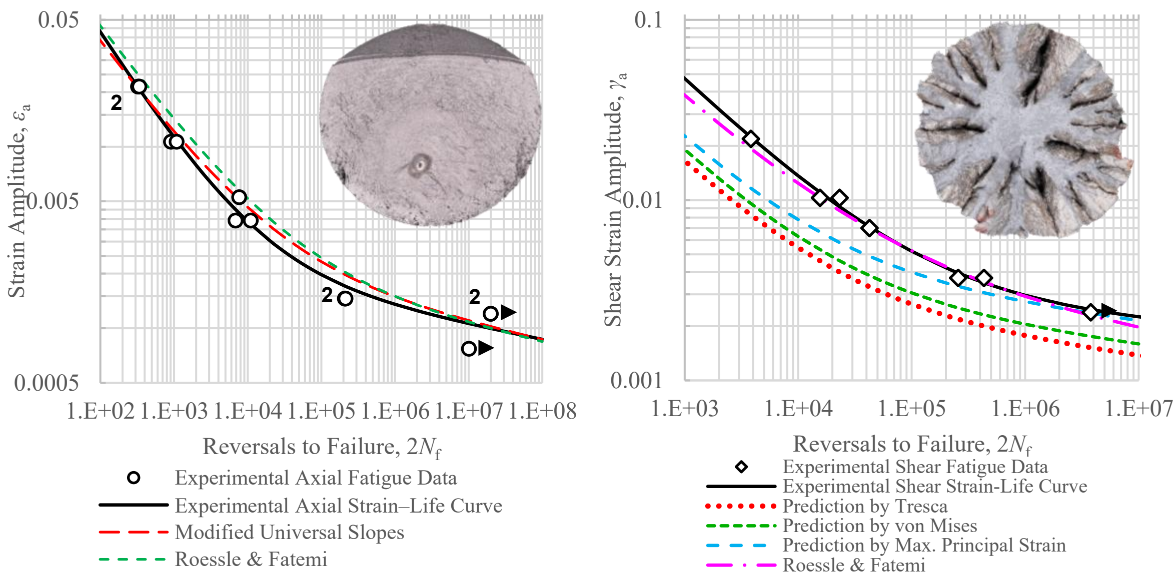
**Tarek M. Diab, Ahmad Razi[1], Ali Fatemi[2]**

[1] *Research Assistant, University of Memphis (USA), arazi@memphis.edu*

[2] *Ring Companies Endowed Professor, University of Memphis (USA), afatemi@memphis.edu*

*Weld Metal Properties* *Cyclic Deformation* *Fatigue Property Prediction*

**Abstract** Characterizing and predicting the mechanical properties of steel weld metals are essential in designing load-bearing welded components. This work investigates methods for obtaining monotonic and cyclic behaviors of steel weld ER70S-3 in the annealed condition as an illustrative example under axial and torsional loading conditions. Monotonic, incremental-step cyclic deformation and fatigue tests were carried out to obtain the tensile, shear, and cyclic stress–strain properties of the weld metal, as well as axial and shear fatigue behaviors in low- and high-cycle fatigue regimes. Predictive methods to approximate cyclic deformation and fatigue properties for weldment design are also presented when such properties are not available. The fracture surface analysis of the tested specimens indicated surface and internal crack initiation sites under axial cyclic loading from the weld defects, and surface crack initiation with factory-roof fracture surface appearance under torsion.




(a) (b)

***Figure 1** – Fatigue behavior and predictions of fatigue properties of steel weld metal ER70S-3 under: a) axial loading and, b) torsion.*

# Numerical study on the defects and surface condition competition affecting the fatigue strength of L-PBF 316L steel, assessed by means of synchrotron X-ray tomography

**Marion Auffray[1], Camille Burton[1], Franck Morel[1], Linamaria Gallegos Mayorga[1]**

[1]*Arts et Métiers institute of technology - LAMPA, France, FR*

*L-PBF 316L* *Surface topography* *Subsurface defects*

**Abstract** Laser Powder Bed Fusion (L-PBF) has recently gained strong academic and industrial interest as it can produce components with complex geometries close to end-used shape (*i.e.* net-shape). However, L-PBF inherently induces a rough surface, defects, and tensile residual stresses, that degrade fatigue performance. While optimized parameters and heat treatment can respectively limit major defects and relieve stresses, the rough surface and pores below it (<200 µm) both remain critical for the High Cycle Fatigue (HCF) of net-shape parts. This work aims to decouple their contributions on the HCF behaviour and better understand how they interact in the case of a net-shape L-PBF 316L material; this by means of an extensive numerical campaign based on experimental data. For this purpose, 37 uniaxial fatigue tests were carried out on net-shape specimens along with a systematic killer defect examination. For defect size below 200 µm, 29/35 initiations involved a surface irregularity (*e.g.* spatter, valley) and/or a subsurface pore being spherical or ellipsoidal, of various sizes, distances from surface (*i.e.* ligaments), and orientations. From then, a high-resolution computed tomography scan was conducted in the whole gauge section of an untested specimen with a voxel size of 1.7 microns. The variety of geometrical features of experimental killer defects were considered to (i) identify the ranges over which they vary, and (ii) select representative portions of the surface topography and subsurface pores from the scan. Afterall, five surface topographies (rough - flat spatter, round spatter, two spatters, valley, or smooth), three subsurface defect conditions (no pore, one gas pore, or one keyhole pore), three pore sizes, five ligaments, twenty-five translations, and nine rotations were combined to run 26,254 finite element-based numerical simulations. The Dang Van fatigue criterion (DV) was then calculated by means of a non-local method and the maximum DV was determined with various regularization radii R*. Numerical simulations showed that, globally, the maximum DV are found for (i) the biggest defects, (ii) the smallest ligaments, (iii) rough surfaces, and (iv) the ellipsoidal morphology, see Fig. 1. Surprisingly, the presence of a pore under a rough surface can decrease the overall criticality compared to that of the rough surface alone. Moreover, the bigger the defect size and the smallest the ligament, the higher the influence of the defect orientation. Translating the defects below the four surface conditions revealed that the surface topography above a pore greatly impacts the fatigue strength.

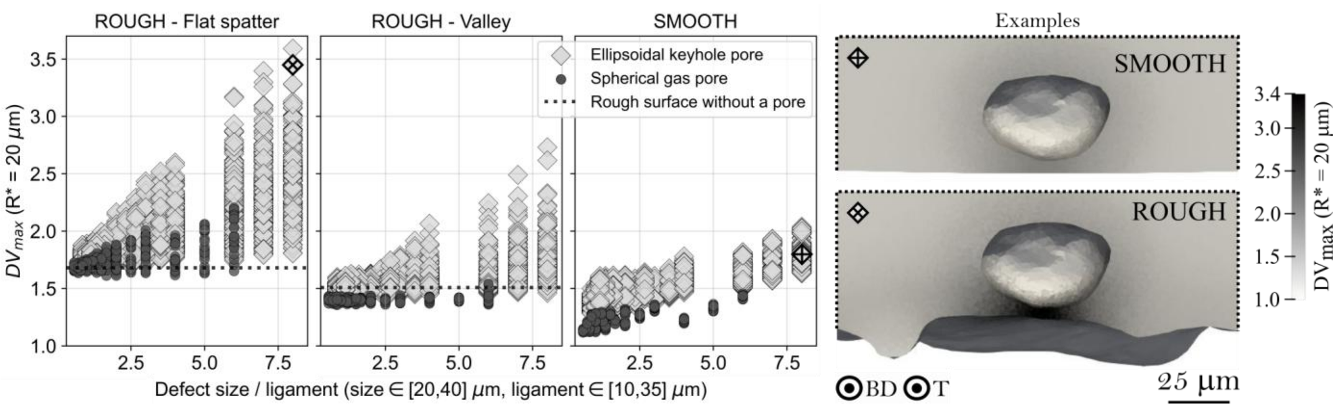



***Figure 1 -*** *Maximum Dang Van fatigue criterion with a 20-µm regularization radius, $DV_{max}$ (R*=20 µm), as a function of the defect size / ligament ratio for the various numerical simulations.*

# Thermal stability of peening induced residual stress and microstructure evolution in Inconel 718 for fatigue life improvement

**Thaviti Naidu Palleda[1,2,*], Phani Mylavarapu[3], P.Prem Kiran[2], T. Jayakumar[4], Jai Prakash Gautam[1]**

[1]*School of Engineering Sciences and Technology, University of Hyderabad, Prof. C. R. Rao Road, Gachibowli, Hyderabad 500046, India. E-mail: shiva.rgukt546@gmail.com*

[2]*School of Physics, University of Hyderabad, Hyderabad, 500046, India*

[3]*Defence Metallurgical Research Laboratory, DRDO, Hyderabad, India*

[4]*Former S.Bhagavantam Chair, Defence Metallurgical Research Laboratory, Kanchanbagh, Hyderabad, India*

**Keywords**: IN 718, Laser shock peening, Shot peening, Residual stress, Hardness, EBSD

**Abstract:** Advanced residual stress engineering processes such as Laser Shock Peening (LSP) and Shot Peening (SP) are widely used to improve the fatigue performance of nickel-based superalloys by introducing compressive residual stresses and beneficial near-surface microstructural modifications. For aero-engine components operating at elevated temperatures, the long-term stability of these induced residual stress and microstructure is critical for fatigue life improvement. In this study, LSP and SP are comparatively evaluated in solution-treated and aged (STA) Inconel 718 to assess the thermal stability and fatigue relevance of peening-induced modifications using surface roughness, microhardnes, and multi-scale microstructural characterization by SEM, EBSD, and TEM.

Surface roughness analysis shows that LSP induces negligible modification of surface topography (Sa~0.42µm), whereas SP produces a significant increase in roughness (Sa ~ 2.4-3.4 µm) with increasing intensity, a factor known to promote fatigue crack initiation. Hardness profiling reveals that LSP establishes a deep hardened layer extending to ~500 µm with moderate surface hardening (~518 $HV_{0.2}$), while SP achieves much higher peak surface hardness (~619 $HV_{0.2}$) but confines the hardened layer to shallow depths (<250 µm). Microstructural characterization further demonstrates that LSP generates a deep and relatively uniform dislocation substructure with multiple slip bands, whereas SP produces a highly deformed near-surface layer characterized by elongated grains/δ phases, deformation bands, and dense dislocation networks. Thermal relaxation up to 650 °C for 100 h shows that LSP-treated samples retain both surface hardness and hardened layer depth, indicating excellent thermal stability of the dislocation substructure and sustained compressive residual stresses. In contrast, SP-treated samples maintain high hardness during thermal exposure mainly due to defect-assisted δ and γ′/γ″ precipitation; however, oxidation in the highly deformed surface layer which could potentially affect near-surface damage tolerance. Overall, the low surface roughness, deeper hardened layer, and superior thermal stability produced by LSP has the potential to improve fatigue life for aero-engine components.

# Notch support effects in specimens and rotors made of electrical steel sheets

**Peter Haefele[1], Patrick Schwarz[2]**

[1]*University of Applied Sciences Esslingen, Laboratory of Material and Joining Technique, Kanalstr. 33, D-73728 Esslingen, Germany, peter.haefele@hs-esslingen.de*

[2]*University of Applied Sciences Esslingen*

*Notch support effect* Statistical size effect *Electrical steel*

**Abstract:** Electrical steels are iron–silicon alloys used in the rotors of electric motors to enhance their efficiency. The thin electrical steel (NO20-13, t = 0.2 mm, NO30-15, t = 0.3 mm) has an average grain size of about 100 µm. The rotors, which are subject to cyclic loading with mean stresses during operation, have very sharp notches at the bridge regions. Due to the high stress gradients, there are only a few grains within the highly stressed volume of the rotor material. The approaches for describing the notch support effect, taking into account the statistical, deformation-based, and fracture-mechanical support effects, are examined experimentally using different notch geometries, R-ratios, cut edge conditions and specimen sizes. New suggestions mainly for the statistical support effect are derived and adapted to the specific material behavior.

To evaluate the statistical size effect macro (width 10 mm) and micro specimen (width 0.5 mm) were tested cyclically with different R-ratios and the Weibull exponents have been derived, Fig. 1a. The results reveal a pronounced mean stress dependency of the statistical size effect, which decreases with increasing mean stress. Strain-controlled tests are carried out to investigate the deformation-based contributions to the support effect using cyclic material laws. The pronounced cyclic hardening behavior, together with the flat slope of the cyclic stress–strain curve, results in negligible deformation-based support effects, Fig. 1b. Despite the sharp notches the fracture mechanics support effect is also negligible.

The accuracy of the calculated fatigue life time for specimen and rotor test for both stress and strain based approaches can be significantly improved when load- and mean stress-dependent Weibull exponents for the statistical size effect are applied, Fig. 1c.

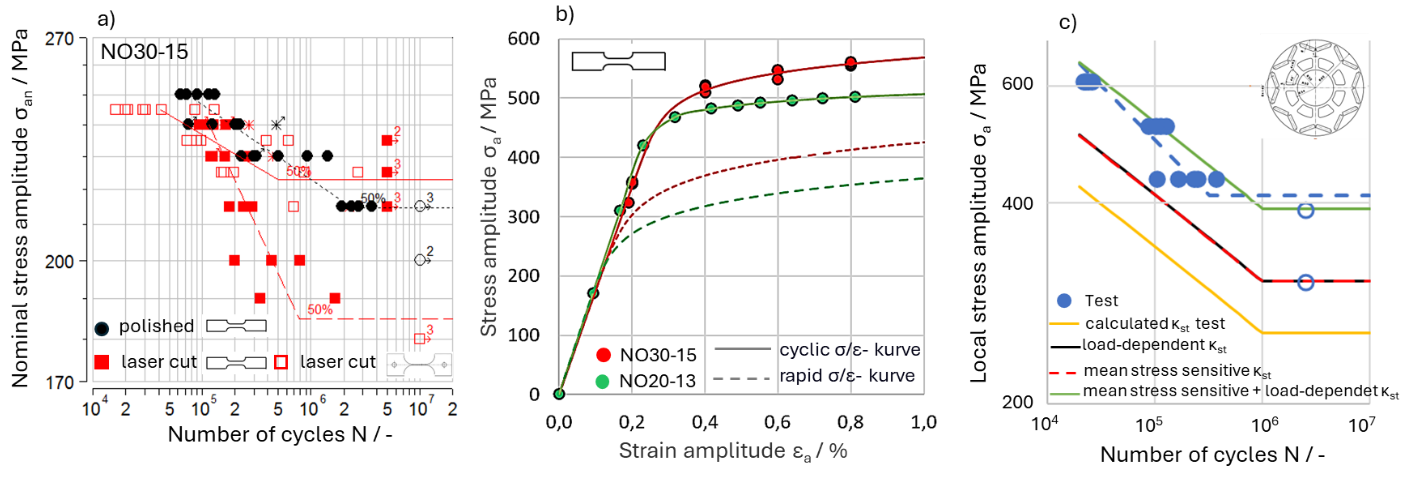



***Figure 1*** *a) Experimental fatigue test results for NO30-15 micro- and macro-specimens at R = 0.1, $P_F$ = 50 %, b) Cyclic and monotonic stress–strain curves of NO30-15 and NO20-13 c) Comparison between calculated and experimental results for rotors made of NO30-19*

# Effect of microstructural changes on fatigue limit in early stage of fatigue process of austenitic stainless steels

**Shota Oikawa[1,2], Noriyasu Oguma[3], Kenichi Masuda[3], Masaki Okane[4]**

[1]*R&D Department KOMATSUSEIKI KOSAKUSHO Co., LTD., 942-2 Shiga, Suwa-city, Nagano 392-0012, Japan, E-mail: s-oikawa@komatsuseiki.co.jp*

[2]*Graduate School of Science and Engineering, University of Toyama, 3190 Gofuku, Toyama-city, Toyama 930-8555, Japan*

[3]*Faculty of Engineering, University of Toyama, Japan*

[4]*National Institute of Technology, Toyama College, Japan*

*Fatigue limit* *Microstructural change* *Austenitic stainless steel*

**Abstract** The fatigue limits of austenitic stainless steels JIS-SUS304 and JIS-SUS316L are often discussed in terms of static strength and initial grain size. Our previous studies have shown that in fully recrystallized ultrafine-grained materials (average grain size 10 µm or less) and heavily rolled materials, the fatigue limit increases with increasing yield strength according to the Hall–Petch relationship. However, there is a significant discrepancy between experimentally determined fatigue limits and those estimated from hardness or tensile strength, and the governing factors remain insufficiently understood. In this study, the relationship between fatigue-induced microstructural changes and the fatigue limit was investigated for SUS304 and SUS316L with different microstructural conditions. The materials used in the rotating bending fatigue test were SUS316Lwith coarse grains, and SUS304 and SUS316L that had been severely processed by warm rolling to have ultrafine-grains of 10 µm or less. The results revealed that, for all materials, the fatigue limits evaluated in terms of nominal stress exceeded the 0.2% proof stress obtained from tensile tests. In particular, the fatigue limits of the ultrafine-grained materials reached approximately 1.7 times the 0.2% proof stress, showing a substantial deviation from conventional estimations based on hardness or tensile strength. In contrast, although the material severely deformed by warm rolling has a very high static strength, the increase in fatigue limit is limited, indicating that the fatigue limit cannot be uniquely rationalized by initial static strength alone. Interrupted fatigue tests at the fatigue limit stress revealed an increase in hardness near stress-concentrated regions along the bending stress gradient, indicating cyclic hardening during fatigue. This suggests that stress-induced microstructural changes due to fatigue contribute to an increase in the fatigue limit by forming a microstructural state distinct from the initial one. EBSD analysis of the cross sections of various specimen gauge portion during the fatigue process revealed that plastic strain is introduced into the crystal grain in the early stage of fatigue, and that the plastic strain region gradually expands in the surface layer of the gauge portion as the number of cycles increases.

# Machine learning-based correction for non-proportional multiaxial high-cycle fatigue criteria

**ANTOINE CHAMBREY[1,2], LORENZO BERCELLI[1], CÉDRIC DOUDARD[1], YOHAN COSQUER[2], SHABNAM ARBAB CHIRANI[1]**

[1]*ENSTA, Campus de Brest, IRDL – UMR CNRS 6027, 2 rue François Verny 29806 Brest Cedex, antoine.chambrey@ensta.fr*

[2]*Direction Générale de l'Armement, 47 rue Saint-Jean 31131 BALMA Cedex,*

multiaxial; high-cycle fatigue; non-proportional loading; machine learning.

Abstract — Multiaxial high-cycle fatigue (HCF) is commonly addressed using criteria such as Sines [1] or Crossland [2]. However, their predictive capability undermined for non-proportional loading paths (e.g., phase-shifted cycles). In such cases, comparisons with experimental data usually show significant non-conservative deviations [3,4]. Since these criteria are widely used in industrial fatigue design procedures, the objective of the present work is to develop correction strategies that remain directly compatible with existing engineering workflows.

In this work, a hybrid modelling strategy is developed that combines an analytical correction law for elliptical non-proportional loading paths with machine learning to improve fatigue-life predictions of the Sines and Crossland criteria. Using reference tension–torsion fatigue data [5], we first identify the systematic error induced by non-proportional elliptical loading paths and propose an interpretable correction law expressed as a function of the stress amplitude ratio and the phase shift. Then an ad-hoc convolutional neural network (CNN) is trained in order to extend the analytical correction to any tension-torsion case from the knowledge of its normalized loading path over one cycle. The training dataset is composed of synthetic elliptical loading paths and is designed to be insensitive to the choice of cycle starting point, enabling generalization beyond the training parametrization.

The proposed model is finally validated on an independent experimental dataset featuring cyclic paths that are markedly different from the training distribution and cannot be reduced to stress amplitude ratio and phase shift descriptors. This external validation includes strongly non-elliptical loops (square, triangular and figure-eight-shaped cycles), and, after Basquin mapping, demonstrates improved agreement between predicted and experimental lives, highlighting generalization well beyond the training distribution.

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# Fatigue Assessment of High Strength Windmill Studs Considering Process Residual Stresses and Cold Formed Layer

**J.A. Esnaola[1], J. Mendiola[1,2], M. Larrañaga [1], N. Otegi[1], X. Telleria[1], I. Llavori[1]**

[1]*Mechanical and Industrial Manufacturing Department, Mondragon Unibertsitatea, Loramendi 4, 20500 Mondragón, Spain.* jaesnaola@mondragon.edu

[2] *Matz-Erreka S. Coop., B. Ibarreta S/N, 20577 Antzuola, Spain*

High strength studs     Cold worked layer     Residual stresses     Multiaxial fatigue

**Abstract**

High-strength wind turbine studs are exposed to severe cyclic loading spectra in harsh environments. Therefore, they are commonly cold-formed from tempered bars to enhance their mechanical performance. The cold thread rolling process generates a work-hardened surface layer with improved mechanical properties and induces compressive residual stresses at the thread root, which delay crack initiation and extend the high-cycle fatigue (HCF) life. After rolling, studs are coated with an electrodeposited zinc-based cathodic layer to prevent environmental corrosion. Zn flakes coating process is conducted at approximately 320 °C, which may partially relax the compressive residual stresses, thereby reducing their beneficial effect on HCF performance. Despite their relevance, the combined influence of manufacturing-induced residual stresses, work-hardened layers, and thermal effects associated with coating processes is often neglected in fatigue assessments.

This study presents a combined experimental–numerical framework for fatigue life assessment of M30 studs manufactured from tempered 32CrB4 steel, typically used in wind blade–to–rotor joints. The framework explicitly accounts for residual stresses and work hardening induced during thread rolling, as well as the effects of subsequent blasting and coating stages. The material behaviour was described using a Hensel–Spittel constitutive model calibrated through experimental torsion and hammer tests. The thread rolling process was simulated using Forge®, while stress relaxation during the coating stage was modelled using the Zenner–Avrami approach. The resulting stress–strain fields were transferred to an ANSYS-based fatigue model through a dedicated mapping procedure.

Model predictions were validated through microhardness measurements, X-ray diffraction residual stress analysis, and full-scale fatigue tests conducted according to ISO 3800 using a 1.5 MN testing machine. The comparison between numerical and experimental results demonstrates that explicitly incorporating residual stresses significantly improves fatigue life prediction accuracy, highlighting the beneficial role of compressive stresses in delaying crack initiation. The proposed methodology provides a robust basis for integrating manufacturing effects into the fatigue design of high-strength fasteners for heavy-duty applications.

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# Multiaxial fatigue evaluation of mooring chains

**Eguzkiñe Martinez-Puente[1], Iñigo Llavori[1], Alaitz Zabala[1] , Jon Ander Esnaola[1] , Markel Penalba[1,2]**

[1]*Mondragon Unibertsitatea, faculty of Egineering, Mechanics and Industrial Produsction, Arrasate-Mondragon, Spain*

[2]*Ikerbasque, Basque Foundation for Science, Bilbao, Spain*

*Multiaxial fatigue* *Mooring chains* *Local analysis*

**Abstract** Mooring chains are critical structural components in offshore systems, where fatigue damage is governed by highly localised multiaxial stress states and complex load histories. Nevertheless, current design practice still relies largely on global uniaxial S–N approaches, which are unable to represent local stress concentrations or the mechanisms controlling crack initiation in chain links.

This work presents a finite element–based framework for the multiaxial fatigue evaluation of mooring chains, focused on crack-initiation assessment. Local stress and strain fields obtained from detailed three-dimensional chain-link models are combined with critical-plane multiaxial fatigue criteria to compute fatigue indicator parameters (FIPs) throughout the material volume. This enables full-field identification of critical regions without the need for predefined hotspots or assumed crack locations.

The methodology is first applied under constant-amplitude loading conditions, allowing validation against experimental fatigue tests on commercial chains. The numerical predictions show good agreement with observed fatigue lives and crack-initiation locations, providing confidence in the local multiaxial formulation.

Building on this validation, the framework is extended to variable-amplitude loading representative of offshore environments. Direct time-domain simulations of long-duration stochastic load histories would be computationally prohibitive for such detailed finite element models. To address this, the analysis is performed in the frequency domain using modal-based finite element simulations driven by load spectra. Stress power spectral densities are obtained at each node and processed using spectral fatigue methods to estimate damage accumulation under random loading.

The proposed approach provides a computationally efficient and physically consistent methodology for multiaxial fatigue assessment of mooring chains, bridging the gap between local crack-initiation modelling and realistic offshore loading conditions.

# Performance of Aluminum alloys components of preventive treatment by laser peening

**Che Zhigang, Sun Rujian and Zou Shikun**

*AVIC Manufacturing Technology Institute, Chaoyang Road No.1,Chaoyang District, Beijing 100024,China,*

*meczgang@163.com*

*Aluminum alloys component* *Intermittent laser peening* *Fatigue performance*

**Abstract** Laser peeing(LP) is the technology that can improve the mental and alloys performance which has been used in many fields. Many applications have been used on the new components. However, researches show LP can be used on the during service components for preventive treatment. The relative parameters, fatigue performance, residual stress and microstructure of aluminum alloys components after LP are investigated in this work.

# In-situ Experimental Investigation on Crack Initiation and Small Crack Propagation from Corrosion Pits

**Dian Wang[1], Lindong Chai [1], Wei Zhang[1,*]**

[1] *School of Reliability and Systems Engineering, Beihang University, Beijing 100191, China*

*Corrosion pit*    *Fatigue crack initiation*    *Small crack growth*

**Abstract** This study investigated fatigue crack initiation and early propagation from a single irregular corrosion pit in 2024-T3 aluminum alloy through in-situ experimentation. The local strain field around the corrosion pit was measured by high-resolution digital image correlation (DIC) technology, and the whole process of small crack initiation and propagation was tracked by in-situ observation. The results show that the crack initiation location is closely related to the strain concentration area identified by DIC, which is caused by the strain concentration caused by the geometric discontinuity at the pit mouth. Furthermore, the early-stage small crack exhibited an accelerated or decelerated unsteady growth behavior, indicating that the corrosion pit has a certain influence on the driving force at the crack tip. Additionally, the phenomena of multiple crack competitive propagation and crack arrest initiated by corrosion pits were also observed. This study provides direct experimental evidence for understanding the behavior of corrosion pit crack initiation and small crack propagation, informing more reliable fatigue life prediction and damage tolerance assessment for engineering structures.

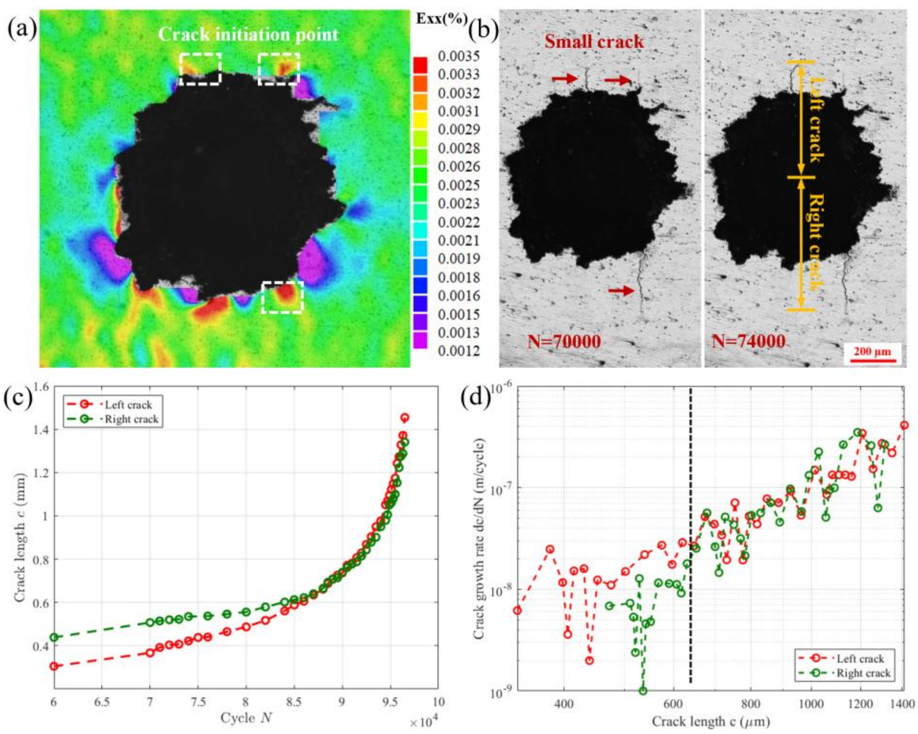


***Figure 1** – (a) Strain contour around the corrosion pit; (b) Micrographs of small cracks at various cycle counts; (c) Crack length vs. Cycles; (d) crack growth rate vs. crack length*

# Mechanical Behaviour and Fracture Characterisation of a WAAM-Produced Tool Steel in the As-Fabricated and Heat-Treated Condition

**Filipe Esteves[1], Gonçalo Rosa[1], Valdemar Duarte[1,2], André Ramalho[1], Eduarda Gomes[3], Telmo G. Santos[1,4], and Rui F. Martins[1,4]**

[1] *UNIDEMI, Department of Mechanical and Industrial Engineering, Nova School of Science and Technology, Universidade NOVA de Lisboa, Campus de Caparica, 2829-516 Caparica, Portugal*

[2] *Instituto Politécnico de Setúbal, Escola Superior de Tecnologia de Setúbal, Campus do IPS, Estefanilha, 2910-761 Setúbal, Portugal*

[3] *proMetheus, Instituto Politécnico de Viana do Castelo, 4900-347 Viana do Castelo, Portugal*

[4] *Laboratório Associado de Sistemas Inteligentes, LASI, 4800-058 Guimarães, Portugal*

*Additive Manufacturing* *WAAM* *Automotive industry*

**Abstract** The investigation presented herein is about the application of Wire-Arc Additive Manufacturing (WAAM) for the production of a tool steel component made of EN14700: S Fe8 (Wearmig Tool 55 from *Voestalpine®)* intended for the automotive industry. The original component was redesigned to enhance sustainability, not only through the adoption of WAAM but also by avoiding full replacement in the event of wear or fracture, and enabling the selective manufacture of the critical component under study.

Material blocks were produced by WAAM using a zig-zag deposition strategy, a 90° layer offset, and a controlled interpass temperature. During deposition, several process parameters and physical phenomena were continuously monitored through dedicated instrumentation, including voltage, electrical current, arc luminosity, temperature and acoustic pressure (sound).

Micro-CT analysis of the manufactured blocks revealed a low level of manufacturing defects and high relative density. Standardised specimens were subsequently extracted by electrical-discharge machining for tensile, microhardness, fatigue, and Charpy impact testing.

Tensile tests showed tensile strengths ranging from 1000 to 1200 MPa, characteristic of this tool steel. In addition, microhardness measurements carried out on the as-fabricated specimens, using a 0.5 kg load applied for 15 seconds, yielded values between 680 and 700 HV. After heat treatment at 550 °C for 2 h, in air, the hardness decreased to approximately 480 HV. Different microstructures were observed between the as-fabricated and the heat treated specimens, as confirmed by optical microscopy and SEM analysis. Thereafter, Charpy tests were conducted, indicating low toughness in the as-fabricated condition, with absorbed energies of approximately 3 J, increasing to approximately 6 J after the heat treatment described above. Fractographic analyses were performed to correlate fracture mechanisms with mechanical behaviour.

Overall, it was possible to confirm the feasibility of producing high-density, high-strength tool steel components by WAAM and its potential for sustainable manufacturing and repair strategies in the automotive sector.

This work was developed under the project "Agenda Drivolution - Transição para a fábrica do futuro" (C644913740-00000022) - Aviso 2021-C05i01-01 PRR, funded by IAPMEI - Agência para a Competitividade e Inovação, I. P., within the scope of the Portuguese "Plano de Recuperação e Resiliência (PRR)" / União Europeia - NextGenerationEU.

# Fatigue behaviour of flow drilling screw joints for automotive applications

**Rita Dantas[1,2], Roya Darabi[1,2], Inês Guedes[1], Rui Amaral[1,2], Rúben Santos[1,2], José Machado[2], Abílio de Jesus[1,2], Ana Reis[1,2]**

[1]*Faculty of Engineering, University of Porto (FEUP), Rua Dr. Roberto Frias, 400, Porto, 4200-465, Portugal and rdantas@fe.up.pt*

[2]*Associate Laboratory for Energy, Transports and Aerospace (LAETA), Faculty of Engineering, University f Porto (FEUP), Porto, Portugal*

*Fatigue* *FDS* *Dissimilar joints*

**Abstract** Flow-drilling screw (FDS) is a new joining process that has been increasingly used in the automotive industry to combine dissimilar materials such as aluminium alloys and steel [1-2]. During the service of FDS joints, fatigue failure may occur. Therefore, this work aims to characterise the fatigue behaviour of FDS dissimilar joints of aluminium alloy AW6082-T6 and DP780 steel in the high-cycle fatigue regime. First, single lap joints were produced, and subsequently fatigue tests were performed under load control at a stress ratio of 0.1 and a testing frequency of approximately 10 Hz. The experimental setup is illustrated in Figure 1 (a). Fatigue cracks initiated from the screwed hole in the base materials, as can be observed in Figure 1 (b). However, a variation in the origin of fatigue crack initiation was observed, since it alternated between the aluminium alloy and the steel. Thus, in this work, the fatigue crack initiation mechanism was also assessed in detail.

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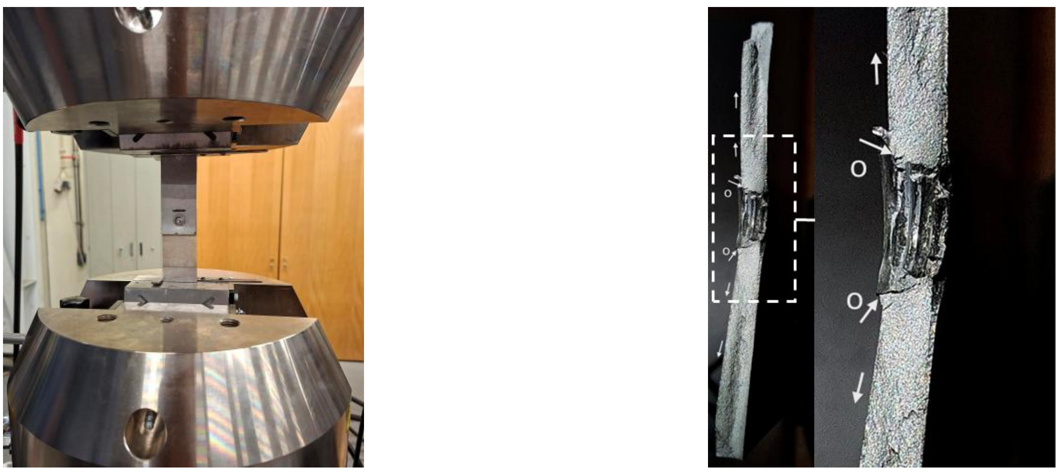
**Acknowledgements** This work was supported by the Projects: "Hi-rEV—Recuperação do Setor de Componentes Automóveis" co-financed by the Plano de Recuperação e Resiliência (PRR), Portuguese, through NextGeneration European Union (EU) under Grant C644864375-00000002, and "EASYSANDING – Intelligent Sanding, Inspection and Control System for the Production of Bicycle Frame", with nr. 18464 and operation code at the Funds Platform (Balcão dos Fundos) COMPETE2030-FEDER-01484100, co-financed by COMPETE 2030, by Portugal 2030 and by the European Union."



(a) (b)

***Figure 1*** *– FDS single lap joint tests under cyclic loading: (a) Experimental Setup; (b) Fatigue fracture surface*

# Surface defect driven fatigue lifetime prediction for additively manufactured titanium alloy miniature components

**Yixuan Hou[1,2], Xiaoqin Zhou[1], Qiang Liu[1], Talemi Reza[2]**

[1] *School of Mechanical and Aerospace Engineering, Jilin University, Renmin street 5988, Changchun, China, yixuan_hou@jlu.edu.cn*

[2] *Department of Materials Engineering, KU Leuven, Leuven, Belgium*

*Additive Manufacturing*  *Fatigue Lifetime Prediction*  *Machine Learning*

**Abstract** Intrinsic surface defects in additively manufactured metallic materials significantly degrade fatigue performance and introduce substantial uncertainty in fatigue design. Reliable lifetime prediction remains challenging because as-built surface morphologies are highly irregular to parameterize, while experimental characterization and fatigue testing are costly and time-consuming. To address these challenges, this study proposes a machine learning framework that predicts the fatigue lifetime of miniature Ti6Al4V components produced by electron beam powder bed fusion (PBF-EB) using geometric features of the critical defect. A generative deep learning model synthesizes surface morphologies to enrich the defect geometry dataset. The synthesized morphologies are used to construct high-fidelity finite element models that quantify defect-induced stress concentrations. A fatigue damage model that integrates Continuum Damage Mechanics with the Theory of Critical Distances is developed to estimate fatigue lifetime based on the computed stress fields. The results indicate that fatigue life scatter is primarily governed by variations in critical notch geometries, and a coalescence band that characterizes the interaction between adjacent-defect stress fields is identified. The resulting defect-lifetime dataset is employed to train and benchmark multiple machine learning models, with hyperparameters optimized via the Tree-structured Parzen Estimator to enhance robustness and mitigate overfitting. Shapley Additive Explanations further provide interpretability by quantifying the contribution of each geometric feature to the predicted lifetime. Overall, the proposed framework overcomes data scarcity and computational burden while providing a scalable route for defect-informed fatigue assessment of PBF-EB Ti6Al4V miniature components.

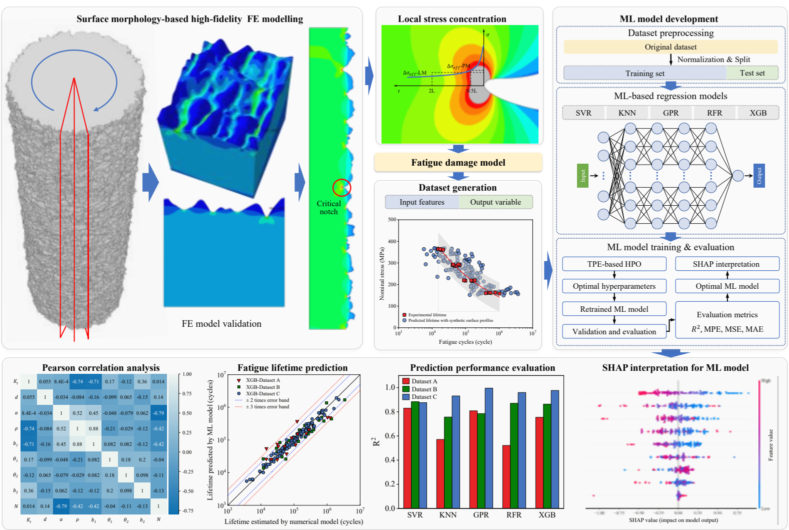



***Figure 1 -*** *Machine learning framework for predicting surface defect induced fatigue behavior in additively manufactured Ti6Al4V miniature components*

# CAI strength and delamination damage suppression of discrete toughened composite under low velocity impact

**LeiLei Yan**[1,2,*], Cong Zhang[1], Keyu Zhu[1], Xitao Zheng[1,2]

[1] *School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, China*

[2] *National Key Laboratory of Strength and Structural Integrity, Northwestern Polytechnical University, Xi'an 710072, China*

*Composite* CAI Strength *Delamination*

**Abstract** Compression after impact (CAI) strength is an important parameter for the structural design of aircraft composite materials, and its delamination damage suppression is of great significance to improve its CAI strength. A novel delamination damage suppression design method of discrete interleaved toughening for laminated composite was proposed for CAI strength improvement. In this study, discrete thermoplastic Polyamide-6,6 (PA 66) films were deployed at between the selected adjected layers, and three toughening dimensions were considered. Besides, three impact positions of specimens were tested under 5 J, 10 J, and 15 J, respectively. Besides, the damage constitutive relation and evolution model applicable to discrete interleaved laminates are explored in detail, numerical model embedded strain-rate-dependent progressive damage criterion and modified cohesive zone model were established to further study the damage mechanism.

The impact behavior and compression after impact (CAI) of specimens were discussed and compared. Experimental results showed that delamination damage was suppressed in the process of propagation outwards across the toughened region, and the path of delamination crack propagation was changed and swerved. Therefore, the delamination damage projected area (DDPA) of all specimens were reduced by 21.09% - 62.85%, compared with the non-toughened plate (base plate). In addition, the finding demonstrated that CAI strength is influenced by the delamination position and DDPA. The proposed method could improve the CAI strength by suppressing delamination and swerving the propagation path of delamination. Moreover, the CAI strength of all toughened plates were improved by 16.35% - 61.94% in contrast to the related base plates.The results demonstrate that the discrete interleaving can manipulate the delamination propagation between interlayers during the impact process, and then maneuver the compressive failure mode of laminates to achieve the so-called benign failure (implying higher residual strength), the main controlling mechanism is the interleaving nanofiber bridging. The potential contribution of the discrete interleaving to improve the damage tolerance of composites is of particular interest.

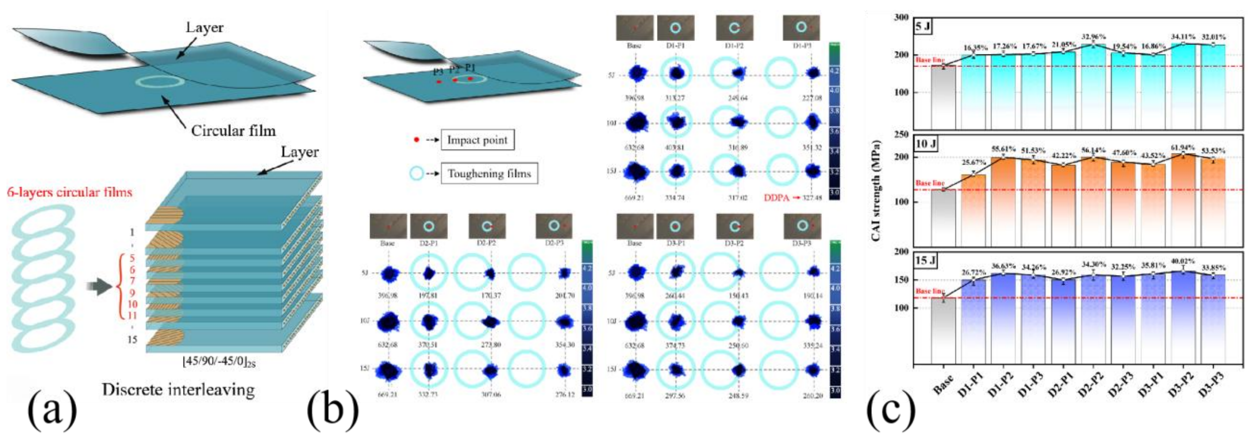



***Figure 1 -*** *Discrete toughened composite: (a) Structure design; (b) Delamination damage; (c) CAI strength*

# Peridynamic modeling of corrosion-assisted fatigue and fracture

**Han WANG[1], Licheng Guo[1]**

[1]*Department of Astronautic Science and Mechanics, Harbin Institute of Technology*

*No.92 Xidazhi Street, Nangang District, Harbin, China, 150001*

*Main author: Han WANG     E-mail: wanghan253626@hit.edu.cn*

*Keywords: Peridynamics  Multi-physical modelling  Corrosion fatigue  Fracture  Damage evolution*

**Abstract:** The self-initiated nature of corrosion damage poses significant challenges for numerical analysis based on conventional continuum mechanics, particularly when corrosion processes are strongly coupled with fatigue damage evolution, as commonly observed in corrosion fatigue. Peridynamics, as a nonlocal theory of solid mechanics, circumvents the numerical singularities induced by discontinuities by replacing spatial differential operators with integral formulations, and is therefore well suited for the unified treatment of both continuous and discontinuous problems. Its applicability to multi-physical problems has been widely demonstrated, indicating its suitability for the numerical analysis of corrosion–fatigue failures.

This paper summarizes and presents a series of systematic studies on corrosion fatigue conducted by the main author using peridynamic methods, covering corrosion–fatigue lifetime prediction as well as crack propagation analysis. The developed simulation framework has been further extended to hot corrosion–fatigue conditions and structural failure analysis, showing good agreement with experimental observations and measured fatigue lives. Mechanochemical effects are further incorporated to improve the modeling of corrosion–fatigue interactions, leading to more accurate lifetime predictions under different loading levels. Furthermore, the framework is extended to environmentally assisted failure mechanisms in composite materials, including stress-assisted oxidation in carbon fiber–reinforced ceramic matrix composites and moisture absorption in polymer matrix composites. On this basis, fatigue damage can be further embedded, enabling future modeling of environmentally assisted fatigue failure in materials and structural components.

# Effect of Heat Treatment on the Tensile Properties and Fatigue Life of Explosion-Welded Zr–Steel Bimetallic Composites

**Mariusz Prażmowski[1], Aleksander Karolczuk[1], Henryk Paul[2]**

[1] *Opole University of Technology, Mikolajczyka Street 5, Opole, Poland*

[2] *Institute of Metallurgy and Materials Science, Polish Academy of Sciences, Krakow, Poland*

*Explosive welding* *Heat treatment* *Fatique life*

**Abstract:** Explosion welding is one of the key industrial technologies used to produce multilayer metallic composites, enabling the formation of a strong metallurgical bond between dissimilar materials. A characteristic feature of joints produced by this method is the pronounced structural and mechanical heterogeneity of the bonding zone, including, among others, a wavy interface, local melted zones, shear bands, and elastic incompatibility between the joined materials. The high strain rates and extreme process conditions also lead to significant residual stresses and strain hardening in the bonding region, which may adversely affect subsequent processing and the fatigue durability of clad composites.

For this reason, explosion-welded systems are often subjected to heat treatment aimed at reducing residual stresses, partially eliminating strain hardening, stabilising the microstructure of the bonding zone, and improving the material's suitability for subsequent technological operations. The selection of heat-treatment parameters is a complex issue that depends on the chemical composition of the joined materials and the dimensions of the components.

This study presents the results of investigations on a two-layer composite Zr 700–P265GH+N steel produced by explosion welding, analysed in the as-bonded condition and after heat treatment by tempering at 600 °C for 1.5 h. Specimens for testing were prepared using electrical discharge machining (EDM). The experimental program included quasi-static tensile tests and fatigue tests under uniaxial, zero-to-tension cyclic loading (stress ratio R = 0).

The results of the static tensile tests showed a significant effect of heat treatment on the composite's mechanical properties. Specimens without heat treatment exhibited higher maximum tensile force than heat-treated specimens; however, failure occurred at lower elongation. The heat-treated material exhibited enhanced plastic deformation and greater elongation to fracture.

Analysis of the force–relative strain curves showed that for heat-treated specimens, the yield force was $FeH$=6.6 kN, whereas for specimens without heat treatment, the 0.2% offset yield force reached $Fp0.2$=10.4 kN, confirming a reduction in strength accompanied by an increase in plasticity as a result of tempering.

Fatigue tests revealed a significant effect of heat treatment on fatigue life. Heat-treated specimens exhibited a systematic reduction in fatigue life across the investigated force range, as reflected by a downward shift of the S–N curve relative to the as-bonded condition. A comparison of crack initiation sites showed that heat-treated specimens exhibited a higher frequency of crack initiation at or near the bonding interface, whereas non-heat-treated specimens predominantly failed by crack initiation in the steel layer, as identified from microscopic observations of the joint interface.

# Fatigue Behavior of Copper Components Manufactured by Fused Filament Fabrication

**P. Gast[1], P. Schüßler[2], A. Klassen[3], V. Schulze[2], S. Dietrich[2]**

[1]*IAM-WK at Karlsruhe Institute for Technology (KIT), Engelbert-Arnold-Straße 4, pierre.gast@kit.edu*

[2]*IAM-WK at Karlsruhe Institute for Technology (KIT)*

[3]*EMA Indutec GmbH*

*High-cycle fatigue* *Additive manufacturing* *Sintered Copper*

Fused Filament Fabrication (FFF) of copper-filled filaments offers a low-cost and geometrically flexible route for producing metallic components, yet the fatigue behavior of such materials remains largely unexplored. In particular, the combined influence of extrusion-induced anisotropy, debinding-related defects, and residual porosity on cyclic lifetime is not well understood. This work investigates the fatigue performance of sintered copper components manufactured by FFF, with emphasis on their applicability under cyclic mechanical loading.

Copper specimens were fabricated using a commercially available, highly filled copper filament and processed through chemical debinding followed by thermal debinding and vacuum sintering. Printing parameters were systematically optimized to achieve stable extrusion and reproducible green density. The internal defect structure was characterized using micro-computed tomography, while density and leak-tightness were evaluated to assess structural integrity. Mechanical fatigue behavior was studied using alternating bending tests, and failure modes were correlated with defect morphology and spatial porosity distribution.

The fatigue performance of the FFF-manufactured copper specimens was evaluated by alternating bending tests and benchmarked against conventional copper materials reported in the literature. The printed and sintered specimens exhibit a lower fatigue strength than ultra-fine-grained (UFG) copper, but show fatigue lives comparable to conventional coarse-grained (CG) copper over a wide range of stress amplitudes. Crack initiation was commonly associated with process-induced defects, including debinding-related delamination and surface irregularities inherent to the FFF process, highlighting the sensitivity of fatigue performance to both internal defect structures and as-built surface condition, particularly for geometries where post-processing is not feasible.

The results indicate that, despite inherent porosity and process-specific defects, FFF-manufactured copper can achieve mechanically meaningful fatigue performance. This positions material-extrusion-based copper additive manufacturing as a viable approach for fatigue loaded components, particularly where complex geometries and internal channels in cooling applications are required.

# The influence of molybdenum and silicon on thermo-mechanical fatigue performance of ferritic compacted graphite iron

**E. Kihlberg[1,*], V. Norman[1], R. Romero Ramirez[1], J. Moverare[1], P. Skoglund[1,2]**

[1]*Division of Engineering Materials, Department of Management and Engineering, Linköping University, SE-58183 Linköping, Sweden*
[2]*Scania CV AB, Materials Technology, Södertälje, Sweden*

*Corresponding author, e-mail: ebba.kihlberg@liu.se*

*Thermo-mechanical fatigue* *Stress relaxation* *Cast iron*

**Abstract** Cyclic thermal and mechanical loading during non-continuous operation causes thermo-mechanical fatigue (TMF), a life-limiting damage mechanism in heavy-vehicle diesel engine components. Improving TMF resistance is essential to enable higher combustion pressures and temperatures for increased engine efficiency and reduced transport emissions. To this end, ferritic compacted graphite iron (CGI) is a promising material for cylinder head applications due to its good machinability and ductility, and alloying with molybdenum (Mo) and silicon (Si) has been shown to improve high-temperature properties in cast iron. However, the influence of these elements on the TMF performance of fully ferritic CGI has remained unstudied.

In this study, three compositions with varying Mo and Si contents, including a reference composition, were evaluated using standard strain-controlled out-of-phase (OP)-TMF tests in the temperature ranges 100-400 °C and 100-500 °C. The observed TMF response was correlated with graphite morphology, matrix microhardness, and elemental distribution.

Both Mo and Si additions increase TMF life at 100-500 °C compared to a reference composition, see **Figure 1** (a). Furthermore, hysteresis analysis reveals that high-temperature stress relaxation is reduced by Mo, thereby limiting tensile stress accumulation during cooling, see **Figure 1** (b), which is linked to Mo-rich carbides in intercellular regions. Thus, a high potential of Mo-alloyed ferritic CGI for heavy-vehicle cylinder head applications is demonstrated.

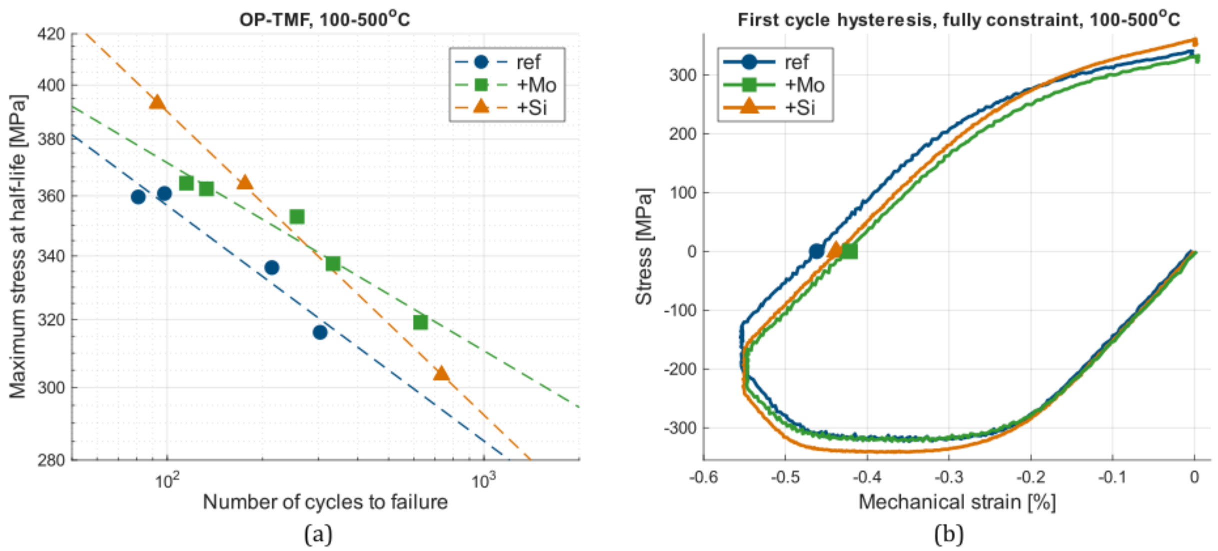



***Figure 1**. Out-of-phase thermo-mechanical fatigue results for three ferritic CGI compositions at 100-500 °C. (a) maximum stress at half-life vs number of cycles to failure, (b) hysteresis loops at first cycle for fully constraint specimens.*

# A framework for fatigue life prediction of fiber reinforced composites with limited testing data

**Lu Yubin[1], Wu Zhen[1,2], Zheng Xitao[1,2]**

[1] *School of Aeronautics, Northwestern Polytechnical University, Shaanxi, Xi'an 710072, China*

[2] *National Key Laboratory of Strength and Structural Integrity, Shaanxi, Xi'an 710065, China*

*Fiber-reinforced composite* *Artificial neural network* *Life prediction model*

**Abstract** To ensure structural integrity, it is essential to establish an accurate fatigue life prediction model. Traditional regression models are constrained by predefined functional forms, which often neglect the effects of material properties. However, purely data-driven methods require large datasets and exhibit poor extrapolation ability. Therefore, this study develops a novel framework to accurately predict fatigue life using limited testing data. The framework consists of two main parts, namely feature selection and iterative generation-estimation process (IGEP). Based on Pearson correlation coefficient, Variance inflation factors and Shapley additive explanations, the stress level, strength, and stiffness are selected as critical features. The IGEP uniquely integrates two synergistic neural networks, namely a generative model *L* (mapping stress to life) and an estimated model *D* (mapping life to stress). Seven neural architectures are evaluated, and then Convolutional Neural Network (CNN) and a combined model including Convolutional Neural Network, Long Short-Term Memory, and Attention module (CNN-LSTM-Attention) are selected to construct *L* and *D*, respectively. Models *L* and *D* form a closed-loop system that iteratively refines life predictions under the constraint of the fundamental *S*-*N* relationship. Compared with experimental data, the predictive accuracy of the IGEP has been verified. Despite the paucity of available experimental data, IGEP can generate reliable fatigue life curves across a wide range of stress levels. Moreover, when applied to stress levels, laminate configurations and material systems beyond those represented in the training data, the IGEP demonstrates robust extrapolation capability. The proposed framework provides a practical and generalizable tool for fatigue life prediction in FRPs under data-limited conditions.

# High cycle fatigue failure behavior and life prediction of LPBF superalloy under heat treatment effects

**Jin Lai[1], Wei Li*[1], Rui Sun[2], Zhenduo Sun[3], Chuanwen Sun[1], Xiaolong Li[4]**

*[1]School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China, lliw@bit.edu.cn*

*[2]Refractory Materials Research Central, Northwest Institute for Non-Ferrous Metal Research*

*[3]College of Quality and Technical Supervision, Hebei University*

*[4]School of Mechanical and Power Engineering, East China University of Science and Technology*

*LPBF superalloy* *High-cycle fatigue* *Heat treatment*

**Abstract** Multiscale fatigue cracking is a critical failure mode in additively manufactured high-temperature alloys, yet the underlying damage evolution mechanisms under different heat treatments remain unclear, particularly regarding dislocation interactions with precipitates and interfaces. This study employs multiscale characterization to investigate axial fatigue behavior at 650 °C ($R = -1$) in alloys with different heat treatment states. Results show that heat treatment governs the spatial organization of dislocation substructures, which controls the distribution of cyclic plastic strain and drives its evolution toward either localization or homogenization. This transition determines micro-void nucleation sites, crack initiation paths, and corresponding threshold behavior. In the as-deposited state, continuously distributed brittle Laves phases promote early damage and crack initiation along these phases. In the solution-treated state, heterogeneous strengthening facilitates persistent slip band formation, leading to strong strain localization and enhanced micro-void and crack initiation. In contrast, the solution-aged state improves resistance to crack initiation through precipitation strengthening, promoting dislocation network formation and strain homogenization, thereby suppressing local damage accumulation. Based on these mechanisms, a fracture-mechanics-based fatigue life model incorporating temperature effects and strain localization was developed, enabling quantitative prediction of high-temperature fatigue life and providing guidance for fatigue-resistant design and microstructural optimization of laser powder bed fusion superalloys.

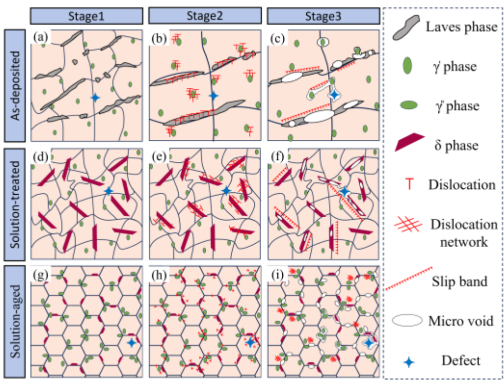



***Figure 1 -*** *Fatigue failure mechanisms under different heat treatments*

# Fatigue deformation and crack growth behavior in Al-containing high manganese austenitic steels

**Lihe Qian**

*State Key Laboratory of Metastable Materials Science and Technology, Yanshan University, China*

*Cyclic deformation* *Crack propagation* *Advanced steel*

***Abstract*** Fe-Mn-C twinning-induced plasticity (TWIP) steels exhibit an excellent combination of high strain hardening rate, large ductility and superior toughness at room temperature, which is associated with the dynamic mechanical twinning during plastic deformation. Such TWIP steels show potentials for many structural applications, which inevitably experience cyclic loading and fatigue damage in service. Addition of Al to TWIP steels can reduce the weight of steels, suppress dynamic strain aging, and retard or alleviate hydrogen-induced delayed fracture. Furthermore, Al may affect the cyclic deformation response and fatigue mechanisms of TWIP steel in a complex way, because Al tends to increase the stacking fault energy (SFE), thus tailoring dislocation and twinning behavior. However, the effect of element Al on the fatigue deformation and cracking behavior of Fe-Mn-C TWIP steel are not quite clear. In this work, the fatigue deformation responses and crack growth behavior in Fe-Mn-C steels with and without Al addition are studied.

The steels studied are Fe-22Mn-0.6C and Fe-22Mn-0.6C-3Al (wt. %), hereafter 0Al and 3Al steels, respectively. The cold-rolled plates were annealed and water quenched to achieve a full austenitic microstructure. Dog-bone plate specimens were used for fatigue tests. Room-temperature tension-compression fatigue tests, with a stress ratio of -1, were conducted under stress amplitude control at a frequency of 0.1Hz. An axial extensometer, with gauge length of 5 mm, was used for strain measurement. Fatigue crack length was measured using a microscope. Full-field strain distributions on specimen surface were in-situ acquired with digital image correlation (DIC) method. Microstructures were examined using EBSD and TEM. Deformation responses and crack growth behavior are analyzed and discussed.

The results show that both 0Al and 3Al steels exhibit initial cyclic hardening, then cyclic saturation, and final cyclic softening until fatigue failure. As compared with 0Al steel, 3Al steel is more cyclically softened, showing lower cyclic yield strength and greater accumulative plastic strain despite its monotonic higher yield strength, mainly due to the role Al in increasing the SFE and reducing dislocation slip planarity. Al promotes the initiation of fatigue cracks, increases the crack growth rate and hence decreases the fatigue lifetime, primarily ascribed to the increased cyclic plastic strain accumulation, reduced crack deflection and decreased crack closure.

# High-velocity impact performance of additively manufactured nickel-based superalloy lattice structures: Experimental and Numerical Study

**Zhihao Xie[1], Bowen Xue[2], Lulu Liu[3], Feng Jin[3], Yi Ren[2], Wei Li[4], Wei Chen[3]**

[1] *College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*

[2] *School of Aeronautics, Chongqing Jiaotong University, Chongqing 400074, China*

[3] *State Key Laboratory of Mechanics and Control for Aerospace Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*

[4] *China Aviation Power Plant Research Institute, Zhuzhou 412002, China*

*Additive manufacturing* *Lattice structure* *High-velocity impact*

**Abstract** Through experimental and numerical simulation studies, the ballistic response of additively manufactured IN625 body-centered cubic (BCC) lattice sandwich panels was systematically investigated. The results demonstrated that the ballistic limit of the lattice sandwich panel was 176.2 m/s, closely aligning with the numerically predicted value of 174.4 m/s, showing a deviation of only 1.02%. During the penetration process, the absorbed energy increased with the rising impact velocity. The impact failure process of the lattice sandwich panel was observed to occur in four distinct stages: (I) partial damage to the top panel, characterized by the highest energy absorption and rapid deceleration of the projectile; (II) complete failure of the top panel, followed by the rapid shear collapse of the lattice core; (III) fracture of the bottom panel, with initial plugging and a further reduction in energy absorption; (IV) complete penetration of the projectile and loss of load-bearing capacity. Notably, the top panel predominantly exhibited shear failure, while the bottom panel showed tearing, compounded by continuously increasing bulging deformation, thus revealing significant damage asymmetry.

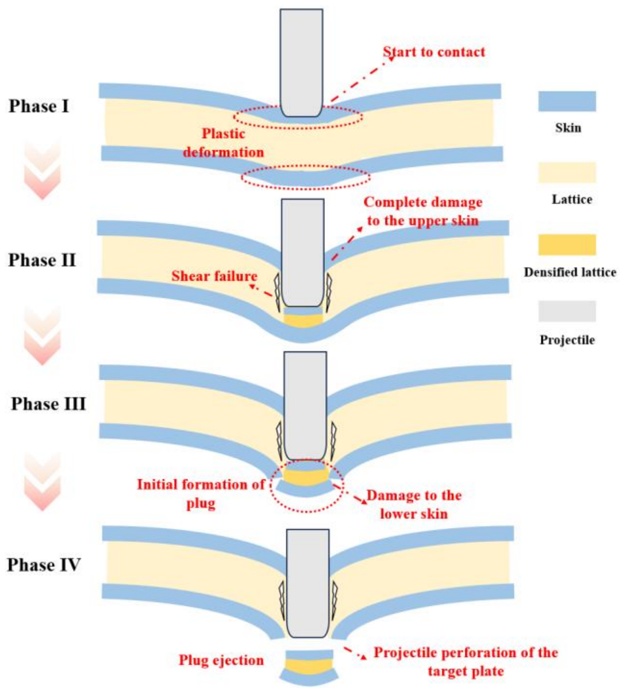



***Figure 1 -*** *Deformation and damage mechanisms of the lattice sandwich panel under high-velocity impact.*

# Fatigue life extension of refill friction stir spot welded AA6082-T6 joints using laser shock peening

**Nadezhda Likhareva[1,*], Volker Ventzke[1], Camila Caroline de Castro[1,2], Falk Dorn[1], Benjamin Klusemann[1,2], Nikolai Kashaev[1]**

*[1]Institute of Materials and Process Design, Helmholtz-Zentrum Hereon, Max-Planck-Str. 1, 21502 Geesthacht, Germany*

*[2]Institute for Production Technology and Systems, Leuphana University Lüneburg, Universitätsallee 1, 21335 Lüneburg, Germany*

*[*]E-Mail: nadezhda.likhareva@hereon.de*

*Laser shock peening* *Fatigue life* *Refill friction stir spot welding* *Residual stress*

**Abstract** The refill friction stir spot welding (refill FSSW) is an advanced solid-state spot-welding technique capable of replacing traditional single-spot joining like resistance spot welding by reducing stress concentrations, improving the mechanical properties of the weld, and involving lower heat input, making it a more environmentally friendly option. The technique can also replace riveted joints, eliminating pre-processing steps such as drilling holes and improving weight efficiency since no additional materials are required. However, despite these advantages, the fatigue performance of refill FSSW joints remains an issue. To overcome this challenge, laser shock peening (LSP) can be employed as an innovative surface engineering technology. In the present study, the influence of LSP on the fatigue properties of AA6082-T6 sheets joined by refill FSSW in an overlap configuration was investigated. The residual stress fields were characterized using multiple measurement techniques, including hole drilling, X-ray diffraction, and high-energy X-ray diffraction. It was demonstrated that a significant enhancement in fatigue behavior was achieved through LSP, with Basquin fatigue strength increasing by factors of 1.55 and 2.10 for the one-sided and two-sided LSP-treated specimens, respectively. The two-sided approach, in particular, yielded a substantial extension of fatigue life. The residual stress profiles confirmed that LSP produces deep, high compressive residual stresses in the welded joint, effectively transforming the tensile stresses intrinsic to the as-welded joint into a beneficial compressive state. The current research indicates that LSP is a promising post-weld treatment technique for improving the fatigue properties and also reveals its suitability as a repair approach for already damaged specimens. These findings demonstrate the potential of LSP to extend the service life of lightweight welded structures in automotive and aerospace applications.

# The influence of the roughness profile on the position of critical planes in multiaxial fatigue

**Anghel-Vasile Cernescu[1], Andrea Spagnoli[2]**

[1]*Politehnica University Timisoara, Department of Mechanics and Strength of Materials, anghel.cernescu@upt.ro*

[2]*University of Parma, Department of Engineering and Architecture, andrea.spagnoli@unipr.it*

*Multiaxial fatigue* *Roughness profile* *Critical plane*

**Abstract** A material point in any loaded body is subjected to a multiaxial stress and strain state. Under the condition of a time-varying external load, the stress and strain states also become variable. Moreover, under conditions of variable multiaxial loadings, the components of the stress and strain states exhibit independent variations. These are conditions that lead to material degradation through the phenomenon of multiaxial fatigue. Due to the nature of fatigue damage of materials involving crack initiation in a critical plane, fatigue life analyses and predictions consider failure criteria for identifying these planes and estimating the stress and/or strain state in them. If in the case of uniaxial fatigue, critical planes are recognised as those in which the maximum principal stress/strain, the maximum shear stress or the octahedral stress are recorded, in the case of multiaxial fatigue the independent variability of the stress state components, during a loading cycle, causes the critical plane to change its orientation. For the case of multiaxial fatigue, different criteria are thus defined for identifying critical planes and analysing the stress state in them.

In many situations, the initiation of fatigue cracks occurs from the surface of the material, and therefore, the identification of critical planes is made by taking into account the stress state at the surface of the material. Also, the stress state is analysed under the conditions of the theory of elasticity on a continuous surface. The real surface of mechanical components is not a continuous and smooth one, but represents a series of asperities resulting from the technological process. The rough appearance of the surface influences the stress state on and near the surface and therefore has an influence on the identification of critical planes, especially in multiaxial fatigue.

Therefore, within this study, an analysis of the influence of the roughness profile on the stress state and the change in the position of the critical plane in multiaxial fatigue is initiated. This involves an extensive numerical analysis in which 1D roughness profiles with different parameters are integrated on the surface of a sample loaded to multiaxial fatigue by a tensile-torsion load. For each type of profile with different parameters $R_a$ and $R_z$, the variable stress states are evaluated, and the critical planes are identified, based on the Findley criterion. The Findley criterion was chosen for its simplicity of use but also for the possibility of searching for and identifying all critical planes during a loading history.

The results indicate a stress concentration effect, determined by the presence of valleys in the roughness profile. This effect increases with $R_z$. The stress state on the rough surfaces, but also the critical planes, indicates a risk of fatigue crack initiation on the circumference of the rough surface, from the top of the deepest valleys towards the interior. Inside, the presence of at least three critical planes is distinguished, which differ slightly in orientation with respect to the loading axis, as a function of $R_z$.

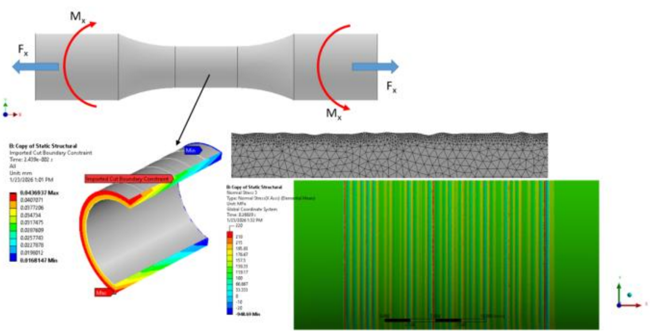



***Figure 1 -*** The submodeling technique for stress state analysis on a rough surface

# Optimal range of processing parameters and a dimensionless factor in AM to dominate fatigue performance of AMed parts

**Youshi Hong[1], Yu Xia[1,2], Aiguo Zhao[2]**

[1]*Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China, hongys@imech.ac.cn*

[2]*College of Civil Engineering, Nanjing Tech University, Nanjing 211816, China*

*Additive manufacturing* *Processing parameters* *Fatigue strength*

**Abstract** As known, additive manufacturing (AM) has been widely adopted for the high-efficiency fabrication of complex metallic engineering components. However, additively manufactured (AMed) metallic materials inevitably exhibit distinct microstructures, along with noticeable internal and surface defects that significantly degrade the fatigue performance and other mechanical properties of AMed parts.

Among various AM methods, laser powder bed fusion (LPBF) or selective laser melting (SLM) is a prevalent technology for fabricating required alloys. A laser energy density parameter of $E_V = P/(v \cdot h \cdot t)$ has been commonly employed to characterize AM processing conditions, where $P$ is laser power, $v$ is scan speed, $h$ is hatch spacing, and $t$ is layer thickness. In our previous work and other studies in literature, the effects of $E_V$ on porosity (defect) formation and the resultant fatigue performance and tensile properties of AMed alloys have been preliminarily investigated. It should be noted that $E_V$ has the dimensional unit of $J \cdot m^{-3}$, which renders it unsuitable as a consistent metric for evaluating and comparing different AM production scenarios.

Nonetheless, the present study comprehensively investigated the effects of AM processing parameters, in terms of $E_V$, on the porosity, fatigue performance and other mechanical properties of AMed parts. Data of defects (porosity), high-cycle and very-high-cycle fatigue strength, and tensile properties as functions of $E_V$ for AMed titanium alloy (Ti6Al4V), aluminum alloy (AlSi10Mg) and nickel alloy (Inconel 718) were collected from our research and published literature. Then, the correlations between $E_V$ and the resulting defects (porosity) as well as fatigue strength and tensile properties of AMed alloys were analyzed, and the optimal or preferable $E_V$ ranges for AM processing of these three alloys were thereby identified.

Subsequently, a novel dimensionless factor with respect to AM processing is proposed, which can serve as a consistent parameter to evaluate different AM production conditions. Physically, this factor characterizes the AM processing status by correlating defect (porosity) formation with the resultant fatigue strength and other mechanical properties, or it dominates the fatigue performance and tensile properties of AMed parts. This dimensionless factor is defined as the combination of $E_V$ and the intrinsic material properties of target alloys, including elastic modulus, shear modulus, Burgers vector, stacking fault energy, melting point and Boltzmann constant. The proposed factor can be applied in AM quality control, thereby facilitating the achievement of minimal porosity and maximized fatigue strength and tensile properties of AMed components.

# On the Consistency of Numerical Fatigue Crack Growth Increments with Plastic CTOD Evolution in 2D Numerical Simulations

**Jose Sandino-Egea, Antonio Gonzalez-Herrera, Daniel Camas, Jose Garcia-Manrique**

*Department of Civil and Materials Engineering, University of Malaga, C/Doctor Ortiz Ramos, s/n, 29071 Malaga, Spain, dcp@uma.es*

*Plastic CTOD* *Numerical Analysis* *Crack Growth Increment*

**Abstract** Fatigue crack growth in numerical simulations is commonly implemented by prescribing a constant crack advance per cycle, independently of local crack tip conditions. However, this approach does not explicitly account for the evolution of local driving forces such as plastic deformation at the crack tip. In parallel, the plastic component of the Crack Tip Opening Displacement (CTODp) has emerged as a physically meaningful parameter to characterize crack tip behavior under cyclic loading.

In this work, a numerical study is carried out to investigate the relationship between CTODp and crack growth in fatigue simulations involving plastic wake development. A two-dimensional finite element model of a Compact Tension (CT) specimen is developed in ANSYS Mechanical APDL, incorporating elastoplastic material behavior. Crack propagation is simulated through incremental node release, assuming a constant crack growth increment per cycle, as commonly adopted in numerical fatigue analyses.

A dedicated post-processing framework implemented in MATLAB is used to extract the evolution of CTODp at different positions behind the crack tip throughout the simulation. This allows tracking the variation of CTODp along the crack propagation process and relating it to the imposed crack growth increments.

The results reveal a clear correlation between the evolution of CTODp and the numerically prescribed crack growth rate. CTODp evolution suggests a non-uniform effective crack driving force along propagation. The analysis provides insight into the consistency between the local deformation state at the crack tip and the assumed crack advance per cycle, and raises questions about the validity of adopting constant crack growth increments in fatigue simulations.

The proposed approach provides a framework to evaluate the validity of numerical fatigue crack growth assumptions based on local mechanical parameters. This work constitutes a first step towards the development of crack growth criteria based on CTODp, which is identified as a key objective for future research.

# Damage Tolerance Assessment of Induction-Hardened High-Speed Railway Axles Considering Gradient Structures

**Xue Lin[1], Jiewei Gao[1,*], Mingsong Wang[1], Junfu Zhang[1], Shunpeng Zhu[2,*]**

*[1] School of Mechanical Engineering, Xihua University*

*#9999, Hongguang Avenue, Pidu District, Chengdu, 610039, China*

*[2] School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China*

*#2006, Xiyuan Ave, West Hi-Tech District, Chengdu, 611731, China*

*17581706602@163.com; jieweig@126.com; zspeng2007@uestc.edu.cn*

*Railway axles    Induction hardening    Gradient Structures    fatigue strength    Remaining life*

**Abstract** High-speed railway axles are safety-critical components designed for unlimited service life. However, complex loading conditions and harsh operating environments often induce various surface damages—such as foreign object impacts, corrosion pitting, friction wear, and scratches—which destroy their structural integrity. To improve the in-service safety performance, EA4T high-speed Railway axles were subjected to induction hardening. Microhardness profiles along the hardened layer depth were measured using an HVS-1000 microhardness tester. Residual stress gradients in the induction-hardened axles were evaluated via electrolytic polishing under a μ-X360s X-ray residual stress analyzer. A fracture mechanics model incorporating both material gradients and residual stress gradients was established to predict the remaining life of induction-hardened axles under different gradient structures. The local fatigue strength method was employed to systematically account for locally distributed material properties—such as residual stress and hardness—along with local load stresses in the depth direction, enabling precise identification of the fatigue-critical location (surface or subsurface) and quantification of the fatigue strength. The results show that induction hardening produces gradients in hardness and residual stress within the axle surface layer. Remaining life predictions and local fatigue strength assessments that include residual stress and microstructural gradient effects demonstrate that induction-hardening axles exhibit longer remaining life compared to untreated axles. This confirms that induction hardening effectively retards crack growth, enhances the fatigue strength, and improves the overall safety of axles.

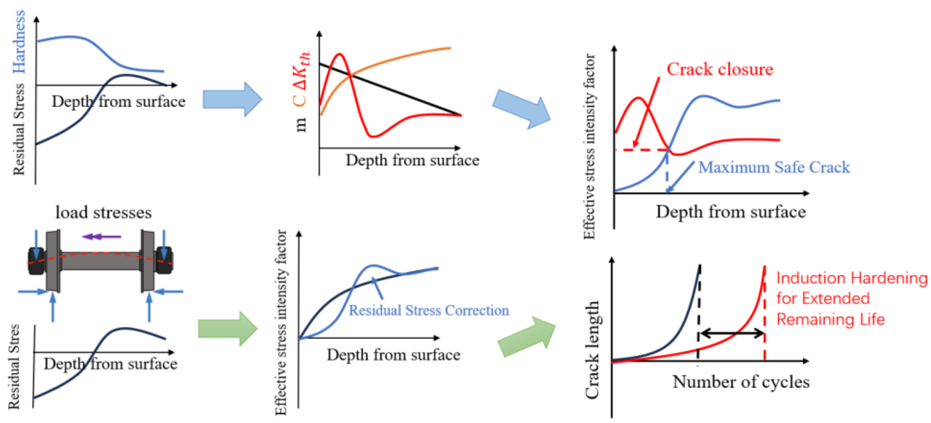



***Figure 1 -*** *Remaining Life Evaluation Method Considering Gradient Structures*

# Macroscopic Fatigue Crack Propagation in Additively Manufactured BCC Lattice Structures

**Hao Xin[1], Lei Gao[1], Xiaofan He[1,*]**

[1] *National Key Laboratory of Strength and Structural Integrity, School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China*

* *Corresponding author. E-mail address: xfhe@buaa.edu.cn (X. He)*

*Selective laser melting* *Lattice structures* *Crack propagation*

**Abstract** The fatigue behavior of additively manufactured lattice structures under pre-damaged conditions remains poorly understood due to their discrete load-bearing nature. In lattice structures, crack propagation does not occur as continuous crack growth, but is instead manifested as macroscopic crack evolution characterized by the progressive failure of multiple struts at the structural scale. In this study, an experimental investigation was conducted to examine macroscopic crack propagation in body-centered cubic (BCC) lattice structures under tensile cyclic loading. Compact tension (CT) specimens filled with BCC lattices were employed to impose a controlled crack-driving force and a localized damage region, where the initial crack was represented by a group of pre-failed struts. All specimens were fabricated from AlSi10Mg using selective laser melting (SLM) and tested under force-controlled cyclic loading. Macroscopic crack evolution and progressive strut failure were examined with the support of X-ray computed tomography. The results show that macroscopic crack propagation in lattice structures is governed by the interaction between the crack-driving force and the lattice architecture, leading to crack path deflection, local load redistribution, and non-uniform damage accumulation through sequential strut failure. Compared with solid CT specimens, the BCC lattice fundamentally alters the apparent crack propagation behavior, highlighting the discrete and architecture-dependent nature of fatigue damage in lattice structures. This study provides experimental insight into macroscopic crack propagation mechanisms in lattice structures and contributes to a clearer understanding of their fatigue performance under tensile loading.

# In Situ Laser Peening Using a Portable Device for Fatigue Improvement under Dead Loads

**Tomoharu Kato[1], Yoshio Mizuta[2,3], Satoshi Tamaki[2], Yuji Sano[2,3], Tomonao Hosokai[2,3], Yoshihiro Sakino[4], Koichi Akita[5]**

[1]*National Institute of Technology, Yonago College,*
*4448 Hikona-cho, Yonago, Tottori, 683-8502, Japan*
*t-kato@yonago-k.ac.jp*

[2]*SANKEN, The University of Osaka*

[3]*Nagoya Industrial Science Research Institute*

[4]*Faculty of Engineering, Kindai University*

[5]*Department of Mechanical Systems Engineering, Tokyo City University*

*Laser peening* *In situ treatment* *Fatigue life extension*

**Abstract** Laser peening (LP) is a surface treatment technique that utilises nanosecond laser pulses irradiated through a water layer to introduce compressive residual stresses to the surface of metallic materials. The efficacy of this technique in suppressing fatigue crack initiation and propagation has been well-documented. However, conventional LP systems are sensitive to environmental factors such as temperature and vibration and require large, fixed installations, which restrict their application to controlled indoor environments. To address these limitations, a portable LP device incorporating a compact microchip laser mounted on a collaborative robotic arm has been developed. The device is designed for field operation with minimal setup, thereby enhancing portability and enabling in situ applications. It is important to note that this portable LP device can be applied to structural components under tensile dead loads (self-weight) after installation at construction sites. LP experiments simulating in situ maintenance were conducted using HT780 fatigue specimens, demonstrating that the introduced compressive residual stresses effectively counteract tensile stresses induced by dead loads. Consequently, the fatigue performance of structural components, including bridges and buildings, can be enhanced. This approach provides a practical means of extending the service life of existing infrastructure.

# Evaluating the effects of film cooling hole manufacturing defects on the high-cycle fatigue strength of a turbine blade specimen

**Yue Wang[1], Rong Jiang[1], Mo Chen[1], Xiaoyu Li[1], Yingdong Song[1,2]**

[1] *College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P.R. China, wangyuecepe@nuaa.edu.cn;*

[2] *Harbin Engineering University, Haerbin 150006, P.R. China*

*Manufacturing defects*   *Fatigue strength prediction*   *Shaped film cooling hole*

**Abstract** To further enhance the performance of aero-engines, shaped film cooling hole (SFCH) with improved cooling efficiency is gradually being applied to turbine blades. However, with the complex geometry, the drilling process introduces numerous manufacturing defects, which can easily lead to high cycle fatigue (HCF) failure. In order to investigate the HCF failure mechanism of SFCH with manufacturing defects, the scanning electron microscopy (SEM) along with electron backscatter diffraction (EBSD) were utilized to characterize the microstructures around the holes, and the X-ray computed tomography (XCT) was employed to characterize the three-dimensional (3D) micro-morphology of initial defects. Vibration fatigue testing of specimens with SFCH were conducted at 900°C to obtain the HCF strength. The results show that due to the enlarged diameter in the diffuser section of the SFCH specimens, the abrasive flow machining cannot achieve fine polishing, leading to numerous defects such as pores and grooves on and beneath the surface of laser-drilled holes. HCF failure is primarily caused by local stress concentration induced by these defects near the holes, with the recast layer and the polycrystalline microstructure region playing a secondary role. Based on quantitative analysis of the XCT characterization results, a parametric model for manufacturing defects was established. With this model a set of SFCH models with manufacturing defects was constructed using the Latin hypercube sampling method, and the probabilistic fatigue strength prediction model for SFCH was developed, taking into account 3D defect characteristic dimension. The simulation results indicate the defect volume and location can reduce the HCF strength of the SFCH specimens to some extent. Comparison with experimentally measured fatigue strength reveals a reasonable accuracy of the predictions. The established probabilistic fatigue strength prediction model, which considers 3D defect characteristics, is expected to provide technical support for the fatigue strength design of aero-engine blades.

# Spectral Method for Fatigue Life Prediction under Non-Gaussian Random Vibration Loading

**Daiyang Gao[1], Zetao Wang[1]**

[1]*Nanjing University of Science and Technology , 200 Xiaolingwei Street, Xuanwu District, Nanjing, People's Republic of China , dygao@njust.edu.cn*

*Non-Gaussian Random Vibration* *Fatigue Life Prediction* *Gaussian Mixture Model*

**Abstract** Vibration load histories in practical engineering are typically non-Gaussian signals, and fatigue life prediction models based on the Gaussian assumption yield non-conservative estimates of fatigue damage. The Gaussian Mixture Model(GMM) is employed to characterize the non-Gaussian properties of random processes. The relationship among variance, kurtosis, and higher-order central moments for non-Gaussian random signals with unimodal spectra is examined. The GMM-Dirlik model is proposed based on the improvement on the calculation methods for the GMM related parameters. Random vibration fatigue tests are conducted on 2A12-T4 aluminum alloy plate specimens, and the corresponding fatigue life results under non-Gaussian random vibration are obtained. The improved GMM-Dirlik model is employed for non-Gaussian random vibration fatigue life prediction, and the comparison with the experimental data indicates conservative prediction results, with errors falling within a scatter band of 3.

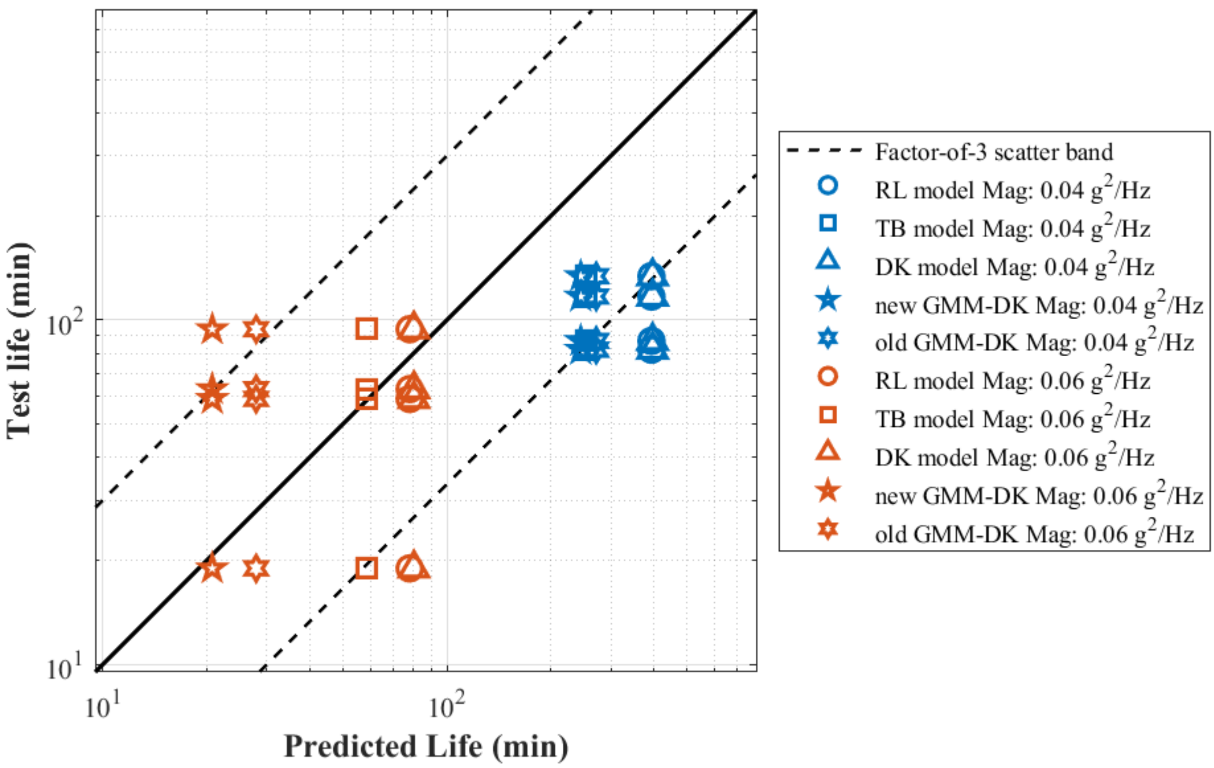



***Figure 1** Life Comparison under Excitation with a Kurtosis of 7*

# Hydrogen-Assisted Fatigue in Vintage API 5L X60 Pipeline Steel Containing Micro-Defects: Experiments and Defect-Based Life Assessment

**H. Wang[1], R. Best[2], D. Engelberg[3], I. Hajirasouliha[4], N. O. Larrosa[5,6], F. Scenini[7,8], L. Susmel[9]**

[1]*School of Mechanical, Aerospace and Civil Engineering, The University of Sheffield, Mappin Street, Sheffield S1 3JD, UK*
[2]*National Gas Transmission, Warwick Technology Park, Gallows Hill, CV34 6DA, UK*
[3]*Corrosion@Manchester, Department of Materials, The University of Manchester, Manchester, M13 9PL, UK*
[4]*School of Mechanical, Aerospace and Civil Engineering, The University of Sheffield, Mappin Street, Sheffield S1 3JD, UK*
[5]*School of Electrical, Electronic and Mechanical Engineering, University of Bristol, UK*
[6]*TECNALIA R&I, Basque Research and Technology Alliance (BRTA), Mikeletegi Pasealekua 2, 20009 Donostia-San Sebastián, Gipuzkoa, Spain*
[7]*Corrosion@Manchester, Department of Materials, The University of Manchester, Manchester, M13 9PL, UK*
[8]*Royce Institute, The University of Manchester, Manchester, M13 9PL, UK*
[9]*Materials and Engineering Research Institute (MERI), Sheffield Hallam University, Harmer Building, Sheffield, S1 1WB, UK*

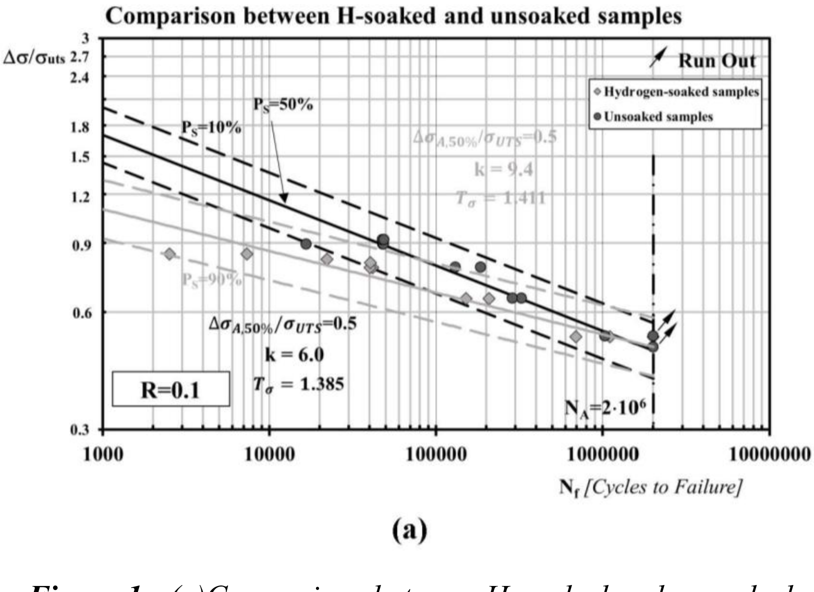
*Fatigue* *Hydrogen embrittlement* *Pipeline steel*

**Abstract** Hydrogen embrittlement can reduce the fatigue resistance of high-strength steels, but many assessment methods still use simplified defects and endurance-limit assumptions that may not capture hydrogen effects. Data on the combined influence of hydrogen and realistic micro-defects in vintage pipeline steel are limited, and common defect-based models are not well validated for ageing steels in hydrogen service.

To address this gap, this project studies 1970s API 5L X60 pipeline steel containing controlled micro-defects representative of corrosion pits. Mechanical and fatigue behavior are measured using dog-bone, V-notched, micro-holed plate, and compact tension (C(T)) specimens tested in both unsoaked and hydrogen-soaked conditions. Hydrogen pre-charging is carried out in pressure vessels using hydrogen gas of 8 bar for up to 2 months, and hydrogen uptake is quantified using LECO measurements.

Force-controlled fatigue testing provides S–N data as a function of defect size, using micro-holes of 50–500 µm. Crack-growth tests provide fatigue crack propagation behavior, and fracture surface analysis is used to interpret hydrogen-assisted crack initiation and propagation mechanisms.

The resulting dataset is used to develop and validate an engineering assessment methodology applicable to pipelines operating in hydrogen-containing service. Results are organized using Kitagawa - Takahashi diagrams and evaluated against established prediction approaches, including Murakami's defect assessment method, the EI Haddad - Toppers' Model and the Theory of Critical Distances (TCD). Model performance is judged by the agreement between predicted and measured fatigue lives, enabling calibration of parameters to reflect hydrogen effects. The outcomes support more reliable defect acceptance and remaining-life estimation for legacy pipeline steels subjected to cyclic loading in hydrogen-containing environments.



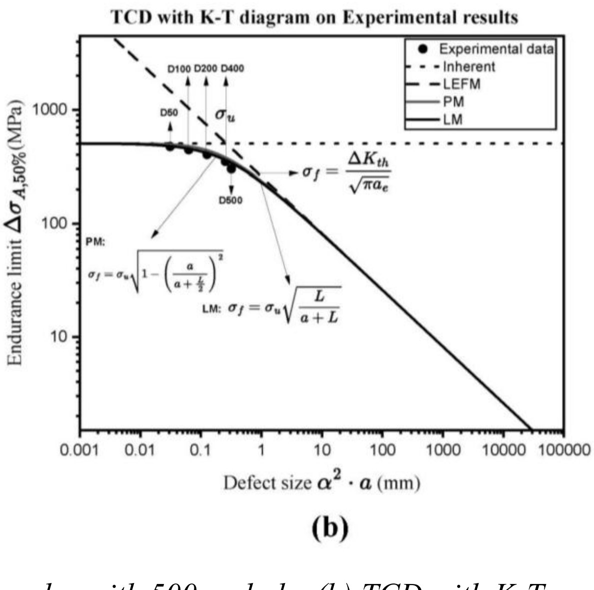




***Figure 1 -*** *(a)Comparison between H-soaked and unsoaked samples with 500µm hole. (b) TCD with K-T diagram on Experimental results.*

# Understanding Fatigue Crack Initiation and Growth in an Additively Manufactured Cu Based Alloy

**Aeriel Leonard[1], Nathan Heniken[2], Jiashi Miao[3]**

*[1]The Ohio State University, Columbus, OH, USA, leonard.649@osu.edu*

*[2]Los Alamos National Laboratory, Los Alamos, Nex Mexico, USA*

*[3]Center for Electron Microscopy and Analysis, Columbus, OH, USA*

*Fatigue* *Crack Initiation* *Electron Microscopy*

**Abstract** In this study a specifically designed methodology using scanning transmission electron microscopy, scanning electron microscopy, electron channeling contrast imaging and electron back scatter diffraction was employed to understand the mechanisms of fatigue crack initiation and growth in wire arc additive manufactured (WAAM) nickel-aluminum-bronze. Flat, rectangular dog bone specimens were extracted from the center of WAAM bar and then tested under tension-compression and tension-tension cyclic loading conditions (R= -0.3, 0.3, -0.15, 0.15, 0). The initial microstructure was composed of α-grains with nanoscale, spherical $\kappa_{IV}$ precipitates distributed homogeneously throughout the matrix as well as interdendritic zones composed of incoherent $\kappa_{III}$ and $\kappa_{II}$ second phase particles. Results showed that as the R-ratio decreased the fatigue life was reduced. Advanced characterization showed that planar slip led to extensive accumulation of dislocations at boundaries between the α-matrix and the interdendritic region. Figure 1 shows the precipitate shearing induced formation of extended stacking faults and three-layer twins via the stair-rod cross slip mechanism.

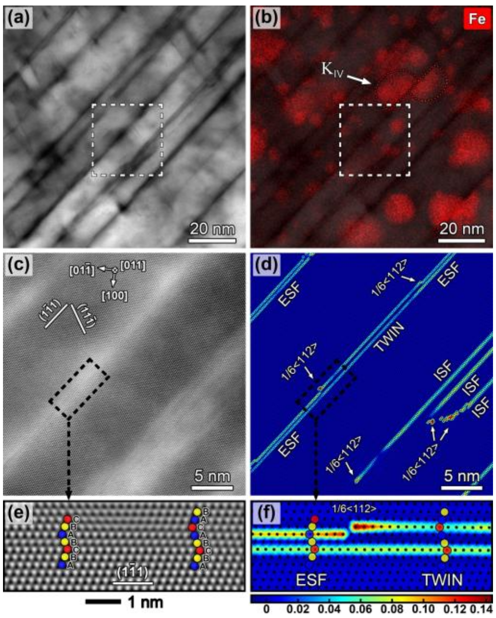



***Figure 1 -*** *(a) Overview BF-STEM DCI micrograph showing array of planar defects propagating throughout the α-matrix. (b) STEM-EDS map of Fe overlapped with image in (a) reveals the presence of sheared $\kappa_{IV}$ precipitates. White dashed rectangle highlights the area which was analyzed further in (c-f). (c) LAADF-STEM DCI detail of planar slip bands consisting of complex defect arrays including ISFs, ESFs and TWINs as confirmed by corresponding COS map in (d). Specific slip band associated with sheared $\kappa_{IV}$ precipitate (highlighted by red dashed circle in (b)) was investigated - black dashed rectangle highlights the transition from ESF to TWIN stacking sequence as detailed in (e-f). Electron beam was parallel with [011] zone axis of the matrix.*

# VHCF four-point bending test system design and improvement

**Martin Bartelt[1], Sebastian Heimbs[1]**

*[1]TU Braunschweig, Institute of Aircraft Design and Lightweight Structures, Hermann-Blenk-Str. 35, 38108 Braunschweig, martin.bartelt@tu-braunschweig.de*

*VHCF* *Four-point bending fatigue* *Test system design*

**Abstract** Testing in the very high cycle fatigue (VHCF) regime comes with a multitude of challenges, such as wear and tear of the testing equipment, long testing times and specimen heating. Taking these challenges into account a highly specialised VHCF test system has been developed and a large series of experimental tests has been performed over the last decade. This system tests composite specimens under four-point bending at frequencies up to 80 Hz. It is actuated by an energy-efficient, durable electrodynamic actuator. The test system is controlled by measuring the deflection and force to keep the test parameters within the specified range. These measurements are used to calculate the flexural modulus in real time during the test run. Transmitted light photography is used to record the damage state of the specimen and determine the crack density and delamination area ratio over the load cycles. With these data, comparative studies for parameter variations such as different materials, ply thickness, stress ratios, and loading types have been conducted. During this time, multiple challenges specific to VHCF testing have been identified. Some of these have already been addressed in the current test system, such as controlled specimen temperature using IR camera sensors and cooling fans, smooth ramping up to high testing frequencies and sufficient sampling rates for deflection and force measurements, which are used for controlling the test system and evaluations. Automated high-resolution photography of the specimens with the test system stopping and restarting has also been integrated. Other identified challenges require more extensive modifications to the test system. For example, vibrations are transmitted between the four parallel test units. To overcome this issue, the entire test system must be separated and vibration damping must be applied. Also, using a combined control system for two test units, results in a slower and less accurate initial adjustment of the control voltage for the actuator, increasing the risk of exceeding the predefined load. In the VHCF range, a single load cycle with higher loading can significantly impact the test results. Therefore, separating the control systems of the test units is perused. Additionally, testing has shown that variations of a few degrees, resulting from the rudimentary on/off control of the climate system have a measurable impact on the complex measurement system. To address these challenges, the newly developed VHCF test system consisting of four separated test units will be presented.

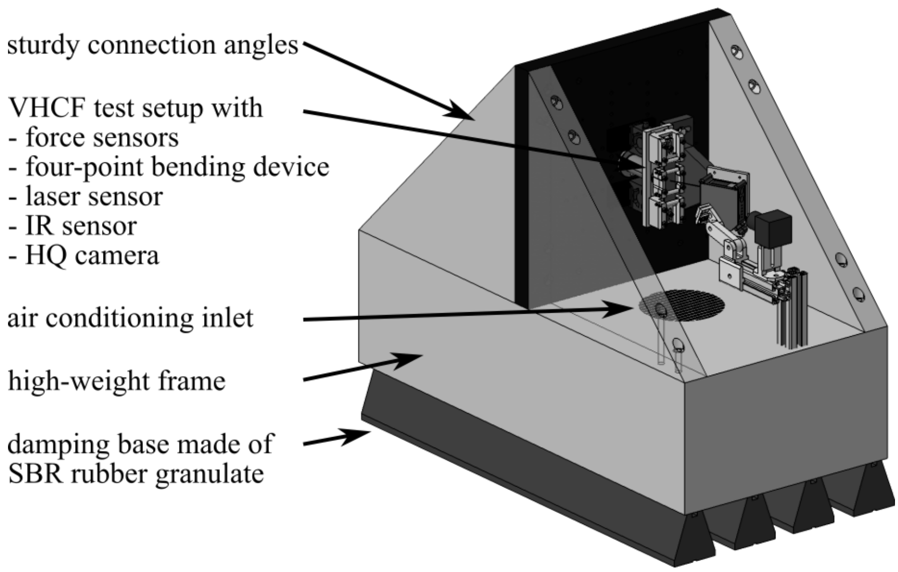



***Figure 1*** *– VHCF four-point bending test system*

# Fatigue and Crack Propagation Behavior of Gradient Structures on Induction-Hardened High-Speed Railway Axles

**Jiewei Gao[1], Chengye Wang[1], Weicheng Xia[1], Junfu Zhang[1], Shunpeng Zhu[2,*]**

[1] *School of Mechanical Engineering, Xihua University*

*#9999, Hongguang Avenue, Pidu District, Chengdu, 610039, China*

[2] *School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China*

*#2006, Xiyuan Ave, West Hi-Tech District, Chengdu, 611731, China*

*jieweig@126.com; zspeng2007@uestc.edu.cn*

*Railway axles    Induction-hardening    Gradient Structures    fatigue    Crack propagation*

**Abstract** High-speed railway is still threatened by derailment caused by failure of infrastructure and component of vehicles. Railway axle is one of the safety-critical components, which will lead to disastrous accident if fracture happened during the railway running at a speed around 300 km/h. No matter failure of railway axles caused by manufacturing defects or service defects, Micro-cracks prefer to initiate from the surfaces, such as corrosion, fretting and foreign object damage. In order to improve the damage tolerance of railway axles, surface modification techniques were employed. Among them, deep rolling and induction-hardening are more effective and efficient. Induction-hardening could induce a deeper hardened layer compared with deep rolling. Regarding to induction-hardening, the process parameters should be optimized under the philosophy of **Service Fitness-Design for Full Life Cycle**. To better understand the relation between process parameters with the mechanical properties of induction hardened layer, full-scale EA4T railway axles were induction-hardened and the microstructure, microhardness, tensile strength were characterized. And then, fatigue and crack propagation tests were conducted with thin specimen from different depth of induction-hardened layers. The fatigue mechanism and crack propagation behavior of the gradient layers were analyzed to correlate with microstructure and process parameters. The results lay a foundation for the design and assessment of induction-hardened railway axles.

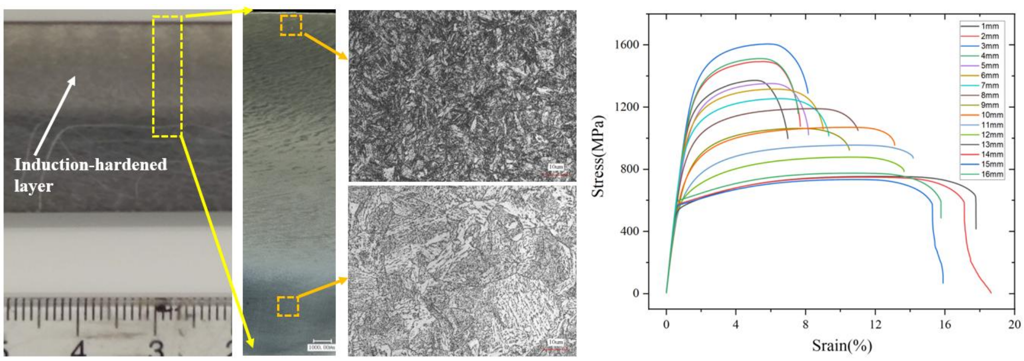



***Figure 1** – Microstructure and tensile strength of gradient structures on induction-hardened EA4T railway axles*

# Influence of Hard-Chrome Coating Thickness on the Fatigue Resistance of Steel Shafts: Experimental Study and Kitagawa–Takahashi-Based Assessment

**Driss El Khoukhi[1], Isabel Huther[1], Guillaume Elbe[2], Gérard Weber[3], Philippe Magat[4], Julien Delgado[1], Christophe Reynaud[1], Yanneck Suchier[1], Fabien Lefebvre[1]**

[1]*CETIM, 52 Avenue Félix Louat, 60300 Senlis, France, driss.elkhoukhi@cetim.fr*

[2]*LIEBHERR-France SAS, 2 Avenue Joseph Rey, 68005 Colmar, France*

[3]*LIEBHERR-Mining Equipment Colmar SAS, 49 Rue Willi Liebherr, 68025 Colmar, France*

[4] *YANMAR, 80 Avenue du Général Leclerc, 95480 Pierrelaye, France*

*Hard Chrome, Fatigue Kitagawa-Takahashi*

**Abstract**

Hard-chrome coatings are widely used on load-bearing mechanical components due to their high hardness, excellent wear resistance, low friction, and corrosion protection. However, they inherently contain networks of microcracks and tensile residual stresses generated during the plating process, which can significantly reduce fatigue performance. Previous studies have also shown that increasing coating thickness further decreases fatigue strength [1]. This study aims to quantitatively assess the influence of coating thickness on the high-cycle fatigue behaviour of a full-scale mechanical shaft.

Test specimens were manufactured from 42CrMo4 steel (50 mm diameter, 400 mm length) with a 3 mm induction-hardened surface layer. Three configurations were evaluated: uncoated shafts, shafts coated with 20 µm of hard chrome, and shafts coated with 50 µm. Fatigue tests were performed under three-point bending at a stress ratio R = 0.1 and a frequency of 3 Hz up to $2\times10^6$ cycles in ambient air. Fractographic analyses were carried out to identify crack initiation sites. The Kitagawa–Takahashi diagram was employed to assess thickness sensitivity, and a predictive S–N model was developed to correlate fatigue life with coating thickness.

The results confirm that increasing the coating thickness reduces fatigue strength. This reduction is driven by coating microcracks and tensile residual stress. Cracks initiated at coating defects and propagated into the induction-hardened substrate. The Kitagawa–Takahashi diagram demonstrated a strong correlation between coating thickness and fatigue strength, consistent with LEFM predictions. The proposed S–N model also captured the changes in fatigue life associated with coating thickness. These findings provide useful guidance for optimizing hard-chrome coating parameters in fatigue-critical components.

**References**

[1] V. P. Nguyen, T. N. Dang, C. C. Le, and D.-A. Wang, "Effect of Coating Thickness on Fatigue Behavior of AISI 1045 Steel with HVOF Thermal Spray and Hard Chrome Electroplating," Journal of Thermal Spray Technology, 2020.

# Structurally Optimized Anti-fatigue SMA Actuator for Morphing Wings

**Lulu Chang[1], Zhi Yi[1], Lei Zhang[1]**

[1]*Institute of Intelligent Manufacturing, Nanjing Tech University, Nanjing, China, 210016; Email: luluchang@njtech.edu.cn*

*SMA actuator* *Anti-fatigue* *Fatigue life prediction*

**Abstract** Morphing wings, capable of real-time shape optimization to adapt to various flight conditions, hold significant potential for inproving overall aircraft performance and efficiency. Shape memory alloy (SMA) actuators incorporating distributed thermoelectric elements for active cooling, are promising candidates due to their high power density and rapid response. These actuators are constructed by integrating an active cooling layer of thermoelectric arrays, an SMA wire actuation layer, and an elastic support layer, all encapsulated within a flexible matrix. However, SMA wires operating under cyclic conditions encounter critical challenges, specifically a reduction in response speed caused by heat accumulation and fatigue failure induced by stress concentrations. These issues hinder their ability to meet the critical demand of morphing wings for high-frequency, long-endurance deformation mechanisms. To address these challenges, efficient thermal management and enhanced anti-fatigue performance must be achieved at the structural design level. This paper proposes a novel actuator configuration for morphing wings that integrates high-efficiency active cooling with superior anti-fatigue characteristics. Simulation results demonstrate that this configuration achieves the required actuation displacement while significantly improving the uniformity of the operational temperature field and optimizing the internal stress distribution.

Firstly, guided by the principle of retarding crack initiation through a surface gradient compressive stress field, this study introduces specific geometric features into the actuator design to generate a beneficial stress gradient distribution. These features include specially shaped elastic support layers, non-uniform thickness distribution of the flexible encapsulant, and the application of pre-stress in the SMA wires. These design elements facilitate the formation of a macroscopic compressive stress or a low stress gradient under load in critical regions, such as the SMA wire termination points, thereby delaying fatigue crack nucleation. A three-dimensional parametrized geometric model of the actuator was developed in COMSOL Multiphysics. Key design variables, including the position, quantity, and input current of the thermoelectric elements, were defined for the multi-objective co-optimization of actuation displacement, cooling efficiency, and structural stress distribution. By constructing a response surface model correlating cooling efficiency and temperature uniformity with the design variables, an optimal structural configuration was obtained.

Subsequently, the optimized actuator model was integrated into a simplified structural model of a morphing wing section. Simulations were conducted to investigate the complex curvature deformation capability of the wing skin achieved through the coordinated work of multiple actuators, thereby validating the deformation efficacy of the optimized actuator in a morphing wing application. Furthermore, a simulation-based fatigue life prediction framework was established for the actuator. This involved simulating the repeated heating/cooling and tensile/recovery cycles corresponding to a typical flight mission profile. The stress-strain hysteresis loops, stress amplitude, and mean stress at critical locations were analyzed. The acquired stress and strain data were post-processed, and the accumulated damage in the actuator was calculated based on a macroscopic fatigue damage mechanics model. This process culminated in a predictive assessment of the actuator's fatigue life.

# Fatigue Life Prediction of Ceramic Matrix Composites Based on Early-Cycle In-Situ Electrical Resistance Monitoring

**Jiaming Li[1], Guoqiang Yu[1,*], Tao Wu[1], Wenxuan Qi[1], Yingdong Song[1,2], Xiguang Gao[1]**

[1]*Key Laboratory of Aero-engine Thermal Environment and Structure, Ministry of Industry and Information Technology, College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, 29 Yudao Street, Qinhuai District, Nanjing 210016, PR China, ygq@nuaa.edu.cn*

[2]*Harbin Engineering University, Harbin, 150001, PR China*

*Ceramic matrix composites* *Fatigue life prediction* *In-situ monitoring*

**Abstract** Ceramic matrix composites (CMCs) are essential for next-generation aero-engines due to their superior thermal stability and high strength-to-weight ratio. However, the complex microstructural degradation under cyclic loading makes reliable fatigue life prediction a persistent challenge. Traditional life assessment relies heavily on extensive experimental data to build S-N curves, which requires massive time and material resources. Furthermore, the stochastic nature of matrix cracking and fiber-matrix debonding often leads to a wide scatter in fatigue data, limiting the accuracy of empirical models. There is an urgent need for a physics-based monitoring technique that can capture the real-time damage state without interrupting the service.

This study develops a rapid characterization framework that uses in-situ electrical resistance (ER) monitoring to track fatigue evolution. The inherent conductivity of the fibers was treated as a self-sensing network within the composite. The fatigue tests were performed under various stress levels and synchronized the loading history with continuous ER measurements. This approach allows to observe how the resistance changes as micro-cracks propagate and fibers fail during each cycle.

The results reveal a critical relationship between the steady-state ER evolution rate during early fatigue cycles and the final failure point. The proposed model demonstrates high predictive accuracy, requiring only the first 20% of the total fatigue life data to forecast the remaining life. To validate the physical basis, we used high-resolution XCT and SEM to characterize the damage morphology at different stages. The transition in failure mechanisms was identified : high stress levels cause sudden fiber fractures and rapid crack coalescence. In contrast, lower stress levels promote progressive interfacial debonding and the accumulation of wear debris between fibers and matrix. The ER signals precisely reflect these microscopic changes, as the disruption of the conductive paths directly correlates with the severity of the wear and breakage.

In conclusion, this study proves that early-cycle ER data can serve as a reliable indicator for macroscopic fatigue life. This physics-driven approach significantly reduces the time and cost required for the qualification of CMCs. It provides a scalable solution for structural health monitoring and the rapid screening of new material candidates in extreme environments.

# 3D kinematics fields in fretting contact from X-ray tomography

**Jérémy Grondin[1,2], Camille Gandiolle[1], Youssef Younes[1], Benjamin Smaniotto[1], Jean-Christophe Teissedre[2], Jan Neggers[1], Pierre Arnaud[2]**

*[1]Université Paris-Saclay, CentraleSupélec, ENS Paris-Saclay, CNRS, LMPS – Laboratory of Mechanics of Paris-Saclay, 91190, Gif-sur-Yvette, France*

*[2]MinesParis, PSL University, Centre for material sciences (MAT), UMR 7633 CNRS, 91003 Evry, France*

*Fretting* *In-situ testing* *Digital volume Correlation*

## Abstract

Mechanical assemblies subjected to vibrations are often prone to fretting at contact interfaces, which can lead to wear, cracking, and a significant reduction in service life. Fretting damage is commonly studied using simplified contact models, which often assume smooth surfaces and homogeneous interfaces and loadings. This is not representative of reality, particularly as damage begins locally in fretting. However, experimental access to the internal kinematics of the contact during loading is obscured by contact and models can only be fed from ante- and post-mortem surface analyses.

This study proposes an in-situ experimental approach combining mechanical contact testing and X-ray tomography to directly investigate contact mechanics and fretting damage within the contact volume. Initially, a cylinder-on-plane indentation test was designed under elastic loading conditions, in accordance with Hertzian contact theory. X-ray tomography and digital volume correlation (DVC) were used to measure three-dimensional displacement fields beneath the contact interface. An integrated DVC strategy was implemented, allowing a direct comparison between the experimentally measured displacement fields and the Hertzian solution, thus providing a robust physical reference for data interpretation. The methodology was then extended to fretting conditions, with the aim of performing in-situ measurements under added tangential loading. The displacement fields obtained during both indentation and fretting tests were quantitatively compared with analytical solutions and finite element simulations offering new experimental insights into fretting mechanisms.

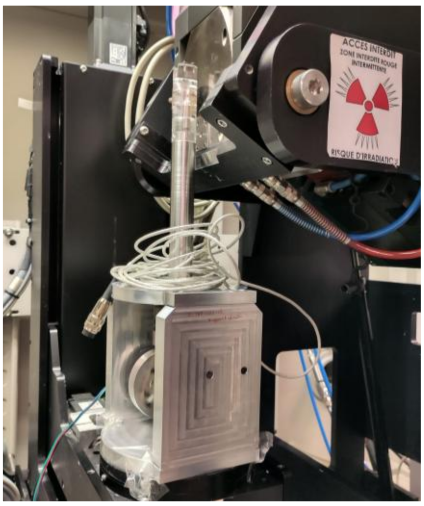


***Figure 1** – In-situ Fretting test*

# High cycle fatigue of LPBF duplex stainless steel: experimental and CPFE modeling

**Maxime Piras[1], Nicolas Ory[2], Anis Hor[1], Eric Charkaluk[2]**

[1]*Institut Clément Ader (ICA), Université de Toulouse, CNRS, ISAE-SUPAERO, UPS, INSA, Mines-Albi, 3 rue Caroline Aigle, 31400 Toulouse, France, maxime.piras@isae-supaero.fr*

[2]*Laboratoire de Mécanique des Solides (LMS), CNRS, UMR 7649, Ecole Polytechnique, Palaiseau Cedex 91128, France*

*Additive manufacturing* *High cycle fatigue* *CPFE modeling*

**Abstract**

Additive manufacturing (AM) offers promising opportunities to overcome the limitations of conventional manufacturing processes by enabling microstructural tailoring through process parameters and heat treatments (HT). Duplex stainless steels (DSSs) produced by laser powder bed fusion (LPBF) can exhibit predominantly ferritic, fine duplex, or coarse duplex microstructures, depending on the applied HT. In addition, defects inherent to the LPBF process can be eliminated by hot isostatic pressing, resulting in a defect-free coarse duplex microstructure. In the literature, limited information is available on the influence of these microstructures on high-cycle fatigue (HCF) behavior, particularly regarding defect–microstructure competition.

This work investigates the competition between defects and microstructure in the HCF behavior of LPBF-processed SAF 2507 DSS using both experiments and modeling. Fatigue tests were conducted on three microstructures: fine duplex with defects, coarse duplex with defects, and defect-free coarse duplex. Fatigue results reveal a stronger sensitivity to defects under tensile loading than under torsion, as well as a beneficial effect of microstructure refinement, whose fatigue limit is comparable to or higher than that of the defect-free coarse microstructure (Figure 1). To overcome the absence of experimental data for a fine defect-free microstructure and to identify the crack-initiating phase (Figure 1), a crystal plasticity finite element framework coupled with extreme value statistics was employed. The simulations reveal that crack initiation occurs in austenite for the Crossland and Dang Van fatigue indicator parameter (FIP), while ferrite governs initiation for the Matake FIP. The latter yields predictions that best match experimental data, emphasizing the critical role of fatigue indicator parameter selection and the necessity for further enhancement of fatigue modelling approaches for AM DSSs.

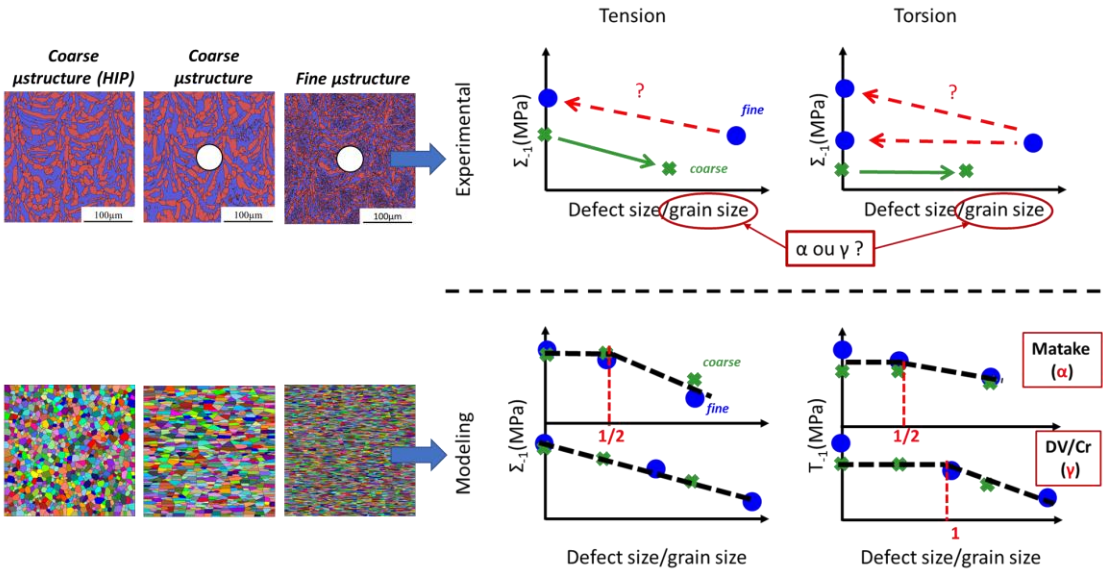



***Figure 1*** *– Overview of experimental and modeled HCF behavior*

# Hetero-deformation mechanisms and GND-associated plastic strain partitioning across single/polycrystal hetero-boundary in nickel-based superalloys

**Xiaoxian Zhang[1], Xinrui Xiao[2], Liwu Liu[2], Yanju Liu[2], Jinsong Leng[2]**

[1]*Harbin Institute of Technology, Harbin, 150001, China, xiaoxian@hit.edu.cn*

[2]*Harbin Institute of Technology, Harbin, 150001, China*

*Heterogeneous materials* *Cyclic loading* *Plastic strain accumulation*

**Abstract**

The hetero-deformation mechanisms near the single/polycrystal interface during cyclic loading, specifically diffusion-bonded single-crystal and polycrystalline, were systematically investigated. The interface, or hetero-boundary (HB), presents significant mechanical and crystallographic discontinuities, making it a preferential site for plastic strain localization and potential failure. This study integrates in-situ scanning electron microscopy and electron backscatter diffraction (EBSD) with crystal plasticity finite element (CPFE) modeling to elucidate the underlying micromechanics during cyclic loading. The methodology involved reconstructing a microstructure-sensitive CPFE model from EBSD data and simulating the local deformation and geometrically necessary dislocation (GND) evolution during the cyclic loading, with results validated against experimental observations.

The results show that the softer single-crystal domain yields first, accumulating plastic strain and developing a high GND density near the HB. This GND accumulation induces pronounced hardening, in which the GND peak sites shift from the vicinity of the HB to the interior of the single-crystal domain during the subsequent cyclic loading. The magnitude and distribution of the GND field are found to be associated with the three key factors: the elastic modulus mismatch along the loading direction ($\Delta E_{xx}$), the minimum crystallographic misorientation (θ′) between the loading direction and the <001> axis of the adjacent polycrystalline grain, and the geometric compatibility factor m' between active slip systems. Low θ′ (≤ 15°) or small $\Delta E_{xx}$ (≤ 30GPa), combined with high m' (≥ 0.8), results in minimal GND accumulation, referring good interfacial compatibility. Conversely, high θ′ with low m' promotes significant GND accumulation and plastic strain localization near the HB.

In conclusion, this study provides a mechanistic understanding of how specific crystallographic and elastic properties control the hetero-deformation and plastic strain partitioning near HB during the cyclic loading. The identification of quantitative thresholds for θ′, $\Delta E_{xx}$, and m' offers critical insights for designing interfaces with enhanced fatigue resistance and damage tolerance in advanced nickel-based superalloy components.

**Reference**

Xiao, X., Liu, L., Zhang, X., Liu, Y., & Leng, J. (2026). Hetero-deformation mechanisms and GND-associated plastic strain partitioning across single / polycrystal hetero-boundary in nickel-based superalloys. International Journal of Plasticity, 199(February), 104636. https://doi.org/10.1016/j.ijplas.2026.104636

# Simulation of complex fatigue specimen geometries and comparison with deformation-induced martensite density mapping for steels used in nuclear components

**Jens Arndt[1], Viktor Lyamkin[2], Kai Donnerbauer[3], Klaus Heckmann[1], Fabian Weber[2], Peter Starke[2], Frank Walther[3]**

*[1]GRS gGmbH, Cologne, Germany, Jens.Arndt@grs.de*

*[2]University of Applied Sciences Kaiserslautern, WWHK, Kaiserslautern, Germany*

*[3]TU Dortmund University, WPT, Dortmund, Germany*

*Short-Term Lifetime Prediction*   *Fatigue Testing*   *Magnetic Force Imaging (MFI) Analysis*

**Abstract** As part of a joint research project, fatigue specimens with graduated diameters are used in which the investigated material is subjected to multiple load levels simultaneously during a fatigue test. Due to the geometry-induced complex loading conditions, a post-mortem interpretation of the microstructural analysis requires a comprehensive understanding of the local stress and strain state.

Therefore, the austenitic steel used, AISI 347, was first tested using conventional specimen geometries in strain-increment tests. Based on the stress–strain hysteresis curves measured, a set of Chaboche plasticity model parameters was fitted for selected total strain levels. The calibrated Chaboche material model enables accurate representation of cyclic plastic behavior in finite element (FE) simulations of the complex (graduated) specimen geometry. These simulations allow the determination of the different local total strains as well as the stress and strain distributions within the specimen, which are crucial for fatigue assessment.

After mechanical testing, the actual specimen was sectioned along its longitudinal axis and subjected to MFI analysis (Magnetic Force Imaging; measurement of the magnetic interaction between an external magnetic probe and the investigated material). The fraction of deformation-induced martensite quantified by MFI was thus mapped across the entire specimen surface. The comparison between the strain amplitudes determined by simulation and the MFI map shows convincing agreement (s. *Figure 1*).

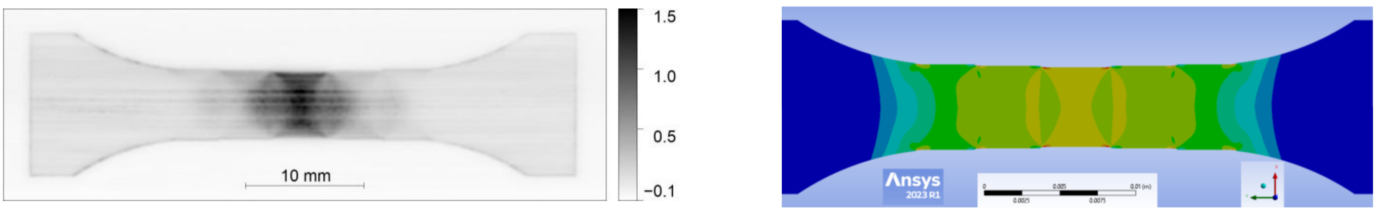



***Figure 1** – Comparison of MFI-analysis (left) with FE-analysis (right). MFI grayscale is calibrated to ferrite volume fraction (Fe%).*

In summary, the approach for material characterization, plasticity model fit and FE simulation was verified by the MFI, which is a prerequisite for analysis of graduated fatigue specimens.

# Raster angle effects on creep and low-cycle fatigue behaviour of FDM 3D-printed polymers

**I. S. Silva[1], K. Sales de Oliveira[1], A. C. Santos[2], T. Doca[1*]**

[1]*Department of Mechanical Engineering, University of Brasilia, Brazil, *doca@unb.br*

*Low-cycle fatigue* *Creep* *FDM* *3D-printed polymers*

**Abstract** Advances in manufacturing processes have increased the use of fused deposition modeling (FDM) parts due to their ease of fabrication of complex geometries, low cost and high production speed. This fabrication process is especially suited for prototyping of mechanical parts, packages and disposable devices in medical applications. However, they are rarely used for industrial components due to their lower strength, creep and fatigue resistance compared to metals or injection-molded polymers. Some printing parameters, such as the raster angle, can be manipulated to improve the mechanical properties of 3D-printed polymers under time-persistent and cyclical loading. Therefore, this work investigates the effects of raster angle on creep and low-cycle fatigue behavior in both tensile and compressive loading. Tests were conducted, according to ASTM D2990 and ASTM D7791, on acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and polyethylene terephthalate glycol-modified (PETG) specimens produced in four different raster angles: 0°, 90°, 45°/135°, and 0°/90°. Creep behavior was investigated under a stress level of 10 MPa, corresponding to 30% of the ultimate tensile strength. Fatigue life was evaluated under loading conditions equivalent to 50%, 60%, and 70% of the ultimate tensile strength, at a frequency of 5 Hz (after a prior analysis of the thermal-frequency effects). The results showed significant dependency on printing orientation. They also revealed important mechanical properties, such as the creep time-to-failure and the fatigue-life. These properties allow for the identification of optimal design configurations and the proposition of ideal usage conditions.

# High to VHCF Testing of Additive Manufactured Cellular Structures

**M. Martins[1], P. R. Costa[2,3], J. H. Lopes[1,4], P. Nogueira[1,4,5], R. Cláudio[4,6], L. Reis[1,4]**

*[1]Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal*

*[2]Atlantica Instituto Universitário, Barcarena, Portugal*

*[3]Centre for Mechanical and Aerospace Science and Technologies (C-MAST), Covilhã, Portugal*

*[4]IDMEC, Instituto Superior Técnico, Lisbon, Portugal – luis.g.reis@tecnico.ulisboa.pt*

*[5]CeFEMA, Instituto Superior Técnico, Lisbon, Portugal*

*[6]ESTSetúbal, Instituto Politécnico de Setúbal, 2910-761 Setúbal, Portugal*

*Ultrasonic fatigue* *Cellular lattice structures* *Additive Manufacturing*

**Abstract** The recent advances in metal additive manufacturing have enabled the production of complex cellular lattice structures with unprecedented geometric freedom, expanding their application in lightweight, adaptable and high-performance engineering systems. However, the fatigue characterization of such structures, particularly in the Very High Cycle Fatigue (VHCF) regime, remains challenging due to geometric complexity and testing limitations. In this study, conventional static and fatigue tests were first conducted on Laser Powder Bed Fusion (L-PBF) AlSi10Mg aluminum lattice specimens with Rhombitruncated Cuboctahedron (RTCO) unit cells, to establish a mechanical behavior baseline. Based on the obtained mechanical data, a novel 20 kHz RTCO lattice resonant specimen was numerically designed, additive manufactured, and experimentally validated. The objective was to develop a methodology compatible with existing tension-compression ultrasonic fatigue systems for complex cellular architectures. Numerical simulations ensured the desired resonance at the required testing frequency and enabled a displacement to induced stress determination method. All fatigue tests were conducted at a stress ratio of R=-1. Results confirmed a stable ultrasonic testing method for cellular materials within the VHCF regime. Stress to Cycle (S–N) analyses showed no frequency-induced effects and a consistent transition from the high-cycle to VHCF regime. These results demonstrate the feasibility and added value of the proposed ultrasonic fatigue methodology for complex additively manufactured cellular structures.

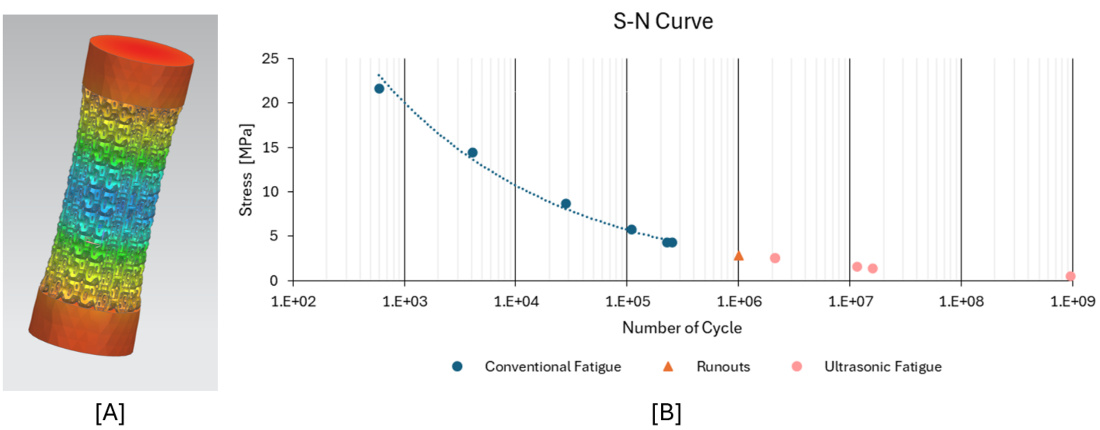



***Figure 1*** *– [A] RTCO Ultrasonic Fatigue specimen [B] Conventional and ultrasonic (S–N) results*

# Fatigue threshold prediction through inverse multiscale construction of the Kitagawa–Takahashi diagram and cyclic R-curve

**Kazuki Shibanuma[1], Qingzhi Yao[1]**

[1]*School of Engineering, The University of Tokyo, 7-3-1 Bunkyo-ku, Tokyo 113-8656, Japan*

*Kitagawa–Takahashi diagram* *Cyclic R-curve* *Fatigue thresholds* *Multiscale fatigue model*

**Abstract** The Kitagawa–Takahashi (K–T) diagram and the cyclic R-curve provide fundamental tools for interpreting defect-driven fatigue behaviour. In current engineering practice, however, the associated fatigue threshold parameters — the fatigue limit ($\sigma_e$), long-crack growth threshold ($\Delta K_{th,LC}$), and their corresponding characteristic crack lengths ($d_1$, $d_2$) — are typically determined empirically or through simplified correlations. A unified and physically consistent predictive methodology remains lacking.

In this study, a physics-based multiscale fatigue model is extended from fatigue life prediction to fatigue threshold prediction. The model integrates macroscopic finite element analysis, explicit microstructural representation, and a physically based crack growth formulation, and has demonstrated accurate fatigue life prediction without adjustable material parameters. Its capability to reproduce small-crack growth behaviour is first validated through comparison with in-situ experimental observations in ferrite–pearlite steel, successfully capturing non-monotonic crack growth behaviour and stress-level dependence.

Building upon this validation, fatigue threshold prediction is reformulated as an inverse problem. Instead of prescribing the applied stress and computing the crack growth rate, the crack arrest condition ($\mathrm{d}a/\mathrm{d}N = 0$) is imposed for a given crack length, and the corresponding critical driving forces are determined iteratively. By applying this inverse analysis over a wide crack-length range, threshold datasets are generated and used to numerically construct the K–T diagram and the cyclic R-curve. From these diagrams, $\sigma_e$, $\Delta K_{th,LC}$, $d_1$, and $d_2$ are consistently identified within a single predictive framework.

The proposed framework moves beyond empirical K–T descriptions by explicitly linking defect size, microstructural configuration, and crack-growth resistance through multiscale simulation. It provides a quantitative and predictive tool for fatigue threshold assessment in structural steels.

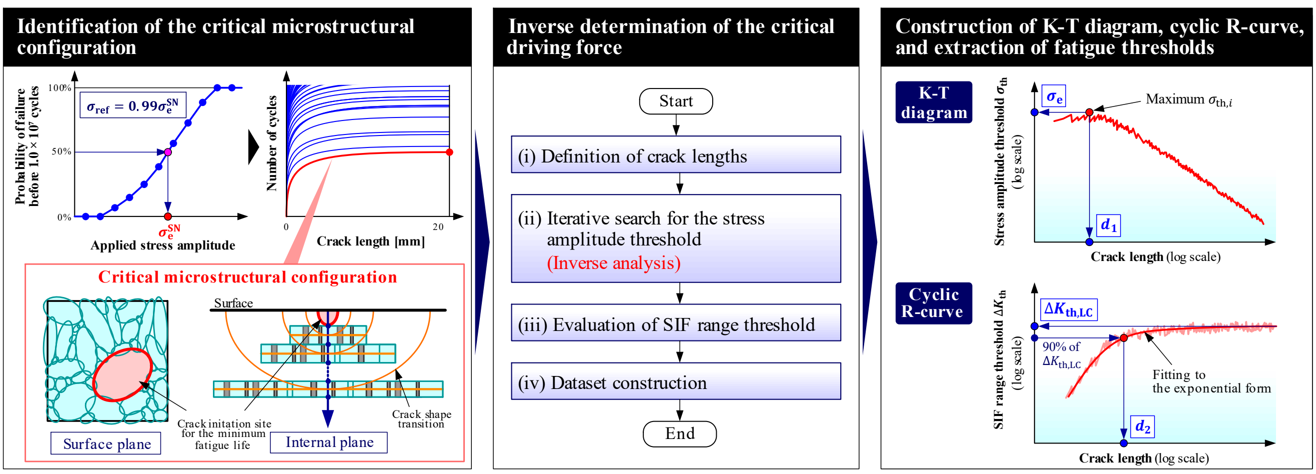



***Figure 1 -*** *Overview of the proposed inverse multiscale framework for fatigue threshold prediction*

# Fatigue behaviour of annealed AA5083 aluminium alloy specimens under block testing sequence

**Zbigniew Marciniak[1], Ricardo Branco[2], Rui F. Martins[3], Wojciech Macek[4], Cândida Malça[5, 6]**

*[1]Opole University of Technology, Department of Mechanics and Machine Design, ul. Mikolajczyka 5, 45-271 Opole, Poland z.marciniak@po.edu.pl*

*2CEMMPRE, Department of Mechanical Engineering, University of Coimbra, Rua Luís Reis Santos, Pinhal de Marrocos, 3030-788 Coimbra, Portugal*

*3UNIDEMI, Department of Mechanical and Industrial Engineering, Nova School of Science and Technology, Universidade NOVA de Lisboa, Campus de Caparica, 2829-516 Caparica – Portugal*

*4Gdansk University of Technology, Faculty of Mechanical Engineering and Ship Technology, 11/12 Gabriela Narutowicza, Gdansk 80-233, Poland*

*5Department of of Mechanical Engineering, Polytechnic Institute of Coimbra, Rua Pedro Nunes, Coimbra, 3030-199, Portugal*

*6Centre for Rapid and Sustainable Product Development, Polytechnic Institute of Leiria, Rua de Portugal, Marinha Grande, 2430-028, Portugal*

*Low cycle fatigue* *Block loading sequence* *AA5083 aluminium alloy*

**Abstract** This work presents the effect of block loading sequence on the fatigue life of 5083 aluminium alloy. The specimens have been subjected to uniaxial loads with different strain amplitudes. Three different strain ratios were selected for the tests, R = -1, -0.5 and 0, and three strain amplitudes ranging from 0.4% to 0.6%. The number of cycles of the first block corresponded to 50% of the fatigue life determined under the same conditions in a constant strain amplitude test. The second block lasts until failure. During the strain-amplitude-controlled tests, the cyclic stress-strain response was recorded, enabling the observation of the evolution of the hysteresis loops. The test showed a significant reduction in fatigue life in almost every case.

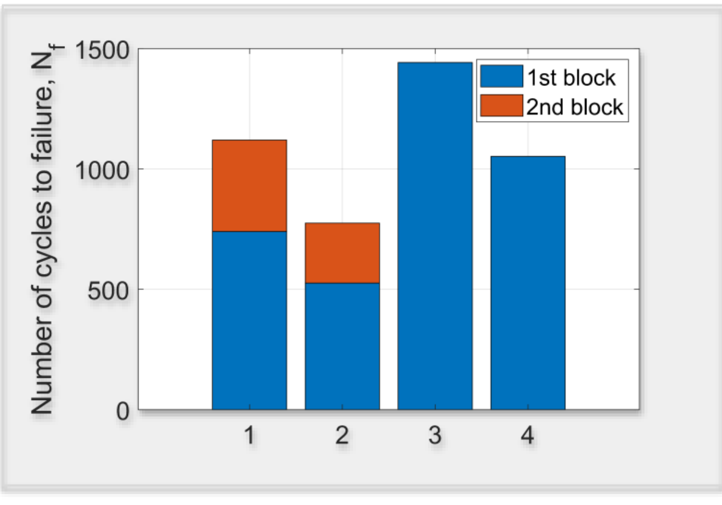



***Figure 1 -*** *Comparison of fatigue lives for a strain amplitude of 0.4%: 1- 1st block R=-1, 2nd block R=0; 2 - 1st block R=0, 2nd block R=-1; 3 - constant amplitude test for R=-1; 4 - constant amplitude test for R= 0*

# Quantification of the influences of composition and microstructure on the mechanisms of FGA formation in quenched and tempered steels by in situ testing and high-resolution analysis

**Praveen Velliyangiri[1], Marion Kreins[1], Ulrich Krupp[1]**

[1]*IEHK, RWTH Aachen, Intzestraße 1, D-52072 Aachen; E-Mail: praveen.velliyangiri@iehk.rwth-aachen.de*

*FGA* *VHCF* *In situ testing*

**Abstract:** In the Very High Cycle Fatigue (VHCF) regime, high strength quenched and tempered steels frequently fail at stress amplitudes significantly below the conventional fatigue limit. These failures typically originate at internal microstructural defects, such as non-metallic inclusions, pores, or grain boundary triple points. A characteristic feature of these initiation sites is the Fine Granular Area (FGA), a nanograined region distinct from the surrounding micrometer-sized martensitic matrix. Despite its prevalence, the mechanism of FGA formation, specifically whether it is a prerequisite for or a consequence of crack initiation, remains a subject of debate. This study investigates the mechanisms of FGA formation in 100Cr6, 50CrMo4 and 25CrMo4 steels using in situ VHCF experiments conducted within a Scanning Electron Microscope (SEM). To simulate the vacuum environment of internal crack initiation, tests are performed in the SEM chamber using specimens with artificial notches acting as stress concentrators. The study focuses on both the microstructural influence of non-metallic inclusions, including their size, morphology, and stiffness, as well as the local chemistry, on dislocation behavior. It is hypothesized that strain localization at the inclusion interface drives initial grain refinement, which is subsequently stabilized by local chemical segregation to form the FGA. This research provides a quantitative analysis of the interactions between inclusion characteristics, local stress states, and nanograin development, offering new insights into the mechanisms governing VHCF life.

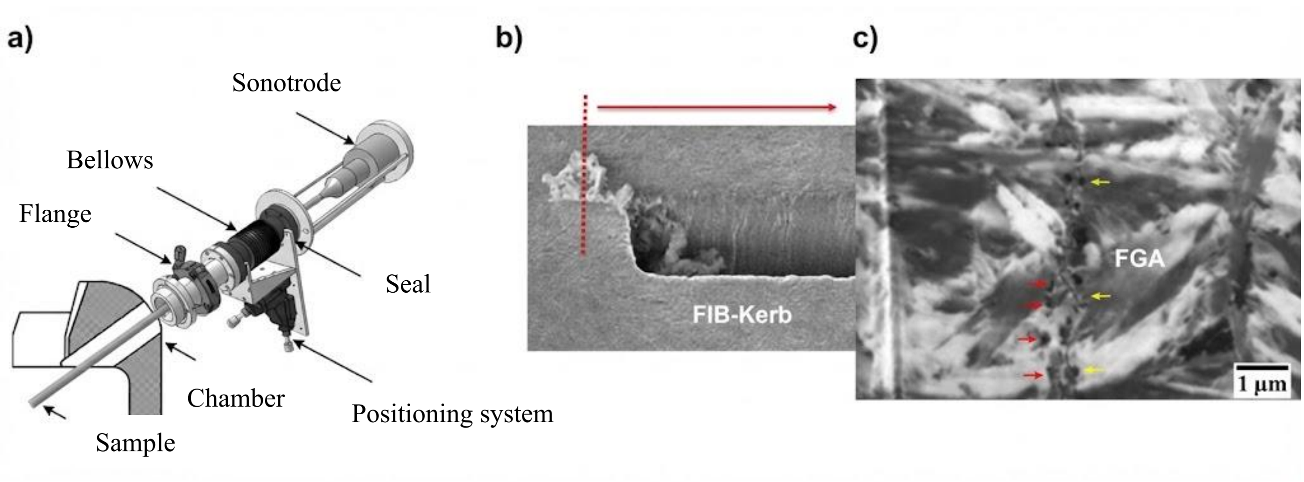



***Figure 1*** *– In situ ultrasonic testing in scanning electron microscope: a) Integration of the test system into the SEM chamber, b) crack initiation on a FIB notch (50CrMo4, 57 HRC, $10^8$ cycles), c) FIB section through the crack with FGA on the artificial notch* ***[Gie21]****.*

# Fractographic observation of small crack propagation in conventional and additively manufactured Ti

**Ondřej Kovářík[1], Anna Kimlová[1], Milan Kocáb[2], Aleš Materna[1]**

*[1]Department of materials, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Trojanova 13,120 00, Praha 2, Czech Republic*

*HiLASE Centre,Institute of Physics of the Czech Academy of Sciences, Za Radnicí 828, 252 41 Dolní Břežany, Czech Republic*

*small cracks* *fractographic marking* *cyclic R-curves*

**Abstract** With the boom of additive manufacturing (AM) techniques, materials with many defects are generated. This calls for the study of small cracks growing from these defect in terms of their initiation, growth and mutual interactions. Several recent studies try to generalize the cyclic R-curves concept built on through thickness cracks to predict the propagation of short cracks radially growing from defects. We attempt to contribute to this topic by describing the crack propagation using fractographic analysis of fractographically marked cracks, growing from artificial and naturally occurring defects. Laser was used to create artificial defects of different shapes and sizes to initiate fatigue cracks. Constant amplitude loading with fractographic marking was used to initiate and grow the cracks. Short marking interval enabled to generate tight spaced marks, similar to fatigue striations. By measuring their spacing, local crack growth was evaluated even for very short cracks. The crack propagation was then described by back integrating the crack growth rate from the known crack front. After obtaining the the corresponding crack driving force by FEM, this concept will allow to efficiently study the small fatigue crack propagation.

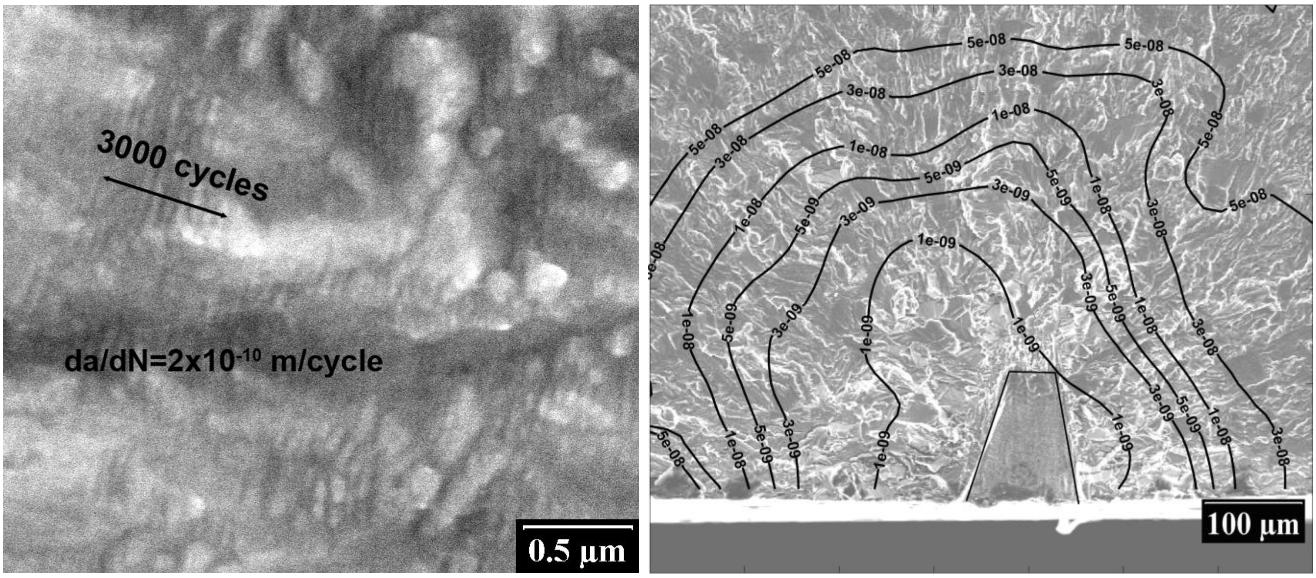



***Figure 1*** *– Ti sheet:fatigue crack marking at low crack propagation rate (left)and the reconstructed crack propagation rate map in m/cycle (right)*

# Evaluation of the Fatigue Behaviour of 3D-printed PEEK Cranial Reconstruction Implants

**P. Rendas [1,2], R. Jordão[2], R. F. Martins[2,3], L. Figueiredo[4], R. Cláudio[1,4], B. A. Soares[2,3]**

*[1]Escola Superior de Tecnologia de Setúbal, Instituto Politécnico de Setúbal, Setúbal, Portugal*
*[2]UNIDEMI, NOVA School of Science and Technology, Universidade NOVA de Lisboa, Caparica, Portugal*
*[3]Laboratório Associado de Sistemas Inteligentes, 4800-058 Guimarães, Portugal*
*[4]IDMEC, Instituto Superior Técnico, Lisbon, Portugal*

*PEEK* *Patient-matched Implants* *High-Cycle Fatigue*

**Abstract** Polyetheretherketone (PEEK) is a high-performance thermoplastic material that combines biocompatibility with a specific strength comparable to certain aluminium alloys. Compared with metallic biomaterials, PEEK is compatible with medical imaging techniques, and its lower rigidity helps mitigate stress shielding in repaired bone structures, known to lead to bone resorption. For these reasons, PEEK has been identified as a leading thermoplastic material for the replacement of metals in implant applications for bone reconstruction. Additionally, its processability via material extrusion (ME) additive manufacturing (AM) has been explored for the production of medical devices personalized to each patient based on medical imaging data. Such 3D-printed devices can improve surgical outcomes by enhancing anatomical fit and shortening preoperative wait times. Despite this potential, the typical route to achieve regulatory conformity for implantable medical devices, which typically requires clinical investigation, is extensive and often negates the lead-time advantages of AM. Consequently, the equivalence route remains the most practical option for 3D-printed implantable devices, requiring manufacturers to provide evidence that the printed device is equivalent to one already available on the market.

In this context, this study investigates the technical equivalence of 3D-printed PEEK implantable devices, focusing on the fatigue performance of cranial reconstruction plates. First, the tension–tension high-cycle fatigue behaviour of 3D-printed PEEK specimens was characterized using Basquin's power law model, comparing the effects of modified printing strategies aimed at the reduction of deposition-related void defects. This analysis is complemented with fracture surface analysis to relate crack nucleation and propagation to the macrostructure generated by printing deposition. Subsequently, an established design and manufacturing workflow was applied to produce patient-matched cranial plates via 3D printing. A custom fixture replicating *in vivo* bone reconstruction conditions was developed to test the plates under cyclic loading and compare the fatigue response between design and manufacturing-equivalent devices. Although limited by sample size, this work represents one of the early efforts to provide manufacturers with essential fatigue data on 3D-printed devices, supporting the equivalence route for regulatory approval and promoting the use of 3D-printed PEEK in clinical practice.

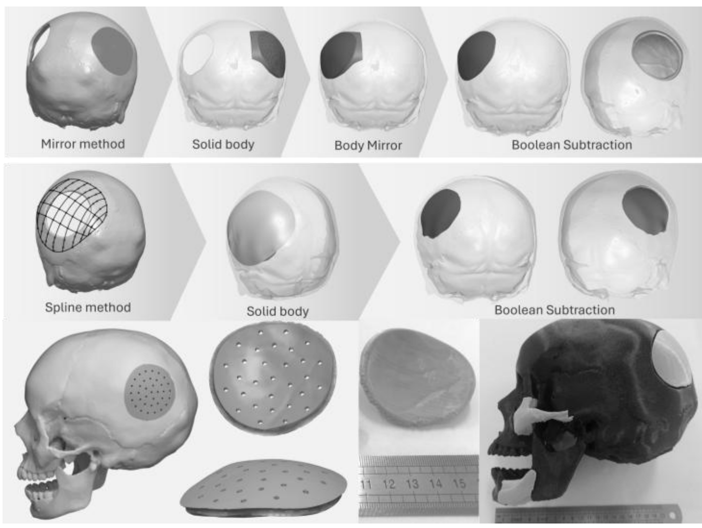



***Figure 1** – Design and manufacture methodology of the 3D-printed PEEK cranial plate*

# Effect of Aging on Tensile and High Cycle Fatigue Performance of 18Ni-300 Maraging Steel

**Chitresh Chandra[1], Supriyo Ghosh[2], *Vidit GAUR[1]**

[1]*Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Uttarakhand 247667, India*

[2]*Department of Metallurgical and Materials Engineering, Indian Institute of Technology Roorkee, Uttarakhand 247667, India*

*vidit.gaur@me.iitr.ac.in

**Keywords:** Maraging steel, Heat treatment, Mechanical properties, High-Cycle Fatigue.

**Abstract:** Maraging steels belong to the class of ultra-high-strength, low-carbon martensitic alloys with excellent mechanical strength, superior toughness, and outstanding dimensional stability. These properties are primarily achieved through precipitation hardening during the aging heat treatment, where nano-sized precipitates form within the martensitic matrix. Due to this unique microstructural strengthening mechanism, maraging steel is widely used in high-performance and safety-critical applications, such as aerospace structures, defense components, tooling systems, and precision engineering parts that are often subjected to cyclic loading conditions. We focus on understanding the effect of aging treatment on mechanical and high-cycle fatigue (HCF) behaviour of 18Ni-300 grade maraging steel. Mechanical testing was performed using strain-controlled tensile tests to evaluate static mechanical properties, while load-controlled high-cycle fatigue tests were conducted to assess fatigue performance. Smooth, dog-bone-shaped specimens were tested in both solution-treated and aged conditions to study the influence of microstructural evolution induced by the aging treatment. To interpret the underlying damage mechanisms, detailed fractographic analysis was carried out using scanning electron microscopy (SEM). The SEM observations enabled the identification of fatigue crack initiation sites, crack propagation paths, and final fracture features, providing insights into the role of microstructural constituents in governing fatigue behaviour. The results indicate that aging treatment significantly enhances tensile strength due to precipitation strengthening; however, a noticeable reduction in fatigue strength was observed in the aged condition compared to the solution-treated state. The study establishes a clear relationship between heat treatment, microstructural evolution, mechanical response, and fatigue performance of 18Ni-300 maraging steel. The findings contribute to a deeper understanding of fatigue behaviour in precipitation-hardened maraging steels and provide useful guidelines for optimizing heat treatment parameters. Overall, the results support the reliable and efficient use of 18Ni-300 maraging steel in fatigue-critical and high-reliability engineering applications.

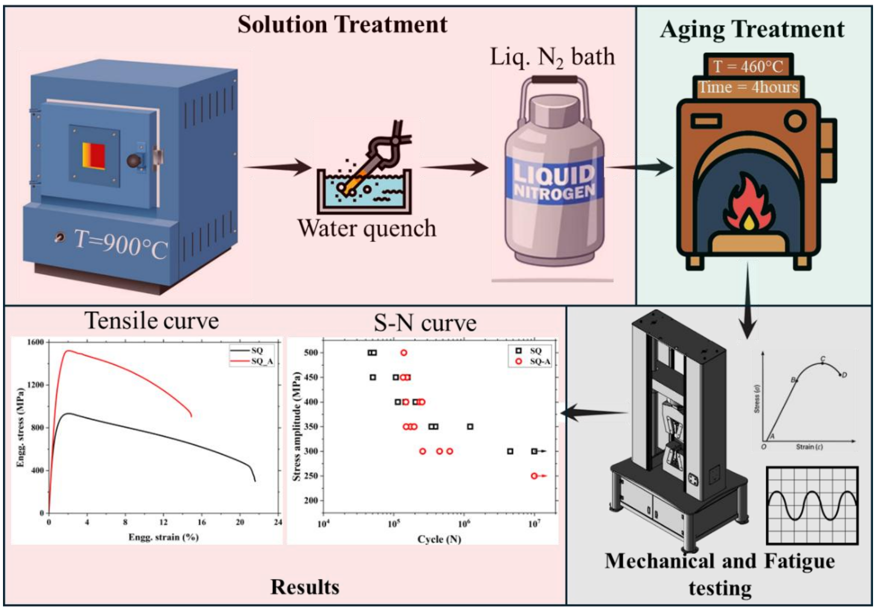



***Figure 1:*** *Methodology*

# Numerical analysis of crack initiation in the nub–groove contact of marine risers including wear

**Arthur Ferreira Padilha Sette[1], Jose Alexander de Araujo[2], André Luis Rodrigues Araújo[3], Raphael Araujo Cardoso[2]**

*[1]University of Brasilia, Department of Mechanical Engineering, 79010-900 Brasília, DF, Brazil,* *arthur.sette@aluno.unb.br*

*[2]University of Brasilia, Department of Mechanical Engineering, 79010-900 Brasília, DF, Brazil,*

*[3]University of Brasilia, Faculty of Science and Technology in Engineering, 70910-900 Brasília, DF, Brazil.*

*Fretting Fatigue* *Wear* *Crack initiation*

Marine risers are a key components in the modern offshore petroleum industry, responsible for transportation of hydrocarbons and operational fluids. A primary challenge of their safe design is the pressure armor layer, which is made of helically wound interlocking steel wires, primarily because waves-induced vibration on the tube promotes fretting in the inter-wire interfaces. Fretting is defined as a type of superficial damage that occurs when two bodies in contact undergo micro-scale relative tangential displacement, initiating cracks that jeopardize operational safety. Differences in external and internal pressure also induce hoop static stress in the armor layer, which effectively acts as an out-of-plane bulk load in the contact problem. Therefore, this work aims to numerically investigate the fretting behavior in a specific nub-groove geometry, characterized by a round-ended flat configuration, by assessing crack initiation risk and comparing it to experimental data. For this purpose, a finite element model is used, including mesh modification and incremental damage calculations to account for material wear. Smith-Watson-Topper (SWT) multiaxial parameter coupled with critical distance was used to address non-proportional and rapidly varying stress fields. Out-of-plane remote load effects were integrated during post-processing by superimposing stress and strain fields from global bulk simulations onto the 2D local model results. The findings demonstrate that incorporating wear improves crack initiation estimates compared to non-wear models, primarily due to the removal of damaged material and the redistribution of contact stresses. Analysis suggests the contact operates predominantly in the gross slip regime, with partial slip occurring only within a narrow range of displacement amplitudes.

# An Innovative Ultrasonic Fatigue Test towards the Characterization of Lap Joint Adhesives in Shear

**Catarina Faria[1], Pedro R. da Costa[2,3], J. Henrique Lopes[1,4], Rosemere Lima[1,4], Manuel Freitas[2,3], Luís Reis[1,4]**

*[1]Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal*

*[2]Atlantica Instituto Universitário, Barcarena, Portugal*

*[3]Centre for Mechanical and Aerospace Science and Technologies (C-MAST), Covilhã, Portugal*

*[4]IDMEC, Instituto Superior Técnico, Lisbon, Portugal*

*Ultrasonic fatigue* *Double Lap Joint (DLJ)* *Shear Stress*

**Abstract** The characterization of adhesive fatigue response through ultrasonic testing methods remains limited to date. Extending ultrasonic fatigue techniques to adhesive joints is of significant interest, as it enables rapid testing under extreme cyclic loading and facilitates the assessment of long-term adhesive performance within a reduced timeframe. This work presents a novel methodology for testing Double Lap Joint (DLJ) specimens manufactured with structural epoxy DP460 bonded to aluminum alloy 7075-T6 under ultrasonic fatigue. Modifications to the ultrasonic testing machine and rig allowed reliable specimen constraint and testing at a stress ratio of R = 0.1. All components were numerically modelled to ensure the desired resonance at the machine's operating frequency (20 kHz), thereby subjecting the adhesive layers to cyclic shear stress. The crack propagation and damage evolution were monitored by frequency response and thermography, as shown in Figure 1.

The innovative methodology successfully induced shear fatigue and enabled testing in the very high cycle fatigue regime. It provides an effective framework for investigating fatigue failure in adhesive joints at high frequencies, and highlights the critical role of specimen geometry, manufacturing quality, and ultrasonic system configuration, contributing to the expansion of ultrasonic fatigue testing methods for structural adhesives.

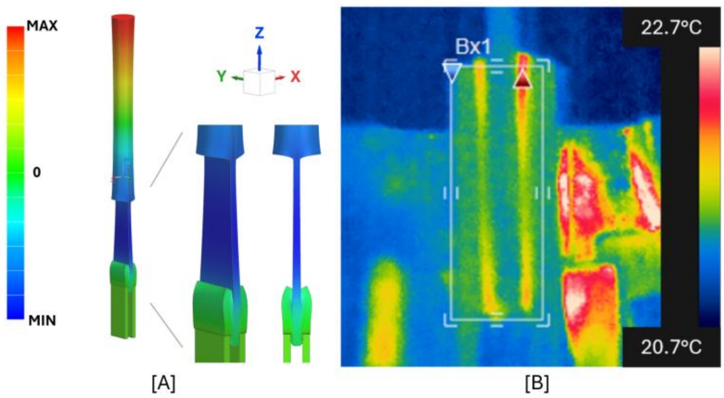



***Figure 1** – [A] DLJ z-displacement for axial resonant mode. [B] Thermal image of the adhesive joint under ultrasonic fatigue*

# Effect of Dynamic Strain Aging-mediated Thermomechanical Treatments on the Fatigue Properties of Notched Commercially Pure Titanium

**Nafiseh Ghavidel[1], Phanuphak Seensattayawong[1], Eberhard Kerscher[1]**

[1] *Working Group Materials Testing, RPTU University Kaiserslautern-Landau, Kaiserslautern, Germany, n.ghavidel@rptu.de*

*Dynamic Strain Aging* *TMT* *Fatigue*

**Abstract** Dynamic strain aging (DSA) can be used as a strengthening mechanism in metals and alloys, resulting from the interaction between diffusing solute atoms and moving dislocations, which enhances the material's mechanical properties under certain conditions. It is reported that a thermomechanical treatment (TMT) involving cyclic plastic deformation in the temperature range of DSA can affect the mechanical properties (e.g., increasing fatigue limit) of steels [1–3]. In our study, the influence of a thermomechanical treatment on the fatigue properties of commercially pure titanium (CP-Ti) was systematically investigated. TMT was conducted within a temperature range conducive to DSA, utilizing cyclic tension-compression loading with either constant or stepwise increasing load amplitudes. The primary objective was to enhance the fatigue properties, particularly in specimens containing inhomogeneities like notches. Fatigue testing demonstrated that TMT with a constant stress amplitude adversely affected the fatigue limit compared to untreated samples, attributed to the roughness changes during TMT. To avoid these detrimental effects, a modified TMT approach was implemented, which successfully reduced unfavourable microstructural characteristics. This modified TMT resulted in an increased fatigue limit of notched samples, suggesting that the improvement can be linked to a stabilized microstructure around critical crack-initiating sites. This stabilization is likely due to the locking of edge dislocations by diffusing solute atoms due to the dynamic strain aging phenomenon during the TMT process, thereby enhancing the material's resistance to fatigue failure. Moreover, the stepwise TMT increased the homogeneity distribution of hardness around the notch.

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# Very high cycle fatigue of high strength steels applied to aeronautic rolling bearings

**Hugo Behlal[1], Daniel Nélias[1], Naïm Naouar[1], Jean-Baptiste Coudert[2], Arnaud Ruellan[2], Geoffray Deterre[3]**

[1]*INSA Lyon, CNRS, LaMCoS, UMR5259*

[2]*SKF Aerospace Valence*

[3]*SAFRAN Aircraft Engines*

*Very High Cycle Fatigue* *Rolling contact fatigue* *Crack propagation*

**Abstract:** The bearings used in aerospace transmission systems are subjected to a very large number of loading cycles due to decades of use, sometimes under extreme stress. These repeated cycles of the rolling elements on the raceway can cause various types of damage, grouped under the term rolling contact fatigue (RCF). Unlike conventional fatigue, which generally involves relatively simple and proportional stresses, RCF is characterized by localized, multiaxial, highly compressive and non-proportional cyclic stresses. Obtaining an S-N curve can be extremely time consuming, especially when focusing on the VHCF range. Consequently, over the past two decades, ultrasonic machines operating at 20 kHz have been widely adopted to reduce test duration, making it possible to study the VHCF domain and generate S-N curves. This is thanks to the drastic reduction in test time.

In order to reproduce the compressive component of the complex stress states encountered in RCF, a static compressive preload is applied prior to high-frequency dynamic loading $\Delta\sigma$. An artificial defect machined by electrical discharge machining (EDM) is introduced to generate a multiaxial and non-proportional stress state. The stress fields typically encountered in RCF are numerically compared through simulations, while, from an experimental standpoint, the resulting S–N curves are evaluated and contrasted. In addition, microstructural evolutions are investigated to strengthen the comparison, both in situ using X-ray tomography and post mortem through SEM analyses.

The primary objective of this study is to demonstrate that ultrasonic fatigue testing is representative of the damage mechanisms occurring in rolling bearings during service. The present results already indicate that the application of a compressive preload has a beneficial effect on the fatigue life of the M50 steel

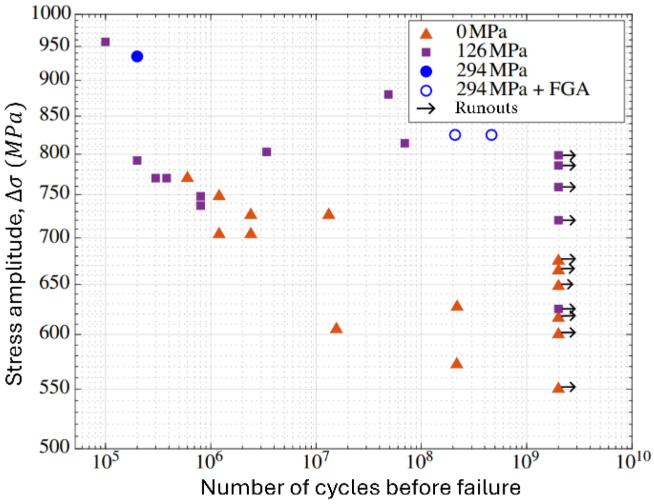


***Figure 1 -*** *M50 S-N curves for different compressive preloads*

# Phase-field modeling of fatigue life for SLM-fabricated Ti6Al4V alloy: synergistic effect of defects and microstructure

**Zhongwen Tao[1], Hao Xin[1], Xiaofan He [1,*]**

[1]*National Key Laboratory of Strength and Structural Integrity, School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China*

* *Corresponding author. E-mail address: xfhe@buaa.edu.cn (X. He)*

*selective laser melted* *Phase-field modeling* *Fatigue life*

**Abstract** Selective Laser Melting (SLM) technique provides a new approach to produce high-performance, complicated Ti6Al4V alloys. However, its quick non-equilibrium solidification produces distinct microstructural characteristics in the manufactured parts, including as pores, the absence of fusion defects, and coarse columnar grains, all of which have a significant influence on fatigue performance. Traditional assessment approaches struggle to uncover the synergistic impact of flaws and microstructure. Furthermore, present mesoscale simulations frequently focus on single parameters or rely on sophisticated crystal plasticity constitutive models, limiting their practical engineering applications.To solve this issue, the current work presents a new phase-field model based on dual-parameter quantification of defects and microstructure. By incorporating characteristic parameters that measure the equivalent sizes of pores and critical microstructural units independently, the phase-field damage development framework unifies and couples the effect of both elements. This technique eliminates the requirement for complicated crystal plasticity factors, allowing for the prediction of fatigue life. Finally, the synergistic failure process is shown by examining the effects of dual defect and microstructure factors on fatigue damage progression and *S*-*N* curves. The model's predictive capability was evaluated against experimental data, resulting in a useful theoretical tool for assessing the fatigue life of additively formed Ti6Al4V alloys using SLM.

# Environmental Effect on Fatigue Behaviour of FSW Joints For Battery Packs

**Rodrigo J. Coelho[1], André Dias[2], Beatriz Silva[1], Carolina Francisco[1], Tiago Domingos[1], Pedro Sousa[1,2], Paulo J. Tavares[1], Daniel Braga[1], Pedro M.G.P. Moreira[1], Fernando Moreira [3]**

[1]*INEGI, Campus da FEUP, Rua Dr. Roberto Frias, Porto, 4200-465, rjcoelho@inegi.up.pt*

[2] *Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, Porto, 4200-465, Portugal*

[3] *TSF, Rua do Sol Poente, Vila Nova de Famalicão, 4764-908, Portugal*

*Friction Stir Welding* *Fatigue* *Corrosion*

**Abstract** The growing adoption of electric vehicles (EVs) is accelerating the demand for advanced battery systems that combine reduced weight, improved safety, and structural integration. Concepts such as load-bearing and structurally embedded batteries require joining technologies capable of delivering high mechanical performance, leak-tightness, and long-term reliability, particularly when dissimilar or corrosion-prone materials are involved. Friction Stir Welding (FSW) has emerged as a promising solution for manufacturing multifunctional battery enclosures, offering superior joint strength and sealing performance compared to conventional fusion welding. However, battery housings and thermal management components are often exposed to aggressive environments, including humid and saline conditions typical of coastal regions and winter road-salting. Such exposure can accelerate corrosion-induced degradation, affecting the microstructure and chemical stability of both base materials and weld zones, ultimately reducing joint integrity and compromising safety. Studying the influence of saline environments on the mechanical performance and durability of FSW joints, provides essential insights for the adoption of FSW in next-generation structural EV battery architectures.

The present study examines the fatigue performance of an aluminium FSW joint intended for use in battery pack structures and assesses how exposure to a salt-rich environment influences this behaviour, providing insight into the environmental durability of such joints.

AA5074/AA6082 FSW joints were obtained and exposed to a salt rich environment in a salt fog chamber for various durations, enabling the assessment of the joint's performance under increasing levels of salt environment exposure. The impact of the corrosion on the joint's mechanical performance and durability was assessed by performing Quasi-static Tensile Tests, Fatigue and Fatigue Crack Growth tests on non-corroded and corroded specimens.

**Acknowledgements** This research was funded by the European Union under the Next Generation EU, through a grant of the Portuguese Republic's Recovery and Resilience Plan (PRR) Partnership Agreement, within the scope of the project PRODUTECH R3— "Agenda Mobilizadora da Fileira das Tecnologias de Produção para a Reindustrialização"—aiming at the mobilization of the production technologies industry toward the reindustrialization of the manufacturing industrial fabric (Project ref. nr. 60—C645808870-00000067; Total project investment: EUR 166.988.013,71; Total Grant: EUR 97.111.730,27).

# Experimental fatigue assessment of carbon fiber–reinforced polyvinylidene fluoride (CF/PVDF) composites for offshore flexible pipe applications

**Tiago Lima Castro[1], Geovane de Almeida da Silva[1], Camila Alves Farias[1], Gabriela Ribeiro Pereira[1], Marysilvia Ferreira da Costa[1], Celio Albano da Costa[1]**

*[1]Department of Metallurgical and Materials Engineering, Federal University of Rio de Janeiro—UFRJ, Avenida Horácio Macedo, 2030, Rio de Janeiro 21941-598, RJ, Brazil; celio@metalmat.ufrj.br*

*Thermoplastic composite pipes (TCP)*    *Fatigue testing methodology*    *Specimen geometry design*

**Abstract** Although well established and widely used in the offshore oil and gas industry, conventional flexible pipe designs rely on multiple concentric metallic and polymeric layers, resulting in complex multilayer mechanics, high structural weight, and susceptibility to corrosion of the metallic armor wires. In contrast, thermoplastic composite pipes (TCP) replace several of these internal layers with a single structural layer made of carbon fiber–reinforced polyvinylidene fluoride (CF/PVDF), combining the high strength of the carbon fibers with the low density, chemical resistance, thermal stability and corrosion immunity of PVDF. Despite their industrial relevance, fatigue data for such thermoplastic composites remain scarce. Since standardized fatigue specimen geometries for composite materials are typically slender, the assessment of push-pull fatigue behavior is limited as specimens are prone to buckling and delamination under compression. Furthermore, torsional fatigue testing and fatigue crack propagation in thermoplastic composites also constitute relevant gaps in the literature. In this context, the present work investigates the fatigue behavior of CF/PVDF with emphasis on experimental methodology. A specimen geometry suitable for fully reversed push–pull and torsional fatigue testing is proposed, improving compressive stability and enabling the assessment of fatigue performance under more representative service loading conditions. Additionally, a modification to the standard compact tension (CT) specimen is introduced to mitigate local plastic strain at the pin-loaded holes, thereby allowing for fatigue crack propagation assessment. Finally, specimens are subjected to accelerated environmental aging in a medium that simulates offshore service conditions, aiming to quantify the influence of aggressive environmental exposure on the fatigue performance of the composite.

# On the fatigue crack growth rate threshold in the very high cycle fatigue regime

**Bernd M. Schönbauer**

*Christian Doppler Laboratory for Defect Tolerance of Steels in the High and Very High Cycle Fatigue Regime, Institute of Physics and Materials Science, BOKU University, Peter-Jordan-Str. 82, 1190 Vienna,* Austria
*bernd.schoenbauer@boku.ac.at*

*Very high cycle fatigue* *Fatigue crack growth* *Threshold stress intensity*

**Abstract** There are two possible reasons for fatigue failure in the very high cycle fatigue (VHCF) regime under constant amplitude loading conditions. The first possibility is that crack formation consumes most of the fatigue lifetime, and crack propagation only occurs after a high number of load cycles has accumulated. One example of this is when corrosion pits form in an aggressive environment and pit-to-crack transition takes place after a pit exceeds a critical size. The second possibility is that cracks initiate in the early stage of cyclic loading, but these cracks growth so slowly that failure can only occur in the VHCF regime, i.e. after $10^7$ cycles. In this case, fatigue crack growth rates (FCGRs) below one Burgers vector per cycle are required.

The present investigation focuses on the second scenario, where fatigue cracks grow below the classical threshold stress intensity factor, $\Delta K_{\mathrm{th,lc}}$, determined at $10^{-10} - 10^{-11}$ m/cycle. This is the case, on the one hand, when fish-eye fracture occurs in the VHCF regime. It has been verified by several researchers that ultra-slow FCGRs of interior cracks can lead to failure even after more than $10^9$ cycles, and that a vacuum-like environment in the sub-surface of a material is essential for this type of fracture. On the other hand, ultras-slow FCGRs can also be observed for surface cracks. In this case, degrading environmental conditions, such as air humidity in ultrahigh-strength steels, can cause surface failure in the VHCF regime.

Fatigue crack growth rate curves below the classical threshold regime for steels and aluminium alloy will be presented. The experiments were conducted using the unique ultrasonic fatigue testing equipment developed at BOKU University, which enables to perform fracture mechanics investigations at a cycling frequency of around 19 kHz. FCGRs as slow as $10^{-15}$ m/cycles were measured in high vacuum, ambient environment, and dry air. Furthermore, true threshold values associated with crack arrest for up to $10^{11}$ cycles were determined. Based on these results, the existence of a fatigue limit associated with interior fracture is hypothesised.

# Challenges in Specimen Representativeness for Aerospace Qualification of PBF-LB/M AlSi10Mg

**Ana Ferramacho[1,2], António Garcês[1], Paulo Machado[1,2], Pedro Rendas[2], Rodolfo Batalha[3], Ricardo Cláudio[2,4,5], Célio Pina[2,6]**

*[1]Lauak Portugal, Rua do Bairro da Estação, 9, 7570-261 Grândola, Portugal (ana.ferramacho@wiprolauak.com)*

*[2]ESTSetúbal, Instituto Politécnico de Setúbal, 2910-761 Setúbal, Portugal.*

*[3]Instituto de Soldadura e Qualidade, Av. Prof. Dr. Cavaco Silva, Porto Salvo, 2780-920, Portugal*

*[4]IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal.*

*[5]DICE Lab, Instituto Politécnico de Setúbal, Setúbal, Portugal.*

*[6]CFEMA, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal.*

*AlSi10Mg* *Additive Manufacturing* *Aerospace Qualification*

**Abstract** Additive manufacturing (AM), particularly Laser Powder Bed Fusion (L-PBF), is increasingly adopted in the aerospace sector due to its ability to produce lightweight, geometrically complex components. However, qualification of AM processes for flight-critical applications requires a rigorous understanding of how processing parameters and build conditions influence material properties. Aluminium alloy AlSi10Mg is widely used in L-PBF because of its good castability, strength-to-weight ratio, and responsiveness to rapid solidification, but it is also highly sensitive to thermal history. Ensuring that mechanical test specimens accurately represent the material conditions within the build is therefore essential for reliable certification.

To evaluate the quality of AlSi10Mg produced by Laser Powder Bed Fusion, as part of the qualification procedure, tensile test specimens were fabricated alongside aerospace components and examined with respect to their mechanical and microstructural consistency. Hardness measurements taken along the build height revealed that specimens extending above the nominal component height exhibited a hardness reduction of approximately 50%, with considerable impact on tensile and fatigue properties. Analysis of build-specific parameters showed a clear correlation between hardness and layer time for such specimens. In regions where hardness is lower, the microstructure exhibits disruption of the Si cellular network, similar to what occurs after heat treatment. These findings indicate that specimens produced under such conditions are not representative of the build, as they experience different processing parameters compared to the remaining parts. The significant reduction in layer time leads to heat accumulation, a phenomenon further amplified by the specimen geometry, which presents a larger cross-sectional area above the tensile stem.

This study highlights the need for careful specimen design, placement and control of layer time, specially in higly productive devices, in order to ensure representative material qualification for aerospace-grade L-PBF components.

# Peridynamic Analysis of Stop-Hole Effects on Fatigue Crack Growth in Aerospace Structures

**Mehmet Dördüncü[1], Hasan Hüseyin Camuz[2], Uğur Altay[3], Erdogan Madenci[4]**

[1]*Izmir Institute of Technology, Department of Mechanical Engineering, mehmetdorduncu@iyte.edu.tr*

[2]*Baykar Technologies, Istanbul, Türkiye*

[3]*Middle East Technical University, Ankara, Türkiye*

[4]*The University of Arizona, Tucson, AZ, USA*

*Peridynamics* *Fatigue crack growth* *Plasticity*

**Abstract** Lightweight engine support components in unmanned aerial vehicles are subjected to repeated cyclic loads, making local stress raisers critical sites for fatigue crack initiation and propagation. Among these components, engine ribs are particularly vulnerable to damage accumulation around bolt holes, fillets, and local geometric discontinuities. Accurate prediction of crack growth and evaluation of practical crack-arrest measures are therefore essential for extending structural life and maintaining operational reliability.

This study presents a peridynamic framework for assessing fatigue crack propagation and crack-arrest strategies in UAV engine ribs under cyclic loading. Owing to its non-local formulation, peridynamics enables direct simulation of crack initiation and growth without requiring supplementary crack-tracking criteria, remeshing, or predefined crack paths. Such a capability is particularly attractive for aerospace components, where multiple stress concentrators may trigger complex and interacting crack trajectories.

To improve the representation of local nonlinear effects near stress concentrations, the bond-based peridynamic fatigue model is combined with Neuber's plasticity correction. This enhancement allows the local elastic stress field to be adjusted to account for elastoplastic behavior at highly stressed regions, leading to a more realistic estimation of the strain amplitude governing fatigue damage evolution. In this way, the framework is better suited for ductile metallic engine-rib components in which purely elastic approximations may overestimate residual life.

Within this formulation, the influence of crack-arrest measures, particularly stop-hole configurations, is investigated by varying repair-hole diameter and placement relative to the crack tip. Numerical simulations are used to examine their effect on crack path deviation, crack growth retardation, and residual fatigue life. The results show that appropriately positioned stop-holes can reduce the local crack-driving force and delay crack extension, whereas poorly selected configurations may generate secondary damage zones and accelerate failure.

The study provides a fatigue-oriented computational framework for the assessment of repaired or damage-tolerant UAV engine ribs. By combining the discontinuity-handling capability of peridynamics with Neuber-based local plasticity correction, the proposed approach offers a distinct contribution that extends beyond conventional crack-growth simulations and supports more reliable maintenance and design decisions for aerospace structures.

# Effect of aging heat treatment on the uniaxial and multiaxial fatigue behavior of the AlSi10Mg alloy obtained by laser powder bed fusion

**Antônio Augusto Couto[1], Gleicy de Lima Xavier Ribeiro[2], Rene de Oliveira[3], Marcos Massi[1], Rodolfo Luiz Goncalves[1], Gisele Fabiane Costa Almeida[1], Luis Reis[4]**

[1]*Engineering School, Mackenzie Presbyterian University, 930 Consolação Street, São Paulo 01302-907, SP, Brazil, e-mail: acouto@mackenzie.br*

[2]*Senai Institute of Innovation in Advanced Manufacturing*

[3]*Institute of Energy and Nuclear Research, IPEN-CNEN/SP*

[4]*IDMEC, Instituto Superior Tecnico, Universidade de Lisboa*

*AlSi10Mg* *L-PBF* *fatigue*

**Abstract.** The need for manufacturing processes to obtain parts with complex and customized geometry, which optimizes weight, saves material, and reduces items in assembly, among other demands, has stimulated the diffusion of additive manufacturing, especially laser powder bed fusion (L-PBF) process. Among aluminum alloys, AlSi10Mg stands out due to its well-balanced combination of mechanical properties, thermal and electrical conductivity, and recyclability. Heat treatments, like direct aging have been show promise in improving mechanical properties as they preserve the cellular microstructure characteristic of the process, precipitating silicon-rich nanoparticles, which are largely responsible for this gain in mechanical strength. Considering the high-tech applications of customized components obtained by L-PBF, understanding the fatigue behavior of these components is of great importance, given that cyclic stress is often present in these applications. Looking at it from the perspective of real-world applications where stresses are mostly multiaxial, understanding multiaxial fatigue behavior becomes important for more accurate fatigue life prediction. Thus, this work aims to evaluate the uniaxial and multiaxial fatigue behavior of the AlSi10Mg alloy obtained by laser powder bed fusion and heat-treated by direct aging. The samples produced by additive manufacturing were fabricated under optimized processing conditions, using a laser power of 300 W, a scanning speed of 800 $mm \cdot s^{-1}$, a layer thickness of 30 µm, a laser beam diameter of 90 µm, a hatch space of 100 µm, and an argon atmosphere. One sample underwent direct aging heat treatment at 170°C for 6 h. The as build condition and the heat-treated samples were characterized by SEM to evaluate the microstructure. X-ray diffraction to evaluate the components phases, and industrial computed tomography to evaluate the tridimensional porosity, and microhardness. Fatigue tests were carried out to both condition – As Build and Heat-treated - combining torsional-axial loading in phase proportional 45° and out of phase 90°, uniaxial, and torsional loading, to R=-1, and 6 Hz frequence. The characterization of both as-build and heat-treated samples revealed the presence of a process-induced cellular microstructure and Si nanoprecipitates within the cells, with a higher density of precipitates observed in the heat-treated condition. The microhardness test results showed an increase in hardness for the heat-treated sample (195 HV0.3) compared to the as-build condition (169 HV0.3). The uniaxial and multiaxial fatigue tests indicate that, for the proportional in-phase 45° loading, the direct aging heat treatment was effective in improving fatigue life. For the uniaxial, torsional, and out of phase loading, both conditions – as-build and heat-treated – exhibited similar fatigue behavior. In addition, the out-of-phase 90° loading path proved to be the most critical, particularly when combined with the heat-treated material.

# *Case study of subsurface fatigue crack in a case-hardened bevel gear*

**Erkka Virtanen[1*], Jarno Jokinen[1], Gabor Szanti[2], Auezhan Amanov[1], Mikko Kanerva[1]**

*[1]Tampere University, Faculty of Engineering and Natural Sciences, Korkeakoulunkatu 6, FI-33720, Tampere, Finland, [*]erkka.virtanen@tuni.fi*

*[2]ATA Gears LTD, Aitolahdentie 75, FI-33101, Tampere, Finland*

*Case study* *Subsurface crack* *Finite element analysis*

Large-size bevel gears are critical power-transmission components used in heavy industry and marine applications. In high demand environments, accurate prediction of gear failures is essential due to high maintenance costs. A failure in a ship's power-transmission system can create a hazardous situation where the vessel becomes immobile, endangering the crew, cargo, and environment. To mitigate these risks, ships are periodically inspected to identify potential component failures.

In recent years, ultrasonic inspection techniques have been increasingly applied to assess the condition of gears. These methods have enabled the detection of subsurface fatigue cracks within gear teeth. However, historical data suggests that many gears have been retired earlier than before these inspection techniques were introduced. ATA Gears, in collaboration with Tampere University, has long studied fatigue failures in large-size bevel gears to understand this phenomenon.

Previous research has shown that subsurface cracks often initiate within gear teeth but may not exhibit observable crack growth until catastrophic failure occurs — the sudden and complete fracture of a single tooth. Furthermore, a notable number of detected cracks appear in wheel teeth, which experience fewer load cycles than the pinion teeth, contradicting the typical phenomena in fatigue failure modes, where higher amount of load cycles lead to higher probability of failure.

This study investigates the behaviour of subsurface cracks in pinion teeth using multiaxial fatigue criteria and fracture-mechanics-based analysis of key crack parameters. The work centres on a specific case study in which a subsurface crack was found in a pinion. The objective is to understand why this crack did not propagate into a fully developed, operationally critical fracture. State-of-the-art finite element–based fatigue initiation models are used to evaluate the risk of crack initiation, alongside fracture propagation analysis to identify the factors that govern whether a crack grows rapidly.

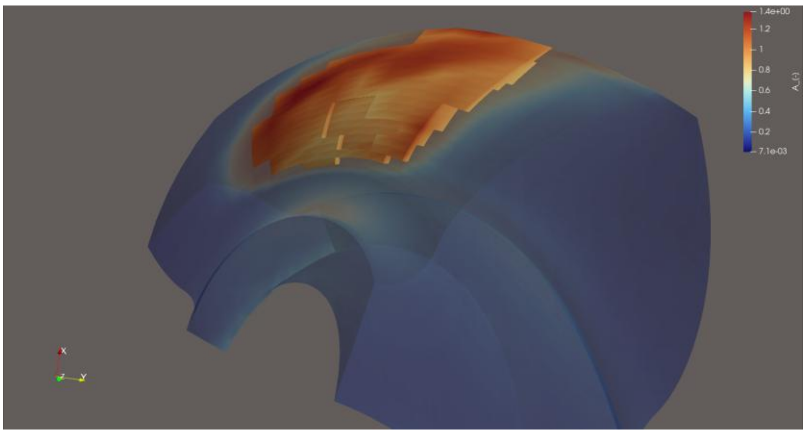

***Figure 1*** *-Visualization of critically loaded subsurface crack initiation volume*

# The ENLO-SED Large-Scale Shell-Element Models for Predicting the Strain Energy Density (SED) of Welded Joints — Part II: Applications to Multiple Geometries.

**Lucertini[1], G. Morettini[1], F. Cianetti[1]**

*1 University of Perugia, Department of Engineering, Via G. Duranti 93, 06125 Perugia, Italy*

*Fatigue* *SED* *Weldments*

The ENLO-SED approach has been tested on several welded-joint configurations, spanning multiple geometries and plate thicknesses, in order to verify its performance against high-fidelity 3D solid FEM analyses. Across the full set of applications, the method consistently reproduces the trend and magnitude of the Strain Energy Density along the weld path, maintaining an error below 8% when compared with the reference SED calculation for pure Mode-I. This agreement holds even when the loading conditions or the geometry deviate from the original calibration models, confirming that the correlation underlying ENLO-SED is not case-specific but broadly transferable.

Beyond accuracy, the practical advantages become immediately evident: shell models require far fewer elements, drastically shorter meshing times, and significantly reduced computational effort. This makes it feasible to analyze assemblies with many welded joints, something that would be prohibitively costly with traditional solid-based SED approaches. The method therefore offers a pragmatic balance between precision and efficiency, providing engineers with a fast and reliable tool for early-stage evaluations, large-scale comparisons, or integrity assessments under tight time and resource constraints. The results collectively suggest that ENLO-SED can serve as a scalable and trustworthy alternative for industrial fatigue prediction workflows.

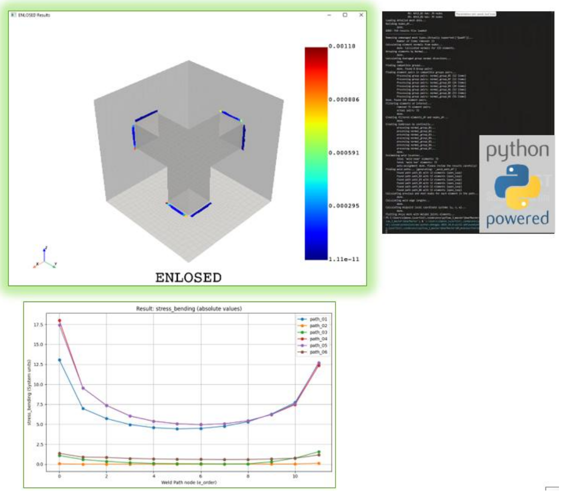


***Figure 1*** *- Final application for Design Engineers*

# Fatigue behaviour of notched L-PBFed AlSi10Mg hollow bars under bending-torsion

**Ricardo Branco[1], J.D. Costa[1], L.P. Borrego[2,1], J. de Jesus[1], R.F. Fernandes[1], J.A. Martins Ferreira[1]**

*[1]CEMMPRE, Department of Mechanical Engineering, University of Coimbra, Rua Luís Reis Santos, Pinhal de Marrocos, 3030-788 Coimbra, Portugal*

*[2]Department of Mechanical Engineering, Polytechnic Institute of Coimbra, Rua Pedro Nunes, Coimbra, 3030-199, Portugal*

*Bending-torsion* *Crack initiation* *Fatigue life*

**Abstract** This study addresses the fatigue behaviour of hollow round bars with lateral holes manufactured by L-PBF from AlSi10Mg aluminium alloy subjected to in-phase bending-torsion loading. Both untreated and stress-relieved material conditions are investigated. The tests are conducted under load-controlled mode considering two bending-to-torsion (B/T) ratios, B/T=1 and B/T=2/3, and two stress ratios (R=0 and R=0.4). After fatigue testing, the fracture surfaces are examined by scanning electron microscopy to identify the main fracture mechanisms. Overall, the heat-treated condition exhibited lower fatigue life scatter, but fatigue crack initiation life was not significantly affected by the heat treatment. The crack initiation sites, crack directions in the early stage of growth and crack locations in the wall of the hole were governed by the B/T ratio and were successfully predicted based on the principal stress field at the notch vicinity. Crack initiation life was also successfully predicted using the Basquin-Coffin-Manson model combined the Theory of Critical Distances and the Equivalent Strain Energy Density concept. Fatigue crack initiation was predominantly caused by surface and near-surface manufacturing-related defects.

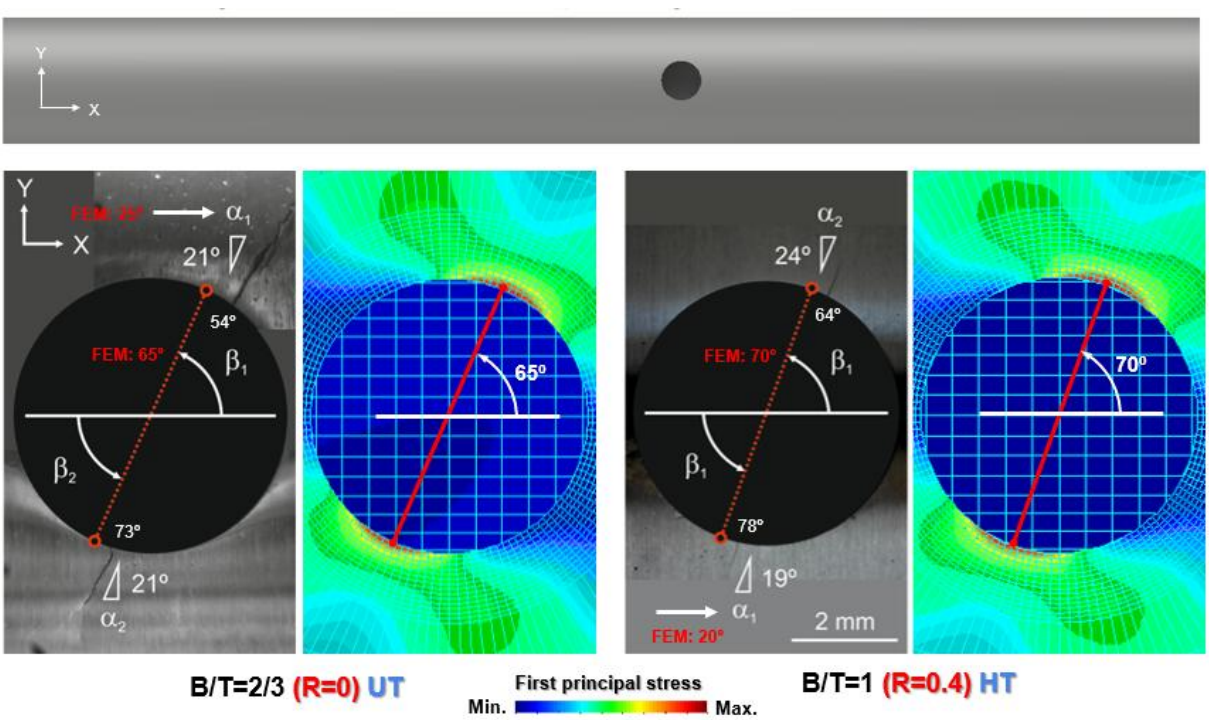


***Figure 1*** *– Experimental and numerically predicted crack initiation sites and early-stage crack growth directions under in-phase bending-torsion for untreated (UT) and heat-treated (HT) AlSi10Mg aluminium alloy*

# Crystallographic study of intergranular cracking during corrosion fatigue crack growth in AA5086

**Rajneesh Jaisawal[1], Vidit Gaur[1]**

[1]*Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Uttarakhand 247667, India*

[*]*Email: vidit.gaur@me.iitr.ac.in*

*Al-Mg Alloy* *Intergranular Cracking* *Corrosion-Fatigue*

**Abstract**

The present study systematically investigates the influence of crystallography on chloride-induced fatigue crack propagation in aluminum alloy 5086 (a naval-grade Al-Mg Alloy), using an in-house-developed corrosion-fatigue crack growth setup at room temperature via fatigue crack growth (FCG) test at 1Hz with fixed R-value of 0.1. The post-mortem microstructural analysis, conducted via electron backscattering diffraction and scanning electron microscopy, was performed around the crack path. Both the transgranular and intergranular cracking mode was observed in chloride [$Cl^-$] media, while only transgranular cracking in air media. The role of microstructural attributes (e.g., Taylor factor mismatch, CSL boundary, Schmid factor mismatch, geometric compatibility factor etc.) on fatigue crack propagation response was statistically investigated using a large dataset of cracked and adjacent un-cracked grain-pairs. Site-specific crystallographic analysis along the periphery of crack pathways provides a comprehensive understanding of microstructure-sensitive crack propagation and an interpretation of observed fluctuations in crack pathways during corrosion-fatigue crack growth. Additionally, grain boundaries were represented within the five degrees-of-freedom space using the octonion formalism and symmetry-reduced into the Voronoi Fundamental Zone (VFZ). Grain boundary energies were computed via the Bulatov-Reed-Kumar (BRK) analytical function. Intergranular crack propagation preferentially occurred along boundaries exhibiting elevated BRK-predicted energy and high ΔM, facilitating boundary decohesion under cyclic loading. The findings, presented in this study, may provide valuable insights to researchers working in the fields of grain boundary engineering and grain-scale computational modeling of corrosion-fatigue crack growth.

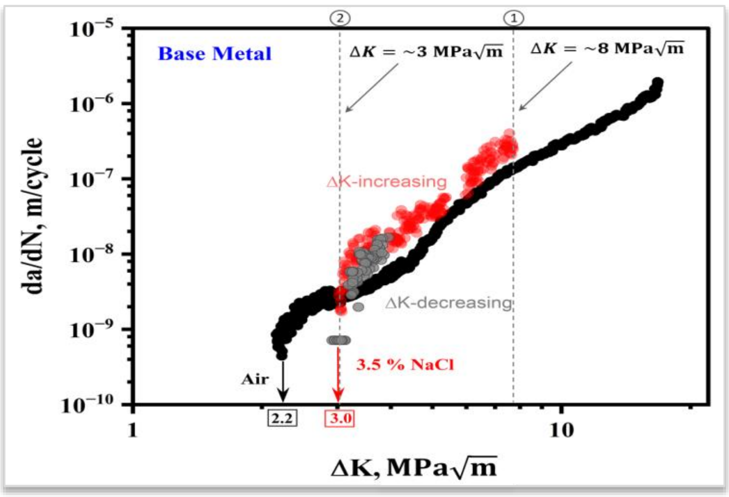


***Figure 1** – Fatigue properties under chloride [$Cl^-$] and air media*

# Influence of Hydrogen-Induced Embrittlement on the Fatigue strength of 316L Stainless-Steel Welded Joints

**M. António[1], J.S. Jesus[1], L.P. Borrego[2], L.Vilhena[1], R. Branco[1], J. D.M. Costa[1] and J.A.M. Ferreira[1]**

[1] *University of Coimbra, CEMMPRE, ARISE, Department of Mechanical Engineering [M. António: uc2022129512@student.uc.pt]*

[2]*Polytechnic University of Coimbra, Coimbra Institute of Engineering, Rua Pedro Nunes, 3030-199 Coimbra, Portugal*

*Hydrogen embrittlement* *TIG weld* *Laser weld* *Fatigue behavior*

**Abstract** Hydrogen embrittlement (HE) is a critical phenomenon that compromises the structural integrity of metallic components, particularly those employed in hydrogen storage and transportation systems. This issue becomes even more pronounced in welded structures, where microstructural heterogeneities and residual stresses can exacerbate susceptibility to hydrogen-assisted damage. In this study, the influence of HE on the fatigue behavior of 316L austenitic stainless-steel butt joints, produced by TIG welding and laser welding, was investigated. Three-point bending (3PB) monotonic and fatigue tests were conducted on the base material, on welded joints, and on hydrogen-charged welded joints to quantify the degradation of their mechanical properties. The experimental results showed that the welding process significantly reduced the fatigue strength of 316L stainless steel. The presence of hydrogen further intensified this degradation, leading to an additional decrease in fatigue life across all cases. Microstructural analyses confirmed the formation of austenitic–ferritic duplex structures within the weld beads. In both welding processes, the presence of δ-ferrite contributed positively to mitigating hot-cracking susceptibility; however, it also increased vulnerability to hydrogen embrittlement. Fractographic examinations of hydrogen-charged weld beads revealed characteristic features of hydrogen-induced cracking, including quasi-cleavage facets and secondary cracking paths consistent with hydrogen-assisted fracture mechanisms.

# A Peridynamic Framework for Fatigue Damage Prediction in Composites under Constant and Variable Amplitude Loading

**Erdogan Madenci[1], Atila Barut[2], Amin Yaghoobi[2]**

*[1]University of Arizona, Tucson, AZ 85721, USA and madenci@email.arizona.edu*

*[2]Global Engineering Research and Technologies, Tucson, AZ 85715, USA*

*Fatigue* *Damage* *Composites*

**Abstract** Fatigue is one of the primary reasons for engineering structures to fail. Prediction of fatigue life and damage path still poses challenges due to the complex nature of cracking and loading cycles. This study presents a fatigue model for constant and variable amplitude cyclic loading by combining kinetic theory of fracture (KTF) with peridynamics (PD). The KTF is applicable to constant and variable amplitude loading, and cumulative damage is inherent in the assumptions. Also, it is extremely suitable for implementation in the PD model of laminates. The standard stress versus cycles to failure data for unnotched laminates provides the determination of necessary parameters for the KTF. Using the test data generated by the Air Force Research Laboratory under the Tech Scout Project, the fidelity of this model is established by simulating three different composite laminates with an open-hole under cyclic loads for stiffness reduction and failure progression. The PD predictions agree with the measured reduction in stiffness as a function of number of load cycles. Also, the progressive damage predictions capture the general characteristics of the experimentally observed damage patterns.

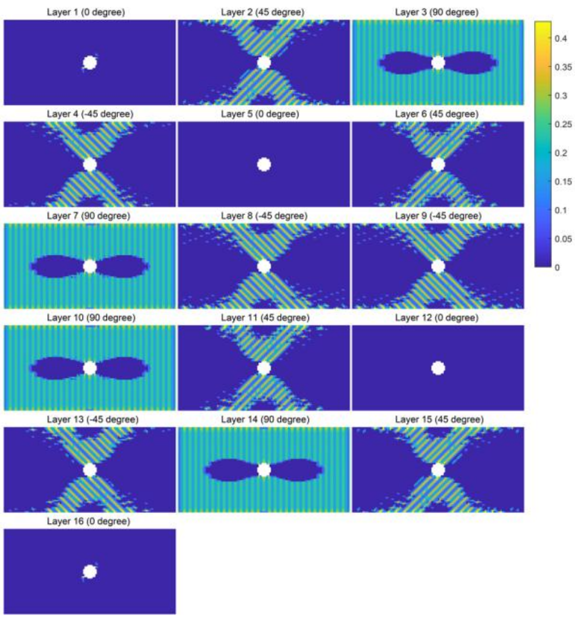


***Figure 1 -** Matrix damage after 1.0 M cycles in each ply for [0°/45°/90°/-45°]2s layup.*

# WAAM Repair of GJS 400 Cast Iron: Mechanical Strength and Fatigue Performance

**Zoé Bourgain[1,2], Fabien Szmytka[1], Philippe Feraud[2], Nicolas Thurieau[1]**

[1] *IMSIA, UMR 9219 EDF-CNRS-ENSTA, Institut Polytechnique de Paris, Palaiseau, France.*
*zoe.bourgain@ensta.fr*

[2] *Agence d'Essai Ferroviaire, Ingénierie du Matériel, SNCF Voyageurs, Vitry-sur-Seine, France.*

*WAAM repair* *Cast iron* *Fatigue life analysis*

**Abstract** In the rail industry, numerous train components, primarily castings, are systematically scrapped and replaced due to wear, corrosion, fatigue or accidental damage. This practice generates high costs, long lead times and significant environmental impacts. Repair, therefore, presents a relevant alternative to extend component life and reduce costs. Wire Arc Additive Manufacturing (WAAM) is particularly well-suited for such applications, as it is adapted to large parts and is already under development within SNCF Voyageurs for the production of train components. Most railway parts are made of steel or cast iron; this study focuses on the repair of GJS 400 spheroidal graphite cast iron, a material known to be difficult to weld. The repair material is an Fe–Ni alloy.

A first study investigates the influence of repair strategy (groove geometry and deposition strategy) on mechanical strength (tensile tests) and microstructure. Analyses included hardness testing, macrography of the interface, tensile tests with Digital Image Correlation (DIC), and SEM (fractography, EDS and EBSD of the interface). Microstructural analysis of the repair interface revealed the presence of multiple phases (martensite, ledeburite, pearlite) with heterogeneous hardness. The maximum stress reached by the repaired tensile specimens is homogeneous and comparable to virgin cast iron, although elongation at break varied with repair parameters (Figure 1). This study validates multiple repair strategies and identifies optimal parameters for the fatigue life analysis of repaired components.

The current work focuses on the fatigue behavior of repaired cast iron samples. Based on an industrial case study, 4-point bending tests are selected, and the fatigue limit of repaired specimens are estimated with a Staircase protocol and compared with plain cast iron samples.

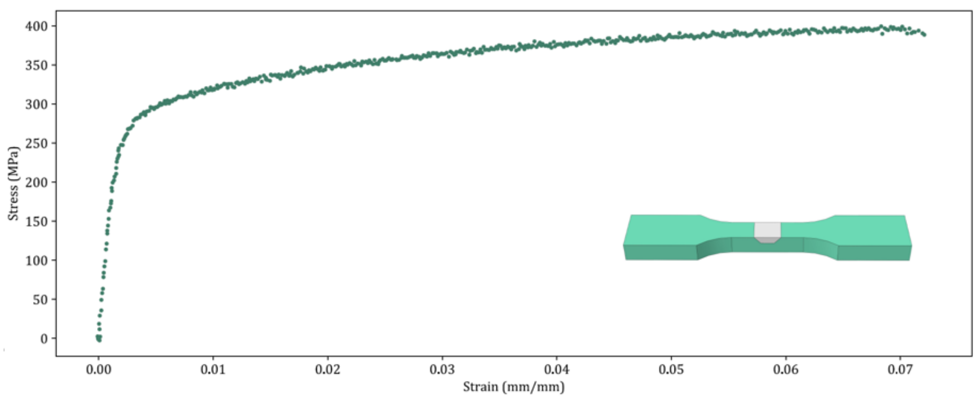


***Figure 1 -*** *Tensile curve for a repaired tensile sample with a 3 mm deep groove, oriented at 135° and filled with a zig-zag strategy.*

# Scale effect on fatigue behaviour of high-strength bolt steels

**Carlos F. C. Rebelo[1,3], Bruno Pedrosa[1,3], Rita Dantas[1,2], Iago Braggio[1], José Correia[1,2,3]**

[1] *Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal,* cfcrebelo@fe.up.pt

[2] *LAETA, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*

[3] *CONSTRUCT, Department of Civil Engineering, University of Porto, Portugal*

*High-strength bolts* *Fatigue* *Scale effect*

## Abstract

Bolted connections play a key role in the structural integrity of metallic structures subjected to cyclic loading. In structural applications, such as wind turbines, the most commonly used materials are high-strength bolt steels, in particular with a strength class of 10.9. Despite their wide applicability, when subjected to cyclic loads, they become critical components. Bolted connections are areas of high stress concentration and are, consequently, susceptible to fatigue damage initiation. Therefore, reliable fatigue life prediction methods are necessary. However, one of the main problems in predicting the fatigue behaviour of these connections is associated with the scale effect of the bolts. It is generally observed that fatigue resistance decreases with increasing bolt size. This behaviour is mainly attributed to increased local stress concentrations and to the larger highly stressed volume. In addition, larger bolts also lead to a higher probability of inclusions or manufacturing defects, which act as favourable sites for the initiation of fatigue cracks.

Thus, this study aims to quantify the penalising effect of the thread for different bolt sizes and evaluate the scale effect on the selected materials. The materials under study are high-strength bolt steels, strength classes 10.9 and 12.9. The materials were characterised for fatigue, considering standardised specimens under axial load without the mean stress effect. The results evidenced the superior fatigue resistance of 12.9 bolt steel. To evaluate the penalising effect of the thread, specimens with a threaded central section were designed. Initially, an M8 thread according to ISO standards was considered for the central section. In the threaded specimens, failure occurred consistently at the first thread. Fatigue results on these specimens revealed a higher notch sensitivity in 12.9 bolt steel, reducing the superior fatigue resistance obtained in standardised specimens. To assess the scale effect on the fatigue behaviour of bolts, the fatigue tests with threaded specimens were extended considering an M14 thread in the central section. The purpose was not only to assess the scale effect, but also to evaluate the material effect for different threads. Stress concentration factors were calculated for both thread sizes. The fatigue probabilistic bands were determined according to the Castillo and Fernández-Canteli model.

# Three-Dimensional Numerical Study of Load Influence on the Evolution of Plastic CTOD in CT Specimens under Cyclic Loading

**Jose Sandino-Egea, Alonso Camacho-Reyes, Jose Garcia-Manrique, Daniel Camas**

*Department of Civil and Materials Engineering, University of Malaga, C/Doctor Ortiz Ramos, s/n, 29071 Malaga, Spain, dcp@uma.es*

*Plastic CTOD*　　*Fatigue Crack Growth*　　*3D Numerical Analysis*

**Abstract** Fatigue crack growth in structural components subjected to cyclic loading is strongly influenced by local plasticity mechanisms occurring at the crack front. Among them, the plastic component of the Crack Tip Opening Displacement (CTODp) has shown to be related to irreversible deformation at the crack tip and has been shown to correlate well with fatigue crack growth rates.

In this work, a three-dimensional finite element model of a Compact Tension (CT) Specimen is developed to investigate the influence of the applied load level on the evolution of plastic CTOD through the specimen thickness under cyclic loading conditions. The numerical model, implemented in ANSYS Mechanical APDL, considers elastoplastic material behavior to model an Al-2024-T351 alloy. A straight crack front configuration is considered in the numerical model. Crack propagation is simulated through successive node release, allowing the development of a plastic wake prior to the extraction of results used for the analysis of plastic CTOD. The study considers a constant specimen thickness of 12 mm, while modifying the maximum stress intensity factor ($K_{max}$) between 15 and 35 MPa·m$^{1/2}$, maintaining a constant load ratio R = 0.1 in all the different cases analyzed. Plastic CTOD values are obtained from the vertical displacements from the first nodes behind the crack front for multiple planes distributed along the thickness.

The results show a non-uniform distribution of CTODp along the thickness. Results at the mid-plane show significantly higher values than at the surface, reflecting the influence of three-dimensional constraint effects. The through-thickness distribution of CTODp shows that, as the applied load increases, both the magnitude of CTODp and the gradient towards the surface become more pronounced. The distribution exhibits a relatively homogeneous region, consistent with near plane-strain conditions, and a transition zone close to the free surface characterize by a sharp reduction in CTODp. From a fatigue perspective, these findings indicate that the crack driving force is not uniformly distributed along the crack front.

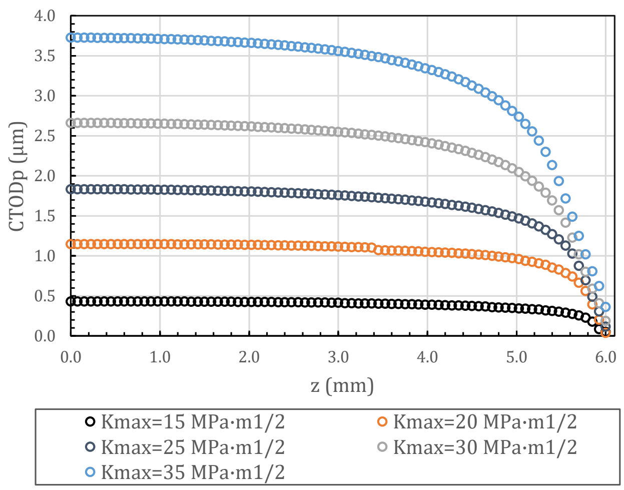


***Figure 1*** *– CTODp along the thickness*

# Low-Cycle Fatigue Behavior of WAAM Carbon Steel under Large Strain Amplitudes

**Yu Jiao[1], Zhenyu Zhao[1], Yoshiharu Sato[2], Hirokazu Nakata[3], Yasushi Furugaichi[3], Yu Mu[3]**

[1]*Tokyo City University, 1-28-1 Tamazutsumi, Setagaya-ku, Tokyo*

*158-8557, Japan, jiao@tcu.ac.jp*

[2]*The University of Tokyo,* [3]*Technology Research Institute, Tokyu Construction*

*WAAM steel* *Low-cycle fatigue* *Cyclic loading test*

**Abstract** Wire Arc Additive Manufacturing (WAAM), a metal additive manufacturing technique utilizing arc welding, has emerged as a promising alternative for fabricating steel structures. Unlike conventional processes, WAAM enables efficient construction of geometrically complex components without expensive molds while maintaining high material utilization and scalability. In addition, the ongoing shortage of skilled welding labor in the construction industry further highlights the potential of WAAM for automated, labor-efficient fabrication of structural steel components.

Existing research on WAAM steels has primarily focused on monotonic mechanical properties, including tensile strength, ductility, microstructural characteristics, and anisotropy. For both stainless steels and carbon steels, previous studies have clarified the influence of deposition direction, surface condition (as-built versus machined), and heat treatment on static mechanical performance. Although some efforts have been made to examine cyclic behavior and develop material models, systematic research on low-cycle fatigue behavior remains relatively limited. In particular, the low-cycle fatigue (LCF) performance of WAAM carbon steels under large strain amplitudes, corresponding to severe seismic loading conditions, has not been sufficiently investigated.

In seismic-resistant steel structures, WAAM technology is particularly suited for highly stressed regions such as beam–column connections or geometrically complex joints, where strain demands may vary significantly depending on earthquake intensity. Therefore, evaluating cyclic behavior over a wide strain amplitude range is essential for reliable seismic design and performance assessment.

The present study aims to investigate the low-cycle fatigue behavior of WAAM carbon steel fabricated using a commercially available Japanese welding wire, JIS YGW18 (Φ1.2 mm), which is widely used in structural applications in Japan. WAAM plates with a thickness of approximately 18 mm were produced under controlled deposition conditions. To assess the inherent anisotropic effects induced by the printing process, round-bar specimens were extracted along three orientations relative to the deposition (layering) direction: 0°, 45°, and 90°.

Strain-controlled cyclic loading tests were conducted over a wide strain amplitude range from ±0.5% to ±12.5%. This range covers small to very large inelastic strain demands relevant to seismic design scenarios, ranging from moderate earthquakes to near-collapse states. The experimental program focuses on examining cyclic stress–strain response, cyclic hardening and softening characteristics, and fatigue life under different strain amplitudes. Particular attention is paid to the influence of deposition orientation on cyclic behavior and low-cycle fatigue performance.

Through systematic experimental evaluation, this study seeks to clarify the cyclic deformation characteristics of WAAM carbon steel under large strain amplitudes and to provide fundamental data for future application of WAAM technology in seismic-resistant steel structures. These findings contribute to a better understanding of low-cycle fatigue performance and anisotropic behavior of WAAM steels under earthquake loading.

# Fatigue Crack Growth Rate Characterization of L-PBF A6061-RAM2 near threshold and Paris regime

**Szymon Dziuba[1], Grzegorz Lesiuk[1], Paweł Zielonka[1], Sebastian Król[1], Marcel Muszyński[1], Emilia Grochowska[1], Andrzej Wojtas[2], Filippo Berto[3], Abilio M.P. De Jesus[4]**

[1]*Wroclaw University of Science and Technology, Wybrzeże Stanisława Wyspiańskiego 27, 50-370 Wrocław, Poland*

[2]*Metlab Sp. z o.o, Ibn Siny Awicenny st. 14, 54-611 Wrocław, Poland*

[3]*Sapienza University of Rome, Piazzale Aldo Moro, 5, 00185 Roma RM, Italy*

[4]*University of Porto, Rua Dr Roberto Frias, 4099-002 Porto, Portugal*

*A6061-RAM2* *fatigue crack growth rate* *L-PBF*

Additive manufacturing (AM), and particularly laser powder bed fusion (L-PBF), is adopted for highly demanding applications, but standardized procedures enabling reliable comparisons of fatigue performance of different AM materials and processes remain limited. This challenge is even greater for aluminum alloys such as AA6061, whose L-PBF processability is hindered by hot cracking. A modified reactive additive manufacturing alloy, A6061-RAM2 enriched with titanium and B4C, has been introduced to reduce cracking susceptibility, but comprehensive fatigue and fracture data, especially for crack propagation, are still limited.

This work focuses on the fatigue crack growth rate (FCGR) behavior of L-PBF A6061-RAM2 under load in Mode I, targeting both the near-threshold and stable propagation regimes. The experimental campaign is designed using ASTM E647 to determine da/dN–ΔK relationships at multiple mean stress levels, quantified by the stress ratio R. At least few R levels are considered, to quantify mean stress effects on FCGR resistance. Near threshold characterization will be performed using ΔK decreasing procedures. The Paris regime will be assessed by constant force amplitude loading to verify curve repeatability.

Creating the standard ΔK-based description, aiming to construct a kinetic fatigue fracture diagram (KFFD) as an material characterization route. The resulting dataset and methodology are expected to support defect-tolerant fatigue assessment and contribute to more reliable life prediction frameworks for AM aluminum components.

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# MODELING FATIGUE CRACK GROWTH USING MACHINE LEARNING

**B. Moreno[1], P. Caballero de Leiva, I. Gonzalez-Tiviño[1], A. Camacho[1]**

[1]*Department of Civil and Materials Engineering, University of Malaga, C/Dr Ortiz Ramos s/n, Malaga, 29071, Spain* bmoreno@uma.es

*Fatigue* *Crack growth* *Machine learning*

**Abstract** Accurately predicting the fatigue crack growth rate is crucial for ensuring the structural safety of mechanical components. Currently, with the rise of artificial intelligence, and within it machine learning, a promising alternative to the classical models used until now is emerging. This work focuses on modeling fatigue crack growth in metallic materials using machine learning techniques, applied to different materials. Two models based on artificial neural networks were implemented and compared: a Multi-Layer Perceptron (MLP) and a Radial Basis Function Network (RBFN). The performance of both models was compared in terms of prediction accuracy and computational efficiency. The difficulties encountered in network design and the advantages and disadvantages of using each model were also analyzed. The results obtained show the good predictive capacity of both models, slightly superior in the MLP model compared to the RBFN, although the latter has greater computational efficiency as it is considerably faster to train and requires less memory. Finally, it is also concluded that the RBFN network has certain limitations in terms of generalisation capacity and stability in predictions outside the training set, while the MLP has proven to be considerably more robust and generalisable, maintaining consistent predictions and fulfilling the expected trend.

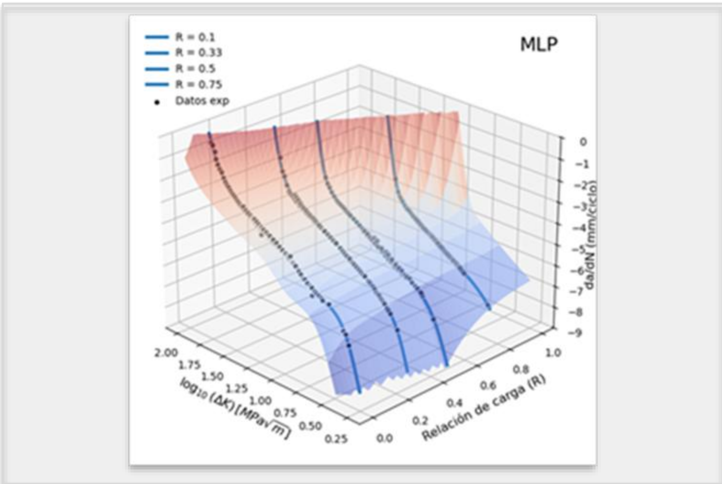


***Figure 1 -*** *MLP model predictions in Ti-6Al-4V*

# Automotive Subframe Fatigue Testing Multi-Axial Compression

**Patrick Tremoureux**

*Zeekr Technology Europe AB, Pumpgatan 1, 417 55 Göteborg, patrick.tremoureux@zeekrtech.eu*

*Multi-axial* *Testing* *Compression*

## Abstract

Automotive project development plans are constantly getting shorter, leading to the need for compression of fatigue testing duration. Various tools and an innovative method used to perform such task are presented and applied to the durability testing of a Mac-Pherson suspension front subframe.

Fatigue duty cycle loading consists of several types of driving manoeuvres on various road surfaces. Corresponding vehicle loads, based on full vehicle measurements and multi-body simulations, are delivered in the form of time signals consuming 300 to 1000 hours, if not more for electric vehicles, hence the need for shortening test duration. Most of suspension components are subjected to multi-axial loading, while methods to compress such loading are sparse, which led to development of in-house methods.

Those methods are based on the linear Palmgren-Miner damage formula, exhaustive use of Load spectrum analysis, identification of loading types, and cross-plots to identify damaging load combinations. Simultaneous loading points of interest are extracted from the time signals, the keypoint being to apply relevant gating on each load channel for each loading type. Then loading is rebuilt two ways. In the first one each channel loading frequency is linked to the rig capacity of corresponding activator - hydraulic cylinder and its fixtures - or to the original load itself. The second way is applied to some loading which are time consuming, like Belgian Pavé. In this case muli-axial blocks are generated, focusing on study of the loading path and replacing it with simplified geometric shapes.

This work results in test durations better fitting the project plan time frame, sometime even allowing increase of test samples, which is beneficial to reliability.

Note: Certains aspects won’t be adressed in this presentation, like FEA based verification, Mean loading , Fatigue Limit or Low Fatigue Life corrections.

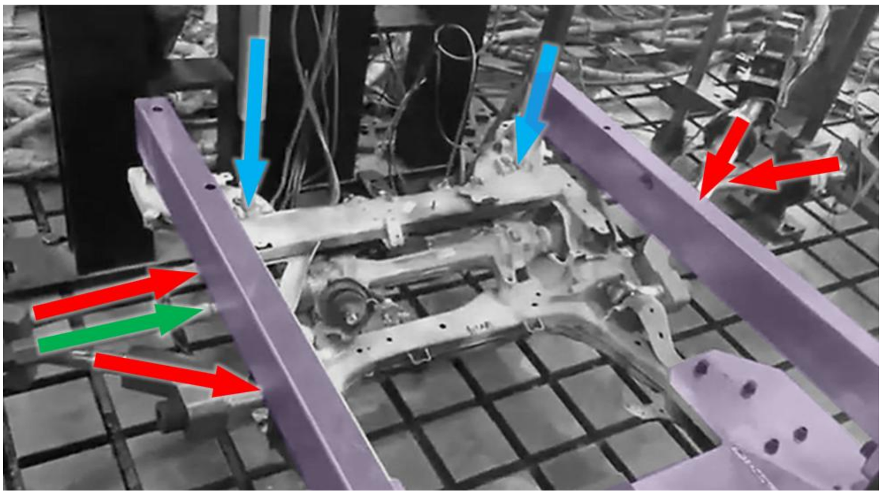

***Figure 1 -*** *Mac-Pherson suspension subframe test set-up*

# High-Cycle Fatigue Behavior of Hot-Work Tool Steel Used in Aluminum Extrusion Dies

**Daniela I. M. Azevedo[1], Mário R. O. Cunha[1], Lucas Azevedo[2], Daniel F. O. Braga[1], Pedro M. G. J. Moreira[1]**

*[1]INEGI, Institute of Science and Innovation in Mechanical Engineering and Industrial Engineering, Rua Dr. Roberto Frias, 400, 4200-465 Porto, Portugal*

*[2]Quantal S.A, 1249-093 Porto, Portugal*

*High-cycle fatigue* *Extrusion dies* *Tool Steel 1.2344*

**Abstract** Aluminum extrusion dies are typically manufactured from hot work tool steels, such as grade 1.2344 (H13), and operate under severe cyclic mechanical loading combined with demanding thermal conditions. Improving the thermal efficiency and durability of these tools requires not only optimized design solutions but also a comprehensive understanding of the fatigue behavior of the base material.

This work is developed within the framework of a project aimed at enhancing the thermal efficiency of aluminum extrusion dies through the integration of advanced design strategies, surface engineering technologies, and process monitoring approaches. In particular, the application of coatings by Cold Spraying is foreseen as a surface modification strategy to improve wear resistance and thermal performance, while preserving the integrity of the substrate material.

As a first step of the project, the high-cycle fatigue (HCF) behavior of tool steel 1.2344, commonly used in extrusion die manufacturing, is being experimentally characterized. Fatigue tests were conducted using a resonance-based testing system, enabling high-frequency cyclic loading suitable for efficient HCF assessment. The experimental campaign performed to date focuses on room temperature conditions, where constant amplitude tests at different stress levels were carried out to obtain the corresponding S–N curve and establish baseline fatigue properties.

An extended testing campaign at elevated temperatures is currently under development, aiming to reproduce the thermo-mechanical conditions experienced during the aluminum extrusion process. This will allow the evaluation of the influence of temperature on fatigue life and support the development and validation of improved die concepts.

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# Methodology for Real-Time Remaining Fatigue Life Estimation: From Deterministic to Probabilistic Models

**D. Díaz-Salamanca [1,*], M. Muñiz-Calvente[1], A. Cebada-Relea[1], E. Martínez-Puente[2], M. López[1], I. Llavori[2], M. Aenlle[1]**

[1] *Department of Construction and Manufacturing Engineering, University of Oviedo, Gijón 33203, Spain (diazsdiego@uniovi.es)*

[2] *Faculty of Engineering, Uviversity of Mondragón, 20500 Mondragón-Arrasate, Spain*

*Real-Time fatigue* *Probabilistic modeling* *Spectral methods*

## Abstract

Numerous critical structures and components are subjected to dynamic loads and therefore vulnerable to fatigue failure during service and beyond. At the same time, recent technological advances have facilitated and democratized access to structural health monitoring systems, enabling the continuous assessment of cumulative structural damage. However, in many practical cases, monitoring activities begin long after the structure has been put into service, meaning that information regarding its total accumulated damage is unavailable. Furthermore, at the end of a structure's design life, the monitored data must be used to support decisions on whether continued operation is feasible. To address these challenges, the present work investigates the influence of the monitored time window on fatigue life predictions, as well as the feasibility of extrapolating damage estimates to unmonitored service intervals. The potential benefits of this probabilistic framework are assessed, highlighting the advantages associated with its application and implementation in fatigue life evaluation.

# Separating Microstructural and Porosity Effects on the Fatigue Strength of Low-Alloyed Steel Manufactured by Laser Powder Bed Fusion

**Philipp Schüßler[1], Volker Schulze[1], Stefan Dietrich[1]**

*[1]Insitute for Applied Materials – Materials Science and Engineering (IAM-WK), Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany,* philipp.schuessler@kit.edu

*Additive Manufacturing* *Tooth root fatigue strength* *Topology optimization*

**Abstract** Additive manufacturing (AM) enables novel design approaches for mechanically loaded components, particularly when combined with topology optimization. However, the fatigue performance of AM parts remains a key challenge, especially for applications governed by tooth root fatigue strength. Building on previous studies of fatigue behaviour in additively manufactured metallic specimens, this work investigates fatigue-relevant differences between conventionally manufactured and additively manufactured gear components.

Three topology-optimized spur gear designs were developed to represent realistic, fatigue-critical geometries while allowing a systematic comparison between manufacturing routes. Each design was produced using a conventional manufacturing process and by laser-based powder bed fusion (PBF-LB). To minimize the influence of microstructural and strength-related factors, all gears were subjected to identical quenching and tempering heat treatments, resulting in comparable hardness levels across all specimens. This approach enables a targeted assessment of manufacturing-induced effects, with particular emphasis on the role of porosity. Fatigue testing focuses on cyclic bending loading at the gear tooth root under conditions representative of service loading. The experimental program is complemented by metallographic and fractographic analyses to characterize defect populations, crack initiation behaviour, and failure mechanisms. Special attention is given to the interaction between topology-optimized geometries and defect sensitivity in additively manufactured gears.

The study aims to provide a structured experimental basis for assessing the suitability of additively manufactured, topology-optimized gears for fatigue-critical applications. By isolating the influence of porosity from heat-treatment and hardness effects, the work contributes to a more reliable understanding of fatigue performance differences between conventional and additive manufacturing routes.

# Influence of mean stress on the defect-driven fatigue strength

**Suraj S. More[1,2], Herwig Mayer[2], Joona Vaara[3], Miikka Väntänen[4], Tero Frondelius[3,5], Bernd M. Schönbauer[1,2,5]**

[1]*Christian Doppler Laboratory for Defect Tolerance of Steels in the High and Very High Cycle Fatigue Regime, BOKU University, Peter-Jordan-Str. 82, 1190 Vienna, Austria,* suraj.more@boku.ac.at

[2]*Institute of Physics and Materials Science, BOKU University, Peter-Jordan-Str. 82, 1190 Vienna, Austria*

[3]*R&D and Engineering, Wärtsilä, P.O. Box 244, 65101, Vaasa, Finland*

[4]*Global Boiler Works Oy, Lumijoentie 8, 90400 Oulu, Finland*

[5]*Materials and Mechanical Engineering, University of Oulu, Pentti Kaiteran katu 1, 90014, Finland*

*Mean stress sensitivity* *Uniaxial and torsional fatigue* *High-strength steel*

**Abstract:** The fatigue strength of high-strength metallic materials is influenced by small defects like notches, grooves, holes, pores, material inhomogeneity and non-metallic inclusions. It is essential to investigate the defect tolerance of such materials to ensure the structural integrity of critical components. Recently, we systematically investigated the defect sensitivity of quenched and tempered 42CrMo4 steel under uniaxial and torsional loading using specimens containing artificially introduced defects of various sizes and shapes. The fatigue limit is defined by crack non-propagation for defects with a notch-root radius below a critical value of $\rho_c \approx 80$ µm and 105 µm under fully-reversed uniaxial and torsional loading, respectively. Non-propagating cracks are observed at and below the fatigue limit. These defects are identified as crack-like defects, and the fatigue limit can be predicted by applying fracture mechanics-based methods, such as the $\sqrt{\text{area}}$-parameter and the El-Haddad model. Defects with a notch root radius higher than the critical notch root radius are identified as blunt, notch-like defects, and crack initiation defines the fatigue limit. The Siebel-Stieler model can be used to predict the crack-initiation threshold of all studied defects. Furthermore, it was demonstrated that the critical notch root radius is constant, independent of defect size, and the critical stress concentration factor depends on the defect size, irrespective of the loading type.

As an extension of our work, the present study investigates the mean stress sensitivity of 42CrMo4 QT steel in the presence of small and large crack-like, as well as notch-like defects, both under uniaxial and torsional loading conditions. Fatigue tests were performed at stress ratios of $R = -1$, 0.05 and 0.3, with specimens containing artificially introduced surface defects using the ultrasonic fatigue testing technique at a cycling frequency of about 19 kHz. By utilising the Walker term $([1-R]/2)^{\alpha}$, the mean stress sensitivity is quantified through the exponent $\alpha$.

It was found that the value of $\alpha$ remains constant at approximately 0.35 for both small and large crack-like defects, regardless of whether the loading is torsional or uniaxial, indicating a uniform material response to changes in mean stress. Conversely, for notch-like defects, $\alpha$ is around 0.09, again under both loading conditions, indicating that blunt defects are less sensitive to mean stress. Further insights are obtained on the observability of non-propagating cracks and the role of crack initiation and propagation, defining the fatigue limit. Finally, the applicability of fracture mechanics and notch fatigue approaches for the prediction of the fatigue limit at different load ratios are discussed.

# Very high cycle fatigue properties of thin steel sheets

**Afshin Khatammanesh[1], Christina Mamagkinidou[1], Suraj S. More[1], Martin Rester[2], Maximilian Prunbauer[2], Michael Proschek[2], Bernd M. Schönbauer[1]**

*[1] Christian Doppler Laboratory for Defect Tolerance of Steels in the High and Very High Cycle Fatigue Regime, Institute of Physics and Materials Science, BOKU University, Peter-Jordan-Str. 82, 1190 Vienna, Austria, afshin.khatammanesh@boku.ac.at*

*[2] Berndorf Band GmbH, Corporate Research and Innovation, Leobersdorfer Str. 26, 2560 Berndorf, Austria*

*Very High Cycle Fatigue* *Thin Steel Sheet* *Residual Stress Profiles*

**Abstract** As industries push for weight reduction and sustainability, components are becoming thinner, exposing them to greater stress levels, and therefore accelerating damage accumulation under cyclic loading. To offset the effect of reduced thickness and maintain load-carrying capacity, high-strength steels are often utilized. However, greater strength – and the associated hardness – increases defect sensitivity, making these materials more susceptible to fatigue damage initiated at inherent defects such as inclusions, pores, microcracks, pits, and machining marks. Even defects only a few micrometers in size can significantly reduce fatigue strength.

This study investigates the high cycle fatigue (HCF) and very high cycle fatigue (VHCF) properties of martensitic, austenitic, and duplex stainless-steel sheets with tensile strengths of 1300–1500 MPa. Test specimens were extracted from 1–3 mm thick steel sheets in different directions with respect to the rolling direction. Experiments were conducted up to more than $10^{10}$ cycles employing the ultrasonic fatigue testing technique. Smooth specimens were used to identify the failure mechanism, while specimens with artificially introduced defects were used to systematically study the defect tolerance of the materials. Through-thickness residual stress profiles were measured using X-ray diffraction method. Fracture surfaces of the test specimens were examined with scanning electron microscopy to investigate the failure mechanisms. Based on the fractographic investigation, the extreme value distributions of crack-initiating defects were obtained.

It was observed that all surface-initiated failures occurred in the HCF regime ($<10^7$ cycles), and a distinct fatigue limit associated with surface failure was determined. In the VHCF regime, failures originated from interior non-metallic inclusions. No clear fatigue limit for interior crack initiation can be established, as failures occurred even beyond $10^{10}$ cycles. It was found that the loading directions, with respect to the rolling direction of the steel sheets, has a significant effect on fatigue lifetimes. This could be attributed to the different residual stress profiles along these directions. In the rolling direction of the steel sheets, the profiles feature pronounced tensile stresses at the center, which alter the local load ratio and govern the fracture locations. Using a fracture-mechanics approach, the fatigue strength of the thin steel sheets can be predicted with good accuracy by considering the defect size and the local load ratio.

# Influence of environment and temperature on fatigue crack initiation and propagation at small defects

**Christina Mamagkinidou[1,2], Suraj S. More[1,2], Michael Fitzka[1,2], Herwig Mayer[2], Joona Vaara[3], Tero Frondelius[3,4], Bernd M. Schönbauer[1,2,4]**

[1]*Christian Doppler Laboratory for Defect Tolerance of Steels in the High and Very High Cycle Fatigue Regime, BOKU University, Peter-Jordan-Str. 82, 1190 Vienna, Austria, christina.mamagkinidou@boku.ac.at*

[2]*Institute of Physics and Materials Science, BOKU University, Peter-Jordan-Str. 82, 1190 Vienna, Austria*

[3]*R&D and Engineering, Wärtsilä, P.O. Box 244, 65101, Vaasa, Finland*

[4]*Materials and Mechanical Engineering, University of Oulu, Pentti Kaiteran katu 1, 90014, Finland*

*Defect tolerance* *Environmental effects* *Kitagawa-Takahashi diagram*

**Abstract** The defect sensitivity of steels is governed by both inherent material characteristics and environmental conditions affecting crack initiation and propagation. Defect size and geometry, particularly the notch root radius, significantly influence the corresponding thresholds. The crack initiation as well as the crack propagation threshold are further affected by environmental factors, such as air humidity and elevated temperature, necessitating their characterization for reliable construction and extension of Kitagawa–Takahashi diagrams under varying conditions.

Ultrasonic fatigue testing was employed to investigate quenched and tempered 42CrMo4 steel containing artificially introduced defects of varying sizes under fully reversed loading ($R = -1$). Fatigue limits, defined by crack initiation and non-propagation criteria, were determined under ambient and inert gaseous environments (ambient air, argon, and vacuum) as well as at elevated temperatures (200 °C and 400 °C). Fracture surfaces were examined via scanning electron microscopy to identify the underlying mechanisms governing crack initiation and non-propagation, with particular emphasis on crack closure effects, including oxide-induced closure at elevated temperatures.

In ambient air, a clear fatigue limit associated with failure from surface defects was found. All failures occurred below $10^7$ cycles and run-outs survived up to $10^{10}$ cycles. At the fatigue limit, non-propagating cracks were observed. Testing in vacuum resulted in a shift of the *S-N* curve's knee point by approximately three orders of magnitude in lifetime. Failure originating from surface defects was observed beyond $10^9$ cycles, and the fatigue limit – identical to that in ambient air – was determined for $10^{11}$ cycles. No evidence of non-propagating cracks was found; instead, pronounced slip bands formed adjacent to the defects in runout specimens. Argon environment produced slightly increased lifetimes relative to ambient air, suggesting partial suppression of environmentally assisted cracking; non-propagating cracks were observed at the fatigue limit, which was comparable to those determined in ambient air and vacuum. At elevated temperature, a lower fatigue limit in argon compared to ambient air was observed, attributed to a lack of oxide-induced crack closure. Furthermore, crack initiation and propagation thresholds were established for the investigated environmental conditions to identify the underlying mechanisms determining the fatigue limit.

# Hybrid Global Optimization for Critical Plane Identification under Multiaxial Random Loading

**Adam Niesłony[1], Dariusz Skibicki[2]**

[1]*Opole University of Technology, Prószkowska 76, 45-758 Opole, Poland, a.nieslony@po.edu.pl*

[2]*Bydgoszcz University of Science and Technology, Kaliskiego 7, 85-796 Bydgoszcz, Poland*

*Critical plane* *Global optimization* *Multiaxial random loading*

**Abstract** Critical-Plane (CP) based multiaxial fatigue criteria, such as those proposed by Findley, Matake, Papadopoulos and Fatemi–Socie, determine fatigue life by evaluating stress–strain components resolved on a material plane whose orientation maximizes a damage-related parameter. In the most general formulation, the CP is identified through maximization of a fatigue damage functional over all admissible orientations. For non-proportional and random loading histories, this leads to a computationally expensive optimization problem, especially when cycle counting (e.g., multiaxial rainflow) and Miner's damage accumulation are embedded in the objective function. The simple search over the orientation space (e.g., spherical angles θ, φ) becomes impractical in engineering-scale applications, particularly when combined with FEM post-processing. Variance-based approaches offer excellent computational efficiency by exploiting the covariance structure of the stress/strain tensor. However, pure variance maximization neglects spectral characteristics of random loading histories: different amplitude distributions with identical variance may produce significantly different fatigue damage, which limits the accuracy of maximum variance method when applied alone to arbitrary non-stationary or broadband signals.

This work proposes a Hybrid Approach (HA) that integrates the computational efficiency of the variance method with the accuracy of maximum fatigue damage evaluation. In the first stage, stress and strain covariance matrices are computed from the time histories. A quasi-uniform set of candidate planes is evaluated using a proxy damage parameter derived from the definition of the chosen multiaxial fatigue criterion. The most promising orientations are selected as initial points. In the second stage, a multistart global optimization framework is applied to the full, time-domain damage evaluation, including i.e. multiaxial rainflow counting and Miner's rule. The optimization problem is formulated as minimization of the negative damage rate over a bounded hemispherical domain. Several global strategies are examined and compared, including GlobalSearch, MultiStart with local polishing (fmincon/patternsearch), simulated annealing, genetic algorithms, particle swarm, and surrogate-based optimization. Numerical examples demonstrate that the proposed hybrid strategy consistently identifies the same damage-controlling plane as exhaustive search while reducing computational time by orders of magnitude. In contrast to existing variance-assisted methods reported mainly for constant-amplitude loading, the proposed framework operates directly on arbitrary time histories and preserves the full damage-spectrum information.

The results show that combining variance-based seeding with global optimization enables efficient CP identification in multiaxial fatigue analysis. The approach can be extended to any critical plane criteria and applied in large-scale FEM models under random loading.

# Development of fatigue load spectra for FOWT moorings based on crack growth

**Abhemanyu P C[1], Bjørn.H.Skallerud[1], Gunnstein.T.Frøseth[1]**

*[1]Department of structural engineering, Norwegian University of Science and Technology*

*Institutt for konstruksjonsteknikk, NTNU*

*Richard Birkelands vei 1A*

*7491 Trondheim*

*Email-Abhemanyu.p.chandrasekaran@ntnu.no*

*Fatigue load spectra* *FOWT moorings* *Surrogate modelling*

**Abstract** Premature mooring chain failures have been a concern in offshore installations. Conventional fatigue analysis is often based on the S–N curve approach combined with the Palmgren–Miner rule, where only the fatigue damage from short-term sea states is considered and the total fatigue damage is computed from the probability distribution of sea-state occurrences. To move beyond this approach, a fully coupled numerical simulation of a floating offshore wind turbine is performed under different environmental conditions, and the mooring line tensions are extracted, forming the basis for a stress-history description of each 1-h sea state. A fracture-mechanics-based numerical simulation of fatigue crack growth using Paris law is then carried out under variable-amplitude loading. The stress intensity factor for a semi-elliptical surface crack in a round bar is used to simulate the crack front evolution based on a cycle-by-cycle increment. The resulting mapping between environmental conditions, initial crack geometry, and final crack front is used to train a surrogate model for damage evolution. Finally, the damage severity associated with each sea state, as predicted by the crack-growth or surrogate model, is combined with the long-term probability of sea-state occurrences to synthesize a reduced fatigue load spectrum that better reflects the actual crack-driving loading experienced by floating offshore wind turbine moorings.

# Fatigue performance degradation of rafted nickel-based single crystal superalloys: tensorial microstructure, constitutive modeling, and fatigue life prediction

**LUO Cheng[1], YUAN Huang[1]**

[2]*School of Aerospace Engineering, Tsinghua University, Beijing, China*

*Single-crystal superalloy* *Tensorial microstructure* *Fatigue performance degradation*

**Abstract** Nickel-based single-crystal superalloys used in aero-engine turbine blades undergo microstructural evolution and mechanical property degradation during long-term service, which compromises safety and reliability. High-temperature fatigue tests reveal that the coarsened and rafted DD6 single-crystal superalloy experiences a fatigue life reduction of 70%. The degradation mechanism and its correlation with microstructure variation remain unclear.

To clarify the roles of the mechanical properties of constituent phases and microstructural evolution on the macroscopic constitutive behavior of the alloy, grid indentation was employed to characterize the evolution of micro-elastoplastic properties of the γ and γ′ phases. Results indicate that after long-term thermal exposure, the chemical composition and elastoplastic properties of the γ/γ′ phases remain stable. Therefore, the degradation of the alloy's macroscopic mechanical properties is primarily attributed to the evolution of the γ/γ′ microstructure.

Based on micromechanics and crystal plasticity, a multi-scale constitutive model was established for the alloy. Simulated stress-strain responses and cyclic mechanical behavior agree well with experimental results. The degradation of the alloy's deformation behavior is attributed to the widening of the γ phase channels and the increased volume fraction of the γ phase. To account for rafting-induced mechanical property degradation in engineering practice, a novel tensorial characterization method for the microstructure is proposed. For the first time, the coarsening and rafting features are decoupled through the independent components of the microstructure tensors of the matrix and precipitate phases. A microstructure-sensitive fatigue life prediction model is developed, which successfully enables the quantitative description of life attenuation in coarsened and rafted alloys.

This study clarifies the influence of the microscopic mechanical properties and microstructural morphologies of the γ/γ′ phases on the macroscopic mechanical performance of nickel-based single-crystal superalloys. The application of the microstructure tensor in fatigue life prediction provides a new approach for the structural integrity assessment of turbine blades after long-term service.

# Gas pore-based fatigue strength and fatigue life prediction models of laser additive manufactured Ti-6Al-4V alloy in very high cycle fatigue regime

**Guanze Sun[1], Zihua Zhao[2]**

[1]*School of Materials Science and Engineering, Beihang University, Beijing 100191, China*

*Keyword: VHCF gas pore defect life prediction*

**Abstract：** Due to the high-density energy input characteristics of laser additive manufacturing (AM), gas pores are often as high-frequency defects in additive manufacturing materials, which makes the long-life fatigue service of structures have potential safety hazards. However, the fatigue researches on AM materials mostly focus on the lack of fusion (LoF) defect induced damage. Therefore, we propose an idea whether we can customize an AM alloy only with pore defects, and explore the very high cycle fatigue behavior. Ti-6Al-4V alloy are widely used in aerospace key components, and the research in additive manufacturing is relatively in-depth. Here, we selected laser additive manufactured Ti-6Al-4V alloy as the model material for ultrasonic fatigue test, and carried out defect tomography reconstruction, defect stress field simulation, and fracture quantitative analysis. Based on this, we introduce a low fatigue stress sensitivity coefficient to modify Murakami 's fatigue strength prediction model, and control the prediction ability within the error range of 10%. Meanwhile, considering the location, size and shape of the pores, the T parameter was established, and the Schmid factor was introduced in combination with the microstructure cracking near the pores, so that the FIP model was optimized, making the predicted lives distribution within 2 times line of actual lives.

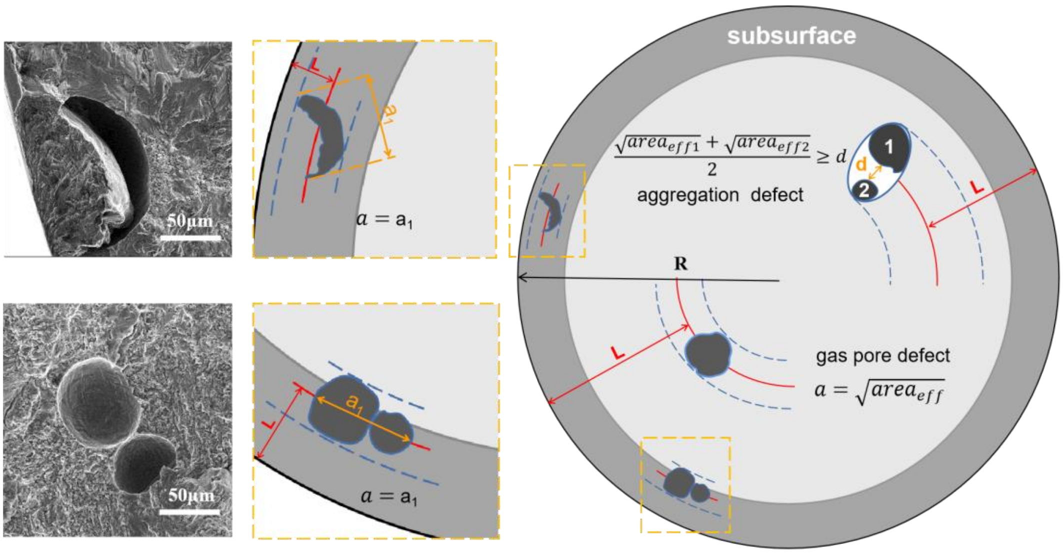



***Figure 1 -*** *The schematic diagram of the position selection, effective defect area, and defect type.*

# Vibration fatigue assessment method for high-speed service-damaged axle

**Feifei Hu[1], Junjiang Liu[1], Yizhong Ma[2], Feng Kang[2], Shengchuan Wu[1]**

[1] *State Key Laboratory of Rail Transit Vehicle System, Southwest Jiaotong University, Chengdu 610031, China, hff510525@163.com*

[2] *Jinxi Axle Company Limited, Shanxi, Taiyuan 030027*

*High-speed axle* *Vibration fatigue* *Lifetime prediction*

**Abstract** Surface defects may occur in high-speed rail axles during production, machining, transportation, service, and maintenance. Serious consequences arise when effective countermeasures are not promptly implemented. On the other hand, critical factors including wheel polygons, turnout impacts, rail wave wear generate abnormal high-frequency vibrations during high-speed train operation. This leads to degraded vehicle dynamic performance and increases uncertainty in axle service loads. It is reported that the overly simplified standard load spectrum clearly fails to adequately account for abnormal vehicle vibrations. However, there remains a lack of reasonable evaluation methods to support the assessment of how current vibration loads impact the safe service life of axles, especially the service-damaged axles. To this end, this study proposes a comprehensive integrity assessment method for high-speed railway induction-hardened hollow axles, incorporating vibration fatigue loading considerations. In this study, the fatigue strength assessment, crack initiation life prediction, and damage tolerance analysis of axle structures throughout their entire lifecycle were systematically performed. The aim is to provide valuable references for formulating operational maintenance strategies and providing service safety research for service-damaged

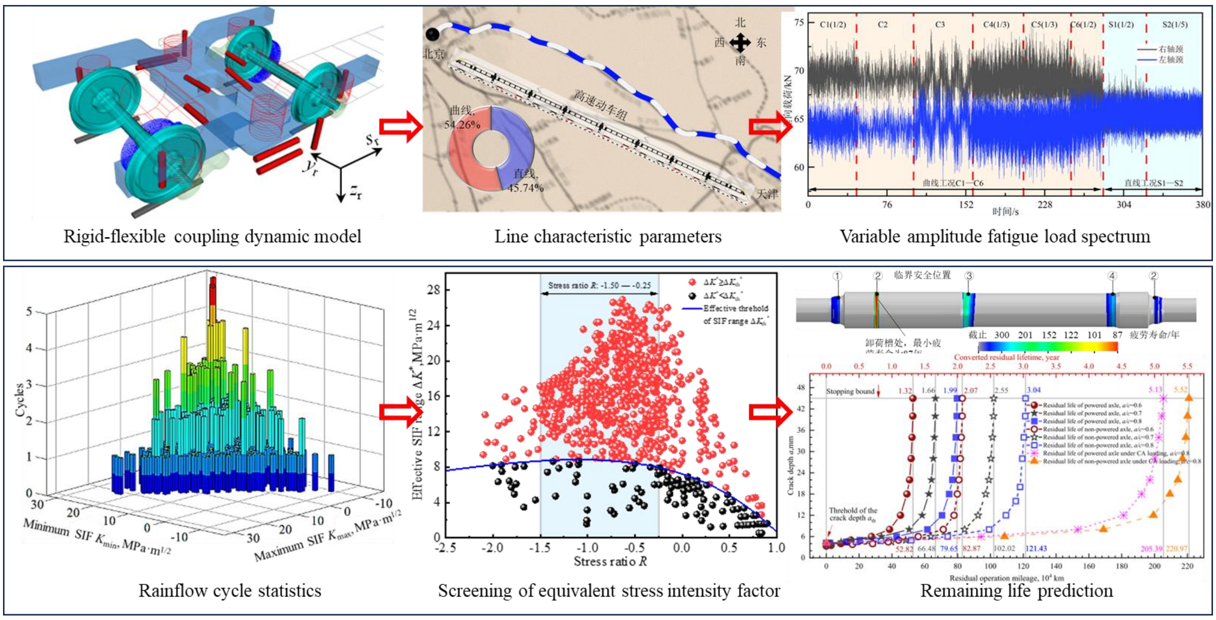



***Figure 1 -*** *Prediction and evaluation of axle variable amplitude fatigue life by integrating vehicle dynamics and structural strength*

# Prediction of Critical Defect Size in Additively Manufactured AISI 316L Using a Coupled Peridynamic – Chappetti Fatigue Model

**Luka Ferlič[1], Nenad Gubeljak[1], Erdogan Madenci[2], Mirco D. Chapetti[3], Filip Jerenec[1]**

[1]*University of Maribor, Faculty of Mechanical Engineering, Maribor, Slovenia*

[2]*University of Arizona, Faculty of Aerospace and Mech. Eng., Tucson, Arizona, USA*

[3]*University of Mar del Plata, Laboratory of Exp. Mech. INTEMA, CONICET, Mar del Plata, Argentina*

*Keywords: Fatigue life Peridynamics Additive Manufacturing*

**Abstract** Additive manufacturing process of metallic components such as Laser Powder Bed Fusion (LPBF) induce material defects such as gas porosity, lack of fusion defects and surface irregularities which serve as crack initiation sites making fatigue failure of additive manufactured components predominantly defect driven as short crack propagation is largely driven by short crack propagation rather than crack nucleation mechanism. Reliable prediction of fatigue life requires characterization of critical defect size and linking it with framework capable of predicting crack growth behavior without predefined crack paths. In this work, a coupled peridynamic fracture mechanics approach is presented that allows predicting critical defect size that governs fatigue life in additively manufacture 316L components. Experimental characterization of material is presented including tensile test, high cycle fatigue S-N curve, and Paris-Erdogan law parameters with long crack threshold $\Delta K_{th}$ and Vickers hardness measurements. A three-dimensional bond based peridynamics (PD) model was used for fatigue crack simulation. Cyclic damage evolution was incorporated in PD model using Kinetic Theory of Fracture (KTF). KTF parameters were calibrated with use of Paris-Erdogan parameters for long cracks on two-dimensional Single Edge Bending specimen to replicate experimentally measured crack growth rates. Short crack behavior was defined using Chapetti fatigue crack growth model that was integrated in PD framework allowing crack to transit from short to long crack regime withing the same framework using predetermined material properties. Fatigue simulations were performed for specimen with as build (AB) and polished (POL) surface under multiple stress levels with maximum stress ranging between 300 and 380 MPa. Initial critical defects size was determined using iterative process until simulated fatigue life matched experimental fatigue life curves. Obtained initial critical defects sizes were similar at all simulated stress levels. Furthermore, using obtained initial critical defects at given stress levels resulted in predicted S-N curves within 10% of fatigue life at given stress level from experimental results. The proposed peridynamic–Chapetti framework provides a defect-based fracture mechanics methodology for fatigue assessment of additively manufactured components, enabling prediction of fatigue strength without prescribing crack initiation sites or propagation paths.

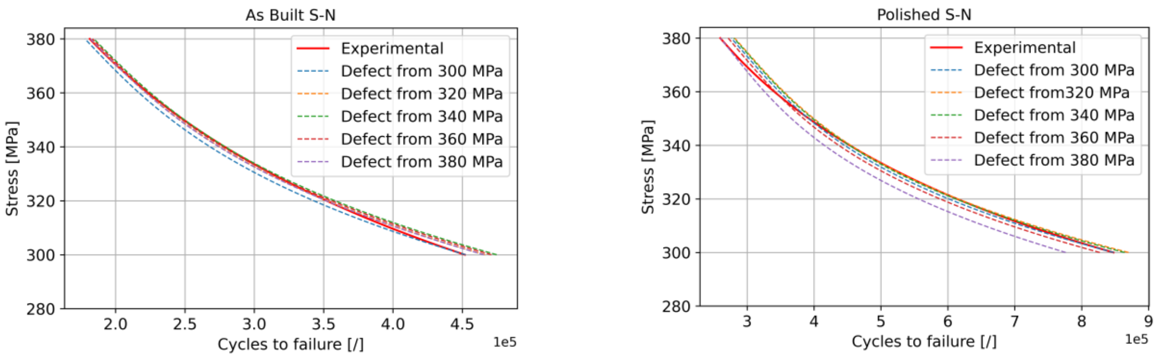



***Figure 1** – S-N prediction of model for a) As Build and b) Polished Specimens*

# Fatigue Crack Growth Prediction in AISI 316L Using a Peridynamic KTF Approach

**Filip Jerenec[1], Nenad Gubeljak[1], Erdogan Madenci[2], Luka Ferlič[1]**

[1]*University of Maribor, Faculty of Mechanical Engineering, Maribor, Slovenia*

[2]*University of Arizona, Faculty of Aerospace and Mech. Eng., Tucson, Arizona, USA*

*Keywords: Fatigue Crack Peridynamics Modeling AISI 316L KTF Approach*

**Abstract** Fatigue crack growth prediction in metallic materials remains a challenge in structural integrity assessment, particularly when accurate life estimation is required across varying load levels and geometries. This study presents a peridynamic fatigue crack growth framework based on bond-based peridynamics combined with a kinetic theory of fracture (KTF) based damage evolution model and its experimental validation for additive manufactured (AM) AISI 316L steel. Model parameters are calibrtated using fatigue crack growth data obtained from compact tension (CT) specimens under different load magnitudes. The calibrated model is then used to predict crack growth behavior in additional CT and Single Edge Bending (SEB) specimens under different loading conditions in terms of a-N curves. These are then directly compared with experimental measurements to predict crack growth. Across all investigated configurations, the model reproduces the overall a–N behaviour and crack growth rate trends with good agreement. The prediction error is found to depend systematically on the stress intensity range at which the simulation is initiated. When crack growth predictions start at stress intensity ranges corresponding to the upper bound or above the lowest ΔK level used during calibration, the deviation in total fatigue life remains within approximately 5%. However, when simulations are initiated at intermediate ΔK values within the calibrated range, larger deviations are observed, with maximum errors reaching approximately 17%. This trend originates from the calibration procedure itself. The KTF parameters are identified using multiple specimens that begin crack growth at different stress intensity ranges, while the numerical model assumes an identical zero-damage initial state for all simulations. As a result, it is not possible to perfectly reproduce the early-stage damage evolution for all starting conditions simultaneously. As crack growth progresses and the damage field evolves beyond this initial regime, the predicted behaviour converges, leading to reduced deviations at higher stress intensity levels, as is shown in Fig.1.

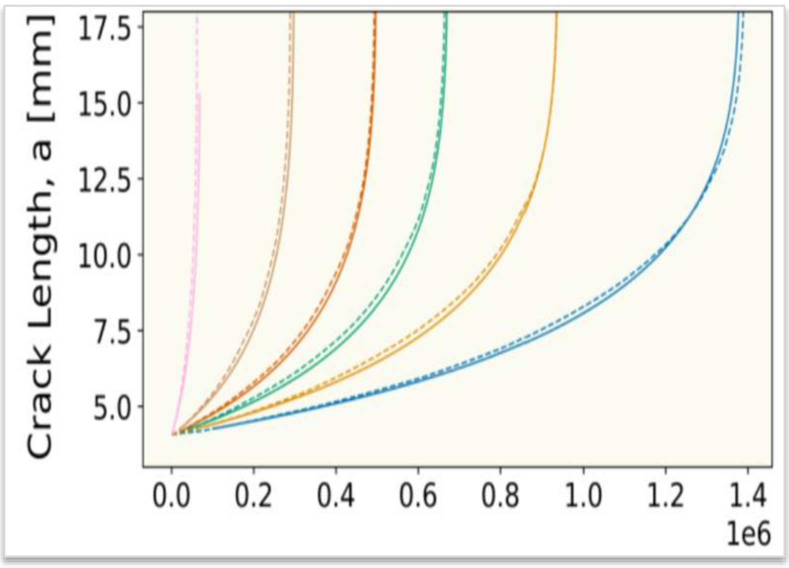



***Figure 1*** *– Agreement between numerically predicted and experimentally obtained a-N curves*

# Fatigue crack growth in a torque link simulated by SMART

**Aleksandar Grbovic[1], Nikola Raicevic[1], Aleksandar Sedmak[1], Gordana Kastratovic[2], Nenad Vidanovic[2]**

*[1]University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia*

*[2] University of Belgrade, Faculty of Transport and Traffic Engineering, Belgrade, Serbia*

*SMART* *Fatigue crack growth* *Torque link*

**Abstract** Fatigue crack was discovered during the pre-flight check of Cessna 172S, located in a nose gear torque link. Since there were no new spare parts to replace the damaged one, a non-standard procedure was adopted, with an aim to evaluate number of cycles needed to get crack up to 5 mm length. Toward this aim numerical simulation of fatigue crack growth was done by ANSYS SMART for two different geometries: original and modified one, obtained by topological optimization. Final goal was to find out if the damage torque link can be used for certain period of time, while in the meantime, a new one with modified geometry would be manufactured using additive production processes. New option in ANSYS – no need for the initial crack – is also presented and used.

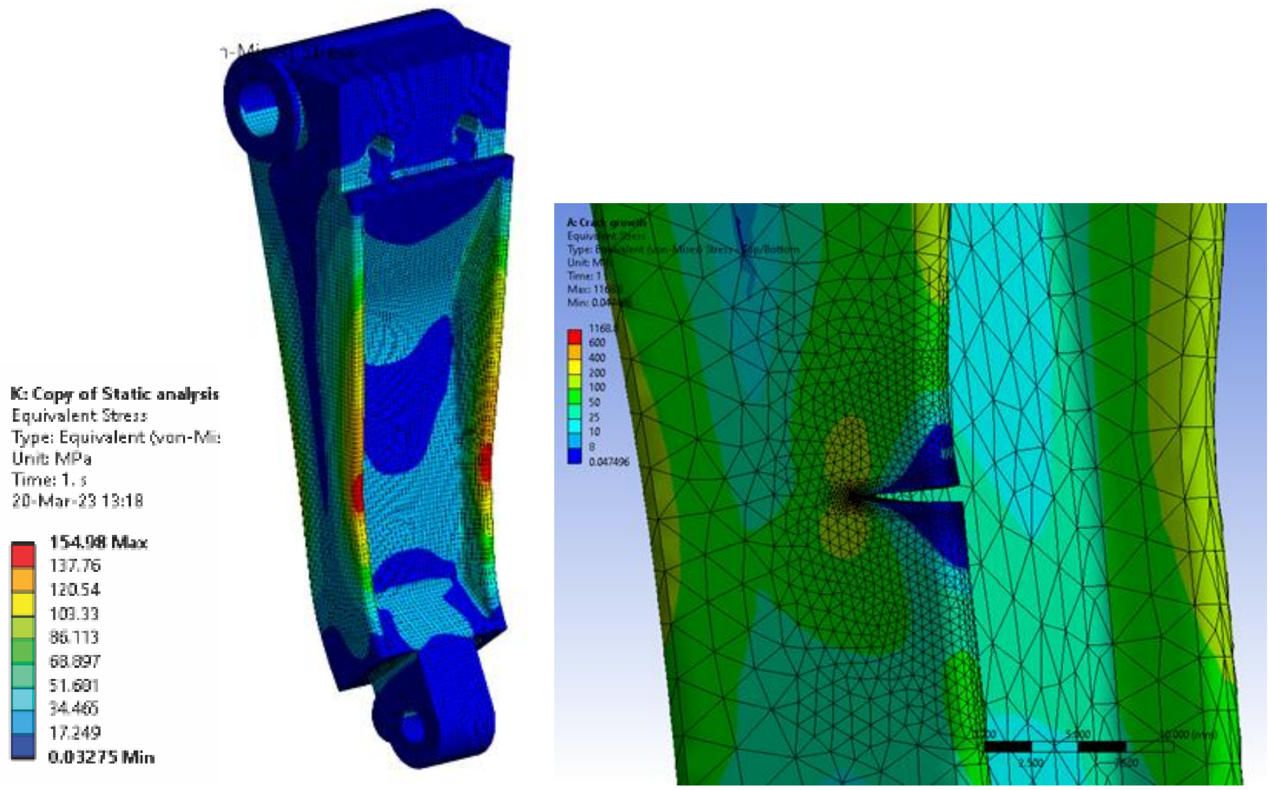



***Figure 1** – Stress distribution and fatigue crack growth in torque link*

# Fatigue crack growth in hip implants – numerical analysis by FEM

**Simon Sedmak [1], Katarina Colic[1], Aleksandar Sedmak[2], Tamar Smoljanic[1]**

*[1]Innovation center of the Faculty of Mechanical Engineering, Belgrade, Serbia*

*[2] University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia*

*FEM* *Fatigue crack growth* *Hip implant*

**Abstract**, A review of recent numerical investigation of hip implant fracture and fatigue behaviour is presented with focus on the effects of body weight, implant geometry and material. It is shown that body weight plays important role, especially for fatigue life. Regarding implant geometry it is demonstrated that the main issue is stress analysis. In the case of full cross-section implants, stress state is more favourable than in the case of implant with holes according to patient bones configuration. It was also shown that stress level in the latter case can be surprisingly high, especially with younger, active patients. Finally, interaction between influencing factors was taken into account, as relatively simple task for numerical simuation.

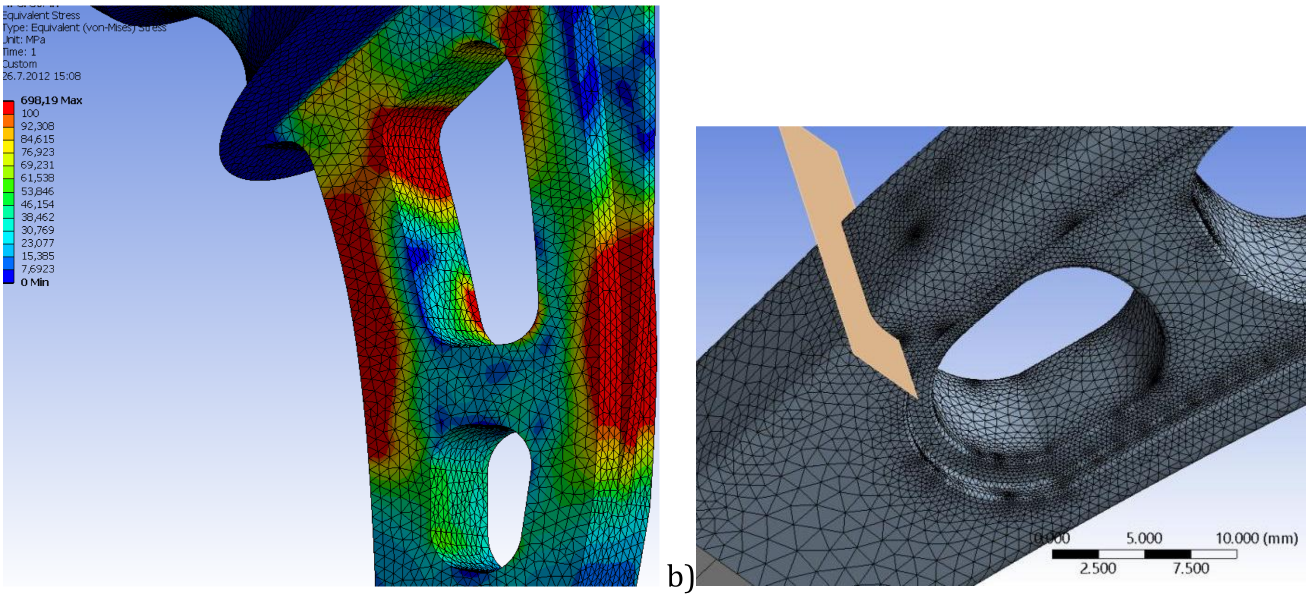
a)  b)


***Figure 1*** *– a) Stress distribution, b) initial fatigue crack in hip implant*

# Numerical simulation of fatigue crack growth in AA2024 T6 stringer panels

**Aleksandar Sedmak[1], Aleksandar Grbovic[1], Đorđe Zrnić[2]**

[1]*University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia*

[2]*Proton doo, Belgrade, Serbi*

*Finite Element Method* *Fatigue crack growth* *Stringer panels*

**Abstract** Numerical simulation of fatigue crack growth of AA2024 T6 stringer panel is presented. Both options for crack growth simulation, FEM using ANSYS SMART and xFEM using ABAQUS, are applied. Number of cycles vs. crack length dependence was obtained on the basis of calculated stress intensity factors (SIFS) along the crack fronts in Laser Beam Welded (LBW) stringer panels, indicating significantly longer life than experimentally measured and numerically simulated fatigue life of simple flat plate. Since the agreement between experimental and numerical results were not good enough, additional efforts were made to determine material coefficients C and m more precisely. After this adjustment, the agreement became excellent proving capabilities of numerical simulations of fatigue crack growth even in complex geometries.

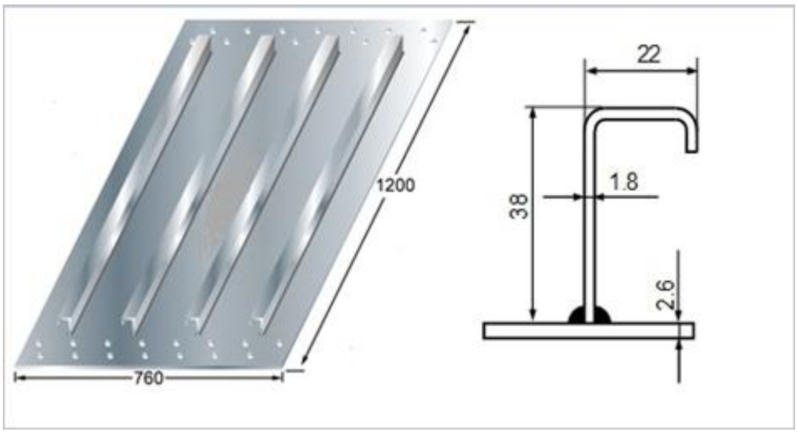



***Figure 1*** *– Stringer panel geometry*

# Fatigue Behavior of Tube-Extracted Specimens: From Experimental Testing to Strain–Life Curve Development

**Sebastian Raczek[1], Adam Niesłony[2], Krzysztof Kluger[3], Tomasz Łukasik[4]**

*[1]Department of Mechanics and Machine Design, Opole University of Technology, ul. Mikołajczyka 5, 45-271 Opole, Poland; sebastian.raczek@student.po.edu.pl*

*[2]Department of Mechanics and Machine Design, Opole University of Technology a.nieslony@po.edu.pl*

*[3]Department of Mechanics and Machine Design, Opole University of Technology; k.kluger@po.edu.pl*

*[4]Tenneco Automotive Eastern Europe Sp. z o.o., ul. Usługowa 20, 44-100 Gliwice, Poland; tlukasik@tenneco.com*

*Manson-Coffin-Basquin* *Confidence bound* *Strain control test*

**Abstract:** This study examines the strain-controlled fatigue behavior of specimens extracted from cold- or hot-rolled, electric-welded, annealed, and redrawn steel tubing. The material was tested in its manufactured condition to capture fatigue properties representative of tubular components used in structural applications. Low and high cycle fatigue experiments were conducted across a range of strain amplitudes, and the resulting fatigue lives were characterized using the Manson–Coffin–Basquin (MCB) relationship. The strain–life parameters were determined through regression of the experimental data, and statistical scatter was quantified to establish confidence bounds corresponding to two standard deviations (2σ). These bounds, together with the experimental points and the resulting MCB curve, are presented in Figure 1. Finite Element Method (FEM) simulations were used during specimen development to verify strain uniformity within the gauge section and to minimize the risk of structural stability loss. The integrated experimental, statistical, and numerical methodology offers a robust framework for characterizing fatigue performance of steel tubing.

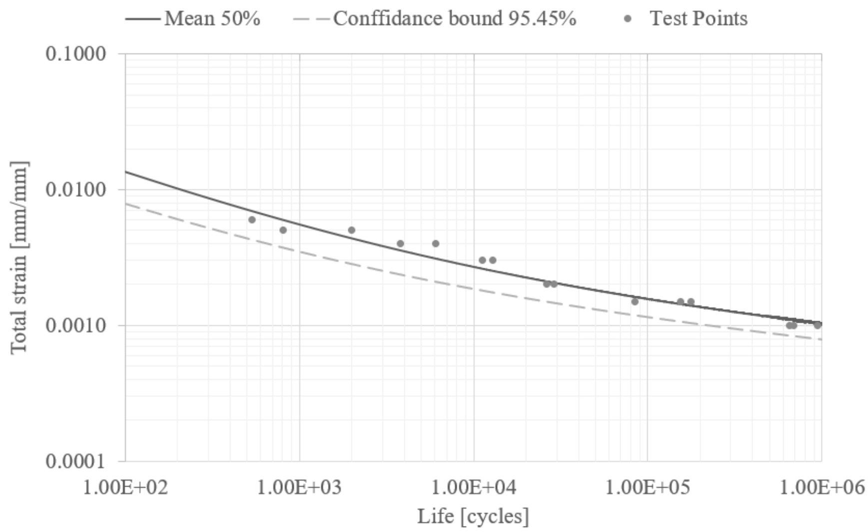



***Figure 1*** *– Manson-Coffin-Basquin curve obtained from conducted tests*

# Effect of heat treatment on very high cycle rotating bending fatigue properties of rail steel

**Noriyasu Oguma[1], Mitsuru Hosoda[2], Jun Mizutani[2], Tadashi Deshimaru[2]**

[1]*Faculty of engineering, University of Toyama, 3190 Gofuku, Toyama-city, Toyama 930-8555, Japan*
*e-mail: oguma@eng.u-toyama.ac.jp*

[2]*Track technology division, Railway Technical Research Institute, Japan*

*Rail steel* *Residual stress* *Crystal distortion*

**Abstract** The bottom of a railway rail is subjected to repeated bending stresses over long periods of time due to the movement of railway vehicles. Rails are required to be replaced at designated intervals to ensure safe operation. Because replacement is extremely costly, extending the replacement interval while maintaining the fatigue strength reliability of railway rails is essential. In this study, fatigue specimens were cut from the bottom of actual railway rails and their very high cycle rotating bending fatigue properties were evaluated. Railway rails were prepared using ordinary steel specified in JIS E1101 and heat-treated steel specified in JIS E1120. The heat-treated steel exhibited a hardness increase of approximately 30 to 80 HV, and residual stress varied depending on the cutting position from the rail, with significant heat treatment strain in the center. As shown in Fig. 1, the fatigue test results show that the heat-treated steel has a higher fatigue strength than ordinary rail steel. In particular, the fatigue strength of the specimens taken from the center (HT middle) where the heat treatment strain is larger, is higher than that of the specimens taken from the edge (HT side). Both steels exhibited a clear fatigue limit, and no specimens were observed to failure in the very high cycle regime. This suggests that the presence of inclusions or segregations that could serve as internal initiation sites is extremely unlikely. Furthermore, the fatigue limits in this experiment were higher than those estimated from Vickers hardness, and were in good agreement with those estimated from hardness calculated from crystal distortion using X-ray diffraction parameter.

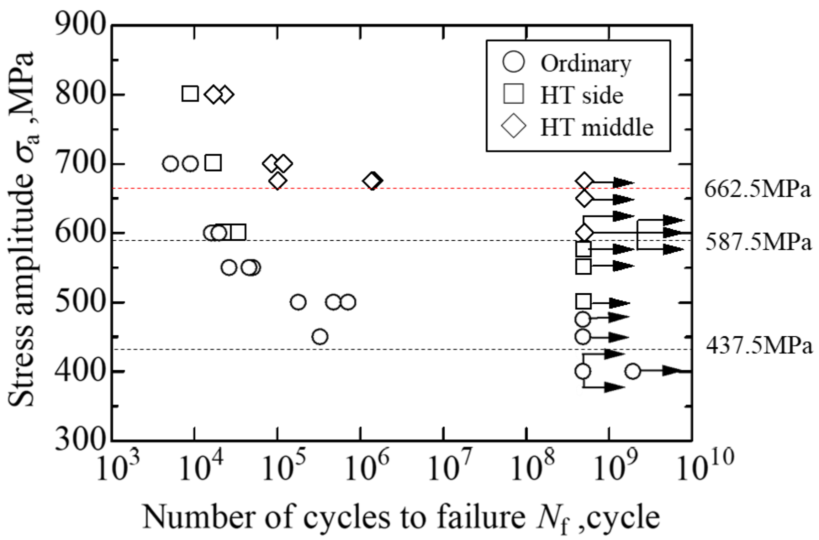



***Figure 1*** *– S-N properties of the ordinary rail steel and the heat-treated rail steel*

# Theoretical Model for the Temperature-Electric Field dependent Ultimate Tensile Strength of Metallic Materials

**Ru Li[1], Weiguo Li[2], Tianzi Shi[2]**

[1] *College of Aerospace Engineering, Chongqing University, China, 1413776434@qq.com*

[2]*College of Aerospace Engineering, Chongqing University, China*

[2]*College of Aerospace Engineering, Chongqing University, China*

*Force-Heat Equivalence Energy Density Principle* *Ultimate tensile strength* *Thermo-electrical coupling environments*

**Abstract** With the continuous advancement of modern industry, higher demands are placed on mechanical processing techniques, leading to the increasingly widespread application of electrically assisted forming technologies. As the foundational and key materials for modern engineering and high-end equipment, the study of the mechanical properties and reliability of metallic materials under thermo-electrical coupling environments has become a research hotspot. Currently, extensive tensile testing of metallic materials under varying temperatures and electric fields has been conducted. However, these destructive tests are time-consuming, labor-intensive, and energy-intensive, limiting research efficiency and material utilization. Establishing predictive models for material properties under thermo-electrical coupling conditions is therefore critical. This study establishes a theoretical characterization model for the temperature-electric field dependent ultimate tensile strength of metallic materials based on the Force-Heat Equivalence Energy Density Principle (Li's principle of energy equivalence). This model enables the quantitative characterization and convenient prediction of the temperature-electric field dependent ultimate tensile strength of metallic materials, providing an effective means for reliability evaluation. Furthermore, it offers a theoretical foundation for advancing electro-pulse assisted machining technology.

# Deformation Mechanisms and Fatigue Behavior of Rubber Composites Investigated Using Digital Image Correlation (DIC)

**Karolina Głowacka[1], Andrzej Kurek[2], Andrej Škrlec[3]**

*[1]Opole University of Technology, k.glowacka@po.edu.pl*

*[1]Opole University of Technology, a.kurek@po.edu.pl*

*[1]University of Ljubljana, andrej.skrlec@fs.uni-lj.si*

*Rubber composite* *Digital Image Correlation* *Fatigue behavior*

**Abstract** Flexible structurally reinforced composites combine elasticity with enhanced strength and fatigue performance. Their mechanical behavior depends strongly on the reinforcement architecture, which controls local strain distribution and damage initiation during cyclic loading. This study examines a rubber matrix (3 mm thick) reinforced with one layer of interwoven nylon cords arranged in two configurations: orthogonal (0/90°) and bias (+/–45°). Such layouts are typical for dynamically loaded components like conveyor belts or flexible couplings.

Cyclic two-sided bending tests were conducted on rectangular specimens, with deformation monitored by high-resolution imaging and analyzed using the Digital Image Correlation (DIC) method, enabling full-field strain evaluation. Distinct deformation mechanisms were identified. In the orthogonal (0/90°) arrangement, the high stiffness mismatch ($E_f \approx 1000 \cdot E_m$) led to significant strain localization at the cord-rubber interface. DIC analysis revealed that while the bulk matrix appeared stable, the interface zones experienced high stress concentrations, resulting in permanent structural set and a brittle-like failure characterized by a sudden drop in load capacity.

In contrast, the bias (+/–45°) configuration exhibited the "scissoring effect" where cords reoriented within the matrix. This layout showed a notably lower force amplitude but did not fail in a sudden manner and the lifetime of samples was longer. However, the longer lifetime of ±45° samples may not reflect true durability, as advanced degradation preceded final failure.

DIC imaging of the cross-section revealed a periodic "checkerboard" shear pattern, illustrating the complex load transfer between the single reinforcement layer and the surrounding rubber. While the 0/90° samples failed abruptly due to interfacial debonding, the ±45° specimens maintained structural integrity through gradual energy dissipation, despite visible micro-cracking. These findings emphasize that fiber orientation dictates not only the global stiffness but also the micro-scale strain distribution, which is critical for the fatigue life of flexible composites.

*Acknowledgement: This paper was funded by the National Science Centre, Poland, under the OPUS call in the Weave programme No 2022/47/I/ST8/00003*

# Using statistical methods from Aeroengine material allowables development for improved characterization of fatigue properties.

**Ryan L Smith[1] , Balajee Ananthasayanam[2], Kazuki Nagao[3], Jerry Cashman[4]**

*[1]Honda Aero LLC., 2989 Tucker St, Burlington, NC 27215, ryan_smith@na.honda.com*

*[2] Honda Aero LLC*

*[3] Honda R&D Co., Ltd.*

*[4] Consulting Engineer*

*Characterization* *Statistics* *Allowable*

**Abstract** A thorough understanding of a material's fatigue response is critical to safe design. To this end, Aeroengine manufacturers use various methods to generate statistically derived fatigue allowables to establish the lower bound of a material's capability. This presentation introduces one such method. This method is applicable to different materials metallic, composites, and ceramics. It is compatible with a range of analysis methods and curve models. Including Least Squares and Maximum Likelihood Estimation (MLE) methods for average curve fitting. Models such as Wohler, Stromeyer and Competing Failure Modes may be used.

The insight gained by this increased scrutiny on the extents of fatigue capability has value beyond aerospace design. It can inform process improvement and alloy development and influence material selection.

This presentation will outline the steps to generate allowables from a typical SN curve using Likelihood based confidence intervals of lower bounds. The impact of sample size on allowables will be demonstrated. Finaly, an example analysis will be shown.

# Contribution of digital image correlation (DIC) to the understanding of initiation and propagation mechanisms of naturally occurring fatigue cracks at a high number of cycles

**L. Gallegos-Mayorga[1], T. Landron[2], A. Alves de Moura[1], F. Morel[1]**

[1]*Laboratoire Angevin de Mécanique, Procédés et Innovation, Arts et Métiers Institute of Technology, Angers, France, linamaria.gallegos@ensam.eu*

[2]*Centre technique des industries mécaniques – Cetim, Nantes, France.*

*Natural cracks* *Digital Image Correlation* *Initiation and propagation kinetics*

**Abstract**

The characterization of the initiation and propagation mechanisms of fatigue-related cracks often requires experimental set-ups where crack initiation is voluntarily triggered. Conventional specimens and methods do exist to measure crack growth under specific conditions. Nevertheless, these methods are often inadequate to observe initiation and propagation of naturally occurring cracks. In such cases, digital image correlation appears as a powerful yet flexible tool capable of capturing kinematic fields on the surface of a specimen, thus allowing the identification of possible material discontinuities.

In this study, crack length measurements based on the gradient calculation of DIC obtained displacement fields reveal both the initiation and propagation kinetics of naturally appearing cracks on different alloys. Image-based analysis was performed on image datasets obtained by means of an experimental set-up comprised of a resonant testing fatigue machine connected to a programmable microcontroller used to trigger both a high-resolution camera and a monochromatic light fixture. A bending load was applied on the specimen at a rate of 116 cycles per second. No interruption of the test was required to capture the images used in the analysis.

The contribution of the presented experimental method to the understanding of naturally occurring cracks will be illustrated by means of: (i) examples showing multiple cracking and the role of microstructural gradients (hardness in particular) and (ii) the role of stop criteria on the scatter found on conventional S-N curves.

# A Phase-Field Framework for Multiaxial Fatigue Crack Initiation and Propagation for Fretting Problems

**Iñigo Llavori[1], Gorka Ruiz-de-Egino[1], Nagore Otegi[1], Eguzkiñe Martinez-Puente[1], Sean Leen[2]**

[1]*Mondragon Unibertsitatea, faculty of Egineering, Mechanics and Industrial Produsction, Arrasate-Mondragon, Spain*

[2]*Mechanical Engineering, College of Science and Engineering, University of Galway, Ireland*

*Multiaxial fatigue* *Phase field* *Fretting*

**Abstract** Fretting fatigue is a critical failure mechanism in mechanical components subjected to small-amplitude oscillatory motion combined with severe multiaxial stress gradients. Predicting both crack initiation and subsequent propagation under such contact conditions remains a major computational challenge. Most existing approaches treat crack initiation and propagation as separate stages or rely on explicit crack growth laws derived from classical fracture mechanics.

This work presents a novel fully coupled phase-field framework for fretting fatigue problems. In contrast to conventional fracture mechanics approaches, the proposed formulation does not rely on an explicit Paris-type crack growth law. Instead, every finite element point is treated as a potential damage location. The local multiaxial stress state is evaluated using the Smith–Watson–Topper (SWT) critical plane criterion, and fatigue damage is accumulated cycle by cycle following Miner's rule. As the phase field damage variable evolves, cracks initiate and propagate in regions experiencing the highest fatigue driving forces. Thus, crack growth emerges naturally from the evolving fatigue damage field rather than being driven by an explicit crack growth law. To maintain computational efficiency over large numbers of cycles, the formulation incorporates a cycle-jump acceleration strategy.

Furthermore, because the phase-field approach relies on the global minimization of the system's energy, it does not require predefined crack paths or complex geometric tracking algorithms. The damage variable is solved as a continuous field across the entire domain simultaneously. This unique feature allows the model to naturally capture simultaneous crack nucleation at multiple contact hotspots, as well as the unconstrained propagation and merging of complex crack networks.

The numerical framework is validated against fretting fatigue experiments performed on a dovetail contact configuration using Aluminum 7075-T6. Tests were conducted at a stress ratio of R = 0.1 to avoid crack-face contact effects. The use of this high-strength aluminum alloy ensures small-scale yielding conditions, consistent with the assumptions of the elastic phase-field formulation. The proposed framework provides a unified computational methodology capable of capturing both early fatigue damage accumulation and subsequent crack propagation in fretting fatigue problems.

# Damage detection in ultrasonic VHCF testing by analysing vibration properties

**Lopes, J. H.[1,2]; Fitzka, M.[3]; R. da Costa, P.[4,5]; Schönbauer, B.[3]; R. Cláudio[6], Mayer, H.[3]; Reis, L.[1,2]**

[1]*Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal - henrique.lopes@tecnico.ulisboa.pt*

[2]*IDMEC, Instituto Superior Técnico, Lisbon, Portugal – luis.g.reis@tecnico.ulisboa.pt*

[3]*Instituto of Physics and Materials Science, BOKU University, Vienna, Austria*

[4]*Atlantica, Instituto Universitário, Barcarena, Portugal*

[5]*Centre for Mechanical and Aerospace Science and Technologies (C-MAST), Covilhã, Portugal*

[6]*ESTSetúbal, Instituto Politécnico de Setúbal, 2910-761 Setúbal, Portugal*

*Very High Cycle Fatigue* *Ultrasonic Fatigue Testing* *Vibration properties*

**Abstract** Fatigue lifetime of a material is determined by damage accumulation, fatigue crack initiation and propagation to failure. With an increasing number of cycles, detecting and monitoring the development of fatigue damage in the Very High Cycle Fatigue (VHCF) regime poses a significant challenge, considering cracks tend, in many cases, to initiate internally, and exhibit a crack extension period, which is a small portion of fatigue lifetime. Ultrasonic Fatigue Testing (UFT) is currently the best appropriate experimental method for VHCF. Specimens are excited to resonant vibrations at a frequency close to 20 kHz, which greatly speed up testing and makes feasible experiments up billions of load cycles. The UFT equipment developed at BOKU University is a high-accuracy system designed to characterize the material behaviour in the VHCF and analyse various process signals. The analysis of various process signals was used to measure the ultrasonic vibration properties of the cast aluminium alloy AlSi8Cu3-t6 and the additively manufactured through Power Bed Fusion aluminium alloy AlSi10Mg. Different possible methods for the detection and monitoring of fatigue damage were investigated: i) evolution of resonance frequency, ii) vibration response behaviour through the nonlinearity parameter $\beta_{rel}$ and Total Harmonic Distortion, iii) variation of power requirements, iv) Quality factor Q during ultrasonic fatigue testing, and v) the change in the symmetry of the vibration of both specimen's ends.

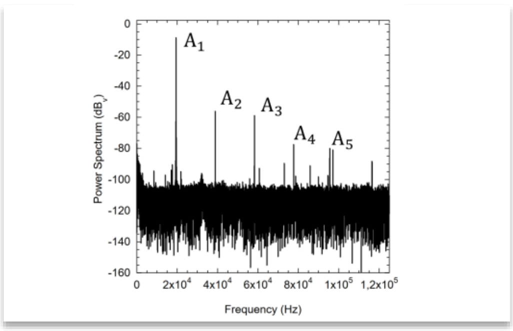



***Figure 1** – Power spectrum obtained from the vibration signal during an ultrasonic fatigue test*

# Very high cycle fatigue life of high strength steels exposed to different levels of corrosion

**Jan Klusák[1], Kamila Kozáková[1], Anna Sandnerová[1,2], Stanislav Seitl[1]**

[1] *Institute of Physics of Materials, Czech Academy of Sciences, Žižkova 22, 616 00 Brno, Czech Republic*

[2] *Faculty of Mechanical Engineering, Brno University of Technology, Technická 289/2, 616 69 Brno, Czech Republic*

*Very high cycle fatigue* *Stress concentration* *Corrosion effect*

**Abstract:** Three different types of high-strength steel (S460NL, S690QL and S960QL) were exposed to a corrosive environment and tested under high-frequency cyclic loading. The specimens were exposed to three levels of corrosion (3, 6 and 9 days in a salty, wet environment). Specimens were designed as smooth without stress concentrations. However, corrosion causes a reduction in fatigue life due to corrosion products such as dimples or notches of various shapes. The fatigue life of the pre-corroded specimens was determined experimentally and correlated with the fatigue life of similar specimens without corrosion (smooth – polished, smooth – as machined, and specimens with machined notches with various stress concentrations).

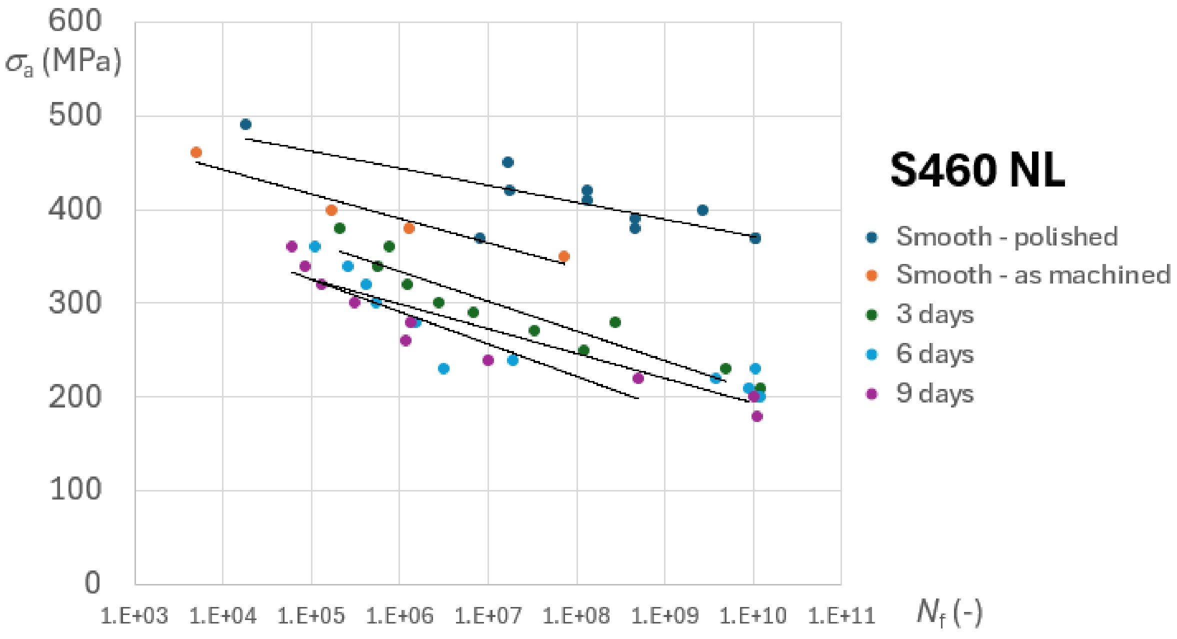



***Figure 1** – Fatigue S-N data for referential and corroded samples (steel S460NL)*

**Acknowledgements:** Research is supported by Czech Science Foundation through the project No 25-15763S Structural steels behavior of thin-walled load-bearing elements during cold joining.

# Determination of the Kitagawa-Takahashi Diagram by means of short crack models

**Mauro Madia[1], Jürgen Bär[2], Larissa Duarte[1]**

[1]*Bundesanstalt für Materialforschung und -prüfung (BAM), D-12205 Berlin, Germany*

[2]*Universität der Bundeswehr München, Institute of Materials Science, D-85579 Neubiberg, Germany*

*Fatigue limit* *Kitagawa-Takahashi Diagram* *Short crack model* *Cyclic R-curve*

**Abstract** The Kitagawa-Takahashi (KT) diagram is a widespread tool for describing the fatigue limit of components containing defects. It is usually determined experimentally by carrying out fatigue test on smooth specimens and specimens with artificial surface micro-notches of different sizes. Despite its simplicity, this procedure is, however, associated with great experimental effort due to the large number of specimens required and duration of a single test. Therefore, simple empirical relationships have been proposed in the past to approximate the KT diagram based on few basic mechanical properties. Among those, the El Haddad model has long proven to describe fatigue data with satisfactory approximation, even though it suffers from major drawbacks, especially in the technically relevant region of physically-mechanically short cracks. Alternatively, short crack models have the potential to describe the main mechanisms behind the fatigue strength given by the propagation and arrest of short cracks at defects.

Based on an extensive experimental campaign carried out on two different structural steels, this work aims to compare the benefits and drawbacks of existing models for the determination of the KT diagram. This includes simple phenomenological relationships, as well as existing short crack models and a more complex methodology based on the so-called cyclic R-curve analysis. The analyses reveal contradictory results, whereby the El Haddad model is mostly non-conservative and short crack models can be overly conservative. The difference between fatigue data and model predictions is discussed based on experimental evidence and additional numerical simulations.

# Effect of Post-Treatments on the High-Cycle Fatigue Behavior of Material-Extrusion Additively Manufactured H13 Tool Steel

**Mahmoud NAIM[1, 2], Mahdi CHEMKHI[1, 2], Delphine AUZENE[3], Julien BOUSSEL[4]**

[1]*LASMIS, University of Technology of Troyes, 10004 Troyes, France*

[2]*EPF School of Engineering, 2 Rue Fernand Sastre, 10430 Rosières-Prés-Troyes, France*

[3]*CRITT Matériaux Innovation, 9 Rue Claude Chrétien, 08000 Charleville-Mézières, France*

[4]*AM Solutions (Rösler Group), Z.I de la Fontaine d'Azon, 2 Rue du Maréchal de Lattre de Tassigny, 89100 Saint-Clément, France*

*Material extrusion additive manufacturing* *High cycle fatigue* *Tool steel*

**Abstract**

Metallic additive manufacturing (AM) of H13 tool steel offers significant potential for molding applications requiring conformal cooling channels. Indirect AM processes such as material extrusion (MEX) additive manufacturing are showing potential in the production of crack-free H13 tool steel parts. In the MEX process, the part is fabricated through several sequential stages: printing, thermo-chemical debinding, thermal debinding, and sintering. Nonetheless, this process typically results in a residual porosity of about 2-4 % and a heterogeneous surface roughness ($S_a$) that vary between the different faces of the part from ~ 8 $\mu$m to 42 $\mu$m. The roughness is the highest in the plane in which the layers are stacked and in the region in which a printing seam is present. All these features have unfavorable consequences on the mechanical properties and specifically on the fatigue limit of the parts. Therefore, surface post-treatments such as sandblasting are applied to reduce surface roughness, close surface defects, and introduce beneficial compressive residual stresses. These modifications improve the surface integrity of MEX components and can delay crack initiation and propagation. This work investigates the influence of sandblasting on the high-cycle fatigue behavior of MEX-processed H13 tool steel. Fractographic analyses were also conducted to identify the fatigue mechanisms before and after post-treatment.

# Research on Fatigue Strength Improvement of GCr15 Bearing Steel

Peng **Zhang**[1*], Peng **Wang**[1], Zikuan **Xu**[1], **Ziheng Shao**[1], **Zhefeng Zhang**[1]

[1]*Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China*

**Corresponding author: pengzhang@imr.ac.cn*

*Inclusions* *High strength steel* *Fatigue strength* *High cycle fatigue*

**Abstract** Improving the fatigue strength of engineering materials is a core strategy to guarantee the service safety of key components; unfortunately, although the tensile strength of numerous high-strength materials exceeds 3 GPa, their fatigue strength under tension-compression loading has not yet broken through 1 GPa. In this study, based on the coupling relationship between defects and the matrix, a critical inclusion size model for fatigue cracking was first established, and on this basis, precise regulation of the microstructure and defects in GCr15 bearing steel was carried out: modification with trace rare-earth elements improved the plasticity of inclusions to effectively suppress their brittle fracture, a novel shearable inclusion/matrix interface structure was formed to further enhance the cooperative deformation ability, and optimized heat treatment achieved an excellent strength–plasticity match to reduce the tendency of fatigue cracking at inclusions. As a result, a tension-compression fatigue strength of 1103 MPa at a stress ratio of R = −1 was achieved, which represents the highest level reported for steel materials to date, providing new ideas and feasible technical approaches for improving the fatigue performance of high-strength metallic materials.

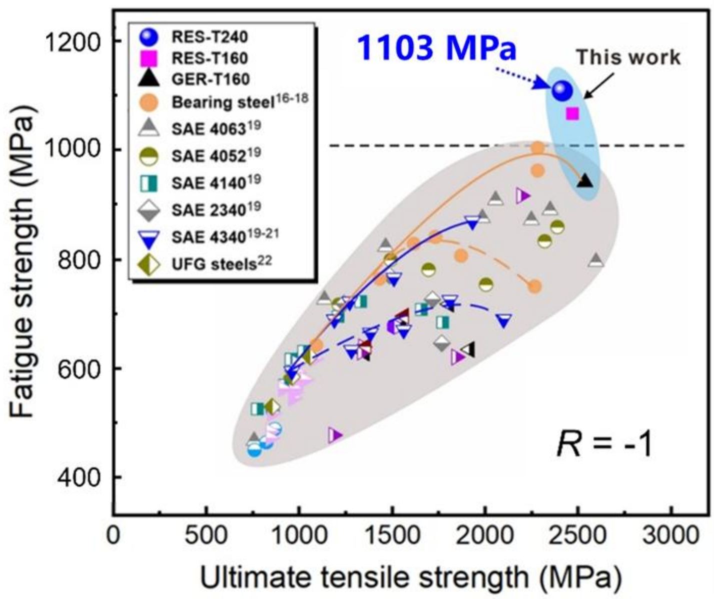



***Figure 1 -*** *The relationship between the tensile strength and fatigue strength of GCr15 in this work and various reported high-strength steels*

# Effect of cyclic pre-strain on the functional fatigue in superelastic NiTi alloys

**Tianyi Hu[1], Xiaoxian Zhang[1]*, Jinsong Leng[1]***

*[1] Harbin Institute of Technology, Harbin 150001, China, E-mail: hu_tianyi@yeah.net*

*Superelastic NiTi alloy* *Cyclic pre-strain* *Functional fatigue*

**Abstract** The functional fatigue of superelastic NiTi alloys under cyclic mechanical loading represents a critical bottleneck for their application in elastocaloric solid-state cooling systems. In this work, the effect of cyclic pre-strain on the functional fatigue performance of a NiTi alloy is investigated by varying the pre-strain amplitude and number of pre-strain cycles. Four pre-straining conditions are designed: specimens pre-strained to 5% for 5 cycles (ET1) and 10 cycles (ET2), and to 10% for 5 cycles (ET3) and 10 cycles (ET4). Stress-controlled fatigue tests are conducted at 0.5 Hz under a maximum load of 1000 N, with in-situ infrared thermography employed to monitor the adiabatic temperature change $\Delta T_{ad}$. All pre-strained specimens demonstrate extended fatigue lives relative to the as-received (AS) specimen, which sustains 290 cycles. Among them, ET3 achieves the best overall performance, with a fatigue life of 632 cycles, representing a 117.9% improvement, alongside an initial $\Delta T_{ad}$ of 11.8 °C, exceeding that of the AS specimen by 8.3%. Specimens subjected to 5-cycle pre-strain maintain higher $\Delta T_{ad}$ throughout cycling compared with the AS specimen indicating that excessive pre-strain cycles accelerate elastocaloric degradation. Infrared thermography reveals that specimens display a spatially uniform temperature field distribution during cycling. EBSD characterization shows that cyclic pre-strain reduces the average grain size from 45.5 μm to 22.3 μm and introduces higher intragranular orientation gradients, while the average Schmid factor increases from 0.3689 to 0.3881, reflecting an improved crystallographic orientation distribution favorable for stress-induced martensitic transformation. These results indicate that the fatigue life improvement is primarily attributed to grain refinement, while the optimization of grain orientation distribution further contributes to the enhancement of elastocaloric performance under cyclic loading conditions.

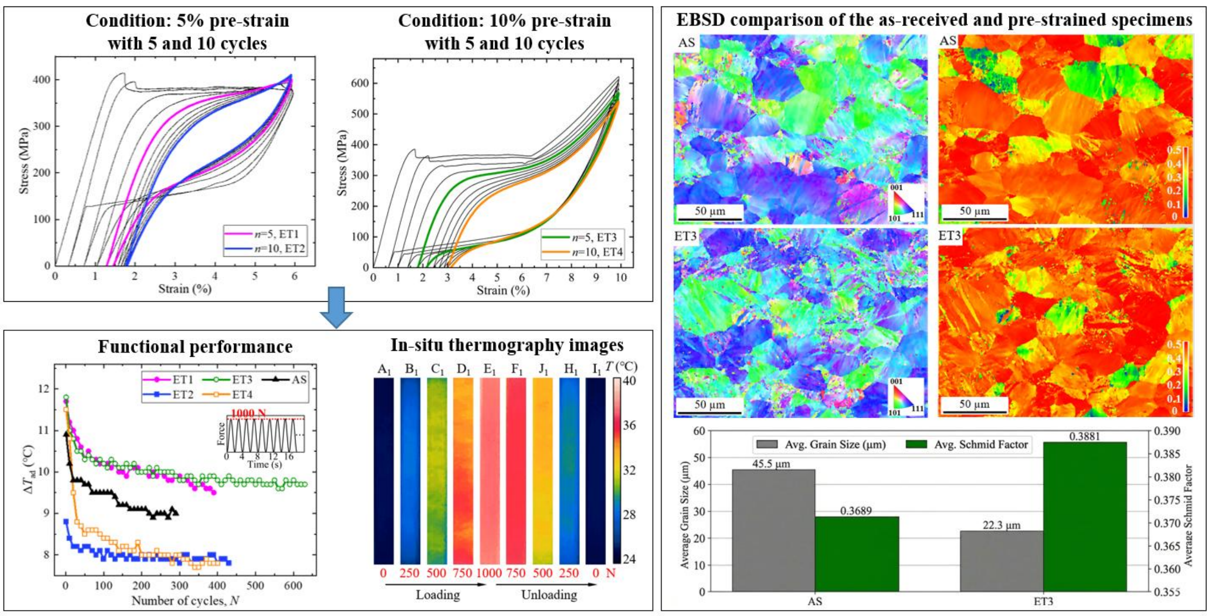


***Figure 1** - Effect of cyclic pre-strain on the functional fatigue and microstructure evolution of the superelastic NiTi alloy. Top left: stress–strain curves of specimens; Bottom left: evolution of adiabatic temperature change as a function of fatigue cycle number N and in-situ infrared thermography images of the ET3 specimen at N = 200; Right: EBSD inverse pole figure and Schmid factor maps and a comparative chart of average grain size and average Schmid factor.*

# Effect of build orientation and loading conditions on the fatigue behaviour of additively manufactured 18 Ni300 maraging steel – part 1

**Marta Kurek[1], Andrzej Kurek[2], Mihiretu Ganta[2], Tadeusz Łagoda[2]**

[1]*Faculty of Mechanical Engineering, Opole University of Technology, Opole, Poland, a.kurek@po.edu.pl*

[2]*Faculty of Mechanical Engineering, Opole University of Technology, Opole, Poland*

*Additive manufacturing* *Maraging steel* *Fatigue behaviour*

**Abstract** Additive manufacturing technologies such as Laser Powder Bed Fusion (LPBF) enable the fabrication of metallic components with complex geometries, but the layer-wise manufacturing process introduces anisotropy that can significantly influence fatigue behaviour. The mechanical response of LPBF materials is therefore strongly dependent on build orientation and loading conditions. This study investigates the influence of printing orientation on the fatigue behaviour of 18Ni300 maraging steel (MS1) specimens manufactured using the Direct Metal Laser Sintering (DMLS) process. Specimens were fabricated on an EOSINT M280 system with three build orientations relative to the build platform: 0°, 45°, and 90° (Figure 1a). Fatigue tests were performed under cyclic loading conditions using an MZGS-100 fatigue testing system. Two loading modes were applied: pure bending and pure torsion in oscillatory conditions. The obtained S–N characteristics reveal a clear influence of build orientation on fatigue life. Specimens manufactured at 0° orientation exhibited the highest fatigue resistance for both bending and torsional loading. The fatigue life decreased for specimens printed at 45° and 90°, indicating a strong relationship between the orientation of melt pools and the direction of cyclic stresses. The influence of orientation was found to be more pronounced under torsional loading than under bending conditions. Additional investigations were conducted for specimens printed at 45°. In this case, fatigue tests in pure bending were performed for specimens rotated around their longitudinal axis by 0°, 90°, and 180° relative to the loading direction (Figure 1b). The results indicate that the orientation of the internal layer structure relative to the bending plane can further modify the fatigue response, highlighting the role of anisotropy in additively manufactured materials. The presented results provide insight into the relationship between build orientation, loading mode, and fatigue performance of LPBF maraging steel. The findings contribute to a better understanding of fatigue behaviour in additively manufactured metallic components and support the development of improved design strategies for structures subjected to cyclic loading.

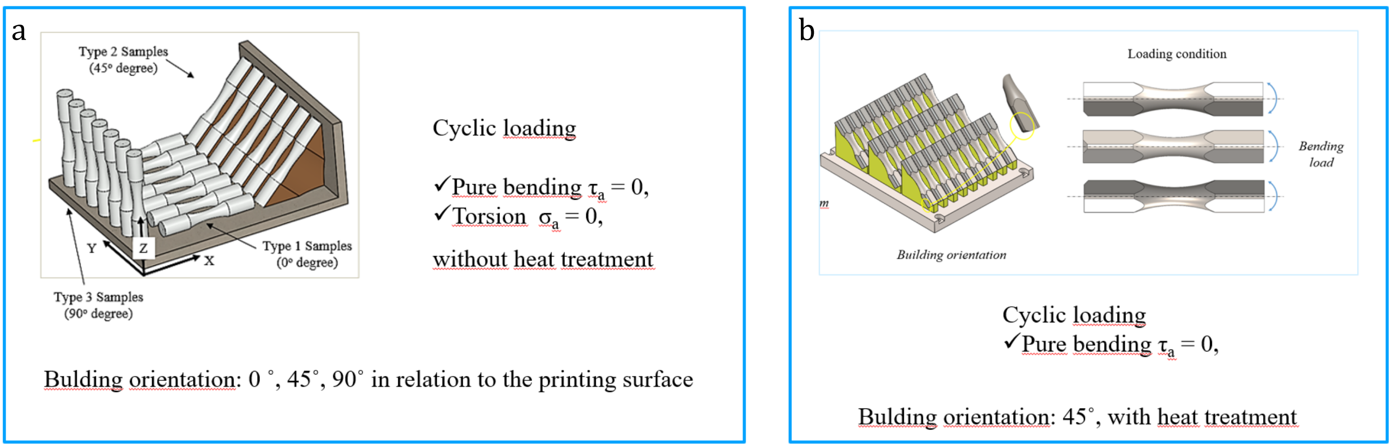



***Figure 1** – Two experiments conducted*

# Effect of build orientation and loading conditions on the fatigue behaviour of additively manufactured 18 Ni300 maraging steel – part 2

**Andrzej Kurek[1], Marta Kurek[2], Abdullah El Sabea[2]**

[1]*Faculty of Mechanical Engineering, Opole University of Technology, Opole, Poland, a.kurek@po.edu.pl*

[2]*Faculty of Mechanical Engineering, Opole University of Technology, Opole, Poland*

*Additive manufacturing* *Lattice structures* *Mechanical properties*

**Abstract** This study investigates the mechanical behaviour of lattice structures fabricated from 18Ni300 maraging steel using the Laser Powder Bed Fusion (LPBF) process. The investigated structures were based on triply periodic minimal surface (TPMS) architectures and manufactured on an EOS M280 system using MS1 powder. Mechanical characterization was performed under both quasi-static and cyclic loading conditions. Static mechanical tests were conducted to determine the apparent elastic modulus, strength, and deformation behaviour of the lattice structures. The results indicate that the mechanical response of the structures is governed primarily by their relative density and architectural topology. The structures exhibit a typical cellular solid behaviour, where stiffness scales with relative density while strength and failure modes are influenced by local geometric features. Fatigue tests were additionally performed to evaluate the durability of the lattice architectures under cyclic loading conditions. The results indicate that fatigue failure typically initiates in localized regions where stress concentrations occur within the lattice geometry, leading to progressive damage accumulation and eventual structural collapse. Surface deviation analysis relative to the nominal CAD geometry revealed manufacturing-induced geometric imperfections that may contribute to fatigue damage initiation. The obtained results provide insight into the mechanical performance and durability of additively manufactured maraging steel lattice structures intended for lightweight structural applications.

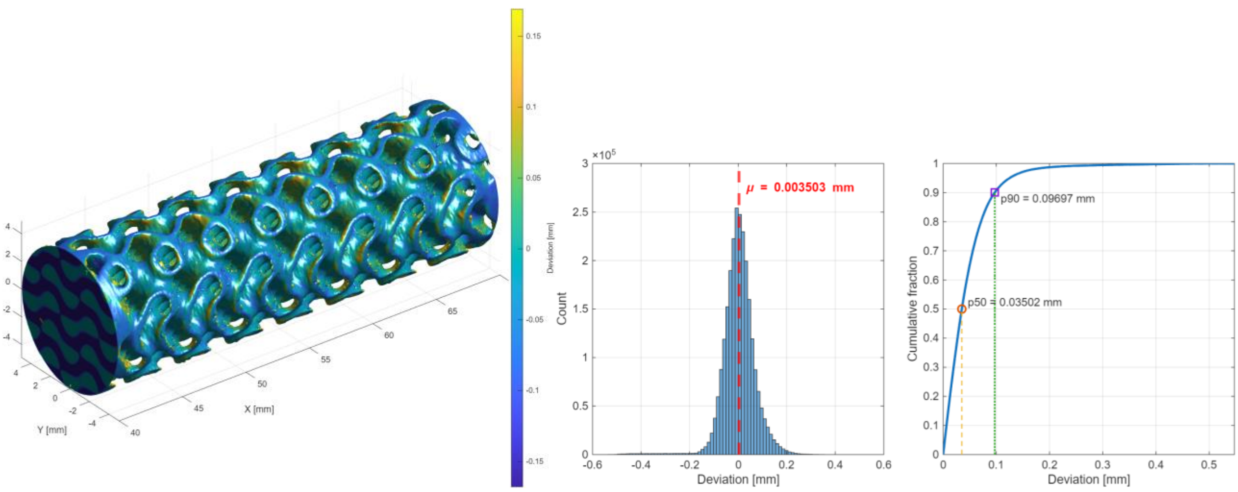



***Figure 1 -*** *Surface deviation analysis of the printed HT-Reference lattice relative to the nominal CAD model. The distribution shows near-zero systematic bias ($\mu$ = 3.5 $\mu$m) but substantial surface scatter (RMSE = 66.3 $\mu$m), with 90% of points lying between p05 = −86.4 $\mu$m and p95 = 107.5 $\mu$m.*

# Fibred laser shock peening without coating: Analysis of the homogeneity of residual stresses related to process parameters

**Gallitelli D.**[1]

[1]*Europe Technologies, 2, rue de la Fonderie, 44475 Carquefou, France*

*Fibred laser shock peening* *Residual stress* *X ray diffraction*

**Abstract** The role of residual stress in the fatigue life of workpieces has been widely studied in the recent decades. Several processes dedicated to enhancing the mechanical properties and lifespan, such as shot peening, are now standard in production. Laser shock peening operates on the same principle as shot peening, impacting the part to introduce compressive residual stresses. In this case, laser pulses create the impacts.

While Laser shock peening is a highly effective process that generates a very deep layer of residual stress, it is not that widespread due to its implementation complexity. Conventional devices are very large, and the process requires careful surface preparation. The surface must be covered with a thermo-absorbent film and a layer of water. For complex geometries, these operations are particularly complicated.

Recent studies have shown that laser peening without coating is possible and effective, respecting some conditions (especially the covering between spots) [1] and allowing the use of more compact devices.

In our laboratory, we studied the influence of process parameters on residual stress, and particularly related geometrical problems which can lead to issues with water film homogeneity and laser beam focusing. We have performed several tests on aluminum alloys, comparing non-homogeneous versus homogeneous water layer, as well as focused and non-focused laser beam. Surface roughness and residual stress by x ray diffraction were measured and compared.

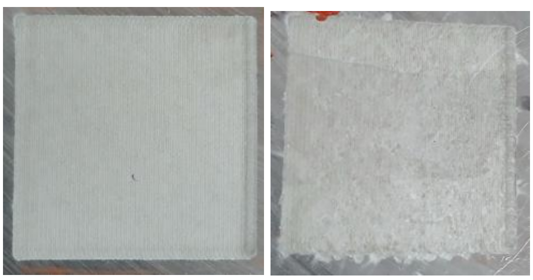


***Figure 1** – comparation between homogeneous and non-homogeneous water layer during the treatment*

[1] Y. Sano, K. Akita, K. Masaki, Y. Ochi, I. Altenberger and B. Scholtes, "Laser Peening without Coating as a Surface Enhancement Technology," Journal of Laser Micro/Nanoengineering Vol. 1, No. 3 (2006).

# Probabilistic Fatigue Life Assessment of Additively Manufactured Maraging Steel

**F. Bumba[1], V. Anes[2], P. Morais[3], R. Batalha[3,4], K. Trojan[5], L. Reis[1]**

[1]*IDMEC, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisbon, Portugal,* *francisco.paca@tecnico.ulisboa.pt; luis.g.reis@tecnico.ulisboa.pt*

[2]*Instituto Superior de Engenharia de Lisboa, 1959-007 Lisboa, Portugal*

[3]*Instituto de Soldadura e Qualidade, Taguspark-Oeiras, 2740-120 Porto Salvo, Portugal*

[4]*Escola Superior de Tecnologia de Setúbal, Instituto Politécnico de Setúbal, 2910-761 Setúbal, Portugal*

[5]*FNSPE, Czech Technical University in Prague, Trojanova 13, Prague 2, Czech Republic*

*Laser powder Bed fusion* *Maraging steel* *Probabilistic analysis*

**Abstract** Densification level approaching 99.99% is already a reality in metals fabricated by laser powder bed fusion (LPBF). Nevertheless, process- induced defects cannot be fully eliminated and this usually leads to significant variability in fatigue performance. Based on this fact, a probabilistic fatigue analysis of LPBF produced maraging steel specimens in the as-built condition is presented.

Fatigue tests were conducted and two parameter Weibull statistical models were used to assess fatigue life variability. To further investigate the sources of fatigue life variability, material characterization was performed through the assessment of internal and external defects. For the external defects a surface roughness measurement was carried out to assess the impact of as-built surface condition, while internal defects were characterized using X-ray computed tomography (µCT) Scan with 5 µm voxel resolution to identify LPBF associated defects. In addition, scanning electron microscopy (SEM) was used to examine fracture surfaces and identify initiation sites. Finally, a residual stress measurement through depth was also included to evaluate their potential contribution in overall fatigue performance.

The combined fractographic and statistical analysis, together with the measured residual stresses which transitioned from compressive near surface to tensile at subsurface, indicated that surface irregularities, internal defects and tensile residual stresses are the main contributors to the observed fatigue life scatter.

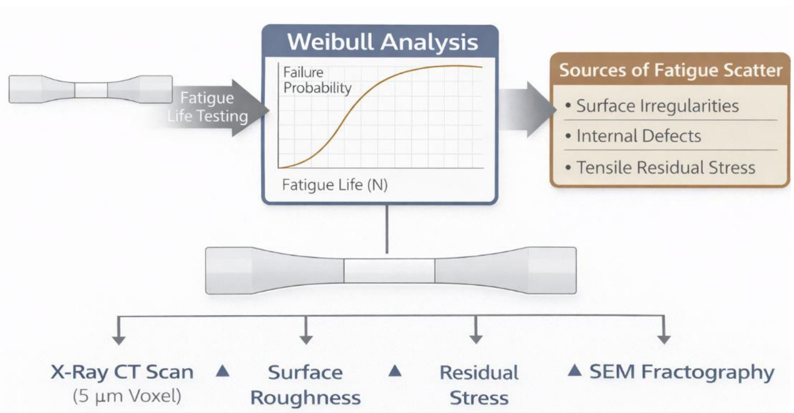



***Figure 1 -****Workflow of probabilistic fatigue life assessment*

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# FEM analysis of the threaded sleeve with the compressed air tank

**Tadeusz SMOLNICKI[1], Paweł MAŚLAK[2]**

[1] *Wroclaw University of Science and Technology, Faculty of Mechanical Engineering, Department of Machine and Vehicle Design and Research, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland, e-mail: tadeusz.smolnicki@pwr.edu.pl*

[2] *Wroclaw University of Science and Technology, Faculty of Mechanical Engineering, Department of Machine and Vehicle Design and Research, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland, e-mail: pawel.maslak@pwr.edu.pl*

*Finite Element Method* *Pressure tank* *Fatigue analysis*

**Abstract:** The subject of the study is the Finite Element Method (FEM) analysis of a 35 L compressed air tank intended for vehicle mounting. The study primarily evaluates the fatigue strength of the threaded sleeve's welded connection, assesses bottom deformation, and verifies the correct bottom thickness.

The structural integrity of the tank was simulated against specific boundary conditions, including accelerations of ±15 g and ±7.5 g in three orthogonal directions (X, Y, Z) for 1,000,000 cycles, as well as working pressures of 8.5 to 12.5 bar for 100,000 cycles.

Key findings from the analysis demonstrate:

- The compressed air tank successfully withstands 100,000 cycles at the 8.5-12.5 bar working pressure range.
- The tank meets ad hoc strength requirements at a short-term pressure of 14 bar, though the bottom with the bushes becomes plasticized.
- Under ±15 g accelerations, the tank fails the 1,000,000-cycle threshold in the X and Y directions, but it withstands this load in the Z direction.
- Under reduced ±7.5 g accelerations, the tank successfully endures 1,000,000 cycles across all three spatial directions.
- The bolted connection meets fatigue strength requirements with a 21.4 kN tension force under a 7.5 g acceleration load.

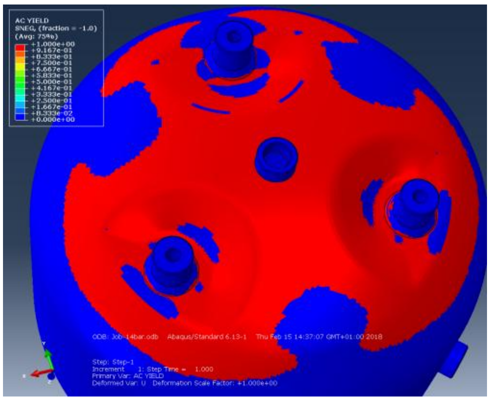


***Figure 1 -*** *Plastic zones in the material – pressure 14 bar*

# Effect of fiber orientation on stiffness reduction in cracked composite laminates subjected to hygrothermal aging

**Billel Boukert[1], Mohamed Khodjet Kesba[1], Amina Benkhedda[1], El abbes adda Bedia[2]**

[1]*Aeronautical Sciences Laboratory, Aeronautics and space studies Institute, University of Blida1, Algeria, bilanosky@hotmail.fr*

[2]*Materials and Hydrology Laboratory, University of Sidi Bel Abbes, Algeria*

*Hygrothermal effect* *Stiffness reduction* *Transverse cracking*

**Abstract** A modified shear-lag model combined with a variational approach was employed to evaluate how crack density influences stiffness degradation in [βm/θn]s composite laminates under varying environmental conditions, including temperature changes and transient moisture diffusion during desorption. The predictions show good agreement with experimental results reported by Joffe and Katerelos, although some discrepancies may arise due to damage in the 40° ply and interface delamination, which were not considered in the model. For uncracked angle-ply laminates exposed to hygrothermal conditions, the non-uniform and time-dependent moisture distribution leads to a reduction in the longitudinal Young's modulus. The findings reveal that plies with higher fiber orientation angles are more sensitive to such conditions, resulting in more pronounced mechanical degradation, especially in stiffness. In cracked laminates of type $[\beta/90_3]_s$, the overall stiffness decreases significantly with increasing transverse crack density and fiber orientation angle in the outer layers, particularly under elevated temperature and moisture levels. In contrast, for $[0/\theta_3]_s$ laminates, the relative stiffness reduction is more severe when the fiber orientation angle in the cracked plies is below 90° under similar environmental conditions. Overall, this study highlights the importance of understanding stiffness degradation in aged and cracked composite laminates, with particular emphasis on the role of fiber orientation.

# Fatigue crack measurement using polarimetric imaging

**Carolina Francisco[1], João M. A. F. Campos[2], Susana Dias[1], Pedro J. S. C. P. Sousa[1,2], Paulo J. Tavares[1], Pedro M. G. P. Moreira[1,2]**

[1]*INEGI, Institute of Science and Innovation in Mechanical Engineering and Industrial Engineering, Rua Dr. Roberto Frias,400, Porto, 4200-465, Portugal*

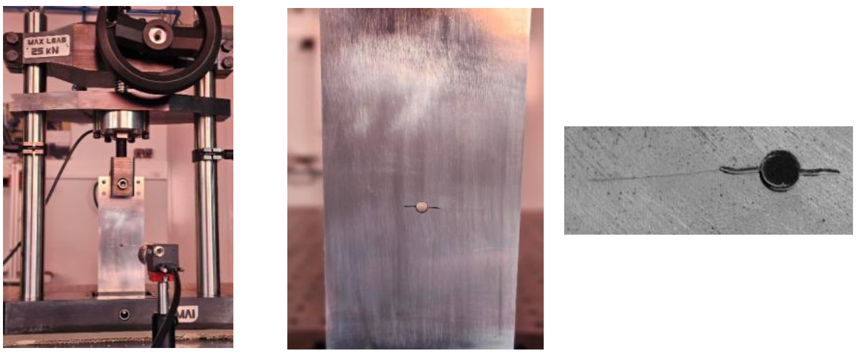
[2]*Departamento de Engenharia Mecânica, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, Porto, 4200-465, Portugal*

*Crack propagation*  *Polarimetric imaging*  *Non-intrusive measurement*

**Abstract** Accurate characterization of crack initiation and propagation is essential for predicting component lifespan and preventing catastrophic failures in safety-critical applications. However, measuring crack propagation throughout a test remains a challenge due to the small scale of cracks, complex geometries, and the need for non-intrusive, real-time monitoring techniques. Besides, measurement automation methodologies are currently subject to great scrutiny due to the potential to greatly expedite crack growth monitoring, but have yet to prove reliable for some specimen geometries.

Conventional crack measurement methods, including optical microscopy, compliance-based techniques, and digital image correlation, are well-established and widely used for fatigue characterization. However, they may present practical constraints related to resolution, experimental complexity, cost, and automation, particularly when applied to small-scale specimens. In such cases, limited optical access and intrusive measurement setups can complicate accurate crack characterization.

This study investigates the feasibility of polarimetric imaging for enhanced fatigue crack detection and measurement. A camera equipped with a polarimetric sensor is used to acquire images of the different polarization directions of the light of the crack and obtain polarimetric features such as the degree or angle of linear polarization. Passive and active illumination strategies are systematically compared and multiple polarimetric features are evaluated to identify those most effective in distinguishing crack regions from the surrounding material.



**(a)** **(b)** **(c)**

***Figure 1 -*** *(a) Experimental setup (b) Specimen with crack analysed and (c) Resulting image with the Degree of Linear Polarization (DoLP) obtained from the camera*

# Condition assessment of the Firing Control Handle Socket and Pivot in the Portuguese Air Force F-16 aircraft

**Inês M. F. de Carvalho[1], T. Barros[1], B. Santos[1], L. Reis[2]**

[1]*Centro de Investigação da Academia da Força Aérea e Centro de Investigação e Desenvolvimento do Instituto Universitário Militar, Granja do Marquês, Pêro Pinheiro, 2715-021, Portugal,* *ifcarvalho@emfa.gov.pt, tobarros@emfa.gov.pt, btsantos@emfa.gov.pt;*

[2]*IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal.*

*Fatigue Cracking*    *Finite Element Analysis*    *Non-Destructive Inspections*

**Abstract** The Firing Control Handle Socket and Pivot of the Advanced Concept Ejection Seat (ACES II), installed in the Portuguese Air Force F-16 fleet, are safety-critical components whose structural integrity is essential for pilot survival, in case there is a need to eject. Historical Non-Destructive Inspection (NDI) records indicate a consistently high rejection rate, primarily due to fatigue cracking that originates at stress-concentration features.

The proposed methodology integrates historical NDI data analysis, material characterization by optical emission spectrometry, numerical simulation, and experimental assessment. Computer-Aided Design (CAD) models of both components were reconstructed from 3D-scanned Stereolithography (STL) data and imported into Abaqus CAE 2020 for finite element analysis under axial tensile loading. This approach aims to replicate the loading conditions expected during service life and subsequent laboratory tensile tests on rejected components.

The material was identified as being consistent with 7075 aluminum alloy. Analysis of the historical NDI dataset revealed a concentration of damage at the socket–pivot and socket–handle interface holes, indicating that these geometric features are critical regions for crack initiation. Ongoing finite element analysis are expected to provide a quantitative assessment of the stress distribution in these areas. Future crack-growth simulations and laboratory tensile tests will further evaluate the structural relevance of the observed damage.

This framework is designed to establish a quantitative, numerical and experimental basis for revising inspection criteria. Therefore, it is expected to support safer and more cost-effective maintenance of legacy fighter ejection systems.

***Figure 1 - ACES II Ejection Seat and Firing Control Handle Socket and Pivot of the F-16 aircraft***

# Integration of Additive Manufacturing in the production of aeronautical components and systems: Regulatory requirements for metallic materials

**C.Monteiro[1], T.Barros[1], B.Santos[1], D.Salgado[1], P.Morais[2]**

*[1] Centro de Investigação da Academia da Força Aérea e Centro de Investigação e Desenvolvimento do Instituto Universitário Militar, Granja do Marquês, Pêro Pinheiro, 2715-021, Portugal,*

*crmonteiro@emfa.gov.pt, tobarros@emfa.gov.pt, tobarros@emfa.gov.pt, dmsalgado@emfa.gov.pt*

*[2]Instituto de Soldadura e Qualidade (ISQ), Av. Prof. Cavaco Silva 33, 2740-120 Porto Salvo, Portugal,*

*pjmorais@isq.pt*

*Military Aviation* *Aeronautical Certification* *Metal Additive Manufacturing*

**Abstract** This study assesses the feasibility of using metal Additive Manufacturing to replace an F-16 Socket and Pivot component within the operational context of the Portuguese Air Force. The topic is relevant due to the difficulty of obtaining legacy aeronautical spare parts, long procurement cycles, and strict airworthiness requirements in military aviation.

The work combines a review of metal Additive Manufacturing technologies with a regulatory and certification-oriented assessment for aeronautical applications. The original component was chemically analysed to identify its base alloy and guide the selection of suitable Additive Manufacturing compatible materials. The results indicate that the Socket and Pivot component is consistent with aluminium alloy 7075-T6. Since conventional 7075 alloys are difficult to process by fusion-based AM, alternative alloys such as 7075NT T6 and Scalmalloy® are considered due to their mechanical performance, processability, ductility, and fatigue resistance.

The next stage will include the production of standardized specimens and mechanical testing, including tensile and fatigue crack growth tests according to applicable ASTM standards. These results will support finite element simulations and a preliminary structural assessment of the component. The final objective is to determine whether metal AM can provide a technically viable route for replacing the F-16 Socket and Pivot, contributing to greater maintenance autonomy and reduced logistical dependence.

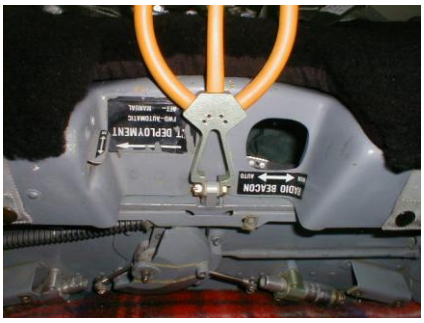


***Figure 1** – F-16 Firing Control Handle: Socket and Pivot*

# Fatigue Testing of Fiber Reinforced Composite Materials on Higher Testing Frequency

**Markus Berchtold, RUMUL, Russenberger Prüfmaschinen AG, Switzerland**

*Darren Foster, Department of Wind and Energy Systems, Technical University of Denmark, Roskilde, Denmark*

**Abstract**

The global effort for maximizing the power output of wind turbines requires the development of wind turbine rotor blades with ever-increasing length. Modern large utility offshore wind turbine rotor blades operate in one of the harshest environments on the planet and require the use of high-performance fiber-polymer composite materials such as pultruded unidirectional glass- and/or carbon fiber planks to live up to these tough performance demands. Rotor blades are subject to an order of magnitude of $10^8$ to $10^9$ load cycles during their +30-year service life where experimental characterization of the fatigue performance of these composites is key for blade manufacturers to evaluate and certify the true mechanical properties of the employed material systems. On the other hand, a reduced time to market creates a strong incentive to decrease the material certification time either by extrapolating the SN-curves or by increasing the test-speed.

Resonance fatigue testing machines represent a highly efficient solution for generating fatigue data quickly and cost-effectively. Operating at high testing frequencies with minimal energy consumption—comparable to that of a light bulb—and without wear parts, these machines offer exceptionally low running costs. The system is excited at its resonant frequency using an electromagnet, analogous to a child on a swing, where nearly all elastic deformation energy is returned to the system. Only the energy dissipated as heat through damping effects, such as plastic deformation or wear, needs to be feed into the system.

In order to establish fatigue testing on higher testing frequency in HCF and VHCF regime and to benefit of the resonance fatigue testing technique an extensive testing campaign has started to compare the fatigue data gained with servo hydraulic testing machines on frequency below 10 Hz and with data produced by resonance fatigue testing machines on 40 to 100 Hz testing frequency. This works summaries some of the results of this ongoing work and possible strain rate effects are discussed.

# Fatigue and Fracture Performance of Additively Manufactured Ti-6Al-4V via Laser Powder Directed Energy Deposition

**Nikolaos D. Alexopoulos[1], Ioannis Goulas[1,2], Alexis Kermanidis[2], Denys Zhumar[3], Olena Karpovych[3], Yevhen Karakash[3], Olexandr Grydin[3]**

*[1]Research Unit of Advanced Materials, Department of Financial and Management Engineering, School of Engineering, University of the Aegean, Kountouriotou 41, 82100, Chios, Greece*

*[2] Laboratory of Mechanics and Strength of Materials, Department of Mechanical Engineering, University of Thessaly, Volos, 38334, Greece*

*[3] Skyrora Ltd, 7 Drum Mains Park Cumbernauld, G68 9LD, Glasgow, UK*

*fatigue* *fracture resistance* *Ti-6Al-4V*

**Abstract**

Laser Powder Directed Energy Deposition (LP-DED) enables the production of Ti-6Al-4V components with refined microstructures and improved strength compared to typically manufactured counterparts [1]. Additionally, post-process heat treatments may effectively modify the microstructure of LP-DED manufactured Ti-6Al-4V, allowing the modification of mechanical properties, reducing brittleness while improving fracture resistance. LP-DED printed Ti-6Al-4V shows good strength levels despite process-induced defects, making it a potential option for structural applications where fracture and fatigue performance are crucial. However, microstructural status and constraint effects have a significant impact on the fracture behavior of Ti-6Al-4V, underscoring the necessity of systematic research on thickness and heat treatment effects.

In the present study, the effect of post heat treatment on the high-cycle fatigue (S-N) behavior of LP-DED produced samples of Ti-6Al-4V is investigated against the baseline samples witout any post-heat-treatment. Additionally, Compact Tension (CT) specimens are used to examine how specimen thickness and heat treatment affect fracture resistance, with a focus on thickness-dependent constraint effects.

**Acknowledgements**

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# Enabling Reliable Fatigue Data - Shimadzu's Contribution to Testing Excellence

**Sebastian Fürst[1], Yano Fumiaki[2], Tsubasa Yamamoto[2] , Takuo Ono[2]**

[1]*Shimadzu Europa GmbH, Albert-Hahn-Straße 6-10, D-47269 Duisburg, s.fuerst@shimadzu.eu*

[2]*Shimadzu Corporation Japan*

*Ultrasonic fatigue testing* · *high-temperature VHCF testing* · *VHCF 3 Point Bending*

**Abstract** Reliable fatigue data are essential for evaluating long-term structural durability, particularly in the very high cycle fatigue regime. This presentation highlights two Shimadzu USF-2000A applications that extend beyond standard VHCF testing and demonstrate how reliable data can be obtained under demanding test conditions. A high-temperature gigacycle fatigue test of Inconel 718 was conducted at 600 °C using the USF-2000A ultrasonic fatigue testing system. By combining ultrasonic loading with induction heating and intermittent operation, stable test conditions were maintained, and subsequent EPMA-8050G analysis enabled identification of inclusion-related crack origins. In addition, a CFRP 3-point bending fatigue application performed at 20 kHz is presented, showing how ultrasonic testing can substantially reduce test time while enabling observation of specimen behavior by high-speed video and DIC analysis. Together, these examples demonstrate how Shimadzu solutions support efficient and reliable fatigue testing across different materials and challenging test environments.

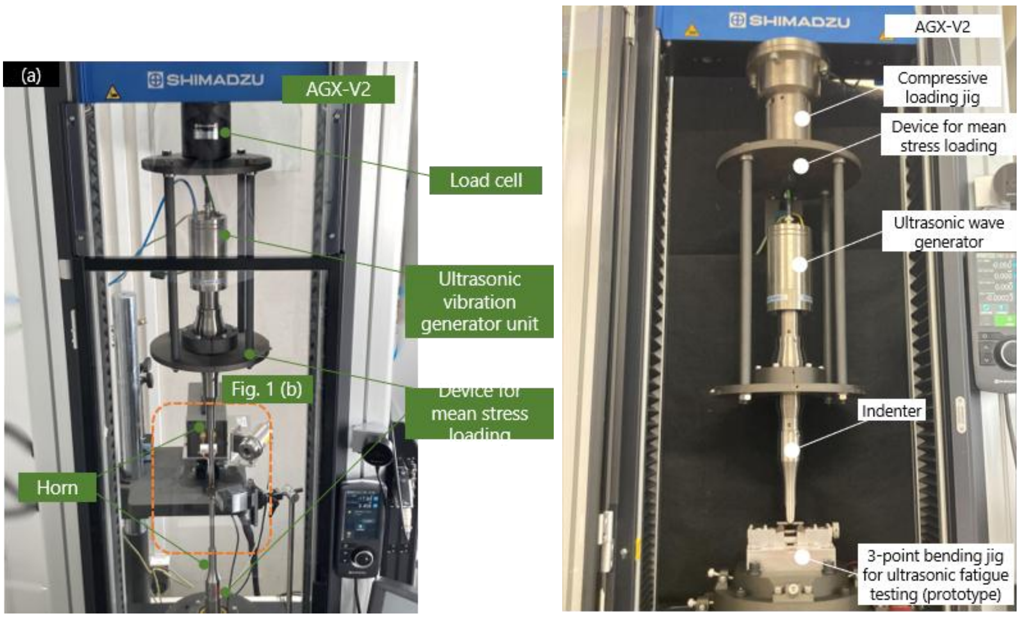


***Figure 1** – Very high Cycle Fatigue test set up for high temperature (left) and 3 Point Bending (right)*

# Fracture Surface Analysis of LPBF-produced Ti-6Al-4V by XPS and AES

**Yu Cao[1] and Lars Nyborg[2]**

[1,2]*Department of Mechanical Engineering, Chalmers University of Technology, Sweden*

*Powder-Bed-Fusion* *Fractography* *XPS and AES*

**Abstract** Additive manufacturing (AM) is the general term for all manufacturing techniques where the component is built by adding material layer by layer from a CAD (computer-aided design) model. Laser beam Powder-Bed-Fusion (LPBF) is a core AM technique in the context of metallic materials. This study aims to establish the correlation of local chemistry with the fatigue fracture in LBPF-produced Ti-6Al-4V. The strain-controlled fatigue test was performed at room temperature with R = 0. Four specimens with two different strain levels (Δε = 0.65% and 0.8%) and varied fatigue lives were chosen to be studied.

The fatigue fractured surfaces were investigated using surface analysis techniques - X-ray photoelectron spectroscopy (XPS) and Auger electron spectroscopy (AES). The crack initiation, propagation and final fracture region were identified. Thanks to the small area XPS together with AES having high lateral resolution, the chemistry of the features at different locations on the fracture surface was investigated. The role of some elements or impurities in crack development was examined, especially for crack initiation. A comparison was made between the specimens with low and high fatigue life at two strain levels. This study provides some insight into fatigue life improvement and scatter reduction for LBPF-produced Ti-6Al-4V.

# From Collaborative Network to Research Infrastructure: A Vision for FABER in Fatigue Benchmarking and Lifetime Engineering

**Theo Zacharis[1], Jan Papuga[2]**

[1]*Greek Scientists Society, Mesogeion 169, Athens 151 26 GR. theo@greek-scientists-society.org*
[2] *FME Czech Technical University in Prague, Technická 4, 166 07 Prague, Czechia*

Fatigue benchmarking research infrastructure lifetime engineering

**Abstract**

The growing demand for resilient infrastructure, sustainable manufacturing, asset life extension through digital twinning, and digital engineering avoiding costly physical experiments is creating new challenges and opportunities for the fatigue community. The same demand increases however the pressure onto quality of fatigue life estimation. While Europe possesses world-class expertise, experimental facilities, and industrial capabilities in fatigue and structural integrity, these resources remain largely fragmented across institutions, sectors, and countries, which inhibits development and validation of more precise fatigue estimation models. Addressing future challenges will require not only advances in fatigue-life prediction methods but also stronger cooperation between academia, research organisations, testing laboratories, and industry.

This contribution presents a forward-looking vision for the evolution of the FABER CA23109 COST Action beyond a collaborative research network towards a European ecosystem for durability, structural integrity, and lifetime engineering. The proposed framework combines FAIR data principles, benchmarking methodologies, open-source analytical tools such as FatPy, provenance-aware workflows, Digital Twin technologies, and future interoperability with engineering data ecosystems. The objective is to create a more transparent, reproducible, and collaborative environment for the development, validation, and deployment of fatigue assessment methodologies.

Particular emphasis is placed on the role of verification and validation as enabling mechanisms for scientific excellence and industrial trust. To this end, the contribution introduces the concept of FABER (Fatigue Benchmark Repository), a community-driven initiative aimed at establishing a common European framework for benchmarking fatigue models, analytical methods, and digital engineering tools. Through shared benchmark datasets, blind prediction FABEST challenges, transparent performance evaluation, and reproducible workflows thanks to FatPy open-source library, FABER seeks to improve comparability, trustworthiness, and knowledge exchange across the fatigue community.

Furthermore, it explores how the integration of experimental facilities, benchmark repositories, digital services, and open-source platforms can strengthen cooperation between academia, research organisations, industry, and software developers while advancing fatigue research, durability assessment, structural integrity, and lifetime engineering across multiple industrial sectors.

By positioning benchmarking, validation, and collaboration at the centre of future developments, FABER can serve as a catalyst for connecting facilities, data, software, and stakeholder communities. Through the establishment of shared methodologies, benchmark repositories, open-source tools, and collaborative networks, the Action is creating foundations that can support the long-term legacy, impact, and continued evolution of European fatigue, durability, and lifetime engineering.