FATIGUE 2022^{+1}

Program & Abstract Book

13th International Fatigue Congress

November 6th to 10th, 2023

International Conference Center Hiroshima, Japan

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Contents

Introduction

Welcome to the website of the 13th International Fatigue Congress, “Fatigue2022+1,” to be held in Hiroshima, Japan.

As an international conference specifically focusing on the subject of fatigue, the International Fatigue Congress was established in 1981 by the initiative of Professor A.F. Blom, Sweden. The first congress was held in Stockholm, and it has been organized every three years in different cities until the venue was again Stockholm in 2002. Meetings such as the International Conference on Mechanical Behavior of Materials (ICM) and International Conference on Fracture (ICF), which are conferences dealing with material strength and solid dynamical systems, are held every four years. Therefore, to avoid overlapping, this meeting was organized every four years after 2002. It was held in Atlanta, USA in 2006 and has continued likewise since then. The last meeting was held in Poitiers, France, in 2018, where 614 presentations were given. In the meantime, the 4th International Fatigue Conference, “Fatigue'90,” was planned in 1990 mainly by The Society of Materials Science, Japan (JSMS) Committee on Fatigue of Materials, but owing to the impact of exchange rates, the conference was held in Hawaii, USA. So, this is the first time the congress is organized in Japan.

“Fatigue” is a term used to describe deformation under repeated loading, a phenomenon starting to manifest during the Industrial Revolution in the 19th century and being the subject of wide ranging investigations. Initially, most of the research was performed using engineering approach to prevent failure by grasping fatigue life based on stress criteria. Subsequently, researches were conducted on life evaluation methods based on plastic strain and on fatigue life estimation methods under actual working load. Moreover, with the development of observation instruments, such as optical microscopes, transmission/scanning electron and atomic force microscopes, extensive research were conducted focusing on the clarification of the mechanism of fatigue crack initiation based on microscopic observation to elucidate the mechanism of fatigue crack propagation and to address the essence of fatigue.

In the initial stage, the research target was limited to metallic materials and was called “metal fatigue,” but with the appearance of engineering ceramics, resin materials and resin-based composites, as well as of new advanced materials that have been developed according to the requirements over time, the scope of research on fatigue has gradually expanded.

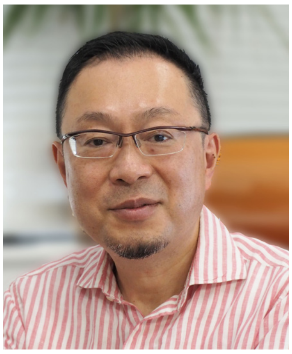
The International Fatigue Congress brings together scientists and engineers engaged in experimental, theoretical, and characterization research on mechanisms of fatigue fracture and provides unique and ideal environment for the exchange of discoveries, ideas, and experiences in related fields.

On a personal note, right after starting my scientific career as a researcher, I joined the executive committee of Fatigue '90 held in Hawaii in 1990, and was present in all meetings except the previous one in France. That time, I intended to participate in the International Fatigue Congress having in mind to invite the Congress to Japan, but to my greatest regret, I was preoccupied with my duties as Head of the Faculty of Engineering. Now I am much honored to act as the Chairperson of Fatigue 2022+1 to be held in Japan for the first time, and I am looking forward to welcoming you to the peaceful city of Hiroshima.

Atsushi Sugeta

Congress Chair

Committees



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Jun KOMOTORI (Co-Chair)
Yoshihiko UEMATSU (Co-Chair)

IFC Steering Committee

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W. S. JOHNSON
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K. TAKAHASHI (Japan)
N. TAKEDA (Japan)
K. TANAKA (Japan)
Y. UEMATSU (Japan)
A. WEIDNER (Germany)
D. YONEKURA (Japan)

Information

PROGRAM INFORMATION

Registration desk

The registration desk will be opened in the main Hall
on Monday 6th November from 4:00 pm to 6:00 pm
on Tuesday 7th November from 7:10 am to 5:00 pm
on Wednesday 8th November from 7:30 am to 5:00 pm
on Thursday 9th November from 7:30 am to 11:00 am
on Friday 10th November from 7:30 am to 2:00 pm

Oral Presentations

Oral presenters are kindly requested to use your laptop for your presentation (.ppt, .pptx or .pdf files preferably).
We have prepared HDMI and Mini D-sub 15 pin (DE-15) for connection cables. If you need other conversion cables, please prepare them by yourself.
Presenters are requested to check the connection between their laptop and the projector by yourself during breaks.

The time for a regular presentation is 15 min + 5 min for questions and answers (Plenary: 60 min including Q&A; Keynote lectures: 40 min including Q&A). The chairpersons are urged to strictly enforce this allocated time, in particular in order to ensure the synchronization between parallel sessions and stick with the timetable.

Prizes for students will be awarded, voted for by the Conference attendees and Committee. Awards ceremony will be held at Closing, Friday 10th.

Social Events

Welcome Reception

Attendees are kindly invited to join the Welcome Reception in the Hall of the International Conference Center Hiroshima on Monday 6th at 6.00 pm.

Banquet

Banquet will be held on Thursday (Day 4), November 9th, 7:00 pm in RIHGA Royal Hotel Hiroshima.
The Eight-Headed Snake Demon (Yamata-no-Orochi) will be performed in Banquet. Hiroshima Kagura is a traditional performing art which has been passed down from generation to generation mainly in northern Hiroshima Prefecture.

Excursion

The visit of the Naka Incineration Plant at Hiroshima city and Itsukushima shrine at Miyajima Island will be organized on Thursday, November 9th from 11:30 am.

Lunchs & Refreshments

Lunchs and Refreshments will be offered during the congress, so please take time to discuss with the presenters and visit the exhibition.

Information

REGISTRATION INFORMATION

Registration Fees

Full Registration

https://fatigue2022.org

In case of problem, contact the registration secretariat.
Mail: fatigue2022@or.knt.co.jp

Wifi

A free wireless internet access will be available for attendees.

Shared Lobby Network
SSID : icch-free
Password : icch

HIMAWARI internal network
SSID : icch-wifi
Password : icch2427777

CONGRESS VENUE

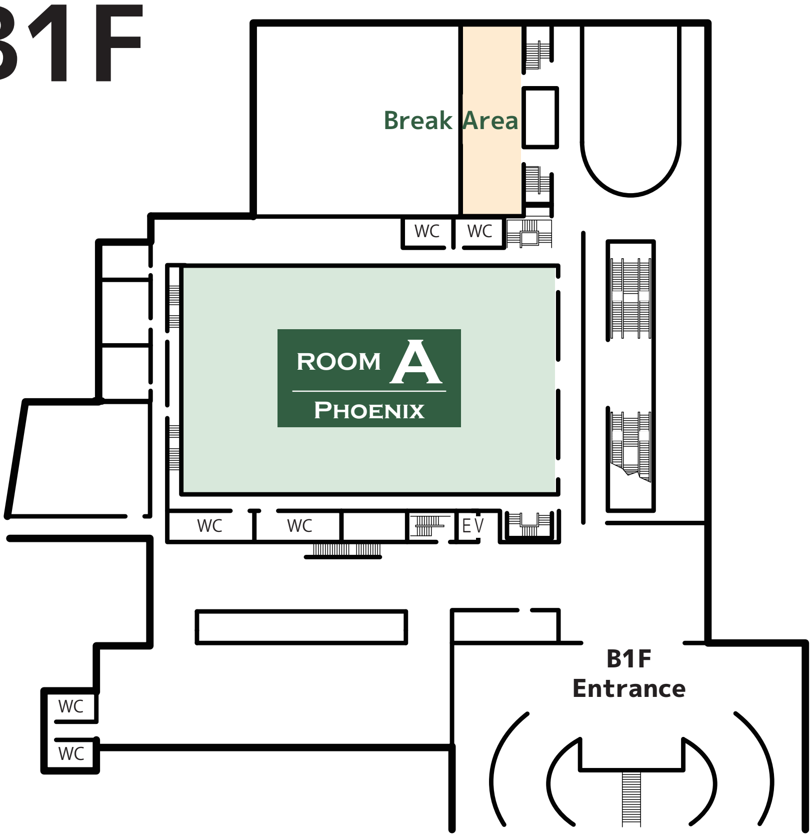
International Conference Center Hiroshima

Address: 1-5, Nakajima-cho, Naka-ku, Hiroshima (in the Peace Memorial Park)
Phone : +81-(0)82-242-7777

Website : https://www.pcf.city.hiroshima.jp/icch/index-e.html

Information

B1F



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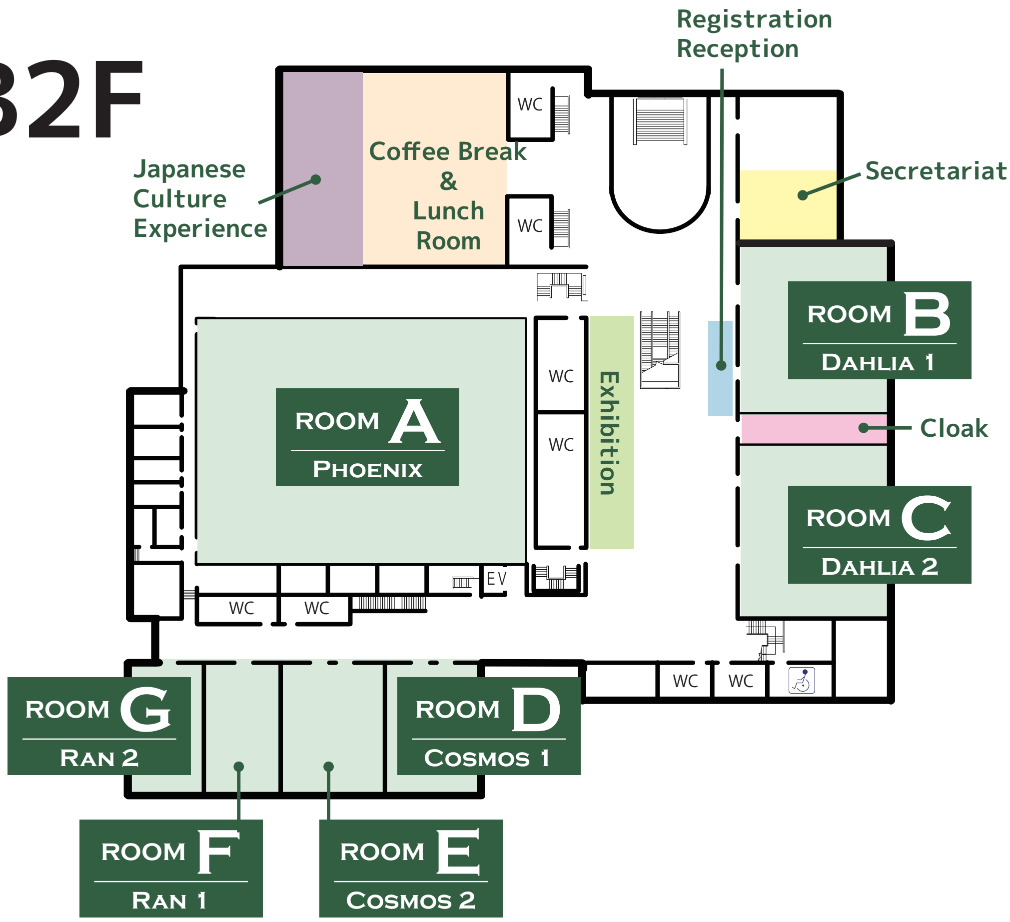


Sponsors & Exhibitors

Exhibitors:

SHINTOKOGIO, PULSTEC, MTS, SHIMADZU

Sponsors:

MITSUBISHI HEAVY INDUSTRIES, INSTRON, MATPLUS, NETUREN, NIPPN STEEL

Supported:

Suzuki Foundation

Electric Technology Research Foundation of Chugoku

Schedule

Day 1 — Monday, November 6 (8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00)

Room A	Phoenix	
Room B	Dahlia 1	
Room C	Dahlia 2	
Room D	Cosmos 1	
Room E	Cosmos 2	
Room F	Ran 1	
Room G	Ran 2	
Exibition	Lobby	
Lunch	Himawari	Welcome Reception
Reception	Lobby	Registration
Cloak	Lobby	Cloak

Day 2 — Tuesday, November 7 (8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00)

Room A	Phoenix	Opening & Plenary Lectures [Zimmermann]; Parallel Sessions; Parallel Sessions; Parallel Sessions
Room B	Dahlia 1	Parallel Sessions; Parallel Sessions; Parallel Sessions
Room C	Dahlia 2	Parallel Sessions; Parallel Sessions; Parallel Sessions
Room D	Cosmos 1	Parallel Sessions; Parallel Sessions; Parallel Sessions
Room E	Cosmos 2	Parallel Sessions; Parallel Sessions; Parallel Sessions
Room F	Ran 1	Parallel Sessions; Parallel Sessions; Parallel Sessions
Room G	Ran 2	Parallel Sessions; Parallel Sessions; Parallel Sessions
Exibition	Lobby	Exibition
Lunch	Himawari	Coffee Break; Lunch; Coffee Break
Reception	Lobby	Registration
Cloak	Lobby	Cloak

Day 3 — Wednesday, November 8 (8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00)

Room A	Phoenix	Plenary Lectures [Fatemi]・[MIYAWAKI]; Parallel Sessions; Parallel Sessions; Parallel Sessions
Room B	Dahlia 1	Parallel Sessions; Parallel Sessions; Parallel Sessions
Room C	Dahlia 2	Parallel Sessions; Parallel Sessions; Parallel Sessions
Room D	Cosmos 1	Parallel Sessions; Parallel Sessions; Parallel Sessions
Room E	Cosmos 2	Parallel Sessions; Parallel Sessions; Parallel Sessions
Room F	Ran 1	Parallel Sessions; Parallel Sessions; Parallel Sessions
Room G	Ran 2	Parallel Sessions; Parallel Sessions; Parallel Sessions
Exibition	Lobby	Exibition
Lunch	Himawari	Coffee Break; Lunch; Coffee Break
Reception	Lobby	Registration
Cloak	Lobby	Cloak

Day 4 — Thursday, November 9 (8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00)

Room A	Phoenix	Plenary Lectures [Hong]・[Uematsu]・[Nakamura]
Room B	Dahlia 1	
Room C	Dahlia 2	
Room D	Cosmos 1	
Room E	Cosmos 2	Excursion Naka Incineration Plant & Itsukushima shrine at Miyajima Island; Bauquet RIHGA Royal Hotel Hiroshima
Room F	Ran 1	(Excursion); (Bauquet)
Room G	Ran 2	(Excursion); (Bauquet)
Exibition	Lobby	Exibition; (Excursion); (Bauquet)
Lunch	Himawari	(Excursion); (Bauquet)
Reception	Lobby	Registration
Cloak	Lobby	Cloak

Day 5 — Friday, November 10 (8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00)

Room A	Phoenix	
Room B	Dahlia 1	Parallel Sessions; Parallel Sessions; Parallel Sessions; Closing
Room C	Dahlia 2	Parallel Sessions; Parallel Sessions; Parallel Sessions
Room D	Cosmos 1	Parallel Sessions; Parallel Sessions; Parallel Sessions
Room E	Cosmos 2	Parallel Sessions; Parallel Sessions; Parallel Sessions
Room F	Ran 1	Parallel Sessions; Parallel Sessions; Parallel Sessions
Room G	Ran 2	Parallel Sessions; Parallel Sessions; Parallel Sessions
Exibition	Lobby	
Lunch	Himawari	Coffee Break; Lunch
Reception	Lobby	Registration
Cloak	Lobby	Cloak

Program

Tuesday, 7 November [Day 2]

■ Room A / Phoenix

Opening Ceremony	08:00 ～ 08:30

Plenary Lectures	08:30 ～ 10:00

Cair：Jun KOMOTORI

Characterization of Microstructural Effects on the Near-Threshold Fatigue Crack Growth by means of Ultrasonic Fatigue Testing

Martina Zimmermann
Institute of Materials Science, TU Dresden
Fraunhofer Institute for Material and Beam Technology IWS, Dresden

New materials	10:30 ～ 12:30

Chair : Benjamin Guennec(Toyama Prefectural Univ) & Takayuki Shiraiwa(The University of Tokyo)

P-201 **Assessment of the four-point bending fatigue properties of zirconia-reinforced Ti6Al-4V nanocomposite processed by laser powder bed fusion**
Benjamin Guennec(Toyama Prefectural University)

P-202 **Effect of Volume Fraction of Network Structure Composed of High-Entropy CrMnFeCoNi Alloy on Fatigue Crack Propagation in 304L Stainless Steel Compact**
Arisa Ito(Shizuoka University)

P-203 **Fatigue damage evaluation of coarse and fine grains in notched austenitic stainless steel with harmonic structure**
Keisuke Fujita(Shizuoka University)

P-204 **Retarded Crack Growth and Self Sensing Ability of Metal-Matrix Composites produced by High-Pressure Torsion**
Valeria Lemkova(Saarland University)

P-205 **Fatigue crack propagation of nano particles reinforced Al matrix composite**
Qingqing Pu(Shanghai Jiao Tong University)

P-206 **Fatigue behavior of accumulative roll bonded Cu/Nb laminate materials**
Takayuki Shiraiwa(The University of Tokyo)

Japanese Activity for New Fatigue Curves and Fatigue Analysis 1 14:00～16:00

Chair : Masahiro Takanashi (IHI Corporation) & Akihiko Hirano (Hitachi-GE Nuclear Energy Ltd) & Masao Itatani (Toshiba Energy Systems & Solutions Corporation)

P-207 **Overview of Japanese Activity for New Fatigue Curves and Fatigue Analysis**
Takeshi Ogawa(Aoyama Gakuin University)

P-208 **Development of Best Fit Curves**
Masanori TOYODA(Mitsubishi Heavy Industries, Ltd.)

P-209 **Definition of Fatigue Life in Best fit Curves and Large Components**
Chihiro Narazaki(Toshiba Energy Systems & Solutions Corporation)

P-210 **Mean Stress Correction Method for Fatigue Analysis**
Takuya OGAWA(Toshiba Energy Systems & Solutions Corporation)

P-211 **Investigation of Mean Stress Effect for Local Strain Behavior at Notch Root of Large-Scale Plate Specimen**
Daiki Takagoshi(Mitsubishi Heavy Industries, Ltd.)

P-212 **Verification of SWT Method for Notched Components**
Yuichiro NOMURA(Mitsubishi Heavy Industries, Ltd.)

Japanese Activity for New Fatigue Curves and Fatigue Analysis 2 16:30-18:30/18:50

Chair : Motoki Nakane (Hitachi-GE Nuclear Energy Ltd) & Saito Toshiyuki (Toshiba Energy Systems & Solutions Corporation)

P-213 **Effect of Machined Surface Finish on Fatigue Life of Carbon Steel**
Yun Wang(Hitachi, Ltd.)

P-214 **Fatigue crack initiation and growth behavior of specimen with machined surface layer under low cycle fatigue regime**
Shota Hasunuma(Aoyama Gakuin University)

P-215 **QA Sheet for Variability Factors in Fatigue Life of S-N Curve –Introduction of Activity for Development of‘ Fatigue Knowledge Platform’ in JWES (1) –**
Nao Fujimura(Hokkaido University)

P-216 **QA Sheet for Fatigue Analysis of Weld Joint –Introduction of Activity for Development of‘ Fatigue Knowledge Platform’ in JWES (2) –**
Hideaki Nishikawa(National Institute for Materials Science)

P-217 **QA Sheet for Difference between Post Construction Code for Pressure Vessel and Damage Tolerance Design of Aircraft –Introduction of Activity for Development of “ Fatigue Knowledge Platform’ in JWES (3) –**
Yuka Miyata(Hitachi-GE Nuclear Energy Ltd)

P-218 **Status of Codification for New Fatigue Curves and Fatigue Analysis**
Seiji Asada(Mitsubishi Heavy Industries, Ltd.)

■ Room B / Dahlia 1

Biomaterials 10:30～12:30

Chair : Tohikazu Akahori (Meijo Univ) & Liguo Zhao(Nanjing Univ of Aeronautics and Astronautics)

D1-201 **Change in mechanical properties and surface morphology of alpha+beta type titanium alloy subjected to gas nitriding duplex treatment**
Tohikazu Akahori (Meijo university)

D1-202 **Fatigue property evaluation of Ti-Ta Alloy Rods Using Spinal Fixation Model**
Akane YANAGAWA(Sophia University)

D1-203 **Evaluation of Corrosion, Wear and Tribocorrosion Properties of Ti-Ta Alloys**
Shuta YAMAMURO(Sophia University)

D1-204 **Effect of Angioplasty on Fatigue Resistance of Nitinol Stent in Femoropopliteal Artery**
Liguo Zhao(Nanjing University of Aeronautics and Astronautics)

Growth of short and long cracks 1 14:00～16:00

Chair : Tilmann Beck(RPTU Kaiserslautern-Landau) & Takayuki Yonezawa(Nippon Steel Corporation)

D1-207 **Experimental and numerical investigations of the influence of grain orientation on the fatigue behavior of coarse-grained nickel-based superalloys**
Tilmann Beck(RPTU Kaiserslautern-Landau)

D1-208 **Fatigue Crack Extension Mode for 18Ni Martensitic Steel and Its Effect on Fatigue Limit**
Shun KINO(Kyushu University)

D1-209 **Carbon content effect on fatigue crack extension behavior and extension mode in 18%Ni martensitic steels**
Pengxu REN(Kyushu university)

D1-210 **Fatigue crack propagation behavior of Ferritic steels with different cyclic softening properties**
Takayuki Yonezawa(Nippon Steel Corporation)

Growth of short and long cracks 2 16:30-18:30/18:50

Chair : Yi SHI(Shanghai Jiao Tong University) & Shigeru HAMADA(Kyushu University)

D1-213 **Investigation of defect induced crack and fatigue crack growth behavior of a P/M nickel based superalloy and corresponding life prediction**
Yi SHI(Shanghai Jiao Tong University)

D1-214 **In-situ Observation of Fatigue Crack Propagation in Soda-Lime Glass with Vickers Indentation-induced Initial Crack under Four-Point Bending**
Hibiki KOMINE(Shizuoka University)

D1-215 **Intrinsic fatigue resistance and the influence of material defects**
Mirco Chapetti(National University of Mar del Plata)

D1-216 **Investigation of the influence of physical notch parameters on fatigue life and fatigue life scatter in EN AW-2618A**
Jan Radners(Fraunhofer Institute for Mechanics of Materials IWM)

D1-217 **Fatigue short crack propagation in a Ni alloy manufactured by Laser powder bed fusion**
Li Jianghua(Institute of Mechanics, Chinese Academy of Sciences)

D1-218 **Fatigue Crack Extension by Damage Accumulation**
Shigeru HAMADA(Kyushu University)

■ Room C / Dahlia 2

Additive Manufacturing 1 10:30～12:30

Chair : Bo Li(East China University of Science and Technology) & Yajing Li(East China University of Science and Technology)

D2-201 **High cycle fatigue behavior of CoCrFeNi high entropy alloy manufactured with laser powder bed fusion**
Bo Li(East China University of Science and Technology)

D2-202 **Fatigue Properties of WAAM-manufactured components**
Moritz Hupka(Clausthal University of Technology)

D2-203 **Inferior fatigue resistance of additively-manufactured Ni-based superalloy 718 and its dominating factor**
Sungcheol PARK(Kyushu University)

D2-204 **Combined effect of surface integrity parameters on the fatigue strength of Laser Powder Bed Fusion (L-PBF) 316L stainless steel**
Marion Auffray(Ecole Nationale Supérieure d'Arts et Métiers)

D2-205 **Effect of Post-Processing on Fatigue Performance of SLM Ti6Al4V Alloy**
LITTON BHANDARI(Indian Institute of Technology Roorkee)

D2-206 **Low Cycle Fatigue Behavior of Wire Arc Additive Manufactured and Solution Annealed 308 L Stainless Steel**
Yajing Li(East China University of Science and Technology)

Additive Manufacturing 2 14:00～16:00

Chair : Aditya Pandey(Indian Institute of Technology Roorkee) & Atsuhiro KOYAMA(Nagasaki University)

D2-207 **A study on fatigue properties of wire-arc additively manufactured Inconel 718 alloy**
Aditya Pandey(Indian Institute of Technology Roorkee)

D2-208 **A study on different heat-treatment cycles for additively manufactured Ni-based alloy and its fatigue properties**
SUMIT CHOUDHARY (Indian Institute of Technology Roorkee)

D2-209 **The effect of surface modification on crack propagation properties and fatigue life on Ti-6Al-4V alloy formed by electron beam lamination**
Yuya ARAKI(Sophia University)

D2-210 **Applicability of non-ideal powders in powder bed fusion processes - Fatigue life of additively manufactured structures**
Julia Richter(University of Kassel)

D2-211 **Influence of Heat-treatment on Fatigue Properties of Super Duplex 2507 Stainless Steel produced by Directed Energy Deposition Process**
Sébastien BALLÉSIO(Institut Polytechnique de Paris)

D2-212 **Influence of manufacturing history and resulting microstructure on the very high cycle fatigue behavior of additively manufactured samples**
Leonhard Stampa(Technical University Dresden)

D2-213 **Very High Cycle Fatigue of Laser Additively Manufactured Titanium and Nickel Alloys**
Yao CHEN (Sichuan University)

Additive Manufacturing 3 16:30-18:30/18:50

Chair : Jakob Blankenhagen(Technical University of Munich) & Koji Takahashi(Yokohama National University)

D2-214 **Cyclic plastic material behavior of novel high manganese austenitic stainless steel Printdur? HSA additively manufactured by PBF-LB/M**
Jakob Blankenhagen(Technical University of Munich)

D2-215 **Effect of Heat Treatment on Fatigue Life of Ti-6Al-4V Alloy with Additively Manufactured Layer and Conventional Wrought Layer**
Atsuhiro KOYAMA(Nagasaki University)

D2-216 **Process Parameters and Fatigue Crack Initiation in Cold Spray**
Hamid Jahed(University of Waterloo)

D2-217 **An assessment of the high-temperature fatigue properties of additively manufactured nickel-based alloys**
Tomáš Kruml(Institute of Physics of Materials, CAS)

D2-218 **Microstructure modification to increase resistance to fatigue crack propagation in titanium alloys made by wire based directed energy deposition process**
Xiang Zhang(Coventry University)

D2-219 **Combined Effect of Shot and Laser Peening on Fatigue Strength of Additively Manufactured Aluminum Alloy**
Koji Takahashi(Yokohama National University)

D2-220 **Anisotropic Fatigue Properties of Laser Additive Manufactured (LAMed) Ni-based Superalloys**
ZhenanZhao(Zhejiang University)

■ Room D / Cosmos 1

Reliability analysis 10:30 ～ 12:30

Chair : Zhiping Xu(Tsinghua University) & Balajee Ananthasayanam(Honda Aero Inc.)

C1-201 **A Data Science Approach to Understanding Fatigue**
Zhiping Xu(Tsinghua University)

C1-202 **Identification of Plastic-Creep Fatigue Damage Rule for Aluminum Alloys Using Particle Swarm Optimization Method**
Towa HAYASHIBE(Akita University)

C1-203 **Dimensioning a Reference Volume Element for Detecting Fatigue Cracks in Equiaxed Titanium Alloy**
Azdine Nait-ali(Institut Polytechnique de Paris)

C1-204 **Slow Adoption of Modern Statistical Methods in Industrial Applications for the Development of Fatigue Curves**
Balajee Ananthasayanam(Honda Aero Inc.)

C1-205 **Development of Fatigue Curve with Multiple Competing Failure Modes**
Balajee Ananthasayanam(Honda Aero Inc.)

C1-206 **Fatigue Deformation Behavior and Life Prediction in a Newly-Developed Cast Aluminum Alloy**
Daolun Chen(Toronto Metropolitan University)

Non-destructive testing 1 14:00～16:00

Chair : Zhe ZHANG(Tianjin University) & Norihiko Hana(Mitsubishi Electric Corporation)

C1-207 **Mechanoresponsive luminogen (MRL)-based real-time and visible detection method for fatigue damage**
Zhe ZHANG(Tianjin University)

C1-208 **Self-heating and rapid fatigue limit prediction for angle-ply thermoplastic composites under tensile fatigue load based on the infrared thermography technology**
Aijia Li(Northwest Polytechnical University)

C1-209 **Using 3D energy-dispersive μ Laue diffraction to study fatigue damage evolution in materials showing wavy and planar slip behaviour**
Carolin Leidigkeit(University of Siegen)

C1-210 **Evaluation of fatigue strength of Cr-Mo steel based on dissipated energy measurement**
Taichi Sugimoto(Kobe university)

C1-211 **Crack shape identification from surface deformation using inverse analysis**
Norihiko Hana(Mitsubishi Electric Corporation)

C1-212 **Fatigue Crack Behavior of 304 Stainless Steels using Synchrotron X-ray Tomography and Diffraction: Influence of the Martensite Fraction and Role of Inclusions**
Djamel KAOUMI(North Carolina State University, USA)

Non-destructive testing 2 16:30-18:30/18:50

Chair : Paul DarioTOASA CAIZA(Karlsruhe Institute of Technology) & Stéphanie DESCHANEL (INSA-Lyon)

C1-213 **Real time fatigue crack detection on welded specimens by applying inductive Thermography. Simulation and experimental results**
Paul DarioTOASA CAIZA(Karlsruhe Institute of Technology)

C1-214 **Evaluation of Fatigue Strength by Dissipated Energy of Dissimilar FSW Joints of Aluminum Alloy and Steel sheets.**
Tenyu Hidaki(Kobe university)

C1-215 **POD modeling of a flexible array eddy current NDT method for near-surface cracks in the tenon-groove structure of a turbine disk and its application for damage tolerance assessment**
Hongzhuo Liu(Beihang University)

C1-216 **Metalayer-based piezoelectric transducer for unidirectional excitation and reception of SH guided wave**
Yuehao Du(Southwest Jiaotong University)

■ Room E / Cosmos 2

Crack closure and shielding 10:30 ～ 12:30

Chair : Carl Fischer(Fraunhofer Institute for Mechanics of Materials IWM) & Emiel Amsterdam(NLR)

C2-201 **Finite element study on the influence of the phase shift on plasticity-induced crack closure and the crack tip opening displacement under thermomechanical fatigue loading**
Carl Fischer(Fraunhofer Institute for Mechanics of Materials IWM)

C2-202 **Mixed mode crack growth behaviour considering plasticity-induced and roughness-induced closure**
Shuancheng Wang(Southwest Jiao tong University)

C2-203 **Improved Analytical Tool for Crack Closure Evolution after Overload and Underload**
Radek Kubíček(Institute of Physics of Materials, Czech Academy of Sciences)

C2-204 **Crack closure effects at negative load ratios**
Gilbert HÉNAFF(University of Poitiers)

C2-205 **On the strain energy release rate and fatigue crack growth rate in metallic alloys**
Emiel Amsterdam(NLR)

Damage evaluation and fatigue design 1 14:00 ～ 16:00

Chair : Jie-WeiGao(Univ of Electronic Science and Technology of China) & Fabien Lefebvre(CETIM)

C2-207 **Damage tolerance assessment of heavy-duty freight railway axle steel with various-shape artificial defects**
Jie-WeiGao(University of Electronic Science and Technology of China)

C2-208 **Fretting fatigue damage of axial interference fit structures subjected to fretting wear**
Yiliang Shu(Beijing Jiaotong University)

C2-209 **Research on fatigue assessment method of high-speed train axle based on axle box acceleration**
Ruiguo Yan(Beijing Jiaotong University)

C2-210 **An entropy-based approach to low cycle fatigue damage evolution for GH4169 at intermediate and elevated temperature**
Shuyang Xia(Beihang University)

C2-211 **Proposition and Development of the General Relation between Tensile and Fatigue Strengths of Metallic Materials**
Jianchao Pang(Institute of Metal Research, Chinese Academy of Sciences)

C2-212 **Effect of internal defects of G20Mn5 cast steel on the fatigue strength**
Fabien Lefebvre(CETIM)

Damage evaluation and fatigue design 2 **16:30-18:30/18:50**

Chair : Bastian Blinn(RPTU Kaiserslautern) & Masayuki Kamaya(Institute of Nuclear Safety System, Inc.)

C2-213 **Analysis of the defect tolerance of bainitic 100Cr6 with high retained austenite content**
Bastian Blinn(RPTU Kaiserslautern)

C2-214 **Cyclic indentation - A new method to estimate the fatigue strength by considering the cyclic deformation behavior**
Bastian Blinn(RPTU Kaiserslautern)

C2-215 **Study on fatigue damage of axle excited by High Frequency**
Ziyu Dong(Beijing Jiaotong University)

C2-216 **A Study of Rate Process Analysis on the Rotating Bending Fatigue Limit of Carbon Steel**
Mai FUKAMI(University of Toyama)

C2-217 **Mean stress sensitivity for carbide-rich PM tool steels**
Lennart Mirko Scholl(RWTH Aachen University)

C2-218 **Influence of Pre-strain on the Fatigue Strength of Stainless Steel**
Masayuki Kamaya(Institute of Nuclear Safety System, Inc.)

■ Room F / Ran 1

Cyclic deformation and crack initiation 1 **10:30～12:30**

Chair : Aeriel Leonard(The Ohio State Univ) & Ulich Krupp(RWTH Aachen Univ)

R1-201 **Fatigue strength evaluation of 1180MPa class recycled steel**
Nobuo NAGASHIMA(National Institute for Materials Science)

R1-202 **Influence of Dislocation Interactions on Fatigue Crack Initiation in Additively Manufactured Nickel-Aluminum-Bronze Alloys**
Aeriel Leonard(The Ohio State University)

R1-203 **Notched High Cycle Fatigue and Macrozones in Ti-6Al-4V**
Yan Gao(Imperial College London)

R1-204 **In situ observation and crystal plasticity simulation of internal fatigue crack initiation and propagation behavior around synthetic hard alpha inclusions embedded in Ti-6Al-4V**
Hongzhuo Liu(Beihang University)

R1-205 **A novel micromechanism-based fatigue model for FCC single crystal combining crystal plasticity with CDM**
Ao Li(Beihang University)

R1-206 **Initiation and Growth of Short Fatigue Cracks in Tempered Martensitic and Bainitic Steels**
Ulich Krupp(RWTH Aachen University)

Cyclic deformation and crack initiation 2 14:00 ～ 16:00

Chair : Yabin Yan(East China University of Science and Technology) & Ankur Chauhan(Indian Institute of Science)

R1-207 **In situ SEM experimental study on the fatigue failure of micro-single-crystal copper**
Yabin Yan(East China University of Science and Technology)

R1-208 **Dislocation networks in the (111) cell boundaries in fatigued near-[-111] copper single crystals**
Bohan Wang(Tokyo Institute of Technology)

R1-209 **Improvement of stress corrosion cracking resistance by low cycle fatigue of a CrNiMoV steel**
Fang-Xin Yang(East China University of Science and Technology)

R1-210 **Cryoforged nanotwinned CoCrNi medium-entropy alloy with exceptional fatigue resistance at cryogenic temperature**
Yu Xie(East China University of Science and Technology)

R1-211 **Elucidation of small fatigue crack initiation behavior on polycrystal Ti-22V-4Al**
Koki Hirazumi(Okayama University)

R1-212 **Low-cycle fatigue response of an equiatomic CrFeNi multi-principal element alloy**
Ankur Chauhan(Indian Institute of Science)

Cyclic deformation and crack initiation 3 16:30-18:30/18:50

Chair : Jean-Bernard VOGT(University de Lille) & Lihe Qian(Yanshan University)

R1-213 **Low cycle fatigue of a fully pearlitic steel**
Jean-Bernard VOGT(University de Lille)

R1-214 **Cyclic plasticity of a 9Ni steel**
Jean-Bernard VOGT(University de Lille)

R1-215 **Secondary orientation effects on the low cycle fatigue behaviors of rectangular-sectional Ni-based single crystal superalloys at medium and high temperatures**
Shao-Shi RUI(Institute of Mechanics, CAS)

R1-216 **Improved fatigue resistance of heterogeneous materials: suppress strain localization and damage accumulation**
Lei Lu(Institute of Metal Research, CAS)

R1-217 **Nanostructure; 316L stainless steel; Low-cycle fatigue life; Ductility; Cumulative plastic strain**
Nairong Tao(Institute of Metal Research, Chinese Academy of Sciences)

R1-218 **Effect of Al on the Low-Cycle Fatigue Properties of Fe-Mn-C TWIP Steel Lihe**
Qian(Yanshan University)

■ Room G / Ran 2

Creep 1 **10:30 ～ 12:30**

Chair : Kohei FUKUCHI(Akita University) & Oliver Jordan(RPTU Kaiserslautern-Landau)

R2-201 **Characterization of low-cycle fatigue fracture surfaces of aluminum alloys at high-temperature using fractal dimension analysis**
Kohei FUKUCHI(Akita University)

R2-202 **Acceleration of Creep-Fatigue Damage in Ni-Base Superalloy due to Viscoelasticity at Elevated Temperature by Considering Local Stress**
Le XU(Tohoku University)

R2-203 **Cold dwell fatigue response of aero-engine component titanium alloys: Influence of hold time and peak stress**
Jianke QIU(Institute of Metal Research, Chinese Academy of Sciences)

R2-204 **Molecular Dynamics Analysis of the Acceleration Mechanism of the Degradation of Grain Boundary Strength in Alloy GH4169 Caused by δ -Phase Precipitation**
Takuto Kudo(Tohoku University)

R2-205 **Modified Kitagawa-Takahashi Approach for Improved Lifetime Prediction under Creep-Fatigue Loading of Polycrystalline Gas Turbine Components**
Oliver Jordan(RPTU Kaiserslautern-Landau)

R2-206 **Probabilistic Modelling of creep-fatigue interaction in polycrystalline Nickel-base alloy based on the Kitagawa-Takahashi diagram**
Tuan Duc Nguyen(Siemens Energy)

Creep 2 **16:30-18:30/18:50**

Chair : Shiyu Suzuki(JAXA) & Tuan Duc Nguyen(Siemens Energy)

R2-213 **Transition from crack retardation to acceleration under high temperature dwell-fatigue loading in a wrought Ni-base superalloy**
Shiyu Suzuki(JAXA)

R2-214 **Evaluation of fatigue and creep-fatigue damage levels on the basis of engineering damage mechanics approach**
Li Sun(East China University of Science and Technology)

R2-215 **Acceleration Mechanism of Intergranular Cracking of Stainless Steel SUS316LN at Elevated Temperature Caused by Local Strain Energy Around Grain Boundaries**
Ayane Yasumura(Tohoku University)

R2-216 **Cyclic deformation behaviors and damage mechanisms in P92 steel under creep-fatigue: Effects of hold condition and oxidation**
Kang-Kang Wang(East China University of Science and Technology)

R2-217 **Numerical Analysis of P91 notched specimen by damage-coupled inelastic constitutive model**
Daisuke Kashiwagi(Tokyo University of Science, JAPAN)

Wednesday, 8 November [Day 3]

■ Room A / Phoenix

Plenary Lectures 08:00 ～ 10:00

Cair：Yoshihiko UEMATSU

Fatigue Life Prediction of Additively Manufactured Metals: A Hybrid Critical Plane-Fracture Mechanics Approach

Ali Fatemi
Ring Companies Professor and Department Chair
Department of Mechanical Engineering, The University of Memphis, Memphis, TN, USA

Mazda's Monotsukuri (Manufacturing)
A building block concept for facilitating flexible production

KATSUNORI MIYAWAKI
General Manager, Hiroshima Plant
Mazda Motor Corporation

Japanese Activity of Fatigue design and Evaluation Committee in Society of Automotive engineers of Japan 10:30 ～ 12:30

Chair : Toshiaki Nakamaru(Nissan Motor Co., LTD) & Hiroaki Kawamura(Toyota motor corporation)

P-301 Key note
Activities of Fatigue design and Evaluation Committee in Society of Automotive engineers of Japan
Toshiaki Nakamaru(Nissan Motor Co., LTD)

P-302
Evaluation of Fatigue Characteristics of CFRP Bonding Materials by Urethane Adhesive
Masayuki Osada(Hiroshima University)

P-303
Investigation of the Effects of Adherend Materials and Epoxy Adhesive Properties on the Fatigue Strength
Hiroaki Kawamura(Toyota motor corporation)

P-304
Investigation of the effects of adhesive edge shape and Adherend stiffness on fatigue strength of adhesive bonded specimens
Masashi Inoue(Toyota Industries Corporation)

Growth of short and long cracks 3 14:00-16:00 /16:20

Chair : Yali Yang (Shanghai University of Engineering Science) & Weifeng Wan(Beihang University)

P-307
The Cyclic R-Curve for Predicting Growth and Arrest of Short Cracks
Keisuke Tanaka(Nagoya University)

P-308
Study on fatigue propagation shape of surface crack
Yali Yang (Shanghai University of Engineering Science)

P-309
Influence of exposure to moist air on the fatigue striation formation in a 7175 7351 alloy
Gilbert HÉNAFF(University of Poitiers)

P-310
A physically small crack growth model based on CTOD
Lu Han(Beihang University)

P-311
The migration of geometrically necessary dislocation density localisation at crack tip in short crack growth of zirconium
Weifeng Wan(Beihang University)

Growth of short and long cracks 4 16:30-18:30/18:50

Chair : Motoki Sakaguchi(Tokyo Institute of Technology) & Xiaoguang Yang(Beihang University)

P-313 **Fatigue crack propagation in a single crystal and a two-dimensional polycrystalline Ni-base superalloys**
Motoki Sakaguchi(Tokyo Institute of Technology)

P-314 **Quantitative analysis of fatigue damage of Inconel 718 after creep-fatigue fracture based on micro-pillar tests**
Ji Wang(East China University of Science and Technology)

P-315 **A Study on Fatigue Crack Propagation in Steel Rail Weld Zones Based on Damage Mechanics and Cohesive Zone Model**
Chenhao Ji(Beihang University)

P-316 **Effect of sustained load on fatigue crack growth behavior of FGH96 at elevated temperature**
Zhifang WANG(Beihang University)

P-317 **Consideration on short crack propagation resistance in SM490 steels with different Δ Kth**
Yoshihiro HYODO(JFE Steel Corporation)

P-318 **Small Crack Growth Behaviors and Its Interaction with Microstructures In A Ni-Based P/M Superalloy At High Temperature**
Xiaoguang Yang(Beihang University)

■ Room B / Dahlia 1

Experimental techniques, corrosion 10:30～12:30

Chair : Catherine MABRU(University de Toulouse) & Damien DESGACHES(AIRBUS Atlantic)

D1-301 **Contribution of the self-heating method in the characterization of the fatigue damage of materials with defects resulting from additive manufacturing**
Catherine MABRU(University de Toulouse)

D1-302 **Study on Mechanical Properties of Anode Material for Lithium-ion Batteries in Water**
Shiori Tagai(Tokyo City University)

D1-303 **Effect of cyclic hardening on stress corrosion cracking behavior of NiCrMoV steel welded joints**
Yuhui Huang(East China University of Science and Technology)

D1-304 **Investigation of Fatigue Crack Growth Behavior in Fine Particle Peened 7075 Aluminum Alloy using Digital Image Correlation**
Yuichi ONO(Tottori University)

D1-305 **Effect of Corrosive Environment on Fatigue Strength Characteristic of Magnesium Alloy Ultrafine Wire**
Yuta Sakamoto(The University of Electro-Communications)

D1-306 **New coating to prevent premature corrosion of aircraft structure**
Damien DESGACHES(AIRBUS Atlantic)

Additive Manufacturing 4 — 14:00-16:00 /16:20

Chair : Lea Strauss(University of the Bundeswehr Munich) & Fabien Szmytka(Institut Polytechnique de Paris)

D1-307 **Fatigue Life Prediction of PBF-LB AlSi10Mg based on Roughness and Residual Stress**
Lea Strauss(University of the Bundeswehr Munich)

D1-308 **Defects tolerance and fatigue limit prediction in additive manufactured titanium alloy Ti6Al4V**
Abdul KhadarSyed(Coventry University)

D1-309 **Structure Integrity Analysis of Additive Manufactured Cabin Door: Design-Manufacture-Fatigue behavior**
Yu'e MA(Northwestern Polytechnical University)

D1-310 **Fatigue damage evolution and tolerance in additive manufactured metals**
Alexander Koch(TU Dortmund University)

D1-311 **Microstructurally Small Fatigue Crack Initiation and Growth Behaviors of Additively-Manufactured Alloy 718**
Hideaki Nishikawa(National Institute for Materials Science)

D1-312 **High-cycle and Low-cycle Fatigue of a Laser-Powder Direct Energy Deposition manufactured Inconel 625**
Fabien Szmytka(Institut Polytechnique de Paris)

Additive Manufacturing 5 — 16:30-18:30/18:50

Chair : Rui Fu(Harbin Institute of Technology) & Baris Telmen(Institut Polytechnique de Paris)

D1-313 **High-Cycle and Very-High-Cycle Fatigue Behavior and Life Prediction of Ti-6Al-4V Fabricated by Laser Powder Bed Fusion**
Rui Fu(Harbin Institute of Technology)

D1-314 **Low-cycle fatigue of conventional and additively manufactured IN939 superalloy**
Tomáš BABINSKÝ(Institute of Physics of Materials, Czech Academy of Sciences)

D1-315 **Coupling effects of microstructure and defects on fatigue properties of 3D-printed Ti-6Al-4V**
Zhenjun Zhang(Institute of Metal Research, Chinese Academy of Sciences)

D1-316 **Cyclic Strain Localization in Fatigued 316L Stainless Steel Manufactured Additively using Selective Laser Melting (SLM)**
Jiří MAN(Institute of Physics of Materials, Czech Academy of Sciences)

D1-317 **Influence of the defect tolerance on the fatigue strength of additively manufactured AlSi10Mg**
Bastian Blinn(RPTU Kaiserslautern)

D1-318 **Assessment of cyclic resistance on stainless steel 316L based cylindrical structures repaired by metal additive manufacturing methods**
Baris Telmen(Institut Polytechnique de Paris)

D1-319 **Enhancing the Fatigue Performance of Additively Manufactured AlSi10Mg Alloy Using A Novel Chemo-mechanical Surface Treatment**
Jidong Kang(CanmetMATERIALS)

■ Room C/ Dahlia 2

Hydrogen embrittlement 10:30 ～ 12:30

Chair : Aman Arora (Kyushu University) & Daniel Osorio(University of Stuttgart)

D2-301 **Development of an experimentally informed model for fatigue crack initiation in metals due to hydrogen**
Aman Arora (Kyushu University)

D2-302 **Influence of the interaction hydrogen/microstructure on low-cycle fatigue behavior and fatigue crack growth in a precipitation-hardened nickel-based superalloy.**
Achraf Radi(University of Technology of Compiègne)

D2-303 **Some impact of hydrogen concentration and distribution on low cycle fatigue behavior of an alpha titanium alloy**
Larissa Caroline Martins Moreira(La Rochelle University)

D2-304 **Review of the antagonists' processes of hydrogen on physical mechanisms of plasticity and their consequences on fatigue behavior of fcc metals**
Xavier FEAUGAS (La Rochelle University)

D2-305 **Experimental investigation of hydrogen embrittlement on the tensile and low-cycle fatigue properties of an X52 steel**
Carl Fischer(Fraunhofer Institute for Mechanics of Materials IWM)

Joint 14:00-16:00 /16:20

Chair : Hsin ShenHo(Zhengzhou University) & Yoshihiko UEMATSU(Gifu University)

D2-307 **Effects of tightening torque on vibration fatigue performance of single-lap joints: modal parameter analyses**
Hsin ShenHo(Zhengzhou University)

D2-308 **Evaluation of Fatigue Properties of Adhesive Bond joint with Laser Patterning Surface Treatment**
Ryuta Yotsutani(Hiroshima University)

D2-309 **Effect of Plate Thickness Ratio on the Fatigue Strength Properties of Friction Stir Spot Welds of Aluminum Alloy**
Yuki NOSE(Hiroshima University)

D2-310 **Influencing Factors on Fatigue Strength of SPR joint in Magnesium AlloyYukio**
MIYASHITA(Nagaoka University of Technology)

D2-311 **Fatigue Strength of Linear Friction Welded Joints for S55C Steel Plates**
Noboru KONDA(Ryukoku University)

D2-312 **Fatigue Behavior of Al/steel Dissimilar Friction Stir Welds and the Effect of Die Press Working**
Yoshihiko UEMATSU(Gifu University)

D2-313 **Fatigue performance of A356/6082 dissimilar aluminum alloys butt joint**
Mei ZHANG(Shanghai University)

Case studies and industrial applications	16:30-18:30/18:50

Chair : Marcel Krochmal(University of Kassel) & Vladimir Chmelko(Slovak University of Technology in Bratislava)

D2-314 **On the fatigue properties of a S550MC+100Cr6 cladded steel in different fatigue regimes**
Marcel Krochmal(University of Kassel)

D2-315 **Fatigue behavior of an Off-highway axle subjected to a variable amplitude strain-based load spectrum derived from field tests**
Jacopo Pelizzari(University of Padua)

D2-316 **Evaluation of Fatigue Strength of Full-scale Induction-hardened Axles for Railway Vehicles and Its Estimation under Very-High-Cycle Regime**
Taizo MAKINO(Nippon Steel Corporation)

D2-317 **Double-sided ultrasonic surface rolling process for improving the surface integrity and vibration fatigue resistance of thin-walled blade-like samples**
Zhang Kaiming(East China University of Science and Technology)

D2-318 **Fatigue properties of thin plates**
Vladimir Chmelko(Slovak University of Technology in Bratislava)

D2-319 **Study of impact-sliding composite fretting corrosion of heat exchanger tubes in different concentrations of NaCl solution**
Guorui Zhu(Tianjin Uninversity)

■ Room D/ Cosmos 1

Surface engineering 1	10:30 ～ 12:30

Chair : Shirin FALAKBOLAND(RPTU Kaiserslautern) & Koichiro NAMBU(Osaka Sangyo University)

C1-301 **Influence of organically modified sol-gel SiO2 coating on the VHCF behavior of austenitic stainless steel AISI 904L**
Shirin FALAKBOLAND(RPTU Kaiserslautern)

C1-302 **Improvement in Fatigue Strength by Ball Burnishing of Aluminum Alloy with a Surface Defect**
Kohei Wakamatsu(Yokohama National University)

C1-303 **Effect of Residual Stress on Internal Crack Initiation and Propagation of Induction Heated and Quenched AISI4140 Steel with Different Hardened Layer Depths**
Tomofumi Aoki(Keio University)

C1-304 **Controlling Factors of Scanning Cyclic Press on the Surface Modification of Magnesium Alloy**
Nao Fujimura(Hokkaido University)

C1-305 **Fatigue behavior of metastable and stable austenitic stainless steels with different surface morphologies**
Tong Zhu(RPTU Kaiserslautern-Landau)

C1-306 **Effect of Surface Roughness on Fatigue Strength of Aluminum and Magnesium Alloys**
Koichiro NAMBU(Osaka Sangyo University)

Surface engineering 2 14:00-16:00 /16:20

Chair : Yang Liu(Northeastern University) & Kiyotaka MASAKI(Saitama Institute of Technology)

C1-307 **High Temperature Stability Mechanism of Fatigue Resistance of Warm Laser Shock Peened IN718 Superalloy**
Yang Liu(Northeastern University)

C1-308 **Effect of Multifunction Cavitation on Rotating Bending Fatigue Properties of Low Alloy Steel Rods**
Keisuke Ono(Shizuoka University)

C1-309 **Evaluation of the effect of stress ratio and compressive residual stress on the fatigue properties of shot-peened AISI4140 specimens, considering residual stress relaxation**
Motoaki Hayama(Keio university)

C1-310 **Effect of Gas Carburizing on Axial Fatigue Strength of SCM420H Steel**
Takayuki Komoriya(The University of Electro-Communications)

C1-311 **Residual stress relaxation in Inconel718 cold expanded hole under loading at elevated temperature**
Moad FATMI(University of Technology of Troyes)

C1-312 **Surface Crack Propagation Behaviour of Peening Treated A2024 Alloy**
Kiyotaka MASAKI(Saitama Institute of Technology)

Surface engineering 3 16:30-18:30/18:50

Chair : Verônica VELLOSO(Sao Paulo State University) & Chang Ye(Zhengzhou University)

C1-313 **Study of the Ti-6Al-4V fatigue behavior superficially treated by plasma immersion ion implantation (PIII) combined with shot peening as pre and post treatment**
Verônica VELLOSO(Sao Paulo State University)

C1-314 **Low-cycle fatigue investigation of Cr/CrN multilayer coated Ti-6Al-4V alloy with equiaxed microstructure**
Martin Ferreira Fernandes(Sao Paulo State University)

C1-315 **Effect of Nitrided-Fine Particle Peening on Formation of Nitrided Layer and Fatigue Properties of Titanium Alloys**
Ryuichi Tachigaya(Shizuoka University)

C1-316 **Effect of Fine Iron-Sulfide Particle Peening on Rotating Bending Fatigue Properties of Low Alloy Steel**
Shotaro NOGUCHI(Shizuoka University)

C1-317 **Effect of Oxide Films on Fatigue Properties of Anodically Oxidized Aluminum Alloys**
Takeshi ANDO(Hiroshima University)

C1-318 **Improving the fatigue performance of Ti64 using electropulsing-assisted ultrasonic peening**
Chang Ye(Zhengzhou University)

■ Room E/ Cosmos 2

Fatigue modelling and simulation 1 **10:30 ～ 12:30**

Chair : Thomas Ebbott(Endurica LLC) & Mauro Madia(Bundesanstalt für Materialforschung und -prüfung)

C2-301 **Life Prediction and Virtual Qualification of an Elastomeric Engine Mount**
Thomas Ebbott(Endurica LLC)

C2-302 **Vibration fatigue life prediction of 60Si2Mn fastener clips based on CDM theory and ML model.**
Yifei Dong(Beihang University)

C2-304 **Deep Learning-enabled Cyclic Deformation Modeling of Single Crystal Ni-based Superalloy Considering the Effect of Microstructure State**
Long TAN(Beihang University)

C2-305 **Determination of the Kitagawa-Takahashi diagram for the EA4T railway axle steel by means of the cyclic R-curve method**
Mauro Madia(Bundesanstalt für Materialforschung und -prüfung)

C2-306 **Microstructure-induced cracking and life prediction of Inconel 713C superalloy for very high cycle fatigue at elevated temperatures**
Xiaolong LI (East China University of Science and Technology)

Fatigue modelling and simulation 2 **14:00-16:00 /16:20**

Chair : Pascale KANOUTE(ONERA) & Wenyi Yan(Monash University)

C2-307 **Multiaxial Fatigue Criteria for the Fatigue Life Assessment of Metallic Assemblies**
Pascale KANOUTE(ONERA)

C2-308 **Crack Closure and Fatigue Crack Growth under Variable Amplitude Loading**
Andrei Kotousov(The University of Adelaide)

C2-309 **A mesoscopic damage model for the low-cycle fatigue of an extruded magnesium alloy**
Ziyi Wang(Southwest Jiaotong University)

C2-310 **A Simple and Accurate Fatigue Life Prediction Method under Variable Loading**
Shoma Ueda(Tokyo City University)

C2-311 **Modelling the influence of clustered defects on HCF properties of Ni-based superalloys**
Arjun Kalkur MATPADI RAGHAVENDRA(Centre des Materiaux)

C2-312 **Numerical Study on Rolling Contact Fatigue Cracks in Curved Railway Tracks**
Wenyi Yan(Monash University)

Fatigue modelling and simulation 3 16:30-18:30/18:50

Chair : Andris Freimanis(VTT Technical Research Center of Finland) &Huang Yuan(Tsinghua University)

C2-313 **Fatigue modelling of martensitic steel for engine components**
Andris Freimanis(VTT Technical Research Center of Finland)

C2-314 **A fast Neuber-type Finite Element simulator to calibrate a multi- mechanism HCF model of alloys with process-induced pores**
Abhishek Palchoudhary(Mines Paris, PSL University)

C2-315 **FFT-based Crystal Plasticity Simulation of Cyclic Loading of SLM AlSi10Mg**
Manoj Singh Bisht(Indian Institute of Technology Roorkee)

C2-316 **Creep Rate of Anode Material for Lithium-ion Batteries under High Temperature Environment**
Kairi Shiraishi(Tokyo City University)

C2-317 **Investigation of Simple Mechanical Model for Fatigue Life Prediction of Anode Material for Lithium-ion Batteries**
Masaya Ueda(Tokyo City Univercity)

C2-318 **Microstructure-based fatigue life assessment of additively manufactured nickel-based superalloy**
Huang Yuan(Tsinghua University)

■ Room F/ Ran 1

Cyclic deformation and crack initiation 4 10:30～12:30

Chair : Viet Duc LE(Arts et Métiers Institute of Technology) & Zhefeng Zhang(Institute of Metal Research, Chinese Academy of Sciences)

R1-301 **Investigation of the torsional fatigue crack initiation mechanisms in the cast AlSi7Mg0.3 aluminum alloy using combined 3D X-ray CT and diffraction contrast tomography in a synchrotron beamline**
Viet Duc LE(Arts et Métiers Institute of Technology)

R1-302 **Fatigue damage and temperature evolution under anisotropic cyclic deformation in a single crystal Ni-base superalloy using notched specimens**
Putt Thanakun(Tokyo Institute of Technology)

R1-303 **Phase-field simulation on the martensitic transformation/reorientation toughening behaviors of single crystal NiTi shape memory alloy**
Junyuan Xiong(Southwest Jiaotong University)

R1-304 **Analysis and modeling of the strain distribution and evolution during a fatigue test in ULCF and LCF. Application on a friction stir welded specimen from steel and aluminum**
Paul DarioTOASA CAIZA(Karlsruhe Institute of Technology)

R1-305 **A review on the fatigue cracking of twin boundaries: crystallographic orientation and stacking fault energy**
Zhefeng Zhang(Institute of Metal Research, Chinese Academy of Sciences)

R1-306 **Low-cycle fatigue of CrCoNi medium-entropy alloy with different grain sizes**
Linlin Li(Institute of Metal Research, Chinese Academy of Sciences)

Cyclic deformation and crack initiation 5 14:00-16:00 /16:20

Chair : Constanze Backes(RPTU Kaiserslautern) & Lei Xu(Institute of Metal Research, Chinese Academy of Sciences)

R1-307 **Influence of mechanical fatigue on magnetic properties of electrical steels**
Constanze Backes(RPTU Kaiserslautern)

R1-308 **Influence of different temperatures on the fatigue behavior of fully ferritic high chromium steel**
Patrick Lehner(RPTU Kaiserslautern)

R1-309 **Cyclic Simple Shear Properties of Single- and Poly-crystalline Fe and Fe?3wt%Si alloys**
Mamoru HAYAKAWA(Nippon Steel Corporation)

R1-310 **Effect of Lüders strain localization on notch fatigue of medium manganese steels**
Xiangbo Hu(Hunan university)

R1-311 **Evaluation of Fatigue Properties of CFRF and Experimental Elucidation of Damage Growth Mechanism**
Yuta Koga(Waseda University)

R1-312 **Achieving superior fatigue strength in a powder-metallurgy titanium alloy via in-situ globularization during hot isostatic pressing**
Lei Xu(Institute of Metal Research, Chinese Academy of Sciences)

Cyclic deformation and crack initiation 6 16:30-18:30/18:50

Chair : Shuxin Chang(Southwest Jiaotong University) & Committee

R1-314 **Experimental investigation of early strain localizations on ferrite-pearlite steel under cyclic loading.**
Nagesh Narasimha Prasad(Univ. Lille)

R1-315 **Multi-mechanism constitutive model for uniaxial ratchetting of extruded AZ31 magnesium alloy at room temperature**
Yu Lei(Southwest Jiaotong University)

R1-316 **Cyclic responses and damage evolution of ultra-high strength steel under low-cycle fatigue**
Feinong Gao(Beijing Institute of Technology)

R1-317 **Mechanism-based assessment of profiles made from directly recycled hot extruded EN AW-6060 aluminum chips**
Alexander Koch(TU Dortmund University)

R1-318 **Phase transformation and ratchetting behavior of medium manganese steel under asymmetrical cyclic stressing: experiments, phase-field simulations and meso-mechanical constitutive model**
Shuxin Chang(Southwest Jiaotong University)

■ Room G/ Ran 2

Very high cycle fatigue 1 10:30 ～ 12:30

Chair : Luis Reis(IDMEC) & Bernd M. SCHÖNBAUER(University of Natural Resources and Life Sciences)

R2-301 **Different Axial/Shear Stress Ratios under Tension/Torsion UFT**
Luis Reis(IDMEC)

R2-302 **Effects of microstructure refinement and metallic adhesion on the sub-surface fatigue crack propagation process in Ti6Al4V alloy**
Hiroyuki OGUMA(National Institute for Materials Science)

R2-303 **20 kHz cantilever fatigue testing of high strength precision strip steels in different load conditions**
Mohamed Sadek(Karlstad University)

R2-304 **Fatigue assessment in the HCF and VHCF regimes of PM-HIPed Inconel 625**
Faezeh Javadzadeh Kalahroudi(Karlstad University)

R2-305 **High and very high cycle fatigue properties of pearlitic rail steel R350HT**
Bernd M. SCHÖNBAUER(University of Natural Resources and Life Sciences)

R2-306 **Crack Initiation and Propagation of Cruciform Specimens in Ultrasonic Fatigue Testing**
Luis Reis(IDMEC)

Very high cycle fatigue 2 14:00-16:00 /16:20

Chair : Yoshinobu Shimamura(Shizuoka University) & Tao Wu(Nanjing University of Aeronautics and Astronautics)

R2-307 **Effect of Mean Torsional Stress on Torsional Fatigue Strength in the Very High Cycle Regime for Spring and Bearing Steels**
Yoshinobu Shimamura(Shizuoka University)

R2-308 **Study and modeling of Fatigue Properties at Very Large Cycles from Self-heating Tests under Cyclic Loads**
Théo SEVEDE(IRDL)

R2-309 **A naturally initiated internal fatigue crack growth process in beta titanium alloy using in situ synchrotron radiation multiscale computed tomography**
Gaoge Xue(Hokkaido University)

R2-310 **Physics-informed neural networks for very high cycle fatigue**
Mingliang Zhu(East China University of Science and Technology)

R2-311 **Interior microstructure induced cracking of a NiCr20TiAl alloy at elevated temperature**
Gang Zhu(East China University of Science and Technology)

R2-312 **A VHCF Life Prediction Method Based on Surface Crack Density for FRP**
Tao Wu(Nanjing University of Aeronautics and Astronautics)

Thursday, 9 November [Day 4]

■ Room A / Phoenix

Plenary Lectures 08:00 ～ 11:00

Cair：Atsushi Sugeta

High-cycle and very-high-cycle fatigue of additively manufactured metallic materials

Youshi Hong
Professor, Institute of Mechanics, Chinese Academy of Sciences
Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

Japan's First Space Cargo Transfer Vehicle, "KOUNOTORI (HTV)," its Glory and Shadows in 24 Years of Development and Operation

Hirohiko Uematsu
Senior Advisor, Human Spaceflight Technology Directorate
Japan Aerospace Exploration Agency (JAXA)

In situ observation of small internal fatigue cracks in high-strength metals using synchrotron radiation multiscale X-ray computed tomography

Takashi Nakamura
Division of Mechanical and Aerospace Engineering, Hokkaido University

Friday, 10 November [Day 5]

■ Room B / Dahlia 1

Thermo-mechanical fatigue 1 08:00 ～ 10:00

Chair : Vincent Maurel(Mines Paris, PSL University) & Xu Chen(Tianjin University)

D1-501 **Anisotropic thermomechanical fatigue assessment of nickel-base single crystal alloys**
Jiawei Xu(Tsinghua University)

D1-502 **Role of temperature gradient in thermo-mechanical fatigue analyzed through micro-cracks growth**
Vincent Maurel(Mines Paris, PSL University)

D1-503 **Crack Growth Behavior of 316LN Stainless Steel under Thermomechanical and Isothermal Fatigue Loading**
Yiming Zheng(Tianjin University)

D1-504 **Material characterization of pearlitic railway steels exposed to simultaneous thermal and mechanical cycling**
Erika Steyn(Chalmers University of Technology)

D1-505 **Thermomechanical fatigue behavior of 316LN stainless Steel**
Xu Chen(Tianjin University)

Thermo-mechanical fatigue 2 10:30 ～ 12:30

Chair : Mi Wang(Beihang University) & Lu ZHANG(Nanjing University of Aeronautics and Astronautics)

D1-507 **A CTOD-based fatigue crack growth model under high temperature and dwell time**
Mi Wang(Beihang University)

D1-508 **A comparison of the thermomechanical fatigue behavior of electron-beam-melted and conventional Inconel 718**
Stefan Guth(Karlsruhe Institute of Technology)

D1-509 **Development of a thermal fatigue characterization protocol for metal alloys, adapted to characterize the strength of repaired structures**
Nicolas Thurieau(Institut Polytechnique de Paris)

D1-510 **Cyclic deformation and fracture mechanisms of powder-metallurgy nickel-based superalloy under thermo-mechanical fatigue**
Lu ZHANG(Nanjing University of Aeronautics and Astronautics)

D1-511 **Constitutive Modelling of alloys under high temperature low-cycle and thermal-mechanical fatigue: a key issue in component design**
Luc REMY(Mines Paris, PSL University)

Crack growth thresholds 14:00 ～ 16:00

Chair : Hisao Matsunaga(Kyushu University) & Salim ÇALIŞKAN(Turkish Aerospace)

D1-513 **Quantitative Evaluation of the Sliding-mode Crack-closure Affecting the Shea-mode Fatigue Crack-growth Threshold in Ni-based Superalloy 718**
Hisao Matsunaga(Kyushu University)

D1-514 **Fatigue crack propagation behavior of Inconel 718 superalloy aged with different temperature/stress coupled fields**
Lei WANG(Northeastern University)

D1-515 **In-situ scanning electron microscopy observation of crack closure of non-propagating fatigue crack in Fe alloy**
Atsushi Takayama(Nippon Steel Corporation)

D1-516 **Fatigue Limit Evaluation of Ni-based Superalloy 718, Considering the Competition between Opening- and Shear-mode Fatigue Crack-growth**
Yuya Tanaka(Fukuoka University)

D1-517 **Investigation of failure analysis for AISI 4340 steels on near threshold region**
Salim ÇALIŞKAN(Turkish Aerospace)

■ Room C / Dahlia 2

Life prediction methodology, software development 1 08:00 ～ 10:00

Chair : Marcos Pereira(Pontifical Catholic University of Rio de Janeiro) & Marion Bartsch(German Aerospace Center)

D2-501 **Investigation on Fatigue Life Estimation of GH4169 Superalloy at Elevated Temperature Based on Thermodynamic Entropy Generation**
Liangliang ZUO(Beihang University)

D2-502 **Modelling the effect of a superficial defect over the fatigue-life structural steels: a modified version of the S-N curve**
Marcos Pereira(Pontifical Catholic University of Rio de Janeiro)

D2-503 **Multiscale Modeling Strategy for Accurately Predicting Fatigue Life of Steels**
YOO CHAN(Korea University)

D2-504 **A Physics-informed Neural Network for Probabilistic Fatigue Life Prediction under Constant Amplitude Loading with Overloads**
Shan Jiang(Minzu University of China)

D2-505 **Probabilistic estimation of the Woehler and Goodman-Haigh curves by considering the stress ratio effect**
Paul DarioTOASA CAIZA(Karlsruhe Institute of Technology)

D2-506 **High Temperature Fatigue Tests on Small-scale Specimens Extracted from High Pressure Turbine Blades for Calibrating an Efficient Lifetime Model**
Marion Bartsch(German Aerospace Center)

Life prediction methodology, software development 2 10:30～12:30

Chair : Tiago Castro(Pontifical Catholic University of Rio de Janeiro) & Yongzhen ZHANG(Institute of Corrosion Science and Technology)

D2-507 **On the influence of mean stresses on the predictive capability of the elliptical curve method**
Tiago Castro(Pontifical Catholic University of Rio de Janeiro)

D2-508 **Machine learning-based fatigue life prediction of metal materials: Perspectives of physics-informed and data-driven hybrid methods**
Haijie Wang(East China University of Science and Technology)

D2-509 **Prediction of fatigue crack growth life under complex environmental loads via cycle-by-cycle algorithm and XFEM**
Zhiying Chen(Tsinghua University)

D2-510 **On the integration of domain knowledge and branching neural network for fatigue life prediction with small samples**
Lei GAN(Harbin Institute of Technology)

D2-511 **Methodology for pore detection and classification with regard to fatigue of PBF-LB/M-manufactured 316L using ?CT and machine learning algorithms**
Johannes Diller(Technical University of Munich)

D2-512 **Prediction of Corrosion Fatigue Crack Growth Rate in Alloys Based on Quantitative Expression of Data Nonlinear Correlation**
Yongzhen ZHANG(Institute of Corrosion Science and Technology)

Effective factors 14:00～16:00

Chair : Masatoshi Kuroda(Kumamoto University) & Wandong Wang(School of Aeronautics, Northwestern Polytechnical University)

D2-513 **Separate Effects of Surface Roughness and Residual Stress on Fatigue Limit of Austenitic Stainless Steels**
Masatoshi Kuroda(Kumamoto University)

D2-514 **Influence of manufacturing process, heat treatment and microstructure on fatigue properties of carbide-rich high-speed steels**
Lennart Mirko Scholl(RWTH Aachen University)

D2-515 **Bidirectional Transformation: A Novel Approach to Enhance Fatigue Durability of Steel**
Fumiyoshi Yoshinaka(National Institute for Materials Science)

D2-516 **Fatigue crack growth behavior of metallic plates reinforced with bonded and prestressed retarders**
Wandong Wang(School of Aeronautics, Northwestern Polytechnical University)

D2-517 **An analytical approach to evaluate fatigue behaviour of notched specimens in VHCF: challenges, accomplishments and limitations**
Abilio Jesus (University of Porto)

D2-518 **Influence of Metallurgical Variables on Corrosion Fatigue Strength of Structural Steels**
Ryuichiro Ebara (Fukuoka University)

■ Room D / Cosmos 1

Life prediction methodology, software development 1 **08:00 ～ 10:00**

Chair : Anja Weidner(TU Bergakademie Freiberg) & Chong Wang(Sichuan University)

C1-501 **Very high cycle fatigue at RT and elevated temperatures on additively manufactured materials**
Anja Weidner(TU Bergakademie Freiberg)

C1-502 **Contribution of self-heating measurements under cyclic loading to the study of VHCF properties at high temperature of nickel-based superalloys**
Alexis MION(Institut Polytechnique de Paris)

C1-503 **Nanograin formation mechanism under fatigue loadings in additively manufactured Ti-6Al-4V alloy**
Weiqian Chi(Beijing Jiaotong University)

C1-504 **Very high cycle fatigue properties of bearing steels at elevated temperature**
Suraj More(University of Natural Resources and Life Sciences)

C1-505 **Factors in ODA-like Morphology on the Fracture Surface in Beta Titanium Alloys**
Rajshree Awasthi(Hokkaido University)

C1-506 **Thermodynamic Investigation on the Crack Growth Behavior at Very High Cycle Fatigue Regime**
Chong Wang(Sichuan University)

Very high cycle fatigue 4 **10:30 ～ 12:30**

Chair : Yuki Nakamura(National Institute of Technology, Toyota College) & Yoshiyuki Furuya(National Institute for Materials Science)

C1-507 **Construction of Probabilistic Model on Interior Crack Nucleation and Propagation in Very High Cycle Fatigue of High Strength Steels**
Yuki Nakamura(National Institute of Technology, Toyota College)

C1-508 **Fatigue Mechanism for an Additively Manufactured Aluminium Alloy up to Very-High-Cycle Regime**
Xiangnan PAN(Institute of Mechanics, Chinese Academy of Sciences)

C1-509 **Localized oxidation assisting microcrack initiation in a LPSO-reinforced Mg-RE alloy up to very-high-cycle-fatigue regime**
Yao Chen(Kyushu University)

C1-510 **Characterizing the very high cycle fatigue behavior of CF-PEKK material under ultrasonic cyclic bending loads**
Aravind Premanand(University of Freiburg)

C1-511 **New fatigue limits in gigacycle fatigue of high-strength steels**
Yoshiyuki Furuya(National Institute for Materials Science)

Very high cycle fatigue 5 **14:00 ～ 16:00**

Chair : Elen Regitz(RPTU Kaiserslautern) & Yevgen GORASH(University of Strathclyde)

C1-513 **Microstructural changes during fatigue loading in the very high cycle regime of the metastable austenitic steel AISI 347 at 573 K**
Elen Regitz(RPTU Kaiserslautern)

C1-514 **Mechanism of nanograin formation and crack initiation for very high cycle fatigue of titanium alloys**
Chengqi Sun(Institute of Mechanics, Chinese Academy of Sciences)

C1-516 **Effects of Induction hardening and Press-Fitting on Very High Cycle Fatigue Properties of Railway Axle Steel**
Makoto AKAMA(Osaka Sangyo University)

■ Room E / Cosmos 2

Fatigue modelling and simulation 4 **08:00 ～ 10:00**

Chair : Franck MOREL(Arts et Métiers Institute of Technology) &Daiyang Gao(Nanjing University of Science and Technology)

C2-501 **Modelling Cyclic Deformation and Fatigue Crack Growth through Coupling of Phase Field and Viscoplasticity**
Liguo Zhao(Nanjing University of Aeronautics and Astronautics)

C2-502 **Process-performance-prediction integration oriented to fatigue life improvement: implementation in high-temperature structures based on dual-scale modeling approach**
Kai-Shang LI(East China University of Science and Technology)

C2-503 **Physics-based modelling of HCF variability in carburized steels**
Franck MOREL(Arts et Métiers Institute of Technology)

C2-504 **Phase-Field and Crystal Plasticity Coupling Model Investigation of Grain Growth under Fatigue Loading**
Wei Peng(East China University of Science and Technology)

C2-505 **Molecular Dynamics Analysis of the Effect of Strain Rate on the Acceleration of the Degradation of the Crystallinity of a Grain Boundary under Creep-Fatigue Loads at Elevated Temperature**
TakumaYamawaki(Tohoku University)

C2-506 **Spectral method for fatigue life estimation of notched metallic structures under broad-band random vibration loadings**
Daiyang Gao(Nanjing University of Science and Technology)

Fatigue modelling and simulation 5 10:30～12:30

Chair : Kazuki Shibanuma(The University of Tokyo) & Larissa Duarte(Bundesanstalt für Materialforschung und -prüfung)

C2-507 **Multiscale Modeling Strategy for Accurately Predicting Fatigue Life of Steels**
Kazuki Shibanuma(The University of Tokyo)

C2-508 **A Bridging Strategy between Microscopic and Macroscopic Crack Growth Simulations for Predicting Fatigue Strength of Steels**
Hongchang ZHOU(The University of Tokyo)

C2-509 **An elastoplastic constitutive model for effect of loading history on ratcheting and cyclic hardening behavior**
Jiawei Bai(School of Aerospace Science and Technology)

C2-510 **Fatigue behavior and cyclic slip irreversibility of AlCoCrFeNi high entropy alloys: A molecular dynamics simulation study**
Dongxing Pan(Hunan university)

C2-511 **A Bridging Strategy between Microscopic and Macroscopic Crack Growth Simulations for Predicting Fatigue Strength of Steels**
Yun-Jae Kim(Korea University)

C2-512 **Fatigue assessment procedure based on effective crack propagation data and cyclic R-curve**
Larissa Duarte(Bundesanstalt für Materialforschung und -prüfung)

Fatigue modelling and simulation 6 14:00～16:00

Chair : Abel Santos (University of Porto) & Yongtao Bai(Chongqing University)

C2-513 **A unified approach for the fatigue categorization of cold-formed mild steel details**
Abel Santos (University of Porto)

C2-514 **A continuum damage mechanics-based machine learning approach for thermal fatigue life prediction of aluminum alloy**
Zhixin Zhan(Beihang University)

C2-515 **Studying the Fatigue Strength in the VHCF Regime of an Epoxy used for Fiber-Reinforced Polymers**
Malo Rosemeier(Fraunhofer Institute for Wind Energy Systems IWES)

C2-516 **Comprehensive Comparison between two different fatigue modeling methods for welded hollow spherical joints**
Yongtao Bai(Chongqing University)

C2-517 **Incorporation of Notch Size Effect Correction Factors into the Correlation Parameter between Fatigue Strength Diagrams of Smooth and Notched Specimens and Induction of Master Diagrams as Base Data for Estimation of Fatigue Strength of Machine Parts and Structural Elements**
Hiroshi MATSUNO(Sojo University)

■ Room F / Ran 1

Fiber composites **08:00 ～ 10:00**

Chair : Sylvie Castagnet(University of Poitiers) & Andreas Baumann(Leibniz-Institut für Verbundwerkstoffe GmbH)

R1-501 **Fatigue Properties of Short Fiber Reinforced Polyamides exposed to acid environment**
Sylvie Castagnet(University of Poitiers)

R1-502 **Evaluation of Fatigue Properties of Injection Molded Plates of Short Glass Fiber Reinforced Composites Based on Matrix Phase Stress**
Kenichi Shimizu(Meijo University)

R1-503 **Fatigue crack evolution of thermoplastic-based fiber metal laminates under application-related temperatures**
Selim Mrzljak(TU Dortmund University)

R1-504 **Fatigue damage evolution and damage tolerance of composite structures**
Selim Mrzljak(TU Dortmund University)

R1-505 **Correlating composite fatigue to its matrix properties**
Andreas Baumann(Leibniz-Institut für Verbundwerkstoffe GmbH)

Cyclic deformation and crack initiation 7 **10:30 ～ 12:30**

Chair : Zhengguan Lu(Institute of Metal Research, Chinese Academy of Sciences) & Marek Smaga(RPTU Kaiserslautern)

R1-507 **Effect of thermal induced porosity on high-cycle fatigue and very high-cycle fatigue behaviors of hot-isostatic-pressed Ti-6Al-4V powder components**
Zhengguan Lu(Institute of Metal Research, Chinese Academy of Sciences)

R1-508 **Effect of powder size on fatigue properties of Ti-6Al-4V powder compact using hot isostatic pressing**
Jie Wu(Institute of Metal Research, Chinese Academy of Sciences)

R1-509 **Creep-fatigue crack initiation criterion for crystallographic evolutions based on damage mechanics descriptions**
Run-Zi Wang(Tohoku University)

R1-510 **Dynamic Evolution and Crystal Plasticity Study of GCr15 Bearing Steel Damage under Cyclic Loading**
Liu Tengyuan(Institute of Metal Research, Chinese Academy of Sciences)

R1-511 **Non-uniform cyclic temperature field induced deformation behavior of IN718 in thermal gradient mechanical fatigue**
Shaochen BAO(Beihang University)

R1-512 **Fatigue behavior of metastable Fe-based austenites**
Marek Smaga(RPTU Kaiserslautern)

Cyclic deformation and crack initiation 8 14:00 ~ 16:00

Chair : Wei Li(Beijing Institute of Technology) & Zhenlei Li(Beihang University)

R1-514 **In-site Mesoscopic Tension and Fatigue Properties of Proton Exchange Membrane for Fuel Cell**
Wei Li(Beijing Institute of Technology)

R1-515 **Study on the effects of inclusions on the fatigue properties of bearing steels**
Peng Zhang(Institute of Metal Research, Chinese Academy of Sciences)

R1-516 **Crystallographic mechanism of fatigue failure of zirconium alloys**
Conghui Zhang(Xi' an University of Architecture and Technology)

R1-517 **High Frequency High Cycle Bending Fatigue Failure Mechanism of Blade-like Specimen at High Stress Ratio under Biaxial Tension-bending Load**
Zhenlei Li(Beihang University)

R1-518 **Improving the fatigue defect tolerance of steels by Cu precipitates**
Dietmar Eifler (RPTU Kaiserslautern)

■ Room G / Ran 2

Variable amplitude loads, multiaxial and mixed mode fatigue 2 08:00 ~ 10:00

Chair : Matus Margetin(Slovak University of Technology in Bratislava) & Michael Marx(Saarland University)

R2-501 **Application of energy-based damage accumulation rule for fatigue monitoring of structure under variable amplitude loading**
Matus Margetin(Slovak University of Technology in Bratislava)

R2-502 **Micromechanical study of low-cycle fatigue behavior of additively manufactured Inconel 718 superalloy at ambient and elevated temperatures**
Xin Zhang(Harbin Institute of Technology)

R2-503 **Strain distribution of a fir-tree tenon/mortise structure under combined high and low cycle fatigue loads**
Han Yan Dr.(Beihang University)

R2-504 **An in-situ SEM investigation on fatigue crack growth mechanism under single overload**
Lindong Chai(Beihang University)

R2-505 **Fatigue of metallic glasses after an overload as a first step to fatigue under variable amplitude loading**
Michael Marx(Saarland University)

R2-506 **An iso-damage model based on residual S-N curves to consider fatigue damage accumulation under HCF-VHCF loads**
Tao Liang(Beihang University)

Variable amplitude loads, multiaxial and mixed mode fatigue 1 10:30 ～ 12:30

Chair : Christian Kontermann(TU Darmstadt) & Peter Haefele(University of Applied Sciences Esslingen)

R2-507 **Crack Initiation and Relaxation Behavior of a 1Cr-Cast Steel under Multiaxial High Temperature Loading**
Christian Kontermann(TU Darmstadt)

R2-508 **Fatigue behaviors and life evaluation of AISI 304 under multiaxial non-proportional random loading**
Yu-Chen WANG(Ritsumeikan University)

R2-509 **Fatigue Life Estimation Method Using Equivalent Stress Amplitude by Smith-Watson-Topper Method for SCM440**
Naoki Hashimoto(Hiroshima University)

R2-510 **Investigation of the test evaluation for the determination of multiaxial material properties**
Alexander Linn(Clausthal University of Technology)

R2-511 **Influence of cut edge and notch on electric steel strip under constant and variable amplitude loading**
Peter Haefele(University of Applied Sciences Esslingen)

Abstract

Tuesday, November 7 8:30 ～ 10:00 Room A / Phoenix

Plenary lecturers

Characterization of Microstructural Effects on the Near-Threshold Fatigue Crack Growth by means of Ultrasonic Fatigue Testing

Martina Zimmermann

Institute of Materials Science, TU Dresden
Fraunhofer Institute for Material and Beam Technology IWS, Dresden

ABSTRACT

Research on the very high cycle fatigue (VHCF) behavior of metallic materials usually focuses on the total service life and the relationship between service life and crack initiation. This approach is justified by the fact that the number of load cycles leading to crack initiation is significantly higher than the number of load cycles located in the crack growth phase. However, a complete description of the damage process must, of course, also include the crack growth phase. The fatigue crack propagation behavior becomes particularly important when a component is already cracked or defect-afflicted right from the beginning. An overview of the specific challenges of fatigue crack growth investigations on the basis of ultrasonic fatigue testing will be given – considering early works performed by the developers of ultrasonic fatigue systems as well as recent own research results on the fatigue crack growth behavior of aluminum and magnesium in the near threshold range.

Wednesday, November 8 8:00 ～ 10:00 Room A / Phoenix

Plenary lecturers

Fatigue Life Prediction of Additively Manufactured Metals: A Hybrid Critical Plane-Fracture Mechanics Approach

Ali Fatemi

Ring Companies Professor and Department Chair
Department of Mechanical Engineering, The University of Memphis, Memphis, TN, USA

ABSTRACT

Although there has been much research and knowledge gained on additive manufacturing (AM) in recent years, its application to safety-critical components prone to fatigue failure remains very limited. This is partly due to the challenges at the current stage of the technology such as defects, surface roughness, and residual stresses. However, another major contributing factor is due to the wide variation in performance resulting from the wide range of the many AM process control parameters and post-process treatments. This contrasts with conventional materials and processes, where such variations in performance are typically much smaller and more predictable. To facilitate better fatigue performance predictability in AM metals, despite the wide variability, a computational framework is proposed where variations such as in microstructure, defects, and residual stresses can be explicitly accounted for with a physics-based approach. This approach combines the successful concept of critical plane based on small crack growth often used for multiaxial fatigue crack initiation, with the fracture mechanics-based crack growth analyses. This talk will present an overview of the proposed approach and demonstrates its application to data generated from Ti-6Al-4V and 17-4 PH stainless steel specimens made by laser-based powder bed fusion (LB-PBF) and with different surface and post-treatment conditions. Different loading conditions including constant as well as variable amplitude axial, torsion, and combined axial-torsion loadings will be considered.

Wednesday, November 8 8:00 ～ 10:00 Room A / Phoenix
Plenary lecturers

Mazda's Monotsukuri (Manufacturing) A building block concept for facilitating flexible production

KATSUNORI MIYAWAKI

General Manager, Hiroshima Plant
Mazda Motor Corporation

ABSTRACT

The automotive industry is in the midst of a period of transformation as it responds to the challenges of carbon neutrality and advances in CASE (connected cars, autonomous driving, shared services, and electrification). To adapt to ongoing changes, Mazda has introduced a building block strategy whereby it continually develops new production technologies and integrates them with existing technologies to provide greater flexibility in production. This enables Mazda to make changes to production lines with minimum preparation and investment. The presentation will introduce Mazda's building block strategy and examples of how Mazda applies it.

Thursday, November 9 8:00 ～ 10:00 Room A / Phoenix
Plenary lecturers

High-cycle and very-high-cycle fatigue of additively manufactured metallic materials

Youshi Hong

Professor, Institute of Mechanics, Chinese Academy of Sciences
Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

ABSTRACT

Additive manufacturing (AM) has become a promising technology to produce complex engineering components with high efficiency and relatively low cost. As an echo of manufacturing process, AM parts inevitably contain intrinsic features such as large amounts of surface and internal defects, fine microstructure with inhomogeneity and anisotropy, and remarkable residual stresses. In engineering practice, the performance of high-cycle fatigue (HCF) and very-high-cycle fatigue (VHCF) for AM parts is much concerned because key engineering components require a long service life under cyclic loading, and the behavior of HCF and VHCF for AM parts is different from that of conventionally made counterparts. Among the mentioned features of AM parts, the influence of defects on fatigue behavior is the most vital issue to be investigated.

The topic of this presentation is on the HCF and VHCF behavior of additively manufactured metallic materials especially titanium alloys and aluminum alloys produced by commonly used selective laser melting or laser powder bed fusion. The presentation will focus on how to reduce the defect content by controlling AM processing parameters and post treatments, how to explain the size effect on fatigue performance caused by defects, and how to understand HCF and VHCF mechanisms at different stress ratios of AM parts.

Thursday, November 9 8:00 〜 10:00 Room A / Phoenix

Plenary lecturers

Japan's First Space Cargo Transfer Vehicle, "KOUNOTORI (HTV)," its Glory and Shadows in 24 Years of Development and Operation

Hirohiko Uematsu

Senior Advisor, Human Spaceflight Technology Directorate
Japan Aerospace Exploration Agency (JAXA)

ABSTRACT

The International Space Station (ISS) is a large observation platform, which was constructed in collaboration of fifteen countries worldwide. The ISS is flying around the earth at an altitude of about 400 kilometers and provides microgravity environment that is hardly available on the ground allowing unique experiments such as protein crystallization in microgravity. Japan participates in this international project with its first manned space facility, Japanese Experiment Module "KIBO" and the first space cargo transfer vehicle "KOUNOTORI," whose development code name was H-II Transfer Vehicle (HTV). The main objective of HTV is to transfer cargo such as food, clothes and various experiment devices to the ISS, where six astronauts are always present to conduct space-unique experiments.

The HTV project started in 1997 to develop Japan's first space cargo transfer vehicle with a unique technology call a rendezvous-capture method, which later became a world standard and was employed by other US space vehicles. The first HTV flight was successfully completed in 2009 and so were consecutive flights, and the 9th and the last HTV flight was completed in 2020. Over those 11 years, the HTV1 thorough HTV9 flights were all successful and the media treated us like a hero. But was it true?

At the beginning, we thought this unique rendezvous-capture method would be a huge breakthrough in the space rendezvous technology, but very few people believed it was possible for two reasons: first, this method was technically so difficult that no one ever tried in space before HTV, and secondly, Japan had no experience in space cargo transfer back then (we were treated as amateurs).

In this lecture, I would like to present our backstage struggles, which have never been explicitly treated in the HTV success stories. They may not be glorious stories, but will certainly put lights on the true engineering, which is inherently a muddy world.

Thursday, November 9 8:00 ～ 10:00 Room A / Phoenix

Plenary lecturers

In situ observation of small internal fatigue cracks in high-strength metals using synchrotron radiation multiscale X-ray computed tomography

Takashi Nakamura

Division of Mechanical and Aerospace Engineering, Hokkaido University

ABSTRACT

The very high cycle fatigue (VHCF) phenomenon has been recognized and extensively studied in the past quarter century. One of the most peculiar and noticeable characteristics of VHCF is the transition of the origin site from the surface to the interior of the material in long-life regimes over 106–107 cycles. In particular, in high-strength metals, a tiny site can become an origin of internal fatigue cracks, such as nonmetallic inclusions of several micrometers to several tens of micrometers in high-strength steels and crystal grains of several tens of micrometers in titanium alloys. However, such small cracks are difficult to detect using conventional nondestructive approaches, such as industrial X-ray computed tomography (CT) or ultrasonic CT. Given this background, the authors' group has attempted to use a synchrotron radiation multiscale X-ray CT provided by SPring-8 in Japan. This system comprises a projection CT with a spatial resolution of approximately 1 μm and a phase-contrast imaging CT with a spatial resolution of approximately 200 nm or higher. The present study introduces our experimental approach to clarify internal fatigue crack behaviors using the multiscale X-ray CT with in-situ fatigue testing. Our basic policy on material selection focusing on the VHCF study is explained with the materials used: (α+β) type Ti-6Al-4V, β type Ti-22V-4Al, and 17-4 precipitation-hardened martensite stainless steel. The outline and primary performance of the multiscale X-ray CT are described, and the initiation and growth behaviors of the internal fatigue cracks of the above materials are discussed for an in-depth understanding of the VHCF phenomenon.

P-201

Assessment of the four-point bending fatigue properties of zirconia-reinforced Ti6Al-4V nanocomposite processed by laser powder bed fusion

Benjamin GUENNEC[1,*], Amine HATTAL[2,3], Azziz HOCINI[2], Kamilla MUKHTAROVA[4], Takahiro KINOSHITA[1], Noriyo HORIKAWA[1], Jenő Gubicza[4] Madjid DJEMAI[3] and Guy DIRRAS[2]

[1] Toyama Prefectural University, JAPAN
[2] Université Sorbonne Paris Nord, FRANCE
[3] Z3Dlab, FRANCE
[4] Eötvös Lorand University, HUNGARY

* Corresponding author: bguennecpro@gmail.com

ABSTRACT:
Additive manufacturing is now widely recognized as a decisive paradigm change by the scientific community. This technology provides a very efficient way to create metallic matrix composites (MMCs). Recently, Z3Dlab has developed nano-yttria-stabilized zirconia (nYSZ) reinforced Ti-6Al-4V alloys processed by laser powder bed fusion (L-PBF). Under static loading, such alloys present superior strengths than its unreinforced counterpart, in addition with features suggesting strengthening by hard particles. To assess the viability of such materials for structural applications, an investigation was carried out on the monotonic tensile and four-point bending fatigue behavior of 1 wt.% nYSZ reinforced compound. In a quest for clarification on the effect of the hot isostatic pressing (HIP) on the fatigue outcomes, both untreated and HIPed specimens were studied. The former material indicated relatively modest fatigue resistance of 431 MPa (see Fig. 1) mainly due to the presence of inherent processing defects, whereas the latter one revealed a promising fatigue endurance of 844 MPa, higher than its unreinforced counterparts. A transgranular fatigue crack nucleation provoked by the crystallographic slip in long-length layers of *α* grain in the HIPed specimen.

KEYWORDS:
Metal matrix composite, Titanium alloy, Additive manufacturing, Hot isostatic pressing.

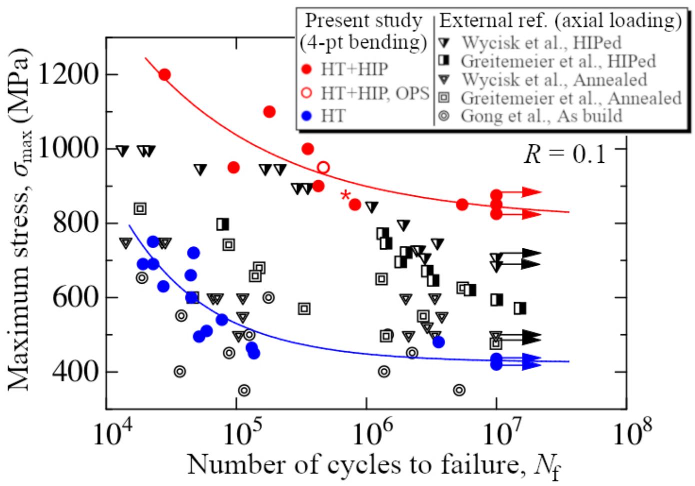


Fig. 1 *S-N diagram of the reinforced materials (HT stands for heat treated and HT+HIP stands for subsequent HIP treatment), along with fatigue data from unreinforced Ti-6Al-4V.*

P-202

Effect of Volume Fraction of Network Structure Composed of High-Entropy CrMnFeCoNi Alloy on Fatigue Crack Propagation in 304L Stainless Steel Compact

Arisa ITO[1,*], Keisuke FUJITA[1], Hiroshi FUJIWARA[2] and Shoichi KIKUCHI[1]

[1] Shizuoka University, JAPAN
[2] Ritsumeikan University, JAPAN

* Corresponding author: ito.arisa.18@shizuoka.ac.jp

ABSTRACT:

High-entropy alloys (HEAs) have several superior mechanical properties. The purpose of the present study is to resolve a tradeoff between tensile strength and fatigue crack propagation resistance by using a bimodal structure. High-entropy alloy (CrMnFeCoNi alloy) and AISI304L stainless steel powders with different particles diameters were mixed and then consolidated using spark plasma sintering to fabricate sintered compacts with a network structure composed of coarse-grained 304L surrounded by fine-grained CrMnFeCoNi alloy microstructure (Fig. 1). Tensile tests and stress intensity factor *K*-decreasing tests were conducted in the ambient laboratory atmosphere. Furthermore, the sintered compacts with different volume fraction of powders were fabricated and the effects of volume fraction on fatigue crack propagation properties and tensile properties were investigated. The elongation of HEA50% and 70% series linearly decreased with CrMnFeCoNi alloy content, while the HEA30% series showed higher elongation than the value estimated using the rule of mixtures. The threshold stress intensity factor range, ΔK_{th}, of the sintered compacts with bimodal structure was higher than that of the homogeneous CrMnFeCoNi alloy at a high force ratio due to the high effective threshold stress intensity factor range, $\Delta K_{eff,th}$, derived from the 304L.

KEYWORDS:

Fatigue crack propagation; High-entropy alloy; Austenitic stainless steel; Spark plasma sintering; Fracture mechanics

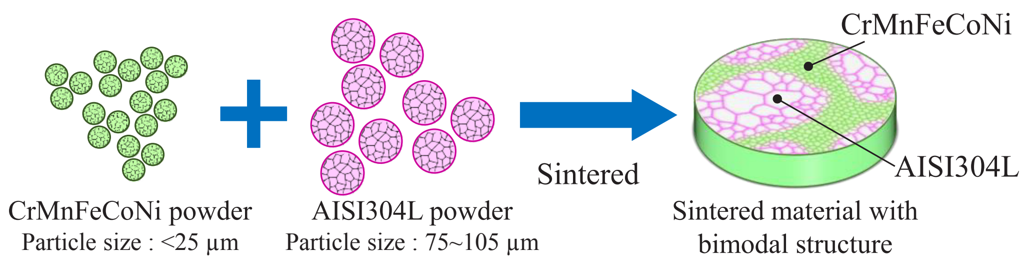


Fig. 1 Schematic illustration of fabrication of sintered compact with network structure composed of fine-grained CrMnFeCoNi alloy.

P-203

Fatigue damage evaluation of coarse and fine grains in notched austenitic stainless steel with harmonic structure

Keisuke FUJITA[1,*], Yoshiki ISHIMURA[1], Yoshikazu NAKAI[2], Mie OTA KAWABATA[3], Hiroshi FUJIWARA[3], Kei AMEYAMA[3] and Shoichi KIKUCHI[1]

[1] Shizuoka University, JAPAN
[2] Kobe University, JAPAN
[3] Ritsumeikan University, JAPAN

* Corresponding author: fujita.keisuke.15@shizuoka.ac.jp

ABSTRACT:

The “harmonic structure”, which is defined as a coarse-grained structure surrounded by a network of fine grains, achieved high strength, high ductility and high fatigue properties. The purpose of this study is to examine the notch effect in austenitic stainless steels with harmonic structure under axial loading. The fatigue limit of the notched austenitic stainless steel with harmonic structure (K_t = 2.53) showed almost the same as the smooth one (K_t = 1.03). In particular, the fatigue limit of the notched specimen (K_t = 1.25) was higher than that of the smooth one. The detailed observation revealed that fatigue cracks initiated from coarse-grained structure in the smooth specimen. On the other hand, fatigue cracks in notched specimen were initiated from fine-grained structure. In addition, Finite element analysis revealed that the stress was distributed and concentrated in the fine-grained structure. The electron backscatter diffraction (EBSD) and electron-channeling contrast image (ECCI) analysis also revealed that the fine-grained structure in the harmonic structure near the notch root was preferentially damaged by stress concentration. Thus, the fractured structure was switched from coarse-grained structure to fine-grained structure with increase of stress concentration factors.

KEYWORDS:

Notch effect; Powder metallurgy; Stainless steel; Grain refinement; Harmonic structure

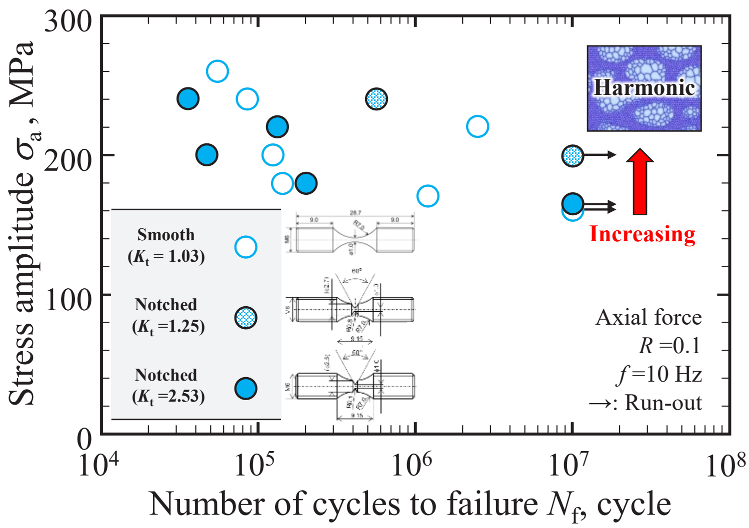


Fig. 1 *S-N curve* of the harmonic structured austenitic stainless steel

P-204

Retarded Crack Growth and Self Sensing Ability of Metal-Matrix Composites produced by High-Pressure Torsion

Valeria LEMKOVA[1*], Juraj TODT[2], Christian MOTZ[1]and Florian SCHAEFER[1]

[1] Saarland University, Materials Science and Methods, GERMANY
[2] Montanuniversität Leoben, Materials Physics, AUSTRIA

* Corresponding author: v.lemkova@matsci.uni-saarland.de

ABSTRACT:

In composites, outstanding properties of two materials can be combined. Metal-Matrix Composites (MMCs) could provide the properties of a high-strength ductile metallic matrix with specialized properties of embedded ceramic particles. This hybrid therefore can be called a functional material. For the synthesis of MMCs, High-Pressure Torsion (HPT), a method of severe plastic deformation, allows not only to achieve an ultrafine-grained metallic matrix but also mechanical alloying without thermal load.

Herein, the attempt to obtain smart MMCs through HPT processing is aimed. For that purpose, Cu-MMCs are produced from mixed powders with ZrO_2 and $BaTiO_3$ (BTO) with the challenge to incorporate their functional phase. ZrO_2 can improve fatigue lifetime by a retarded crack growth. These MMCs feature a retarded fatigue crack initiation and an earlier crack closure during fatigue crack growth due to the volume expansion once ZrO_2 experiences a phase transformation from the metastable tetragonal to the ambient monoclinic phase triggered by the propagating crack (see Fig. 1). In addition, BTO can provide a sensing ability for internal stress through the piezoelectric effect when strained. This is shown by in situ scanning Kelvin probe force microscopy. The amount of the stabilized phase is evaluated by X-ray diffraction and Rietveld refinement.

KEYWORDS:

metal-matrix composites; hybrid materials; functional materials

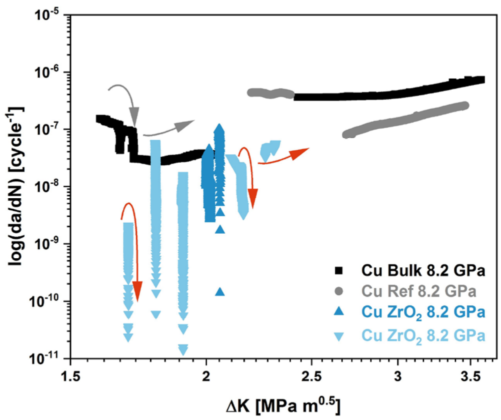


Fig. 1 *Crack growth curves for short cracks in the reference specimens (grey, black) and ZrO_2–MMC specimens (blue) with arrows showing the direction of advancing load cycles. Especially for the blue curves from the MMCs, the deceleration, although partially after prior crack re-initiation, is obvious. The cracks in the reference material start crack growth to final failure and thus without a later deceleration already a smaller ΔK.*

P-205

Fatigue crack propagation of nano particles reinforced Al matrix composite

Qingqing Pu[1], Jiwei Geng[1, *], Dong Chen[1] and Haowei Wang[1].

[1] School of Materials Science & Engineering, Shanghai Jiao Tong University, Shanghai 200240, CHINA

* Corresponding author: gengjiwei163@sjtu.edu.cn

ABSTRACT:

Nano particles reinforced Al matrix composites have been identified as a promising candidate aerospace industry because they combine the benefits of Al alloys with reinforcing particles to overcome the drawbacks of Al alloys, and possess remarkable properties such as high modulus and low weight. Like the alloy, the fatigue damage of the composite is affected by the characteristics of slip bands, precipitates, grain boundaries and grain orientation of the alloy matrix. Importantly, the reinforcing particles play a key role in the cyclic deformation of the composite since they exhibit significantly different performances with the matrix. The effect of particle distribution on the anisotropy behavior of fatigue crack propagation, as well as the beneficial role of particles in designing high strength and low fatigue crack propagation rate in Al matrix composites was investigated. Multiscale characterization, such as digital image correlation, synchrotron tomography, scanning electron microscopy, and transmission electron microscopy, was used to reveal the influence of microstructures on the fatigue crack propagation behavior and the corresponding crack propagation mechanism in nano particles reinforced Al matrix composite.

KEYWORDS:

Al matrix composite; Nano particles; Microstructure; Fatigue crack propagation.

P-206

Fatigue behavior of accumulative roll bonded Cu/Nb laminate materials

Takayuki SHIRAIWA[1,*], Koki YASUDA[1], Fabien BRIFFOD[1] and Manabu ENOKI[1]

[1] Department of Materials Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan.

* Corresponding author: shiraiwa@rme.mm.t.u-tokyo.ac.jp

ABSTRACT:

High-strength and high-conductivity (HSHC) materials are in high demand across various fields, including integrated circuit leadframes, ultra-compact connectors for electronic devices, and high magnetic field generators for research applications. Copper/niobium (Cu/Nb) laminates, produced through accumulative roll bonding (ARB), are considered highly promising for HSHC materials due to their strength resulting from the Hall-Petch effect and the potential for bulk production. Recent studies have demonstrated their excellent mechanical and electrical properties. However, to utilize them in electronic devices, it is crucial to evaluate their fatigue behavior. In this study, Cu/Nb laminates with varying layer thicknesses were prepared using different rolling processes. The microstructure was characterized through SEM-EBSD analysis. Four-point bending fatigue tests were conducted on the Cu/Nb laminates. The fatigue crack initiation and propagation life were determined by continuously capturing optical images of the specimen bottom and sides throughout the test. The figure below illustrates an example of fatigue test results. When subjected to loading in the rolling direction (RD), the fatigue life surpassed that in the transverse direction (TD). Additionally, a polycrystalline model was constructed based on the EBSD data, enabling a crystal plasticity finite element analysis to quantitatively examine the effect of the microstructure on fatigue properties.

KEYWORDS:

Hig-strength high-conductivity materials; metallic composites; crack initiation; crack propagation; crystal plasticity finite element method

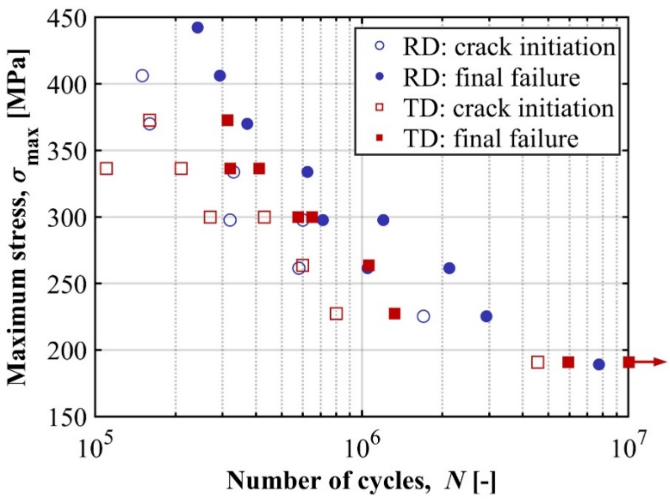


Fig. 1 S-N curve of ARB Cu/Nb laminate.

P-207

Overview of Japanese Activity for New Fatigue Curves and Fatigue Analysis

Takeshi OGAWA[1], Seiji ASADA[2], Keisuke KIMURA[3]

[1] Aoyama Gakuin University, JAPAN
[2] Mitsubishi Heavy Industries, Ltd., JAPAN
[3] The Kansai Electric Power Co., Inc., JAPAN

* Corresponding author: ogawa@me.aoyama.ac.jp

ABSTRACT:
This presentation gives an overview of this organized session for new fatigue curve and analysis. The activities are held at Japan Welding Engineering Society (JWES), where fatigue knowledge platform is developed by a FQA subcommittee in the Atomic Energy Research Committee. First, the fatigue knowledge platform is introduced. It consists of summaries of the research reports produced by many fatigue subcommittees from 1970s, question and answers (Q&A) sheets, and information on important knowledge on fatigue. Recent subcommittee for design fatigue curve (DFC) developed a new fatigue curve and analysis, which are briefly summarized. In this organized session, detailed presentations will follow on this topic including development of best fit curves, new methods for design factors, mean stress correction based on SWT, effect of surface finish, and size effect verification by large scale testing. Finally, some of the Q&A activities will be introduced. These Q&As are unique topics on fatigue analysis.

KEYWORDS:
Fatigue curve; Fatigue analysis; Mean stress; Surface finish; Size effect

P-208
Development of Best Fit Curves used for New Design Fatigue Curves

Masanori TOYODA[1], Seiji ASADA[1]

[1] Mitsubishi Heavy Industries, Ltd., JAPAN

* Corresponding author: masanori.toyoda.pa@nu.mhi.com

ABSTRACT

To develop new design fatigue curves and design fatigue evaluation method, Design Fatigue Curve (DFC) Phase 1 to Phase 4 subcommittee were established in the Atomic Energy Research Committee in the Japan Welding Engineering Society (JWES).

Domestic and foreign fatigue data of small test specimens in air were collected and a comprehensive fatigue database (≈6000 data) was constructed. Based on this fatigue database, the accurate best-fit curves of carbon steels & low-alloy steels and austenitic stainless steels were developed using tensile strength as a parameter, and design factors were investigated. Also, a Japanese utility collaborative project performed large scale fatigue tests using austenitic stainless steel piping and low-alloy steel flat plates as well as fatigue tests using small specimens. Those tests were to obtain not only basic data but also fatigue data of mean stress effect, surface finish effect and size effect. Those test results were provided to the subcommittee and utilized in the above studies.

Based on the above studies, new design fatigue curves and a fatigue evaluation method have been developed.

In this presentation, the best-fit curves of carbon steels & low-alloy steels and austenitic stainless steels are explained.

191 words

The abstract should not exceed 200 words in length.

KEYWORDS:

Design fatigue curve; fatigue database; fatigue evaluation

P-209

Definition of Fatigue Life in Best fit Curves and Large Components

Chihiro NARAZAKI[1]*, Masahiro TAKANASHI[2], Yuichiro NOMURA[3]

[1] Toshiba Energy Systems & Solutions Corporation, JAPAN
[2] IHI Corporation, JAPAN
[3] Mitsubishi Heavy Industries, Ltd., JAPAN

* Corresponding author: chihiro.narazaki@toshiba.co.jp

ABSTRACT:

The design fatigue curve is based on the best-fit fatigue curve (BFC) obtained from fatigue tests using small specimens. According to NUREG/CR-6909 Rev.1, the BFC, which is defined by 25%-stress-drop cycles, equates to fatigue lives when crack depths in small round bar specimens are approximately 3 mm. Large-scale fatigue tests for ferritic steels plates and austenitic stainless steel piping were performed to compare with the BFC of small specimens. The crack propagation behaviors were observed on the large-scale specimens. It was found that the BFC of small specimens was equivalent to that of which crack depth is approximately 3 mm of a large-scale specimen, since the stress gradient in large-scale specimen is gentle and is almost flat in 3 mm from surface. The size effect on the BFC can be negligible if the stress on the crack surface is equivalent to the stress of the small specimen regardless of the specimen size. As for the fatigue design of large actual components, the applicability of the design fatigue curve based on small specimens was confirmed without considering size effect.

KEYWORDS:

Best-fit fatigue curve; Size effect; Large-scale test; Crack growth behavior

P-210

Mean Stress Correction Method for Fatigue Analysis

Takuya OGAWA[1,*], Masahiro TAKANASHI[2] and Yuichiro NOMURA[3]

[1] Toshiba Energy Systems and Solutions Corporation, JAPAN
[2] IHI Corporation, JAPAN
[3] Mitsubishi Heavy Industries, JAPAN

* Corresponding author: takuya4.ogawa@toshiba.co.jp

ABSTRACT:
Generally, the tensile mean stress causes a reduction of fatigue strength. The Modified Goodman approach for mean stress correction is well-known and used in the various industries. For example, the design fatigue curves in the JSME and ASME Design Codes use the Modified Goodman approach. Recently in Japan, new design fatigue analysis method and curves were investigated in Design Fatigue Curve (DFC) subcommittee established in the Atomic Energy Research Committee, the Japan Welding Engineering Society (JWES). As a part of the study, several mean stress correction methods were investigated and compared based on a lot of test data. It was confirmed that the SWT (Smith-Watson-Topper) approach provided more adequate correction than the Modified Goodman approach and others. Therefore, the SWT approach was adopted and will be incorporated into the JSME Code “Environmental Fatigue Evaluation Method for Nuclear Power Plants”, 2022 edition. In this presentation, comparison of various approaches for mean stress correction, the reason why the SWT approach was selected, and the applicability to design fatigue analysis will be presented.

170 words

KEYWORDS:
Design fatigue curve; Fatigue analysis; Mean stress correction; SWT approach; Modified Goodman approach

P-211

Investigation of Mean Stress Effect for Local Strain Behavior at Notch Root of Large-Scale Plate Specimen

Daiki Takagoshi[1], Yuichiro NOMURA[1], Seiji ASADA[1], Keisuke KIMURA[2]

[1] Mitsubishi Heavy Industries, Ltd., JAPAN
[2] The Kansai Electric Power Co., Inc., JAPAN

* Corresponding author: daiki.takagoshi.ta@mhi.com

ABSTRACT:

In load-controlled fatigue tests with positive mean stress (stress ratio, R>-1) for notched specimens, mean stress at notch root is supposed to decrease with increasing number of fatigue cycles when cyclic plastic-deformations occur only near the notch root. Usually, the local stress cannot be measured in the test, so FE analyses should be performed to estimate local stress-strain behavior. However, in fatigue tests of small-scale notched specimens, local strain at the notch root cannot be measured because of too small space for strain gauge. Consequently, results of FEA cannot be verified. In this study, to verify FEA for notched specimens, a cyclic loading test by using large-scale notched plate specimen was performed. During the test, local strains near notch root were measured and analyzed by FEA. As a result, the local strains measured and analyzed were confirmed to be almost the same. It indicates that local strain for small-scale notched specimens can be estimated by FEA. Also, fatigue tests of small-scale notched specimens were performed, and the relations between the fatigue lives and the strain at notch root estimated by FEA were in good agreement with the best-fit curve obtained by round-bar specimens.

193 words

KEYWORDS:

Fatigue test; Finite Element Analysis; Notched specimen; Local strain; mean stress

P-212
Verification of SWT Method for Notched Components

Yuichiro NOMURA[1,*], Yun WANG[2], Masahiro TAKANASHI[3], Masao ITATANI[4], Atsushi SUGETA[5], and Keisuke KIMURA[6]

[1] Mitsubishi Heavy Industries, Ltd., JAPAN
[2] Hitachi. Ltd, JAPAN, JAPAN
[3] IHI Corporation, JAPAN
[4] Toshiba Energy Systems and Solutions Corporation, JAPAN
[5] Hiroshima University, JAPAN
[6] The Kansai Electric Power Co., Inc., JAPAN

* Corresponding author: yuichiro.nomura.cf@mhi.com

ABSTRACT:
The presentation gives mean stress correction based on Smith-Watson-Topper (SWT) method. This activity is held at Japan Welding Engineering Society (JWES), subcommittee for design fatigue curve (DFC) Phase 1 to 4 in the Atomic Energy Research Committee. SWT method has been proposed as a method to correct fatigue strength against mean stress. Using carbon steel STPT370 and low alloy steel SQV2A, fatigue tests were carried out with mean stress applied by circular notched bar type specimens with different stress concentration factors (K_t=1.5 and 1.8). In addition, elasto-plastic FEM analysis simulating the specimen was performed to examine the applicability of the SWT method when stress concentration due to notching and mean stress act simultaneously. As a result, by setting the stress and strain values of the notched bottom obtained by the FEM analysis, it was confirmed that the evaluation on the maintenance side was possible by the SWT method.

KEYWORDS:
Fatigue curve; Fatigue analysis; Mean stress; Circular notched bar type specimens

P-213

Effect of Machined Surface Finish on Fatigue Life of Carbon Steel

Yun WANG[1], Motoki NAKANE[2], Akihiko HIRANO[2], Masahiro TAKANASHI[3], Masao ITATANI[4]
Keisuke KIMURA[5]

[1] Hitachi, Ltd., JAPAN
[2] Hitachi-GE Nuclear Energy, Ltd., JAPAN
[3] IHI Corporation, JAPAN
[4] Toshiba Energy Systems & Solutions Corporation, JAPAN
[5] The Kansai Electric Power Co., Inc., JAPAN

* Corresponding author: yun.wang.tt@hitachi.com

ABSTRACT:

The effect of machined surface finish on fatigue life was discussed on carbon steel STPT370 by comparing the polished and machined specimens of both smooth and notched round bar. Several levels of target roughness were introduced in the specimens by emery paper polishing and machining. The material properties of smooth specimens including thickness of the surface layer, residual stress, roughness and hardness were investigated before the fatigue tests. Based on fatigue test results, the contributions to the fatigue life change of these material property parameters were compared and discussed. Surface finish effect factor K_{sf} of notched specimens tended to be larger than that of smooth specimens under high stress amplitude even at the same level of roughness. However, this tendency was not obvious under low stress amplitude. According to the microscopic observation, the different tendency was assumed to be associated with different behavior of crack coalescence relevant to the profile of surface. After reviewed by the DFC4 subcommittee of the JWES, this result was supposed to be a unique phenomenon for small specimens, which will probably not occur in actual components. It was concluded that the JSME K_{sf} equation could evaluate the influence of surface finish at notched portion.

KEYWORDS:

Surface finish,
Carbon steel,
Roughness,
Notched specimen,
Crack coalescence

P-214

Fatigue crack initiation and growth behavior of specimen with machined surface layer under low cycle fatigue regime

Shota HASUNUMA[1,*], Tomoyuki HAYASE[1] and Takeshi OGAWA[1]

[1] Aoyama Gakuin University, JAPAN

* Corresponding author: hasunuma@me.aoyama.ac.jp

ABSTRACT:
In this study, low cycle fatigue tests of steels were performed for specimen with machined surface layer in order to reveal the fatigue crack initiation and growth behavior. The present study used carbon steel, STS410, and austenitic stainless steel, SUS316L, for fatigue tests. For changing the machined surface layer, round bar specimens were machined by different condition of turning. When rotation speed or feed speed was slow, long scratches were generated due to a build-up edge. Then, fatigue tests were carried out for the specimens machined by the different conditions. Results of fatigue tests show that scratches reduced the fatigue lives. If there were scratches on specimen surface, many cracks initiated from the valley of scratches in a row. The cracks coalesce grew rapidly to be a semicircular crack almost as large as the scratch in early stage of fatigue life. These behaviors reduced fatigue life. But, fatigue lives of a specimen which had a few small scratches was similar to that of a specimen whose scratches were removed. These trends of fatigue life can be observed for both of STS410 and SUS316L.

KEYWORDS:
Machined surface layer; Low cycle fatigue; Fatigue crack initiation and growth; Steels; Scratch.

P-215

QA Sheet for Variability Factors in Fatigue Life of *S-N* Curve - Introduction of Activity for Development of ‘Fatigue Knowledge Platform’ in JWES (1) -

Nao FUJIMURA[1,*], Hideo KOBAYASHI[2]

[1] Hokkaido University, JAPAN
[2] Professor Emeritus of Tokyo Institute of Technology, JAPAN

* Corresponding author: fujimura@eng.hokudai.ac.jp

ABSTRACT:
The FQA subcommittee in the Atomic Energy Research Committee of the Japan Welding Engineering Society has developed a fatigue knowledge platform. From the platform, this presentation introduces the Q&A sheet that explains the variability factors in the fatigue life of the *S-N* curve. Fatigue fracture, which occurs due to cyclic loading, is a time-dependent-type fracture and is represented by using the *S-N* curve, which shows the relationship between stress and fatigue life. The fracture process consists of two processes: crack initiation and propagation, and the fatigue life is the sum of these lives. The fatigue life variability is mainly caused by crack initiation. Generally, fracture occurs from defects (weak points of material microstructure). Fatigue crack is initiated at the surface’s weak points, such as slip bands in coarse grains oriented in the slippery direction or inclusions. These weak points relate to the structure-sensitive property. The effect of the structure-sensitive property on crack initiation differs depending on stress levels, and this results in fatigue life variability. On the other hand, the structure-sensitive property is weak for crack propagation because the weak points are averaged, therefore, the variability in crack propagation life is smaller than that in crack initiation.

KEYWORDS:
Fatigue life, Crack initiation, Crack propagation, Structure-sensitive property.

P-216

QA Sheet for Fatigue Analysis of Weld Joint –Introduction of Activity for Development of 'Fatigue Knowledge Platform' in JWES (2) –

Hideaki NISHIKAWA[1], Hideo KOBAYASHI[2]

[1] National Institute for Materials Science, JAPAN
[2] Professor Emeritus of Tokyo Institute of Technology, JAPAN

* Corresponding author: NISHIKAWA.Hideaki@nims.go.jp

ABSTRACT:
The question and answers (QA) sheets which are included in the 'Fatigue Knowledge Platform' were developed by the FQA subcommittee in Japan Welding Engineering Society (JWES). In this activity, simple and practical questions of fatigue issues and its brief answers were organized. One of the notable features of the QA sheets is the cross-cutting description covering different industrial fields and scientific understanding. For example, from the perspective of fatigue design of weld joint, there are two different major fatigue design concept for the construction field and the pressure vessel field. Usual articles are individually explaining the fatigue analysis method of each fields. On the other hand, the QA sheet simultaneously describes these concept and the technical difference briefly. In addition, there are also several simple QAs related to weld fatigue such as the effect of residual stress on fatigue. Such brief descriptions help engineers understand the fatigue design concept correctly. This presentation introduces an example of QA sheet related to fatigue analysis of weld joint.

KEYWORDS:
Fatigue analysis; Weld joint;

Research center for structural material

P-217

QA Sheet for Difference between Post Construction Code for Pressure Vessel and Damage Tolerance Design of Aircraft –Introduction of Activity for Development of 'Fatigue Knowledge Platform' in JWES (3) –

Yuka MIYATA[1]* and Hideo KOBAYASHI[2]

[1] Hitachi-GE Nuclear Energy Ltd, JAPAN
[2] Professor Emeritus of Tokyo Institute of Technology, JAPAN

* Corresponding author: yuka.miyata.ja@hitachi.com

ABSTRACT:

The FQA subcommittee of the Atomic Energy Committee of the Japan Welding Engineering Society has developed a Fatigue knowledge platform which summarizes important knowledge on fatigue. In this presentation, as an example of the contents in the platform, the QA sheet which explains the difference between the concept of post construction codes for pressure vessels and the damage tolerant design for aircraft will be introduced.

Based on the construction codes, pressure vessels are designed and manufactured with a appropriate fatigue life margin, not allowing for the occurrence of damage. In addition, the post construction codes provide (1) methods for detecting damage with planned inspections, (2) evaluation and prediction of detected damage, and (3) repair/replacement methods. Therefore, the service life of the equipment can be extended by applying the post construction codes to equipment when the damage occurs during the operation.

On the other hand, the damage tolerant design of aircraft is similar to the post construction codes in that damage is predicted through planned inspections. However, it differs from the design of pressure vessels in that it allows to progress of the damage during design stage and adopts a fail-safe structure based on the assumption that replacement will be performed. (200 words)

KEYWORDS:

Pressure vessel; Post construction code; Damage tolerance design, Aircraft

P-218
Status of Codification for New Fatigue Curves and Analysis

Seiji ASADA[1]

[1] Mitsubishi Heavy Industries, Ltd., JAPAN

* Corresponding author: seiji.asada.mx@nu.mhi.com

ABSTRACT:
The DFC subcommittees in the Atomic Energy Research Committee of the Japan Welding Engineering Society (JWES) developed new fatigue curves and a fatigue analysis method, and the outcomes were brought to the JSME Committee on Power Generation Facility Codes. The Code Committee approved to incorporate the new fatigue analysis method into JSME Environmental Fatigue Evaluation Method 2022Edition.
Also, the new fatigue analysis method is being proposed to the ASME BPV Code Committee (Working Group on Fatigue Strength in BPV III) as a code case.
The status of these code activities is introduced.

92 words

KEYWORDS:
Fatigue curve; Fatigue analysis; Design Code

D1-201

Change in mechanical properties and surface morphology of alpha+beta type titanium alloy subjected to gas nitriding duplex treatment

Toshikazu AKAHORI[1,]*, Akihiro MIZUTANI[1], Mitsuo NIINOMI[2] and Hisao FUKUI[3]

[1] Meijo University, JAPAN
[2] Tohoku University, JAPAN
[3] Aichi Gakuin University, JAPAN

* Corresponding author: akahori@meijo-u.ac.jp

ABSTRACT:

Biomaterials are continuously used under dynamic loading condition in vivo, which shows relatively corrosive environment, where some damage such as frictional wear and fatigue are also easily accumulated. Therefore, high reliability not to cause failure under the environment as mentioned above has been demanded. The surface modification layer controlling and improvement in mechanical properties of biomedical α+β type Ti-6Al-7Nb (Ti67) subjected to gas nitriding duplex treatment combined with gas nitriding and fine particle bombarding with ZrO_2 were systematically investigated in this study.

The microstructure near specimen surface of Ti67 subjected to gas nitriding duplex treatment was composed of very thin nitride layer with some dimples on its surface by fine particle bombarding and nitrogen rich region at the subsurface. The frictional wear characteristics of Ti67 with nitride layer were remarkably improved as compared with that before treatment. The balance between fatigue properties (Fig. 1) and frictional wear characteristics after gas nitriding duplex treatment showed much better than those of Ti67 subjected to single gas nitriding. From these results, it was judged that there is a possibility of high mechanical strengthening and formation of surface modification layer by the optimized gas nitriding duplex treatment.

KEYWORDS:

Metallic biomaterials, titanium alloy, surface modification, mechanical properties.

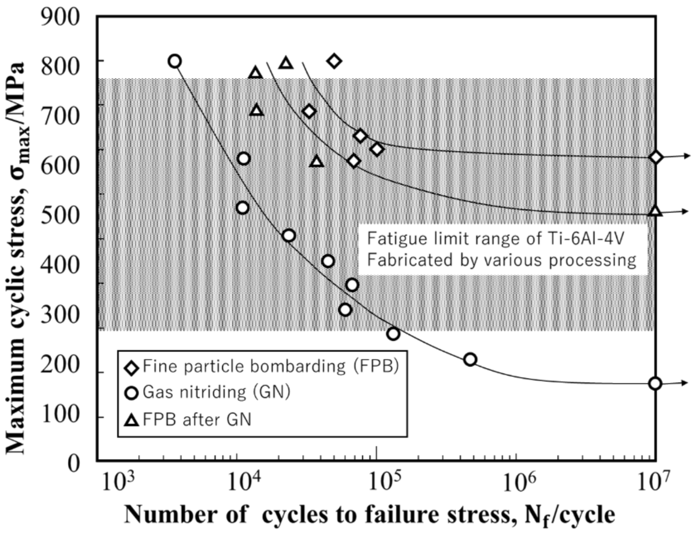


Fig. 1 S-N curves of Ti-6Al-7Nb subjected to fine particle bombarding (FPB) with ZrO_2, gas nitriding (GN) and FPB after GN.

D1-202

Fatigue Property Evaluation of Ti-Ta Alloy Rods Using Spinal Fixation Model

Akane YANAGAWA[1], Noriyuki HISAMORI[2], Masahiro SHINZAWA[3] and Yuki KIMURA[3]

[1] Graduate School of Science and Technology, Sophia University, JAPAN
[2] Faculty of Science and Technology, Sophia University, JAPAN
[3] New Product Development Group, NIPPON PISTON RING CO., LTD., JAPAN

* Corresponding author: a-yanagawa-1x1@eagle.sophia.ac.jp

ABSTRACT:

There is a demand for the development of low-elasticity titanium alloys whose modulus is near to that of bone. This study evaluates the fatigue properties of low cytotoxic Ti-Ta alloys rods, heat-treated to have different elastic modulus: Solution treated (ST) at 890°C and aged (Ag) at 500°C(ST890-Ag500), ST700°C and Ag500°C(ST700-Ag500), aged-treated at 500°C(Ag500), and solution-treated at 750°C(ST750).

We constructed a spinal fixation system which consists of two bone-like ultra-high molecular weight polyethylene (UHMWPE) blocks, a screw, a screw socket, a rod and a set screw. The rod to be tested is fixed to the UHMWPE blocks by screw socket and set screw. Bending or torsional moment is exerted to the rod by applying compressive load to polyethylene blocks.

The fatigue test conducted was a compression bending load test conforming to ASTM-F1717 under the condition of a load ratio of 0.1, a frequency of 5Hz, and maximum load 150N. Depending on the necessary amount of displacement, the frequency is lowered to keep the load ratio of 0.1.

Table 1 shows the result of fatigue test. Although breakage of the screw occurs in most cases, the result showed that the difference of the elastic modulus affects the fatigue fracture of rods.

KEYWORDS:

Ti-Ta alloys, Ti-6Al-4V alloys, Fatigue, Spinal fixation system

Table 1 Fatigue test results of Ti-Ta alloys using spinal fixation model.

Rods material	Number of cycles to failure (cycles)	Displacement (mm)	Broken part
Ti-6Al-4V (Comparative)	5,000,000	4	Not broken
ST890-Ag500	210,158	6.7	Screw in bloke
ST700-Ag500	587,288	5.5	Screw in bloke
Ag500	938,193	4.6	Screw in bloke
ST750	2,660,000	7.5	Experimenting

D1-203

Evaluation of Corrosion, Wear and Tribocorrosion Properties of Ti-Ta Alloys

Shuta YAMAMURO[1] , Noriyuki HISAMORI[2] , Masahiro SHINZAWA[3] , Yuki KIMURA[3]

[1] Graduate School of Science and Technology, Sophia University, JAPAN
[2] Faculty of Science and Technology, Sophia University, JAPAN
[3] New Product Development Group NIPPON PISTON RING CO.,LTD., JAPAN

* Corresponding author: s-yamamuro-2I0@eagle.sophia.ac.jp

ABSTRACT:

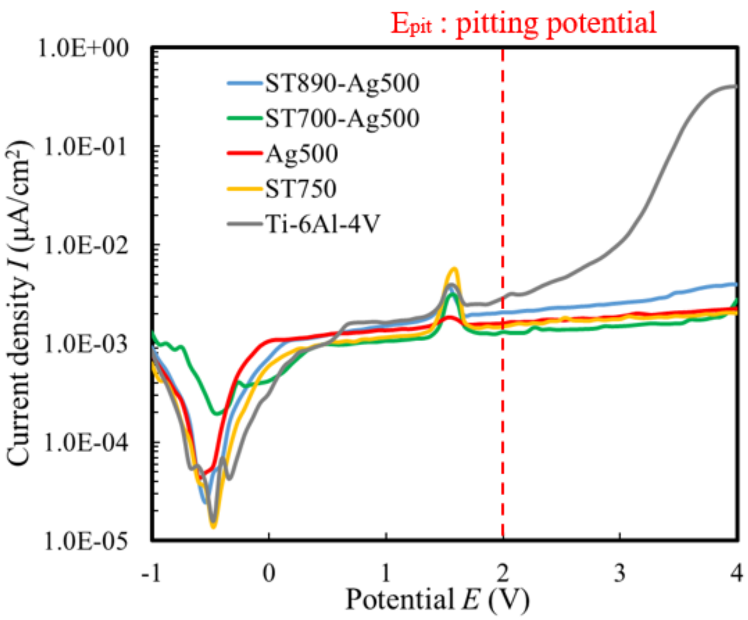
Joint replacement is one of the most common arthrosurgical procedures, but ion elution due to stress shielding and long-term implantation is a problem. In this study the corrosion, wear, and corrosive wear properties of the titanium-tantalum(Ti-Ta) alloys which has low modulus and low cytotoxicity is evaluated and compare those with the Ti-6Al-4V alloys.

Four different heat-treated Ti-Ta specimens were prepared: solution heat treatment (ST) at 890ºC and aging treatment (Ag) at 500ºC, ST 700ºC and Ag 500ºC, Ag 500ºC, and ST 750ºC. The crystal structure of these specimens was β+α' phase, α+β+α' phase, α+β+α' phase, and α+β phase.

The corrosion properties were measured with three-electrode anodic polarization test in 37°C physiological saline solution. Fig.1 shows the results of anodic polarization tests. In the figure, the Ti-6Al-4V alloys shows a rapid increase of potential above 2.0V, indicating pitting potential. On the other hand, the Ti-Ta alloys does not show a sudden increase, which is due to formation of the passive film consisting of Ta_2O_5, indicating that the Ti-Ta alloys has higher corrosion resistance than the Ti-6Al-4V alloys. The results of the ball-on-disk type friction wear test showed that the Ti-Ta alloys has almost the same wear characteristics with the Ti-6Al-4V alloys.

KEYWORDS:

Ti-Ta alloys, Biomaterial, Corrosion, Wear, Tribocorrosion



D1-204

Effect of Angioplasty on Fatigue Resistance of Nitinol Stent in Femoropopliteal Artery

Liguo ZHAO[1,*] and Ran HE[2]

[1] Nanjing University of Aeronautics and Astronautics, China
[2] Loughborough University, UK

* Corresponding author: L.Zhao@nuaa.edu.cn

ABSTRACT:

Clinically, blocked arteries undergo balloon angioplasty before stenting, especially for nitinol stent to be deployed in femoropopliteal artery. The aim of this study is to investigate the effect of angioplasty on the fatigue resistance of the stent subjected to walk-induced motion of the artery using advanced finite-element analysis. Angioplasty was simulated before stenting, with a peak inflating pressure of 1.8 MPa applied to the inner surface of the balloon. The process of stent deployment in the diseased artery consisted of crimping and releasing steps. Following the stent deployment, its in-service fatigue behaviour was studied under a combined bending, torsion and axial compression fatigue caused by walking-induced artery motion. The deployment of stent after angioplasty achieved larger lumen gain compared to that without angioplasty. The maximum stress value appears to be lower for the stent when deployed after angioplasty. However, more elements are in the dangerous zone (i.e., above the fatigue limit line) for the case simulated with angioplasty due to the increased stress amplitude under fatigue. This is because the lower stress associated with angioplasty makes the stent easier to deform under fatigue. Angioplasty introduces pre-dilation to the diseased artery which facilitates the expansion of stent and thus lowers the stress level in the stent after deployment. However, it increases the risk of fatigue failure of implanted nitinol stent.

KEYWORDS:

Nitinol stent; Angioplasty; Pre-dilation; Fatigue resistance; Femoropopliteal artery.

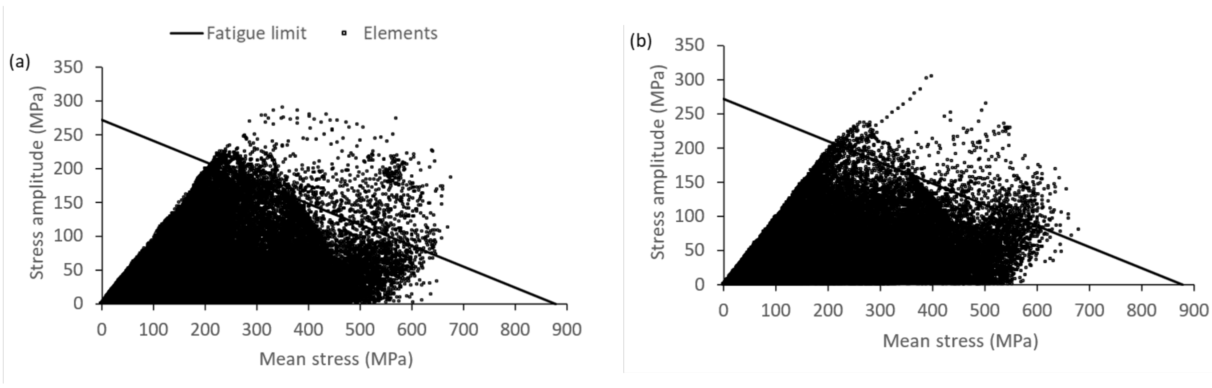


Fig. 1 *Goodman's diagrams (a) with and (b) without angioplasty.*

D1-207

Experimental and numerical investigations of the influence of grain orientation on the fatigue behavior of coarse-grained nickel-based superalloys

Philipp LION[1], Tilmann BECK[1,*], Moritz LIESEGANG[1], Mathis HARDER[2], Lucas MAEDE[3], Hanno GOTTSCHALK[2]

[1] RPTU Kaiserslautern-Landau, GERMANY
[2] BUW, GERMANY
[3] Siemens Energy Global GmbH & CO. KG, GERMANY

* Corresponding author: Tilmann Beck – t.beck@mv.rptu.de

ABSTRACT:

The elastic anisotropy, and thus the grain orientation distribution, is mainly responsible for the scatter in the fatigue life of coarse-grained fcc nickel-based superalloys (Fig. 1a). Due to the arbitrary grain orientation, highly inhomogeneous deformation occurs within the material volume, resulting in significantly higher local strains than the total strain applied. To find correlations between the grain orientations, fatigue crack initiation and propagation, a finite element (FE) model, based on EBSD of the investigated specimen in the initial state and after crack initiation was developed. Finite element (FE) analyses of fatigue specimens with a thickness well below the grain diameter showed elevated stress in the same regions (Fig. 1b) where fatigue crack initiation occurred in the respective experiments. Intermitted fatigue tests showed the effect of grain orientation on crack propagation, i.e., a change of crack growth rate, and direction, at grain boundaries. Correspondingly, the stress intensity at the crack tip changes for different configurations of cracks and grain orientation (Fig. 1c).

In the presented work, experimental and numerical results show the dependence between the extent of deformation and the stiffness of the grain in load direction considering the respective grain periphery. The resulting normal and shear stress fields are exaggerated in i) grains of high stiffness surrounded by grains of lower stiffness, ii) in grains of moderate stiffness but high Schmid factors, and iii) at grain boundaries where the adjacent grains have a largely different stiffness.

KEYWORDS:

Nickel based superalloy; grain orientation; crack initiation; crack propagation; stress intensity;

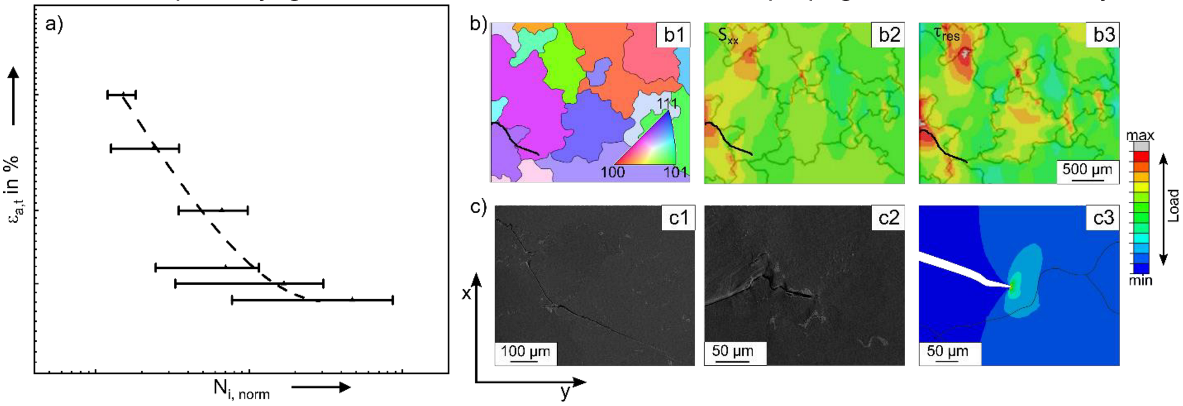


Fig. 1 a) ε - N curve b) Crack initiation: 1-Grain structure and IPF-map 2-Stress in loading direction 3-Resolved shear stress c) Crack propagation: 1-Pre-damgaged specimen 2-Crack formation at a grain boundary 3-Stress in the crack tip

D1-208

Fatigue Crack Extension Mode for 18Ni Martensitic Steel and Its Effect on Fatigue Limit

Shun KINO[1], Daisuke ITOH[1, 2], Shohei UEKI[1] and Shigeru HAMADA[1, *]

[1] Kyushu University, JAPAN
[2] Nippon Steel Co., JAPAN

* Corresponding author: hamada@mech.kyushu-u.ac.jp

ABSTRACT:

Fatigue cracks in 18Ni martensitic steel propagate in damage accumulation (DA) mode in addition to the normal mode. To clarify the types of damage accumulation, the authors conducted fatigue tests. First, the fracture surface and specimen surface around the crack were observed, and microstructure evolution caused by the crack propagation was observed. Then the authors clarified that three types of DA mode fatigue crack propagation (FCP) exist at least. The first one is a crack propagation along with the grain boundary. In this crack propagation, the grain boundary separation is caused by accumulated dislocation in the grain boundary. The second one is a crack propagation caused by dislocation cell wall separation. The last one is that the coalescence of the main crack with the sub-crack in an active slip system causes this crack to propagate. In addition, the authors showed the possibility that the dislocation cells created ahead of the crack tip are the key to ceasing the crack extension. Finally, the authors clarified the existence of DA mode FCP decreases the fatigue limit. That is because DA mode FCP expands the √area region from the fatigue crack initiation site, which acts as an initial crack.

KEYWORDS:

Lath Martensite; Metal Fatigue; DA mode FCP; Fatigue Limit

D1-209

Carbon content effect on fatigue crack extension behavior and extension mode in 18%Ni martensitic steels

Ren Pengxu[1*], Daisuke Itoh[1 2] and Shigeru Hamada[1]

[1] Kyushu University, JAPAN
[2] Nippon Steel Corporation, JAPAN

* Corresponding author: ren.pengxu.512@s.kyushu-u.ac.jp

ABSTRACT:

In order to verify the effect of carbon additions on 18% Ni martensitic steels, rotating bending fatigue tests were conducted at various carbon contents. The effect of the carbon content on the fatigue extension and the extension mode was investigated because carbon content would influence some material factors that could affect the fatigue crack morphology and fatigue properties. Because the hierarchical microstructure of martensite significantly influences the crack extension path considerably, the interaction between the fatigue crack extension behavior and the microstructure should be considered. Therefore, the fatigue crack extension path and microstructure near the crack path were observed on the specimen surface. The authors found that the crack extension was a discontinuous process and was processed by sub-crack initiation ahead of the main crack and coalescence with the main crack. Factors such as dislocation density and grain size would vary as the carbon addition content changes. Among these factors, the most important point was the grain size, which was the dominant factor for the fatigue limit. And the crack extension mode in this material was considered to be the damage accumulation mode, and the crack extension behavior was independent of changes in carbon content.

KEYWORDS:

Fatigue damage, martensitic steel, fatigue crack propagation, carbon content, fatigue limit.

D1-210

Fatigue crack propagation behavior of Ferritic steels with different cyclic softening properties

Takayuki YONEZAWA[1,*], Takashige MORI[1] and Seiichiro TSUTSUMI[2]

[1] Nippon Steel Corporation, JAPAN
[2] Osaka University, JAPAN

* Corresponding author: yonezawa.94m.takayuki@jp.nipponsteel.com

ABSTRACT:

Cyclic hardening / softening properties affect fatigue crack propagation properties of steels, but few reports have quantitatively evaluated their effects. In this study, the effect of cyclic softening properties on fatigue crack propagation rate in ferritic steel was investigated. The cyclic softening behavior was changed by introducing dislocations by cold rolling. As a result of fatigue tests under constant strain amplitude, steel with high cold rolling ratio showed remarkable cyclic softening behavior. In the cyclic softened steels, the dislocations became cell structures and their density decreased. The fatigue crack propagation rate was slower in steels with higher cyclic softening rates. Dislocation cell structures were observed around fatigue crack, suggesting the matrix softening. Furthermore, the strain at the fatigue crack tip during fatigue tests was measured by digital image correlation (DIC). Steel with high cyclic softening rate showed small strain change at the fatigue crack tip in the same stress intensity factor range, which may be the reason for the higher fatigue crack propagation properties.

KEYWORDS:

Fatigue crack propagation, cyclic softening, dislocation, DIC, Ferritic steel

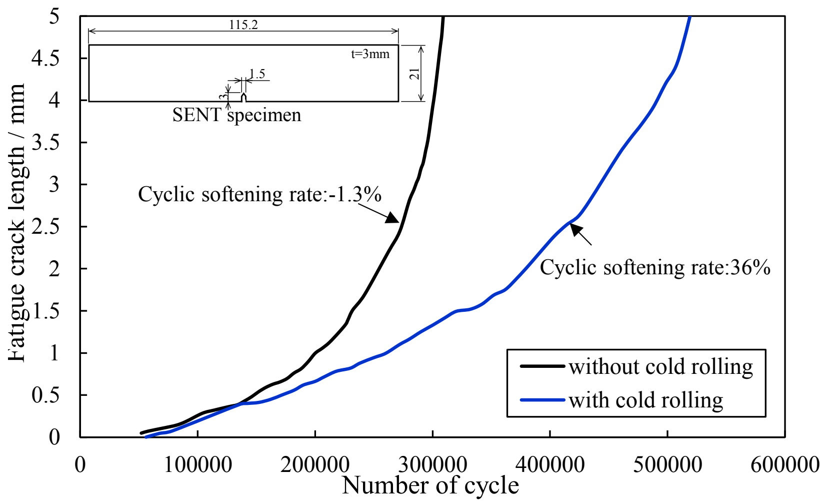


Fig. 1 *Fatigue crack growth curve.*

D1-213

Investigation of defect induced crack and fatigue crack growth behavior of a P/M nickel based superalloy and corresponding life prediction

Yi SHI[1], Xiao LIN[2], Xiaoguang YANG[3] Hua SUN[1] and Qing Lian[1,*]

[1] School of Materials Science and Engineering, Shanghai Jiao Tong University, China
[2] Shanghai Space Propulsion Technology Research Institute, China
[3] School of Energy and Power Engineering, Beihang University, China

* Corresponding author: lianqing@sjtu.edu.cn

ABSTRACT:

Powder metallurgy nickel based superalloys are widely applied in turbine disc due to their excellent mechanical performance at elevated temperature. However, the existence of defect is inevitable and this could result in early crack initiation and propagation. In this study, a series fatigue tests at elevated temperature were conducted, including high and low cycle fatigue tests and fatigue crack growth tests. To better compare the influence of surface defect, artificial surface defects were introduced by EDM. In addition, the trapezoid loading spectrum was added to examine the time-dependent effect. The fatigue life tests show that the existence of defect and hold time significantly reduce the fatigue life. Defect with various size, shape and location could be treated as initial crack. Thus, a fracture mechanic based life prediction method was proposed. The stress intensity factor estimation based on Murakami method and small crack propagation modification model were proposed. In addition, the influence of oxidation environment was included. Tests with different frequency were also conducted to better quantify this time-dependent influence. Finally, this life prediction method shows moderately conservative prediction method which is valuable for engineering application.

KEYWORDS:
Please enter keywords separated by semicolons. (Limit 5 Keywords)
Fatigue crack growth; fracture mechanic based life prediction method; high temperature; nickel based superalloys; time dependent effect

D1-214

In-situ Observation of Fatigue Crack Propagation in Soda-Lime Glass with Vickers Indentation-induced Initial Crack under Four-Point Bending

Hibiki KOMINE[1,*], Keisuke FUJITA[1], Akifumi NIWA[2], Yusuke KOBAYASHI[2], Ryunosuke KURODA[2] and Shoichi KIKUCHI[1]

[1] Shizuoka University, JAPAN
[2] AGC Inc., JAPAN

* Corresponding author: komine.hibiki.18@shizuoka.ac.jp

ABSTRACT:
Small cracks propagate at the glass surface due to the combined effects of water vapor and applied load. This phenomenon is known as glass fatigue. In this study, four-point bending fatigue tests under static and cyclic loading conditions were conducted for the soda-lime glass plate specimens with the initial crack and indentation pit by Vickers diamond indentation. Fatigue cracks were also observed by optical microscopy in order to obtain the relationship between crack growth rate, d*a*/d*t*, and stress intensity factor, *K*, during fatigue tests. The crack growth rate, d*a*/d*t*, decreased and then increased with the *K* value. In addition, photoelasticity was applied to measure the residual stress distribution around initial crack formed on the surface of the glass. The initial fatigue crack growth rate varied with residual stress induced by the indentation of the Vickers indenter. In order to examine the effect of residual stress on crack propagation behavior in more detail, the fatigue crack propagation of annealed glass specimens was also observed.

KEYWORDS:
Glass; Fatigue; Static Fatigue; Fatigue Crack Propagation; Fracture mechanics

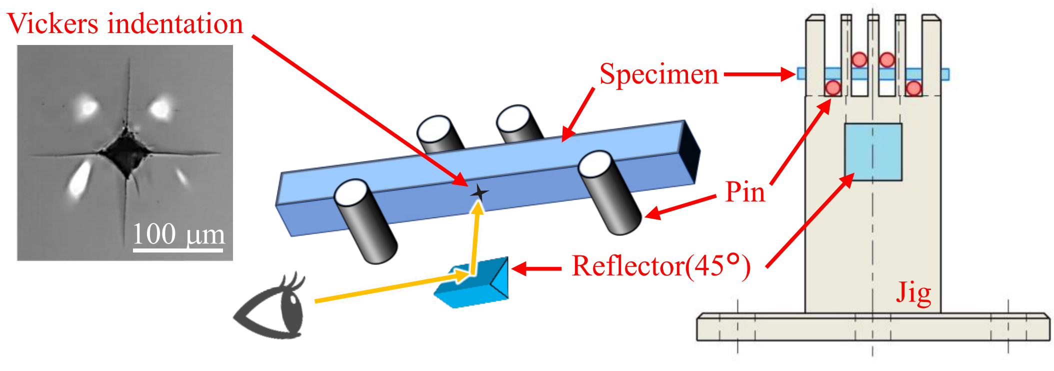


Fig. 1 Schematic illustration for in-situ observation of cracks under four-point bending fatigue test.

D1-215

Intrinsic fatigue resistance and the influence of material defects

Mirco Daniel CHAPETTI

Laboratory of Experimental Mechanics (LABMEX)
INTEMA (Research Institute for Materials Science and Technology)
CONICET - University of Mar del Plata
Av. Colón 10850, (7600) Mar del Plata, Argentina

Corresponding author: mchapetti@fi.mdp.edu.ar

ABSTRACT:

The demand for reliability and safety in mechanical components used in industrial applications has led to an increased focus on prediction approaches in the field of long-life fatigue. With the evolution of fracture mechanics tools, it has become possible to estimate the fatigue lives and limits associated with mechanical components that have small cracks or crack-like defects generated during manufacturing. Inherent defects in some manufacturing processes, such as additive manufacturing, can eliminate or minimize the initiation stage of fatigue cracks. As a result, the damage process primarily involves the propagation of a crack from the critical defect until it causes the component to fracture. Fracture mechanics is crucial in developing predictive models, and combined with the advancements in understanding the behavior of small cracks, the damage tolerance methodology has become the best tool for designing safe mechanical components. However, fracture mechanics analysis necessitates estimating the resistance curve of the material in the absence of defects. The intrinsic fatigue limit of the material, which represents the material's resistance without defects, is required to estimate the resistance curve if the defects are inherent to the manufacturing process. This work presents basic concepts and hypotheses related to fatigue limit and fracture mechanics models, as well as experimental evidence on the intrinsic fatigue limit and its association with naturally-nucleated non-propagating cracks. Two simple expressions are proposed for estimating the intrinsic fatigue resistance of metallic alloys.

KEYWORDS:

Fatigue resistance; Fracture mechanics; Defect assessment; Estimation

D1-216

Investigation of the influence of physical notch parameters on fatigue life and fatigue life scatter in EN AW-2618A

Jan RADNERS[1,*], Philipp VON HARTROTT[1]

[1] Fraunhofer Institute for Mechanics of Materials IWM, Freiburg, Germany

* Corresponding author: jan.radners@iwm.fraunhofer.de

ABSTRACT:

In this work, the effect of notches on fatigue life is investigated for the widely used precipitation hardened high temperature, high strength aluminum alloy EN AW-2618A. The alloy is used for a multitude of turbo-applications and similar, in which notches are unavoidable due to the components design.

Instead of tracing the influence of notches back to common geometric parameters such as notch radius or notch depth, the dependence of a physically active notch parameter, namely the normalized stress gradient G', is investigated. For this purpose, fatigue specimens were developed that isolate G' as influencing parameter. This is done by introducing multiple notches in the specimens, so that the specimens exhibit the same highly stressed volume V_{90} whilst having different normalized stress gradients G'.

The experimentally observed influence of G' on the fatigue life and the fatigue life scatter depending on the notch root stress $\sigma_{a,max,K}$ is depicted in Fig.1. The results are discussed and a fatigue life modeling approach incorporating microstructural parameters like grain size and grain orientation is presented. The concept is compared with existing fatigue life models from the literature.

KEYWORDS:

notch fatigue; fatigue scatter; normalized stress gradient; aluminum; EN AW-2618A

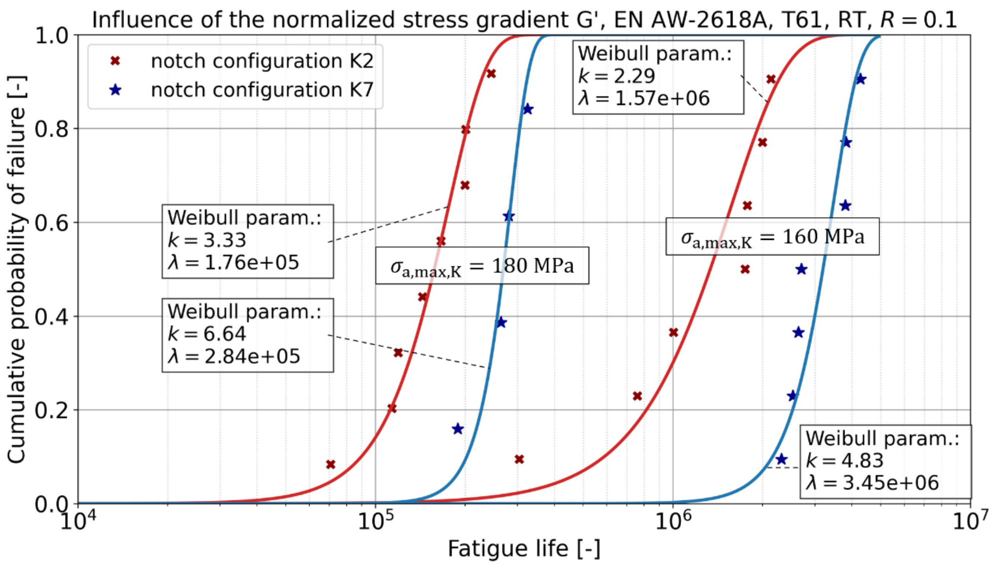


Fig. 1: *Influence of the normalized stress gradient G' on the experimental fatigue life of notched specimens. The notch configurations K2 ($G' = 1\ \mathrm{mm}^{-1}$) and K7 ($G' = 3.3\ \mathrm{mm}^{-1}$) have the same highly stressed volume V_{90}.*

D1-217

Fatigue short crack propagation in a Ni alloy manufactured by Laser powder bed fusion

Jianghua Li[1], Qinghui Huang[1], Ningyu Zhang[1], Yadong Zhou[1], Ruiyang Li[1], Guian Qian[1]*

[1] Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

* Corresponding author: qianguian@imech.ac.cn

ABSTRACT:

Fatigue crack spends most of lifetimes at the microstructural level or short crack stage and may be heavily influenced by the microstructure. Additive manufactured materials have been gradually used as engineering structural materials. Thus, investigation and understanding of small-scale crack propagation may be useful in characterizing the development of fatigue damage and fatigue life prediction. The results show that small fatigue crack propagation of LPBF GH4169 alloy is strongly dependent on twist angle, Schmid factor and geometrical compatibility factor. In addition, subgrain boundaries also exhibit a significant impact on small crack growth. The cross slip was activated to accompany crack retardation or deflection. In order to reveal the correlation between the crack path and crystal orientations, the crack initiation region was measured by EBSD. Persistent slip bands on the specimen surface, acting as stress concentration sites, provide a preferred path for crack propagation. The crack path and crack growth rate were influenced by the persistent slip bands developed on the crack flanks. Finally, a small crack growth relationship based on Paris law was discussed.

KEYWORDS:

LPBF GH4169, Small fatigue crack, Misorientation, Low angle boundary, Propagation model

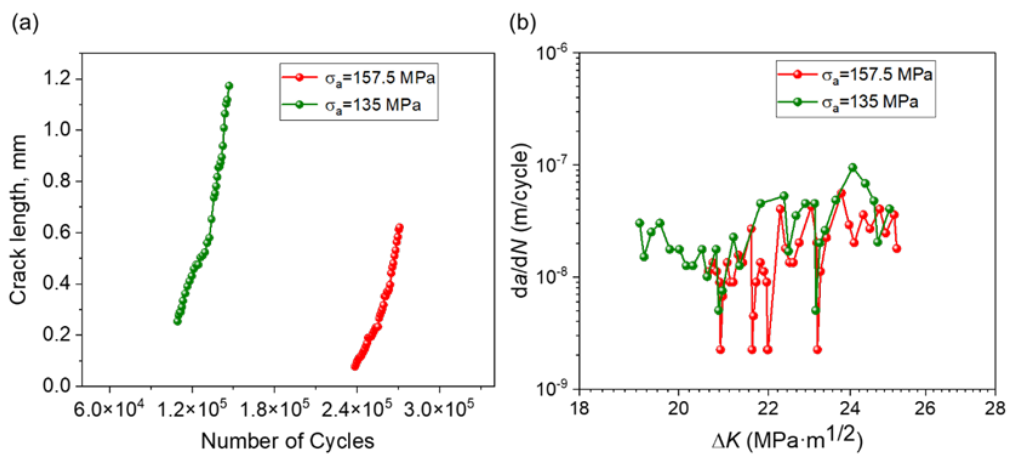


Fig. 1 *(a) Fatigue crack length versus the number of cycles, and (b) fatigue short crack propagation rate da/dN versus stress intensity range ΔK curves for LPBF GH4169 alloy*

D1-218

Fatigue Crack Extension by Damage Accumulation

Shigeru HAMADA[1,*]

[1] Kyushu University, JAPAN

* Corresponding author: hamada@mech.kyushu-u.ac.jp

ABSTRACT:
A mechanism of fatigue crack extension which is different from the generally accepted mechanism of fatigue crack propagation, is proposed. It is generally accepted that fatigue crack extension occurs by alternating slip from the crack tip. In other words, the fatigue crack propagates by plastic deformation. The authors conducted experiments to show that there exists a fatigue crack extension mode that is different from this mechanism. Experiments were performed on stainless steels with a cold-rolled microstructure subjected to pure Mode II cyclic loading. Crack tip evolution was observed successively. Fatigue crack extension along the pre-crack direction was successfully observed through the process of void initiation, growth, subcrack formation, and coalescence with the main crack. The accumulation of dislocations and dipoles causes this fatigue crack extension. Therefore, it is named damage accumulation mode fatigue crack propagation (DA-FCP). Since it is an intermittent extension, it is named propagation instead of growth. This DA-FCP does not require dislocation emission from the crack tip. Therefore, at loading near the threshold, the Frank-Read source and grain boundary become the source of dislocation emission, which is the basis of damage. DA-FCP has been observed in Mode I loaded martensitic steels and high entropy alloys.

KEYWORDS:
Fatigue crack extension mechanism; Damage accumulation; Dislocation accumulation; Threshold condition

D2-201

High cycle fatigue behavior of CoCrFeNi high entropy alloy manufactured with laser powder bed fusion

Bo LI[1,2,3]*, Haijie WANG[1,2], Yinan CHEN[1,2] and Fuzhen XUAN[1,3]

[1] School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, PR China
[2] Additive Manufacturing and Intelligent Equipment Research Institute, East China University of Science and Technology, Shanghai 200237, PR China
[3] Shanghai Collaborative Innovation Center for High-end Equipment Reliability, Shanghai 200237, PR China

* Corresponding author: libo@ecust.edu.cn (Bo Li)

ABSTRACT:
This paper focuses on the microstructure of CoCrFeNi high-entropy alloys in different forming directions based on the L-PBF forming process, and their evolution laws and mechanical behavior under high-cycle tension-tension fatigue. The influence of laser scanning path on microstructure, including grain orientation, grain morphology, and substructure, and the mechanism of microstructure strengthening and toughening of additively manufactured specimens are revealed. Under the same grain size, the microstructure of additively manufactured specimens endows them with better strength than cast specimens. Using material characterization methods such as EBSD and TEM, the microstructure of TD direction specimens in different fatigue loads and different life stages are analyzed to determine the conditions for inducing nano-twinning and improving their fatigue performance through the effect of twin boundaries on dislocation motion. The fatigue performance of TD and BD direction specimens manufactured by L-PBF is analyzed by studying the effect of construction direction on fatigue performance under fatigue loads of σmax=200, 250, 300, 350, and 450 MPa. Under high-cycle fatigue loads of σmax above 250 MPa, the fatigue life of BD direction specimens under the same fatigue load is higher than that of TD direction specimens. The fatigue fracture mechanism of specimens is analyzed by combining fracture morphology and microstructure characterization. This can provide a scientific basis for the strength design and service evaluation of additively manufactured parts of this type of alloy.

KEYWORDS:
Laser powder bed fusion; High-entropy alloy; Fatigue; Nano-twin

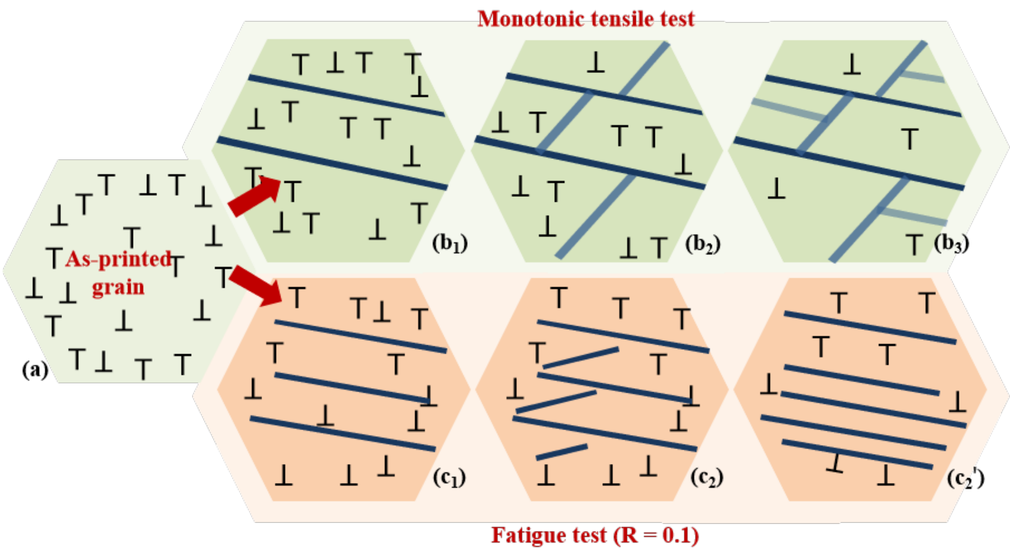


Fig. 1 *Schematics describing the twin formation mechanisms: (a) as-built condition; (b) after monotonic tensile deformation; (c) after cyclic fatigue. Under monotonic loading, primary twins form (b1), followed by the secondary twins (b2), which have a certain angle (usually about 70°) with the primary twins, and tertiary twins (b3), which also have a certain angle (usually about 70°) with the secondary twins. Under fatigue loading, nano-twins nucleate within a grain, followed by the formation of other nano-twins inclined (c2) or parallel to (c2') the primary ones.*

D2-202

Fatigue Properties of WAAM-manufactured components

Moritz HUPKA[1,*], Michael WÄCHTER[1], Alfons ESDERTS[1], Marcel LEICHER[1], Kai TREUTLER[1], Volker WESLING[1]

[1]Clausthal University of Technology, GERMANY

*Corresponding author: moritz.hupka@tu-clausthal.de

ABSTRACT:
In recent years, additive manufacturing has gained relevance in the field of mechanical engineering due to the rising importance of sustainable and resource-saving manufacturing methods. Wire Arc Additive Manufacturing (WAAM) offers several advantages, including:

1. The production of near-net-shape parts
2. The use of typical materials in the field of mechanical engineering, such as steel
3. High manufacturing rates

However, the use of WAAM in safety-critical applications requires either costly experimental fatigue assessments on components or a more efficient analytical assessment. To develop a reliable analytical fatigue assessment, it is necessary to understand the fatigue properties of the material itself, as well as the influence of component-related properties, such as:

- Notches
- Mean stresses
- WAAM-specific properties, such as a rough surface

This contribution will demonstrate how material and component-related fatigue properties can be determined. The former can be characterized on unnotched specimens, as used for conventional metals. For the latter, it is necessary to develop WAAM-manufactured specimens that represent WAAM-specific properties, as mentioned before. The contribution will therefore present innovative methods to manufacture fatigue specimens for WAAM, with a focus on the following aspects:

1. The necessary force during testing
2. The manufacturing of sharp notches
3. The control of the microstructure in the area of failure

KEYWORDS:
Additive Manufacturing; WAAM; Fatigue Properties; Analytical Fatigue Assessment; Manufacturing strategy

D2-203

Inferior fatigue resistance of additively-manufactured Ni-based superalloy 718 and its dominating factor

Sungcheol PARK[1,*], Yuya TANAKA[2], Saburo OKAZAKI[3], Hideto KAWASHIMA[4], Yusuke FUNAKOSHI[4], and Hisao MATSUNAGA[1]

[1] Kyushu University, JAPAN
[2] Fukuoka University, JAPAN
[3] Kobe Materials Testing Laboratory Co., Ltd., JAPAN
[4] Japan Aerospace Exploration Agency, JAPAN

* Corresponding author: park.sungcheol.331@s.kyushu-u.ac.jp

ABSTRACT:
Push-pull and torsional fatigue tests were conducted using additively-manufactured, Ni-based superalloy 718 (AM Alloy 718) samples with various defects and different microstructures, aiming to comprehensively examine fatigue limit determining factors such as detrimental defects and microstructural features. Test results revealed that the fatigue limit in each loading condition was governed by a shear-mode, crack-growth threshold ($\Delta K_{\tau th}$), exhibiting a crack-size ($\sqrt{area}$) dependence similar to that of the wrought (WR) alloy. The additively-manufactured materials displayed a substantially reduced crack threshold as compared to wrought ones, potentially attributed to a high volume of low twist angles between neighboring crack-planes.

KEYWORDS:
Additive manufacturing; Ni-based superalloy; Fatigue limit; Small crack; Fatigue threshold

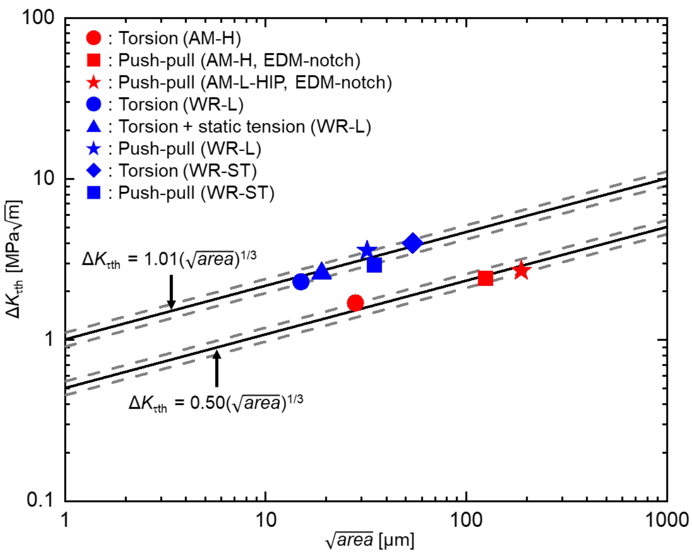


Fig. 1 $\Delta K_{\tau th}$ of AM and WR Alloy 718 as a function of $\sqrt{area}$. The regression line (solid black line) is defined using the least squares fitting for all experimental data.

D2-204

Combined effect of surface integrity parameters on the fatigue strength of Laser Powder Bed Fusion (L-PBF) 316L stainless steel

Marion AUFFRAY[1,2,*], Pierre MEROT[1,2], Franck MOREL[1], Etienne PESSARD[1], Linamaria GALLEGOS MAYORGA[1], Paul BUTTIN[2] and Thierry BAFFIE[3]

[1] Ecole Nationale Supérieure d'Arts et Métiers, LAMPA, FRANCE
[2] CEA, CEA Pays de la Loire, FRANCE
[3] Univ. Grenoble Alpes, CEA, LITEN, FRANCE

* Corresponding author: marion.auffray@ensam.eu

ABSTRACT:

In recent years, the L-PBF additive manufacturing process has attracted much academic and industrial interest. The resulting metal parts exhibit a unique microstructure driven by process parameters and can have both a complex shape and a high mechanical resistance. The L-PBF process, however, generates internal and surface defects, a rough surface, and residual stresses that adversely affect fatigue life. This study aims to better understand the combined effect of these parameters on the fatigue behaviour of an L-PBF 316L stainless steel by conducting a comprehensive experimental campaign. For this purpose, uniaxial fatigue tests were carried out on 8 different batches. Various microstructural conditions (as-built, heat-treated) and surface conditions (net-shape, pre-corroded net-shape, polished, pre-corroded polished and EDM-defect polished) were considered, resulting in a very scattered S-N curve (Fig. 1). Once tested, critical defects on each specimen were identified as either process-induced (lack of fusion, spatter, gas pore, hole, surface micro-geometry) or artificial (corrosion pit, electric discharge machined defect). A Kitagawa-Takahashi diagram was then plotted to represent the influence of the nature and size of such defects (between 10 and 700 µm), as well as the influence of residual stresses and microstructure. Residual stresses and defect size seem to be the most influential factors on the fatigue strength of net-shape L-PBF 316L over other surface parameters. The local microstructure seems to play a minor role.

KEYWORDS:

Additively Manufactured 316L Stainless Steel; High Cycle Fatigue; Surface Roughness; Defects; Residual Stresses; Microstructure.

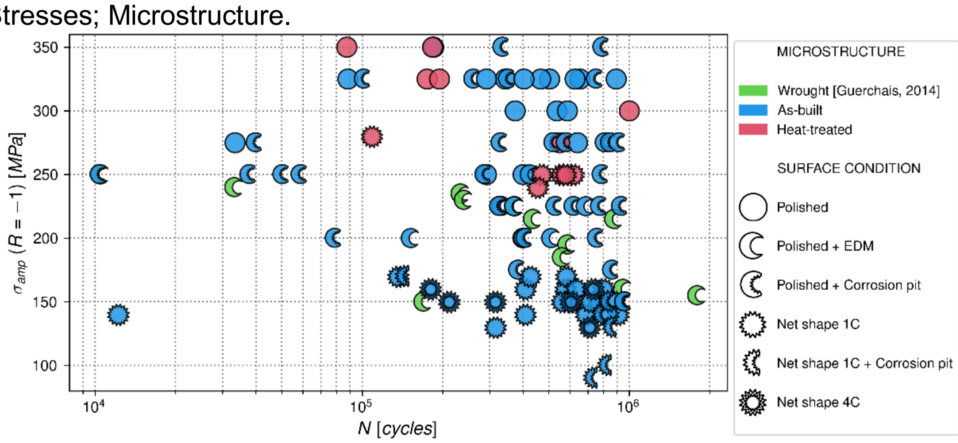


Fig. 1 *S-N curve of net-shape, pre-corroded net-shape, polished, pre-corroded polished and EDM-polished L-PBF 316L fatigue specimens. Wrought 316L [Guerchais, 2014] is added for comparison.*

D2-205

Effect of Post-Processing on Fatigue Performance of SLM Ti6Al4V Alloy

Litton Bhandari[1] and Vidit Gaur[1,*]

[1] Indian Institute of Technology Roorkee, Uttarakhand 247667, India

* Corresponding author: vidit.gaur@me.iitr.ac.in

ABSTRACT:

Additive Manufacturing (AM) facilitates design freedom with near-net complex shape structures. Despite several advantages, AM parts are associated with process-inherent defects that affect fatigue performance and thus need to be investigated. The aim of this research is to investigate the defects-based fatigue performance and the effect of different post-processing methods on the fatigue behavior of selective laser melted (SLM) Ti6Al4V alloy. Specimens for fatigue tests were fabricated using SLM process and were subjected to different post-processing such as heat treatment (HT), hot isostatic pressing (HIP), etc. Microstructural and texture characterizations were carried out and fatigue tests were done using MTS servo-hydraulic fatigue testing machine. Furthermore, Fracture surfaces of broken specimens were examined using FE-SEM to investigate the fatigue damage mechanism. As-built Ti6Al4V alloy consists of α' martensitic phase with needle-like microstructure and coarsening of these α' martensitic laths takes place with HT and HIP treatment. The μ-XCT analysis revealed that the defects fraction was reduced to 0.01% from 0.31% after HIP treatment. The endurance limit improved significantly after HT and HIP treatment, as depicted in Fig. 1. Defects based SN curve was reported and an experimentally calibrated defects-based model was formulated to predict the fatigue performance. The observed results with possible underlying mechanisms shall be discussed and presented during the conference.

KEYWORDS:

Additive Manufacturing, Titanium, Fatigue, Defects, HIP

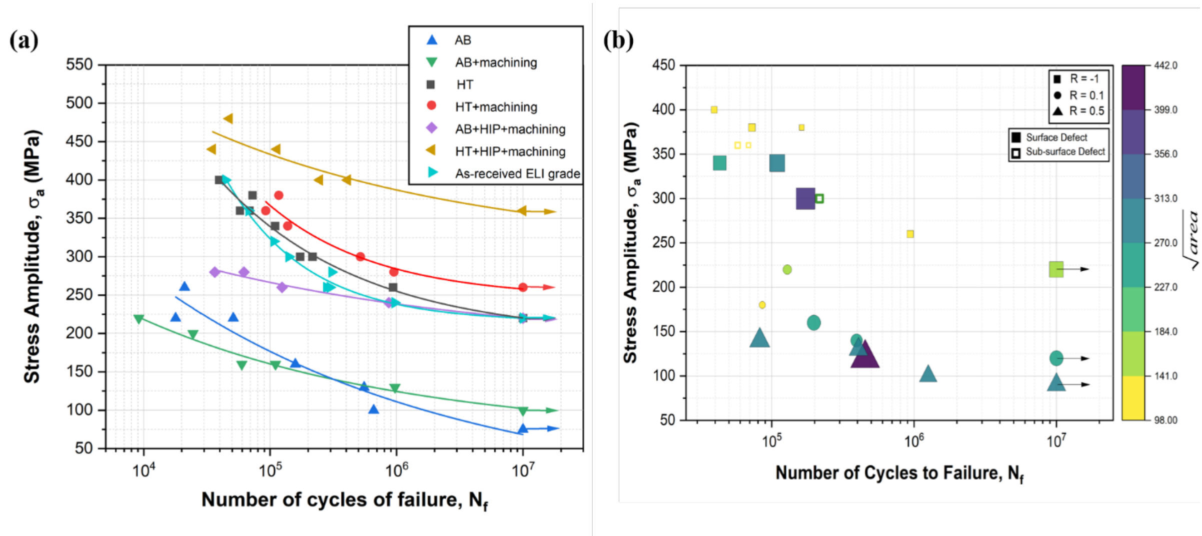


Fig 1. (a) SN curve for as-built and different post-processed conditions (b) Defects-based SN curve for HT SLM Ti6Al4V alloy.

D2-206

Low Cycle Fatigue Behavior of Wire Arc Additive Manufactured and Solution Annealed 308 L Stainless Steel

Yajing Li[1,2], Bo Li[1], Fuzhen Xuan[1,*] and Xu Chen[2,*]

[1] East China University of Science and Technology, CHINA
[2] Tianjin University, CHINA

* Corresponding author: fzxuan@ecust.edu.cn; xchen@tju.edu.cn

ABSTRACT:

Wire arc additive manufacturing (WAAM) has attracted much attention for many industrial fields owing to its high productivity and flexibility. However, little is known about the fatigue behavior of WAAM austenitic stainless steel (SS). In this study, microstructural characterization, quasi-static tensile tests, and strain controlled low cycle fatigue tests were carried out on a 308 L SS fabricated by WAAM and solution annealing. Hot-rolled 308 L SS was also studied as a reference material. The quasi-static tensile properties, cyclic deformation behaviors, fatigue lives and fatigue failure mechanisms are comparably investigated and found to be dependent on their distinct microstructures. Compared with the hot-rolled counterparts, the WAAM specimens showed slightly longer fatigue life at relatively high strain amplitudes, but shorter fatigue life at low strain amplitudes, which is attributed to their worse crack initiation, but better crack propagation resistance.

KEYWORDS:

Additive manufacturing; Wire arc additive manufacturing; Austenitic stainless steel; Low cycle fatigue; Fatigue failure mechanism

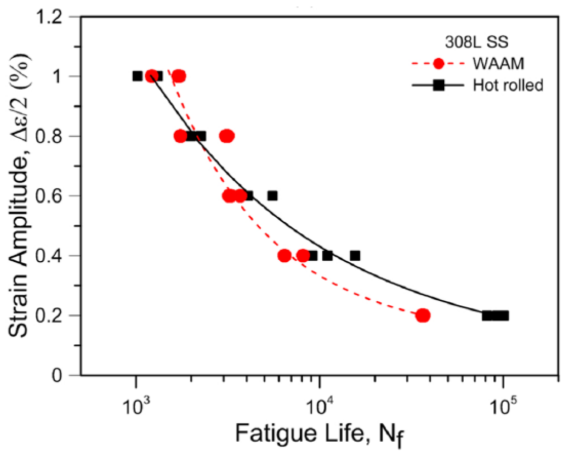


Fig. 1 *Strain amplitude versus fatigue life curves of WAAM and hot-rolled 308 L SS*

D2-207

A study on fatigue properties of wire-arc additively manufactured Inconel 718 alloy

Aditya Pandey[1] and Vidit Gaur[1,*]

[1] Indian Institute of Technology Roorkee, Uttarakhand 247667, India

* Corresponding author: vidit.gaur@me.iitr.ac.in

ABSTRACT:

Wire-arc additive manufacturing (WAAM) process is a direct energy deposition (DED) based additive manufacturing process, having the capability to produce medium to large-sized components. Like other additive manufacturing (AM) techniques, process-induced defects can affect the mechanical and fatigue performance of the component which needs proper addressing and attention. In this work, we investigated the effect of inter-layer delay time (i.e. dwell time 10s and 90s) of the WAAM process on the mechanical and fatigue performance of IN718 alloy built. The microstructural characteristics, porosity-quantification, mechanical testing along with fatigue testing were carried out. Fracture surfaces of tested specimens were investigated to understand the fatigue damage mechanisms. Additionally, a numerical modeling framework was established to investigate the effect of thermal history and residual stresses on fatigue performance. The laves phase, coarser dendritic structure, and high porosities were formed at 10s dwell time while the finer structure and less porosity were found at the 90s dwell time. The numerical analysis revealed that the lower dwell time generates larger residual stresses as compared to the higher dwell time, due to high heat accumulation. The fatigue lives improved with increasing dwell time, as shown in Fig. 1. The results along with the possible explanation shall be presented and discussed during the conference.

KEYWORDS:

Additive Manufacturing, Inconel, Fatigue, Porosity, Residual Stress

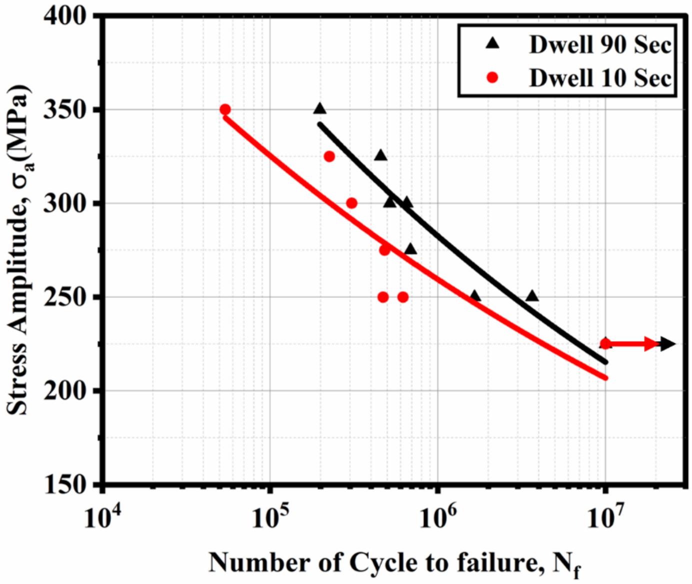


Fig 1. SN curve for as-built machined WAAM IN718 at different dwell times.

D2-208

A study on different heat-treatment cycles for additively manufactured Ni-based alloy and its fatigue properties

Sumit CHOUDHARY[1], Vidit GAUR[1,*]

[1] Indian Institute of Technology Roorkee, Uttarakhand 247667, India

* Corresponding author: vidit.gaur@me.iitr.ac.in

ABSTRACT:
The fatigue performance of the powder bed fusion based additively manufactured Inconel 718 was investigated at different heat-treatment conditions, including the standard heat-treatment. Based on the observed trend in their mechanical properties such as tensile strength and micro-hardness, the three best conditions were selected to study the fatigue performance of new heat-treated samples. The results have proven that the detrimental laves phase and micro-segregated alloying elements were not dissolved at standard heat treatment, which dissolved effectively after new heat treatments. However, grain growth occurred, and undissolved metal carbides and oxides were still existing on grain boundaries and inside the grains. A sufficient amount of γ″ and γ′ strengthening precipitates also evolved at single aging of 13 hours at 730 ºC. Consequently, the tensile and microhardness were improved by ~10-17%, as compared to the standard heat treatment (SHT). The fatigue properties at heat treatment conditions of 1130 ºC/2hour/Air-cooled+730 ºC/13hour/Furnace-cooled, were deteriorated by ~12% with respect to the SHT. However, the fatigue properties were improved by 25% at other heat-treatment conditions (1130 ºC/2hour/Water-Quenched+730 ºC/13hour/Air-Cooling or Furnace-Cooled). The solution treatment stage affects the microstructure-linked properties significantly as compared to the aging stage. The arguments based on evolved precipitates and microstructural features shall be presented and discussed to support the observed experimental results.

KEYWORDS: Fatigue, Additive manufacturing, Nickel, Heat treatment, Precipitates.

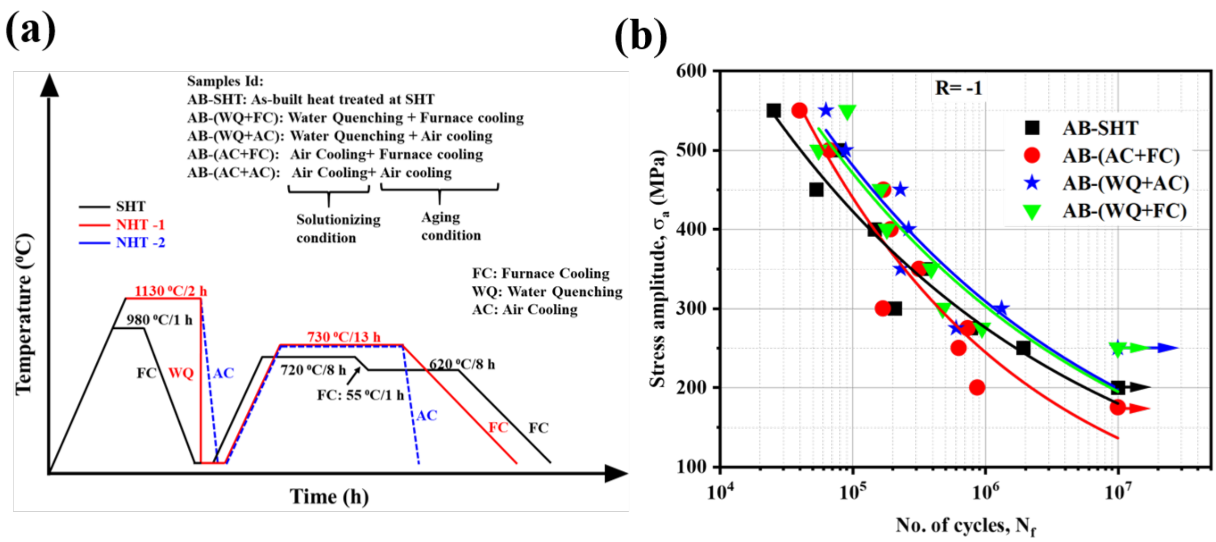


Fig. 1 *(a) Different heat-treatment cycles and (b) the corresponding S-N curve or fatigue lives*

D2-209

The effect of surface modification on crack propagation properties and fatigue life on Ti-6Al-4V alloy formed by electron beam lamination

Yuya ARAKI[1], Noriyuki HISAMORI[2], Masahiro TSUKAHARA[3], Yoshitaka MISAKA[3], Yuji KOBAYASHI[4], Toshiya TSUJI[4], Yuta SAITO[4], Munehisa UCHIYAMA[5], Makoto YAMAGUCHI[5]

[1,] Graduate School of Science and Technology, Sophia University, JAPAN
[2,] Faculty of Science and Technology, Sophia University, JAPAN
[3,] Research and Development Headquarters, NETUREN Co., LTD, JAPAN
[4,] Development Group, SINTOKOGIO, LTD, JAPAN
[5,] PULSTEC INDUSTRIAL CO., LTD, JAPAN

* Corresponding author: y-araki-0f4@eagle.sophia.ac.jp

ABSTRACT:

It has been reported that the fatigue properties of Ti-6Al-4V alloys produced by the Electron Beam Melting (EBM) technique is deteriorated by vacancies generated during fabrication, which act as microstructural defects. Such phenomena can be improved by the induction heating and quenching (IHQ) and shot peening (SP). We found that martensitic transformation by IHQ and plastic deformation and residual stress by SP causes improvement through microstructural refinement and increase of strength.

In this study, the effect of surface modification on crack propagation properties and fatigue life on EBM material was evaluated. Crack propagation tests and torsional fatigue tests were performed. Figure 1 shows fatigue crack growth properties of forged, EBM and EBM-IHQ treated Ti-6Al-4V materials. The threshold value of stress intensity factor range of both EBM materials was lower than forged material due to lower toughness caused by increased strength. Although, the m value of the Paris law was forged > EBM > EBM-IHQ materials due to the effect of microstructure refinement. The fatigue properties were EBM-IHQ > EBM ≒ forged materials due to the increase in strength. It is clear that the application of IHQ and SP treatment to EBM material is effective in improving fatigue properties.

KEYWORDS:

Ti-6Al-4V, Additive Manufacturing, Surface modification, Fatigue life, Crack propagation properties.

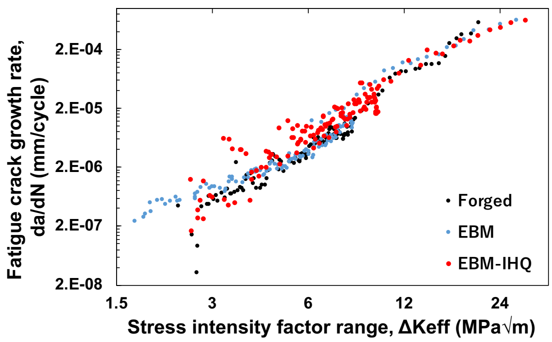


Fig.1 Fatigue crack growth properties of forged, EBM and EBM-IHQ treated Ti-6Al-4V materials

D2-210

Applicability of non-ideal powders in powder bed fusion processes – Fatigue life of additively manufactured structures

Julia RICHTER[1, *], Robert KRATZSCH[2], Malte VOLLMER[1]; Christof TORRENT[1], Marcel KROCHMAL[1], Thomas WEGENER[1], Urs PEUKER[2] and Thomas NIENDORF[1]

[1] University of Kassel, Institute of Materials Engineering, Metallic Materials, GERMANY
[2] Freiberg University of Mining and Technology, Institute of Mechanical Process Engineering and Mineral Processing, GERMANY
* Corresponding author: julia.richter@uni-kassel.de

ABSTRACT:
Process-inherent high cooling rates and intrinsic heat treatments of additive manufacturing techniques lead to unique microstructures with concomitantly tempting mechanical properties. However, these process-inherent properties also possess drawbacks such as the formation of pores being crucial for the applications of components under fatigue loading. In the present studies, non-optimal feedstock materials, such as recycled or spattered powders, were employed in additive manufacturing processes, i.e., laser-based and electron-based powder bed fusion of metals. After production, the microstructure and defect distribution were analyzed via electron-backscattered diffraction and micro-computed tomography. The mechanical properties were tested under quasi-static loading and fatigued from low cycle to high cycle fatigue regime and compared to material manufactured under optimal process conditions.
For the laser-based powder bed fusion process, commercially pure iron revealed only slight differences with respect to defect distribution. In contrast, specimens built from non-ideal aluminum powder showed a reduced relative density. However, distinctions in the mechanical properties were mainly explained by chemical impurities.
In the electron-based additive manufacturing process, recycled Ti6Al4V powder grades were utilized leading to a higher defect population in the non-ideal process. Under mechanical loading, differences between the ideal and non-ideal manufactured specimens were found with respect to varying recycling content.

KEYWORDS:
Additive manufacturing; Defects; Coffin-Manson-Basquin; Low cycle fatigue; High cycle fatigue

D2-211

Influence of Heat-treatment on Fatigue Properties of Super Duplex 2507 Stainless Steel produced by Directed Energy Deposition Process

Sébastien BALLÉSIO[1,2,*], Fabien SZMYTKA[1], Cédric DOUDARD[2] and Matthieu DHONDT[2]

[1] ENSTA Paris, IMSIA UMR 9219, Institut Polytechnique de Paris, 91120 Palaiseau, FRANCE
[2] ENSTA Bretagne, UMR CNRS 6027, IRDL, 2 rue François Verny F-29200 Brest, FRANCE

* Corresponding author: sebastien.ballesio@ensta-paris.fr

ABSTRACT:

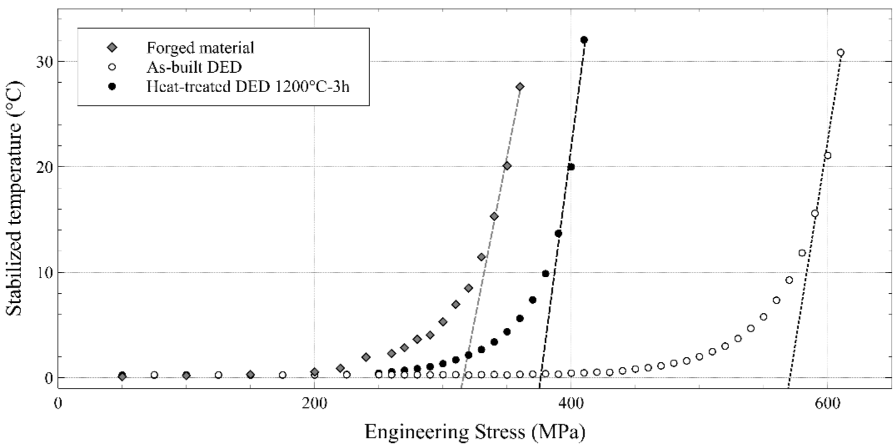
Super duplex 2507 (2507 SDSS) is a two-phase austeno-ferritic stainless steel known for its good mechanical properties, especially for fatigue as well as corrosion resistance, due to its mixed microstructure. Metal additive manufacturing, and in particular the Directed Energy Deposition (DED) process, allows the construction or repair of structures for more complex geometries than conventional processes. DED process uses powder that is projected by an argon flow and melted by a laser in the printing area to form the material. This manufacturing protocol however results in different microstructures (grain sizes and orientation, phases repartition) from those observed in conventional processes and particularly forging.

The objectives of the study are first to carefully analyse the microstructure of DED-manufactured 2507 SDSS and the effect of different heat treatments on it. Effects on the ratio between austenite and ferrite is particularly discussed. Then, the fatigue limit of this new "material-process" combination is investigated both with Staircase protocols and self-heating tests campaigns. A same grade forged steel is used as reference material.

Fatigue limit modelling of DED-manufactured 2507 SDSS is finally performed on the basis of self-heating tests and a dedicated plastic constitutive model.

KEYWORDS:

Super duplex stainless steel; Additive manufacturing; Heat-treatment; Fatigue; Microstructure



D2-212

Influence of manufacturing history and resulting microstructure on the very high cycle fatigue behavior of additively manufactured samples

Leonhard STAMPA[1*], Sebastian SCHETTLER[2], Thomas TÖPPEL[3], Paul SCHULZ[4], Martina ZIMMERMANN[1, 2] and Maik GUDE[4]

[1] Institute for Materials Science, Technische Universität Dresden, GERMANY
[2] Fraunhofer Institute for Material and Beam Technology IWS, GERMANY
[3] Fraunhofer Institute for Machine Tools and Forming Technology IWU, GERMANY
[4] Institute of Lightweight Engineering and Polymer Technology, Technische Universität Dresden, GERMANY

* Corresponding author: leonhard.stampa@mailbox.tu-dresden.de

ABSTRACT:
Additively manufactured (AM) parts lead to a complex microstructure and are usually post-processed using different heat treatment strategies. Thereby fatigue assessment of AM parts primarily focuses on defect morphology and location – irrespective of the notch sensitivity of the surrounding matrix. However, fatigue assessment due to computer tomography is often only based on pores or inclusions. Investigating different batches of Ti6Al4V specimens, manufactured by laser powder bed fusion, will show that classical metallography combined with serial sectioning will give valuable insights into refining the interpretation of fatigue results. The investigations focused on the Very High Cycle Fatigue regime up to 10^8 load cycles. The fatigue strength of the specimens was correlated to the overall manufacturing process, not only taking AM process parameters into account but also the corresponding microstructure resulting from different heat treatments. Crack-initiating defects were analyzed by scanning electron microscopy and evaluated. Fracture occurred almost exclusively due to crack initiation at lack of fusion defects. Higher defect sizes and a vertical building direction were found to correlate with lower fatigue strength. Nonetheless, an influence of the individual microstructures was observable. Fatigue results are evaluated according to state of the art prediction models and the applicability of the models discussed.

KEYWORDS: Fatigue life; Very High Cycle Fatigue (VHCF); Murakami method; Ti6Al4V; Additive Manufacturing

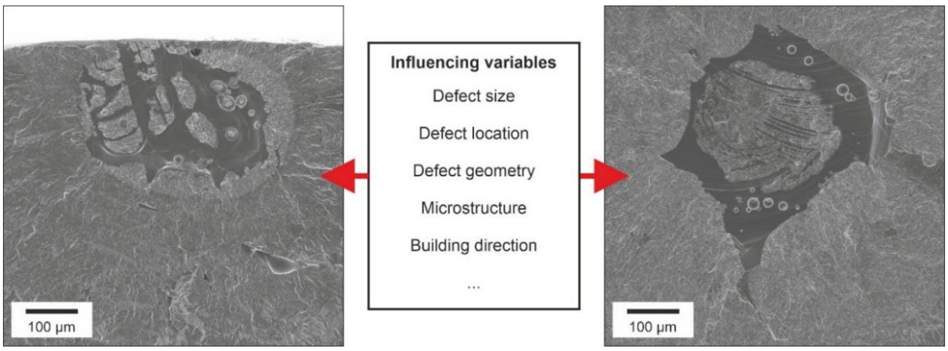


Fig. 1: *Effect of influencing variables on the fatigue behavior for the crack initiation location.*

D2-213

Very High Cycle Fatigue of Laser Additively Manufactured Titanium and Nickel Alloys

Qingyuan WANG[1,2,*], Kun YANG[1,2,*], Fulin LIU[2], Chao HE[2], Yao CHEN[2], Yongjie LIU[2]

[1] Institute for Advanced Study, Chengdu University, Chengdu 610106, CHINA
[2] Failure Mechanics and Engineering Disaster Prevention and Mitigation Key Laboratory of Sichuan Province, Sichuan University, Chengdu 610065, CHINA

* Corresponding author: wangqy@cdu.edu.cn & scu_yangkun@163.com

ABSTRACT:

The studies on very high cycle fatigue (VHCF) of laser additively manufactured metals can promote the widespread application of additively manufactured metals in key equipment, which need to possess a very long service life. By the advantage of loading frequency from ultrasonic fatigue testing, the present work investigates the VHCF behavior of some typical alloys fabricated by the laser powder bed fusion (LPBF), such as the IN718 superalloy and the Ti6Al4V alloy. The alloys show obviously lower fatigue strength than wrought alloys, especially in VHCF regime. A separate *S*-*N* curve may appear due to the competition failure behavior between surface and interior crack initiation. The fatigue crack can initiate from manufacturing defects (gas pore and lack of fusion) and columnar grains (matrix). The critical size of defects for fatigue failure is analyzed by the K-T diagram. A new parameter model is established based on defect characteristics for evaluating the fatigue life. The fine granular area (FGA) region is composed of many discontinuous nanograins, which result from grain refinement. Grain refinement is associated with dislocation movement within martensite laths. Dislocation pile-up and rearrangement in martensitic laths form dislocation cells, which further develop into nanograins and low-angle grain boundaries.

KEYWORDS:
Very High Cycle Fatigue; Additive Manufacturing; Fatigue Performance; Fracture Mechanics; Fatigue Failure Mechanism

D2-214

Cyclic plastic material behavior of novel high manganese austenitic stainless steel Printdur® HSA additively manufactured by PBF-LB/M

Jakob BLANKENHAGEN[1,*], Johannes DILLER[1], Dorina SIEBERT[1], Christina RADLBECK[1] and Martin MENSINGER[1]

[1] Chair of Metal Structures, Technical University of Munich, Germany

* Corresponding author: Jakob.Blankenhagen@tum.de

ABSTRACT:

The newly introduced high manganese high strength stainless steel Printdur® HSA was developed exclusively for the additive manufacturing process PBF-LB/M. It consists of a fully austenitic grain structure.

The scope of this study is to evaluate the cyclic plastic material behavior of Printdur® HSA. Due to its fully austenitic grain structure either twinning-induced plasticity or transformation-induced plasticity can be expected. Therefore, tensile tests were carried out, using a DIC-system for strain field measurement. Subsequently, strain-controlled fatigue tests were conducted. Strain amplitudes of 0.5% to 2.0% were applied. Furthermore, the microstructure was examined. In particular surface etching, fracture surface analysis, x-ray-diffraction, and electron-backscatter-diffraction were applied. In Fig. 1 the maximum and minimum engineering stresses versus the number of cycles for different strain amplitudes are plotted. For all strain amplitudes, a general softening behavior is visible. The strain amplitude of 0.5% results in primary hardening within the first 30 cycles. Therefore, a dependency of the cyclic material behavior on the applied strain amplitude can be assumed. This behavior correlates with the investigated characteristics of the microstructure. Further experimental results are presented in the full treatise to completely characterize and discuss the cyclic material behavior of Printdur® HSA.

KEYWORDS:

Low cycle fatigue; cyclic plastic material behavior; new material; additive manufacturing; powder-bed fusion of metals using a laser (PBF-LB/M)

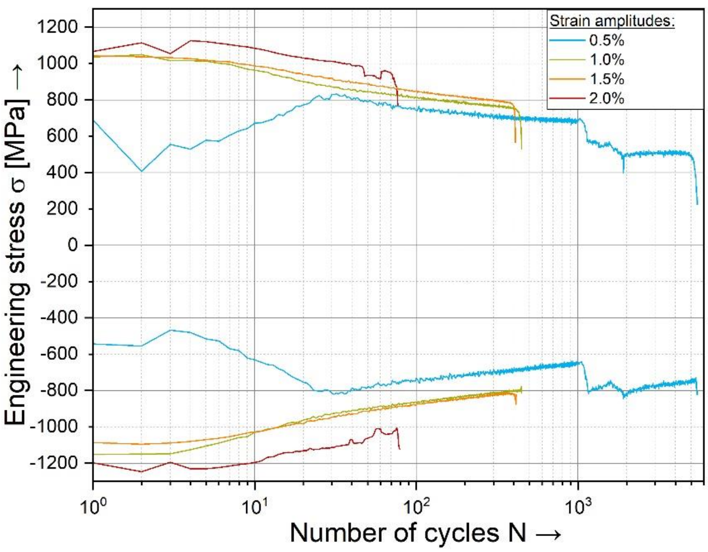


Fig. 1: *Maximum and minimum engineering stress vs. number of cycles for strain amplitudes 0.5%, 1.0%, 1.5%, and 2.0%*

D2-215

Effect of Heat Treatment on Fatigue Life of Ti-6Al-4V Alloy with Additively Manufactured Layer and Conventional Wrought Layer

Atsuhiro KOYAMA[1,*], Yohei SONOBE[1], Akihide SAIMOTO[1] and Yoshihiko UEMATSU[2]

[1] Nagasaki University, JAPAN
[2] Gifu University, JAPAN

* Corresponding author: a-koyama@nagasaki-u.ac.jp

ABSTRACT:
To investigate the fatigue life of the two-layered Ti-6Al-4V alloys with additively manufactured layer and conventional wrought layer, the fatigue tests were conducted under constant amplitude loading. The effect of heat treatment on fatigue life was also examined. Three types of specimens were used as test materials: specimens without heat treatment (As-built material), specimens with solution aging treatment (950°C for 2 hours followed by air cooling and 540°C for 4 hours followed by air cooling) after additive manufacturing on conventional wrought titanium plate (STA material), and specimens with heat treatment (1100°C for 1 hour followed by air cooling) after additive manufacturing on conventional wrought titanium plate (1100AC material). The test results show that the fatigue life in the finite life region is the longest for the As-built material, but there is no difference in the fatigue limit. It was also found that the additively manufactured layer contained numerous micro vacancies, which served as fracture initiation site.

KEYWORDS:
Fatigue Life; Ti-6Al-4V; Additive Manufacturing; Selective Laser Melting;

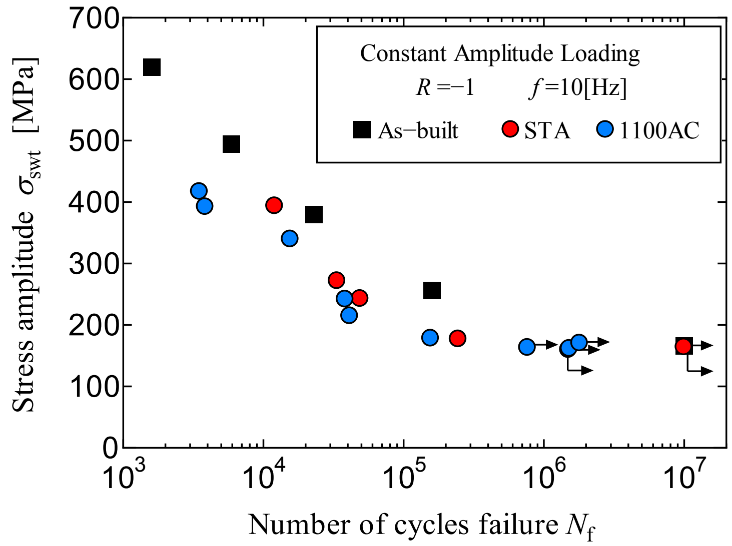


Fig. 1 *S-N curve.*

D2-216

Process Parameters and Fatigue Crack Initiation in Cold Spray

Bahareh Marzbanrad, and Hamid Jahed[1]

[1] University of Waterloo, CANADA

* Corresponding author: hamid.jahed@uwaterloo.ca

ABSTRACT:

Cold spray is a solid-state additive manufacturing technique that utilizes a carrier gas to propel powder particles to supersonic velocities upon impact with a substrate or previously deposited particles, enabling layer-by-layer construction of 3D components. This versatile technology finds applications in coating, repair, and standalone 3D printing. Key processing parameters include impact velocity, which can be adjusted by selecting the carrier gas, its temperature, and pressure, as well as the amount of heat transferred during the process. In this presentation, we explore the influence of process parameters on the residual stresses in both the AZ31B magnesium alloy substrate and AA7075 coating [1-3]. Specifically, we investigate how controlled variations in these parameters can modify crack initiation under cyclic loading conditions (with a positive R-ratio), shifting the typical delamination location from the substrate/coating interface to the surface of the protective AA7075 coating (Figure 1). We will discuss the experimental design, coat/substrate morphology, stress state, cyclic loading setup (following ASTM D790 guidelines), crack monitoring, and provide SEM and CT-scan micrographs to elucidate the cracking mechanism.

KEYWORDS:

Cold Spray, Additive Manufacturing, Process Parameters, Residual Stress, Crack Initiation

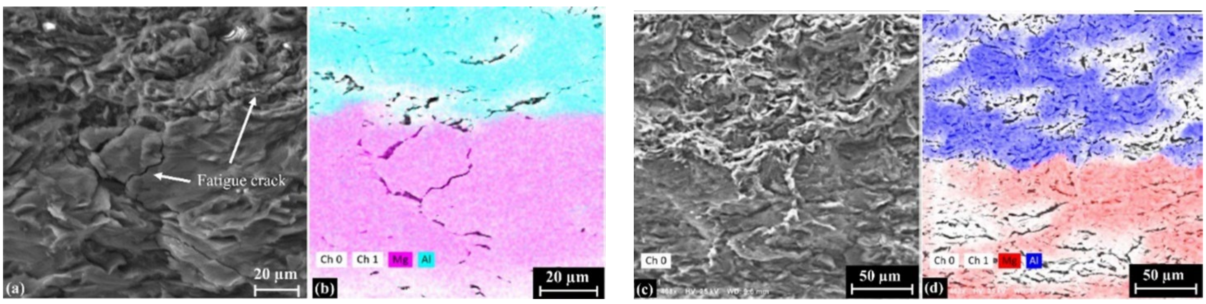


Fig. 1 *Distinct Crack Initiation Mechanisms in AA7075 Coated AZ31B: a) fracture of the sample with crack initiation at the interface, b) EDS elemental mapping, c) defect-free interface for the second sample, d) EDS elemental mapping.*

References:

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D2-217

An assessment of the high-temperature fatigue properties of additively manufactured nickel-based alloys

Ivo Šulák[1], Ladislav Poczklán[1], Tomáš Vražina[1], Bhupesh Verma[2], Benedikt Nowak[3], Ulrich Krupp[4], Tomáš Kruml[1,*]

[1] Institute of Physics of Materials, Czech Academy of Sciences, 61600 Brno, CZECH REPUBLIC
[2] RWTH Aachen University, Digital Additive Production, 52074 Aachen, GERMANY
[3] VDM Metals International GmbH, 58762 Altena, GERMANY
[4] RWTH Aachen University, Steel Institute, D-52072, Aachen, GERMANY

* Corresponding author: kruml@ipm.cz

ABSTRACT:

For the last few years, additive technologies have been at the forefront of research and development, bringing a range of advantages in components' design as well as opportunities to create unique microstructures with app-tailored properties. Associated with these rapid technological advances is the intensive research into mechanical properties with a direct link to the unique hierarchical structure. Given the limited choice of commercially available alloys for additive manufacturing, it is also essential to evaluate new alloy compositions to optimize their production and improve overall performance. In this study, two different nickel-based alloys developed by VDM Metals were fabricated using the laser powder bed fusion (L-PBF) technique with a relative density higher than 99.5%. Printed parts of VDM Alloy 699XA was delivered in solution-annealed conditions, whereas VDM602CA was examined in as-build conditions. Stress-controlled high-temperature fatigue experiments were performed on miniaturized cylindrical specimens up to 1223K. Direct comparison with conventionally prepared materials (bulk) showed the strengths and weaknesses of the L-PBF materials (Fig. 1). The results of the fatigue tests are discussed with respect to the manufacturing specifics and microstructural features revealed by SEM and TEM analyses.

KEYWORDS:

Additive manufacturing; High temperature fatigue; Wöhler curves; Dislocation arrangement; Electron microscopy.

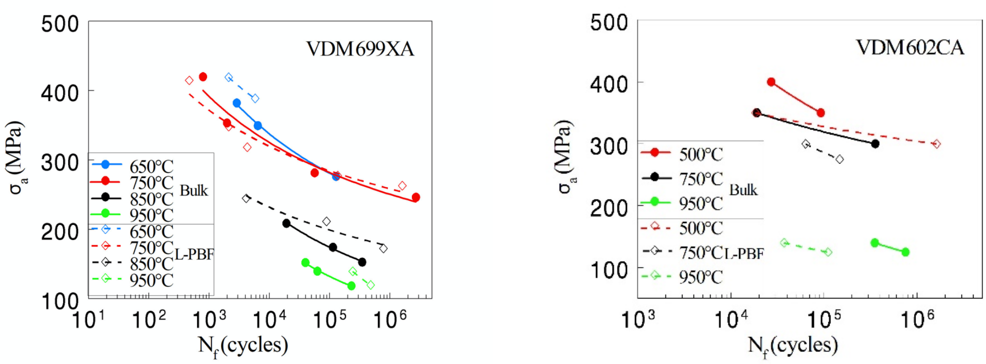


Fig. 1 *S-N curve of VDM 699XA and VDM 602CA at different temperatures.*

D2-218

Microstructure modification to increase resistance to fatigue crack propagation in titanium alloys made by wire based directed energy deposition process

Xiang ZHANG[1]*, Farhana ZAKIR[1], Abdul Khadar SYED[1], Stewart WILLIAMS[2]

[1] Centre for Manufacturing and Materials, Coventry University, Coventry, UNITED KINGDOM
[2] Welding and Additive Manufacturing Centre, Cranfield University, Cranfield, UNITED KINGDOM

* Corresponding author: xiang.zhang@coventry.ac.uk

ABSTRACT:
Titanium alloys are the workhorse of the aerospace industry. Mechanical properties of additive manufactured (AM) titanium alloys are comparable with their conventional counter parts. The next step is to make the best use of AM freedom in design by microstructure modification to reduce crack growth rate and increase the threshold for crack growth onset; hence synergistically enhance the damage tolerance capability. Ti64 and Ti6242 were studied; desired microstructure was produced with in-process cold working and post-deposition heat treatment. Samples were studied in two orientations, i.e., loading axis in parallel with and perpendicular to the build layers. Significant refinement of the primary β grains was achieved after cold working which also led to isotopic tensile properties with 10-14% increase in yield and tensile strengths compared to the as built condition. Cold-working followed by controlled heat treatment led to increased α lath size along with large colony microstructure that resulted in 2.5 times increase in the threshold stress intensity factor range and a magnitude decrease in fatigue crack growth rate compared to the as-built and clod worked samples. The much lower crack growth rate in heat treated samples is owing to the consequence of crack path deviation and crack branching.

KEYWORDS:
Additive Manufacturing; Wire and Arc Additive Manufacturing; Fatigue crack growth rate; Crack deflection; Titanium alloys

D2-219

Combined Effect of Shot and Laser Peening on Fatigue Strength of Additively Manufactured Aluminum Alloy

Koji Takahashi[1,*], Misato Nakamura[1] and Yuta Saito[2]

[1] Yokohama National University, JAPAN
[2] Shintokogio, LTD., JAPAN

* Corresponding author: takahashi-koji-ph@ynu.ac.jp

ABSTRACT:

The combined effects of shot peening and laser peening on the fatigue strength of additively manufactured (AM) aluminum alloy (AlSi12) specimens with rough surfaces were examined. Surface roughness, distributions of the residual stress, and hardness from the surface to the depth direction were obtained. Plane bending fatigue tests were conducted, and the fracture surface was observed. Figure 1 shows the S-N diagram. The fatigue strengths of the as-built specimens subjected to shot peening (as-built+SP), laser peening (as-built+LP), and LP followed by SP (as-built+LP+SP) at 10^7 cycles were 59%, 76%, and 100% higher than that of the as-built specimen, respectively. Surface roughness increased after application of LP, but was reduced by subsequent application of SP. In the LP+SP specimen, both high surface compressive residual stresses and deep compressive residual stresses could be achieved. Thus, the fatigue strength of the as-built+LP+SP specimen is the highest. Thus, the combination of LP and SP is useful in the AM aluminum alloy.

KEYWORDS:

Additive manufacturing, Aluminum alloy, Fatigue strength, Shot peening, Laser peening, Surface roughness, Residual stress.

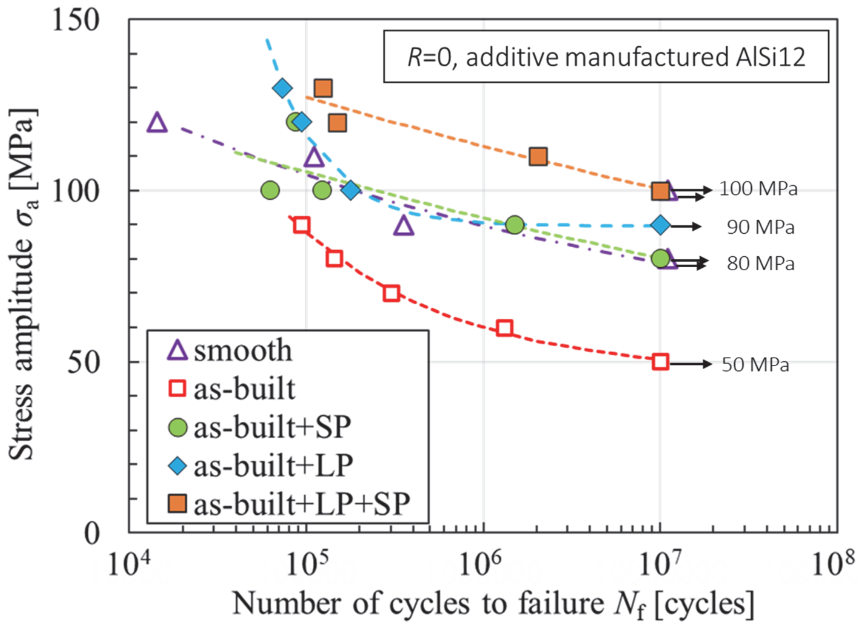


Fig. 1 S-N curve for additive manufactured AlSi12.

D2-220

Anisotropic Fatigue Properties of Laser Additive Manufactured (LAMed) Ni-based Superalloys

Zhenan ZHAO[1,2], Weizhu YANG[2,*], Zeng YAN[2] and Shouyi SUN[2]

[1] Zhejiang University, CHINA
[2] Northwestern Polytechnical University, CHINA

* Corresponding author: wzhyang@nwpu.edu.cn

ABSTRACT:

Laser additive manufacturing is a promising technique to fabricate hot-section components of gas turbines and blades, which is made of Ni-based superalloys. One of the major concerns of these components is the fatigue properties. In this study, the anisotropic fatigue properties depending on the loading directions of LAMed Ni-based superalloy was investigated. The influential factors is characterized by the microstructure and grain morphologies. Results show that the fatigue crack of both LAMed vertical and horizontal specimens are both initiated from the defects on or near the surface. Afterwards, the fatigue crack propagates trans-granularly until the effective bearing area is too small that instant ductile fracture occurs. However, the vertical specimens with loading direction parallel to the building direction has better fatigue performance. This anisotropic fatigue behavior is ascribed to different strength and crack propagation behavior during the long crack propagation period of specimens.

KEYWORDS:

Ni-based superalloy; Anisotropic Properties; Failure Mechanism; Laser Additive Manufacturing

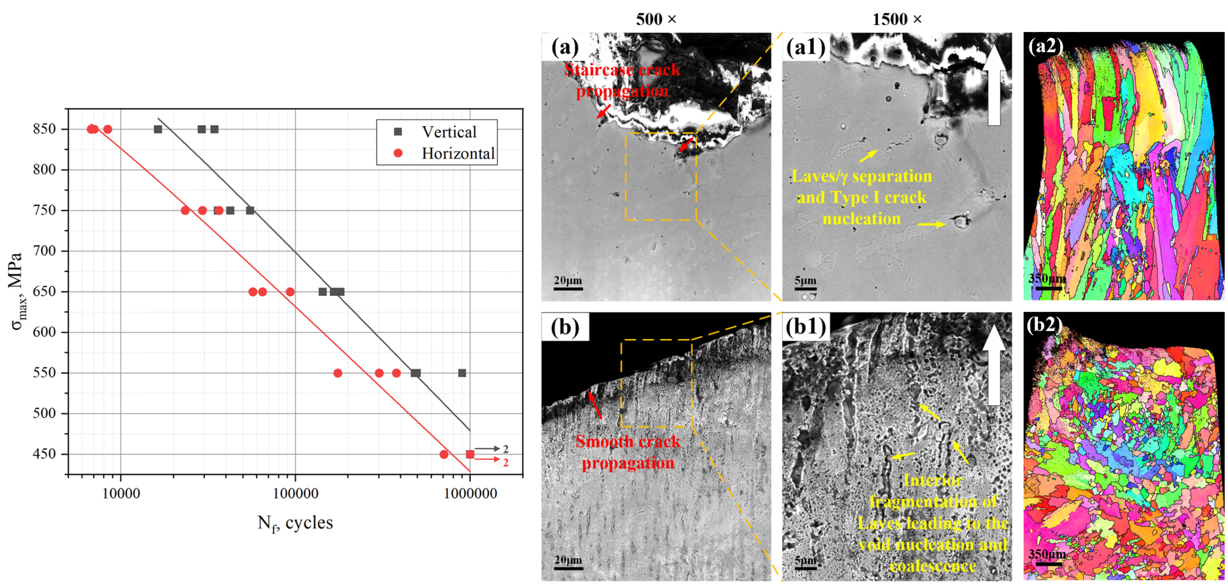


Fig. 1 *S-N curve and microstructure of lateral fractured surface with different loading directions*

C1-201

A Data Science Approach to Understanding Fatigue

Zhiping XU[1]

[1] Tsinghua University, CHINA

* Corresponding author: xuzp@tsinghua.edu.cn

ABSTRACT:

First-principles understanding of fatigue is limited for engineered materials. To address this issue, we developed a data science-based framework to address the complexity of fatigue in the physics of damage development and microstructural features such as defects and residual stresses. We first collected fatigue performance of conventional, additive manufactured, and complex (multi-principal element alloys, metallic glasses) from the literature (thousands of journal articles and technical reports) using state-of-the-art natural language processing and computer vision techniques. The qualities of reported data are assessed by specific rating scores, suggesting a need of standards for data reporting. The evolution of fatigue performance and data dispersion is used to measure the technology readiness level that aligns well with the breakthroughs in material fabrication and processing. Theoretical understandings of fatigue are then analyzed by exploring microstructure-sensitive (e.g., crystal plasticity) models. The consistence between different models reported in the literature are evaluated by correlation analysis. The alignment between theoretical predictions and experimental results across the whole datasets is then used to assess the predictive power of the models. The result is much less positive compared to the conclusions from individual studies, which signifies our limited knowledge. These results offer an alternative perspective to understanding fatigue.

KEYWORDS:

Fatigue; Complexity; Data science; Fatigue data, Microstructure-sensitive models

C1-202

Identification of Plastic-Creep Fatigue Damage Rule for Aluminum Alloys Using Particle Swarm Optimization Method

Towa HAYASHIBE[1], Ken-ichi OHGUCHI[1], Kohei FUKUCHI[1], Katsuhiko SASAKI[2], Yorimasa TSUBOTA[3], Takuro MITA[4], Wataru NAGAI[3], Kouji OHSATO[3] and Nobuaki SHINYA[3]

[1] Akita University, JAPAN
[2] Hokkaido University, JAPAN
[3] ISUZU Motors Limited, JAPAN
[4] ISUZU Advanced Engineering Center, Limited, JAPAN

* Corresponding author: m8022222@s.akita-u.ac.jp

ABSTRACT:

Automobile engine components made of aluminum alloys are often subjected to cyclic loading at high-temperature ranges that exceed 1/2 of the melting temperature (T_m) of aluminum alloys. The fatigue life of an aluminum alloy due to such loading must be evaluated by a fatigue damage rule that considers both plastic and creep damages. In this study, we first quantified the plastic and creep strains of an Al-Si-Cu-Mg-Ni alloy generated in low cycle fatigue (LCF) tests conducted at several temperatures using the plastic-creep separation method. Based on the quantification results, we derived a plastic-creep fatigue damage rule for the aluminum alloy. The parameters in the rule were identified using the particle swarm optimization (PSO) method. The derived fatigue damage rule was applied to evaluate the fatigue life in the thermo-mechanical fatigue (TMF) test using the aluminum alloy. The results showed that the derived fatigue damage rule with the parameters estimated by the PSO method can properly evaluate the fatigue lives due to the loading with a strain rate change and temperature change in the TMF test.

KEYWORDS:

Aluminum alloy; Low-cycle fatigue; Fatigue life prediction; Plastic-creep separation method; Particle swarm optimization

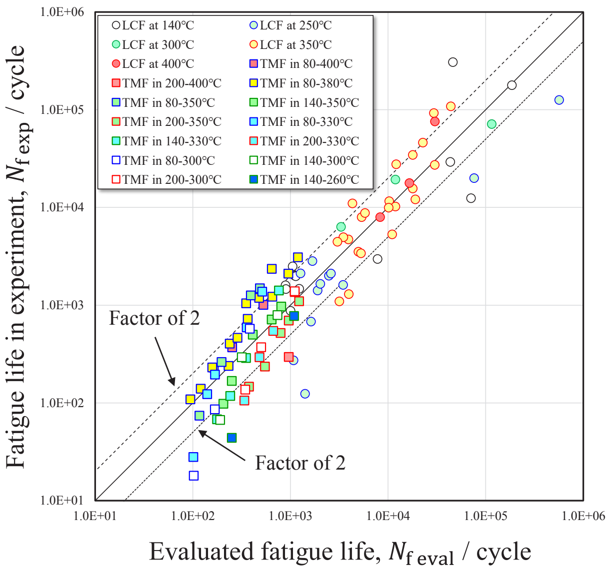


Fig. 1 *Relationship between $N_{f\,exp}$ and $N_{f\,eval}$ for LCF and TMF tests.*

C1-203

Dimensioning a Reference Volume Element for Detecting Fatigue Cracks in Equiaxed Titanium Alloy

Azdine Nait-Ali* [1], Samuel Hèmeri[1,*]

[1] ISAE-ENSMA, France

* Corresponding author: azdine.nait-ali@ensma.fr

ABSTRACT:

We aim to size a RVE (Reference Element Volume) to highlight fatigue cracks in an equiaxed titanium alloy. Two different approaches are explored here. The first involves visualizing fatigue cracks in a SEM (Scanning Electron Microscope). We size the RVE using a covariogram that allows us to determine the size with a fixed reliability. The second approach involves detecting Twist joints in a real 3D aggregate of an alloy containing fatigue cracks and examining whether the presence of these joints has an influence on the size of our RVE

KEYWORDS:

RVE; TA6V; Fatigue cracks

C1-204

Slow Adoption of Modern Statistical Methods in Industrial Applications for the Development of Fatigue Curves

Balajee Ananthasayanam[1,*], Masahiro Hayashi[2], Kazuki Nagao[1], and William Q. Meeker[3]

[1] Honda Aero Inc., Burlington, NC, USA
[2] Honda R&D Co., Saitama, JAPAN
[3] Iowa State University, Ames, IA, USA

* Corresponding author: bananthasayanam@na.honda.com

ABSTRACT:
Within the jet engine community, there is a regulatory requirement for the development of probabilistic fatigue curves. The life limits for critical parts are set based on failure probability of 1/1000. Currently, published standards, and recommended practices utilize archaic statistical methods that were developed in the 1960s. Specifically, linear least-squares regression is recommended in military handbooks, ISO, and ASTM documents. Such approaches often require assumptions such as (a) standard deviation across stress levels is constant and (b) suspended test data (runouts) are either ignored or assumed to be failures. Such assumptions are not required with maximum likelihood (ML) method and the resulting fatigue life estimates become more representative of the data. There is a widely accepted myth that archaic regression methods make the life predictions more conservative. While this may be true for some cases, there is no guarantee for conservatism. Here, we present a few examples where the fatigue curves are developed from the ML and least-squares methods and their corresponding probabilistic lives at prescribed stress levels are compared. The ML estimation method for fatigue curve creation is a more accurate method for assessment of fatigue data that allows for non-constant variance across stress levels and properly handles runouts.

KEYWORDS:
ML Regression, Least-squares Regression, Quantiles, Lower Tolerance Limit, Fatigue.

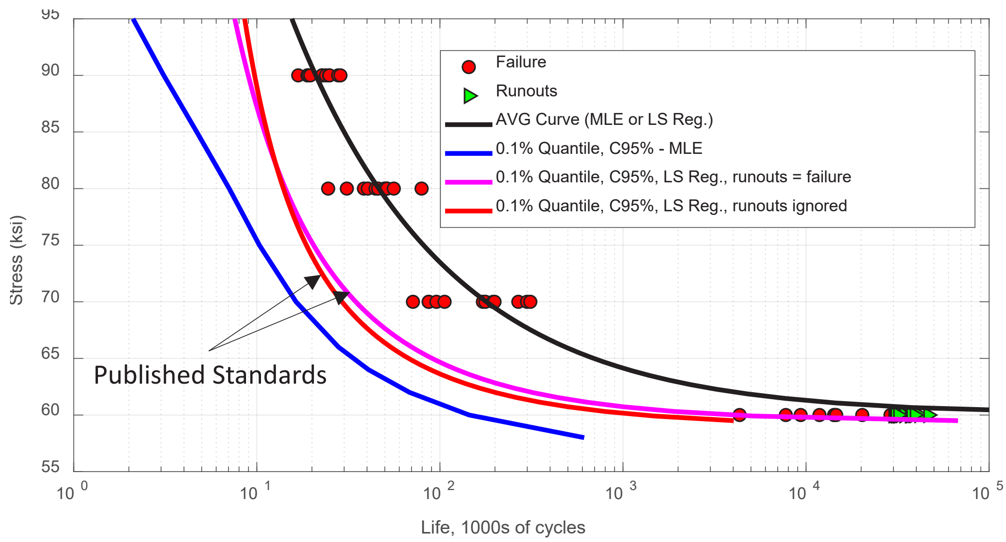


Figure 1. Effect of improperly handling runout data points on Lower Tolerance Limit Estimates from Various MLE and Least-Square Regression Methods.

C1-205

Development of Fatigue Curve with Multiple Competing Failure Modes

Balajee Ananthasayanam[1,*], Masahiro Hayashi[2], Gerald T. Cashman[3]

[1] Honda Aero Inc., Burlington, NC, USA
[2] Honda R&D Co., Saitama, JAPAN
[3] Cashman Consulting, USA

* Corresponding author: bananthasayanam@na.honda.com

ABSTRACT:
Competing modes fatigue failure has been observed for powder metallurgy (PM) alloys that is widely used in jet engines. Specifically, PM alloys are used to make rotating disks in jet engines. Disks are categorized as life-limited part because the energy of the rotating disks is high and failure of such disk during flight can cause catastrophic damage to the engine. Hence there is a lot of engineering interest in understanding the failure modes in disks including the competing failure modes so that such failure can be prevented in the field by rigorous engineering design. Competing modes fatigue failure is defined as the presence of two or more failure modes that can drive failure of a part. In powder metallurgy components, the failure can be triggered by a crack initiation site located either on the surface or within the volume of the component. The surface flaw usually dominates the failures at higher stress ranges and the internal flaws dominates failures at low stress ranges. In this paper, a maximum likelihood-based approach with system reliability concepts is described for development of fatigue curves that involves two failure modes. The article also describes how to obtain probabilistic fatigue curves for competing failures modes.

KEYWORDS:
Maximum Likelihood, MLE, Competing Modes, Surface Initiation, Internal Initiation, System Reliability, Fatigue, Probabilistic, Quantile.

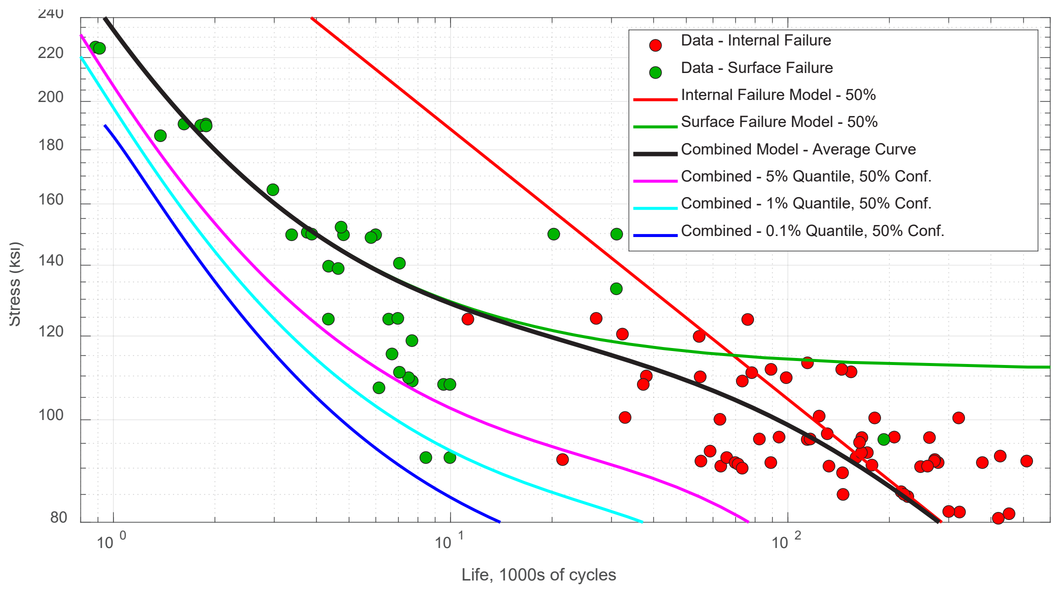


Figure 1. Individual, Combined System and probabilistic Fatigue Curves

C1-206

Fatigue Deformation Behavior and Life Prediction in a Newly-Developed Cast Aluminum Alloy

Soumya DASH[1], Zhiying LIU[2], Yu ZOU[2], Dejiang LI[3], Xiaoqin ZENG[3], Dongyang LI[4] and Daolun CHEN[1,*]

[1] Toronto Metropolitan University, CANADA
[2] University of Toronto, CANADA
[3] Shanghai Jiao Tong University, CHINA
[4] University of Alberta, CANADA

* Corresponding author: dchen@torontomu.ca

ABSTRACT:

Lightweighting trend keeps constantly growing in the automotive industry due to the demand of energy-efficient hybrid and electric vehicles. Aluminum alloy plays a major role in the manufacturing of lightweight structural components. This study is aimed at evaluating the cyclic deformation behavior of a newly-developed low-iron containing, vacuum-assisted high-pressure die-cast aluminum alloy. It was observed that the alloy exhibited a longer fatigue life, along with strong cyclic hardening in the as-cast and T4 heat-treated conditions and cyclic stabilization in the T5 and T7 heat-treated conditions. The degree of cyclic hardening was qualified on the basis of the slope of the stress amplitude vs. the number of cycles. To understand fatigue damage in the alloy during cyclic deformation, a modified method was proposed to evaluate the intrinsic fatigue toughness of the alloy, which acted as a material constant in different conditions. This further served as a key parameter to more accurately predict the fatigue life (Fig.1(a) for the as-cast alloy). Upon altering the strain ratios, a mean stress relaxation was present in the cast alloy (Fig.1(b)). The trajectory of the relaxation paths at the strain ratios from -1 to -∞ (negative infinity) was qualified for the first time.

KEYWORDS:

Al-Si alloy; Cyclic deformation; Intrinsic fatigue toughness; Fatigue life; Strain ratio.

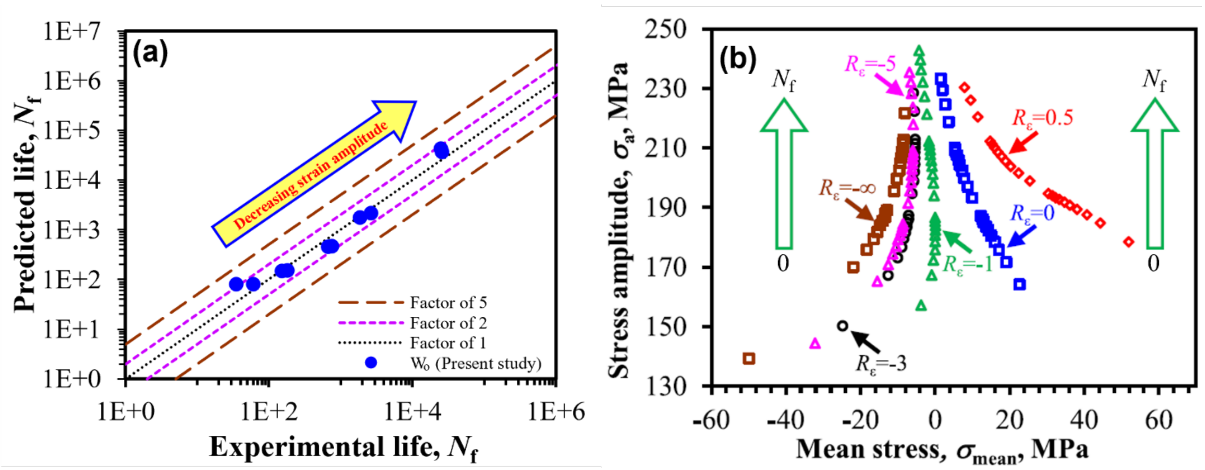


Fig. 1 *(a) Fatigue life predicted via intrinsic fatigue toughness (W_o) vs. experimental fatigue life, and (b) stress amplitude vs. mean stress plot at different strain ratios in the cast Al-Si alloy.*

C1-207

Mechanoresponsive luminogen (MRL)-based real-time and visible detection method for fatigue damage

Zhe ZHANG*, Hong GAO, and Xu CHEN

School of Chemical Engineering and Technology, Tianjin University, CHINA

* Corresponding author: zhe.zhang@tju.edu.cn

ABSTRACT:

Fatigue damage is crucial for safety assessment of structures. Owing to the characteristics of visualization, rapid response and nondestructive measurement, mechanoresponsive luminogen (MRL)-based methods have a great potential for stress sensing and damage detection. In this study, fatigue behavior and life prediction in structures are detected using a pure organic mechanochromic luminescent material. Both fatigue damage and luminescence emission are investigated simultaneously. The fatigue crack initiation and crack propagation path can be successfully converted into a visible green fluorescence. Based on the fluorescence intensity and distribution, the real-time fatigue crack length and life prediction can be evaluated. The MRL-based methods may open up new opportunities for nondestructive evaluation and structural damage evaluation.

KEYWORDS:

Fatigue damage, Detection method, Visualization, Fatigue crack propagation, Life Prediction.

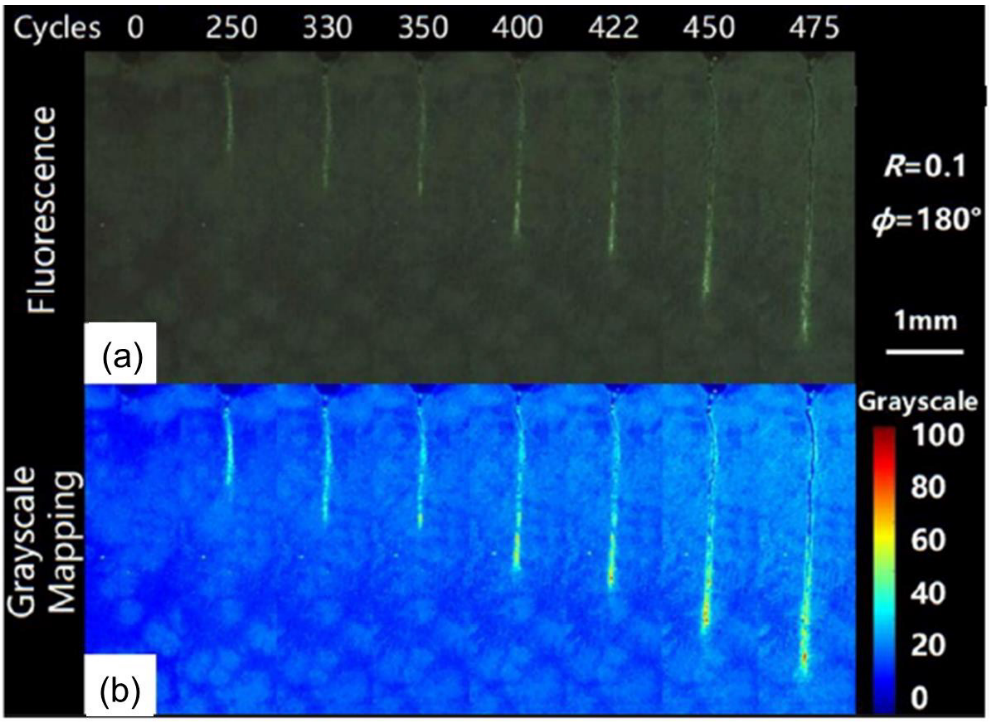


Fig. 1 *Real-time and visualization of fatigue crack propagation using fluorescence response:(a) fluorescence images; (b) corresponding fluorescence intensity.*

C1-208

Thermoplastic composites have been widely used in aerospace, aeronautics and automobiles due to their easy-processing, recyclability and good mechanical properties. Compared with thermoset composites, thermoplastic composites have obvious differences in fatigue behaviors and temperature sensitivity, so this paper studied the self-heating of angel-ply thermoplastic composite laminates ($[\pm 25]_{3s}$, $[\pm 35]_{3s}$, $[\pm 45]_{3s}$) under tensile-tensile fatigue loads and proposed a rapid prediction method for fatigue limit to decrease workloads in fatigue research. First, thermo-mechanical behaviors of such materials were investigated in terms of fatigue mechanisms and thermodynamics. Then, a fatigue experiment using the infrared thermography technology was conducted to provide temperature information for fatigue limit prediction and thermodynamic analysis. Last, the influence of loading amplitude and fiber orientation on self-heating of specimens was characterized, and the fatigue limit of different specimens was estimated by using the proposed method, with a good agreement with experimental data.

C1-209

Using 3D energy-dispersive µLaue diffraction to study fatigue damage evolution in materials showing wavy and planar slip behaviour

Carolin LEIDIGKEIT[1,*], Mohammad SHOKR[2], Amir TOSSON[2], Cafer Tufan CAKIR[3], Martin RADTKE[3], Ullrich PIETSCH[2] and Hans-Jürgen CHRIST[1]

[1] Universität Siegen – Institut für Werkstofftechnik, GERMANY
[2] Universität Siegen – Festkörperphysik, GERMANY
[3] Bundesanstalt für Materialforschung und -prüfung, GERMANY

* Corresponding author: carolin.leidigkeit@uni-siegen.de

ABSTRACT:
The evolution of dislocation arrangement of a metallic material caused by cyclic plastic strain is usually monitored by time-consuming and destructive methods as long as no fatigue crack has formed. The present work shows an alternative approach using white X-ray radiation in combination with a 3D energy-dispersive detector allowing for non-destructive microstructure analysis of polycrystalline specimens by a single-shot experiment.
The method is demonstrated by experiments performed on nickel and α-brass at BESSY II which represent the pure wavy and pure planar dislocation slip behaviour, respectively. In order to correlate the resulting diffraction patterns with various dislocation arrangements of both metals, fatigue tests were carried out up to certain numbers of cycles and at predetermined plastic strain amplitudes. As a consequence of the different kind of dislocation slip behaviour, the resulting dislocation arrangements were found to differ strongly, and this holds also true for the internal stress distributions within the grains. In turn these differences in dislocation microstructure give rise to an appreciable change in the peak shape of Laue reflection leading to unique characteristics in the respective diffraction patterns of the particular dislocation network. Moreover, deviations from a theoretical prediction were determined.

KEYWORDS:
dislocation arrangements, microstructure evolution, µLaue X-ray diffraction, damage monitoring

C1-210

Evaluation of fatigue strength of Cr-Mo steel based on dissipated energy measurement

Taichi SUGIMOTO[1]*, Daiki SHIOZAWA[1], Yuki OGAWA[1],
Taizo MAKINO[2], Hideki UEDA[2] and Takahide SAKAGAMI[1]

[1] Kobe University, JAPAN
[2] Nippon steel corporation

* Corresponding author: shiozawa@mech.kobe-u.ac.jp

ABSTRACT:

Since most fracture accidents are caused by fatigue failure, it is necessary to consider the fatigue strength of materials in the design of mechanical structures. However, the fatigue limit determination method using S-N curves requires long fatigue tests and a large number of specimens. Recently, a method for rapid estimation of fatigue limit based on measurement of dissipated energy using infrared thermography has attracted attention. This method uses infrared thermography to measure the dissipated energy, which is the irreversible heating of a material due to cyclic loading. This dissipated energy is related to crack initiation, and the fatigue limit can be estimated from the change in dissipated energy when a single specimen is subjected to short cyclic loading at various stress levels. In this study, we examined the applicability of this method to Cr-Mo steel, a high-strength material that is in increasing demand due to the demand for lighter weight machine parts and structures. In this material, locally high dissipated energy was observed at the same location in the evaluation area at stress amplitudes above the fatigue limit. The estimated fatigue limit based on this high dissipated energy point was close to the actual fatigue limit.

KEYWORDS:

Fatigue limit estimation; Dissipated energy; Infrared thermography; Non-destructive evaluation

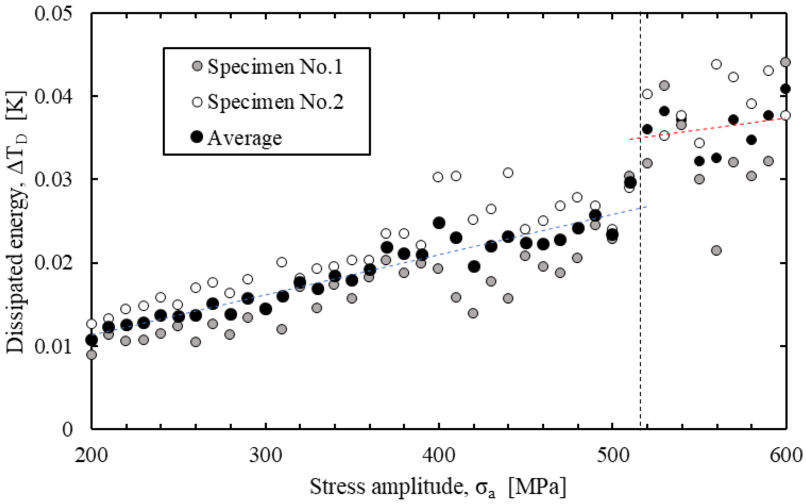


Fig.1 Relationship between stress amplitude and average value of top 2.5% dissipated energy.

C1-211

Crack shape identification from surface deformation using inverse analysis

Norihiko Hana [1], Masaki Umeda [1,*] , Masao Akiyoshi[1,*] ,and Kenji Amaya[2]

[1] Mitsubishi Electric Corporation, JAPAN
[2] Tokyo Institute of Technology, JAPAN

* Corresponding author: Hana.Norihiko@ab.MitsubishiElectric.co.jp

ABSTRACT:

A new crack identification method that estimates the cracks in invisible locations based on the surface deformation measured by digital image correlation (DIC) is developed. An inverse problem is set up to estimate such invisible cracks from surface deformations. The inverse problem has an ill-condition because of noise contained in surface deformations. The JE-MAP and CSP-EAP methods are proposed as regularization methods to solve this inverse problem.

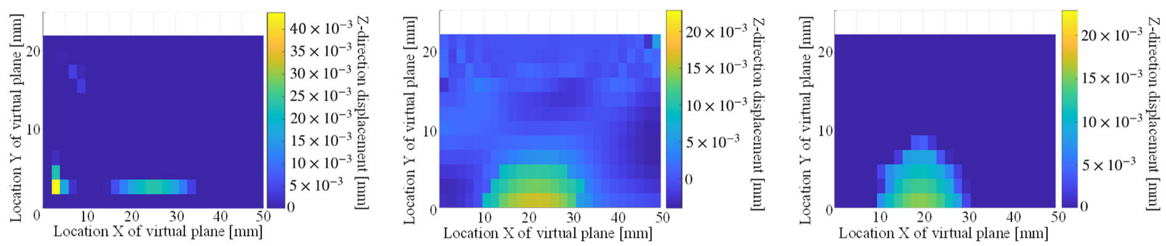
The JE-MAP algorithm alternates between Maximum a Posteriori (MAP) estimation and the grab-cut (GC) method to avoid ill-conditions. The physical constraints on displacement and the forces at the cracks and the crack perimeters (ligaments) are added to the MAP estimation.

The CSP-EAP algorithm uses prior information and Expectation a Posteriori (EAP) estimation. The prior information includes candidate crack shapes and surface deformations due to cracks.

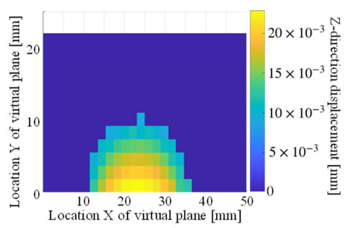
In this study, we compare the JE-MAP and CSP-EAP methods for a crack in a flat plate. Figure 1 shows an example of the estimation results and the correct solution, showing the results of the JE-MAP and CSP-EAP methods and the conventional L1-norm regularization for comparison. Both the JE-MAP and CSP-EAP methods can predict a shape closer to the correct answer than the L1-norm regularization.

KEYWORDS:

Crack identification; MAP method; EAP method; Digital image correlation



(a) L1-norm regularization (b) JE-MAP method (c) CSP-EAP method



(d) Distribution of ground truth

Fig. 1 *Crack opening displacement obtained by regularization methods*

C1-212

Fatigue Crack Behavior of 304 Stainless Steels using Synchrotron X-ray Tomography and Diffraction: Influence of the Martensite Fraction and Role of Inclusions

Ryan SCHOELL[1], Li XI[1], Harvey WEST[1] Peter HOSEMANN[2], Jun-Sang PARK[3], Peter KENESEI[3], Jonathan ALMER[3], Zeev SHAYER[4], Djamel KAOUMI[1,*]

[1] North Carolina State University, USA
[2] University of California Berkeley, USA
[3] Argonne National Laboratory, USA
[4] Colorado School of Mines

* Corresponding author: djamelkaoumi@gmail.com

ABSTRACT:
The effect of fatigue on the microstructure of four-point bend specimens of three heats of 304 stainless steels (Commercial 304, 304H, and 304L) was investigated using synchrotron x-ray tomography and diffraction. X-ray tomography revealed the formation of the fatigue-induced microvoids and crack while the diffraction data was used to quantify the amount of deformation-induced martensite found after fatigue in all samples. Transmission electron microscopy evidenced the role of the precipitates/inclusions on the microvoid formation. It was found that both ε-Fe and α'-Fe form during the fatigue process. The impact of the precipitates on the crack formation was found to depend on their chemical nature; particularly sulfides were found to play a determining role. The shape of the precipitates/inclusions was also found to have an effect on the microvoid shape leading to the crack formation.

KEYWORDS:
Fatigue, 304 Stainless Steel, Synchrotron, X-ray tomography, crack propagation

C1-213

Real time fatigue crack detection on welded specimens by applying inductive Thermography. Simulation and experimental results

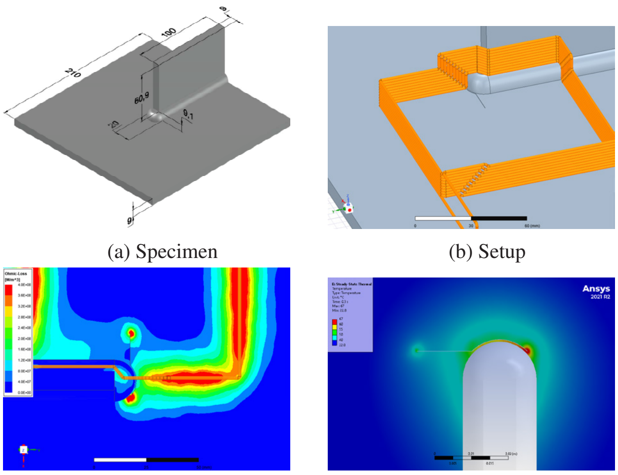
Paul Dario TOASA CAIZA[1],*, Daiki SHIOZAWA[2], Thomas UMMENHOFER[3], and Takahide SAKAGAMI[4]

[1,3]KIT Stahl- und Leichtbau, Versuchsanstalt f¨ur Stahl, Holz und Steine,
Karlsruher Institut f¨ur Technologie (KIT). Otto-Ammann-Platz 1, 76131 Karlsruhe, Germany
[2,4]Graduate School of Engineering / Department of Mechanical Engineering, Kobe University, Kobe, Japan

*Corresponding author: paul.toasa@kit.edu

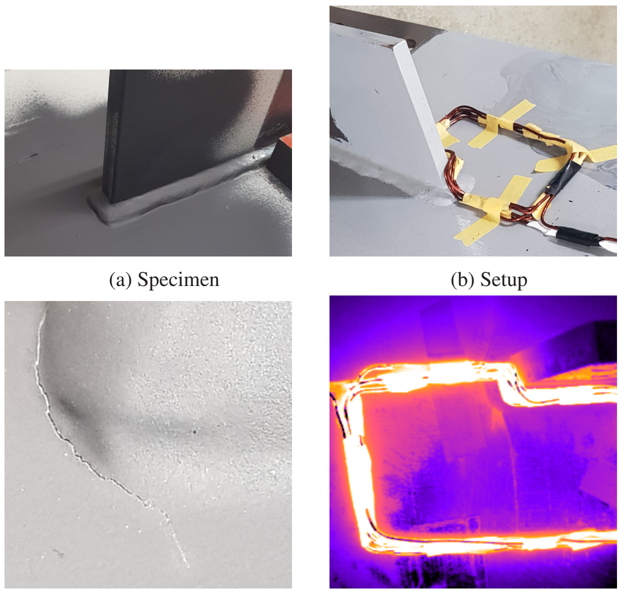
ABSTRACT:
For years the Eddy currents principle together with inductive thermography have been applied to detect cracks or defects in metallic machine components. In case a component has a crack, by inducing Eddy currents within a coil, it is possible to cause a temperature increase in the edges of the crack. This temperature variation is possible to visualize by using an Infrared camera. Thus, the crack is registered and detected in infrared images, which are later analyzed. However, currently used systems require an enormous amount of power and a long time for image processing. For this reason, applying this method to large steel structures such as bridges, cranes, wind power towers, pipe lines or offshore oil stations has been much more complex. To overcome these limitations, a light portable system that optimally recreates the Eddy currents principle has been developed. This system uses considerably less power and it is capable of detecting cracks in real time. This paper presents the simulations and experiments carried out on different structural steel specimens to demonstrate the efficiency of the system and its potential in the field of NDT.

KEYWORDS:
Fatigue, Crack detection, Inductive thermography, Real time



(a) Specimen (b) Setup (c) Ohmic Loss (d) Temperature distribution

Figure 1: FEM simulation of the crack detection process



(a) Specimen (b) Setup (c) Micro crack (d) Temperature distribution

Figure 2: Experimental crack detection process

C1-214

Evaluation of Fatigue Strength by Dissipated Energy of Dissimilar FSW Joints of Aluminum Alloy and Steel sheets.

Tenyu HIDAKI[1], Naoki IWATANI[1], Miu HAYASHI[2], Yuki OGAWA[1,*], Daiki SHIOZAWA[1], and Takahide SAKAGAMI[1]

[1] Kobe University, JAPAN
[2] Hiroshima University, JAPAN

* Corresponding author: yogawa@mech.kobe-u.ac.jp

ABSTRACT:

In recent years, multi-material structures have been attracting attention. However, to ensure the safety and reliability of welded structures, a rapid evaluation method for their fatigue characteristics is desirable. This study focuses on fatigue limit estimation by dissipated energy, and discusses the feasibility of a fatigue limit estimation based on the dissipated energy for dissimilar FSW joints of aluminum alloy and steel sheets. Dissipated energy refers to irreversible heat generation in the material. To estimate the fatigue limit, a staircase stress amplitude increase test was conducted. Empirical results suggest that the point of rapid increase in temperature due to dissipated energy in this test may coincide with the fatigue limit. Figure 1 shows the measured temperature change due to dissipated energy in the test. The low temperature group was grouped by linear approximation and the high temperature group by quadratic function approximation, and the boundary value was used as the estimated fatigue limit. As a result, the estimated fatigue limit was close to the actual fatigue limit. Therefore, it was found that the fatigue limit estimation based on the dissipated energy is possible for dissimilar FSW joints of aluminum alloy and steel sheets.

KEYWORDS:

Fatigue, Dissipated energy, Infrared thermography, FSW, Dissimilar welds

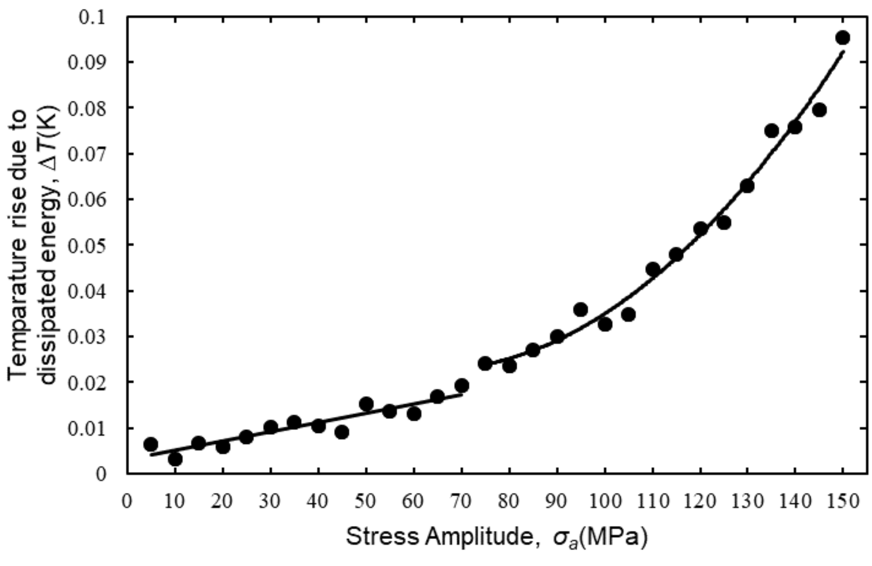


Fig.1 Measured results of dissipated energy for FSW joint.

C1-215

POD modeling of a flexible array eddy current NDT method for near-surface cracks in the tenon-groove structure of a turbine disk and its application for damage tolerance assessment

Liu Hongzhuo[1], Huang Dawei[1,2,3]*, and Yan Xiaojun[1,2,3,4]

[1] School of Energy and Power Engineering, Beihang University, Beijing 100191, China
[2] National Key Laboratory of Science and Technology on Aero-Engine Aero-thermodynamics, Beijing 100191, China
[3] Beijing Key Laboratory of Aero-Engine Structure and Strength, Beijing 100191, China
[4] Collaborative Innovation Center of Advanced Aero-Engine, Beijing 100191, China

* Corresponding author: huangdawei@buaa.edu.cn

ABSTRACT:
The damage tolerance (DT) assessment takes the probability of detection (POD) of the nondestructive testing (NDT) as an input condition. For aero-engine turbine disks, there is a paucity of NDT data for constructing POD models of realistic cracks, especially for the failure-susceptible tenon-groove structure. In this study, a prediction method of POD model for near-surface cracks in the tenon-groove structure of turbine disk is proposed. The conventional eddy current NDT technique is first applied to test two types of simple plate specimens, one containing femtosecond laser drilled notches and the other containing real cracks obtained by cyclic loading. After that, a flexible array eddy current test is carried out for the femtosecond laser drilled notches in the real tenon-groove structure. A transfer function is then constructed to predict the POD model of near-surface cracks in the tenon-groove structure using the results of simple specimens. The model is finally applied to the damage tolerance assessment, and the failure probability of the disk is calculated under typical low-cycle fatigue loads.

KEYWORDS:
Eddy-current NDT, probability of detection, damage tolerance, near-surface cracks, tenon-groove structure

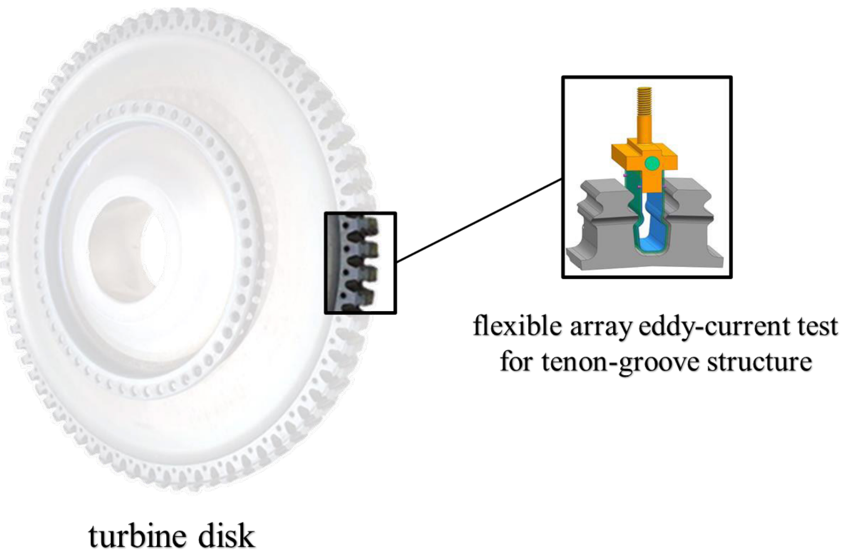


Fig. 1 *Array eddy-current NDT for tenon-groove structure in turbine disk.*

C1-216

Metalayer-based piezoelectric transducer for unidirectional excitation and reception of SH guided wave

Yuehao Du, Hongchen Miao*, Qianhua Kan, Xu Zhang, and Guozheng Kang

Southwest Jiaotong University, China

* Corresponding author: miaohongchen@swjtu.edu.cn

ABSTRACT:
Unidirectional excitation of a single-mode guided wave (GW) is of great significance in GW-based non-destructive testing (NDT). Currently, very few transducers are capable of generating unidirectional propagation GW in plate-like structures, so such a goal is usually achieved by using the phased array method, which is relatively expensive and only works within a narrow frequency range. In this work, a metalayer-based piezoelectric transducer (MBPT) is developed for unidirectionally generating and receiving pure SH_0 wave (fundamental shear horizontal wave). The MBPT consists of a metalayer and two rectangular thickness-shear mode piezoelectric wafers. The metalayer component of the MBPT is designed for achieving the phase gradient over a wide range of frequencies, so in both unidirectional excitation and reception, no extra time delay is required for the proposed MBPT. Both simulated and experimental results show that pure SH_0 wave is generated by the MBPT and its wave energy is successfully focused along a given direction in a plate over a wide range of frequency. Moreover, the reception performance of the MBPT also shows excellent unidirectionality. Due to the excellent performance and easy fabrication process, the proposed MBPT will be very useful in unidirectional excitation and reception of SH_0 wave in NDT.

KEYWORDS:
Shear horizontal wave; Piezoelectric transducer; Guided wave; Non-destructive testing.

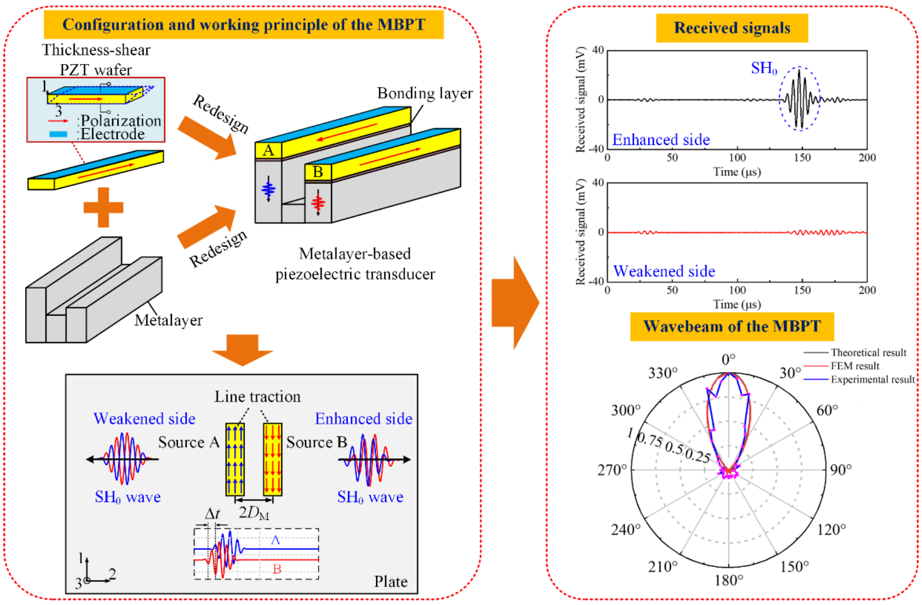


Fig. 1 *Piezoelectric transducer for unidirectional excitation and reception of SH guided wave.*

C2-201

Finite element study on the influence of the phase shift on plasticity-induced crack closure and the crack tip opening displacement under thermomechanical fatigue loading

Carl FISCHER[1,*], Christoph SCHWEIZER[1] and Thomas SEIFERT[2]

[1] Fraunhofer Institute for Mechanics of Materials IWM, Freiburg, GERMANY
[2] Offenburg University of Applied Sciences, Offenburg, GERMANY

* Corresponding author: carl.fischer@iwm.fraunhofer.de

ABSTRACT:

In high-temperature components, mechanical and thermal loads are acting simultaneously during start-up and shutdown, which results in thermomechanical fatigue (TMF) and fatigue crack growth. Because of temperature-dependent material properties, the mean stress strongly changes with the phase between temperature and mechanical loading. Since fatigue crack growth in ductile materials involves plastic deformations at least in a small zone around the crack tip, plasticity-induced fatigue crack closure, the dominant mechanism for the explanation of mean stress effects, becomes load history-dependent.

Finite element simulations for a plane strain penny-shaped crack were performed for the nickel-based superalloy IN100 under large-scale yielding and strain-controlled TMF conditions. The influence of the phase shift on the crack opening stress $\sigma_{\rm op}$ is studied. The results for the function U giving the fraction to which the crack is opened during the TMF cycle show that more crack closure is present under in-phase than under out-of-phase TMF loading (Fig. 1). The clockwise and counterclockwise cycles are found in between. Similar observations are made for the crack tip opening displacement. Here, the evolution during the loading and unloading branch, and the points of crack opening and crack closure deviate significantly.

KEYWORDS:

Plasticity-induced crack closure; Thermomechanical fatigue; Crack opening stress; Crack tip opening displacement, Finite element simulation

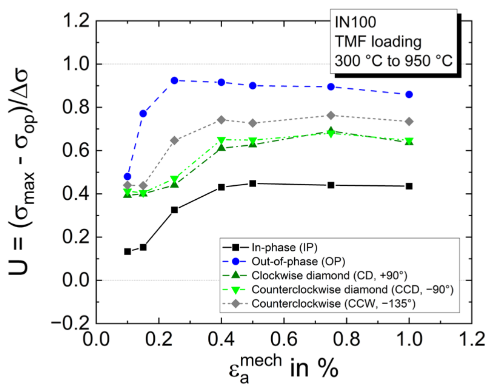


Fig. 1: *Crack closure under TMF loading depending on the phase shift and the applied strain amplitude.*

C2-202

Mixed mode crack growth behaviour considering plasticity-induced and roughness-induced closure

Shuancheng WANG[1], Bing YANG[1,*], Jian LI[1], Shuwei ZHOU[1], Shoune XIAO[1], Guangwu YANG[1] and Tao ZHU[1]

[1] State Key Laboratory of Traction Power, Southwest Jiao tong University, CHINA

* Corresponding author: yb@swjtu.edu.cn.

ABSTRACT:

A theoretical analytical solution of the Christopher-James-Patterson (CJP) model in mixed mode is presented in this paper, where the influence of roughness-induced crack closure (RICC) on fatigue crack growth is considered and a new effective stress intensity factor range ($\Delta K_{P\text{-}R}$) is proposed as the driving force for crack propagation. The solution showed that both the maximum tangential stress criterion (MTS) and the minimum strain energy density criterion (S) can reasonably well predict the crack deflection angle. Experimental testing on EA4T axle steel samples showed that both the 8 % compliance offset criterion in the conventional ASTM procedure and the parabolic-line method were suitable for the determination of the crack-opening force. The solution includes plasticity-induced crack closure (PICC) and RICC effects, therefore the crack propagation behaviour can be described in a more effective way. Compared with the traditional mixed model crack growth models with higher fitting correlation coefficient, the fitting effect of the CJP model has been improved by 12 % in this solution, and the residual stress in the pre-crack stage increased the crack-closure level. Due to the influence of residual stress, the rate of roughness value (R_A) showed a fluctuation of 4.5 %, which indirectly affected the fatigue crack growth rate (FCGR) value of the test.

KEYWORDS:

Mixed-mode; Crack deflection; Roughness-induced crack closure; Plasticity-induced crack closure.

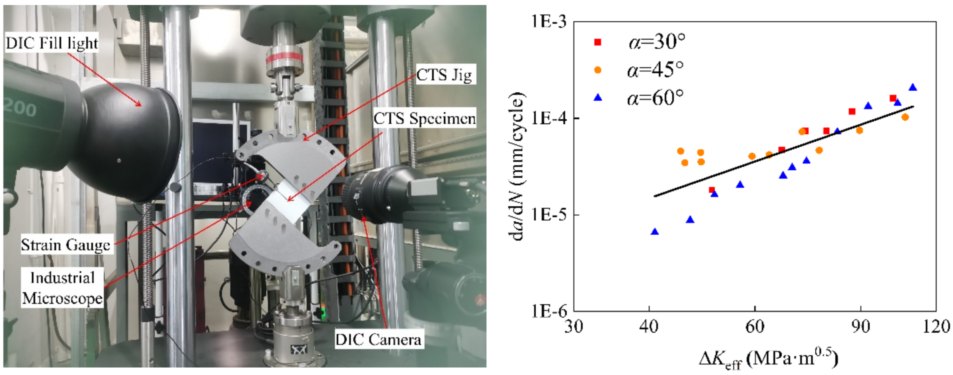


Fig. 1 *Mixed mode FCGR as a function of* $\Delta K_{P\text{-}R}$.

C2-203

Improved Analytical Tool for Crack Closure Evolution after Overload and Underload

Radek Kubíček[1,2,*], Tomáš Vojtek[1], Pavel Pokorný[1], Luboš Náhlík[1], Pavel Hutař[1]

[1] Institute of Physics of Materials, Czech Academy of Sciences, Zizkova 22, 612 62 Brno, Czech Republic
[2] Department of Engineering Mechanics, Faculty of Mechanical Engineering, Brno University of Technology. Technicka 2896/2, 61669 Brno, Czech Republic

* Corresponding author: kubicek@ipm.cz

ABSTRACT:
The accurate prediction of crack growth behaviour is crucial for ensuring the safety and reliability of structures, particularly in the industrial sector. Current standard approaches for predicting crack growth under variable amplitude loading, such as finite element method simulations and the strip yield model, can be very time-consuming and computationally expensive. On the other hand, simpler overload and underload models, such as the Willenborg approach do not accurately account for the effects of crack closure mechanisms, since they are solely based on residual stress generation around the crack tip. This can lead to inaccurate predictions.

This study focuses on development of analytical formulas providing a more precise and physically meaningful description of crack propagation following overload or underload using the FASTRAN software. The new approach is more accurate than the simpler approaches and less computationally expensive than the standard approaches. We demonstrate the applicability of our approach by a case study focused on estimation of residual fatigue life of steel components in transportation. Higher precision of crack propagation enables optimization of design and maintenance of structures subjected to cyclic loading, leading to significant improvements in safety and reliability. Our study highlights the importance of consideration of correct mechanisms of fatigue crack growth and shielding. The results provide a useful tool for residual fatigue life estimations under changing loading conditions.

KEYWORDS:
Plasticity-induced crack closure, Strip yield model, Variable amplitude loading, Fatigue crack growth, High cycle fatigue

C2-204
Crack closure effects at negative load ratios.

Théotime ASSELIN[1,2*], Olivier ANCELET[2], Valéry VALLE[1], Guillaume BENOIT[1], Florence HAMON[1], Gilbert HÉNAFF[1]

[1] Institut Pprime, FRANCE
[2] Framatome, FRANCE

* Corresponding author: theotime.asselin@ensma.fr

ABSTRACT:

A nuclear power plant primary circuit component is subjected during its operating life to a stress-controlled primary loading (155bar operating pressure) to which a secondary loading, originating from shutdowns/restarts and operating transients is added. Some of these loadings, for instance thermal shocks can cause Low Cycle Fatigue with a negative stress ratio on the components. In order to improve the accuracy of the life calculation of the component, the magnitude of crack closure effects must be assessed for the above-mentioned loading conditions.

With this aim, fatigue tests under strain control at R_ε=-1 are first conducted on tension-compression specimens containing a defect. The investigated materials are a 304L austenitic stainless steel and a low-alloyed 18MND5 steel (equivalent to ASTM A508 Cl. 3), so as to compare the crack closure effects for two materials exhibiting a different behaviour.

A new metrology is introduced, combining the potential drop method and a Heaviside-DIC (H-DIC) techniques. The H-DIC technique allows and detects the presence of a discontinuity (in this case a fatigue crack) in the displacement field, enabling a better localization of the crack tip and lips.

This experimental setup allows to monitor both crack propagation and closure, and an effort is made to exploit the DCPD signal over one fatigue cycle and extract a crack closure load. The surface crack opening and closure loads are determined through the implementation of virtual extensometers and strain gauges on the displacement and strain maps obtained using the XCorrel™ H-DIC software.

KEYWORDS:
Crack closure; DIC; Heaviside-DIC; Potential Drop Method; Steels

C2-205

On The Strain Energy Release Rate And Fatigue Crack Growth Rate In Metallic Alloys

Emiel AMSTERDAM[1,*], Jan Willem WIEGMAN[1], Marco NAWIJN[2] and Jeff Th. M. DE HOSSON[3]

[1] Royal Netherlands Aerospace Centre (NLR), THE NETHERLANDS
[2] Colosso, THE NETHERLANDS
[3] University of Groningen, THE NETHERLANDS

* Corresponding author: emiel.amsterdam@nlr.nl

ABSTRACT:
In 1963, Paris et al. used a fracture mechanics' parameter to introduce an equation for the fatigue crack growth rate in ductile materials that is commonly known as the 'Paris law'. However, the Paris law and the semi-empirical models that followed ever since do not fully account for the main intrinsic and extrinsic properties involved with fatigue crack growth in metallic alloys. In contrast, here a dimensionally correct fatigue crack growth rate equation is introduced that is based on the original crack driving force as introduced by Griffith and the presence of plasticity in a metal to withstand crack propagation. It is 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 (see Fig. 1). The new description gives a physical explanation for the stress ratio/mean stress effect during constant amplitude loading and for crack growth retardation under variable amplitude loading. The method has been successfully applied to variable amplitude crack growth with spectra that are representative of different fatigue dominated aircraft locations. As such, it allows for accurate predictions of variable amplitude fatigue crack growth life in aerospace structures.

KEYWORDS:
Linear elastic fracture mechanics, Fatigue, Design, Engineering, Metals

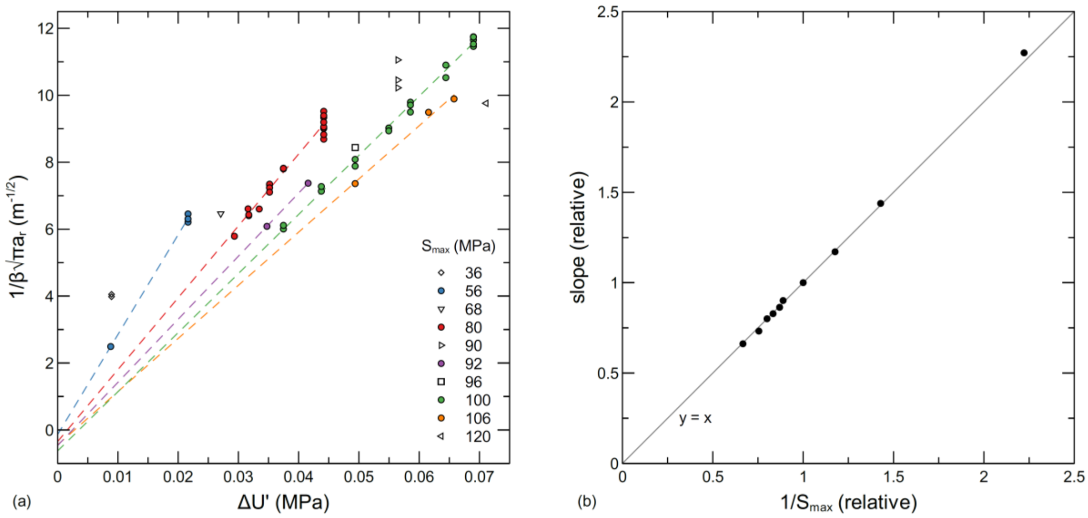


Fig. 1 *(a) Inverse crack length term at 6.18·10*$^{-8}$ *m/cycle as a function of the cyclic strain energy density (ΔU') for different* S_{max}*. (b) Relative slope in (a) as a function of the relative inverse* S_{max}*. The slope and maximum stress of the 80 MPa fit was used as a reference.*

C2-207

Damage tolerance assessment of heavy-duty freight railway axle steel with various-shape artificial defects

Jie-Wei GAO[1,*], Shun-Peng ZHU[1]

[1] School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China

* Corresponding author: jieweig@126.com

ABSTRACT:
Heavy-duty freight railway axles are no less important than that of passenger ones, due to the potentially catastrophic results caused by the derailment of trains carrying hazardous substances. Intrinsic and extrinsic imperfections challenge classical design theories built based on the safe life concept, and damage tolerance assessment becomes vital for the safety and reliability of long-term serviced railway axles. In this work, four-point rotating bending fatigue tests of the AAR-CM railway axle steel specimens with semi-circular notches and hemi-spherical notches were conducted. The non-propagating cracks on run-out specimens and fracture surfaces were observed under SEM. Stress gradient on the root of notches were analyzed by finite element simulation. The results show that a more reliable fatigue limit prediction could be obtained by taking the crack closer effect and the local stress gradient.

KEYWORDS:
Heavy-duty freight railway axles; notches; fatigue prediction; crack closer effect; stress gradient.

C2-208

Fretting fatigue damage of axial interference fit structures subjected to fretting wear

Yiliang Shu, Guangxue Yang, Zhiming Liu

School of Mechanical and Electronic Control Engineering, Beijing Jiaotong University, Beijing 100044, China

* Corresponding author: gxyang@bjtu.edu.cn

Abstract: Fretting fatigue is a type of fatigue that often occurs at the contact interface of various tightly connected mechanical structures, which can significantly reduce the service life and fatigue strength of the structure when compared to plain fatigue. One of the main research issues at present is how to account for fretting wear and analyze fretting fatigue for axial interference fit joint structures. A rotating, bending, and cyclic load are applied to an interference-fit specimen in this study using the finite element simulation method, and the stress-strain data of the contact surface of the shaft under cyclic load are obtained. The damage parameters for all elements in the contact surface area under cyclic loading are acquired, combined with the critical plane approach, and SWT fretting fatigue damage model, and the maximum fretting fatigue damage location is then predicted. The wear depth of the specimen shaft's contact surface node is calculated and simulated using ABAQUS' Umeshmotion subroutine, and the evolution law of the surface profile under fretting wear, as well as the evolution characteristics of the contact parameters and damage parameters of the contact interface with the number of loading cycles, are obtained.

Keywords: Fretting fatigue; Fretting wear; Damage model; Umeshmotion

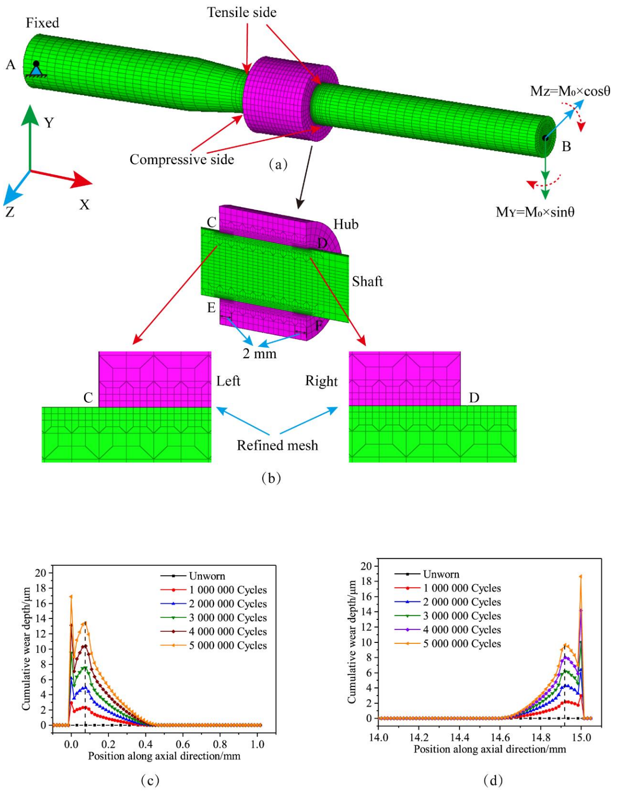


Fig. 1 *Finite element model and wear depth*

C2-209

Research on fatigue assessment method of high-speed train axle based on axle box acceleration

Ruiguo YAN[1], Wenjing WANG[1,*] and Yiyue CHEN[1]

[1] School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, CHINA

* Corresponding author: wjwang@bjtu.edu.cn

ABSTRACT:

As a key safety component of high-speed trains, axle fatigue and fracture can lead to major accidents such as train derailment or overturning. The difficulty of testing dynamic stresses in axles severely limits the difficulty of fatigue damage analysis of axles. In this paper, a high-speed train axle dynamic stress test was conducted, and the change in axle box acceleration was implemented and monitored during the test. The relationship between the change in dynamic axle stress and axle box acceleration during operation is analyzed. The results show that there is a linear and normal distribution between the equivalent stress in the critical section of the axle and the effective value of the axle box acceleration. There is a strong correlation between axle box vertical acceleration and axle equivalent stress, and a weak correlation between lateral acceleration and equivalent stress. The results quantify the relationship between axle box acceleration and axle equivalent stress and provide new ideas for subsequent axle dynamic stress monitoring.

KEYWORDS:

High-speed train; Axle box acceleration; Axle dynamic stress; Fatigue damage

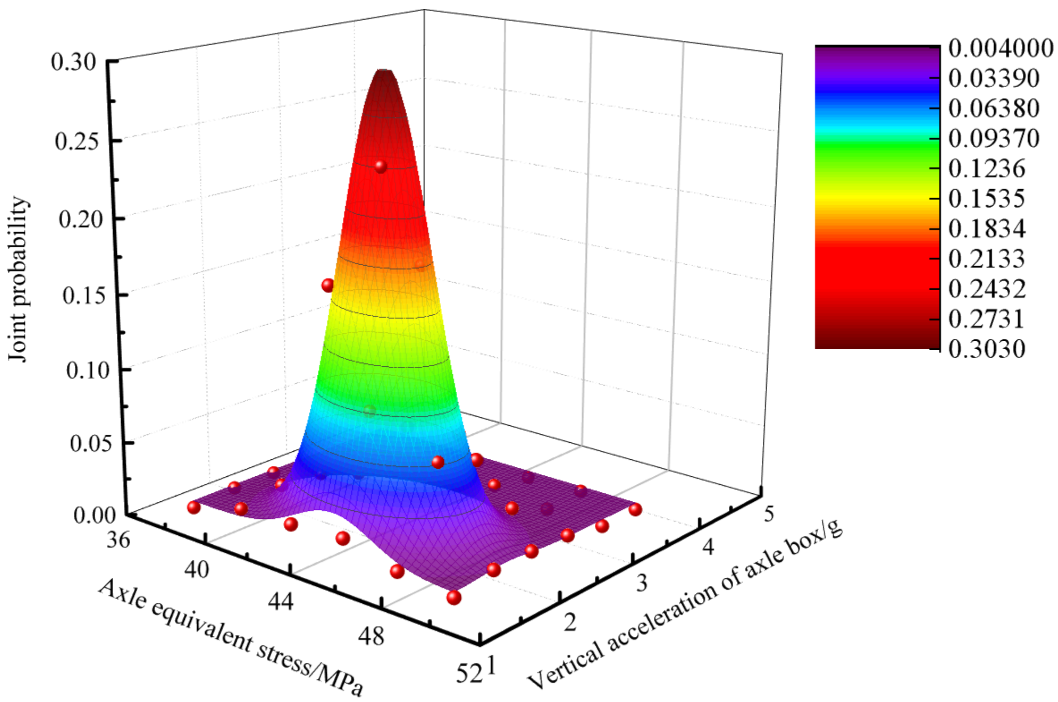


Fig. 1 *Correlation analysis between axle equivalent stress and effective value of axle box acceleration.*

C2-210

An entropy-based approach to low cycle fatigue damage evolution for GH4169 at intermediate and elevated temperature

Shuiting Ding[1], Shuyang Xia[2], Zhenlei Li[3], Liangliang Zuo[2], Shaochen Bao[3], Kaiqi Chen[2] and Guo Li[2,4]*

[1] Civil Aviation University of China, Tianji, 300300, China
[2] School of Energy and Power Engineering, Beihang University, Beijing, 100191, China
[3] Research Institute of Aero-Engine, Beihang University, Beijing, 100191, China
[4] Tianmushan Laboratory, Hangzhou, 310051, China

* Corresponding author: lg666@buaa.edu.cn

ABSTRACT:
This paper utilizes thermodynamic entropy generation to study the system degradation process of GH4169 under cyclic loading. The 3D finite element analysis was performed for the GH4169 smooth specimen within the framework of cyclically plastic material constitutive theory to obtain cyclic stress-strain response and accumulation of entropy generation. Then, a non-linear model was utilized to establish the relationship between accumulation of damage and entropy generation for describing the system degradation in material. A series of results were reported to simulate the damage evolution behavior in LCF process for GH4169 under full-reversed (R_ε = -1) cyclic loading with various strain amplitudes at 400℃ and 650℃. Compared with the existing experimentally validated non-linear predictive methods of damage evolution, such as continuum damage mechanics (CDM) approach and damage approach based on exhaustion of static toughness, the non-linear entropy-based model provided a fairly good agreement to characterize fatigue damage for GH4169 at 400℃ and 650℃. The thermodynamic entropy generation provides an effective method to investigate fatigue damage evolution for further assessment of remaining life in material system.

KEYWORDS:
Low cycle fatigue ; Damage evolution ; Thermodynamic entropy generation ; GH4169

C2-211

Proposition and Development of the General Relation between Tensile and Fatigue Strengths of Metallic Materials

Jianchao PANG[1,*], Yu CHEN[1], Chenglu ZOU[1], Xiaoyuan TENG, Shouxi LI and Zhefeng ZHANG[1,*]

[1] Institute of Metal Research, Chinese Academy of Sciences, PR China

* Corresponding author: jcpang@imr.ac.cn; zhfzhang@imr.ac.cn

ABSTRACT:
With the emergence of a large number of high-strength materials, especially ultra-high strength steel, in the 20th century, the linear relationship between fatigue strength and tensile strength proposed by Whöler may be not applicable. In order to find the fatigue relation, a high-strength steel was chosen to investigate and those were found and confirmed: the fatigue strength first increases and then decreases with the tensile strength increasing; there is a linear relation between fatigue ratio (the ratio of fatigue strength to tensile strength) and tensile strength; and then the general relationship (parabolic one) between fatigue and tensile strengths was first proposed; the decrease of the fatigue strength at high-strength level can be attributed to the transition of fatigue cracking sites from surface to the inner inclusions; the general relationship can be successfully deduced by using fracture mechanics. After conducting experiments and collecting data, the newly proposed relation is applicable to various metallic materials and components (including traditional materials, new materials, and engineering components) at room and even high temperatures; it has been recognized and developed by some colleagues in fatigue research, and then it will provide a new clue for designing and choosing the materials and the corresponding processing.

KEYWORDS:
Metallic materials; Tensile strength; Fatigue strength; Parabolic relation; Fatigue damage mechanism

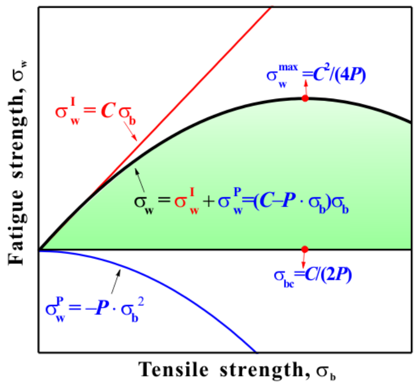


Fig. 1 *The general relation between tensile and fatigue strengths of metallic materials.*

C2-212

Effect of internal defects of G20Mn5 cast steel on the fatigue strength

Fabien LEFEBVRE*, Driss EL KHOUKHI, Pierre OSMOND; Benaouda ABDELLAOUI, Bhimal BHOLAH; Sébastien BRZUCHACZ, David MANNETIER, Gilles REGHEERE, Stephane MAGRON, Fréderic HOFFMANN

Cetim, 52 avenue Félix Louat, Senlis, France

* Corresponding author: fabien.lefebvre@cetim.fr

ABSTRACT:

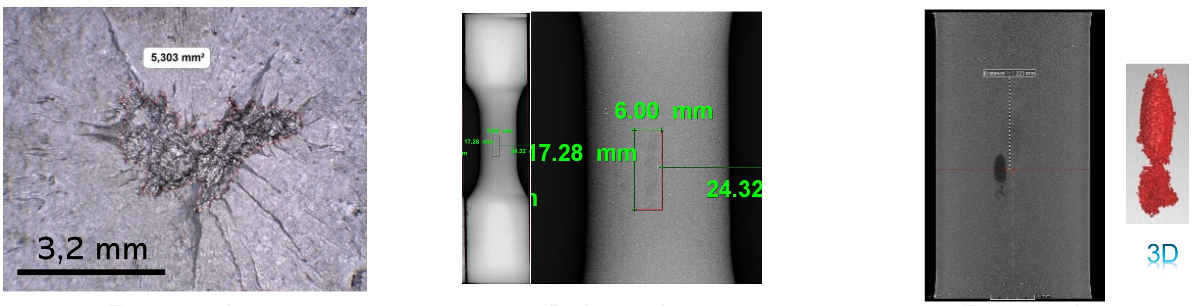
The quality and reliability of mechanical properties must be controlled throughout the service life of a mechanical component. Among the existing processes in manufacturing engineering, casting is widely used for its cost effectiveness in producing complex geometries. Like any other process, it can generate material defects that can affect the structural integrity of a component in a mechanical system in service. Therefore, there is an industrial need for the prediction and control of the impact of casting defects.

This study combines both an experimental and a physical modelling approach to evaluate the response of a natural casting defect – representative of an industrial based case – when subjected to fatigue loadings. The modelling part focusses on the effect of defects on the fatigue strength.

The retained testing protocols and the fatigue strength modeling approach were based on the state of the art of a literature review on explicit effects of defects. For this reason, non-destructive techniques, such as radiography and tomography, have been used to test and develop natural defect characterization methods, with an emphasis on industrial applications. The Murakami model is therefore chosen to analyse the fatigue results. The Kitagawa-Takahashi diagrams are plotted with the corresponding model parameter sets.

KEYWORDS:

Fatigue, defects, Murakami model, Kitagawa-Takahashi diagram



Fractography Radiography Tomography

Fig. 1 *Defect characterisation.*

C2-213

Analysis of the defect tolerance of bainitic 100Cr6 with high retained austenite content

P. Ostermayer[1]*, B. Blinn[1], K. Burkart[2], T. Allam[3,4], W. Song[3,5], B. Clausen[2], W. Bleck[3], U. Krupp[3], T. Beck[1]

[1] Institute of Materials Science and Engineering, RPTU Kaiserslautern-Landau, Kaiserslautern, Germany
[2] Leibniz Institute for Materials Engineering, IWT Bremen, Germany
[3] IEHK Steel Institute, RWTH Aachen University, Germany
[4] Department of Metallurgical and Materials Engineering, Suez University, 43528 Suez, Egypt
[5] Institute of Materials Engineering, University of Kassel, Germany

* Corresponding author: p.ostermayer@rptu.de

ABSTRACT:

To consider the influence of microstructural defects for the design of components made of 100Cr6, the defect tolerance of the material is relevant, which can be improved by high contents of retained austenite (RA). This is caused by its relatively high deformability, and its deformation-induced transformation into α'-martensite. However, since excessive phase transformations lead to undesired dimensional changes, a defined phase stability is required.

Consequently, three variants of 100Cr6, having an increased content of Al (1.5 wt.-%) and Si (0.6 and 1.5 wt.-%), respectively, were bainitized to achieve high RA contents with different stabilities. The respective bainitization parameters were determined as described in [1]. For each variant, Woehler curves were determined at ambient temperature and 100°C, respectively. Moreover, Murakami's √area approach [2] was applied to evaluate the defect tolerance. To investigate the austenite stability and the contribution of phase transformations on the defect tolerance, these tests were complemented by X-ray diffraction phase analyses.

These investigations show for all variants a higher defect tolerance in relation to standard 100Cr6. Moreover, the variant with 1.5 wt.-% Si shows an appropriate stability of the RA, leading to only local phase transformations at defects, which results in a strong improvement of the defect tolerance.

KEYWORDS:

Defect tolerance; high retained austenite content; bainitic 100Cr6; high cycle fatigue

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C2-214

Cyclic indentation – A new method to estimate the fatigue strength by considering the cyclic deformation behavior

Bastian BLINN*, David GÖRZEN, Patrick LEHNER, Pascal OSTERMAYER, Dietmar EIFLER, Tilmann BECK

Institute of Materials Science and Engineering (WKK), RPTU Kaiserslautern-Landau, GERMANY
*Corresponding author: b.blinn@mv.rptu.de

ABSTRACT:
For the design of technical components, the materials fatigue limit σ_w is crucial. Since the determination of σ_w requires a high experimental effort, efficient approaches for its estimation are of great relevance, especially for material optimization. Common approaches based on hardness lead to relatively high deviations. This is mainly caused by neglecting the cyclic deformation behavior, as its common quantification based on conventional fatigue tests is time- and material-consuming. However, as shown in [1], instrumented cyclic indentation tests (CIT) can be used to efficiently quantify the cyclic deformation behavior, while the cyclic hardening exponent$_{CHT}$ e_{II} represents the cyclic hardening potential. Consequently, in this work the common estimation approaches based on Vickers hardness *HV* are extended by $|e_{II}|$. Using the experimental results obtained, a high correlation of σ_w and the product of *HV* and $|e_{II}|$ was shown for low-alloyed steels, leading to a modified equation to estimate σ_w (see Fig. 1a and [2]). With this approach, a significantly improved estimation of the fatigue strength was achieved, as shown in Fig. 1b. Moreover, a decrease of the indentation force in CIT enabled to determine σ_w locally in failure-relevant areas.

[1] Blinn et al.: https://doi.org/10.1016/j.ijfatigue.2018.09.025
[2] Görzen et al.: https://doi.org/10.3390/met12071066

KEYWORDS:
Fatigue strength; low-alloyed steels; cyclic deformation behavior; cyclic hardening potential; cyclic indentation testing

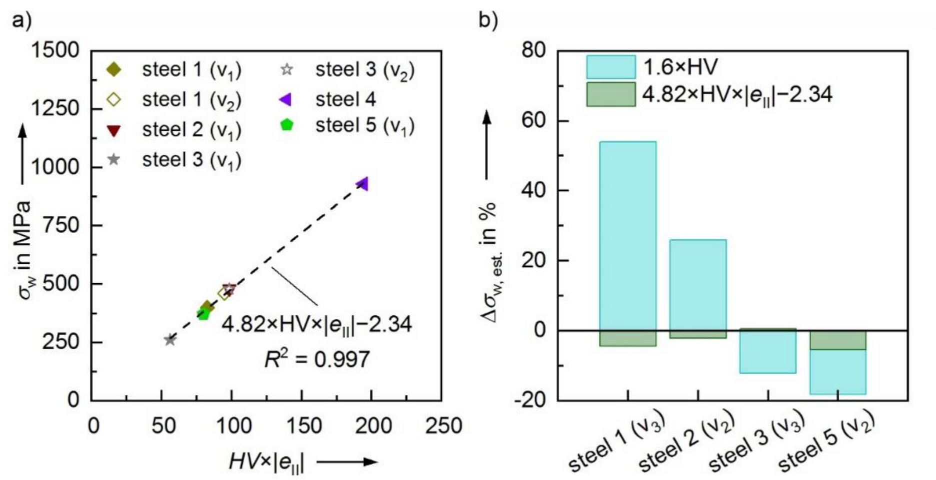


Fig. 1 *a) Correlation analysis of the fatigue strength σ_w with the product of the Vickers hardness HV and the cyclic hardening exponent$_{CHT}$ $|e_{II}|$ obtained at different conditions of low-alloyed steels; b) comparison of the deviation of estimated fatigue strength $\Delta\sigma_{w,est}$ resulted from the established approach based on hardness (1.6xHV) and the approach developed based on the correlation shown in Fig.1 a.*

C2-215

Study on fatigue damage of axle excited by High Frequency

Wenjing WANG[1,*], Ziyu Dong[1], Xiaoyi Hu[2]

[1] School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, CHINA
[1] Railway Science and Technology Research and Development Center, China Academy of Railway Sciences Co., Ltd., Beijing 100081, CHINA

* Corresponding author: wjwang@bjtu.edu.cn

ABSTRACT:
The wheel polygonal wear will lead to the impact load between the wheel and rail and cause the high-frequency vibration of the wheel-rail system. To study the contribution of high frequency excitation to axle fatigue damage, wheel polygonal bench tests were carried out with the high-speed wheel rail test rig, and a vehicle-rail rigid-flexible coupling dynamic model considering wheelset and track flexibility was constructed. The variation rules of wheel-rail force, axle box vibration acceleration and axle dynamic stress at different speed levels were studied, and the relationship between high frequency components and axle fatigue damage was established. The results show that under the wheel polygon excitation, the dynamic stress of the key section of the axle fluctuates slightly at the peak and valley position, and this phenomenon will be more obvious when the polygon excitation frequency is close to the wheelset modal frequency. Under the amplitude 0.03mm, 20 order wheel polygon and 50~400km/h, the high frequency response component of the axle dynamic stress can account for up to 20% of the total equivalent stress, indicating that the effect of high frequency excitation on the fatigue damage of the axle can not be ignored.

KEYWORDS:
High-speed train; High frequency excitation; Wheel polygon; Axle; Fatigue damage

Fig. 1. *Wheel polygon bench test site*

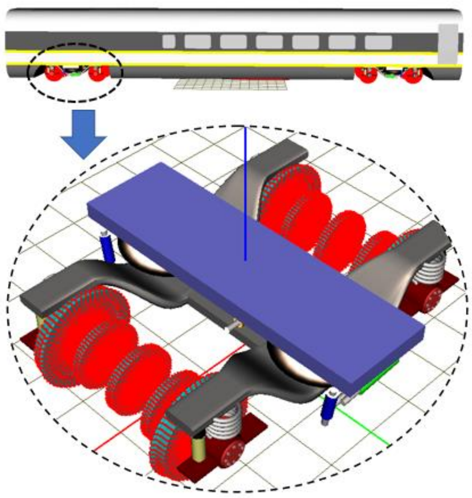


Fig. 2. *Rigid-flexible coupling dynamic model*

C2-216

A Study of Rate Process Analysis on the Rotating Bending Fatigue Limit of Carbon Steel

Mai FUKAMI[1,4,*], Noriyasu OGUMA[1], Benjamin GUENNEC[2], Noriyo HORIKAWA[2], Tatsuo SAKAI[3] and Tsuyoshi ANNE[4]

[1] University of Toyama, JAPAN
[2] Toyama Prefectural University, JAPAN
[3] Ritsumeikan University, JAPAN
[4] Tohshin Technical Co., Ltd., JAPAN

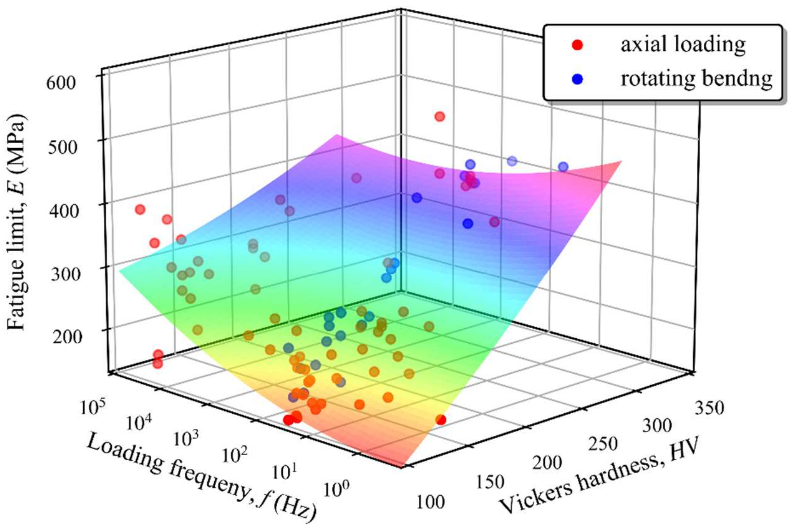
* Corresponding author: m.fukami@tohshin-inc.co.jp

ABSTRACT:

In this study, a dual-spindle cantilever-type rotating bending fatigue testing machine was adopted t conduct on the fatigue tests of low carbon steel JIS S10C, JIS S25C and medium carbon steel JI: S45C. The low carbon steel was fatigue tested under the loading frequency of 7 Hz, and the mediur carbon steel was fatigue tested under the loading frequency of 7 Hz and 70 Hz. As a result, the fatigu limit of the low carbon steel was 235 MPa and 265 MPa, repectively. And the fatigue limit for mediur carbon steel under different frequency condition was 359 MPa and 415 MPa, respectively. Based o the results of this research and the values of the rotating bending fatigue limit in various literatures, was confirmed that these results can be applied to the model proposed by Guennec et al. to analyz the loading frequency dependence on the fatigue limit. When the effects of loading frequency an Vickers hardness on the fatigue limit were expressed in the 3D plots as shown in Fig. 1, it wa confirmed that the axial loading fatigue and rotating bending fatigue data were on a single quadrati regression phase.

KEYWORDS:

Fatigue limit, Carbon steel, Rotating bending fatigue test, Loading frequency, Vickers hardness



C2-217

Mean stress sensitivity for carbide-rich PM tool steels

Lennart Mirko SCHOLL[1,*], Alexander BEZOLD[1] and Christoph BROECKMANN[1]

[1] RWTH Aachen University, Chair and Institute for Materials Applications in Mechanical Engineering (IWM), Augustinerbach 4, 52062 Aachen, Germany

* Corresponding author: L.Scholl@iwm.rwth-aachen.de

ABSTRACT (max. 200 words + max. 1 Figure):
Designing cold working tools against fatigue fracture is of great economic relevance to increase tool service life and thus the productivity of cold forming processes. Besides other factors like non-proportional loading, multiaxiality and notch effects, the mean stress sensitivity plays a particularly important role for tool design and construction issues. Mathematical descriptions of the mean stress influence were developed by Goodman, Gerber, Soderberg or El-Magd & Troost and graphical representations by Morrow, Haigh or Smith for practical component design. However, all these approaches do not address wear-resistant, ultra-high strength PM tool steels. Experimental fatigue data with mean stress variations are not available for PM tool steels, so a realistic estimation of mean stress sensitivity is not possible so far.
In this work a comprehensive database of statistically validated fatigue strengths under axial loading with systematic variation of mean stress is presented for the industrially used steel grades M3 PM (HS6-5-3C PM) and D2 PM (X153CrMoV12 PM). Haigh diagrams are constructed for existing mathematical approaches to mean stress sensitivity and compared to new, material-specific approaches developed from the database. Validations show that these new approaches are significantly better at describing the mean stress sensitivity for carbide-rich PM tool steels.

KEYWORDS (max. 5 tags): Carbide-Rich PM Tool Steels; HCF Strength; Mean Stress Sensitivity; Haigh Diagram; Fatigue Influencing Factors

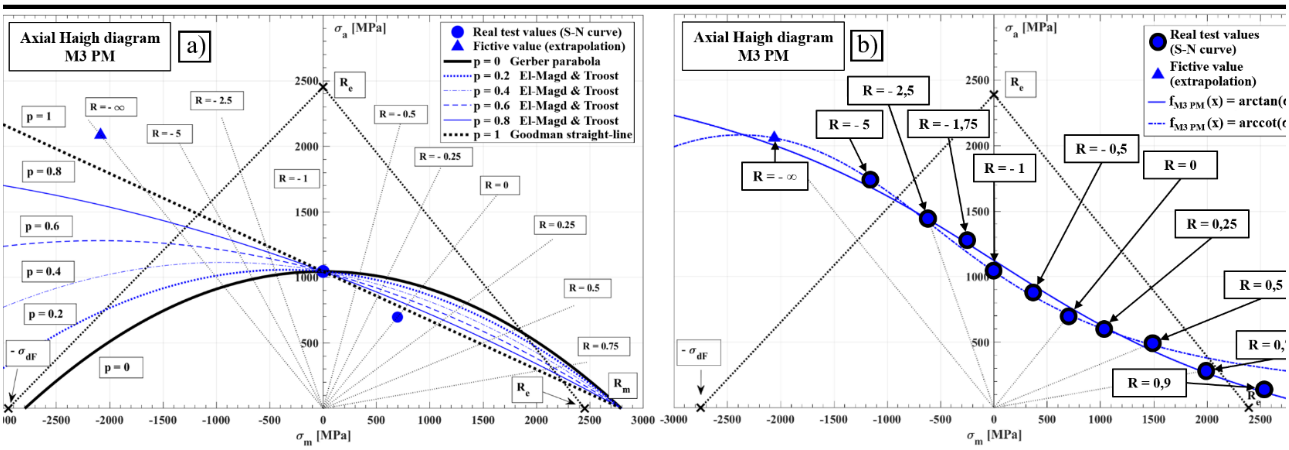


Fig. 1: *Haigh diagram under axial loading for the carbide-rich high-speed steel HS6-5-3C PM: Comparison of continuous fit curves according to a) Goodman, Gerber, El-Magd & Troost, and b) new approaches with trigonometric functions (arctan and arccot)*

C2-218

Influence of Pre-strain on the Fatigue Strength of Stainless Steel

Masayuki KAMAYA[1*]

[1] Institute of Nuclear Safety System, Inc., JAPAN

* Corresponding author: kamaya@inss.co.jp

ABSTRACT:

Influence of pre-strain on the fatigue strength was investigated using Type 316 stainless steel specimens. First, tensile tests were conducted to induce pre-strain of 10%, 20% and 30% in nominal strain using specimens machined from cylindrical bar. Then, the fatigue test specimens were machined and the surface was finished using 3 μm diamond paste. The fatigue tests were conducted by strain-control at room temperature. Test results showed that the application of pre-strain reduced the fatigue life particularly for low-cycle fatigue regime, although the magnitude of the change in fatigue life was not significant (Fig. 1). The pre-strained specimen exhibited cyclic softening throughout the tests. The strain distribution observation using the digital image correlation technique revealed that the cyclic strain softening induced strain localization when the applied strain range $\Delta\varepsilon$ was 1.2%, although the localization was not observed for $\Delta\varepsilon$ = 0.5%. It was concluded that the reduction in fatigue life due to the pre-straining was caused by the strain localization. The pre-strain had little influence on the fatigue life for the same local strain range.

KEYWORDS:

pre-strain, stainless steel, fatigue life, cold working, localized strain

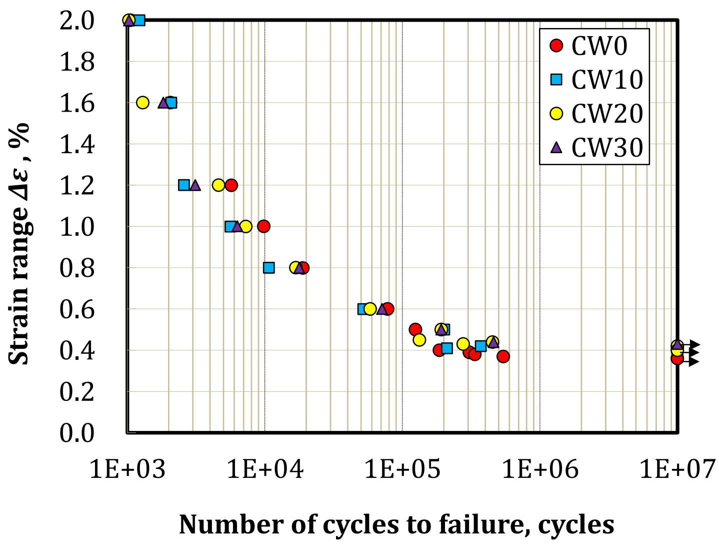


Fig. 1 Fatigue life obtained by strain-controlled tests at room temperature.

R1-201

Fatigue strength evaluation of 1180MPa class recycled steel

Nobuo NAGASHIMA[1], Masao HAYAKAWA[1], Kotobu NAGAI[1], Hiroyuki MASUDA[1], Eizaburo NAKANISHI[2], Noriyuki NAKANISHI[2], Masaru IWASAKI[2]

[1] National Institute for Materials Science, JAPAN

[2] Tokyo Steel Manufacturing Co. LTD. JAPAN

* Corresponding author: NAGASHIMA.Nobuo@nims.go.jp

ABSTRACT:

The present study investigated the material properties of 1180MPa class recycled steel fabricated from waste scraps to evaluate the required performance of parts as steel sheets for automobiles. The recycled steel showed a strength-ductility performance: tensile strength of 1234 MPa, total elongation of 18%, stretch-frangibility λ of 21%, limiting dome height of 12.2 mm, and limiting drawing ratio of 2.09%. In the fatigue test with a stress ratio R = -1, the mirror finish material had a fatigue limit of 600 MPa at 10^7cycles to failure for both bending load and axial load. The fatigue limit corresponds to half tensile strength that is believed to be the maximum fatigue limit in cases of surface initiation of fatigue. The fatigue limits obtained by changing the stress ratio under bending load well matched the corrected goodman line. Therefore, the effect of average stress can be reliably evaluated from the fatigue limit diagram. In this way, the 1180MPa class recycled steel sheet has high fatigue strength with sufficient reliability and satisfactory meets the required performance of parts as a steel sheet for automobiles.

KEYWORDS:

high-strength recycled steel; 10^7 cycles fatigue limit; stress ratio; fatigue limit diagram

Reference

N. NAGASHIMA[1], M. HAYAKAWA, K. NAGAI, H. MASUDA, E. NAKANISHI, N. NAKANISHI, M. IWASAKI, Vol.53, No.4, p.808-814, Transuctions of Society of Automotive Engineers of Japan.

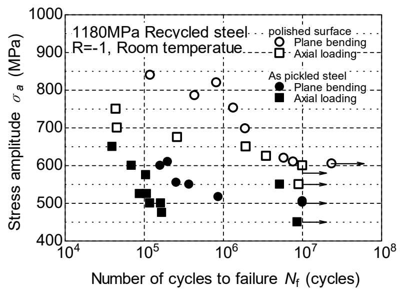


Fig. 1 *S-N curves obtained under stress ratio of R* = -1.

R1-202

Influence of Dislocation Interactions on Fatigue Crack Initiation in Additively Manufactured Nickel-Aluminum-Bronze Alloys

Aeriel Murphy-Leonard[1*], Veronika Mazánová[1]

[1] The Ohio State University, USA

* Corresponding author: leonard.649@osu.edu

ABSTRACT:

Ni-Al bronze is widely used in marine applications due to combination of good mechanical properties and corrosion resistance. Recent studies showed that the mechanical properties of this material system can be further enhanced by using WAAM additive manufacturing (AM). However, there is still a knowledge gap in understanding of the effect of the AM microstructure on the deformation mechanisms, especially strain localization. Our work focuses on the detailed multi-scale characterization of the WAAM processed Ni-Al bronze in relation to monotonic tensile and cyclic fatigue properties. As-deposited microstructure is studied as well as that after deformation combining SEM-SE, BSE, FIB, EBSD techniques with STEM and EDS. Strain localization and crack initiation is studied on the samples strained close to YS and UTS. Key microstructural aspects and deformation mechanisms are identified and discussed related to the performance of the material.

KEYWORDS:

additive manufacturing; crack initiation; low cycle fatigue

R1-203

Notched High Cycle Fatigue and Macrozones in Ti-6Al-4V

Yan GAO[1]*, Jamie MOSCHINI[2], Nigel MARTIN[2] and David DYE[1]

[1] Imperial College London, United Kingdom
[2] Rolls-Royce plc, United Kingdom

* Corresponding author: yg5015@ic.ac.uk

ABSTRACT:
Ti-6Al-4V is widely used in aerospace application. A high cycle fatigue life debit of about 40% has sometimes been observed when the loading cycle exceeds 1E7 cycles for Ti64. This phenomenon leads to industrial concern in applications such as engine fan blade plates and discs, and even for some aerostructures. It is hypothesized that the existence of notch-like features in Ti64 interacting with macrozones is the underlying cause for the life debit. HCF samples with notches placed at the macrozone boundaries were created and tested. Life differences were observed between hard macrozone-notch and soft macrozone-notch samples. SEM and EBSD were used to characterize the fracture surface and the texture around the crack initiation facet. FIB milling was used to lift out foils from the facets and the corresponding dislocation systems in the facets were analyzed with TEM.

KEYWORDS:
High Cycle Fatigue; Macrozone; Dislocation; Notch; Titanium

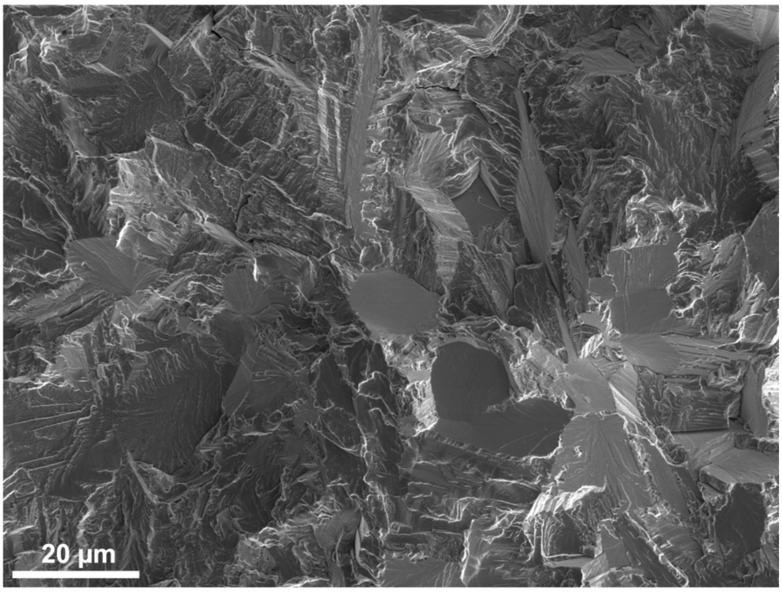


Fig. 1 *SEM scan of the crack initiation region of a soft macrozone-notch sample.*

R1-204

In situ observation and crystal plasticity simulation of internal fatigue crack initiation and propagation behavior around synthetic hard alpha inclusions embedded in Ti-6Al-4V

Liu Hongzhuo[1], Huang Dawei[1,2,3*], Yan Xiaojun[1,2,3,4], and Shi Puying[5]

[1] School of Energy and Power Engineering, Beihang University, Beijing 100191, China
[2] National Key Laboratory of Science and Technology on Aero-Engine Aero-thermodynamics, Beijing 100191, China
[3] Beijing Key Laboratory of Aero-Engine Structure and Strength, Beijing 100191, China
[4] Collaborative Innovation Center of Advanced Aero-Engine, Beijing 100191, China
[5] Western Superconducting Technologies CO.,Ltd, Xi'an 710018, China

* Corresponding author: huangdawei@buaa.edu.cn

ABSTRACT:
The hard alpha (HA) inclusions within Ti-6Al-4V alloy are usually the initiation of low-cycle fatigue cracks, which significantly reduce the component fatigue life. In this study, the internal fatigue crack initiation and propagation behavior around HA inclusion is investigated by means of in situ tests, micro-CT reconstruction, and crystal plasticity simulations. The effect of the presence of HA inclusions on the crack initiation in Ti-6Al-4V is analyzed, crystal plasticity simulation shows an excellent agreement with the experimental data. The crack propagation results of this study are compared with those of the literature for cracks initiate at artificial femtosecond laser drilled grooves. The uncertainty induced by the effect of HA inclusions on the crack growth rate is more significant than that of artificial grooves.

KEYWORDS:
hard alpha inclusions, internal fatigue cracks, micro-CT, crystal plasticity simulation, titanium alloys

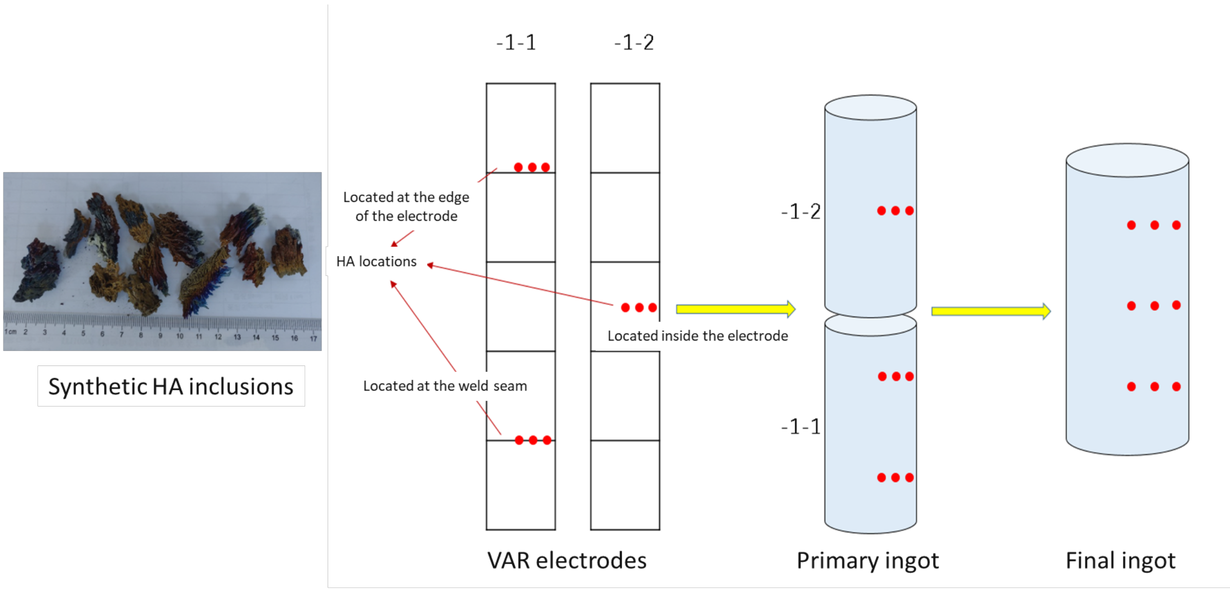


Fig. 1 *Processing of ingot containing synthetic embedded hard alpha inclusions defects.*

R1-205

A novel micromechanism-based fatigue model for FCC single crystal combining crystal plasticity with CDM

Ao LI, Weiping HU*, Zhixin ZHAN and Qingchun MENG

School of Aeronautic Science and Engineering, Beihang University, CHINA

* Corresponding author: huweiping@buaa.edu.cn

ABSTRACT:
Fatigue is a vital issue for metals under cyclic loading. In this study, micro damage variables are defined at the slip system scale, and the damage variable of grains is obtained through the total energy equivalence assumption. Then, a damage coupled cyclic plasticity constitutive equation is developed by introducing the concept of effective stress into a cyclic crystal plasticity model. The micro damage mechanisms of FCC metals under the fatigue load are investigated. Based on experimental observations, a novel damage driving force is proposed, and the fatigue damage evolution equations are derived in the framework of thermodynamics. The proposed model has clear physical significance. A numerical calculation method for fatigue life prediction is developed based on the proposed model. Besides, a fast particle swarm optimization-based method is used for parameter calibration. Finally, the fatigue lives of single crystal copper are tested, and the numerical results are in good agreement with the experimental data, which shows a good capability of the proposed model. The evolution of the microstructures of copper is also investigated based on the calculated results.

KEYWORDS:
Fatigue damage mechanism; Cyclic crystal plasticity; Fatigue life prediction; Single crystal copper.

R1-206

Initiation and Growth of Short Fatigue Cracks in Tempered Martensitic and Bainitic Steels

Ulrich KRUPP[1]*, Oguz GÜLBAY[1], Alexander GRAMLICH[1], Alexander GIERTLER[2] and Kevin KOSCHELLA[2]

[1] IEHK Steel Institute, RWTH Aachen University, GERMANY
[2] University of Applied Sciences Osnabrück, GERMANY
* Corresponding author: krupp@iehk.rwth-aachen.de

ABSTRACT:
A large portion of cyclically loaded components in mobility, power generation and machinery are made of tempered martensitic and bainitic steels. From numerous studies it is known that the fatigue endurance strength (fatigue limit) correlates with the size and type of non-metallic inclusions and the hardness of the diffusion-less transformed ferrite. However, high-resolution thermography revealed that in the case of moderate hardness levels (37HRC, 0.5wt%C-1wt%Cr alloys steel), microstructurally short fatigue cracks are initiated along persistent slip markings during an early stage of the fatigue life. By *in-situ* tracking fatigue cracks using light optical microscopy and evaluating the results by means of EBSD mapping of the crystallographic orientations of the respective areas, we found that occurrence of persistent slip markings can be attributed to dislocation plasticity either *within* or *between* martensite/bainite blocks. In the latter case, cyclic plasticity is confined to thin films of retained austenite (RA) between the blocks. By means of high-frequency (1000Hz) resonance fatigue testing of two lab-scale carbide-containing and carbide-free bainitic steels, it was shown that homogeneously distributed thin RA films increase the fatigue endurance strength. The underlying mechanisms of RA film adjustment and the interactions with microstructurally short fatigue cracks are discussed in the present paper.

KEYWORDS:
Bainitic Steel, Martensitic Steel, Short Fatigue Cracks, Retained Austenite, *in-situ* Crack Monitoring, Thermography

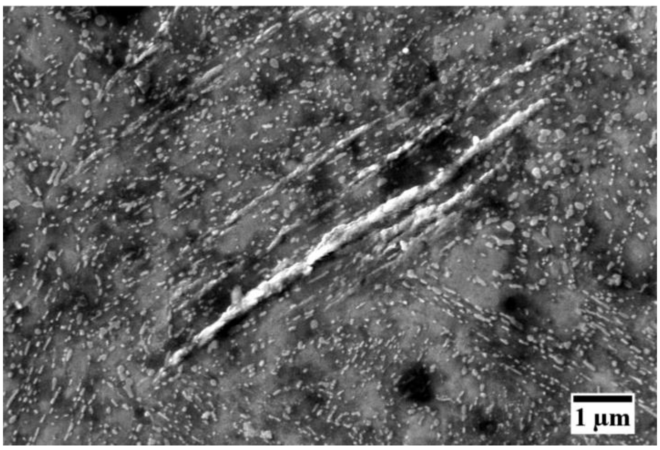


Fig. 1 *Persistent slip band in tempered martensitic steel as prerequisite of fatigue crack initiation.*

R1-207

In situ SEM experimental study on the fatigue failure of micro-single-crystal copper

Yabin YAN*, Zhenkai LI and Fuzhen XUAN

Mechanical and Power Engineering, East China University of Science and Technology, Shanghai, CHINA

*Corresponding author: yanyabin@ecust.edu.cn

ABSTRACT:
With the development of microelectronics technology, microscale metallic components have been widely used in micro- and nanoelectromechanical systems, but fatigue failure of metals due to cyclic loading has been a major factor in reducing the reliability of these devices. Therefore, to ensure the mechanical reliability of microsystems in long-term service, there is an urgent need to investigate the fatigue failure behavior of microscale metals. To address this issue, we investigated the fatigue failure behavior of micro-single-crystal copper at different loading amplitudes and loading frequencies by using an in situ uniaxial cyclic tensile loading experimental device. Based on in-situ SEM observations, the influence of the extrusion/intrusion structure at the slip zone on the fatigue crack initiation was revealed, and the influence of strain amplitude and loading frequency on the crack propagation was quantitatively obtained as well. The cyclic softening and hardening behaviors of micro-single-crystal copper under different loading conditions were revealed by analyzing the variation of peak stresses. In addition, the *S-N* curves of micro-single-crystal copper show that its fatigue life is insensitive to the loading frequency.

KEYWORDS:
Microscale, in situ experiment, fatigue short crack, single-crystal copper

R1-208

Dislocation networks in the (111) cell boundaries in fatigued near-$[\bar{1}11]$ copper single crystals

Bohan Wang[1,*], Yuuki Umeda[1], Tomotaka Miyazawa[1], Masahiro Ohtsuka[2], Shunsuke Muto[2], Shigeo Arai[2], and Toshiyuki Fujii[1]

[1] Tokyo Institute of Technology, JAPAN
[2] Nagoya University, JAPAN

* Corresponding author: wang.b.ah@m.titech.ac.jp

ABSTRACT:
In this study, fatigue tests of copper single crystals with the near-$[\bar{1}11]$ stress axis were performed at room temperature under different constant plastic shear strain amplitudes. The characteristic dislocation cell structure was observed by using a high-voltage scanning transmission electron microscope (HV-STEM). The cell boundary is considered to be formed by a dislocation network, which is a twist boundary in the (111) plane. During the dislocation network formation process, the perfect screw dislocations of the primary ($\mathbf{b}$ = $a/2[\bar{1}01]$) and coplanar ($\mathbf{b}$ = $a/2[\bar{1}10]$) slip systems react with each other to form another screw dislocation ($\mathbf{b}$ = $a/2[01\bar{1}]$). As the dislocation network becomes more dense, these perfect dislocations gradually dissociate into three types of Shockley partial dislocations ($\mathbf{b}$ = $a/6[\bar{1}2\bar{1}]$, $a/6[11\bar{2}]$, and $a/6[\bar{2}11]$).

KEYWORDS:
Fatigue; Copper Single crystal; Dislocation network; Twist boundary; Scanning transmission electron microscopy.

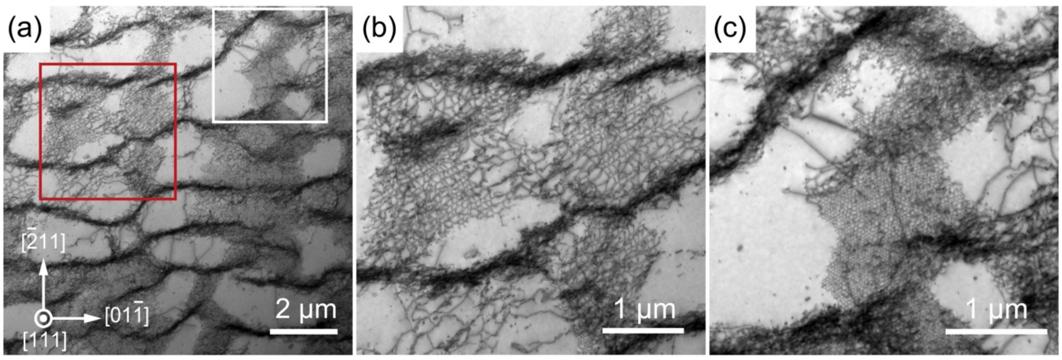


Fig. 1 *HV-STEM images of dislocation structures in fatigued single crystal copper viewed on the (111) plane. (b) Low- and (c) high- dislocation density networks corresponding to the magnified images of the red and white regions in (a), respectively.*

R1-209

Improvement of stress corrosion cracking resistance by low cycle fatigue of a CrNiMoV steel

Yu-Hui Huang [1], Fang-Xin Yang[1] , Nan Wang[1], Ming-Liang Zhu[1,*] and Fu-Zhen Xuan[1,*]
[1] East China University of Science and Technology, CHINA
* Corresponding author: mlzhu@ecust.edu.cn (M.-L Zhu), fzxuan@ecust.edu.cn (F.-Z Xuan)

ABSTRACT :

Low cycle fatigue often interacts with stress corrosion cracking behavior. In this work, the effect of low cycle fatigue on stress corrosion cracking susceptibility of a CrNiMoV steel was investigated by interrupted fatigue tests in air and slow strain rate tensile tests in 3.5 w.t.% NaCl solution at 180 ℃. Microstructure evolution characterization verified cyclic softening and was found to improve stress corrosion cracking resistance with crack deflection along lath martensites due to a decrease of residual stress, phase transformation and increase of low-energy structures. According to the results of SSRT experiments, the effect of fatigue damage on stress corrosion sensitivity can be better characterized by the reduction of area (φ) and the area included in the stress-strain curve (A). As a semi-quantitative damage indicator, the microstructure evolution due to LCF damage can be well described by the Kernel Average Misorientation (KAM) from the Electron Backscatter Diffraction technique. The KAM value and stress corrosion cracking sensitivity factor $I\varphi$ show an approximated decrease tendency with the accumulation of fatigue damage. The effect of fatigue damage on stress corrosion sensitivity could be predicted by the linear relationship between KAM and stress corrosion sensitivity factor of reduction of area.

KEYWORDS:

cyclic softening; low cycle fatigue; electron backscatter diffraction; stress corrosion cracking; dislocation density; lath martensite

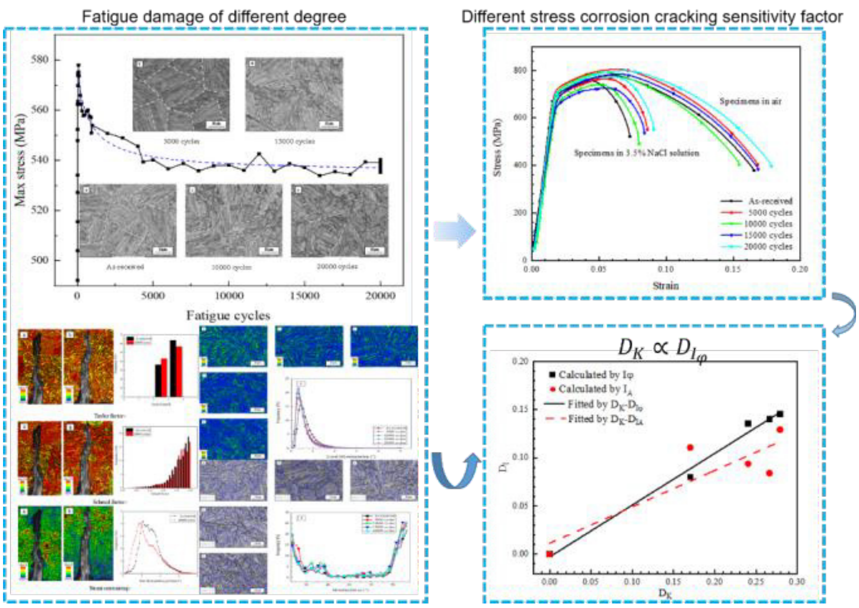


Fig.1 Low-cycle fatigue damage changes the mechanical properties and microstructure of CrNiMoV steel, decreases the KAM value, and the SCC resistance was improved. The linear relationship between KAM value and stress corrosion sensitivity was established to characterize the change of fatigue damage sensitivity to SCC sensitivity

R1-210

Cryoforged nanotwinned CoCrNi medium-entropy alloy with exceptional fatigue resistance at cryogenic temperature

Yu Xie[1], Tiwen Lu[1], Binhan Sun, Pengcheng Zhao[1], Jianping Tan[1], Xiancheng Zhang[1*], Shan-Tung Tu[1]

[1] Key Laboratory of Pressure Systems and Safety, Ministry of Education, East China University of Science and Technology, Shanghai 200237, China

* Corresponding author: xczhang@ecust.edu.cn (X.C. Zhang)

ABSTRACT:

Enhancing the fatigue resistance of metallic materials under cyclic loading is a significant challenge in particular for major structural applications at cryogenic temperatures. In this work, a stable hierarchical twin architecture in coarse grained CoCrNi medium-entropy alloy (MEA) was developed by multidirectional cryoforging (MDCF) technique combined with low-temperature annealing, in order to increase σ_f' and decrease $|b|$ in empirical basquin equation, $\sigma_f = \sigma_f'(2N_f)^b$. The unique substructure not only enhanced the cryogenic tensile strength-ductility balance, but also imparted a 10^6-cycle fatigue limit as high as 1100 MPa at 100 K, which is superior to other alloys under the similar conditions. The high density of dislocations and built-in nanotwin/microband network provided high strength. The abilities to suppress local surface roughening and crack initiation improved final fatigue resistances. Our work is expected to demonstrate a potential route to extend CoCrNi MEA for cryogenic applications.

KEYWORDS:

CoCrNi medium-entropy alloy; Multidirectional cryoforging; Hierarchical nanotwins; Cryogenic fatigue resistance

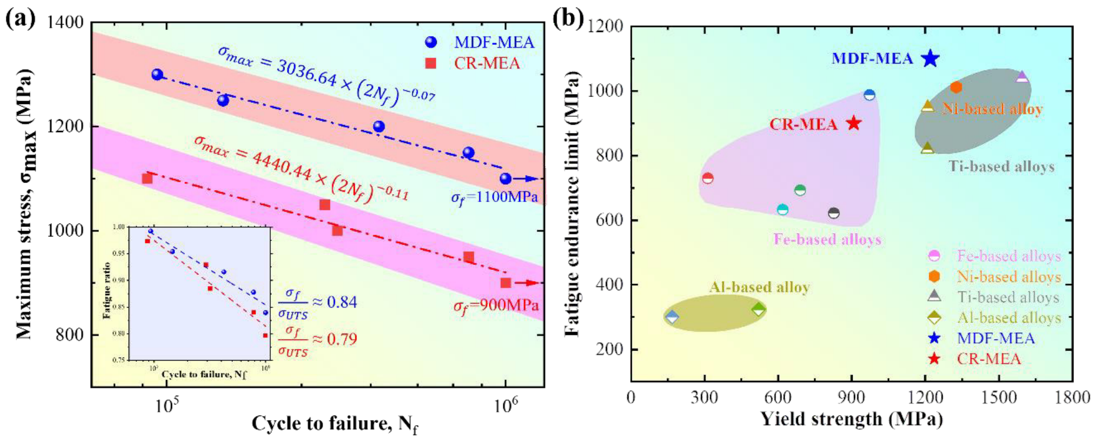


Fig. 1 Mechanical properties at 100 K: (a) S-N relationship of the MDCF-MEA and CR-MEA. (b) Yield strength versus fatigue endurance limit of metals which applicated at cryogenic temperature.

R1-211

Elucidation of small fatigue crack initiation behavior on polycrystal Ti-22V-4Al

Koki Hirazumi[1], Jinta Arakawa[1]*, Takeshi Uemori[1] and Yoshito Takemoto[1]

[1] Okayama University, Okayama-shi 3-1-1 Tsushimanaka, Kita-ku, Okayama, 700-8530, Japan
* Corresponding author: jarakawa@okayama-u.ac.jp

ABSTRACT:

In this study, the quantitative evaluation of small fatigue crack initiation was performed using Ti-22V-4Al to ensure the safety and reliability of β-type titanium alloys for long-term use. This study showed that cracks occur from the slip system which has the maximum value of Schimd factor in the grain where the crack occur at first. So that, Schmid factor can approximately predict the slip system, which generate crack for single crystals. When we conducted that the comparison of Schmid factor for different grains around the crack initiation site, fatigue crack did not initiate from the grain with the largest Schmid factor. This result indicates that the Schmid factor cannot predict crack initiation in polycrystalline materials. Therefore, in order to predict fatigue crack initiation site, in addition to the Schmid factor, it will be necessary to use the finite element analysis for the polycrystal.

KEYWORDS:

Fatigue crack initiation, Schmid factor, Crystal plasticity FEM

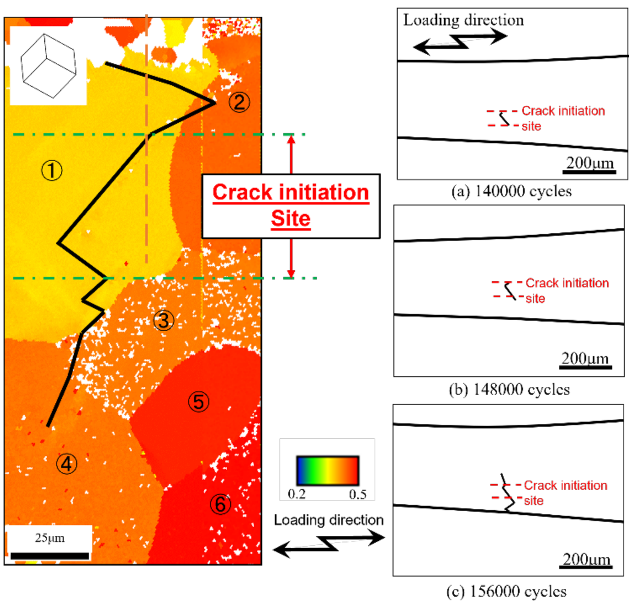


Fig. *SF-map* and crack initiation behavior.

R1-212

Low-cycle fatigue response of an equiatomic CrFeNi multi-principal element alloy

Shubham Sisodia[1], Maik Rajkowski[2], Guillaume Laplanche[2], and Ankur Chauhan[1, *]

[1] Department of Materials Engineering, Indian Institute of Science, Bengaluru, Karnataka-560012, India
[2] Institut für Werkstoffe, Ruhr-Universität Bochum, Bochum D-44801, Germany

* Corresponding author: ankurchauhan@iisc.ac.in

ABSTRACT:
For multi-principal element alloys (MPEAs) potential engineering applications, understanding their low-cycle fatigue (LCF) behavior is of decisive importance. Recently, an equiatomic face-centered cubic (FCC) CrFeNi has been shown to offer an excellent combination of monotonic properties. In the present study, we report on its LCF behavior at room temperature. Fully reversed strain-controlled fatigue tests were conducted in air under three different strain amplitudes (± 0.3%, ± 0.5% and ± 0.7%). The measured cyclic stress response reveals a rapid increase (i.e., cyclic hardening) followed by a relatively gradual decrease of peak stresses (i.e., cyclic softening) until failure. Electron microscopy investigations on post-fatigue samples revealed strain amplitude dependent dislocations slip-modes and resulting substructure evolutions. These observations are linked to the observed cyclic stress response and lifetime. Furthermore, the origin of CrFeNi's cyclic stress response is analyzed by partitioning hysteresis loops. Lastly, a comparison with similar grain-sized (60-67 µm) CoCrFeMnNi, and 316L alloys pinpoints the peculiarities of CrFeNi LCF response, which is discussed in terms of the difference in their solid solution strengthening, grain boundary strengthening and stacking fault energy.

KEYWORDS:
High-entropy alloys; Low-cycle fatigue; Dislocation structures; Effective stress; Back stress

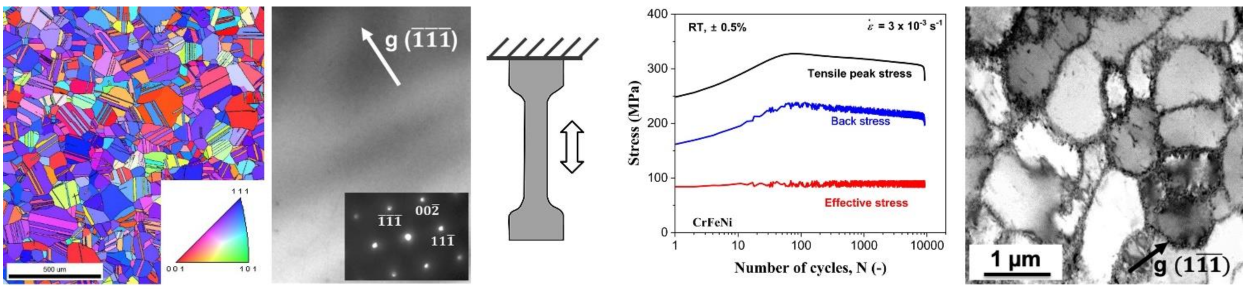


Fig. 1: Graphical abstract of the work showing (from left) EBSD orientation map, *TEM bright field micrograph from the undeformed sample; schematic of the LCF loading on the sample; Tensile, back, and effective stresses versus number of cycles plot, and TEM bright field micrograph from the deformed sample revealing dislocation structures.*

R1-213

Low cycle fatigue of a fully pearlitic steel

Laís ÁVILA de OLIVEIRA SILVA[1,2], Isadora Maria OLIVEIRA ANÍCIO COSTA[1,3]
Jean-Bernard VOGT[1]* and Jérémie BOUQUEREL[1]

[1]Centrale Lille Institute and CNRS, FRANCE
[2]now at Université de Lorraine, France
[3]now at CBMM BRAZIL

* Corresponding author: jean-bernard.vogt@centralelille.fr

ABSTRACT:
Fully pearlitic steels are composite materials consisting of two phases: cementite and ferrite. Pearlite is organized in a typical lamellar arrangement resulting from the cooperative growth of the Fe_3C phase and the α phase from the parent austenite phase. It is admitted that the mechanical properties are controlled by the interlamellar spacing, which is not completely true. It is more complex than that since the pearlite exhibits a hierarchical structure. Moreover, the fatigue behavior and the link with the microstructure are few documented. The present communication aims at investigating the effect of metallurgical features of pearlite on the low cycle fatigue behavior. This includes not only the interlamellar spacing but also the morphology of pearlite controlled by thermo-mechanical treatment. Dislocation motion was affected by the width of the ferrite phase and also by the likely variation in carbon partition in ferrite. The dislocation gliding in ferrite promoted more or less developed extrusions in ferrite (Figure 1). From FIB lamella extracted at the external surfaces of the specimen, it is proved that intrusions are formed in the ferrite from which crack nucleation started.

KEYWORDS:
Pearlite morphology; Cyclic plasticity; Cyclic accommodation; Extrusion/intrusion

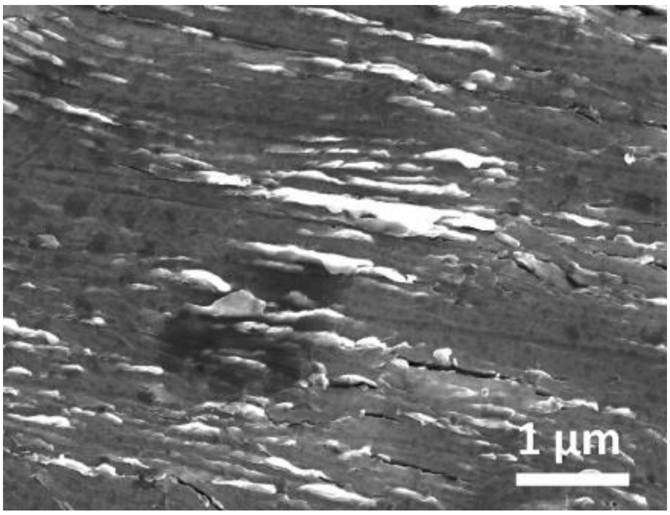


Fig. 1 *Fatigue slip bands and microcracks in the pearlite steel with large interlamellar spacing after fatigue at Δεt = 1.2%*

R1-214

Cyclic plasticity of a 9Ni steel

Mahira A. COTA ARAUJO[1,2], Jean-Bernard VOGT[1]* and Jérémie BOUQUEREL[1]

[1]Centrale Lille Institute and CNRS, FRANCE
[2]now at Villares Metals,BRAZIL

* Corresponding author: jean-bernard.vogt@centralelille.fr

ABSTRACT:
9Ni steels with a martensitic microstructure have also the particularity to contain an austenitic phase, either retained austenite or reversed austenite, depending on the heat treatment. A study of the low cycle fatigue behavior of a 9Ni steel after different tempering durations (water quench -no tempering, 1/2h and 10 h) was carried out. Strain-controlled LCF tests performed at room temperature revealed that the stress response to strain cycling was microstructural dependent and impacted the fatigue resistance (Figure 1). This included as well the amount and nature of the austenite as the microstructural state of the martensitic matrix. Fatigue extrusions were observed to emerge from martensite laths suggesting a huge contribution of the martensitic matrix in the accommodation of the plastic deformation. Fatigue crack also initiated from intrusions nucleated in the martensite laths. It was found that (retained or reversed) austenite plays an indirect role on the accommodation of cyclic plasticity, since a major part of austenite did not transform. Advanced microscopies allowed understanding the cyclic plasticity mechanism of the 9Ni steel. Dislocation gliding was facilitated in the martensite matrix with a predisposition to accumulate at lath boundaries. Austenite then allowed the flowing of matter along interfaces by a lubrication effect.

KEYWORDS:
Martensite; Cyclic plasticity; Crack nucleation; Extrusion/intrusion

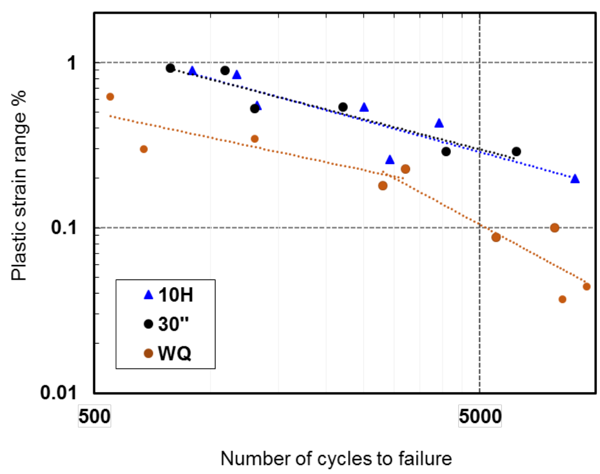


Fig. 1 *Fatigue life dependence on tempering duration*

R1-215

Secondary orientation effects on the low cycle fatigue behaviors of rectangular-sectional Ni-based single crystal superalloys at medium and high temperatures

Shao-Shi RUI[1], Zhiwu HE[2], Xianfeng MA[3,*] and Hui-Ji SHI[4,*]

[1] Institute of Mechanics, Chinese Academy of Sciences, CHINA
[2] Anker Innovations Technology Co., Ltd., CHINA
[3] Sun Yat-Sen University, CHINA
[4] Tsinghua University, CHINA

* Corresponding authors: maxf6@mail.sysu.edu.cn; shihj@mail.tsinghua.edu.cn

ABSTRACT:
Turbine blades made of Ni-based single crystal superalloys (NBSXs) have long-strip shaped cross sections and rectangular-sectional structures, where the secondary orientation produces potential effects even the primary orientation is fixed at [001]. Low cycle fatigue behaviors between [010] and [110] transversely oriented rectangular-sectional NBSX specimens were compared. Obvious differences existed under 600˚C but disappeared under 850˚C, with the deformation mechanism and fracture mode transitions. Secondary orientation effects on stress asymmetry and fatigue life cannot be described by conventional LCP model and critical plane method, but were well explained by dislocation path length dependent back-stress model and A.N. May's random slip model.

KEYWORDS:
NBSXs; secondary orientation effects; low cycle fatigue; stress asymmetry; fatigue life.

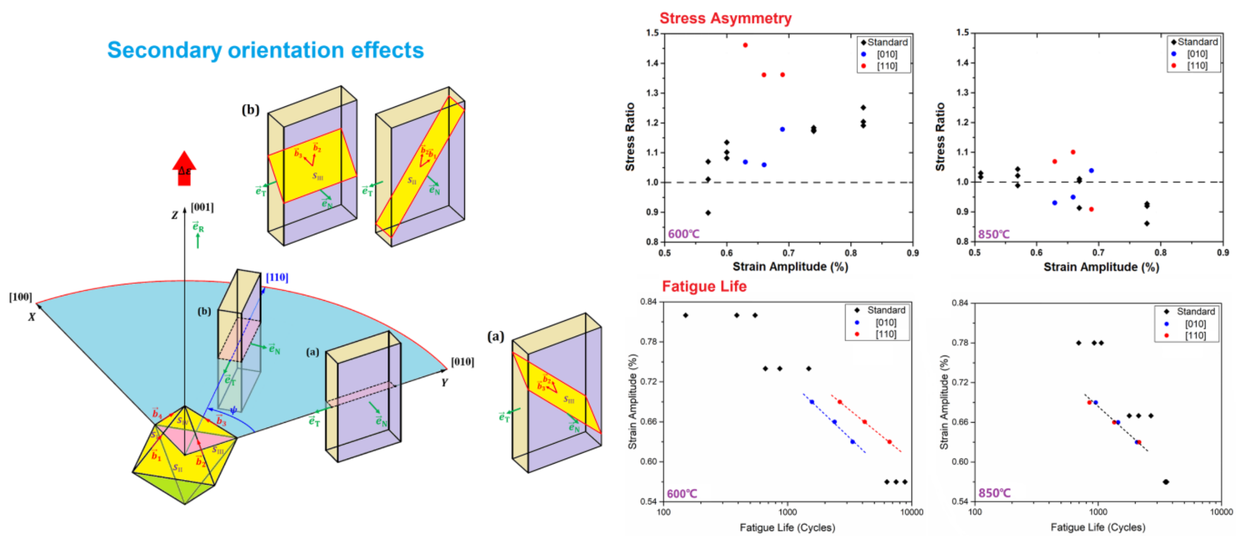


Fig. 1 Secondary orientation effects on *Stress Asymmetry* and *Fatigue Life* of NBSXS under 600˚C

R1-216

Improved fatigue resistance of heterogeneous materials: suppress strain localization and damage accumulation

Qingsong Pan[1] and Lei Lu[1]

[1] Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016

* Corresponding author: llu@imr.ac.cn

ABSTRACT:
The imposition of fluctuating mechanical loads on homogeneous crystalline metals and alloys leads to a continuous change in microstructure with increasing fatigue cycles. Generally, the surface roughening or strain localization serve as micro-notches where fatigue cracks nucleate and advance into the interior to eventually cause catastrophic failure. To address this issue, we presented that a thin superfificial layer of graded surface nanostructure over a coarse-grained core suppresses strain localization and surface roughening, thereby imparting unprecedented resistance to both low-cycle and high-cycle fatigue without compromising ductility. Progressive homogenization of the surface-graded copper is shown to be superior in fatigue properties compared to that of any of its homogeneous counterparts with micro-, submicro- or nanograined structures. Since the findings here for enhancing resistance to fatigue are broadly applicable to a wide spectrum of engineering metals and alloys, the results offer unique pathways to mitigate fatigue damage using a broad variety of processing routes in many practical applications. The challenges and prospects on exploring fatigue resistance of gradient nanostructured materials in the future are also addressed.

KEYWORDS:
Heterogeneous materials; Gradient structures; Fatigue property; Strain localization;

R1-217

Low-cycle fatigue behaviors of the nanostructured 316L stainless steels

Pengcheng Han, Qian Li and Nairong Tao

[1] Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Wenhua Road 72, Shenyang 110016, People's Republic of China

* Corresponding author: nrtao@imr.ac.cn

ABSTRACT:

We investigated the low-cycle fatigue behaviors (LCF) of both nanotwinned and nanostructured 316L stainless steels. The α'-martensitic transformation is activated to undertake the localized deformation of nanotwinned grains, and thus the fatigue strength and fatigue life in low-cycle fatigue are simultaneously enhanced. For the single-phase heterostructured 316L stainless steel consisting of recrystallized grains and nanostructures, the tensile ductility increases monotonically with increasing the volume fraction of recrystallized grains, while the strain-controlled LCF life first decreases and then increases, partially deviating from the monotonically increasing LCF-ductility relation. The reason is that the recrystallized grains with a low volume fraction (≤25 vol. %) in heterostructured 316L stainless steel sustain high cumulative plastic strain due to plastic strain partitioning, leading to cracking in the recrystallized grains at the early stages of LCF and thus reducing the LCF life.

KEYWORDS:

Nanostructure; 316L stainless steel; Low-cycle fatigue life; Ductility; Cumulative plastic strain

R1-218

Effect of Al on the Low-Cycle Fatigue Properties of Fe-Mn-C TWIP Steel

Lihe QIAN [1,2*]

[1] State Key Laboratory of Metastable Materials Science and Technology, Yanshan University, China
[2] National Engineering Research Center for Equipment and Technology of Cold Strip Rolling, Yanshan University, China

* Corresponding author: dlhqian@163.com

ABSTRACT:
High-Mn austenitic twinning-induced plasticity (TWIP) steels exhibit an excellent strength–ductility combination, primarily due to mechanical twinning that occurs during plastic deformation. Al is an effective alloying element to increase stacking fault energy (SFE). Al can be thus used to tune the SFE and control the occurrence of deformation twinning. Al has also been known to increase the resistance to delayed fracture of TWIP steels in hydrogen environment. However, the effect of Al on the low-cycle fatigue properties of TWIP Steel is not quite clear. In this work, the cyclic deformation behaviors and fatigue lifetimes in a Fe-Mn-C TWIP steel and a Fe-Mn-C-Al steel were comparatively investigated under total strain amplitude control. It is shown that, as compared with the control steel (i.e. Al-free steel), the Al-containing steel exhibits weaker cyclic hardening initially but severer cyclic softening at later-stage fatigue loading. Consequently, the Al-containing steel experiences larger cyclic plastic strain during the entire fatigue loading under any given total strain amplitude, in spite of its higher yield strength under monotonic tensile loading. Moreover, Al addition largely decreases the low-cycle fatigue lifetime, ascribed to the increased plastic strain accumulation and decreased crack growth resistance.

KEYWORDS:
Twinning-induced plasticity steel; Low-cycle fatigue; Cyclic deformation; Fatigue lifetime

R2-201

Characterization of low-cycle fatigue fracture surfaces of aluminum alloys at high-temperature using fractal dimension analysis

Kohei FUKUCHI[1,*], Ken-ichi OHGUCHI[1], Towa HAYASHIBE[1], Katsuhiko SASAKI[2], Yorimasa TSUBOTA[3], Takuro MITA[4], Wataru NAGAI[3], Kouji OHSATO[3] and Nobuaki SHINYA[3]

[1] Akita University, JAPAN
[2] Hokkaido University, JAPAN
[3] Isuzu Motors Limited, JAPAN
[4] Isuzu Advanced Engineering Center, Limited, JAPAN

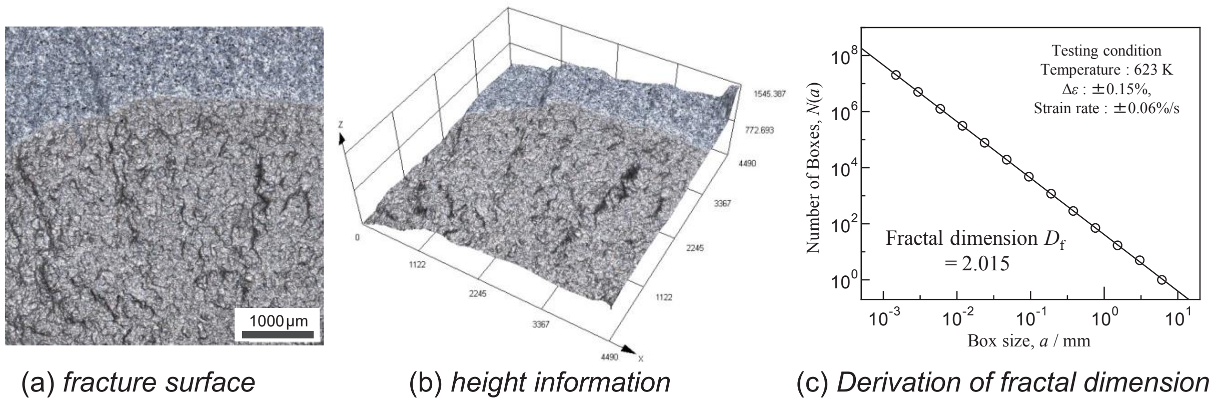
* Corresponding author: fukuchi@gipc.akita-u.ac.jp

ABSTRACT:

Aluminum alloy components used in automobile engines are subjected to cyclic loading in high-temperature ranges that exceed 1/2 of the melting temperature T_m of aluminum alloys. Thus, the fatigue resistance of aluminum alloys has been investigated. It is known that the fatigue life of aluminum alloys is strain-rate dependent. Therefore, it is considered that the condition of the fatigue fracture surface is also affected by the strain rate. However, there are few examples of quantitative evaluation of the fracture surface condition and investigation of the relationship between the value and the test conditions. In this study, we attempted to characterize the fracture surface using fractal dimension analysis, which is also used to evaluate the complexity of figures. First, low-cycle fatigue tests were conducted at 623 K, which was a higher temperature region than $T_m/2$ for aluminum alloys, with different strain rates for tensile and compressive processes. Next, fractal dimension analysis of the curved surface was performed using the box-counting method with the height information of the fracture surface. Then, it was investigated whether the fractal dimension can be used to characterize the fracture surface by examining the relationship between the numerical values obtained from the analysis and the testing conditions.

KEYWORDS:

Aluminum alloy; Low-cycle fatigue; Creep and plastic strain; Fracture surface; Fractal dimension analysis



(a) *fracture surface* (b) *height information* (c) *Derivation of fractal dimension*

Fig. 1 *Fractal dimension analysis using the box-counting method.*

R2-202

Acceleration of Creep-Fatigue Damage in Ni-Base Superalloy due to Viscoelasticity at Elevated Temperature by Considering Local Stress

Le Xu[1,*], Run-Zi Wang[1], Ken Suzuki[2], and Hideo Miura[1]

[1] Fracture and Reliability Research Institute, Graduate School of Engineering, Tohoku University, Sendai, Miyagi 980-8579, Japan
2 Green X-Tech Center, Green Goals Initiative, Tohoku University

* Corresponding author: lexu@rift.mech.tohoku.ac.jp

ABSTRACT:
Creep-fatigue interaction has been found to be the key restriction for increasing outputs of the components serving under cyclic loading at elevated temperatures. The accelerated intergranular cracking and reduced failure life caused by creep-fatigue loads strongly degraded the structural integrity of real components. Therefore, it is necessary to construct a damage evaluation model based on clear physical bases for the creep-fatigue interaction. In this study, intermittent creep-fatigue tests under stress-controlled loads were performed using Alloy 617. Based on the experimental results, a new constitutive model incorporating with creep-fatigue damages such as dislocation accumulation and grain boundary sliding was proposed to describe the variation of the local stress and damage. The experimental results showed that the fast unloading-rate led to large drop of failure life. Such decrease was explained by the degradation of the crystallinity of grain boundaries by dislocation accumulation and grain boundary sliding. The insufficient relaxation during fast unloading condition due to viscoelasticity and further fluctuation of local stress obtained by damage-incorporated constitutive model led to the accelerated the crystallinity degradation of grain boundaries. The strain accumulation and failure life decrease were well explained by the proposed damage-incorporated constitutive model as shown in Fig. 1.

KEYWORDS:
Creep-fatigue interaction; local stress; dislocation accumulation; grain boundary sliding; viscoelasticity.

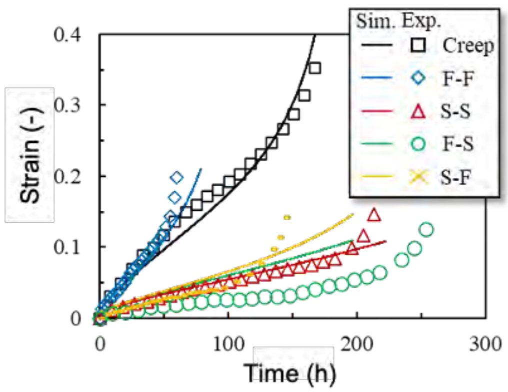


Fig. 1 *Strain-rate-induced variation of the creep-fatigue damage*

R2-203

Cold dwell fatigue response of aero-engine component titanium alloys: Influence of hold time and peak stress

Jianke QIU[1,2,*], Mengmeng ZHANG[1,2], Chao FANG[1,2], Jiafeng LEI[1,2] and Rui YANG[1,2]

[1] Institute of Metal Research, Chinese Academy of Sciences, CHINA
[2] School of Materials Science and Engineering, University of Science and Technology of China, CHINA

* Corresponding author: jkqiu@imr.ac.cn

ABSTRACT:
The accident to GP7270 engine in 2017 showed once again that the potential cold dwell fatigue failure in the titanium components of gas turbine engines is still a troublesome industrial issue. Based on the laboratory samples extracted from the aero-engine disc forgings of near-α IMI834 and Ti6242 alloys, the influences of hold time and peak stress on the dwell sensitivity have been investigated. The results demonstrated that relatively small microstructure variations could be significantly reflected in the dwell fatigue response by changing the dwell time. With the decrease of peak stress, the stress threshold value for the occurrence of dwell effect in titanium alloy was obtained. The failure features and deformation mechanism of the cold dwell fatigue were characterized using OM, SEM, XCT and TEM. The correlation between microstructure, external loading manner and dwell effect of titanium alloy forgings was experimentally presented. The results could be useful for the laboratory evaluation and the design consideration for the dwell effect of titanium alloys.

KEYWORDS:
Titanium alloy; Cold dwell fatigue; Fatigue fracture; Dislocation slip; Microtexture

R2-204

Molecular Dynamics Analysis of the Acceleration Mechanism of the Degradation of Grain Boundary Strength in Alloy GH4169 Caused by δ-Phase Precipitation

Takuto KUDO[1], Ken SUZUKI[2], Run-Zi Wang[3], and Hideo MIURA[3]

[1] Department of Finemechanics, Graduate School of Engineering, Tohoku University, JAPAN
[2] Green X-Tech Center, Green Goals Initiative, Tohoku University, JAPAN
[3] Fracture and Reliability Research Institute, Graduate School of Engineering, Tohoku University, JAPAN

* Corresponding author: takuto.kudo.r5@dc.tohoku.ac.jp

ABSTRACT:

Nickel-based superalloys used in gas turbine disks are required to operate under frequent random change of output at elevated temperatures. It was found that the crystallinity and fracture time of the alloys were degraded drastically due to the acceleration of intergranular cracking. In particular, accumulation of fine voids around the interface between the precipitate and matrix accelerated the high temperature damage. In this study, molecular dynamics analysis was applied to the clarification of the acceleration mechanism observed in GH4169, which is one of the representative alloys for jet engines. At temperatures higher than 650°C, d-phase started to grow around grain boundaries, and the accumulation of fine voids around the interface between the d-phase and matrix accelerated intergranular cracking. The degradation process of the crystallinity around the interface was analyzed as shown in Fig. 1. The main reason for the degradation was attributed to the acceleration of the outdiffusion of component elements from the interface for relaxing the localized strain energy caused by the large lattice mismatch between the precipitate and matrix. The integrity of the interface was degraded drastically at elevated temperatures due to the drastic decrease of the activation energy of the self-diffusion only around the interface.

KEYWORDS:

δ-phase; GH4169; Molecular Dynamics; Creep-Fatigue Damage; Ni-base Alloy

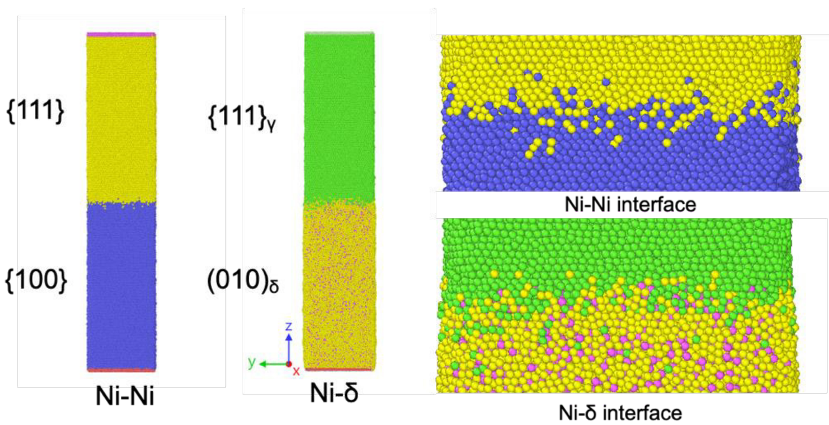


Fig. 1 Molecular dynamics analysis on the degradation process of the integrity of a grain boundary and interface

R2-205

Modified Kitagawa-Takahashi Approach for Improved Lifetime Prediction under Creep-Fatigue Loading of Polycrystalline Gas Turbine Components

Oliver JORDAN[1,*], Tuan Duc NGUYEN[2], Philipp LION[1] and Tilmann BECK[1]

[1] Institute of Materials Science and Engineering, RPTU Kaiserslautern-Landau, Germany
[2] Siemens Energy, Mülheim a.d. Ruhr, Germany

* Corresponding author: o.jordan@mv.rptu.de

ABSTRACT:

Polycrystalline nickel-base alloy gas turbine components used in the rear turbine stages are subjected to a complex combination of creep and fatigue loading, due to high centrifugal forces at high temperatures, resonances, and vibration excitations. Creep-induced deformation leads to the formation, growth, and coalescence of pores at unfavorably oriented grain boundaries perpendicular to the loading direction. While the conventional Kitagawa-Takahashi (KT) approach addresses the critical defect size depending on the applied stress amplitude, above which fatigue crack initiation and propagation can occur, the new Kitagawa-Takahashi with Creep (KTC) method presented here integrates the creep-fatigue interaction to enhance the lifetime prediction of polycrystalline components. Therefore, a probabilistic creep pore model was developed to simulate the pore size distribution. These distributions are validated by experimental data and computer tomographic investigations. To verify the KTC lifetime predictions, an isothermal high temperature Alloy 247 test series (T = 900°C) with high superimposed mean stresses (R = 0.5) was performed. Comparing the lifetime prediction of the KTC method with the experimental results, it becomes clear that the method is useful to determine the influence of creep-induced, time-dependent defects, i.e., pores, on the fatigue behavior, which can improve the design of creep-fatigue loaded polycrystalline components.

KEYWORDS:

Creep; Creep-fatigue; creep cavitation; Kitagawa-Takahashi; nickel-base superalloy

NOTE:

The presentations by myself, Oliver Jordan, and the presentation by Tuan Duc Nguyen entitled "Probabilistic Modelling of creep-fatigue interaction in polycrystalline nickel-base alloy based on the Kitagawa-Takahashi diagram" are complementary. Please plan the lectures in a way that Mr. Nguyen gives his lecture after mine. Thank you very much.

R2-206

Probabilistic Modelling of creep-fatigue interaction in polycrystalline Nickel-base alloy based on the Kitagawa-Takahashi diagram

Tuan Duc NGUYEN[1,*], Oliver JORDAN[3], Lucas MAEDE[2], Tilmann BECK[3], and Dirk KULAWINSKI[1]

[1] Siemens Energy, Mülheim a.d. Ruhr, Germany
[2] Siemens Energy, Berlin, Germany
[3] Institute of Materials Science and Engineering, RPTU Kaiserslautern-Landau, Germany

* Corresponding author: tuan.nguyen@siemens-energy.com

ABSTRACT:

The Kitagawa-Takahashi (KT) diagram and the El Haddad equation are widely used to predict the allowable stress range $\Delta\sigma$ for a defect size a. This approach divides the regions into a non-propagation and propagation of short and long cracks, or alternatively, it describes the transition between the infinite and finite life region. The KT diagram is not capable to describe the damage under creep conditions, as the self-arrest condition for fatigue-crack propagation is invalid and must be considered as time dependent. In this study, the Kitagawa-Takahashi method is adapted to take the creep damage into account by modelling of the increasing defect sizes of creep pores over time. This new approach is suitable to characterize the interaction of creep-fatigue loading. The proposed Kitagawa-Takahashi with Creep (KTC) method combines pore size distributions predicted by a probabilistic creep pore model as well as the El Haddad equation. Within this work, a temperature and R-Ratio model for the KTC diagram is presented and validated with creep-fatigue experiments as well as HCF test at pre-crept specimens from the polycrystalline Nickel-base Alloy 247.

KEYWORDS:

Kitagawa-Takahashi diagram; Creep-fatigue; Fatigue-crack; creep cavitation; Nickel-base superalloy

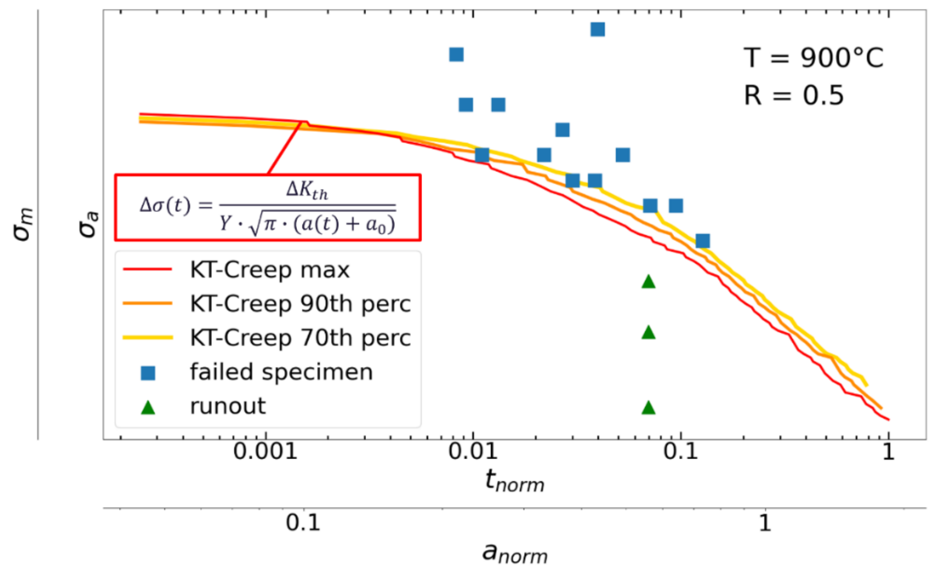


Fig. 1 *Novel Kitagawa-Takahashi with Creep approach with different pore size percentiles as* $a(t)$*.*

R2-213

Transition from crack retardation to acceleration under high temperature dwell-fatigue loading in a wrought Ni-base superalloy

Shiyu SUZUKI[1,2]*, Hayato MATSUOKA[2], Qihe ZHANG[2], Itsuki SASAKURA[2], Motoki SAKAGUCHI[2]

[1] Japan Aerospace Exploration Agency (JAXA), JAPAN
[2] Tokyo Institute of Technology, JAPAN

* Corresponding author: suzuki.shiyuu@jaxa.jp

ABSTRACT:

Effect of tension dwell load on crack propagation under the subsequent fatigue loading during dwell-fatigue crack propagation in a wrought Ni-base superalloy, Inconel 718, was investigated both experimentally and numerically. Crack propagation tests were conducted by applying single tension dwell load during pure fatigue loading with various conditions of stress intensity factor K and dwell time. When the K value was high ($K \geq 12$ MPam$^{1/2}$), fatigue crack acceleration occurred along grain boundaries after the dwell load (Fig. 1(a)). Contrarily, when the K value was low ($K \leq 16.7$ MPam$^{1/2}$), fatigue crack retardation occurred after the dwell load (Fig. 1(b)). The acceleration was attributed to stress-assisted oxygen diffusion along grain boundaries caused by the tension dwell load and resultant grain boundary embrittlement based on results of the spectroscopic analysis on fracture surfaces. On the other hand, the retardation was attributed to stress relaxation induced by creep deformation and resultant compressive residual stress based on results of finite element analyses. The transition from the retardation to the acceleration depending on the K value was rationalized based on a simple comparison between sizes of the compressive residual stress field and grain boundary embrittlement area around of the crack tip (Fig. 1(c)).

KEYWORDS:

Ni-base superalloy; Dwell-fatigue crack propagation; Grain boundary damage; Creep deformation; Compressive residual stress

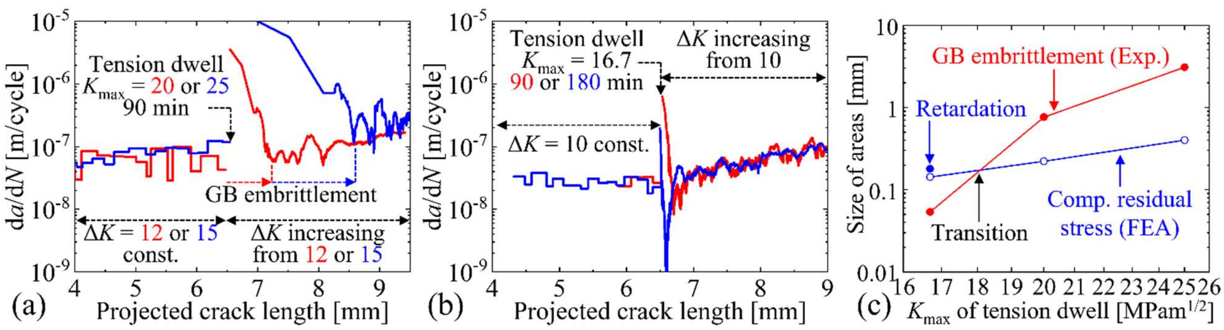


Fig. 1 (a) Acceleration after dwell load with high K value. (b) Retardation after dwell load with low K value. (c) Size comparison between grain boundary embrittlement area and compressive residual stress area.

R2-214

Evaluation of fatigue and creep-fatigue damage levels on the basis of engineering damage mechanics approach

Li Sun[1], Run-Zi Wang[1,2], Xian-Cheng Zhang[1,*] and Shan-Tung Tu[1,*]

[1] Key Laboratory of Pressure Systems and Safety, Ministry of Education, East China University of Science and Technology, P.R. CHINA
[2] Fracture and Reliability Research Institute, Graduate School of Engineering, Tohoku University, JAPAN

* Corresponding author: xczhang@ecust.edu.cn; sttu@ecust.edu.cn

ABSTRACT:
Progressive degradation of material mechanical properties in the low cycle fatigue (LCF) and creep-fatigue (CF) interaction at high temperature affects the safe operation of in-service materials. The present work aims to develop a method for evaluating LCF and CF damage levels by considering material degradation, which is applied to reliability assessment using cumulative damage-damage threshold interference principle. Material-level data accumulations as well as theoretical foundations of LCF and CF are presented, including interrupted LCF and CF tests, subsequent tensile tests and energy-based damage models. Damage summation rules representing mechanical property degradation is proposed based on the tensile plastic strain energy. A new three-dimensional (3D) damage interaction diagram is established, where the additional third axis indicates the material degradation level. Finally, with the help of finite element analysis, a procedure of reliability assessment is executed for a low-pressure turbine disk based on the probabilistic damage and damage threshold distributions.

KEYWORDS:
Creep-fatigue; Mechanical properties degradation; Damage level evaluation; Reliability assessment

R2-215

Acceleration Mechanism of Intergranular Cracking of Stainless Steel SUS316LN at Elevated Temperature Caused by Local Strain Energy Around Grain Boundaries

Ayane YASUMURA[1*], Ken SUZUKI[2], and Hideo MIURA[3]

[1] Department of Finemechanics, Graduate School of Engineering, Tohoku University, Sendai, Miyagi, JAPAN
[2] Green X-Tech Center, Green Goals Initiative, Tohoku University, JAPAN
[3] Fracture and Reliability Research Institute, Graduate School of Engineering, Tohoku University, JAPAN

* Corresponding author: ayane.yasumura.p4@dc.tohoku.ac.jp

ABSTRACT:

Nuclear power generation is still expected to play an important role for achieving carbon neutrality. The generation IV nuclear power system, which is currently under development, uses liquid sodium as coolant and its operating temperature will be 550°C, which is higher than that of conventional reactors. Stainless steel SUS316LN is a candidate material for pressure vessels and pipes because of its high corrosion resistance against liquid sodium. The fracture life of alloys under high pressure environment at elevated temperatures, however, was found to significantly decrease due to the acceleration of intergranular cracking. The acceleration of generation and accumulation of voids and dislocations near grain boundaries caused the significant decrease in its fracture life. The generation and accumulation of voids were caused by the outdiffusion of constituent atoms from the grain boundaries during the energy release process of the local strain concentration field caused by the lattice mismatch between crystals adjacent to the grain boundaries. In this study, the degradation process was visualized by EBSD analyses as shown in Fig. 1 and the change in the activation energy of the local atomic diffusion was explained by the modified Arrhenius equation considering the stress-induced acceleration of the diffusion quantitatively.

KEYWORDS:

SUS316LN, Creep damage, Crystallinity, EBSD analysis, intergranular fracture

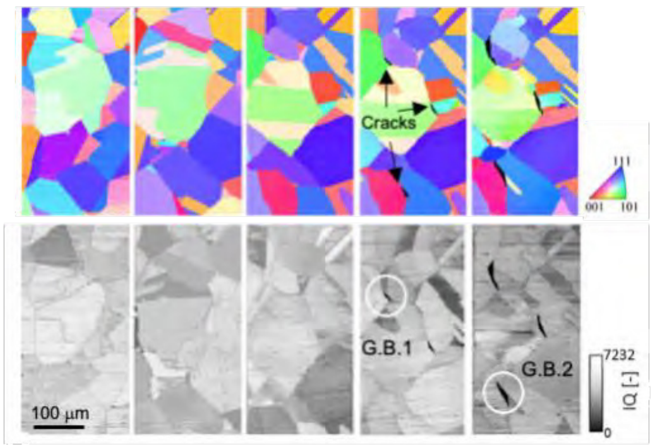


Fig. 1 *Visualization of the degradation process of the local crystallinity (IQ value) of SUS316LN*

R2-216

Cyclic deformation behaviors and damage mechanisms in P92 steel under creep-fatigue: Effects of hold condition and oxidation

Kang-Kang Wang[1], Jian-Feng Wen[1], Run-Zi Wang[2], Xian-Cheng Zhang[1], Shan-Tung Tu[1*]

[1] Key Laboratory of Pressure Systems and Safety, Ministry of Education, East China University of Science and Technology, Shanghai 200237, China
[2] Fracture and Reliability Research Institute, Graduate School of Engineering, Tohoku University, Sendai, Miyagi 980-8579, Japan
* Corresponding author: sttu@ecust.edu.cn (S.T. Tu)

ABSTRACT:

The increasing demand in improving the energy conversion efficiency of power plants has prompted significant interest in P92 steel as a leading candidate material for steam generator components and main steam tubes. However, the interaction of creep and fatigue damage caused by typical dwell fatigue loading conditions limits its service lifetime and triggers premature failure. In this research, the general creep-fatigue behaviors of P92 steel were investigated under strain-controlled cyclic testing at 873K in air. Particular attention was paid to the influence of hold position, hold time and oxidation on both cyclic deformation behaviors and damage mechanisms. Results revealed that introducing hold time reduced the number of cycles to failure, with compressive hold causing more damage than tensile hold. Based on metallographic observations, oxidation becomes more severe with increasing hold time, resulting in increased surface roughness, number of crack initiation sites and density of secondary cracks. Furthermore, a three-dimensional oxidation-creep-fatigue damage interaction diagram is proposed to achieve quantitative assessment in practice. This research provides new insights for ensuring the safe operation of critical components subjected to mechanical-environmental attacks.

KEYWORDS:

P92 steel; Creep-fatigue; Oxidation; Damage interaction diagram

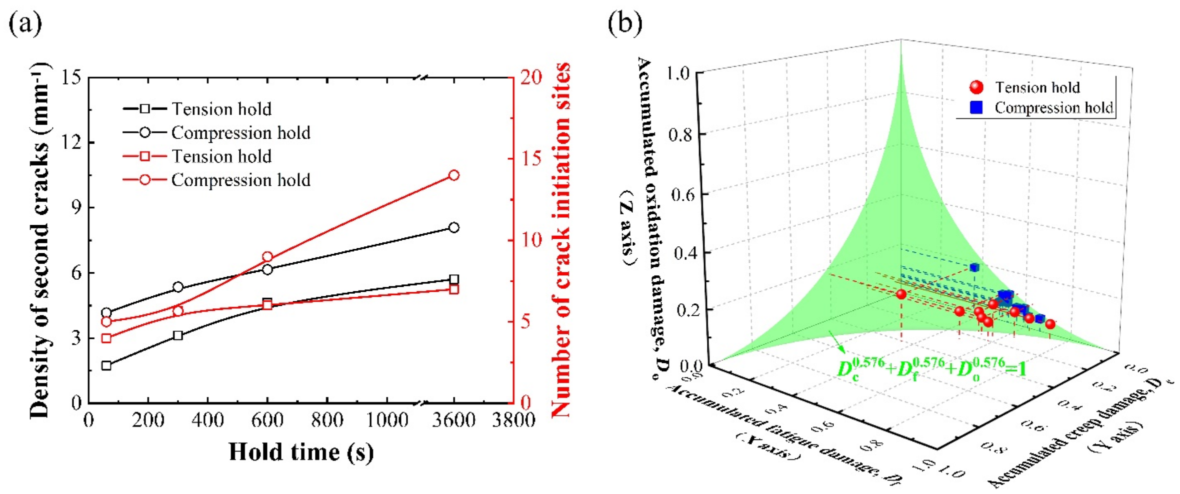


Fig. 1 (a) Variations of crack initiation site and second crack under different holding conditions, (b) proposed three-dimensional oxidation-creep-fatigue damage interaction diagram.

R2-217

Numerical Analysis of P91 notched specimen by damage-coupled inelastic constitutive model

Daisuke KASHIWAGI[1,*], Kazuma OKUNO[2] and Masayuki ARAI[3]

[1] Tokyo University of Science, JAPAN
[2] Tokyo University of Science, JAPAN
[3] Tokyo University of Science, JAPAN

* Corresponding author: 4522508@ed.tus.ac.jp

ABSTRACT:

In major high-temperature components of thermal power plants, fatigue damage due to starting and stopping operation and creep damage due to steady operation accumulate with operating time. The creep-fatigue damage is mainly localized at the geometry discontinuities such as circular holes and notches involved in high-temperature components. It is therefore necessary to accurately estimate the accumulation of creep-fatigue damage and the crack initiation lifetime at the geometry discontinuities in high-temperature components. In this study, a damage-coupled inelastic constitutive model is developed for P91 steel, which is used in thermal power plants, by coupling the Chaboche-type constitutive model and damage evolution equation. The developed constitutive model was incorporated into the commercialized finite element analysis software MARC. Additionally, a crack propagation algorithm was developed based on the non-localization theory using the damage parameter. Fig.1 shows an example of the creep-fatigue analysis results for the circumferentially notched bar specimen. It was confirmed that the crack initiation and propagation behavior from the notch was properly simulated.

KEYWORDS:

P91 steel, Creep-fatigue, Multiaxial stress, damage-coupled inelastic constitutive model, Numerical Analysis.

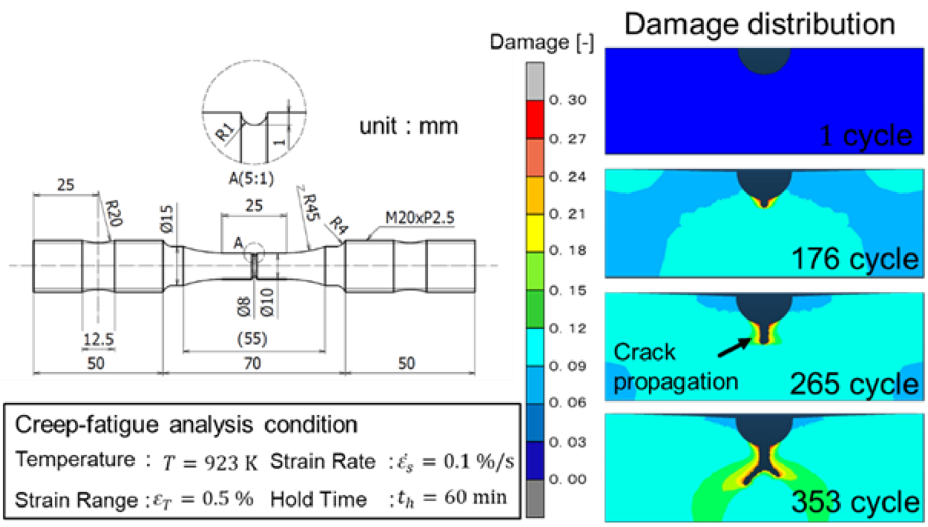


Fig. 1 *Creep-fatigue analysis result of circumferentially notched bar specimen.*

P-301

Activities of Fatigue design and Evaluation Committee in Society of Automotive engineers of Japan.

Toshiaki NAKAMARU[1,*] , Takuya YUASA[1]

[1] Nissan Motor Co., LTD.

* Corresponding author: t-nakamaru@mail.nissan.co.jp

ABSTRACT:

The Fatigue Deign and Evaluation Committee (FD&E) in Society of Automotive engineers of Japan (JSAE) is studying the fatigue evaluation and design methods for various joint structure, several welds, Self-piercing Rivet (SPR) and adhesive bonding around 50 years. The activities in FD&E are divided into 4 main periods. In 1st period, spot welding joint (SW) was mainly focused and fatigue evaluation was implemented by structure specimen. In addition, fracture mechanics was applied for SW. In 2nd period, fatigue life prediction methods were studied for SW and arc welding (Arc). As a results, Normal structural stress for SW and Cyclic plastic zone size (ω *) for Arc were developed. Then, Fatigue test method was improved to apply high-tensile strength steel, laser and SPR joints in 3rd period. Furthermore, the studies on adhesive bonding began in earnest during this period.

In 4th period, new fatigue test method specific to car body structure was proposed and adhesive bonding research expanded from initial condition to time-related deterioration.

And FD&E are continuing the research on the fatigue strength with a focus on adhesion for multi-materials body structure. In this report, major results in each period are introduced and explain some deliverables in 4th period.

KEYWORDS: Fatigue strength, Welding joint, Adhesive joint, Fatigue test

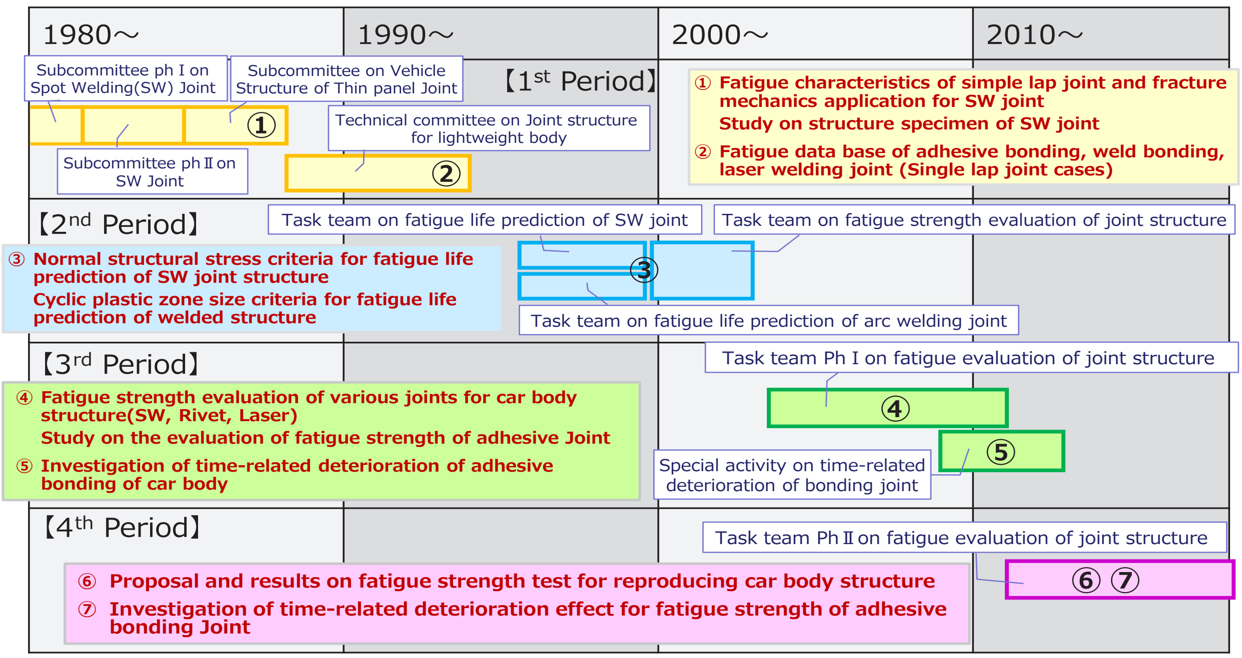


Fig. 1 History of FD&E activities.

P-302

Evaluation of Fatigue Characteristics of CFRP Bonding Materials by Urethane Adhesive

Masayuki OSADA*[1], Toshiaki NAKAMARU[2], Hiroyuki AKEBONO[1], Atsushi SUGETA[1],

[1] Hiroshima University, JAPAN
[2] Nissan Motor Co., *Ltd.*, JAPAN

* Corresponding author: m235274@hiroshima-u.ac.jp

ABSTRACT:
CFRP is one of important materials of body structure for weight reduction. Adhesive joint is the key technology for multi material body structure and urethane adhesive should be studied for the fatigue strength of CFRP structure. In this study, a static tensile test and a fatigue test were performed to evaluate the strength of joints using urethane adhesives. Two types of joints (*CF/CF joint*, which joins CFRP together, and *CF/ST joint*, which joins CFRP and high-strength steel) were used in the experiment. Furthermore, the fatigue crack propagation behavior was investigated from the cross-sectional observation results and strain data. Although voids in the adhesive were occurred at the time of making specimen, no influence of static and fatigue strength was observed. The fatigue life of the *CF/ST joint* exceeded that of the *CF/CF joint* in the high applied force range, but there was no difference in fatigue strength in the low force range. The cohesive failure rate decreased in the low applied force range for both joints. As a result of strain behavior and cross-section observation, fatigue crack was occurred at the very early cycles of fatigue test.

KEYWORDS: CFRP, Adhesive, Urethane, Fatigue, Crack

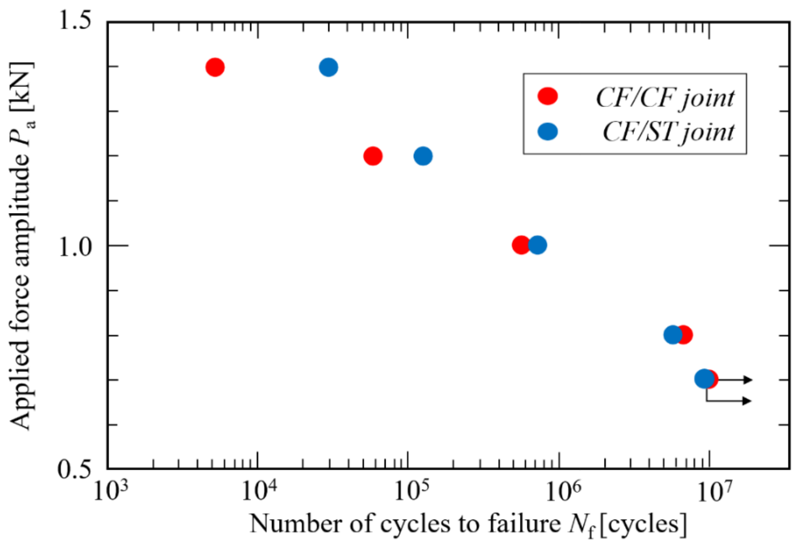


Fig. Results of fatigue test.

Fig. 1 S-N curve

P-303

Investigation of the Effects of Adherend Materials and Epoxy Adhesive Properties on the Fatigue Strength

Hiroaki KAWAMURA[1,*], Takahiro SUZUKI[2], Toshio KOBAYASHI[3], Toshiaki INOUE[3], Takefumi MURAI[3], Kazuo HATTORI[4], Naoaki MUNEMURA[5], Akihiko TATSUMI[6], Hiroyuki OGUMA[7] and Yoshihiko UEMATSU[8]

[1] Toyota Motor Corporation, JAPAN
[2] Toyota Auto Body, JAPAN
[3] Sunstar Engineering, JAPAN
[4] Aisin Chemical Co., Ltd., JAPAN
[5] JFE Steel Corporation, JAPAN
[6] Kobe Steel, JAPAN
[7] National Institute for Materials Science, JAPAN
[8] Gifu University, JAPAN

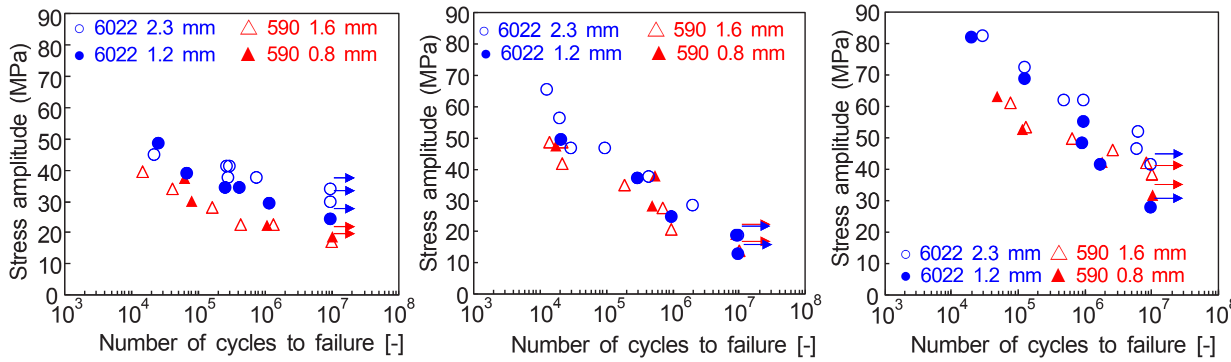
* Corresponding author: hiroaki_kawamura@mail.toyota.co.jp

ABSTRACT:

This paper repots the investigation results for the fatigue strength about the influence of the material of adherends (590 MPa class cold-rolled steel or 6022 aluminum), sheet thickness, and type of adhesive bonds. Recently, non-ferrous metals are adopted for lightweight automotive bodies. Adhesive bonding has advantages to joining different materials. It is important to clarify the fatigue properties of the adhesive bonding in the car body. In this paper, fatigue tests are carried out, and investigated the fatigue properties using numerical analysis. Three kinds of adhesive bonds are compared in the fatigue tests. Figure 1 shows the relationship between principal stress amplitude from numerical simulations and the number of cycles to failure. Using principal stress at the bonding edge in the adhesive layer, we can obtain one S-N curve for steel/aluminum coupons for each adhesive type.

KEYWORDS:

Epoxy Adhesives; Joining; Fracture; Finite Element Method



(a) Adhesive A (b) Adhesive B (c) Adhesive C

Fig. 1 Fatigue results using principal stress at adhesive layer

P-304

Investigation of the effects of adhesive edge shape and Adherend stiffness on fatigue strength of adhesive bonded specimens

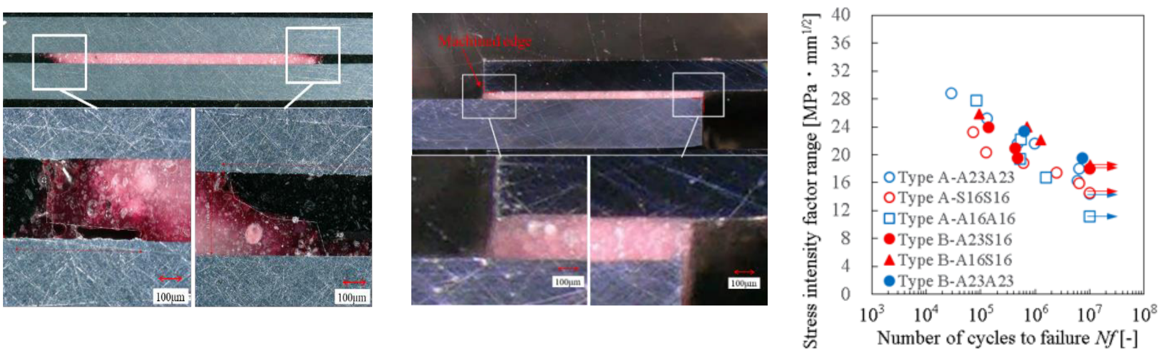
Masashi INOUE[1,*], Atsushi SHIMAZAKI[2], Kouhei YAMAMOTO[3], Eiji SAKAI[4], Takahiro MIYAWAKI[4], Teppei OE[5], Hiroyuki OGUMA[6], Atsushi SUGETA[7] and Izuru NISHIKAWA[8]

[1] Toyota Industries Corporation, JAPAN
[2] Toyota Motor Kyushu Corporation, JAPAN
[3] Yamaha Motor Corporation, JAPAN
[4] Mitsubishi Motors Corporation, JAPAN
[5] Mazda Motor Corporation, JAPAN
[6] National Institute for Materials Science, JAPAN
[7] Hiroshima University, JAPAN
[8] Osaka Institute of Technology, JAPAN

* Corresponding author:masashi.inoue@mail.toyota-shokki.co.jp

ABSTRACT:
This paper reports the investigation results for the fatigue strength about the influence of the material of adherends, sheet thickness, and adhesive edge shape. Recently, non-ferrous metals are adopted for lightweight automotive bodies. Adhesive bonding has advantages to joining different materials. Adhesive bonding is suitable for dissimilar materials joining. However, there are many factors affect strength reliability, and it is necessary to expand the knowledge of reliability evaluation methods. In this paper, fatigue tests are carried out to control the specifications that are expected to affect fatigue life, and investigated the fatigue properties using numerical analysis. Two bonding methods having different of adhesive edge shape and combination of several adherend materials and thicknesses are compared in the fatigue tests. Figure 1 shows the comparison of adhesive edge shape and the fatigue test result. Although there are differences in the edge shape of adhesive between both type specimens, no significant differences are observed in the test results.

KEYWORDS:
Material; Adhesive; Fatigue; Adhesive edge shape; Fatigue strength



(a) Adhesive edge shape of Type A (b) Adhesive edge shape of Type B (c) Fatigue test results

Fig. 1 Adhesive edges of both Type specimen and the fatigue test results

P-307

The Cyclic R-Curve for Predicting Growth and Arrest of Short Cracks

Keisuke TANAKA[1,*] and Yoshiaki AKINIWA [2]

[1] Nagoya University, Nishinomiya 662-0037, JAPAN
[2] Yokohama National University, Yokohama 240-8501, JAPAN

* Corresponding author: tanakakt@sirius.ocn.ne.jp

ABSTRACT:

The fatigue limit of components with sharp notches or small defects is controlled by crack propagation not by crack initiation. To predict the nonpropagation of small cracks, the present authors proposed the cyclic R-curve method based on the bulidup of crack closure with crack extension (1988,1997). The cyclic R-curve has been successfully applied in predicting the fatigue limits of materials with defects and notches. In order to examine systematically the effects of precrack length and material yield stress on fatigue thresholds, a strip-yield model is applied to simulate the buildup of plasticity-induced crack closure with crack extension from precracks with various lengths. Two types of precracks are examined: open precracks which remain open even under cyclic compression, and closed precracks which may close under compression. Assuming a constant threshold value of ΔKeff for steels, new master curve equations are proposed for the cyclic R-curve. The effects of the precrack type and material yield strength on fatigue thresholds is successfully derived for different precrack lengths. Fig. 1 shows the opening stress intensity factor ΔK_{opth} vs crack extension till arrest Δa_{np} for open precracks under fully reversed loading. The R-curve is confirmed to be independent of the precrack length.

KEYWORDS:

Short crack propagation; Crack closure; Crack growth threshold; Fatigue limit; Strip-yield model

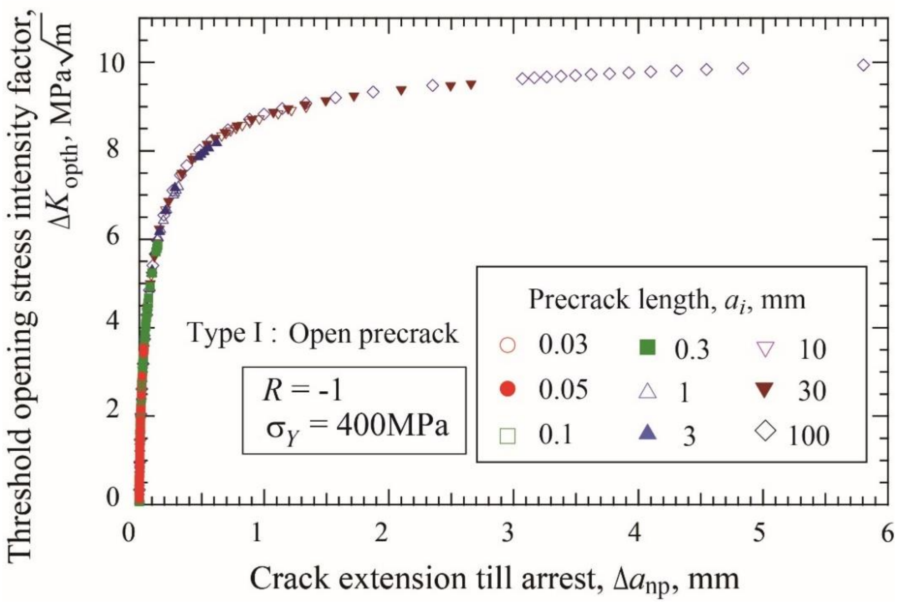


Fig. 1 Effect of precrack length on the relation between ΔK_{opth} and Δa_{np} for steels under R = -1.

P-309

Influence of exposure to moist air on the fatigue striation formation in a 7175 7351 alloy

Sarah SAANOUNI[1], Thomas BILLAUDEAU[2], Manuel de ARAUJO[2], Jérôme ROUSSET[2], Hadi BAHSOUN[1], Patrick VILLECHAISE[1] and Gilbert HÉNAFF[1]

[1] Institut Pprime, FRANCE
[2] Airbus Operations SAS, FRANCE

* Corresponding author: gilbert.henaff@isae-ensma.fr

ABSTRACT:

The effect of the exposure to moist air on the fatigue crack growth in 7175 T7351 aluminium alloy is investigated, with a special attention paid to the crack-tip deformation mechanisms. Two extreme fatigue crack growth conditions have been considered with this aim, namely a moist air and at low loading frequency, corresponding to a high exposure rate, and a low exposure rate condition obtained in an inert atmosphere. Observations of the corresponding fracture surfaces along with subsurface deformation structures indicate that a high exposure rate induces the development of a thin surface layer divided into subdomains characterized with a pronounced and highly localized lattice rotation. In contrast, under very low exposure rate, a significantly lower lattice rotation associated with a smoother gradient is observed. A scenario of striation formation is proposed on the basis of an enhancement of lattice rotation by highly accumulated hydrogen atoms resulting from the dissociation of adsorbed molecules. Furthermore, a one-to-one correspondence between the striation spacing on the hand, and the distance separating two successive subdomains exhibiting the highest lattice disorientation on the other hand, is established.

KEYWORDS:

Fatigue crack propagation; striation; water vapour; hydrogen; EBSD

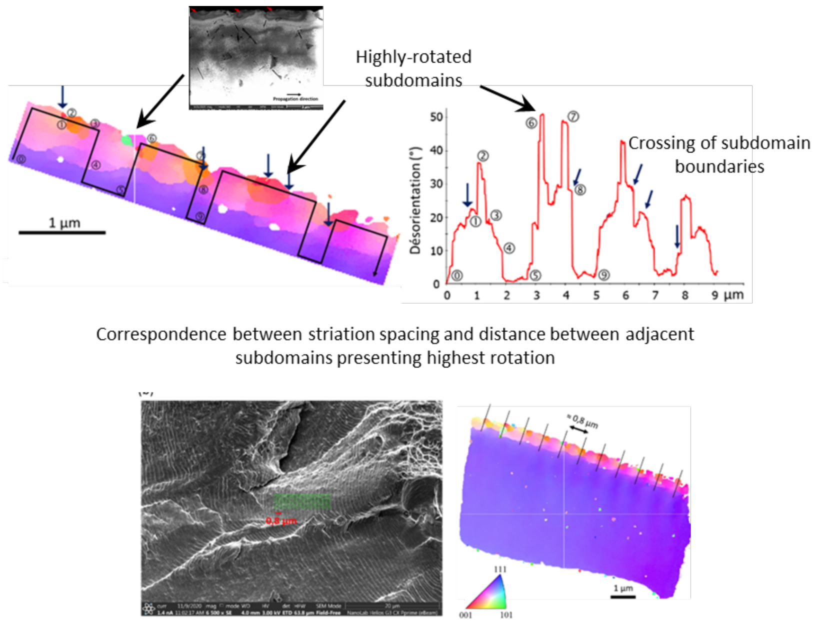


Fig. 1 *Graphical abstract.*

P-310

A physically small crack growth model based on CTOD

Lu Han[1], Lindong Chai, Weifang Zhang[1] and Wei Zhang[1,*]

[1] Beihang University, CHINA

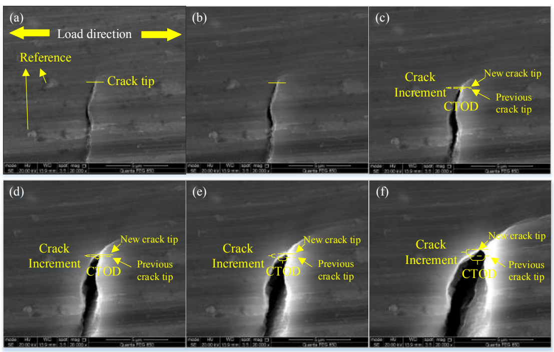
* Corresponding author: zhangwei.dse@buaa.edu.cn

ABSTRACT:

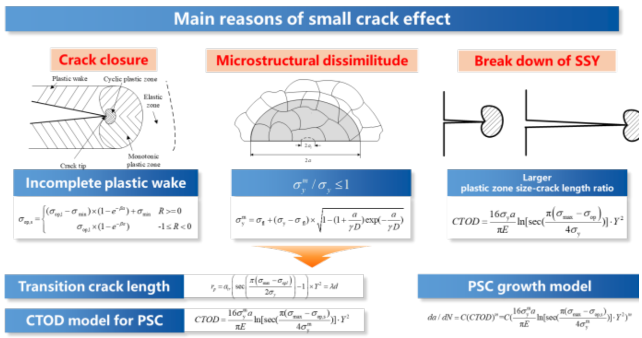
In this study, a prediction model driven by crack tip opening displacement (CTOD) is proposed to account for the physically small crack growth. Firstly, an in-situ SEM testing indicate that CTOD can be a unique crack growth driven parameter. Then, considering the difference of crack closure and crack tip plasticity between small cracks and long cracks, the CTOD model for physically small cracks is developed by modifying Dugdale's model. Subsequently, a crack growth model is established for both of the small cracks and long cracks. In addition, a criterion of the transition crack length from physically small cracks to long cracks is given. Finally, several datasets of different alloys are used to validate the proposed model. For the materials involved in the current study, the model predictions agree well with the experimental data. And the calculated transition crack length is approximately consistent with that estimated from the experimental data trend.

KEYWORDS:

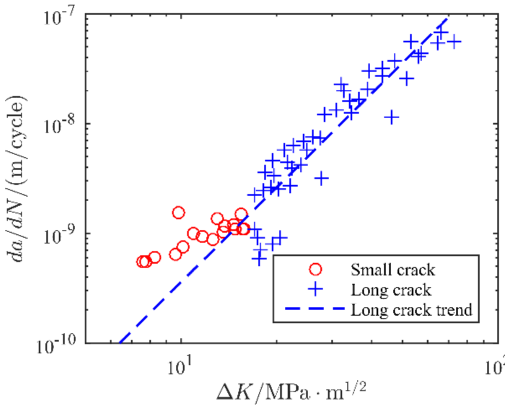
Physically small cracks; Crack tip opening displacement; crack closure; Microstructural dissimilitude; Crack growth model



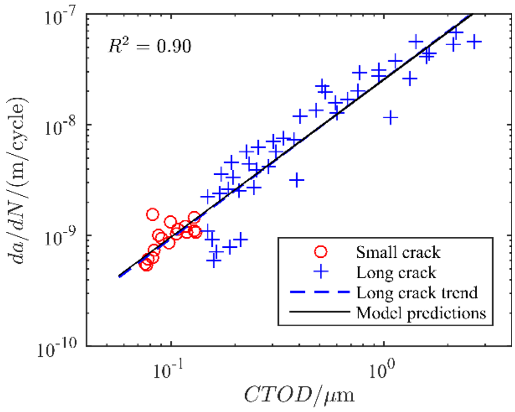
(a)Crack increment and CTOD during loading cycle



(b)PSC crack growth model



(c)da/dN versus ΔK(GH4169)



(c)da/dN versus CTOD(GH4169)

Fig. 1 Modeling and some results

P-311

The migration of geometrically necessary dislocation density localisation at crack tip in short crack growth of zirconium

Weifeng Wan [1],*, Yilun Xu [2]

[1] School of Energy and Power Engineering, Beihang University, Beijing 100191, China

[2] Institute of High Performance Computing (IHPC), Agency for Science, Technology and Research (A*STAR), 1 Fusionopolis Way, #16-16 Connexis, Singapore 138632, Republic of Singapore

* Corresponding author: Weifeng Wan (wanweifeng@buaa.edu.cn)

ABSTRACT:

Microcracks in a zirconium beam sample was induced through a three-point bending fatigue test at room temperature, resulting in the growth of a short crack in a specific grain characterised with its c-axis aligned perpendicular to the loading direction. Multiple prism-<a> slips were observed in the vicinity of the crack tip. Geometrically necessary dislocation (GND) density was found to be highly localised in bands, and the GND bands were characterised to migrate as the short crack propagated. The experimental results were underpinned by discrete dislocation plasticity (DDP) simulations, which shows that the GND density localisation and corresponding hardening at crack tip are given rise by both single-slip and multi-slip activation.

KEYWORDS:

short crack; zirconium; geometrically necessary dislocation; discrete dislocation plasticity

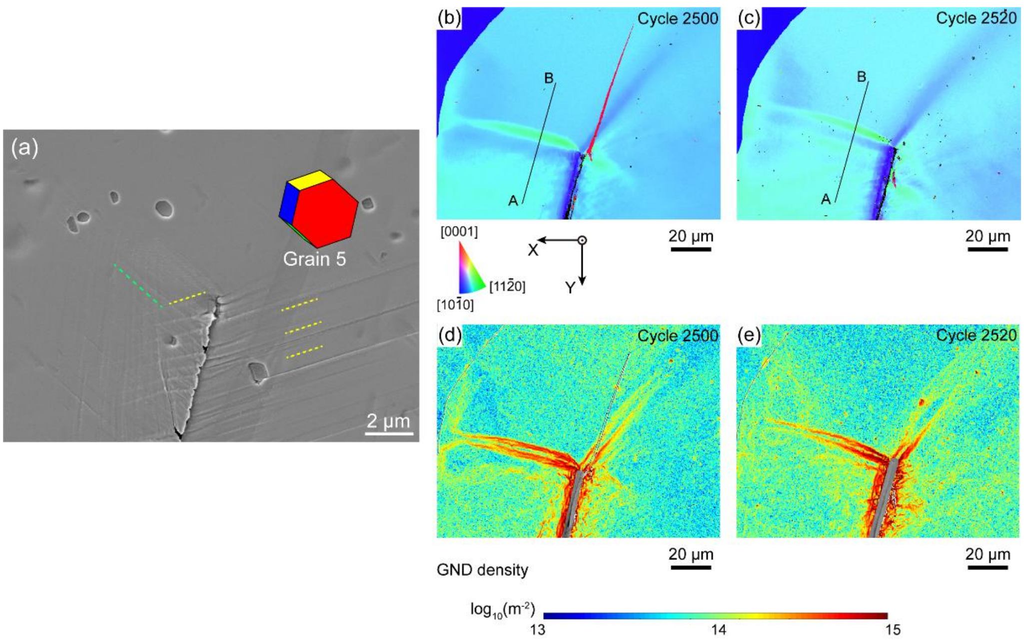


Fig.1 (a) SEM image showing activation of slip systems at the crack-tip; inverse pole figure showing microstructures at crack tip at (b) cycle 2500 and (c) cycle 2520; GND density distribution at crack tip at (d) cycle 2500 and (e) cycle 2520

P-313

Fatigue crack propagation in a single crystal and a two-dimensional polycrystalline Ni-base superalloys

Motoki SAKAGUCHI[1,*], Shiyu SUZUKI[1,2] , Putt THANAKUN[1],
Takanori KARATO[3] and Kenta SUZUKI[3]

[1] Tokyo Institute of Technology, JAPAN
[2] Japan Aerospace Exploration Agency (JAXA), JAPAN
[3] Mitsubishi Heavy Industries, Ltd., JAPAN

* Corresponding author: sakaguchi.m.ac@m.titech.ac.jp

ABSTRACT:
Fatigue crack propagation (FCP) behavior in cast Ni-base superalloys were investigated experimentally and numerically, using a single crystal and a two-dimensional (2D) poly-crystal materials. Firstly to interpret FCP behavior in grain interior, the FCP tests were conducted at room temperature (RT), 450℃, 700℃ and 900℃ for four types of single crystal specimens with different combinations of crystal orientations in loading and crack propagation. Secondary, the FCP tests were conducted at RT, 700 °C and 900 °C using 2D polycrystalline specimens extracted from a directionally solidified material, and distinctive FCP behavior both in grain interior and around the grain boundary (GB) was investigated. A series of FCP tests revealed that the FCP behavior both in grain interior and around the GB was affected by testing temperature associated with temperature dependent cracking mode, that is crystallographic shearing mode at lower temperature, while Mode I opening mode at higher temperature. Finally, a crystal plasticity finite element analysis was conducted to quantify the slip activities of the octahedral slip systems and rationalize the temperature and delta K dependence of crystallographic orientation and GB effect on the FCP behavior in cast Ni-base superalloys.

P-311

The migration of geometrically necessary dislocation density localisation at crack tip in short crack growth of zirconium

Weifeng Wan [1],*, Yilun Xu [2]

[1] School of Energy and Power Engineering, Beihang University, Beijing 100191, China

[2] Institute of High Performance Computing (IHPC), Agency for Science, Technology and Research (A*STAR), 1 Fusionopolis Way, #16-16 Connexis, Singapore 138632, Republic of Singapore

* Corresponding author: Weifeng Wan (wanweifeng@buaa.edu.cn)

ABSTRACT:

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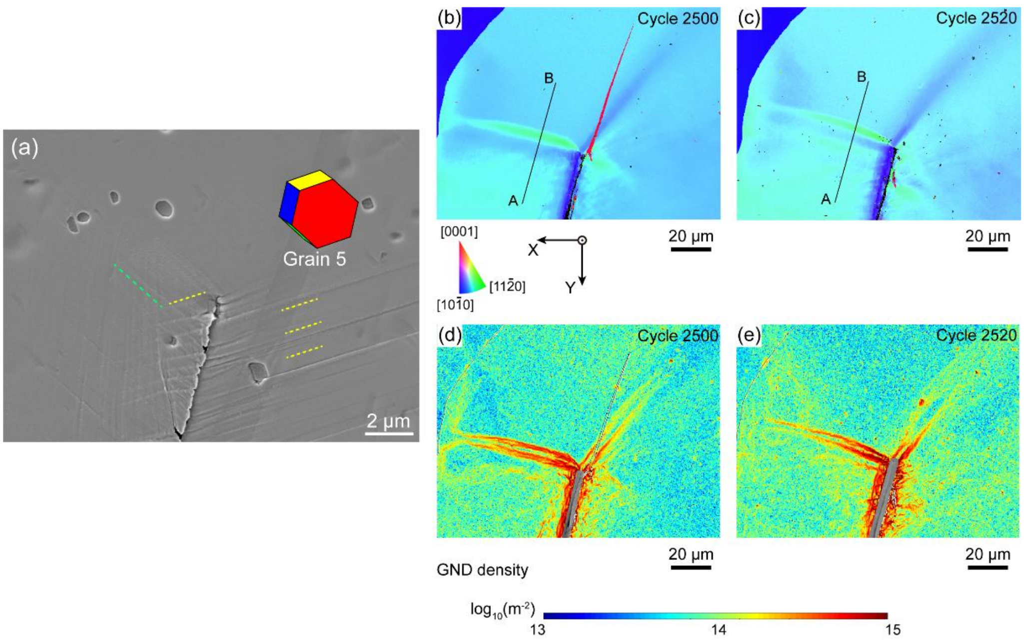
KEYWORDS:

short crack; zirconium; geometrically necessary dislocation; discrete dislocation plasticity



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P-313

Fatigue crack propagation in a single crystal and a two-dimensional polycrystalline Ni-base superalloys

Motoki SAKAGUCHI[1,*], Shiyu SUZUKI[1,2] , Putt THANAKUN[1],
Takanori KARATO[3] and Kenta SUZUKI[3]

[1] Tokyo Institute of Technology, JAPAN
[2] Japan Aerospace Exploration Agency (JAXA), JAPAN
[3] Mitsubishi Heavy Industries, Ltd., JAPAN

* Corresponding author: sakaguchi.m.ac@m.titech.ac.jp

ABSTRACT:
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P-314

Quantitative analysis of fatigue damage of Inconel 718 after creep-fatigue failure based on micro-pillar tests

Ji Wang[1,*], Kai-shang Li[1], Run-zi Wang[2], Xian-cheng Zhang[1], Shan-tung Tu[1]

[1] East China University of Science and Technology, CHINA
[2] Tohoku University, JAPAN

* Corresponding author: roycecust@gmail.com

ABSTRACT:

A series of continuous and interrupted cyclic tests in Inconel 718 with the dwell times ranging from 0 s to 10800 s at 650 ℃ are carried out in order to study the multi-stage creep-fatigue crack growth behavior. EBSD, TEM and micro-pillar tests are carried out to analyze the creep and fatigue damage after specimens' failure. Creep-fatigue lives show that, specimens with dwell time from 90s to 1800s have great creep-fatigue interaction damage. Microstructural characterizations also show that creep damage increases with the increase of dwell time. Micro-pillar tests indicate the decrease of compressibility inside the grain which refers to the degradation of material properties. Lastly, a fatigue and creep-fatigue crack propagation model based on effective strain energy density is proposed in this study.

KEYWORDS:

Creep-fatigue; micro-pillar; crack propagation, Nickel-based superalloy

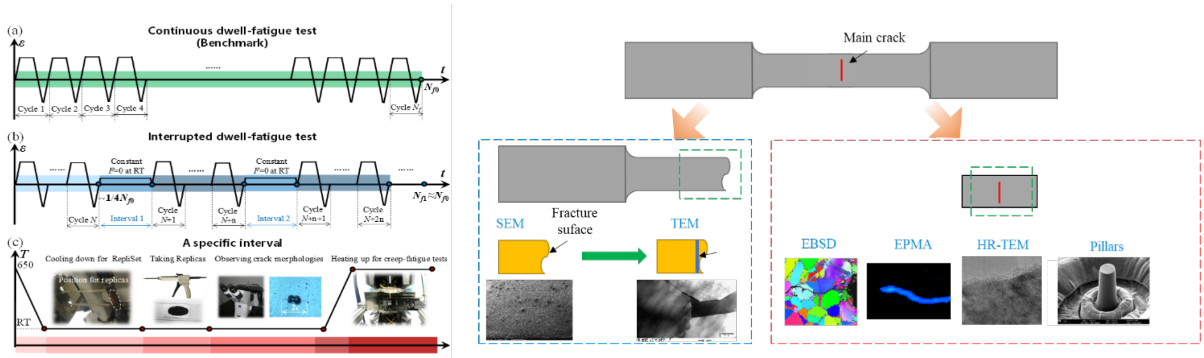


Fig. 1 *Detail of creep-fatigue tests and microstructural characterizations*

P-315

A Study on Fatigue Crack Propagation in Steel Rail Weld Zones Based on Damage Mechanics and Cohesive Zone Model

Chenhao Ji[1], Zhixin Zhan[1,*], Weiping Hu[1], Qingchun Meng[1]

[1] School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China

* Corresponding author: zzxupc@163.com

ABSTRACT:

In railway systems, steel rails are commonly interconnected via thermite welds, which may harbor internal flaws such as porosity and inclusions. These imperfections, when subjected to fatigue loads, can lead to the initiation and propagation of cracks, thereby posing a significant safety hazard to railway operations. To address this issue, a fatigue crack propagation theory model and numerical calculation method were developed. The model builds upon the monotonic cohesive zone model by introducing cyclic damage, which influences the material's input parameters as field variables, realizing damage evolution and then develops into the cyclic cohesive zone model (CCZM). The numerical calculation method incorporates a calibration process for the CCZM, based on crack propagation tests utilizing compact tension (CT) samples. Finite element calculation outcomes demonstrated good agreement with experimental data, thereby validating the method's effectiveness. The calibrated material parameters were employed to compute the fatigue crack propagation life of steel rail structural components. Furthermore, this study examined the effects of pre-existing initial defects of varying sizes and positions on the fatigue crack propagation life. The results of this research can be utilized to establish detection intervals for inspection vehicles, contingent upon their capabilities, ensuring a safer and more reliable railway infrastructure.

KEYWORDS:

Crack Propagation; Cyclic Cohesive Zone Model; Damage Mechanics; Steel Rail

P-316

Effect of sustained load on fatigue crack growth behavior of FGH96 at elevated temperature

Zhifang WANG[1], Xiaoguang YANG[1,*] and Duoqi SHI[1]

[1] School of Energy and Power Engineering, Beihang University, CHINA

* Corresponding author: yxg@buaa.edu.cn

ABSTRACT:

PM Nickel-based superalloys are preferred materials of turbine disks because of their excellent mechanical properties at high temperature. The sustained load involved in the load spectrum of aero-engine will impact on the fatigue crack growth behavior of turbine disk. Understanding the characteristics of fatigue crack growth behavior under dwell fatigue condition is essential to damage tolerance analysis of turbine disk. Fatigue crack growth tests were conducted with compliance method under various temperature (600℃, 650℃, 700℃) and holding time (from 1s to 60s) conditions to investigate the effect of sustained load on fatigue crack growth behavior, the influence of temperature and holding time were also explored. The results show that the sustained load can accelerate fatigue crack growth rate of FGH96 significantly at elevated temperature, and it is more pronounced as the temperature rises. Especially at 700℃, just 1s short-lived dwell loading can produce remarkable acceleration effect on fatigue crack growth rate. The crack growth rate increases with holding time in a decelerated manner at identical temperature. The inherent time-dependent damage mechanism for crack growth under dwell fatigue condition was further discussed.

KEYWORDS:

Ni-based superalloy; dwell fatigue; crack growth; elevated temperature; damage mechanism

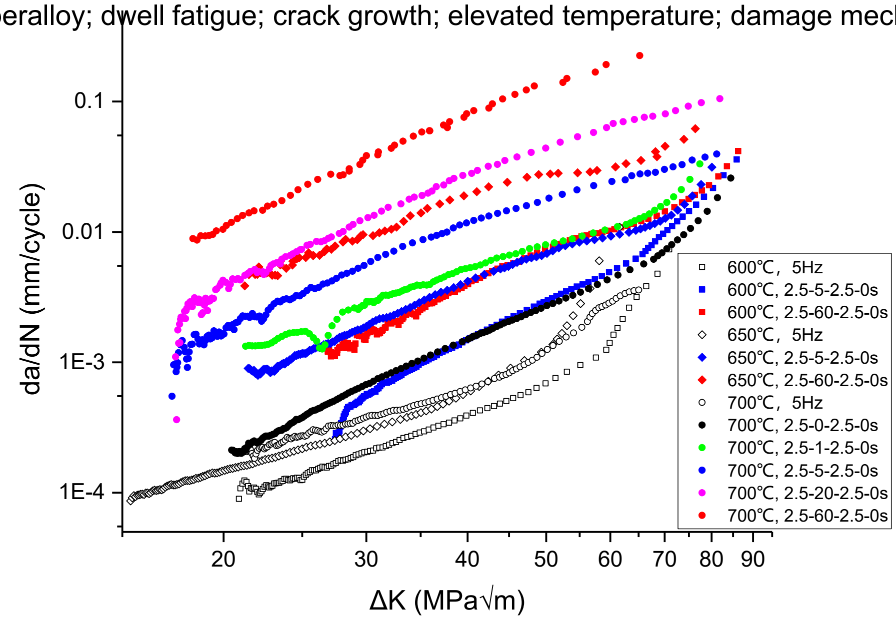


Fig. 1 *Tested fatigue crack growth rates.*

P-317

Consideration on short crack propagation resistance in SM490 steels with different ΔK_{th}

Yoshihiro HYODO[1*], Masao YUGA[1], Yasuyuki KURIHARA[1], Thi-Huyen Doan[1], Takahiro SAKIMOTO[1], Yoshiaki MURAKAMI[1], Koji GOTOH[2] and Tetsuya TAGAWA[1]

[1] JFE Steel Corporation
[2] Kyushu University, Department of Marine Systems Engineering, Faculty of Engineering

* Corresponding author: y-hyodo@jfe-steel.co.jp

ABSTRACT:

In order to improve fatigue life of steel structures, fatigue crack propagation properties in region I near ΔK_{th} have been studied. However, fatigue crack resistance for long crack propagation does not necessarily improve the fatigue life in a condition of increasing ΔK from a small defect, which is usually detected in practical fatigue damage in actual structures in service. In this study, developed and conventional SM490 steels with different ΔK_{th} were fabricated, and surface crack propagation tests were performed using specimens with artificial small defects to investigate the effect of ΔK_{th} under more practical conditions. The fatigue life of the developed steel was about three times longer than that of the conventional steel. The surface crack propagated below ΔK_{th} only in the developed steels, which suggested the short crack regime. The crack propagation that deviated from long crack behavior was convincingly explained by the corrected threshold using the R-curve model of a short crack proposed in the literature. Based on the experimental fatigue life improvement and its analytical estimation of the propagation resistance in the short crack regime, the effect of the ΔK_{th} value for a long crack in the initial propagation stage just after fatigue crack initiation was discussed.

KEYWORDS:

low carbon steel; fatigue crack propagation; threshold stress intensity factor range; short crack regime

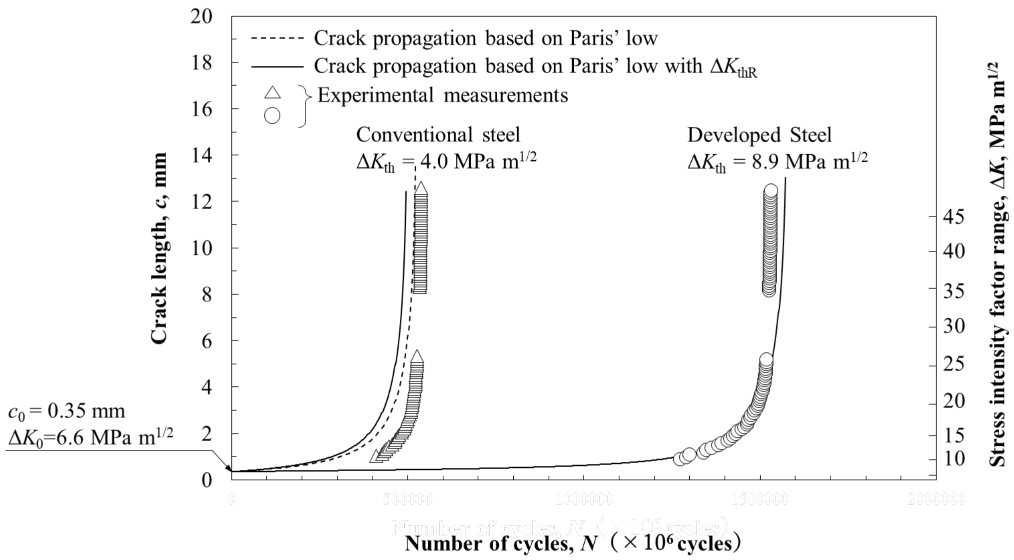


Fig. 1 Experimental *c-N* relations in surface crack propagation test and crack propagation analysis based on Paris' law with ΔK_{th} and ΔK_{thR}.

P-318

Small Crack Growth Behaviors and Its Interaction with Microstructures In A Ni-Based P/M Superalloy At High Temperature

Xiaoguang Yang[1*], Qinzheng Yang[2,]

[1] Beijing University, China
[2] Nanchang Hangkong University, China

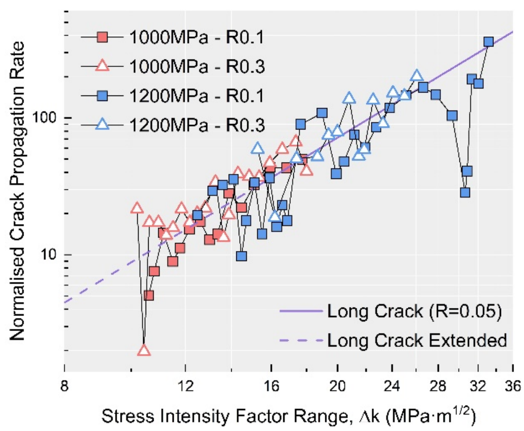
* Corresponding author: yxg@buaa.edu.cn

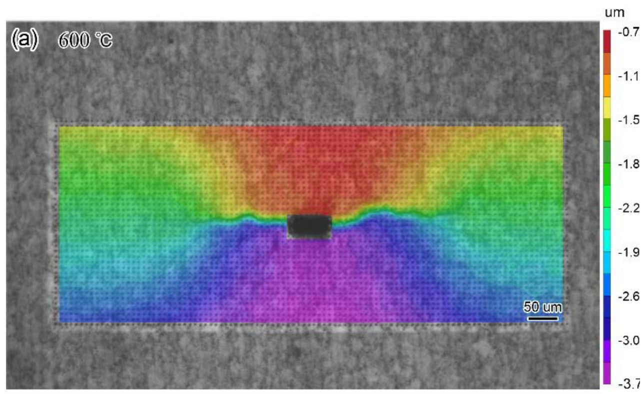
ABSTRACT:

The experimental investigations have been carried out to understand the small crack growth behaviors and its interactions with microstructures both at 600℃ and RT in the air for a Ni-based P/M superalloy, using Kb-Type specimen with EDM defects of 65-80μm. With the help of photomicroscopy and digital image correlation, the crack lengths and displacements were measured from their initial sizes to ~1000μm under two max. stress levels and two stress ratios. The results show the zig-zag propagation path that are mainly controlled by the slip in grains at crack tip and grain boundary. Meanwhile, it also finds the phenomenon of regular crack propagating and arresting regardless of stress levels and stress ratios. The links of this particular growth behaviors with the microstructure features, such as the orientation and boundary of grains, are discussed with EBSD. Based on the DIC-measured crack opening displacement, the closure mechanisms and evolution are discussed. At the first, stress ratios have little effects on the crack closure, secondly, oxide-induced crack closure (OICC) level is low, but consist of a basic part of Kop. The delayed opening of the crack face indicates roughness-induced crack closure (RICC) existed, combined with OICC, which mainly contributed to Kop at the early propagation stage. Eventually, the transition length concept was proposed and the small crack closure level and its evolution were modelled.

KEYWORDS:

Small Crack, P/M Superalloy, DIC, Crack Closure





(b)

Fig.1 (a) Small crack growth rates at 600℃ in air, (b) Small crack full-filed displacement at 86000 cycles 600℃

D1-301

Contribution of the self-heating method in the characterization of the fatigue damage of materials with defects resulting from additive manufacturing

Sabrine ZIRI[1], Anis HOR[2] and Catherine MABRU[2,*]

[1] Capgemini, FRANCE
[2] Institut Clément Ader (ICA) ; Université de Toulouse ; CNRS, IMT Mines Albi, INSA, ISAE-SUPAERO, UPS, FRANCE

* Corresponding author: catherine.mabru@isae.fr

ABSTRACT:
This paper investigates the fatigue behavior of 316L stainless steel (316L SS) produced by Laser Powder Bed Fusion (LPBF). Nearly dense cylinders are built vertically using various process parameters corresponding to various volumetric energy densities. Fatigue specimens are then machined from these cylinders and polished. Fully reversed tensile-compression fatigue tests (R = -1) are conducted in order to obtain S-N curves in the high cycle regime. The fatigue limits are determined for run out specimens at 2 10^6 cycles. The self-heating method is also used for the rapid estimation of the fatigue limits. This method consists in measuring the temperature at the surface of the specimen during cyclic loading for several increasing stress increments using thermocouples.
For each stress increment, the temperature at the surface of the specimen is recorded. After few thousand cycles, the recorded temperature tends to stabilize. This stabilized value increases with the increasing stress increments following a non-linear trend. Whatever the set of process parameters, the self-heating curves show three distinct domains of heat dissipation (Fig. 1). Thanks to microstructure analysis, fractographic observations and correlations with S-N curves, these domains can be closely linked to damage mechanisms associated or not to defects.

KEYWORDS:
Laser Powder Bed Fusion; High-cycle fatigue; Fatigue limit; Self-heating; Stainless steel

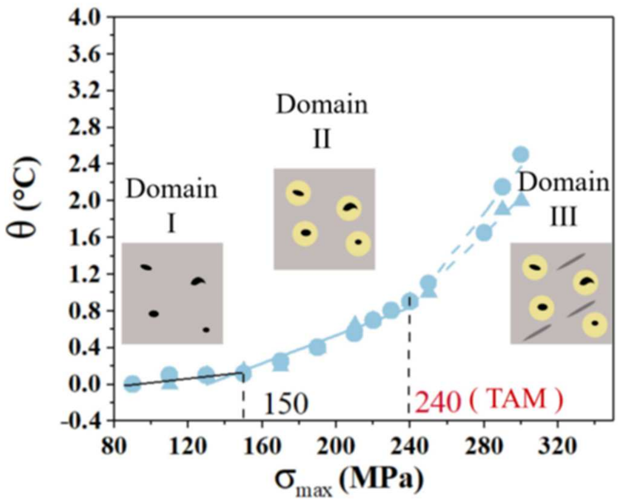


Fig. 1 *Self heating curves and fatigue damage mechanisms*

D1-302

Study on Mechanical Properties of Anode Material for Lithium-ion Batteries in Water

Shiori TAGAI[1,*], Kairi SHIRAISHI[1], Masaya UEDA[1], Kohta KIKUCHI[1], Yoshinao KISHIMOTO[1] and Yukiyoshi KOBAYASHI[1]

[1] Tokyo City University, JAPAN

* Corresponding author: g2381033@tcu.ac.jp

ABSTRACT:
Since lithium-ion batteries have high energy density, damage to the components of the batteries lead to thermal runaway and serious accidents. This study has focused on that electrodes are immersed in electrolyte solution inside the batteries. In order to investigate basic mechanical properties of electrode materials in liquid, tensile tests in air and water were conducted on a carbon-based anode material consisting of carbon powder and polyvinylidene fluoride (PVDF) binder. This study has also developed a self-made environmental chamber that enables testing in liquids. The test results show that the macroscopic deformation and fracture of the anode material were the same in both conditions. On the other hand, the initial slope of the stress-strain curve in water was higher than that in air, and the strain at the fracture in water was smaller than that in air. These indicate that the stiffness of the PVDF in water became higher than in air considering that the PVDF binder supported the anode material. The stiffness enhancement seems to be due to hydrogen bonds formed by the contact between the non-polar molecules of the PVDF and water molecules.

KEYWORDS:
Lithium-ion battery; Anode material; Composite material; Tensile test; Underwater test

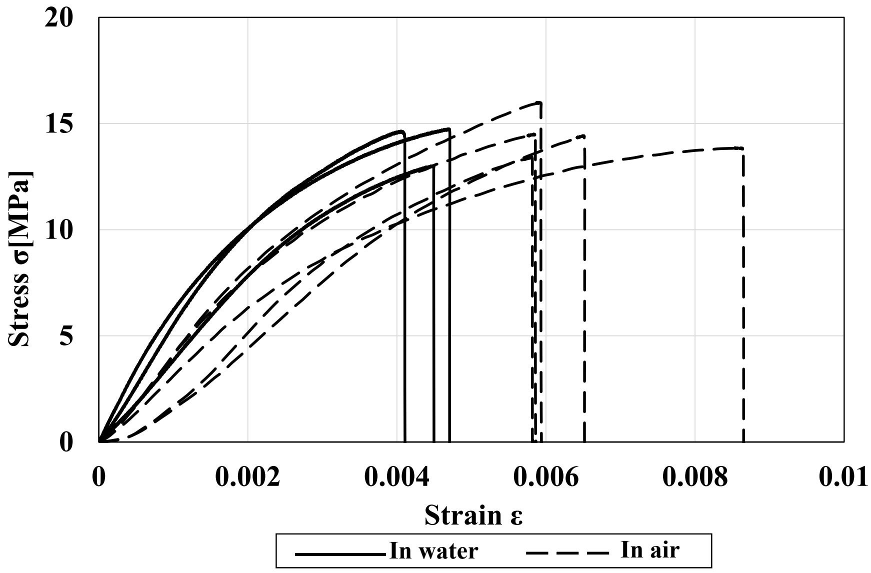


Fig. 1 *Stress-Strain curve of anode material.*

D1-303

Effect of cyclic hardening on stress corrosion cracking behavior of NiCrMoV steel welded joints

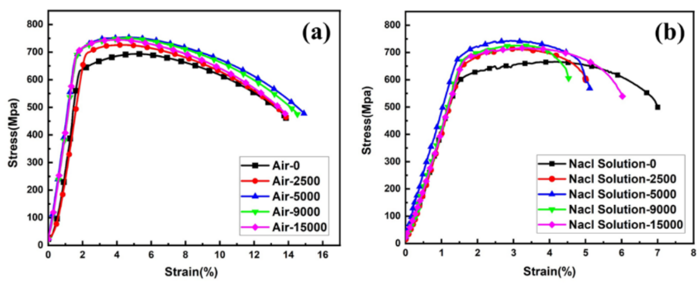
Yu-Hui Huang[1,*],Shuo Weng[1] , Ming-Liang Zhu[1] and Fu-Zhen Xuan[1,*]
[1] East China University of Science and Technology, CHINA
[2] University of Shanghai for Science and Technology, CHINA
* Corresponding author: yhhuang@ecust.edu.cn (YH Huang), fzxuan@ecust.edu.cn (F.-Z Xuan)

ABSTRACT :

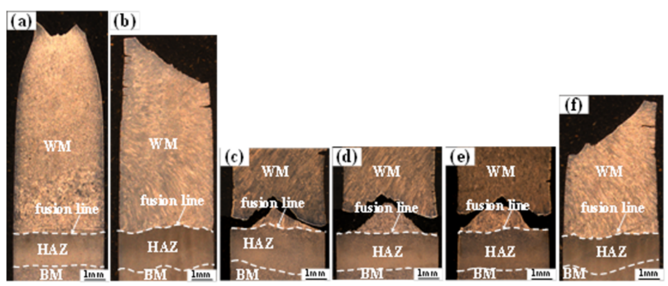
The influence of stress-controlled fatigue (SCF) damage on the fracture location shifting of welded joints for NiCrMoV steels in the corrosive solution of 3.5wt.% NaCl is systematically investigated by electrochemical measurements, immersion tests, slow strain rate tensile (SSRT) tests, and fractural morphology observations in the present work. The results show that both the yield strength (YS) and the ultimate tensile strength (UTS) of welded joints are increased after the SCF tests. The susceptibility of stress corrosion cracking (SCC) and galvanic corrosion of the SCF damaged welded joints are higher than that of the as received specimens. In addition, the fracture locations of welded joints after SSRT tests in the corrosive solution are shifted with the degree of SCF damage. Different degrees of fatigue damage are accumulated in the three zones of welded joints during the cyclic deformation, which could change the competitive relation of the most susceptive SCC zone between the fusion zone and the middle of WM.

KEYWORDS:

Welded joints; Stress-controlled fatigue damage; cyclic hardening; stress corrosion cracking



The slow strain rate tensile curves of the SCF damaged welded joints with various given cycles in different solutions: (a) air at 180° C and (b) 3.5wt.% NaCl at 180° C.



The total cross-sectional fracture specimens of the as-received welded joints after SSRT tests in the air (a) and the SCF damaged welded joints with different given cycles: the as-received specimen (b), N=2500 (c), N=5000 (d), N=9000 (e) and N=15000 (f) in the corrosive solutions of 3.5wt.% NaCl at 180° C

Fig.1 The slow strain rate tensile curves and cross-sectional fracture morphologies after SSRT tests

D1-304

Investigation of Fatigue Crack Growth Behavior in Fine Particle Peened 7075 Aluminum Alloy using Digital Image Correlation

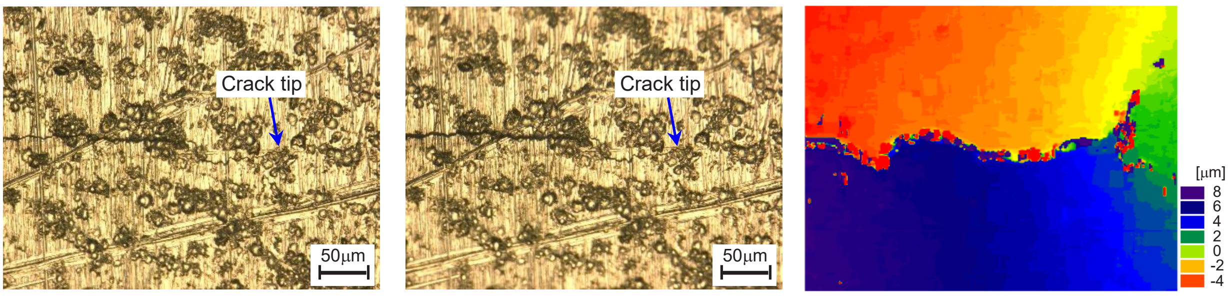
Yuichi ONO[1,*], Guyue SUN[1] , Hayate KUBO[1] and Souma OHKUBO[1]

[1] Tottori University, JAPAN

* Corresponding author: ono@tottori-u.ac.jp

ABSTRACT:
Surface residual stress, *S-N* curves and surface crack growth curves of fine particle peened aluminum alloys were investigated and compared with unpeened ones. Residual stress measurements revealed that a compressive residual stress of about 300 MPa was induced on the surface by fine particle peening, resulting in the improvement of the fatigue strength of the fine particle peened aluminum alloy in the *S-N* curve. Digital image correlation also revealed that the residual compressive stress increased the crack opening stress level under the crack growth process, resulting in a decrease in the crack growth rate of the fine particle peened aluminum alloy in the surface crack growth curve. The crack growth rates of the fine particle peened and unpeened aluminum alloy were arranged by the effective stress intensity factor range calculated from the crack opening stress. All data collapsed into a single narrow scatter band, suggesting that the effective stress intensity factor range dominates the surface crack growth rate, even when the aluminum alloy is subjected to fine particle peening.

KEYWORDS:
Fine particle peening, Digital image correlation, Crack closure, Stress intensity factor



(a) Digital image under σ = 0 MPa (b) Digital image under σ = 140 MPa (c) Displacement distribution

Fig. 1 Digital microscope images and displacement distribution around crack tip calculated by digital image correlation.

D1-305

Effect of Corrosive Environment on Fatigue Strength Characteristic of Magnesium Alloy Ultrafine Wire.

Yuta SAKAMOTO[1], Daito SUZUKI[1], Michiru ABE[1], Takashi MATSUMURA[1]

[1] The University of Electro-Communications, JAPAN

* Corresponding author: matsu@mce.uec.ac.jp

ABSTRACT:

Because the magnesium alloy WE43 is a material without the aluminum, WE43 are expected to be applied to medical materials. The mechanical properties of macro materials may differ from those of bulk materials. Therefore, it is necessary to evaluate the mechanical properties of micro-sized machines and structures using specimens with micro size and shape. In this study, in order to investigate the effect of concentration and pH of phosphate buffer on fatigue strength properties, fatigue tests were carried out using WE43 ultra fine wire with a diameter of 200 μm. Three types of phosphate buffers, pH 7.0:1/150 mol/L, pH 7.0:1/15 mol/L and pH 12:1/10 mol/L were used. As the results of fatigue tests, it was found that the fatigue strength under three types of the phosphate buffer was much lower than that under the air with RH25% due to the effects of corrosion. Also, it was found that the fatigue strength was longer in the order of pH 7.0:1/15 mol/L, pH 7.0:1/150 mol/L and pH 12:1/10 mol/L under the phosphate buffer. In order to discuss the fatigue strength characteristics under the phosphate buffer, the fracture surface, wire diameter, corrosion reaction, etc. were investigated.

KEYWORDS:

Magnesium alloy; Fatigue strength; Corrosive environment; Phosphate buffer; Micromaterial

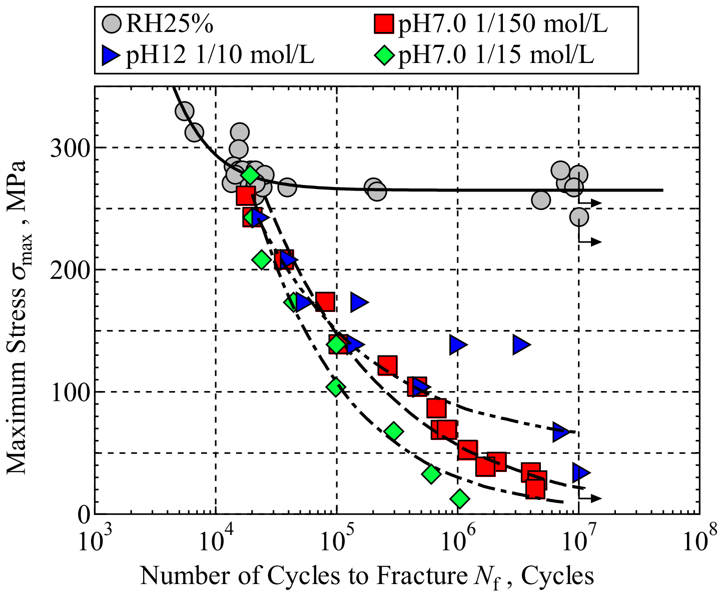


Fig. 1 *S-N* curves of WE43.

D1-306

New coating to prevent premature corrosion of aircraft structure

Damien DESGACHES[1]

[1] AIRBUS Atlantic, 1 boulevard de l'Europe, 31770 Colomiers, FRANCE

* Corresponding author: damien.desgaches@airbus.com

ABSTRACT:
Corrosion of metallic parts is an important problem affecting the life of the aircraft structure. The occurrence of corrosion damage on an aircraft depends on several parameters:

- The degree of corrosion protection during manufacturing / assembly process
- The degree of maintenance performed during operational life (prevention)
- Environmental conditions in which the aircraft is operated

Floor structure is one the most impacted area by premature corrosion, mainly in the wet area, i-e lavatories, galleys, door entrances.

When the floor structure is the assembly of only aluminum alloy parts, the current surface treatment is sulphuric acid anodizing. But this protection does not give efficient result. In-service damages of the surface protections make the floor porous and lead to liquid retention. This initiates both self and galvanic corrosion

The current alternative is to replace aluminum parts by titanium parts. A solution for having a corrosion free structure is to use a corrosion free material for exposed parts in wet areas. Titanium alloy ensures good properties and so validate this requirement. But this solution impacts directly the recurrent cost and the weight of the floor structure.

The aim is to introduce modifications on floor structure enabling a significant reduction of corrosion.

- Allow inspection interval to be increased
- Reduce workload during maintenance phases

This new coating has to be REACH compliance and so chromate free, with always usual objectives to minimize aircraft weight and recurrent cost.

Life cycle assessment has been done to prove the benefit of this new coating.

The main challenge is to prove the viability of this new coating to prevent corrosion on structure with the validation of tribologic behavior.

KEYWORDS:
Corrosion, Aircraft structure, Floor, Coating, Tribology

D1-307

Fatigue Life Prediction of PBF-LB AlSi10Mg based on Roughness and Residual Stress

Lea STRAUSS[1]*, Genny A. PANG[1], Stefan BRENNER[1], Vesna NEDELJKOVIC-GROHA[1] and Günther LÖWISCH[1]

[1] University of the Bundeswehr Munich, Department of Mechanical Engineering, GERMANY

* Corresponding author: lea.strauss@unibw.de

ABSTRACT:

Laser-based powder bed fusion (PBF-LB) is a frequently used additive manufacturing process for metals. Here, a laser beam is used to fuse powder layer by laser. The usage of the laser beam results in high thermal gradients and high cooling rates, leading to process-related characteristic effects like inhomogeneities, surface roughness, anisotropy, and residual stress. These effects significantly alter the part's fatigue characteristics. Material properties, such as the brittleness of materials like the aluminum alloy AlSi10Mg further reduce the fatigue life.

This study presents fatigue experiments of PBF-LB-manufactured AlSi10Mg samples with various surface roughness and residual stress conditions at different geometries. The variation of surface roughness and residual stress due to different printing parameters was investigated and the resulting influence on the fatigue life was systematically examined. Additionally, the crack-initiating inhomogeneity for each fatigue sample was experimentally determined according to Murakami [1] and Shiozawa [2].
From the data, an empirical model to predict fatigue life of PBF-LB AlSi10Mg parts, based on the experimentally measured peak in surface roughness and residual stress was derived.

KEYWORDS:
AlSi10Mg; fatigue life prediction; PBF-LB; residual stress; surface roughness

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2. Shiozawa, K., Lu, L.: Effect of Non-Metallic Inclusion Size and Residual Stresses on Gigacycle Fatigue Properties in High Strength Steel. AMR (2008). https://doi.org/10.4028/www.scientific.net/AMR.44-46.33

D1-308

Defects tolerance and fatigue limit prediction in additive manufactured titanium alloy Ti6Al4V

Abdul Khadar SYED[1]*, Xiang ZHANG[1], Ben DUTTON[2] and Wilson VESGA[2]

[1] Centre for Manufacturing and Materials, Coventry University, UNITED KINGDOM
[2] The Manufacturing Technology Centre, Coventry, UNITED KINGDOM

* Corresponding author: abdul.syed@coventry.ac.uk

ABSTRACT:

Load bearing aerospace structures must meet performance requirements including the durability and damage tolerance requirement under the fatigue loads. In additively manufactured parts, fatigue cracks initiating from defects has been a major concern; defect size and location can influence the life prediction models and cause large scatters in test data. In this work, porosity defects were purposedly built within test samples during the laser powder bed fusion process. These seeded defects were located either within or near the surface of a standard cylindrical dog-bone tensile and fatigue specimens of 5-6 mm diameter. Tensile tests showed that seeded pores did not affect the yield and ultimate tensile strengths but reduced the elongation by 25%. Under cyclic loads, seeded defects caused a 50% reduction in fatigue life. Despite some seeded defects were larger than process inherent defects, the latter, if present at or near the sample surface, was the source for fatigue crack initiation. Defect location and size also caused considerable scatter in the test data. The stress intensity factor range of the crack initiating defect provides good correlation with the fatigue life. A modified Kitagawa-Takahashi diagram was used to demonstrate the capability of fatigue limit prediction considering porosity defects.

KEYWORDS:

Defects; Fatigue life; Laser powder bed fusion; Additive Manufacturing; Titanium alloys

D1-309

Structure Integrity Analysis of Additive Manufactured Cabin Door: Design-Manufacture-Fatigue behavior

Yu'e MA[1,*], Wenbo SUN[2] and Weihong Zhang[3]

[1] Northwestern Polytechnical University, CHINA
[2] Northwestern Polytechnical University, CHINA
[3] Northwestern Polytechnical University, CHINA

* Corresponding author: ma.yu.e@nwpu.edu.cn

ABSTRACT:
Aircraft cabin door was designed and manufactured by additive manufacturing (AM) technology. Lattice structures were used to save weight. Before designing, the building direction and the defects in AM titanium alloy were studied. Fatigue behavior and mechanical response of AM titanium alloy in different aircraft load types including tensile, compressive, bending loads and so on. The defect distributions along the build direction, the scanning direction, and the radial direction were compared. Defect size, sphericity, and defect orientation were characterized.
Mechanical response and failure modes of AM samples with different lattice structures were studied and compared. One lattice was chosen and used in AM cabin door. It was shown that porosity of the as-built samples decreased with the increasement of the build direction, and stress relieving process can cause the coalescence of small defect and higher porosity. The lack of fusion defects is prone to grow along the build direction. The defect size distribution can be fitted by the lognormal function, while the sphericity distribution of defects was fitted by the two-phase exponential growth function. The crack initiation site was controlled by the defect orientation and the effective bearing aera. The AM cabin door was tested to meet all design goals.

KEYWORDS:
Additive Manufactured; Cabin Door; Structure Integrity Analysis; Defect; Fatigue crack behavior

D1-310

Fatigue damage evolution and tolerance in additive manufactured metals

Mustafa AWD, Daniel KLEMM, Felix STERN, Mirko TESCHKE, Jochen TENKAMP, Frank WALTHER*

TU Dortmund University, Chair of Materials Test Engineering (WPT), Dortmund, Germany

* Corresponding author: frank.walther@tu-dortmund.de

ABSTRACT:
The microstructure, defects, and roughness in additive manufacturing (AM) processes determine the fatigue performance in engineering applications. Modern testing strategies and measurement techniques enable accurate monitoring of the influence of process-induced characteristics on the fatigue behavior. Intermittent fatigue testing revealed the interaction between microstructure, local porosity, and fatigue crack initiation until the very high cycle fatigue (VHCF) region. For 316L, AlSi, TiAl, and Ni alloys, the effect of defects, building direction, and stress ratio on fatigue evolution was investigated. The fatigue strength could be correlated with the hardness and the effective defect or pore size relative to load direction using the Murakami-Noguchi concept. By elastic-plastic modification by J-integral of Heitmann, the effect of microstructure on cyclic stress-strain behavior and fatigue damage tolerance could be proofed. The studies reveal the potential to enhance the fatigue lifetime and damage tolerance based on comprehensive structure-property relationships to be integrated into uniform fatigue damage tolerance approaches (Figure 1).

KEYWORDS: Fatigue, damage tolerance, additive manufacturing, metals, very high cycle fatigue (VHCF)

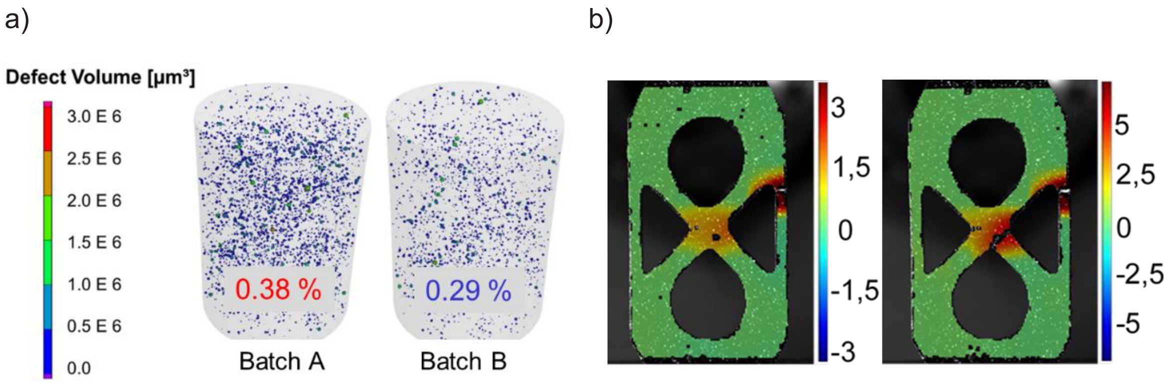


Fig. 1 Enhanced pre- and post-damage techniques in fatigue strength analysis: a) 3D-µCT defect analysis and b) DIC damage inspection in lattice structures.

D1-311

Microstructurally Small Fatigue Crack Initiation and Growth Behaviors of Additively-Manufactured Alloy 718

Hideaki Nishikawa[1]*, Yoshiyuki Furuya[1], Houichi Kitano[1], Terumi Nakamura[1], Kosuke Kuwabara[2], Yoshiharu Kanegae[2], Dong-Soo Kang[2], Kinya Aota[2]

[1] National Institute for Materials Science, JAPAN
[2] PROTERIAL, Ltd., JAPAN

* Corresponding author: NISHIKAWA.Hideaki@nims.go.jp

ABSTRACT:
To reveal the effects of microstructural features on fatigue property, microscopic fatigue crack initiation and growth behavior were successively observed for rolled plate and additively-manufactured nickel base 718 alloy. Three types of additive manufacturing (AM) methods: powder bed Electron Beam Melting (EBM), Selective Laser Melting (SLM), and wire-fed Electron Beam Additive Manufacturing (EBAM) were adopted for specimen preparation to create various microstructures for comparison. The results showed that the fatigue lives of the EBM and EBAM specimens, which have a robust (001) texture, were shorter than those of the rolled plate and SLM specimens. The acceleration of the early stage fatigue crack growth rate (FCGR) was found in the EBM and EBAM specimens. Cross-sectional electron back scatter diffraction (EBSD) observations also showed that early stage cracks initiated and grew along the {111} slip plane; but in the EBAM specimens, the cracks continuously propagated straight to an adjacent grain due to their (001) texture.

KEYWORDS:
Additive manufacturing; Small fatigue crack; Texture; Alloy 718

D1-312

High-cycle and Low-cycle Fatigue of a Laser-Powder Direct Energy Deposition manufactured Inconel 625

Fabien SZMYTKA[1,*], Josiane NGUEJIO [1,2] and Yosra HICHRI [1,3]

[1] ENSTA Paris, IMSIA UMR 9219, Institut Polytechnique de Paris, 91120 Palaiseau, FRANCE
[2] Université Paris-Saclay, CEA, Service de recherche en Corrosion et Comportement des Matériaux, 91191 Gif-Sur-Yvette, FRANCE
[3] Safran Transmission Systems, 18 Bd Louis Seguin, 92700 Colombes, FRANCE

* Corresponding author: fabien.szmytka@ensta-paris.fr

ABSTRACT:
Inconel 625 is a superalloy widely used in industry for its good high temperature properties. It is usually elaborated by forging as a solid solution-strengthened material, but with the rising interest of the additive manufacturing techniques, Inconel 625 powder has been regularly used to provide superior clad, which exhibit good mechanical properties. Inconel 625 produced by Laser-Powder Direct Energy Deposition (LP-DED) has indeed been shown, with appropriate heat treatment, to have microstructures close to the wrought alloy.

A broad study of the fatigue strength of Inconel 625 LP-DED has been conducted with the wrought material taken as a reference. For high cycle fatigue, the judicious choice of process parameters, associated with a 1h annealing at 1100°C, enable us to reach an endurance limit less than 10% lower than for the forged alloy. For low cycle fatigue (LCF), the elasto-viscoplastic behavior of the printed alloy is first observed to be very different from the forged material with higher yield strengths and a completely different hardening behavior. However, it appears that the as-printed material gives a better resistance to strain-controlled LCF tests (with loading range up to +/- 0.6% of mechanical strain) over the whole temperature range tested (ambient to 800°C).

KEYWORDS:
Additive Manufacturing; Laser Powder Direct Energy Deposition; nickel-based superalloy; viscoplasticity;

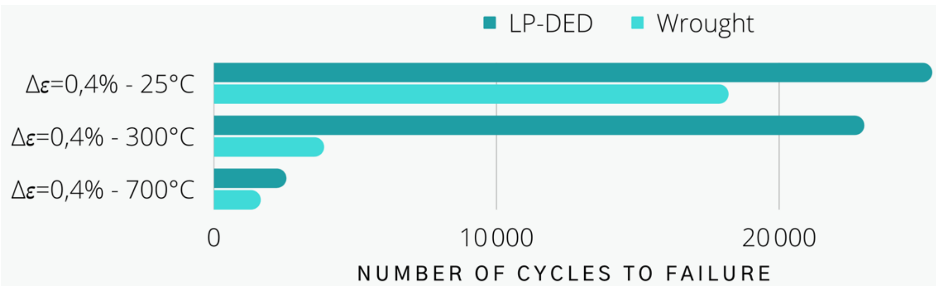


Fig. 1 *Comparison of LCF lifetimes according to the process.*

D1-313

High-Cycle and Very-High-Cycle Fatigue Behavior and Life Prediction of Ti-6Al-4V Fabricated by Laser Powder Bed Fusion

Rui FU, Yinfeng JIA, Chao LING, Liang ZHENG*, Zheng ZHONG*

School of Science, Harbin Institute of Technology (Shenzhen), CHINA

* Corresponding author: icon_lzheng@hit.edu.cn; zhongzheng@hit.edu.cn

ABSTRACT:

Microstructural defects of titanium alloys fabricated by laser powder bed fusion (LPBF) make their fatigue behaviors much more complicated than the conventionally made ones, especially in very-high-cycle fatigue (VHCF) regime. In this paper, the fatigue behavior of LPBF-fabricated Ti-6Al-4V was investigated to reveal the effects of surface state and stress ratio on fatigue performance up to VHCF regime. In addition, a deep belief neural network-back propagation (DBN-BP) model was proposed to predict the fatigue life of LPBF-fabricated Ti-6Al-4V up to VHCF regime. The comparisons of experimental fatigue life and predicted fatigue life are presented in Fig. 1a and Fig. 1b, respectively. Fig. 1a indicates that the *S-N* data display a continuously descending trend at different stress ratios and surface states. In addition, the applied stress amplitude (σ_a) decreases with the difference of surface states with the order of: σ_a(HT) > σ_a (polish) > σ_a (as-built), implying that the fatigue strength can be improved by surface polishing. Fig. 1b reveals that the DBN-BP model exhibits high precision and strong stability in predicting the fatigue life of LPBF-fabricated Ti-6Al-4V. Results in this paper provide valuable guidance for further investigation of LPBF-fabricated Ti-6Al-4V.

KEYWORDS:

Fatigue behavior, Life prediction, Ti-6Al-4V, Laser powder bed fusion, Very-high-cycle fatigue

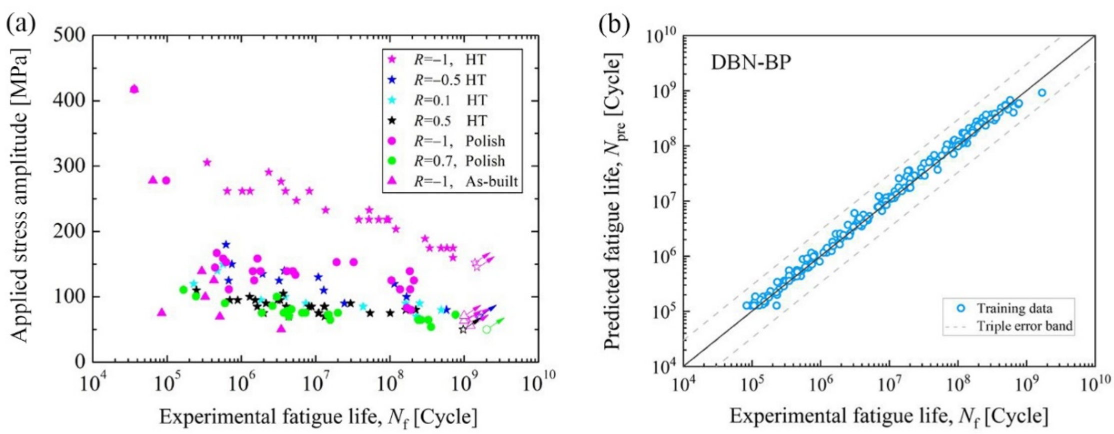


Fig. 1 The experimental fatigue life versus (a) applied stress amplitude and (b) predicted fatigue life.

D1-314

Low-cycle fatigue of conventional and additively manufactured IN939 superalloy

Tomáš BABINSKÝ[1,*], Ivo ŠULÁK[1], Ivo KUBĚNA[1], Alice CHLUPOVÁ[1] and Luboš NÁHLÍK[1]

[1] Institute of Physics of Materials, Czech Academy of Sciences, CZECH REPUBLIC

* Corresponding author: babinsky@ipm.cz

ABSTRACT:

Fatigue behavior of IN939 superalloy was studied. To relate the fatigue performance of additively manufactured (AM) to conventional cast superalloy, three thermodynamical states were considered: cast heat-treated, AM as-built and AM heat-treated. A three-step heat treatment was performed (1160 °C/4h + 1000 °C/6h + 800 °C/4h). Cylindrical specimens were machined out of blocks which were AM with 0° and 90° building to loading orientation using direct metal laser sintering. Fatigue tests were performed at room temperature in low-cycle fatigue regime in total strain amplitude control. Subsequently, specimens were analyzed by means of scanning and transmission electron microscopy. Microstructure of cast IN939 comprised polyhedral dendritic grains with casting defects, the AM microstructure was textured and hierarchical with grains separated into honeycomb dislocation cells elongated in <001> direction (Fig. 1). The cellular substructure exhibited high stability under cyclic plastic loading with only a little tendency to form persistent slip bands. Regarding fatigue lifetime, both AM orientations performed better than the conventional counterpart. Specimen orientation was found to affect the cyclic stress levels but the influence on fatigue performance was low.

KEYWORDS:

Additive manufacturing, cyclic plasticity, fatigue, superalloy, IN939

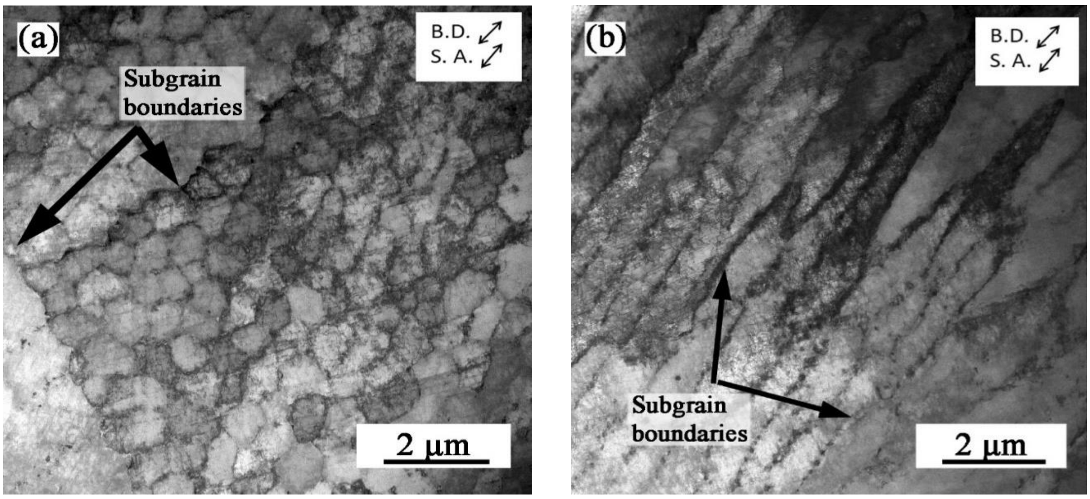


Fig. 1. *TEM micrographs of as-built IN939. (a) Honeycomb and (b) columnar cellular dislocation structures.*

D1-315

Coupling effects of microstructure and defects on fatigue properties of 3D-printed Ti-6Al-4V

Zhenjun ZHANG[1,2,*], Zhan QU[1,2], Zhefeng ZHANG[1,2]

[1] Institute of Metal Research, Chinese Academy of Sciences, China
[2] University of Science and Technology of China, China

* Corresponding author: zjzhang@imr.ac.cn

ABSTRACT:
The coupling effects of microstructure and macro-scale defects are significant for the fatigue properties of metals. However, this correlation is still vague for additively manufactured materials. Therefore, the fatigue properties and microstructure of selective laser melted (SLM) Ti-6Al-4V were studied in this work, revealing that there is an anomalous trade-off relationship between the hardness and the high-cycle fatigue properties. Surprisingly, the softest microstructure has better fatigue resistance, i.e., its tensile strength is reduced by over 23%, while its fatigue strength is increased by ~28%, compared with the hardest as-printed state. Statistical analysis on the fatigue source morphologies indicates that the hard α′ microstructure is sensitive to lack of fusion (LOF)-type defects while the soft lamellar (α+β) microstructure is sensitive to pore-type defects, which may be related to the higher tolerance concerning sharp defects for the soft microstructure relative to the hard one. Through considering the transition of the fatigue cracking mechanism and the effect of the microstructure, a fatigue life prediction model has been developed based on the Murakami theory, which does not only give a sound explanation for the trade-off relationship but is also in good agreement with the fatigue data for different defect characteristics and microstructure states at different applied stress amplitudes.

KEYWORDS:
Selective laser melting; Ti-6Al-4V alloy; Fatigue properties; Defects; Microstructure.

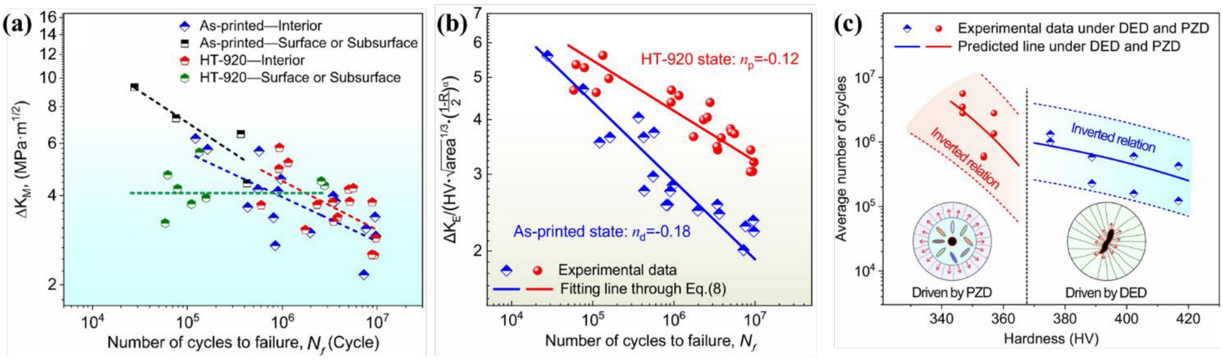


Fig. 1 Predicting effect of traditional life prediction model (a) and the present model (b) and (c).

D1-316

Cyclic Strain Localization in Fatigued 316L Stainless Steel Manufactured Additively using Selective Laser Melting (SLM)

Jiří MAN[1,*], Alice CHLUPOVÁ[1], Miroslav VALTR[2], Miroslav ŠMÍD[1], Ivo KUBĚNA[1], Ivo ŠULÁK[1], Michal ACKERMANN[3], Jiří ŠAFKA[3] and Jaroslav POLÁK[1]

[1] Institute of Physics of Materials, Czech Academy of Sciences, Brno, CZECH REPUBLIC
[2] Czech Metrology Institute, Brno, CZECH REPUBLIC
[3] Technical University of Liberec, CZECH REPUBLIC

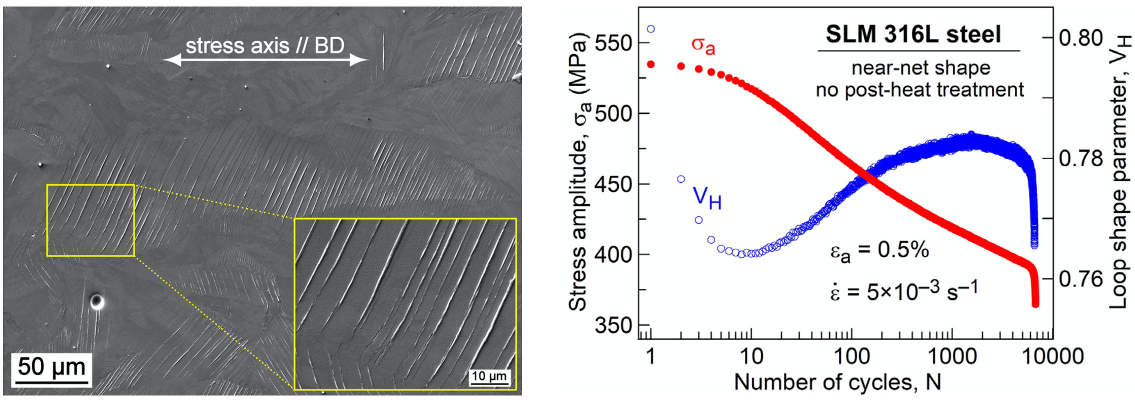
* Corresponding author: man@ipm.cz

ABSTRACT:

Near-net shape specimens were built vertically using selective laser melting (SLM) from 316L austenitic stainless steel recycled powder with a relative density higher than 99.5%. Fatigue specimens submitted only to mild mechanical polishing were fatigued at room temperature in the as-built state without any post-heat treatment with a constant total strain amplitude of 0.5%. Cyclic straining of the virgin, non-equilibrium microstructure composed of subgrains with fine SLM process-induced solidification/dislocation cells and spherical oxide nano-particles resulted in the pronounced cyclic strain localization into PSBs (persistent slip bands) as evidenced by transmission electron microscopy (TEM). Atomic force microscopy (AFM) and scanning electron microscopy (SEM) were adopted to characterize the topography of sharp surface slip markings, nowadays called persistent slip markings (PSMs), arising in places where PSBs intersect free surface (see Fig. 1a). Experimental data on cyclic strain localization, as documented both on the surface and in the bulk of fatigued SLMed 316L steel, are confronted with the cyclic stress-strain response of material (see Fig. 1b), namely the presence of permanent cyclic softening and characteristic changes in loop shape parameter.

KEYWORDS:

Additive manufacturing; low cycle fatigue; 316L stainless steel; persistent slip band; atomic force microscopy



(a) (b)

Fig. 1 (a) *PSMs within individual columnar grains and* (b) *cyclic hardening/softening curve and variations of loop shape parameter in SLMed 316L steel fatigued with* ε_a *= 0.5% until the end of fatigue life.*

D1-317

Influence of the defect tolerance on the fatigue strength of additively manufactured AlSi10Mg

Bastian BLINN*, Patrick LEHNER, Tilmann BECK

Institute of Materials Science and Engineering (WKK), RPTU Kaiserslautern-Landau, GERMANY

*Corresponding author: b.blinn@mv.rptu.de

ABSTRACT:

To exploit the lightweight potential of additively manufactured components made of Al-alloys, a comprehensive design is indispensable. This requires a sound knowledge of the fatigue behavior, which highly depends on process-induced defects. Despite the strong influence of the defect tolerance on the fatigue life, most works only analyze the defect characteristics, while the ability of the material to counteract the resulting stress concentrations is not considered. Consequently, in this work the defect tolerance of AlSi10Mg manufactured via Laser-based Powder Bed Fusion using two different layer thicknesses *t* was investigated. Therefore, "as-built" and artificially aged (T6) specimens were analyzed to vary the material volume properties.

Despite a hardness decrease, for *t*=60µm, the T6-treatment results in an increased fatigue life, caused by an increased defect tolerance represented by higher $|e_{II}|$ determined in cyclic indentation tests (see Fig.1a). Since the crack initiating defects are smaller for *t*=30µm (see Fig.1b), these specimens show higher fatigue strengths and the effect of improved defect tolerance due to T6 is less pronounced, leading to equal fatigue life for T6 and "as-built" condition. These results demonstrate that the fatigue strength of additively manufactured AlSi10Mg can be increased by both, decreasing the defect size and improving the defect tolerance.

KEYWORDS:

Defect tolerance; Laser-Based Powder Bed Fusion; artificial aging; cyclic indentation testing; process-induced defects

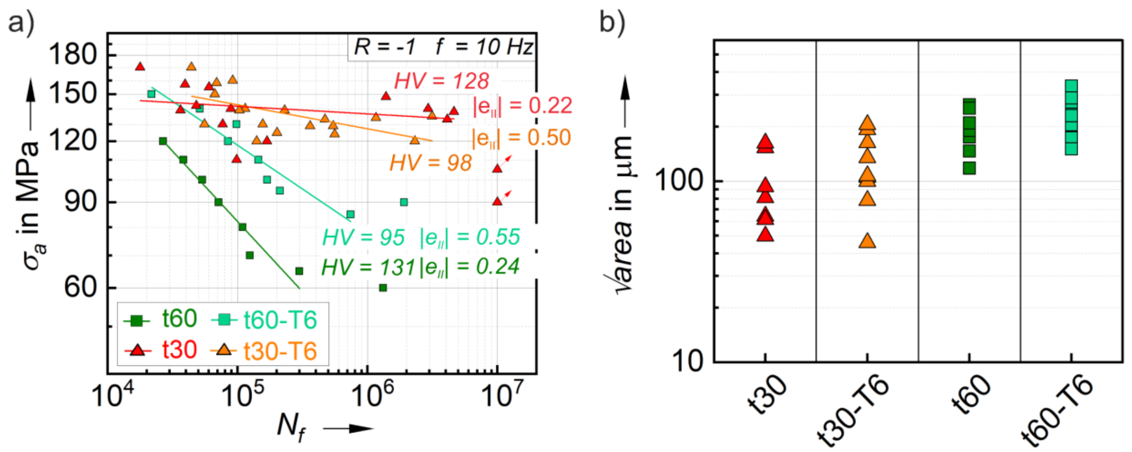


Fig. 1: *a) S-N curves of the specimens manufactured with layer thicknesses 30µm (t30) and 60µm (t60) in artificially aged (T6) and "as-built" condition including their respective hardness and cyclic hardening exponent*$_{CHT}$ $|e_{II}|$*; b) size distribution of the crack initiating defects obtained in fracture surface analyses performed on the different material conditions*

D1-318

Assessment of cyclic resistance on stainless steel 316L based cylindrical structures repaired by metal additive manufacturing methods

Baris TELMEN[1,*], Fabien SZMYTKA[1], Gilles ROLLAND[2], Nicolas THURIEAU[1] and Anne-Lise GLOANEC[1]

[1] Institute for Mechanical Sciences and Industrial Applications UMR EDF/CNRS/CEA/ENSTA 9219, ENSTA Paris, Institut Polytechnique de Paris, Palaiseau
[2] Institute for Mechanical Sciences and Industrial Applications UMR EDF/CNRS/CEA/ENSTA 9219, Electricité de France (EDF R&D), Palaiseau, France

* Corresponding author: baris.telmen@ensta-paris.fr

ABSTRACT:

The technological maturity of metal additive manufacturing (MAM) processes makes them a promising option for repairing industrial structures. However, to widespread the use of repaired structural metallic components which are experiencing cyclic load during industrial applications, it is crucial to understand the relationship between process parameters, microstructure and mechanical properties as well as the inherent interface behavior, and defects formation. Post-treatment effects should also be investigated. Moreover, resistance under cyclic loading is a must to assess for the applicability on critical components.

Within this framework, 316L stainless steel is here used as both substrate and repair/coating material. To assess post-repair fatigue strength, this work proposes an original reparation application with MAM methods (Directed Energy Deposition-DED and Cold Spray-CS) on cylindrical samples for evaluating resistance to cyclic loading. The samples' geometrical choice is done to investigate the contribution of the interface on fatigue resistance. Repaired samples fatigue strength is first estimated with classic staircase protocol and then evaluated with self-heating tests (Fig.1) to assess their heat dissipation characteristics. Fractography analysis finally enables to better understand the interface role and crack initiation/propagation on fatigue failure. Additionally, both AM reparations methods shown particularities which should be considered for optimizing the fatigue resistance.

KEYWORDS:
Metal Additive Manufacturing, Reparation, Directed Energy Deposition, Cold Spray, Self-heating

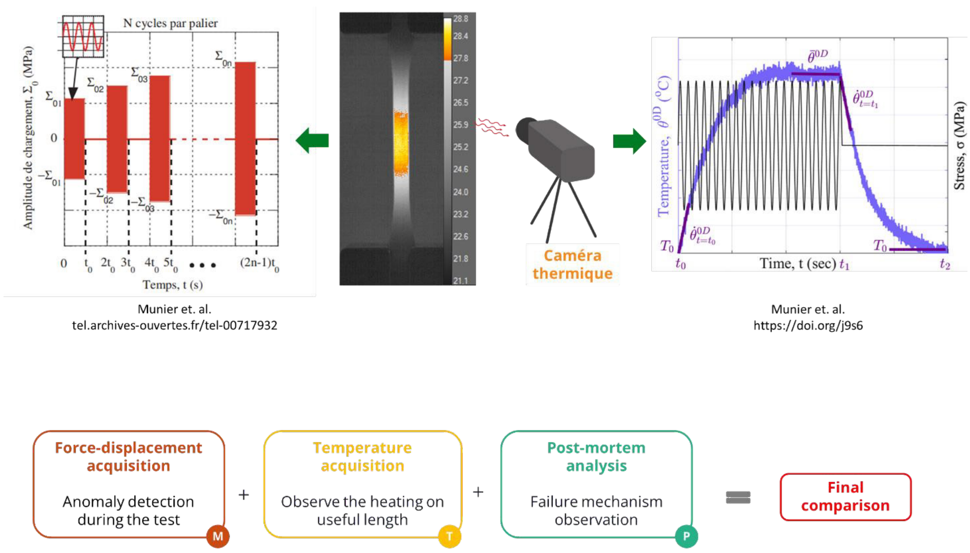


Fig. 1 *Demonstration and application of Self-heating test on repaired samples*

D1-319

Enhancing the Fatigue Performance of Additively Manufactured AlSi10Mg Alloy Using A Novel Chemo-mechanical Surface Treatment

Waqas MUHAMMAD[1], Jidong KANG[2]*, Jie LIANG[2], Kaan INAL[1], and Agustin DIAZ[3]

[1] University of Waterloo, CANADA
[2] CanmetMATERIALS, CANADA
[3] REM Surface Engineering, USA

* Corresponding author: jidong.kang@nrcan-rncan.gc.ca

ABSTRACT:

Surface roughness remains as a significant challenge for aluminum parts fabricated using laser-based powder bed fusion (PBF-LB) additive manufacturing (AM) process. Several surface post-treatments have been proposed to mitigate the negative impacts of surface defects and high surface roughness on the fatigue of AM materials.

In this contribution, a newly developed chemo-mechanical surface processing treatment (CMP) is applied to AlSi10Mg alloy round-bar fatigue specimens fabricated using PBF-LB. This new treatment combines the benefits of both chemical (i.e. ability to be applied to complex AM geometries while achieving superior surface finish) and mechanical (i.e. generation of compressive residual stresses) surface treatments to achieve significantly lower surface roughness of S_a = 0.3 μm. Stress controlled fatigue testing was conducted at a stress ratio, R of -1, and 0.1 for both as-built and CMPed AM specimens. When testing at stress ratio of 0.1, the fatigue strength at 1-million cycles improved from 94 MPa for as-built specimens to 212 MPa for CMPed ones while for R=-1, i.e., the fully reversed loading case, the fatigue strength improved from 47 MPa for as-built specimens to 150 MPa for CMPed ones, i.e., three times improvement in fatigue strength of the alloy (see Fig. 1).

KEYWORDS:

Additive manufacturing; Fatigue strength; AlSi10Mg; Chemo-mechanical surface treatment

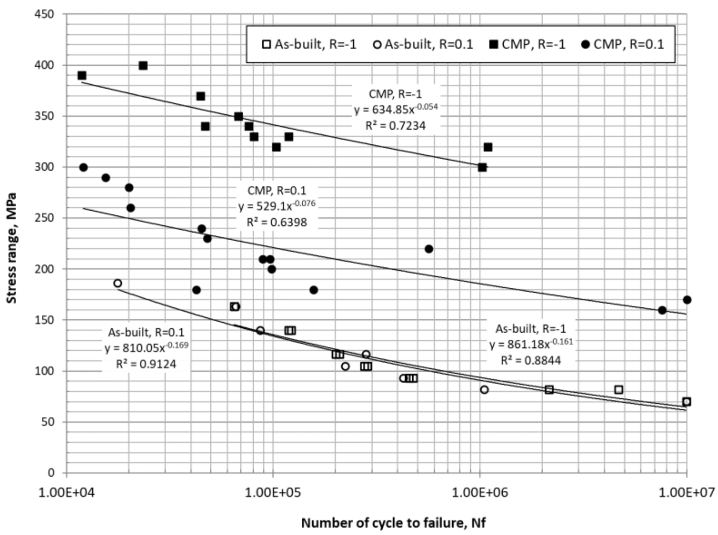


Fig. 1 *S-N curve.*

D2-301

Development of an experimentally informed model for fatigue crack initiation in metals due to hydrogen

Aman ARORA[1,2*], Mohit SINGH[2], Dhiraj K. MAHAJAN[2]

[1] Kyushu University, JAPAN
[2] IIT Ropar, INDIA

* Corresponding author: arora.aman.462@m.kyushu-u.ac.jp

ABSTRACT:
Hydrogen Embrittlement (HE) describes the degradation of mechanical properties of metallic materials when exposed to hydrogen environments. HE causes catastrophic brittle failures, earlier crack initiation, reduced ductility, fracture toughness, and fatigue life of metallic components. For a better understanding, it is essential to recognize the role of microstructural arrangements enabling various mechanisms of HE leading to crack initiation and propagation. In particular, crack initiation due to hydrogen is the least understood due to the difficulty in the characterization of local hydrogen content at various microstructural sites. In this work, we performed extensive experimentation to characterize fatigue crack initiation (FCI) during in-situ low-cycle fatigue loading in relation to the microstructural features. Specimens of pure nickel and 316L austenitic stainless steel under hydrogen charged and uncharged configurations are investigated to focus on grain/twin boundaries as prime defect sites. The prevalent atomic structure, elastic anisotropy, grain boundaries type, and plastic inhomogeneities make grain/twin boundaries as most susceptible sites for crack initiation in these polycrystals. Based on these investigations, a model for hydrogen-linked FCI is proposed that links the microstructural features with the prevalent mechanisms of HE such as Hydrogen Enhanced Local Plasticity (HELP) and Hydrogen Enhanced Decohesion (HEDE).

KEYWORDS:
Hydrogen Embrittlement, Fatigue crack initiation, Scanning electron microscope, Nickel, SS316L

D2-302

Influence of the interaction hydrogen/microstructure on low-cycle fatigue behavior and fatigue crack growth in a precipitation-hardened nickel-based superalloy.

Achraf RADI[1,2,*], Marion RISBET[1], Gilbert HENAFF[2], Xavier FEAUGAS[3], Abdelali OUDRISS[3]

[1] Université de Technologie de Compiègne, France
[2] Ecole Nationale Supérieure de Mécanique et d'Aérotechnique, France
[3] Laboratoire des sciences de l'Ingénieur pour l'Environnement, France

* Corresponding author: Achraf.radi@utc.fr - achraf.radi@ensma.fr

ABSTRACT:
Nickel-based superalloys are renowned for their exceptional mechanical strength, and high corrosion and oxidation resistance. However, exposure to hydrogen can significantly alter their mechanical properties, leading to premature damage due to hydrogen embrittlement (HE). Moreover, this phenomenon is also dependent on the metallurgical state and on the interactions of hydrogen with microstructural heterogeneities (grain boundary, precipitates, dislocations, vacancies, etc.). The goal of the present study is to investigate the consequence of hydrogen-precipitate interactions on the Low-Cycle fatigue (LCF) behavior and fatigue crack growth (FCG) of a specific nickel-based superalloy, Waspaloy, within the underaged domain. Two precipitation states, HT0 and HT4, with a constant grain size of 100 μm and varying precipitate sizes (d=10 nm and d=30 nm, respectively), are investigated. Cathodic hydrogen pre-charging is performed for the specimens used for LCF tests, while gaseous hydrogen charging is conducted for fatigue crack growth tests. The first results provide insights into the impact of hydrogen on LCF behavior and FCG in Waspaloy within the underaged domain. The influence of hydrogen concentration in relation with the precipitate state on fatigue performance and crack growth characteristics is identified. The cyclic behavior and fatigue crack growth rate (FCGR) were compared to those of uncharged states, while internal stresses were evaluated using Cottrell-Dickson partitioning of hysteresis loops. Additionally, this study discusses the relationship between internal stresses, dislocation structures, extrusion heights of slip bands, and fracture path. These characteristics were respectively characterized using TEM, AFM, and SEM.

KEYWORDS:
Nickel alloys; Low cycle fatigue; Fatigue crack growth; Hydrogen embrittlement; Slip localization.

D2-303

Some impact of hydrogen concentration and distribution on low cycle fatigue behavior of an alpha titanium alloy

L. C. Martins Moreira[1-2*], A. Oudriss[1], J. Bouhattate[1], C. Berziou[1], G. Lotte[1], S. Cohendoz[1], X. Feaugas[1], S. Frappart[2], A. Mathis[2], T. Millot[2]

[1] La Rochelle University, LaSIE UMR CNRS 7356, Avenue Michel Crépeau, 17042 La Rochelle, FRANCE
[2] NAVAL GROUP / CESMAN, Technocampus Océan, 5 Rue de l'Halbrane, 44340 Bouguenais, FRANCE

* Corresponding author: larissa.martins_moreira@univ-lr.fr,

ABSTRACT:

The impact of hydrogen on the low-cycle fatigue behavior of a α-titanium (T40, grade 2) was investigated in the present study. The samples were charged with different hydrogen concentrations using cathodic polarization in a glycerinated H_3PO_4 medium followed by a homogenization heat treatment. Then, low cycle fatigue tests (LCF) were carried out under total strain control at room temperature. The mechanical behavior (hardening and softening) under LCF seems to be correlated to the evolution of hydrogen in solid solution and hydrides interactions with dislocations. Both impact the number of cycles to fracture and toughness. Different hydride morphologies (γ- and δ-hydrides) and their interactions with cyclic dislocations structures have been related based on *post mortem* observations using transmission electron microscopy (TEM) and correlated with the mechanical properties depending on hydrogen content. In addition, the stress-strain hysteresis loops are investigated to understand the internal stresses evolutions as a function of cycles, as well as its relationship with the formation of defects and dislocations patterns. This reveals that either the physical effect of hardening or softening on the effective and back stresses depends on the hydrogen content and location (hydride or interstitial solid solution). The relationship between the microstructural observations and the mechanical results is discussed.

KEYWORDS:

Hydrogen; hydrides; dislocation patterns; fatigue; titanium alloys.

D2-304

Review of the antagonists' processes of hydrogen on physical mechanisms of plasticity and their consequences on fatigue behavior of fcc metals

Caroline TRAISNEL[1], Guillaume HACHET[1], Abdelali OUDRISS[1], Xavier FEAUGAS[1]*

[1] La Rochelle University, LUDI, LaSIE UMR-CNRS 7356, FRANCE

* Corresponding author: xfeaugas@univ-lr.fr

ABSTRACT:
The fundamental aspects of hydrogen embrittlement (HE) are based on the consequences of the solute on the elementary mechanisms of plasticity. We highlight that the hydrogen-induced microplasticity antagonistic processes is a key feature to improve HE in fcc metals. The impact of hydrogen on the monotonic and cyclic plasticity of <001> oriented nickel single crystal was investigated using loading and unloading tests and nanoindentation. Static and dynamic nanoindentations were performed on undeformed and pre-strained samples with and without hydrogen. The indented surfaces were analyzed by SEM-FIB, EBSD and TEM to characterize the development of dislocation structures and any other defects and hence to establish the hydrogen-plasticity correlation near the surface. The long-range internal stresses developed in the hydrogen charged samples during the dynamic nanoindentation were compared to the results of TEM (dislocation density) and cyclic micro-tensile test (effective and back stresses). A competition between cyclic hardening/softening was observed with and without hydrogen, attributed to the hydrogen induced differences in the development of dislocation structures and subsequent internal stresses. Both can be correlated with hydrogen and/or vacancies clusters formation. Based on atomistic calculations we have commented and elucidated some fundamentals mechanisms in relation with experimental results.

KEYWORDS:
Cyclic hardening rate, dislocation pattern, internal stresses, vacancies, nano-indentation.

D2-305

Experimental investigation of hydrogen embrittlement on the tensile and low-cycle fatigue properties of an X52 steel

Carl FISCHER*, Heiner OESTERLIN and Thorsten MICHLER

Fraunhofer Institute for Mechanics of Materials IWM, Freiburg, GERMANY

* Corresponding author: carl.fischer@iwm.fraunhofer.de

ABSTRACT:

Components in hydrogen service can exhibit hydrogen embrittlement in critical locations with high local stresses or strains, which may result in a reduced component lifetime. Hence, the characterization of candidate materials must include hydrogen exposure during the tests. The tensile and cyclic material behavior is usually investigated on cylindrical specimens in autoclaves under a high-pressure hydrogen atmosphere.

To increase test capacities and provide convenient test possibilities, other test methods and specimen geometries must be developed. One promising approach is cylindrical hollow specimens, where hydrogen is applied in the borehole. The objective of this study was to investigate the influence of high-pressure gaseous hydrogen on the tensile and cyclic properties of an X52 pipeline steel. Therefore, tensile, and low-cycle fatigue (LCF) tests at room temperature on hollow specimens were performed in air and gaseous hydrogen. The tensile tests on hollow specimens show a good agreement with standard cylindrical specimens, see Fig. 1. Hence, the hollow specimen technique is also adapted for LCF tests. The influences of hydrogen exposure and a different borehole surface roughness (deep-hole drilled and honed) on the lifetime are investigated. Furthermore, differences between both specimen geometries are addressed and discussed.

KEYWORDS:

Hydrogen embrittlement; Low-cycle fatigue; Tensile tests; Hollow specimens; Pipeline steel

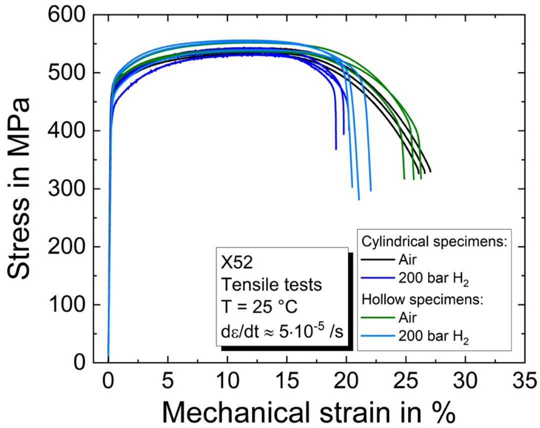


Fig. 1: *Tensile tests on X52 steel in air and 200 bar hydrogen on smooth cylindrical and hollow specimens.*

D2-307

Effects of tightening torque on vibration fatigue performance of single-lap joints: modal parameter analyses

Hsin Shen HO*, Yonghui HE and Erliang ZHANG

School of Mechanical and Power Engineering, Zhengzhou University, Science Road 100, 450001 Zhengzhou, CHINA

* Corresponding author: hsinshen.ho@zzu.edu.cn

ABSTRACT:

Joints are essential for various engineering structures as they are widely used in many engineering fields. As joints often work in a complex vibration environment, it is thus of importance to have an enhanced understanding of their vibration fatigue damage and failure. Thereby, the vibration fatigue performance of joint specimens tightened with a range of torque levels is investigated in the present work. It is done by detecting the modal parameter changes during the vibration fatigue process, and also by conducting the fatigue failure analyses after the vibration fatigue testing is stopped. The vibration fatigue results show that on the one hand, modal parameters can be effectively used for assessment of cumulative fatigue damage; and on the other hand, among all investigated joints, the one with an optimal tightening torque level is found to have the highest fatigue life. The latter finding is revealed from the fatigue failure analyses to be associated with the decreased number of fatigue crack initiation sites. Thus, the use of an optimal tightening torque level can bring beneficial effects in slowing down the early fatigue damage process.

KEYWORDS:

Vibration fatigue; Bolted joints; Tightening torque; Modal parameters; Cumulative fatigue damage.

D2-308

Evaluation of Fatigue Properties of Adhesive Bond joint with Laser Patterning Surface Treatment

Ryuta YOTSUTANI[1], Saimon KAWABATA[1], Koki USUI[1] ,Yukihiro SUGIMOTO, Hiroyuki AKEBONO[1] and Atsushi SUGETA[1*],

[1] Hiroshima University, JAPAN

* Corresponding author: m225614@hiroshima-u.ac.jp

ABSTRACT:
In the application of adhesive bonding, surface treatment is used to create a rough surface on the adherend. While sandblasting, in which fine particles are hit onto metallic materials, has been the mainstream surface treatment method, this study focuses on laser patterning surface treatment using a fiber laser as an alternative technology. By adjusting the laser output and loop number, we aimed to create arbitrary groove shapes and surface compositions, generate an anchor effect, and activate the surface. This study suggests that the dynamic strength properties are affected by adjusting the laser conditions. The surface morphology and surface composition are related to the strength enhancement factor. The conditions for excellent dynamic strength properties were elucidated through shape observation, composition analysis, and fatigue tests.

KEYWORDS:
Adhesive joining ; Surface treatment ; Laser treatment ; Fatigue properties

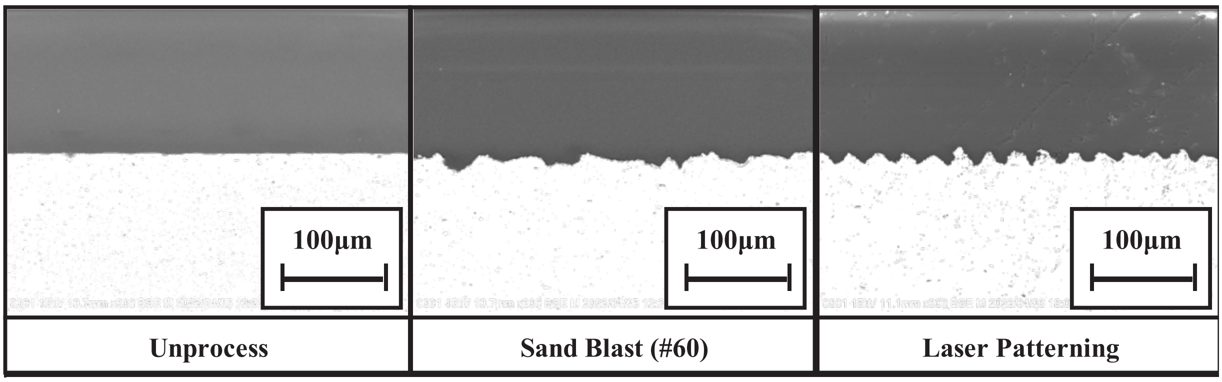


Fig.1 Cross section of specimen with surface treatment.

D2-309

Effect of Plate Thickness Ratio on the Fatigue Strength Properties of Friction Stir Spot Welds of Aluminum Alloy

Yuki NOSE[1,*], Yukihiro SUGIMOTO[1], Hiroyuki AKEBONO[1] and Atsushi SUGETA[1]

[1] Hiroshima University, JAPAN

* Corresponding author: m221673@hiroshima-u.ac.jp

ABSTRACT:
In recent years, the automotive industry has been expanding the use of lightweight materials to achieve vehicle weight reduction. This study investigated the effect of the plate thickness ratio on the fatigue strength characteristics in friction stir spot welding (FSSW) of aluminum rolled materials, aiming to clarify the applicability of FSSW technology to structural components of car bodies. This study revealed that when using different plate thicknesses, inserting the tool from the thicker plate resulted in an improvement in fatigue life. Besides, it was found that the fracture morphology changed depending on combination of plate thickness. At high applied force range, base metal crack from the thin plate tends to initiate and lead to rupture in thin plates. At low applied force range, crack from the hooking (hooking is the appearance of accelerated plastic flow in the vertical direction, causing the lower plate to roll up and flow into the upper plate.) propagates upward direction of thickness of the plate, leading to rupture of the upper plate.

KEYWORDS:
FSSW, Lightweight materials, Al alloy, Plate thickness ratio, Fatigue strength properties

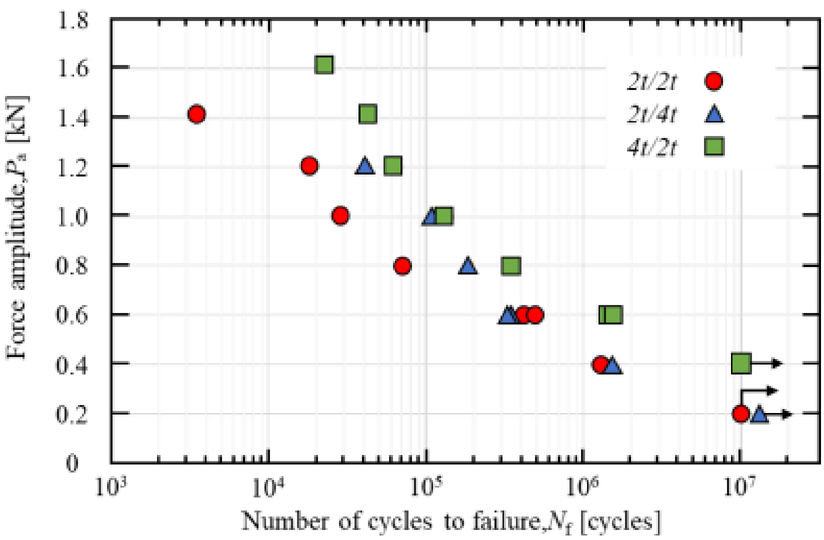


Fig. 1 *P-N curves.*

D2-310

Influencing Factors on Fatigue Strength of SPR joint in Magnesium Alloy

Yukio MIYASHITA[1*], Moriaki OGIDO[2], Shao XUANYI[2], Keiko SASAKI[3]

[1] Department of Mechanical Engineering, Nagaoka University of Technology
[2] Graduate School of Engineering, Nagaoka University of Technology

* Corresponding author: miyayuki@mech.nagaokaut.ac.jp

ABSTRACT:
In order to apply self-piercing rivet (SPR) joining to magnesium alloy, influencing factors on the joint strength were investigated. Fatigue tests were carried out under tensile shear loading in similar and dissimilar materials joint of magnesium alloys. Cracks occurred in a lower sheet during joining process when magnesium alloy was used as a lower sheet. Fatigue strength of SPR joint increased by suppressing occurrence of the cracks. These cracks affected fatigue strength of the SPR joint as course of fatigue crack initiation and by inducing loosening of a rivet. In case of dissimilar materials SPR joints, fatigue strength changed by combination of upper and lower sheets as shown in Fig.1. Fatigue crack initiated around a rivet due to bending motion of upper sheet in case of that a magnesium alloy was used as an upper sheet. Stress state and deformation behavior were investigated with finite analysis method by using a model following an actual SPR joint to study influencing factors on the joint strength. The analysis results suggested that the geometry factors at the joint part might has minor effect on stress state around fatigue crack initiation point. On the other hand, it was speculated that stiffness of a joint could be a major influencing factor on fatigue strength of SPR joint.

KEYWORDS:
Joint strength, Self-Piecing Rivet joint, Magnesium alloy, dissimilar materials joint

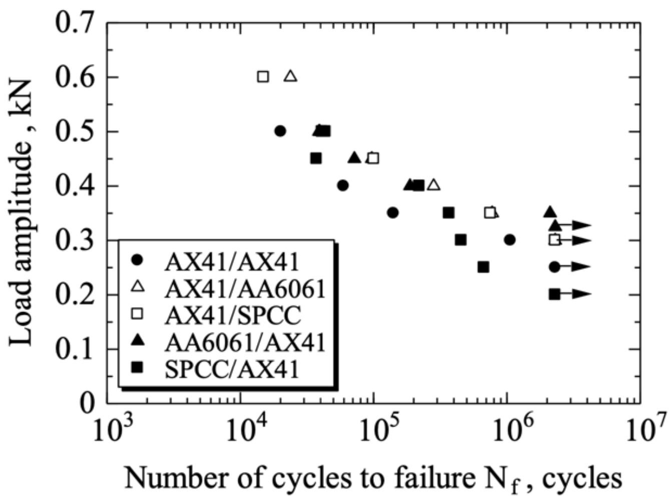


Fig. 1 *Fatigue strength of similar and dissimilar materials SPR joint in AX41 magnesium alloy.*

D2-311

Fatigue Strength of Linear Friction Welded Joints for S55C Steel Plates

Noboru KONDA[1], Masakazu MORI[1], Yasunori SHINDOH[1], Tomotaka KITAMURA[2], Yoshihiro AOKI[3], Yoshiaki MORISADA[3] and Hidetoshi FUJII[3]

[1] Ryukoku University, JAPAN
[2] Sharp Fukuyama Laser Co., Ltd., JAPAN
[3] Osaka University, JAPAN

* Corresponding author: konda@rins.ryukoku.ac.jp

ABSTRACT:

Linear Friction Welding (LFW) was applied to medium-high carbon steel S55C, which had difficulty in arc welding process, and fatigue strength of welded joints were evaluated. In LFW process, peak temperature can be easily controlled and fatigue strength of welded joints for two level of peak temperature are compared. As a result, the harmful welding defects are not detected in the joints. A remarkable difference was recognized for the hardness distribution between two kinds of joints, and low peak temperature joint came to have almost equivalent fatigue strength with a base material. The fatigue crack initiated at the interface of welded area.

KEYWORDS:

Linear Friction Welding; Fatigue Strength; S55C; Peak Temperature; Residual Stress

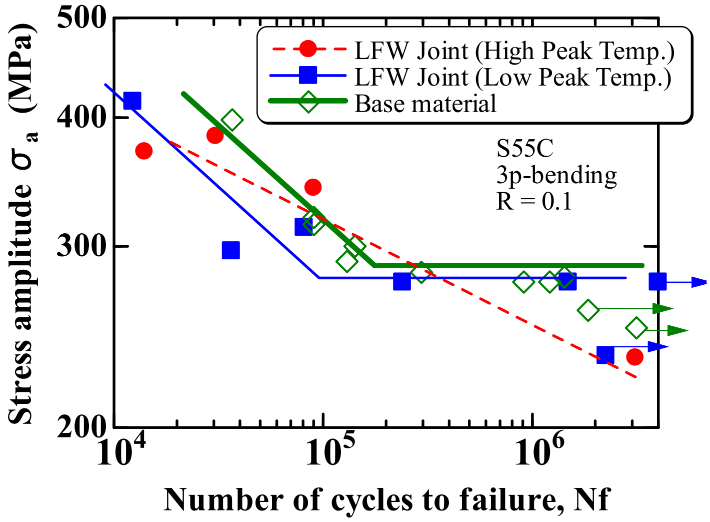


Fig. 1 *S-N curve for LFW joins.*

D2-312

Fatigue Behavior of Al/steel Dissimilar Friction Stir Welds and the Effect of Die Press Working

Yoshihiko UEMATSU[1,*], Ryosuke MIYATA[1] and Paul Dario TOASA CAIZA[2]

[1] Gifu University, JAPAN
[2] Karlsruher Institut für Technologie (KIT), GERMANY

* Corresponding author: uematsu.yoshihiko.z3@f.gifu-u.ac.jp

ABSTRACT:
Friction stir welding (FSW) is a solid-state welding process, and thus it is recently used for the joining of dissimilar alloys. It is known that FSW could fabricate Al/steel dissimilar joins, which are important for the concept of multi-material car body fabrication. To use Al/steel dissimilar FSW joint for the actual car components, it is important to understand the fatigue properties of dissimilar welds, while the number of studies is limited. Furthermore, the welded plates experience die press working before they are integrated into the car components. However, the effect of die press working on the fatigue properties is not investigated at all. In the present study, 6000 series Al alloy plates were joined to the mild steel sheets by FSW technique, and fatigue properties were investigated. Furthermore, dissimilar welds were die pressed to the hat shape, and some samples were machined from the plate, which experiences severe deformation by die press working It was found that the die-press-worked samples had better tensile properties than the as-welded ones due to the work hardening. It indicates that die press working is applicable for the Al/steel dissimilar FSWed sheets. However, detrimental effect of die press working on the fatigue performances were found due to the formation of voids near the Al/steel interface by sever plastic deformation.

KEYWORDS: Fatigue; Friction stir welding; Dissimilar weld; Die press working

D2-313

Fatigue performance of A356/6082 dissimilar aluminum alloys butt joint

Mei Zhang*, Yangfei Chen, Qing Xu, Siwei Luo

School of Materials Science and Engineering, Shanghai University, Shanghai 200444, China

ABSTRACT:
The low-cycle fatigue tests with 0.2%~0.6% strain amplitudes of the cold metal transfer (CMT) welded butt joints of dissimilar aluminum alloys (cast A356 alloy and wrought 6082 alloy) were carried out, and the related low-cycle fatigue parameters were obtained by linear regression method, and the cyclic characteristics were analyzed respectively. The results manifest that severe cyclic hardening occurs during fatigue testing until the final fatigue fracture for the weld joints. Cyclic hardening is mainly related to the material of aluminum alloy. As strain amplitude increasing the cyclic hardening becomes more pronounced. The fatigue fracture morphology can be divide into initial source, crack propagation zone and final fast rupture region. The surface appearance of the initial source and crack propagation zone are both smooth, while the morphology of the fast rupture region is similar to that of the ductile tensile fracture morphology showing dimples and tear edges.

KEYWORDS: low-cycle fatigue, butt joint of dissimilar aluminum alloys A356/6082, cyclic hardening, fatigue fracture mechanism

D2-314

On the fatigue properties of a S550MC+100Cr6 cladded steel in different fatigue regimes

Marcel KROCHMAL[1, *], Thomas WEGENER[1] and Thomas NIENDORF[1]

[1] University of Kassel, GERMANY

* Corresponding author: krochmal@uni-kassel.de

ABSTRACT:

Cladded steels are layered composites manufactured by joining cladding materials like stainless steel to one or both sides of a carbon steel or low-alloy steel substrate. These composites can be used to combine otherwise contrary material properties like strength, ductility and cost-efficiency of a structural material with resistance to heat, wear or corrosion in the clad layer. By using a favorable arrangement of layers, layered composites can even surpass the individual properties of the monolithic base materials and offer reliable process routes to create graded part properties. The fatigue behaviour of cladded steels is interesting because it can be affected by various factors such as manufacturing methods, resulting residual stress distributions and bonding interface strength. Understanding the fatigue behaviour of cladded steels can help to improve their design and performance in engineering structures and therefore offer new possibilities in structural design. Thus, the present study focusses on the cyclic behaviour of a S550MC steel which was cladded with one layer of the medium-alloyed bearing steel grade 100Cr6, known for its high wear resistance. Varying loading conditions and fatigue regimes as well as microstructural features of the individual layers of the composite will be evaluated and discussed.

KEYWORDS:
cladded steels; LCF; HCF; residual stress; fatigue limit; microstructure

D2-315

Fatigue behavior of an Off-highway axle subjected to a variable amplitude strain-based load spectrum derived from field tests

Jacopo PELIZZARI[1,2], Alberto CAMPAGNOLO[1], Carlo DENGO[2] and Giovanni MENEGHETTI[1,*]

[1] Department of Industrial Engineering, University of Padova, Via Venezia, 1 - Padova, Italy
[2] Virtual Validation Department, Carraro S.p.A., Via Olmo, 37 - Campodarsego (Padova), Italy

* Corresponding author: giovanni.meneghetti@unipd.it

ABSTRACT:
The industry of off-highway vehicles is one of the fields of major application of nodular cast irons, which guarantee to manufacture complex geometries and ensure good mechanical properties. The present investigation deals with the fatigue design of off-highway axles made of GJS 500-7. As a result of the external loads, the axles are subjected to variable amplitude local strain spectra. An axle has been instrumented with fifteen strain-gauge channels; among these, a strain gauge rosette measured the highest maximum principal strain which was found after a preliminary finite element analysis. Then a number of maneuvers has been performed during in-field tests and the design spectrum at the critical strain gauge location has been derived by extending and mixing the in-field acquisitions of the maneuvers to the design life of 5000 hours. Fig. 1 reports the comparison between the design spectra in terms of the Smith-Watson-Topper fatigue parameter against the number of cycles and the fatigue design curves determined by means of constant amplitude laboratory fatigue tests on specimens taken from axles. Finally, the Palmgren-Miner damage index relevant to design spectrum of the overall vehicle life has been assessed.

KEYWORDS:
Off-highway axle; nodular cast iron; strain-controlled fatigue tests; field spectrum.

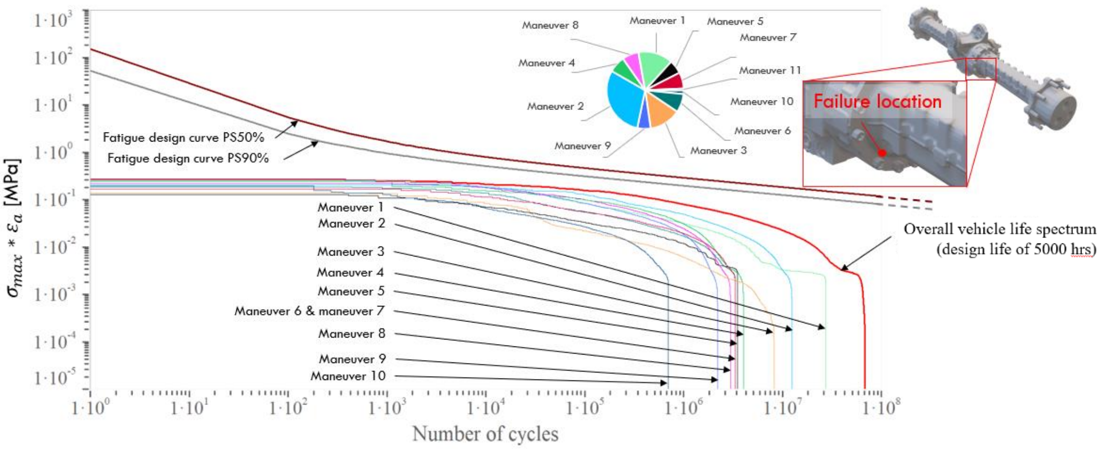


Fig. 1 *Comparison of the field spectra with the fatigue design curves.*

D2-316

Evaluation of Fatigue Strength of Full-scale Induction-hardened Axles for Railway Vehicles and Its Estimation under Very-High-Cycle Regime

Taizo MAKINO[1,*], Chihiro KOZUKA[1], Toshiyuki HATA[1], Takanori KATO[1], Miyuki YAMAMOTO[2] and Kohji MINOSHIMA[3]

[1] Nippon Steel Corporation, JAPAN
[2] Osaka University, JAPAN
[3] National Institute of Technology, Anan College, JAPAN

* Corresponding author: makino.hb3.taizo@jp.nipponsteel.com

ABSTRACT:

To investigate the use of fatigue damage evaluation in the design process, full-scale induction-hardened axles were fatigue-tested for 10^7 cycles, and the S-N curve and fatigue limit were clarified (Fig. 1). The origin of failure for most axles was the internal boundary between the hardened layer and matrix of the axle body. The fatigue limit was predicted by applying the local fatigue strength approach, wherein the local fatigue limit and stress distribution were compared at various radial positions on the test axle. Subsequently, the local fatigue limit was estimated using the relaxed residual stress distribution in the fatigue-tested axle and the dependency of mean stress and hardness on the fatigue limit of small specimens cut from the full-scale axle internal region. Additionally, the local stress was calculated using finite element analysis under the fatigue testing condition, where the predicted fatigue limit corresponded to the experimental value, and the small specimens were fatigue-tested over 10^9 cycles, without any failure between 10^7 and 10^9 cycles. This suggests that the fatigue limit of full-scale axles does not decrease in the very-high-cycle fatigue regime, i.e., the experimental fatigue limit (10^7 strength) of the full-scale axle corresponds to the very-high-cycle fatigue limit (10^9 strength).

KEYWORDS:

Full-scale Induction-hardened axle; Railway vehicle; Very high-cycle regime; Local fatigue strength approach; *S-N* curve

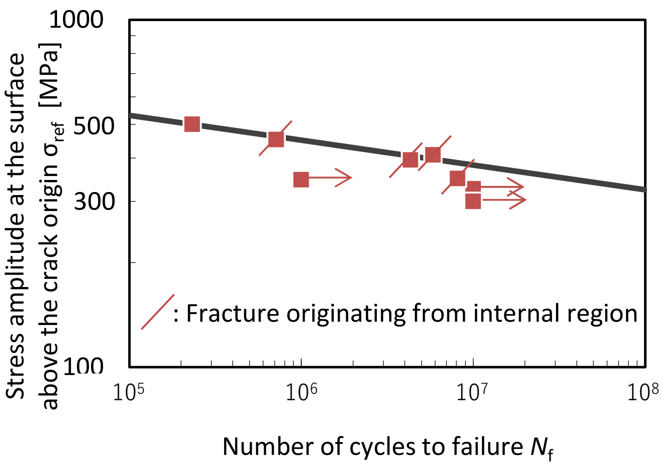


Fig. 1 *S-N* curve of the full-scale induction-hardened axles.

D2-317

Double-sided ultrasonic surface rolling process for improving the surface integrity and vibration fatigue resistance of thin-walled blade-like samples

Kaiming Zhang, Ji Wang, Shuang Liu, Xiancheng Zhang*

School of Mechanical and Power Engineering, East China University of Science and Technology, China

* Corresponding author: xczhang@ecust.edu.cn

ABSTRACT:

Ultrasonic surface rolling process (USRP) is a promising surface strengthening technology, which is gradually used to improve the mechanical properties and service life of aircraft blades. However, applying USRP onto the blade remains a challenge due to the thin-walled leading/trailing edges and the pre-load force on the blade during the USRP process. In this study, the surface integrity and vibration fatigue resistance of Ti-6Al-4V alloy treated by synchronous double-sided USRP are investigated. First, blade-like fatigue sample is designed based on the characteristics of thin-walled blade structure. Second, the surface integrity of samples before and after USRP are compared. The characterization results shows that the USRP produces 9~13 μm refined grain deformation layers, minimum roughness of Ra = 0.198 μm and Sa = 0.481 μm, and the thicknesses and maximum of the compressive residual stress (CRS) field are 715.32 μm and -760.35 MPa, respectively. Finally, the fatigue test and strengthening mechanism of the samples before and after USRP are studied. The highest increase in fatigue life of USRP samples is about 85.9 times. The introduced refined grain hardening layer and CRS stability are the key to prolong the fatigue performance. This work is expected to provide reference for USRP parameter optimization.

KEYWORDS:

Ultrasonic surface rolling process, Surface strengthening, Double-sided, Vibration fatigue

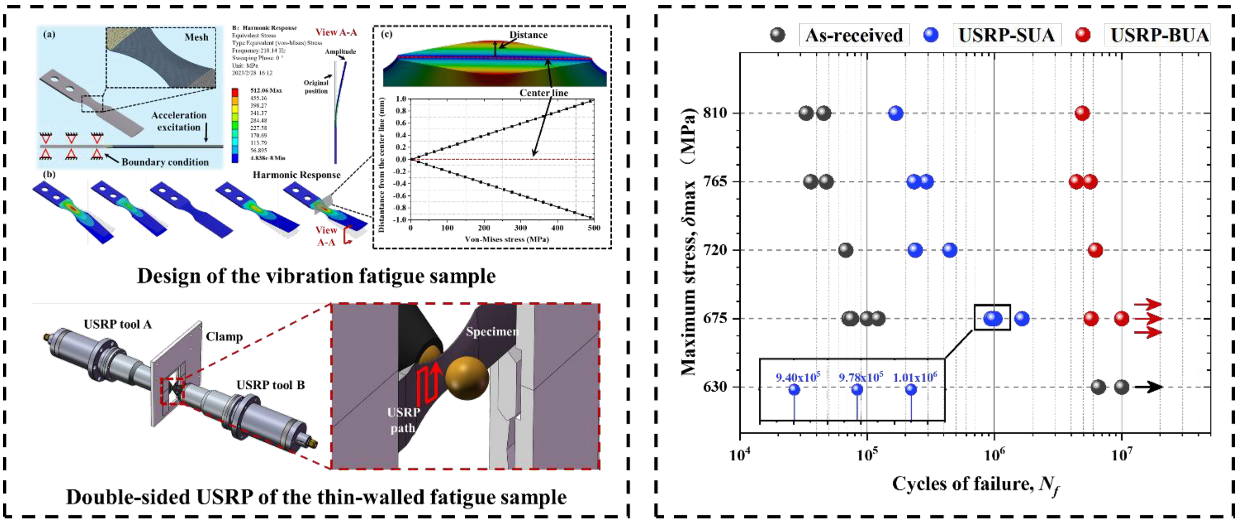


Fig. 1 *Design, double-sided USRP, and fatigue performance of thin-walled samples*

D2-318

Fatigue properties of thin plates

Vladimir Chmelko[1]*, Miloslav Kepka[2], Matúš Margetin[1], Miroslava Kučerková[1]

[1] Slovak University of Technology in Bratislava , SLOVAKIA
[2] University of West Bohemia, CZECH REPUBLIC

* Corresponding author: vladimir.chmelko@stuba.sk

ABSTRACT:

Thin plates are a common semi-finished product for the production of various components in the automotive industry but also in other constructions. Components made of thin plates are often also load-bearing elements that require stress-strain analysis. When assessing their fatigue life, this type of component has specific features that need to be analysed and taken into account when assessing fatigue strength and life.

The study will analyze the influence of the edge due to the rectangular cross-section, the influence of residual stresses and strain hardening as a consequence of the manufacturing and the material cutting technology used. In this study, three different low carbon steel sheet materials (S355, S500, S700) will be analyzed. Comparison of the results of cyclic tests of the sheet metal specimens and different cutting technologies (punching, laser cutting) as well as analysis of fatigue crack initiation sites will be presented.

KEYWORDS:

steel plates; fatigue strength; residual stresses;

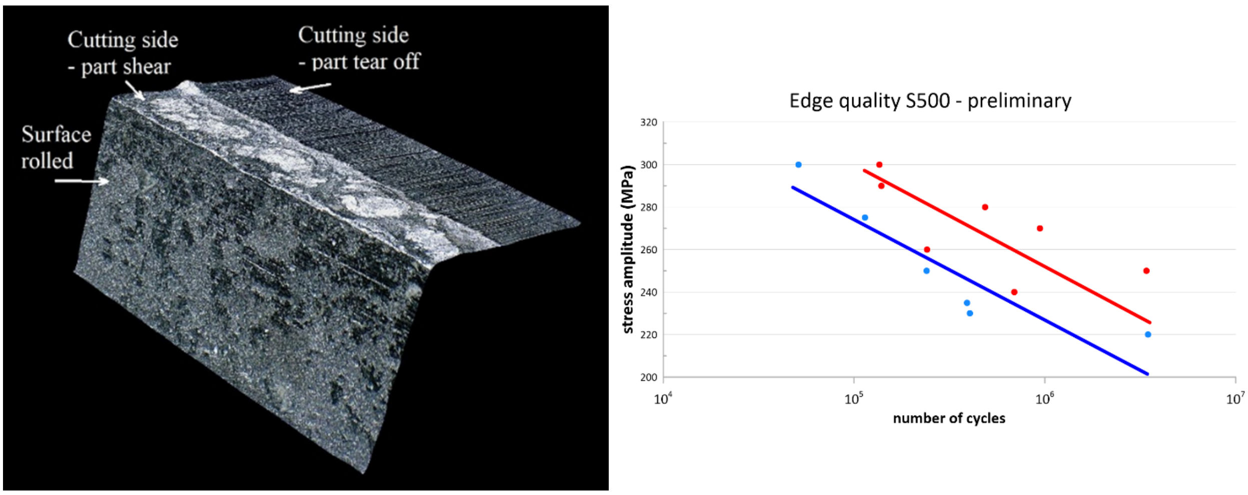


Fig. 1 Cutting edge and *S-N curves.*

D2-319

Study of impact-sliding composite fretting corrosion of heat exchanger tubes in different concentrations of NaCl solution

ZHU Guo-rui, TAN Wei

(School of Chemical Engineering and Technology, Tianjin University, 300350, China;
Zhejiang Institute of Tianjin University, Ningbo, Zhejiang, 315201, China)

ABSTRACT:

Turbulent excitation can cause impact-sliding composite fretting wear between the heat exchanger tubes and the supports, and corrosive environment can accelerate material loss, which makes it more difficult to predict the life of the heat exchanger tubes. This paper focuses on the impact-sliding fretting corrosion behavior of heat exchanger tubes and investigates the effect of NaCl concentration. An impact-sliding fretting corrosion device with in-situ electrochemical measurement was built to carry out experiments of 316L heat exchanger tubes. The damage mechanism was elaborated in combination with morphological features. The results show that the scale of damage on the wear scars gradually decreased with increasing the NaCl concentration. The total mass loss increased gradually in the range of 0.0-0.5 wt.% and decreased in the range of 0.5-5.0 wt.%. Large-scale damage enhanced by corrosivity and small-scale damage reduced by lubricity dominated the material loss at low and high concentrations, respectively.

KEYWORDS:

Fretting wear, Fretting corrosion, concentration, impact-sliding, heat exchanger tube

C1-301

Influence of organically modified sol-gel SiO_2 coating on the VHCF behavior of austenitic stainless steel AISI 904L

Shirin FALAKBOLAND[1,*], Marek SMAGA[1], Jolanta SZCZUREK[2], Justyna KRZAK[2], and Tilmann BECK[1]

[1] Institute of Material Science and Engineering (WKK), RPTU Kaiserslautern-Landau, GERMANY
[2] Faculty of Mechanical Engineering, Wrocław University of Science and Technology, POLAND

* Corresponding author: s.falakboland@mv.rptu.de

ABSTRACT:

Silica (SiO_2) coatings obtained by sol-gel method are anticipated to protect metallic substrates under synergistic operating conditions, such as fatigue and corrosion. However, pure inorganic sol-gel SiO_2 coatings are brittle and porous, and thus failed to bring protection to metallic substrates. Nevertheless, organically modified sol-gel SiO_2 coatings with less brittle mechanical behavior can increase the fatigue life and corrosion resistance especially in the very high cycle fatigue (VHCF) regime, if (i) fatigue cracks are initiated at the surface and (ii) the fatigue life is controlled by the crack initiation phase. In this study, specimens of austenitic stainless steel AISI 904L with and without organically modified sol-gel SiO_2 coating were subjected to ultrasonic fatigue with a load frequency of 20 kHz for up to 10^9 cycles. The organically modified sol-gel SiO_2 coating with a thickness of about 700 nm was applied at the specimen surface by dip-coating method. In interrupted VHCF tests, scanning electron microscopy (SEM) and focused ion beam (FIB) investigations were performed for the analysis of the fatigue induced changes in the specimen surface. The influences of the SiO_2 coating on the slip band and micro crack formation as well as fatigue life are discussed in detail.

KEYWORDS:

organically modified sol-gel silica coating; austenitic stainless steel; VHCF; FIB.

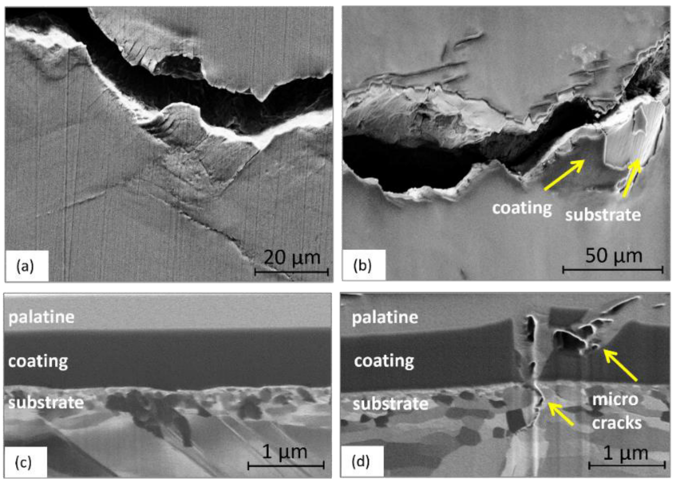


Fig. 1 *View of macro crack propagation in specimen without (a) and with organically modified sol-gel silica coating (b) as well as FIB cross sections in an intact area (c) and at a micro crack in specimen with coating (d)* after *cyclic loading in the VHCF regime.*

C1-302

Improvement in Fatigue Strength by Ball Burnishing of Aluminum Alloy with a Surface Defect

Kohei Wakamatsu[1], Koji Takahashi[1,*], Yuka Koyama[2] and Masanori Taniguchi[2]

[1] Yokohama National University, JAPAN
[2] SHIMANO INC., JAPAN

* Corresponding author: takahashi-koji-ph@ynu.ac.jp

ABSTRACT:
Ball burnishing (BB) is one of the surface finishing processes. By moving the tool while pressing on the workpiece, the surface roughness is reduced and compressive residual stress is introduced due to the plastic deformation. Compared to shot peening, which also introduces compressive residual stress, BB can reduce surface roughness. The effects of BB on the bending fatigue strength of an aluminum alloy specimen with a semi-circular slit simulating a pre-existing surface defect were investigated. Bending fatigue tests were conducted to determine the fatigue strength and depth of a semi-circular slit that can be rendered harmless via BB. Fig. 1 shows the experimental results. BB increased the fatigue strength of the smooth specimen by 32% and prevented the reduction of fatigue strength by the semi-circular slit of 0.1 mm in depth. It indicates that the semi-circular slit less than 0.1 mm in depth could be rendered harmless in terms of fatigue strength via BB. The estimated value of the critical depth of the semi-circular slit that can be rendered harmless based on fracture mechanics was consistent with the experimental results.

KEYWORDS:
ball burnishing, aluminum alloy, fatigue strength, surface defect, fracture mechanics

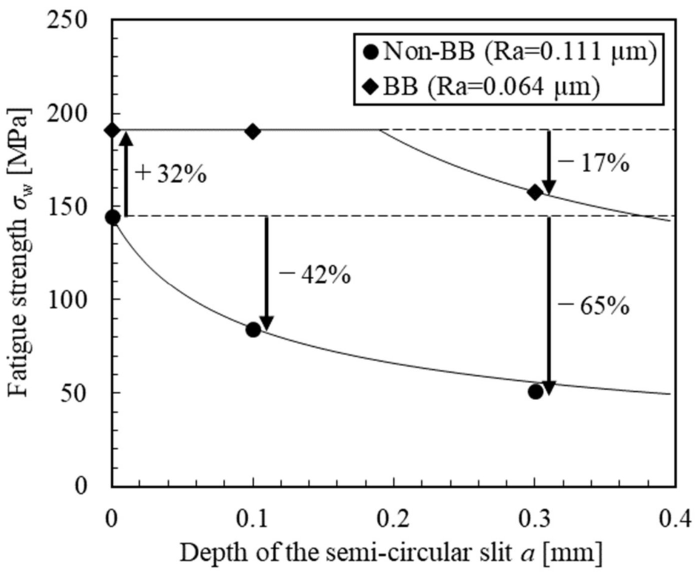


Fig. 1 Relationship between fatigue strength and depth of semi-circular slit.

C1-303
Effect of Residual Stress on Internal Crack Initiation and Propagation of Induction Heated and Quenched AISI4140 Steel with Different Hardened Layer Depths

Tomofumi AOKI[1], Motoaki HAYAMA[2], Shogo TAKESUE[3], Atsushi EZURA[4], Yoshitaka MISAKA[5], and Jun KOMOTORI[2,*]

[1] Graduate School of Keio University, JAPAN
[2] Keio University, JAPAN
[3] Kyoto Institute of Technology, JAPAN
[4] Sanjo City University, JAPAN
[5] Neturen Co., Ltd., JAPAN

* Corresponding author: komotori@mech.keio.ac.jp

ABSTRACT:
In this study, fatigue tests were performed under axial loading on induction heated and quenched (IHQ) specimens of AISI4140 steel with different hardened layer depths. Three types of fracture modes were observed (Fig.1). The first type is a fracture surface with the crack initiation site just below the hardened layer, as shown in Fig.1(a), which is caused by the tensile residual stress (TRS) generated by IHQ. The second type is a fracture surface with the crack initiation site within the core region, as shown in Fig.1(b), which is due to TRS relaxation during the fatigue process. Crack initiation is possible in the entire core region due to TRS relaxation. The third type is a crack that initiates at the core region and then propagates into the hardened layer, as shown in Fig.1(c). This type of fracture mode was mainly observed in specimens with a relatively thick hardened layer and lower compressive residual stress. These findings suggest that the relaxation of residual stress during the fatigue process strongly affects the location of the crack initiation site. *In situ* X-ray stress measurements were performed to validate the correspondence between the residual stress relaxation behavior during the fatigue process and the location of the crack initiation site.

KEYWORDS:
fatigue; surface treatment; fractography; internal failure; residual stress.

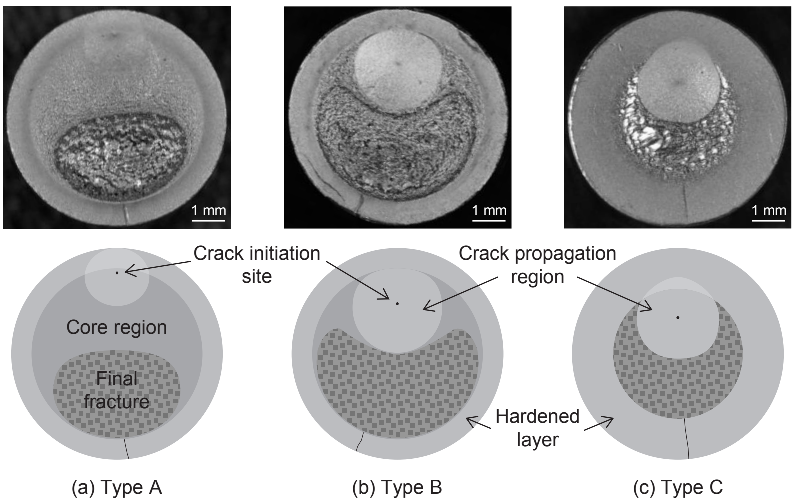


Fig.1 Macrographs and schematic illustrations of fracture surface.

C1-304

Controlling Factors of Scanning Cyclic Press on the Surface Modification of Magnesium Alloy

Nao FUJIMURA[1,*], Takashi NAKAMURA[1], Kosuke TAKAHASHI[1] and Tatsuki WAJIMA[2]

[1] Division of Mechanical and Aerospace Engineering, Hokkaido University, JAPAN
[2] HyBridge Co. Ltd., JAPAN

* Corresponding author: fujimura@eng.hokudai.ac.jp

ABSTRACT:

Surface modification using severe surface plastic deformation improves mechanical properties, such as hardness and fatigue strength, by creating a nanocrystalline layer on a metal surface. Scanning cyclic press (SCP), a surface modification technique we developed, created a modified layer, including a refined microstructure. Using a servo control method, SCP scans a metal surface with a vibrating indenter, which can cyclically apply a variable and precise compressive load. This study applied SCP to magnesium alloy AZ31 and investigated the effects of processing parameters such as the magnitude of the compressive load and the number of cyclic loadings on the fatigue property and surface layer of the SCP-treated AZ31. The results of uniaxial fatigue tests showed that the fatigue lives of the SCP-treated specimens extended due to the shifting of the fracture origination from the surface to the interior of the specimens. SEM/EBSD observation on the cross section of specimens showed that a modified surface layer, including a high-density strain region and deformation twins, formed (Fig. 1). This layer suppressed crack initiation from the surface. The layer's depth and the density of strain in the layer can be controlled by the magnitude of the compressive load and the number of cyclic loadings.

KEYWORDS:

Surface modification; cyclic loading; fatigue life improvement; microstructure refinement

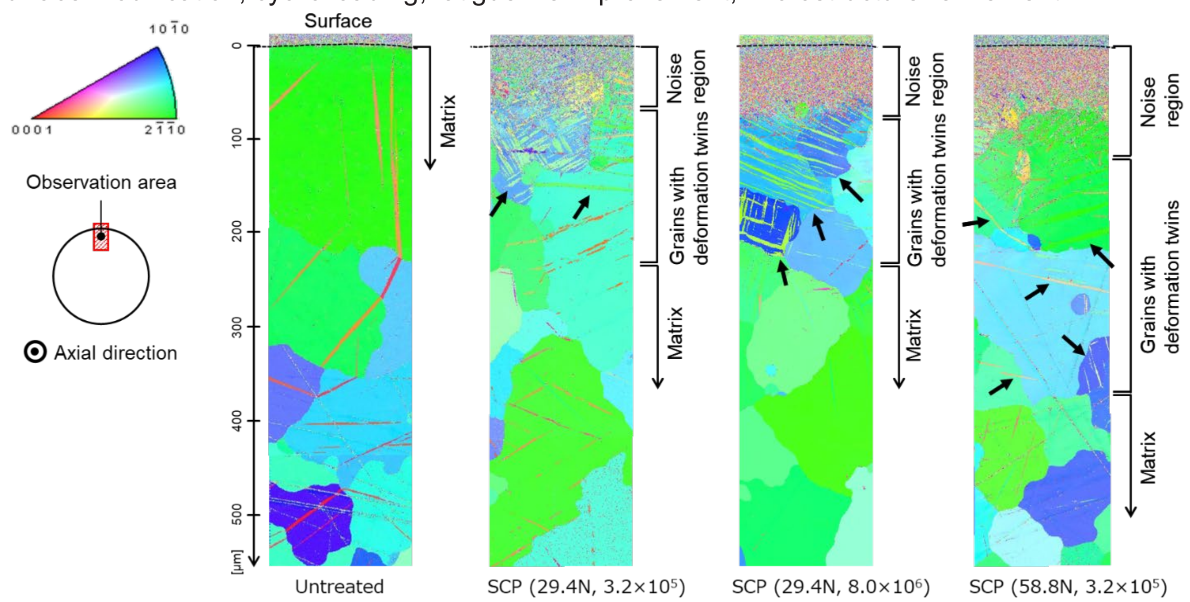


Fig. 1 Microstructure observations of the cross section in untreated and SCP-treated specimens.

C1-305

Fatigue behavior of metastable and stable austenitic stainless steels with different surface morphologies

Tong ZHU[1,*], Marek SMAGA[1] and Tilmann BECK[1]

[1] Institute of Material Science and Engineering (WKK), RPTU Kaiserslautern-Landau, GERMANY

* Corresponding author: t.zhu@mv.rptu.de

ABSTRACT:

The surface morphology can have a significant influence on the fatigue behavior of components. For austenitic stainless steels (ASSs), this issue is even more pronounced due to the metastability of the material. Based on the complex deformation mechanisms of metastable ASSs, which include dislocation slip, deformation twinning, and deformation-induced martensitic phase transformation, the metastable stainless steel AISI 347 was investigated in this study together with the stable AISI 904L as a reference material. 4-point bending fatigue tests with R = -1 and f = 10 Hz at ambient temperature were carried out on specimens with 5 technically relevant surfaces ranked from low to high surface roughness: polished surface, milled surface, micro-shot peened (MSP) surface, laser shock-peened surface (LSP), and ultrasonic modified surface (USM). Systematic material characterizations were carried out to elucidate the key influences of these morphologies on the fatigue behavior of metastable and stable ASSs. Within a certain range of surface roughness, deformation-induced martensite layers were proven to improve the fatigue life of the substrate material, which provides interesting perspectives to extend the lifetime of metastable austenitic stainless components.

KEYWORDS:

Metastable austenitic stainless steel; deformation-induced martensite; 4-point bending fatigue; surface modification.

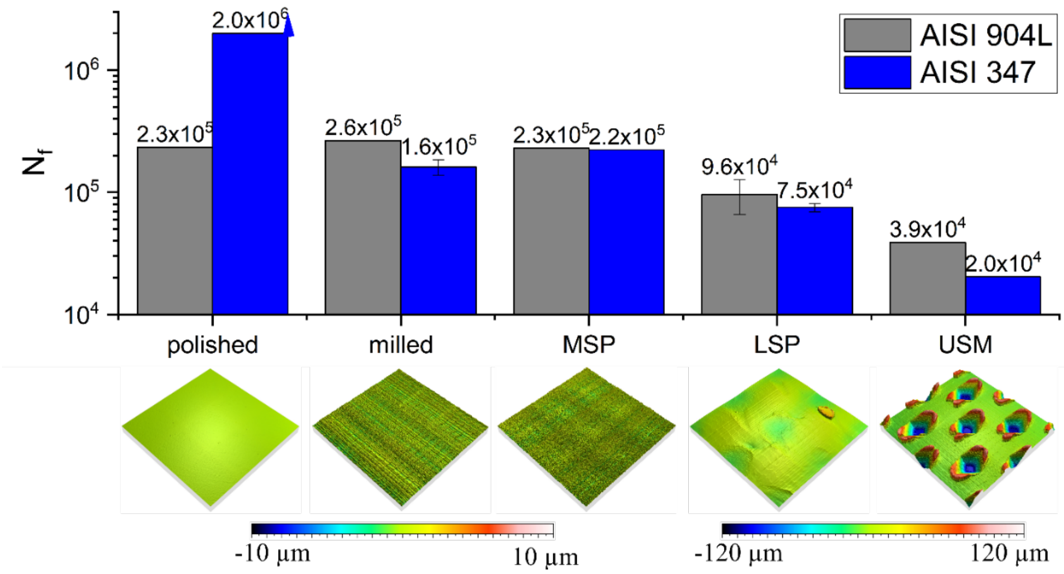


Fig. 1 *Fatigue life of stable and metastable ASSs with technically relevant surface morphologies at* $\sigma_{max.\ bending}$ *= 900 MPa, R = -1, f =10 Hz, AT.*

C1-306

Effect of Surface Roughness on Fatigue Strength of Aluminum and Magnesium Alloys

Koichiro NAMBU[1], Kenta TAKASHIMA[2,*] and Masahiro OKUMIYA[3]

[1] Osaka Sangyo University, JAPAN
[2] Formerly of Toyota Technological Institute, JAPAN
[3] Toyota Technological Institute, JAPAN

* Corresponding author: knambu.mech@ge.osaka-sandai.ac.jp

ABSTRACT:
Shot peening, one of the surface modification treatments, has been reported to be less effective for magnesium alloys. One of the reasons for this is that magnesium alloys are highly susceptible to notching, but the details have not been clarified. In order to evaluate the effect of notch sensitivity, specimens with different surface roughness were prepared and the effect of surface roughness on fatigue strength properties of magnesium alloys was evaluated in this study. The effects of surface roughness on fatigue strength properties of magnesium alloys were also compared with those of aluminum alloys. Specimens with three different surface roughness were prepared: machined, buffed, and emery polished. The specimens were then annealed, and only the surface roughness of each material was different. Fatigue test results showed that fatigue strength decreased with increasing surface roughness. Comparison between aluminum alloy and magnesium alloy showed that the rate of decrease was almost the same. These results indicate that there is no difference in notch sensitivity between these materials.

KEYWORDS:
Surface roughness, Notch sensitivity, Shot peening, Magnesium Alloys

C1-307

High Temperature Stability Mechanism of Fatigue Resistance of Warm Laser Shock Peened IN718 Superalloy

Yang LIU[1,*] , Lei WANG[1,*] , Mengya LIU[1] , Xiu SONG[1] and Fanqiang MENG[2]

[1] Key Lab for Anisotropy and Texture of Materials, Northeastern University, P. R. CHINA
[2] Sino-French Institute of Nuclear Engineering and Technology, Sun Yat-Sen University, P. R. CHINA

* Corresponding author: liuyang@mail.neu.edu.cn; wanglei@mail.neu.edu.cn

ABSTRACT:

The high cycle fatigue properties of IN718 alloy treated by warm laser shock processing (WLSP) were studied after high-temperature ageing. It was found that the thermally assisted surface hardening techniques had more obvious advantages in maintaining fatigue resistance and prolonging fatigue life of the alloy with the hardened surface layer during long-term service at elevated temperature, comparing with the conventional laser shock peening (LSP). After WLSP treatment, complex structures of γ″ phase/high-density dislocation with stacking faults and nano-sized twins in γ″ phases surrounded by the more stable and higher density of geometrically necessary dislocations, formed in the hardened surface layer. Meanwhile, the substructure evolution, compressive residual stress reduction and γ″ phase growth in the hardened layer of WLSP alloy were also inhibited during high-temperature ageing, owing to the existence of the pecial structure, contributing stability of microstructure and strengthening effect under conditions of high-temperature ageing and subsequent cyclic loading at high temperature. This is the main reason why after high-temperature ageing the fatigue resistance of WLSP sample can be kept stably and the median fatigue strength can be improved at high temperature.

KEYWORDS:

IN718 superalloy; warm laser shocking processing; fatigue resistance; nano-sized twins; high temperature stability.

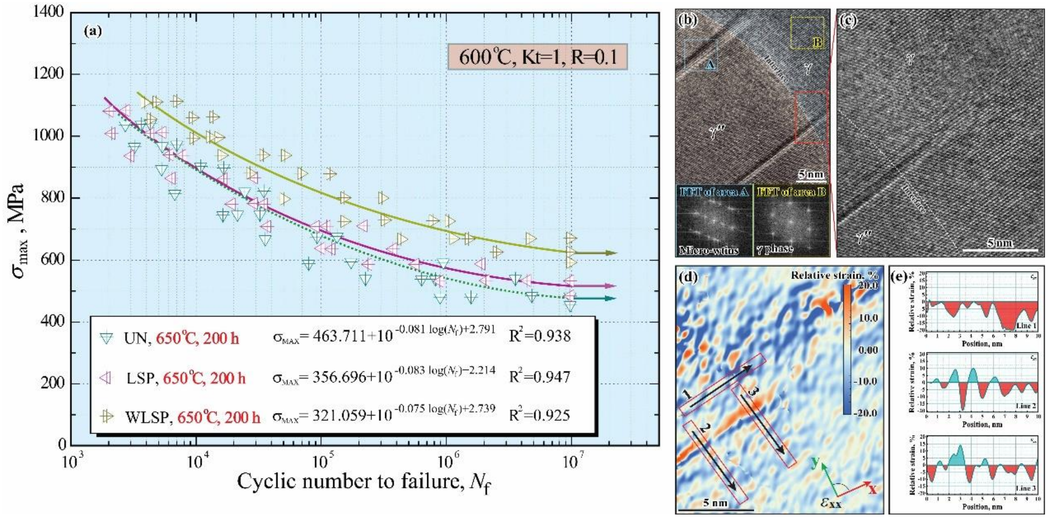


Fig. 1 *S-N curve at 600 centigrade of UN, LSP and WLSP samples of IN718 superalloy after high-temperature ageing (a); HRTEM image of γ" phase containing SFs and nano-sized twins in the hardened surface layer of WLSP samples (b, c); in the (c) corresponding map of the in-plane GPA strain component of SFs at the interface of γ/γ" (d, e).*

C1-308

Effect of Multifunction Cavitation on Rotating Bending Fatigue Properties of Low Alloy Steel Rods

Keisuke ONO[1*], Toshihiko YOSHIMURA[2], Masataka IJIRI[3] and Shoichi KIKUCHI[4]

[1] Shizuoka University, JAPAN
[2] Sanyo-Onoda City University, JAPAN
[3] Tokyo Metropolitan University, JAPAN
[4] Shizuoka University, JAPAN

* Corresponding author: ono.keisuke.18@shizuoka.ac.jp

ABSTRACT:

In this study, multifunction cavitation (MFC) was performed for low alloy steel (AISI4140 steel) rods with different hardness to generate compressive residual stress without forming surface dent (Fig. 1). MFC repeats isothermal expansion and adiabatic compression by irradiating ultrasonic waves to cavitation bubbles generated by injecting high-pressure water in water and grows them into bubbles with high temperature and high pressure. It was found that high compressive residual stress was generated on the surface by MFC. The value of the compressive residual stress for the MFC treated specimens tended to increase with the hardness. However, pits were formed from red rust on the surface during MFC treated in water. As results of rotating bending fatigue tests, the fatigue crack was initiated from the pits. Therefore, black oxide treatment was also performed before MFC to suppress the generation of red rust. In addition, the value of compressive residual stress remaining after the fatigue test was also investigated to examine the relaxation behavior of the compressive residual stress during the fatigue test. The fatigue limit estimation of MFC treated steels was conducted considering the residual stress relaxation and pit formation.

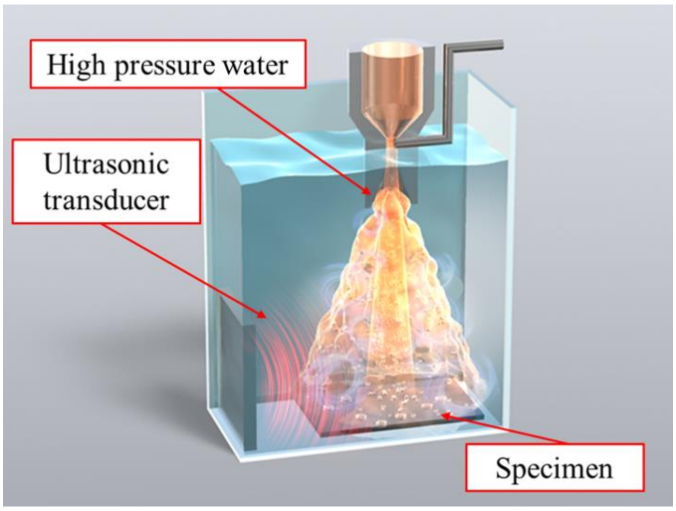


Fig. 1 Schematic diagram of MFC treatment system.

KEYWORDS:

Fatigue; Multifunction cavitation; Residual stress; Surface morphology; Fatigue limit estimation

C1-309

Evaluation of the effect of stress ratio and compressive residual stress on the fatigue properties of shot-peened AISI4140 specimens, considering residual stress relaxation

Motoaki HAYAMA[1] and Jun KOMOTORI[1,*]

[1] Keio University, JAPAN

* Corresponding author: komotori@mech.keio.ac.jp

ABSTRACT:

This study investigated the effect of stress ratio and compressive residual stress induced by shot peening on fatigue properties. Fatigue tests were conducted on shot-peened AISI4140 specimens with stress ratios $R = -1$ and 0. Changes in the compressive residual stress during the fatigue tests were analyzed through *in situ* X-ray stress measurements. The compressive residual stress relaxed during the fatigue test with a stress ratio of −1, whereas no relaxation occurred during the fatigue test with a stress ratio of 0. This relaxation of the compressive residual stress was attributed to compressive yielding. The fatigue limit diagram of the shot-peened specimen demonstrated that compared to the results considering only mean stress, those considering the compressive residual stress and its relaxation agree more with a modified Goodman line. The result indicates that the fatigue limit of steel with shot-peening-induced compressive residual stress can be estimated using the modified Goodman line by considering the compressive residual stress and its relaxation.

KEYWORDS:

Fatigue, Residual stress, Relaxation, Stress ratio, Peening.

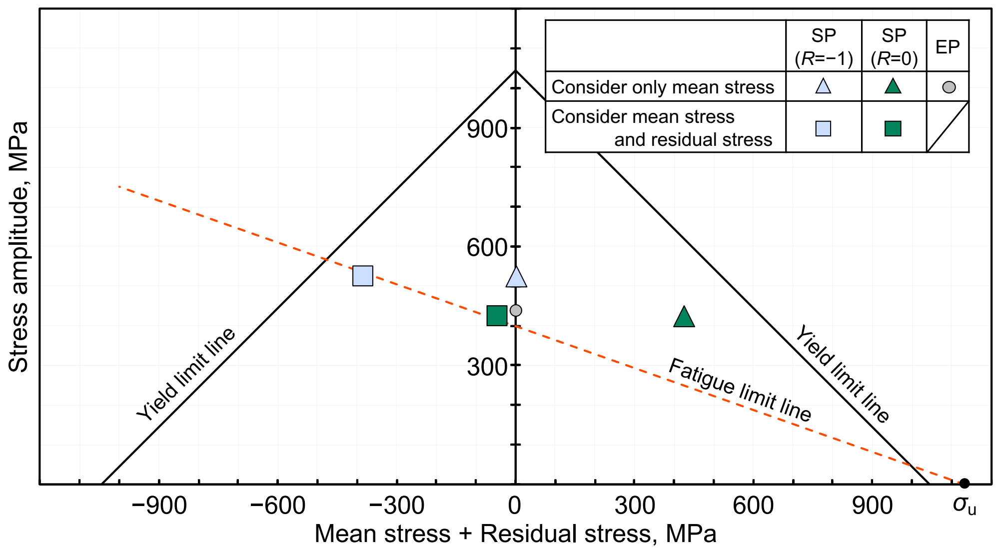


Fig. 1 Fatigue limit diagram of the shot-peened specimen, considering the compressive residual stress and its relaxation.

C1-310

Effect of Gas Carburizing on Axial Fatigue Strength of SCM420H Steel

Takayuki KOMORIYA[1,] *, Ryo ANZAI[1], and Takashi MATSUMURA[1]

[1] The University of Electro-Communications, JAPAN

* Corresponding author: matsu@mce.uec.ac.jp

ABSTRACT:

High strength steel used for high-load power transmission devices is often carburized to improve wear resistance and fatigue strength properties. Because carburizing generates a surface hardened layer by infiltrating carbon into surface layer of the material, it is known that this improves fatigue strength properties due to the increase in surface hardness, generation of compressive residual stress, and presence of retained austenite. In this study, the axial load fatigue tests were carried out using carburized chrome molybdenum steel SCM420H to investigate the effect of the surface-hardened layer on fatigue strength. As the results of fatigue tests, it was found that the fatigue strength of the carburized steel was about 2.65 times higher than that of the untreated steel. As a results of measuring the hardness of the cross section of the specimen, it was found that the hardness of the specimen surface was about 2.76 times higher than that of the inside. Therefore, the rate of improvement of fatigue strength properties by surface modification is almost equal to the rate of improvement of hardness. All the crack initiation sites of the untreated specimen were on the specimen surface, and multiple crack initiation sites were observed. But, in the case of the carburized specimens, both surface and internal crack-initiated fractures were observed. In the case of carburized specimens, the stress intensity factor range ΔK_{ini} for surface crack initiation type was found to be slightly smaller than that for internal crack initiation type.

KEYWORDS:

Surface modification, Gas Carburizing, Fatigue strength properties, Chrome molybdenum steel

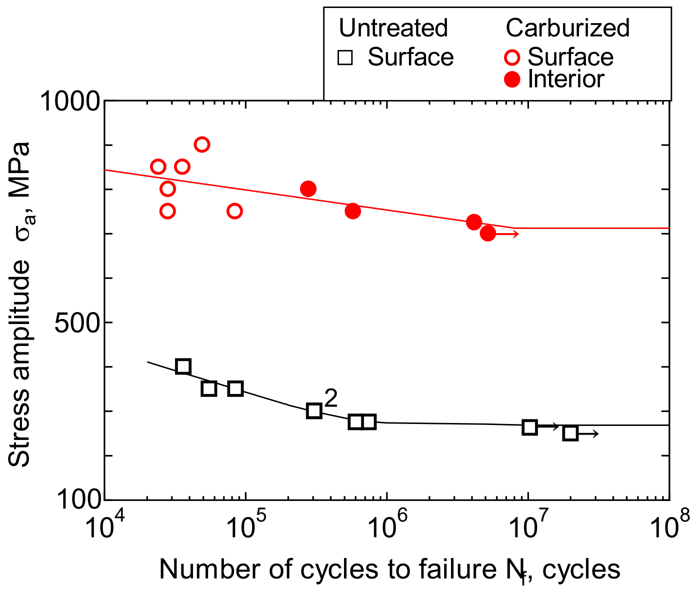


Fig. 1 *S-N* curve.

C1-311

Residual stress relaxation in Inconel718 cold expanded hole under loading at elevated temperature

Moad FATMI[1,2,*], Manuel FRANÇOIS[1], Carl LABERGERE[1] and Emmanuel FESSLER[2]

[1] LASMIS, University of Technology of Troyes, UMR 6281, CNRS, Troyes, France
[2] SAFRAN AIRCRAFT ENGINES, Moissy-Cramayel, France

* Corresponding author: moad.fatmi@utt.fr / moad.fatmi@safrangroup.com

ABSTRACT:

Turbine disks are critical components of aeroengines. The failure of such component is strictly forbidden for safety reasons. These components must meet the certification requirements in terms of fatigue life to initiation as well as crack growth life via damage tolerance approach. Fastener holes are highly stressed areas. The cold expansion process is used in aeronautical industry on fastener holes to introduce compressive residual stress around the hole up to 4 mm beneath the surface of the hole. This residual stress will prevent early initiation and will reduce the crack growth rates. However, residual stress relaxation may occur due to the thermomechanical loading of the area. This residual stress relaxation must be characterized and modeled to take into account the beneficial effect of cold expansion on the crack growth rates during the lifting procedure. This study aims at characterizing the initial residual stress state on cold expanded Inconel718 samples and its thermomechanical relaxation for several loading cases. FE simulations are performed and correlated to experimental data obtained by neutron diffraction method.

KEYWORDS:

Turbine disks, Cold expansion, Inconel718, Residual stress, FE simulation, Neutron diffraction

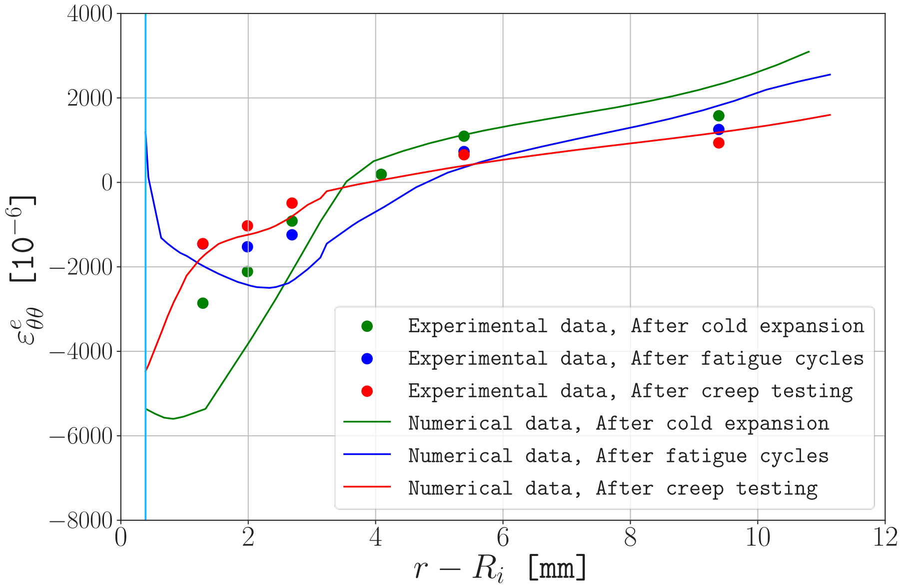


Fig. 1 *Comparison between the three elastic strain components predictions from the numerical model and neutron diffraction measurements.*

C1-312

Surface Crack Propagation Behaviour of Peening Treated A2024 Alloy

Kiyotaka MASAKI[1]*, Tomokazu SANO[2], and Yuji SANO[3]

[1] Saitama Institute of Technology, JAPAN
[2] Osaka University, JAPAN
[3] Institute for Molecular Science / Osaka University, JAPAN

* Corresponding author: masaki-k@sit.ac.jp

ABSTRACT:

High cycle fatigue life can be improved by prevention of surface crack propagation. In this study, in order to improve the fatigue life of the A2024-T3 aluminum alloy plate with 3mm thickness, three types of peening treatments such as fine shot peening (FSP), hand-held laser peening (HH-LP) and dry laser peening (DLP) were applied. Plane bending fatigue test of a peened specimen which have a small drilled hole was conducted and surface crack propagation behaviour was observed using replication technique at same stress level condition. As a result of the fatigue test, the fatigue life of all peened specimens was 2.6 times longer than that of the base metal (BM) specimen as shown in Fig.1. In addition, as a result of observing the surface crack propagation behaviour, the fatigue life until the surface fatigue crack length reached 2mm after generated from drilled hole was remarkably prolonged in the peened specimens. And then, crack propagation rates of HH-LP and DLP specimens were slower than that of BM and FSP specimens. These crack propagation behaviours were discussed using the results of peening effects and fracture surface observations.

KEYWORDS:

Plane bending fatigue, Surface crack propagation behaviour, Fine shot peening, Dry laser peening, Hand-held laser peening

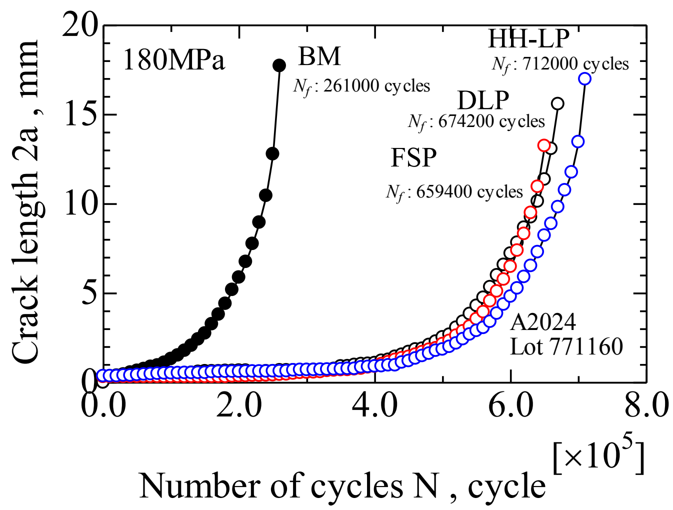


Fig.1 Surface crack propagation curves.

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Study of the Ti-6Al-4V fatigue behavior superficially treated by plasma immersion ion implantation (PIII) combined with shot peening as pre and post treatment.

Verônica VELLOSO[1], Natália CAMPOS[1], Rogério OLIVEIRA[2], Maria Odila CIOFFI[1], Herman VOORWALD[1]

[1] Department of Materials and Technology, Fatigue and Aeronautic Materials Research Group, School of Engineering, São Paulo State University (UNESP), Guaratinguetá, Brazil
[2] Associated Laboratory of Plasmas, Instituto Nacional de Pesquisas Especiais – INPE, Brazil

* Corresponding author: veronicamcaoliveira@gmail.com

ABSTRACT:
Ti-6Al-4V alloy presented chemical stability, low specific mass, high mechanical strength, and it is applied in the aeronautical area. However, this alloy reacts with oxygen and forms oxides on its surface, decreasing surface protection, specially at high temperatures. Plasma immersion ion implantation (PIII) improves, through the diffusion of nitrogen on the surface, properties such as corrosion and wear resistances. Additionally, the surface treatment shot peening (SP) is an alternative to increase the fatigue life of metallic alloys, including those of the titanium family. Here, the aim of this work is to carry out an analysis of the fatigue life correlated to the change in the surface of the Ti-6Al-4V alloy, when subjected to the PIII treatment associated with a pre- or post-treatment by shot peening. The Ti-6Al4V fatigue behavior was studied through rotating-bending fatigue tests, followed by a comparison between the fatigue behavior of the material as received, pre-treated by shot peening (SP+PIII) and post-treated by shot peening (PIII+SP). Comparing the S-N curves of all experimental conditions, it was observed fatigue resistance increase of 18% at 752 MPa and 74% at 675 MPa for the PIII+SP condition; and 17% at 752 and 50% at 675 MPa for the SP+PIII condition.

KEYWORDS:
Ti-6Al-4V alloy; rotating-bending fatigue; plasma immersion ion implantation, shot peening.

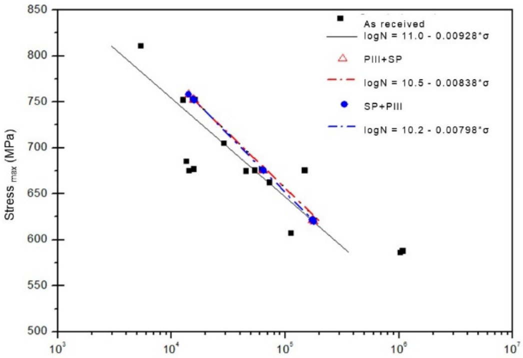

Fig. 1 Ti-6Al-4V alloy S-N curves: as received, PIII+SP, and SP+PIII treatment conditions.

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Low-cycle fatigue investigation of Cr/CrN multilayer coated Ti-6Al-4V alloy with equiaxed microstructure

Martin Ferreira FERNANDES[1,*], Verônica Mara de Oliveira VELLOSO[2], Herman Jacobus Cornelis VOORWALD[1]

[1] São Paulo State University (Unesp), School of Engineering and Sciences, Guaratinguetá, BRAZIL.
[2] Faculdade Serra Dourada, Lorena, BRAZIL.

* Corresponding author: martin.fernandes@unesp.br

ABSTRACT:
Titanium alloys, such as Ti-6Al-4V, are applied in the aerospace industries due to high specific mechanical strength. However, turbine engines are subjected to airborne particles, environmental deterioration and fatigue loadings during operation. The Cr/CrN multilayer coating offers wear and erosion resistance. The aim of the present work is to investigate the effect of the Cr/CrN multilayer coating on the fatigue performance of a titanium alloy. The material applied in this work was the Ti-6Al-4V with an equiaxed microstructure and yield strength of 1000 MPa. Axial fatigue tests were performed at room temperature with sinusoidal waveforms, a frequency of 10 Hz and a fatigue ratio of 0.1. The coating was deposited by pulsed DC magnetron sputtering with 8 bilayers of chromium (Cr) and chromium nitride (CrN). The results showed a fatigue life debit of the coated alloy. The average fatigue life at a maximum stress level of 1000 MPa for the Ti-6Al-4V alloy reduced from 34×10^3 to 4.6×10^3 cycles after the coating deposition. The SEM analysis of fracture surfaces reveals that the coated samples had multiple crack nucleation sites, and the coating damage produced by the fatigue process may be correlated to a reduction of the fatigue crack nucleation period.

KEYWORDS:
Fatigue life; Cr/Cr multilayer coating; surface treatment; titanium alloy.

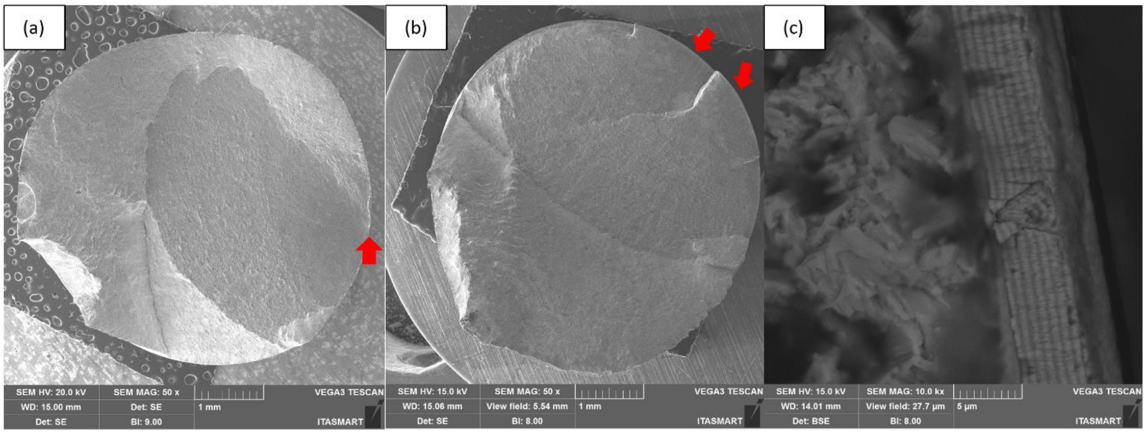

Fig. 1 *SEM of fracture surfaces tested at 1000 MPa. Details of (a) uncoated, (b) coated and (c) coating damage.*

C1-315

Effect of Nitrided-Fine Particle Peening on Formation of Nitrided Layer and Fatigue Properties of Titanium Alloys

Ryuichi TACHIGAYA[1, *], Keisuke FUJITA [2], Shoichi KIKUCHI[3]

[1] Graduate School of Integrated Science and Technology, Shizuoka University, JAPAN
[2] Graduate School of Science and Technology, Shizuoka University, JAPAN
[3] Faculty of Engineering, Shizuoka University, JAPAN

* Corresponding author: tachigaya.ryuichi.19@shizuoka.ac.jp

ABSTRACT:

Conventional nitriding improves the tribological properties of titanium alloys; however, reduces their fatigue strength owing to grain-coarsening. The purpose of this study is to examine the effect of the nitrided-fine particle peening (N-FPP) on the formation of nitrided layer and fatigue properties of titanium alloys. The surfaces of titanium alloys were bombarded with nitride CP-titanium fine particle powders having nitrided layer at room temperature (Figure 1). The N-FPP formed the nitrided layer on the surface of titanium alloys. Nitrogen concentration for the treated titanium alloys tended to increase with increasing the bombarding pressure and the number of particles, and with decreasing the particle diameter. The fatigue limit of the N-FPP treated specimen under four-point bending fatigue tests were higher than that of the conventional nitrided one due to the generation of compressive residual stress suppression of grain coarsening, whereas the fatigue limit was lower than those of the un-treated one. This was because a fatigue crack in the N-FPP treated specimen was initiated from the surface dent formed by N-FPP due to the stress concentration.

KEYWORDS:

Fine particle peening; Nitriding; Titanium alloy; Residual stress; Fatigue

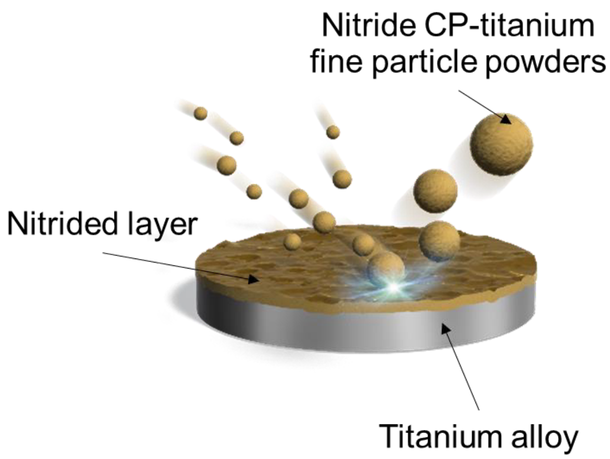

Fig. 1 *Schematic of the nitrided-fine particle peening (N-FPP).*

C1-316

Effect of Fine Iron-Sulfide Particle Peening on Rotating Bending Fatigue Properties of Low Alloy Steel

Shotaro NOGUCHI[1,*], Kiyotaka MITAKE[2], Kosuke DOI[2], Hisashi HARADA[2] and Shoichi KIKUCHI[1]

[1] Shizuoka University, JAPAN
[2] Yamaha Motor Co., Ltd.

* Corresponding author: noguchi.shotaro.19@shizuoka.ac.jp

ABSTRACT:
In this study, fine iron-sulfide particle peening was conducted for low alloy steel in order to form iron-sulfide particles transferred layer and improve rotating bending fatigue properties. Iron-sulfide particles transferred layer induced by fine iron-sulfide particle peening was analyzed using EPMA. Rotating bending fatigue tests were conducted on specimen of low alloy steel treated with fine iron-sulfide particle peening after electrolytic polishing. The fatigue limit of specimen treated with fine iron-sulfide particle peening was higher than that of electrolytic polished specimen (Fig.1). This is because high compressive residual stress was generated on the surface of specimen by fine iron-sulfide particle peening. Additionally, cross-sectional microstructure of the specimen was analyzed using EBSD. Fine grains were formed on the surface of specimen treated with fine iron-sulfide particle peening; therefore, grain-refinement was also one of the factors that improved the rotating bending fatigue properties of low alloy steel by fine iron-sulfide particle peening.

KEYWORDS:
Fine particle peening; Surface modification; Iron sulfide; Rotating bending fatigue test; Compressive residual stress

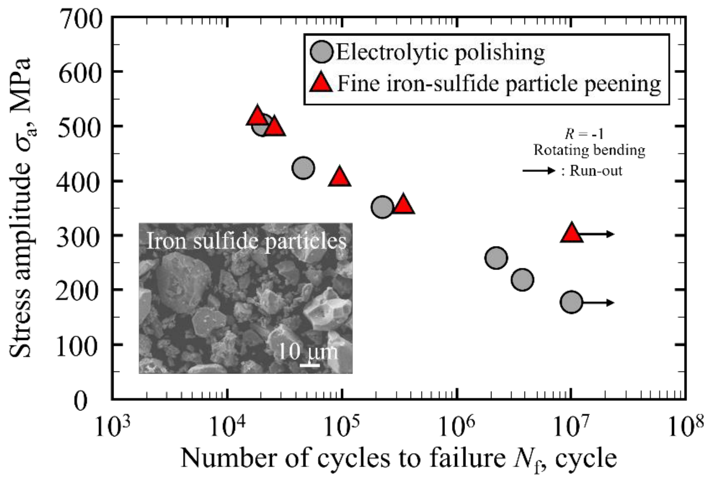

Fig. 1 Results of rotating bending fatigue tests of specimen treated with fine iron-sulfide particle peening and electrolytic polishing.

C1-317

Effect of Oxide Films on Fatigue Properties of Anodically Oxidized Aluminum Alloys

Takeshi ANDO[1,]* Atsuki KOMEYA[1], Miu HAYASHI[1], Hiroyuki AKEBONO[1] and Atsushi SUGETA[1]

[1] Hiroshima University, JAPAN

* Corresponding author: m225001@hiroshima-u.ac.jp

ABSTRACT:
Aluminum alloys are widely used in our daily lives, from large structural parts such as automobiles to small items such as aluminum cans and aluminum foil, because of their light weight and high strength. However, aluminum alloys have the disadvantage of being soft and susceptible to surface damage, which is generally remedied by anodizing. In this study, fatigue tests were conducted with and without anodic oxidation treatment in order to evaluate the strength of anodic oxide. As a result, it was confirmed that anodic oxidation treatment reduced fatigue strength in a certain stress range. It was also inferred that cracks in the oxide film were the cause of the decrease in fatigue strength. Therefore, the condition of crack generation was also discussed by observing the surface condition during tensile and fatigue tests. From these tests, it was confirmed that the oxide film exhibits brittle fracture, and that these cracks lead to the notch effect, which results in the reduction of fatigue strength.

KEYWORDS:
Fatigue, Anodized Coating, Aluminum Alloy, Crack

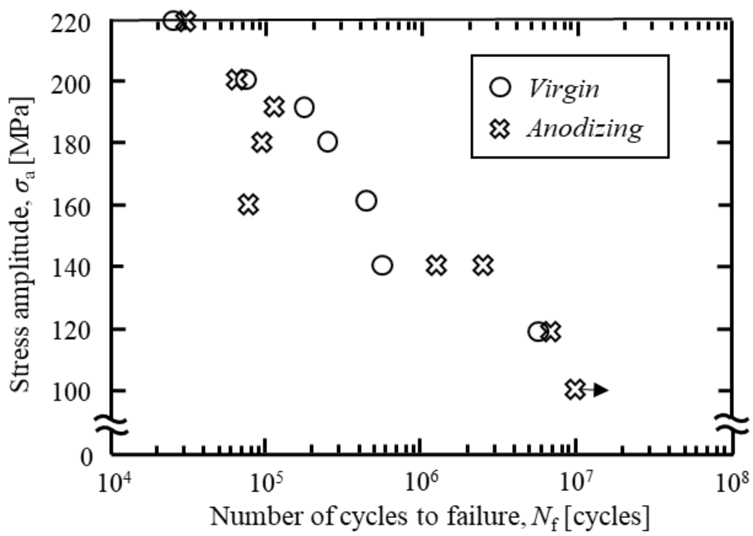

Fig. Results of fatigue test.

Acknowledgment:
This research was supported by Light Metal Educational Foundation, Inc. in Japan. We would like to express our gratitude here.

C1-318

Improving the fatigue performance of Ti64 using electropulsing-assisted ultrasonic peening

Chang Ye[1],* Weidong Zhao[2], Yixuan Ye[1], Yu Zhang[1] and Yalin Dong[3]
[1] School of Mechanical Science & Engineering, Huazhong University of Science & Technology, Wuhan, China
[2] College of Materials Science and Engineering, Zhengzhou University, Zhengzhou, China
[3] Department of Mechanical Engineering, University of Akron, Akron, Ohio, USA

* Corresponding author: cye@hust.edu.cn

ABSTRACT:
In this study, the effectiveness of high-amplitude short duration pulsed current in improving the peening efficacy was examined in a process called electropulsing-assisted ultrasonic nanocrystal surface modification (EP-UNSM). During the EP-UNSM process, the target metal, i.e., Ti64, is subjected to simultaneous ultrasonic peening and electropulsing. The high energy pulsed current can generate a critical magnetic field that can induce the transition of the radical pairs formed by dislocations and the pinning obstacles from the singlet state to the triplet state. This leads to higher dislocation mobility and thus higher plasticity for more effective peening treatment. The results show that the sample treated with EP-UNSM had a deeper plastically deformed layer than that for samples subjected to UNSM and continuous current–assisted UNSM (CC-UNSM). Due to microstructure refinement, work hardening, and dynamic strain aging, the EP UNSM sample had a 50% higher surface hardness compared with the control sample. Moreover, the compressive residual stresses generated by EP-UNSM were higher in magnitude and greater in depth compared to those generated by traditional UNSM. These results demonstrate that pulsed current can effectively improve the peening efficacy and EP-UNSM is an effective method for improving the fatigue performance of Ti64.

KEYWORDS: Electropulsing-assisted ultrasonic peening; Pulsed current; Electroplasticity; fatigue

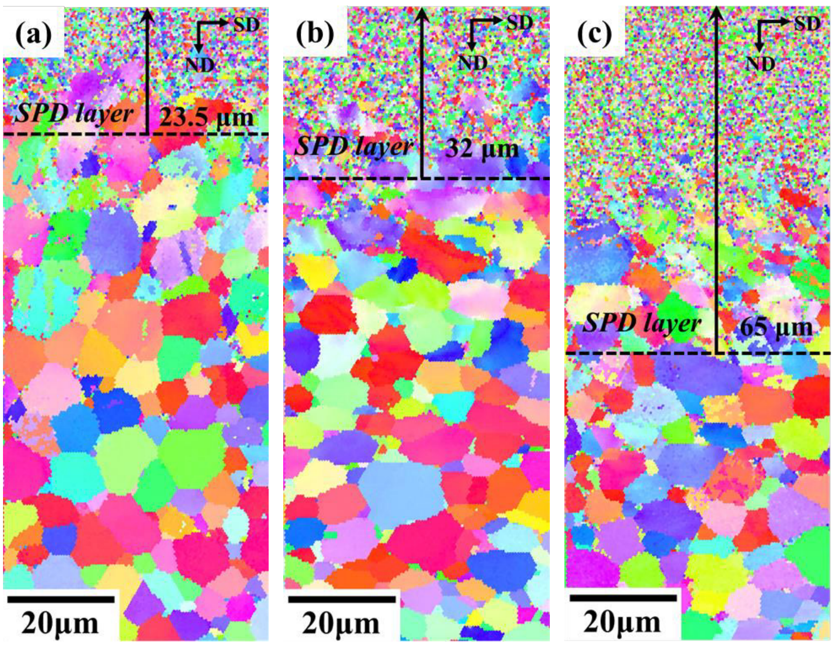

Fig. 6. Inverse pole figures from EBSD observations in the cross sections of samples treated by (a) traditional ultrasonic peening, (b) continuous current assisted ultrasonic peening and (c) electropulsing-assisted ultrasonic peening

C2-301

Life Prediction and Virtual Qualification of an Elastomeric Engine Mount

Will Mars & Tom Ebbott, Endurica LLC

Fatigue 2022+1
November 2023
Hiroshima

ABSTRACT:

An elastomeric engine mount sees complex loads in service, and engineers must demonstrate that the mount can endure those loads. This presentation shows how the entire qualification procedure used by Ford for an elastomeric motor mount can be simulated in Abaqus and post-processed with Endurica to predict lifetime and estimate the demonstrate qualification for durability. The loading schedule is composed of 144 different events recorded at the test track, each having as many as 6 input channels (3 forces and 3 moments). The analysis begins by computing a nonlinear map of finite element model stress-strain fields to a series of sampling points in the global load input space. This map is then used in Endurica EIE to rapidly generate full transient stress-strain history (15.6 million time steps) for each finite element. This process produces 3.2 TB of stress-strain history, which is then passed to Endurica CL to solve for fatigue life. The analysis takes into account the elastomer's nonlinear material properties, and correctly predicts failure location and fatigue life. The entire process was executed in 90 hours of compute time on a typical Windows workstation.

C2-302

Vibration fatigue life prediction of 60Si2Mn fastener clips based on CDM theory and ML model.

Yifei DONG[1], Zhixin ZHAN[1,*], Qingchun MENG[1] and Weiping HU[1]

[1] School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, CHINA

* Corresponding author: zzxupc@163.com

ABSTRACT:

This paper presents a novel approach for predicting the fatigue life of railway fastener clips based on continuous damage mechanics and machine learning models. First, static and fatigue tests were conducted to obtain material parameters, and a continuous damage mechanics model was established. The fatigue life of the fastener clips was then simulated under several different conditions by the finite element method, and a large number of numerical simulation results were used to train the machine learning models. Finally, the well-trained SVM and ANN models were employed to estimate the fatigue life under various conditions. The research demonstrates that this spring steel has high strength and anti-fatigue properties, with a fatigue life exceeding 10^8 times under normal railway conditions. However, as surface wave wear of the railway increases, fatigue life is significantly reduced. When vertical vibration displacement due to wear exceeds 1.5mm or vibration frequency is between 500-800Hz (resonant frequency), clips life is less than the design life of 5 million times. This study also establishes a mapping relationship between railway working conditions and fastener clips fatigue life using a machine learning approach, which provides a feasible and convenient method for predicting part life in the railway industry.

KEYWORDS:

High-speed railway; Fastener clips; Continuous damage mechanics; Machine learning; 60Si2Mn spring steel

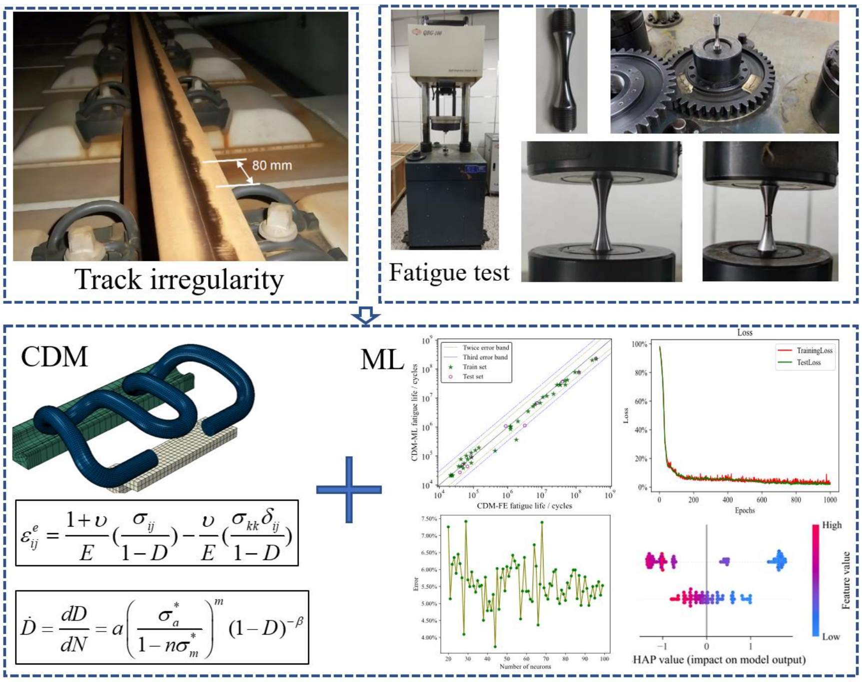

Fig. 1 *Technology roadmap.*

C2-304

Deep Learning-enabled Cyclic Deformation Modeling of Single Crystal Ni-based Superalloy Considering the Effect of Microstructure State

Long TAN[1], Xiaoguang YANG[1], Duoqi SHI[1] and Yongsheng FAN[1,*]

[1] Beihang University, CHINA

* Corresponding author: fanys@buaa.edu.cn

ABSTRACT:
The single crystal (SC) Ni-based superalloy inevitably undergoes microstructural rafting during service under elevated temperature and high stress for long term. Such global microstructure degradation significantly influences the mechanical behaviours of the superalloy. In the present work, the effect of rafting on the elastoplastic deformation behaviour of a SC Ni-based speralloy was experimentally investigated and quantitatively modelled with the aid of machine learning models. Cyclic deformation tests were conducted at 760℃and 980℃ with four different rafting states. The rafting microstructure weakened the plastic deformation resistance and decreased the yield stress significantly. Subsequently, the statistic microstructure features that contains microstructure information of γ/γ′ phase were quantitated using the two-point correlation and principal component analysis. Then, machine learning models, namely deep neural network, were constructed to predict the yield stress under different rafting state and experimental conditions. Both the experimental parameters and microstructure features were applied as input variables of the machine learning models. The results showed that the machine learning model achieve high prediction accuracy. The proposed machine models provide faster and cheaper tool for analyzing microstructural state effect on elastoplastic deformation behaviour.

KEYWORDS:
Ni-based superalloy; Microstructure state; Machine learning; Deformation behaviour.

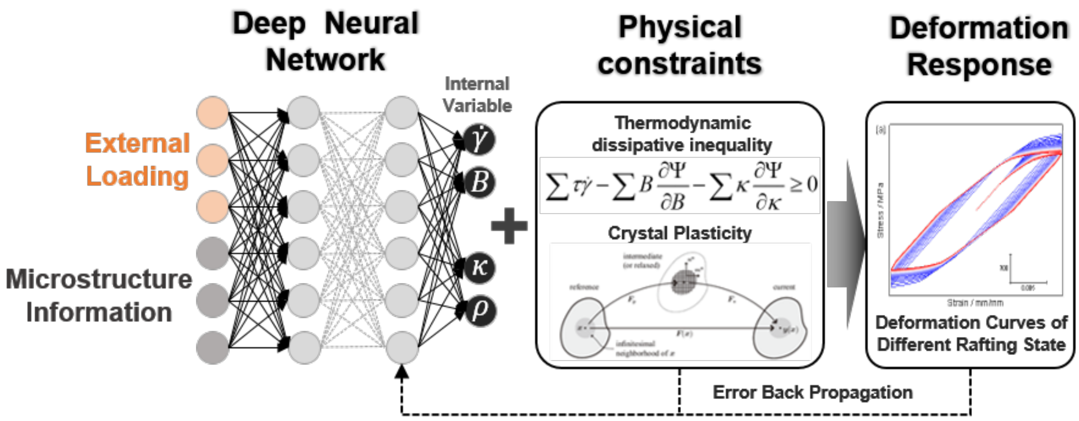

Fig. 1 *Workflow of microstructure related elastoplastic deformation modeling of Ni-based superallopy.*

C2-305

Determination of the Kitagawa-Takahashi diagram for the EA4T railway axle steel by means of the cyclic R-curve method

Jiewei GAO[1], Mauro MADIA[2,*], Julius KRUSE[2], Tiago WERNER[2], Larissa DUARTE[2]

[1] University of Electronic Science and Technology of China, CHINA
[2] Bundesanstalt für Materialforschung und -prüfung (BAM), GERMANY

* Corresponding author: mauro.madia@bam.de

ABSTRACT:

The Kitagawa-Takahashi (KT) diagram is a well-established tool in the fatigue community for the prediction of the fatigue limit of metallic materials in presence of defects. Nevertheless, its determination is associated with a large number of fatigue tests carried out on specimens with artificial defects (notches) to describe the fatigue limit-defect size relationship in the short crack regime. The preparation of the specimens and the execution of the tests is time expensive. Therefore, few phenomenological models have been introduced in the past to provide a first approximation of the KT diagram based solely on the fatigue limit for smooth specimen and the fatigue crack propagation threshold for long cracks. Despite the use of such models is widely spread, these suffer from problems related to the uncertainties of the material parameters. Furthermore, the mechanics of short cracks, which is the physical mechanism behind the concept of the fatigue limit, is not considered. This work discusses the advantages and drawbacks of using short fatigue crack propagation models for predicting the fatigue limit of flawed metallic materials. The KT diagrams for a EA4T railway axle steel in as-received and full-hardened condition are approximated by means of the cyclic R-curve method.

KEYWORDS:

Fatigue limit; Crack propagation; Short crack; Cyclic R-curve; EA4T railway axle steel

C2-306

Microstructure-induced cracking and life prediction of Inconel 713C superalloy for very high cycle fatigue at elevated temperatures

Xiaolong LI[1], Mingliang ZHU[1,]* and Wei LI[2 ,]*

[1] East China University of Science and Technology, CHINA
[2] Beijing Institute of Technology, CHINA

* Corresponding author: [1] mlzhu@ecust.edu.cn; [2] lliw@bit.edu.cn

ABSTRACT:

Fatigue failure behavior at 25 °C, 750 °C and 1000 °C, as well as microstructure and constitutive relation, of a Ni-based superalloy was investigated by using multi-scale testing technologies including axial loading tests with stress ratio of 0.1, electron-backscattered diffraction and transmission electron microscope. Results show that the life at 750 °C is longer than that at 25 ° C, but shortens as temperature keeps rising to 1000 ° C. Based on the analysis of grain orientation difference, the microcracks are mainly nucleated from the larger grains with the soft orientation especially under the assistance of defect, and mainly propagate as the mode II microcrack along {111} slip plane in the direction of the maximum shear stress, leading to the formation of crystallographic facets. Moreover, due to the effects of temperature and vacuum environment, threshold values for small and long cracks, and the transition crack size decreases as the temperature increases. Furthermore, further analysis of dislocation structures such as tangled dislocations, dislocation loops and stacking faults shows that the deformation mechanism with faceting cracking should be the combined effect of anti-phase boundary shearing, precipitates bypassing and stacking fault shearing, especially under the stress concentration effect of crack or defect. Finally, using fatigue-index-parameter, a microstructure based life prediction approach for interior facet induced cracking is proposed, and the estimated results are acceptable.

KEYWORDS:

Ni-based superalloy; Very high cycle fatigue; Elevated temperature; Interior crack initiation; Life prediction

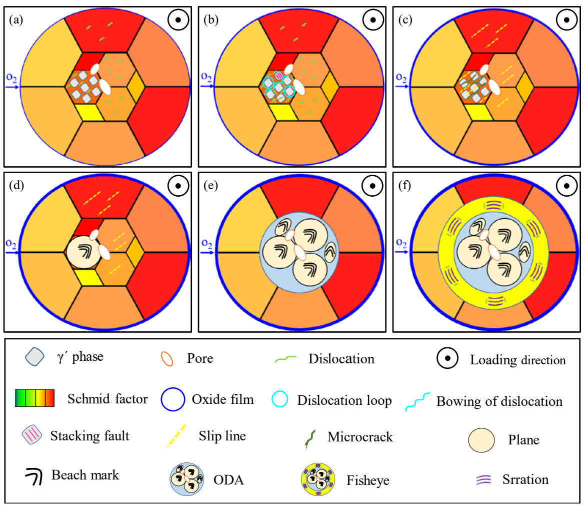

Fig. 1 failure mechanism induced by multiple crystallographic planes at elevated temperature.

C2-307

Multiaxial Fatigue Criteria for the Fatigue Life Assessment of Metallic Assemblies

Maxime NUTTE[1], Pascale KANOUTE[1], Vincent BONNAND[1], Benjamin DELPUECH[2], Vincent JACQUES[2] and Serge KRUCH [1]

[1] Onera, The French Aerospace Lab, Châtillon, France
[2] Dassault Aviation, Saint Cloud, France.
* Corresponding author: Pascale.Kanoute@onera.fr

ABSTRACT:
Assembled aircraft structures present complex stress states where several non-linear phenomena interact (non-linearity of the behavior of material, contact with friction,...). A main critical concern for the fatigue lifetime assessment of such components is related to multiaxial fatigue. A major experimental campaign has then been conducted on an aluminum alloy, ranging from biaxial characterization on cruciform specimens to complex biaxially loaded assemblies by means of a fatigue biaxial (tension/compression) experimental device. All the tests have been monitored using complementary techniques such as image correlation, potential drop method...to fuel the numerical-experimental comparison. In parallel, a full non-linear cyclic analysis has been conducted for each test condition in order to obtain the local multiaxial cyclic stress-strain responses and the stabilized mean-stress level. Several existing multiaxial fatigue criteria have then been evaluated for different biaxial loading paths on the cruciform specimens to determine their suitability at correlating the generated multiaxial fatigue data. Regarding the observed limitations, a new criterion proposed at Onera is considered with the objective to estimate correctly shear and biaxial fatigue conditions together with a correct description of mean stress effects. The use of such criterion is finally discussed regarding its application on several metallic assemblies to estimate fatigue life.

KEYWORDS:
multiaxial fatigue; metallic assemblies; fatigue initiation ; fatigue criterion ; cyclic behavior

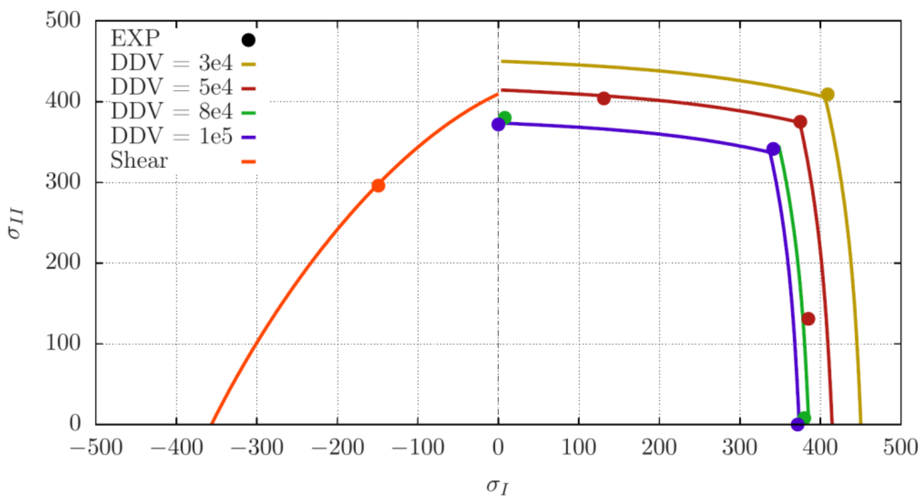

Fig. 1 *Estimated multiaxial fatigue envelops and comparisons with the experimental data in a biaxial stress diagram ($\sigma_{III} = 0$)*

C2-308

Crack Closure and Fatigue Crack Growth under Variable Amplitude Loading

Andrei KOTOUSOV[1,*], James M. HUGHES[2] and Chris WALLBRINK[3]

[1] The University of Adelaide, AUSTRALIA
[2] Defence Science and Technology Group, AUSTRALIA

* Corresponding author: andrei.kotousov@adelaide.edu.au

ABSTRACT:
Fatigue life evaluation methods under constant amplitude loading are well developed but rare in practice. Theoretical predictions in the case of variable amplitude loading can disagree with the actual fatigue life by an order of magnitude or even more. In this presentation we discuss a new method for the fatigue life evaluation of typical structural components. The method is based on recent advances in experimental techniques, which make possible for the first time, the investigation of crack opening/closure and the crack driving force for large numbers of fatigue cycles representative of real-world loading scenarios (>1 million cycles of variable load amplitude) [1, 2]. The method is demonstrated and validated for a specific material (7075-T7351 aluminium alloy) and loading conditions (military transport aircraft load spectra).

KEYWORDS:
Fatigue, crack closure, variable amplitude loading, crack growth, fatigue life.

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C2-309

A mesoscopic damage model for the low-cycle fatigue of an extruded magnesium alloy

Ziyi Wang[1], Qianhua Kan[1], Guozheng Kang[1]*

[1] Applied Mechanics and Structure Safety Key Laboratory of Sichuan Province, School of Mechanics and Aerospace Engineering, Southwest Jiaotong University, Chengdu, 610031, China

* Corresponding author: guozhengkang@home.swjtu.edu.cn

ABSTRACT:

This paper presents a novel mesoscopic damage model to characterize the low-cycle fatigue damage evolution of an extruded magnesium (Mg) alloy, taking into account the effect of twinning. The damage caused by the slip bands (SBs)-twin boundaries (TBs) and SBs-grain boundaries (GBs) interactions is treated based on the Tanaka-Mura model and the Eshelby inclusion theory. Strain energy values at the TBs and GBs are defined as the TB and GB damage variables, respectively. Explicit formulae are derived from the characteristics of the $\{10\bar{1}2\}$ extension twin and the basal texture. A fracture energy-based crack initiation criterion is established, and the capability of the proposed damage model is validated through a comparison of simulations and experiments. The model demonstrates its ability to reproduce the damage evolution processes, and the predicted crack initiation life results are within the twice error band.

KEYWORDS:

Extruded AZ31 Mg alloy; Twin; Dislocation slip; Low-cycle fatigue; Mesoscopic damage model

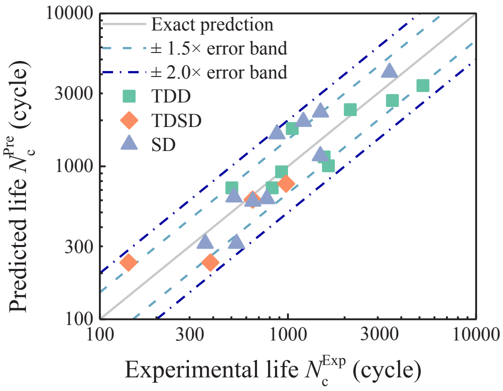


Fig. 1 Experimental crack initiation lives vs. predictions.

C2-310

A Simple and Accurate Fatigue Life Prediction Method under Variable Loading

Shoma UEDA[1,*], Yukiyoshi KOBAYASHI[1] and Yoshinao KISHIMOTO[1]

[1] Tokyo City University, JAPAN

* Corresponding author: g2381009@tcu.ac.jp

ABSTRACT:

Currently, the most accurate prediction of crack growth is based on the crack closure model proposed by J. C. Newman, Jr. However, this model takes a considerable amount of time and requires skills. Therefore, a simple and accurate fatigue life prediction method is required. Under the high and low two-step loading, the fatigue failure follows the following process: the crack initiation process under all loading, the crack retardation process under low loading and crack propagation process under all loading. Rates of these three process are affected by the stress field at the crack tip. Especially, the life of the first and second processes are greatly affected by acceleration and retardation. Therefore, it is attempted to develop the life prediction method using fatigue life obtained from fatigue tests in which the effective stress range is adjusted by changing the stress ratio with the same stress ranges.

KEYWORDS:

Effective stress range; crack closure model; minor measurement; J.C.Newman;

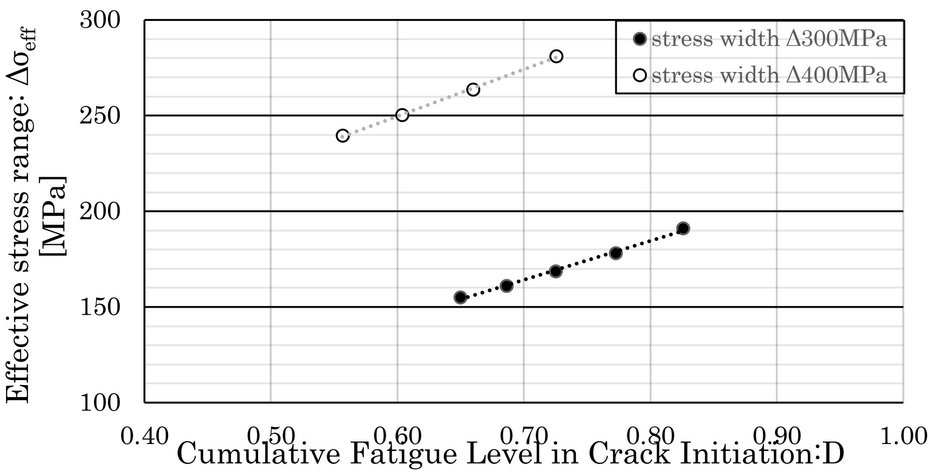


Fig. 1 Cumulative Fatigue Degree Relationship in Crack Initiation

C2-311

Modelling the influence of clustered defects on HCF properties of Ni-based superalloys

A. K. Matpadi Raghavendra[a,b,*], L. Marcin[b], V. Maurel[a], H. Proudhon[a]

[a] Centre des materiaux, Mines Paris, FRANCE

[b] Safran Aircraft Engines, FRANCE

* Corresponding author: arjun-kalkur.matpadi_raghavendra@minesparis.psl.eu

ABSTRACT:

Casting defects like shrinkages and pores are very detrimental for material's High Cycle Fatigue (HCF) performance. It is known that defect's size and their location from free surface are the most important parameters to take into account regarding HCF properties. However, this conclusion is questionable in the case of clustered defects: specimen lifetime seems to also depend on other characteristics of the defect cluster. The distribution of defect size in an individual cluster is found to be dependent on clustered defects volume and thus influencing the ASTM grades of the material. The gradient associated to the same isolated defect is modified in the presence of cluster further modifying the fatigue predictions via non-local approaches like volumetric homogenization.

However, this type of analysis requires a very large number of three-dimensional observations of casting defects dataset which is impractical and very expensive. Therefore, in this work, a Generative Adversarial Network (GAN) is integrated with Convolutional Neural Network (CNN) to generate synthetic defects (see figure 1.a) and are distributed in material space with the aid of spatial point pattern analysis of defects to generate synthetic microstructures that mirrors real specimens as shown in figure 1.b. Four Inconel 100 and nine Rene 125 specimens tomographed via X-Ray Computed Tomography have been used to study the spatial point pattern of defects and to train Deep Neural Networks (DNN). Spatial point pattern analysis helps to understand how the defects are distributed in material space whilst GANs generate synthetic defects which can be placed randomly respecting the statistics of real specimens.

These N synthetic samples are submitted to numerical simulations to exploit the fatigue behavior via non-local approaches, see figure 2. Furthermore, some of the important features of defect clusters such as, defect volumes, cluster thickness, density of defects in a cluster etc., are controlled to analyze the influence on stress gradients in the synthetic microstructures.

KEYWORDS:

Ni-based Superalloys; HCF; Deep learning; X-ray Tomography; Casting defect

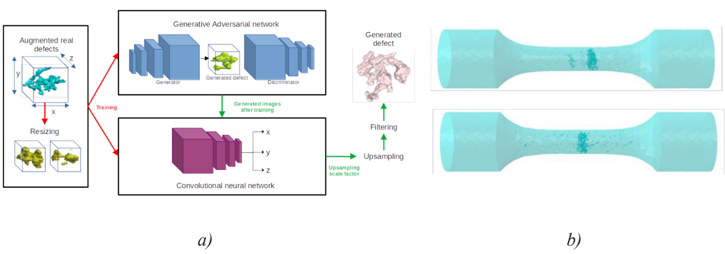


Fig. 1 a) Representation of DNN to generate synthetic defects b) Examples of few generated synthetic microstructures

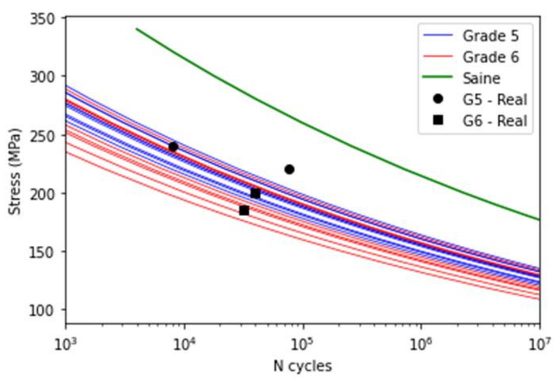


Figure 2. *Wohler curves of synthetic microstructures*

C2-312

Numerical Study on Rolling Contact Fatigue Cracks in Curved Railway Tracks

Yiping WU[1], Chung Lun PUN[1], Darrien WELSBY[1], Peter MUTTON[1] and Wenyi YAN[1]*

[1] Monash University, AUSTRALIA

* Corresponding author: tl25sh8v@kjakdsjfaksjdf.ac.jp

ABSTRACT:
Numerical simulations were conducted to calculate the stress intensity factors of mixed-mode rolling contact cracks on curved railway tracks in the presence of longitudinal, lateral and spin creepages. The whole procedure combined multi-body dynamic simulation, static finite element analysis and the extended finite element method. The modified FaStrip theory was applied to obtain traction distributions based on elastoplastic contact pressure, which were then applied in an XFEM model to predict surface crack growth directions and calculate the stress intensity factor history during a full rolling contact cycle. A parametric study was also conducted to further quantify the effect of different creepages on the stress intensity factors. It is concluded that the increase of either of the three creepages can significantly influence the phase and magnitude of the stress intensity factors. The numerical study will be applied with our laboratorily measured fatigue crack growth behavior to predict the rolling contact fatigue crack growth under service loading in our future work.

KEYWORDS:
Rolling contact fatigue; creepage; stress intensity factor; multi-body dynamics; finite element method.

C2-313

Fatigue modelling of martensitic steel for engine components

Andris FREIMANIS[1,*], Abhishek BISWAS[1], Matti LINDROOS[1], and Anssi LAUKKANEN[1]

[1] VTT Technical Research Center of Finland, FINLAND

* Corresponding author: andris.freimanis@vtt.fi

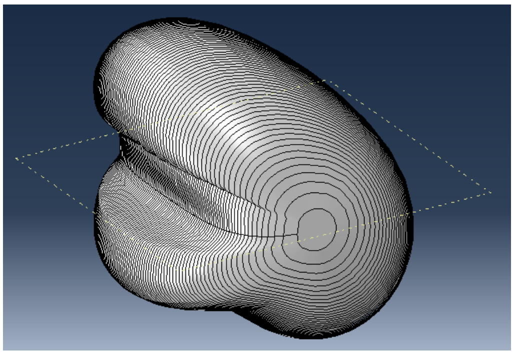
ABSTRACT:

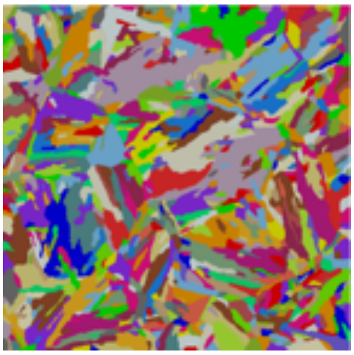
High-cycle fatigue - the leading failure mode in engine connecting rods - is often due to microstructural properties of the martensitic steel these components are typically constructed from. Such fatigue failures often initiate from impurities within the material's microstructure. In this study, the authors examine the influence of these microstructural properties, specifically the quantity of impurities, their location (either intra or intergrain), and the overall grain size, on the fatigue behavior of the material.

A fatigue model based on the peridynamic theory is implemented to explore these effects in depth. This computational approach is well-suited for modeling cracking behaviors such as independent initiation, crack branching, and merging, due to its inherent capability to handle discontinuities. The model encompasses all three critical stages of fatigue – crack initiation, propagation, and ultimate failure.

The simulation results derived from this peridynamic model are verified against conventional finite-element simulations, offering a comparative analysis between the two modeling techniques. Additionally, the results are compared physical experiments.

KEYWORDS: Crystal plasticity; fatigue; modelling; peridynamics. (Limit 5 Keywords)





a b

Figure 1. Martensitic microstructure: a – model of an inclusion, b – grain structure.

C2-312

Numerical Study on Rolling Contact Fatigue Cracks in Curved Railway Tracks

Yiping WU[1], Chung Lun PUN[1], Darrien WELSBY[1], Peter MUTTON[1] and Wenyi YAN[1]*

[1] Monash University, AUSTRALIA

* Corresponding author: tl25sh8v@kjakdsjfaksjdf.ac.jp

ABSTRACT:
Numerical simulations were conducted to calculate the stress intensity factors of mixed-mode rolling contact cracks on curved railway tracks in the presence of longitudinal, lateral and spin creepages. The whole procedure combined multi-body dynamic simulation, static finite element analysis and the extended finite element method. The modified FaStrip theory was applied to obtain traction distributions based on elastoplastic contact pressure, which were then applied in an XFEM model to predict surface crack growth directions and calculate the stress intensity factor history during a full rolling contact cycle. A parametric study was also conducted to further quantify the effect of different creepages on the stress intensity factors. It is concluded that the increase of either of the three creepages can significantly influence the phase and magnitude of the stress intensity factors. The numerical study will be applied with our laboratorily measured fatigue crack growth behavior to predict the rolling contact fatigue crack growth under service loading in our future work.

KEYWORDS:
Rolling contact fatigue; creepage; stress intensity factor; multi-body dynamics; finite element method.

C2-314

A fast Neuber-type Finite Element simulator to calibrate a multi-mechanism HCF model of alloys with process-induced pores

Abhishek PALCHOUDHARY[1*], Vincent MAUREL[1,] Cristian OVALLE[1], Pierre KERFRIDEN[1]

[1] MINES Paris, PSL University, Center of Materials (CMAT), CNRS UMR 7633, BP 87 91003 Evry, France
* Corresponding author: abhishek.palchoudhary@minesparis.psl.eu

ABSTRACT:
The presence of process-induced meso-scale pores, typically present in a variety of cast and additively manufactured alloys, can cause elevated plasticity close to the pores, which reduces the life of components. Therefore, a new fatigue model with two mechanisms – a stochastic approach for the micro-plasticity based on a separation of scales [1], and a criteria using Chaboche-type laws for the meso-scale plasticity, is proposed. A new Neuber-type method for fast approximation of the full-field plasticity in structures with spherical pores [2] alongside a multi-fidelity correction using CNNs was implemented, and will be transferred to complex pores. The finite element method is used to take into account the complex morphology of pores. The parameters of the multi-mechanism model may be obtained via a maximum likelihood estimate on a combination of fatigue experiments and thermographic data.

KEYWORDS:
Fatigue life prediction, Machine learning, Model reduction, Infrared thermography

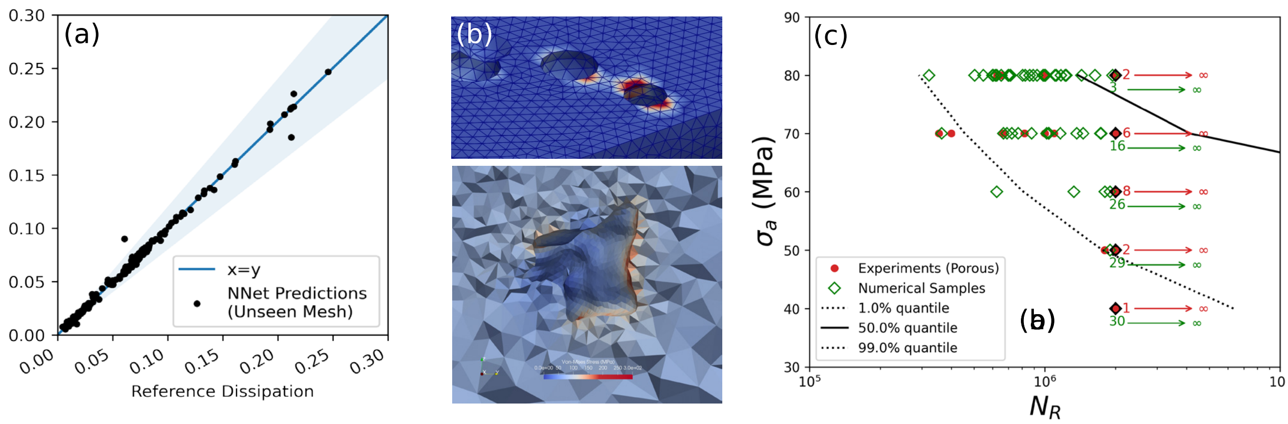


Fig. 1. (a) Results of the CNN corrected Neuber-type method for fast approximation of the dissipation in structures with spherical pores, with 96% of approximations falling in a 20% error cone (b) An example of the spherical pores corrected by the Neuber+AI approach and a complex tomographied pore meshed via FEM (c) Fatigue life predictions for specimens with complex pores, using a maximum likelihood estimate on the micro-structures for parameter identification

REFERENCES:
[1] Rémi Munier, Cédric Doudard, Sylvain Calloch, Bastien Weber. *Determination of high cycle fatigue properties of a wide range of steel sheet grades from self-heating measurements.* International Journal of Fatigue, 2014, 63, pp.46-61.
[2] A. Palchoudhary, C. Ovalle, V. Maurel, P. Kerfriden, *A fast Neuber-type finite element simulator to enable deep-learning-based fatigue life predictions from thermographic data*, Congrès Français de Mécanique, 2022.

C2-315

FFT-based Crystal Plasticity Simulation of Cyclic Loading of SLM AlSi10Mg

Manoj Singh BISHT[1], Vidit GAUR[1,*] and I. V. SINGH[1]

[1] Indian Institute of Technology Roorkee, Uttarakhand – 247 667, India

* Corresponding author: vidit.gaur@me.iitr.ac.in

ABSTRACT:

Additive Manufacturing (AM) offers greater flexibility in the design of complex structural parts. AlSi10Mg fabricated through AM-based Selective Laser Melting (SLM) has applications in the aerospace and automotive industries. AlSi10Mg has a hierarchical microstructure that requires micromechanical simulations to predict the mechanical behavior at different scales as it considers different microstructural features. In this work, an exact microstructural 3D RVE has been generated for performing the fast Fourier transformation (FFT) based crystal plasticity simulations. A comparative study of the phenomenological and dislocation density-based crystal plasticity model has been conducted. As the structural components are prone to fatigue failure, the deformation has been studied under cyclic loading. The misorientation evolution during the cyclic loading has been assessed using Kernel Average Misorientation (KAM). The result shows that the plastic strain and dislocation density is concentrated around Si-particles at the grain boundaries. The KAM is highly loading path dependent. The study carried out gives a better understanding of the role of microstructural features of Al-Si alloys in the evolution of stress and strain during fatigue loading.

KEYWORDS:

Crystal Plasticity; Additive Manufacturing; Al-Si alloy, Fatigue; Micromechanical Simulation

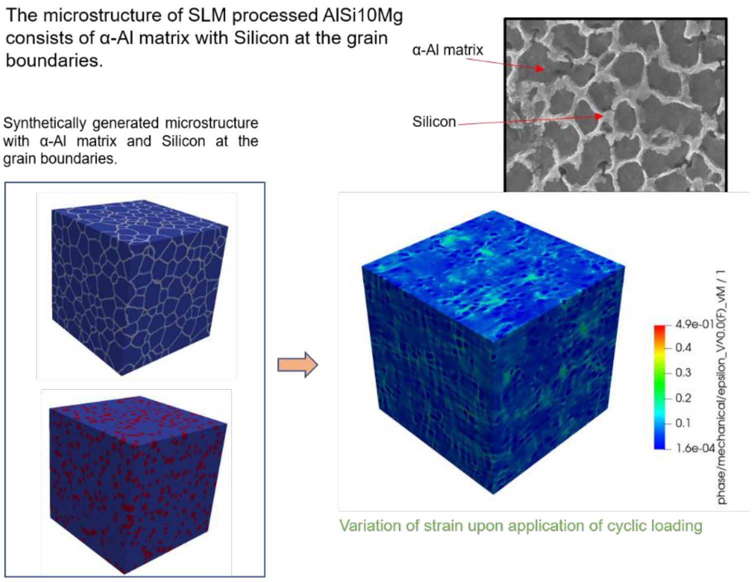


Fig. 1 *Crystal Plasticity Framework of SLM AlSi10Mg.*

C2-316

Creep Rate of Anode Material for Lithium-ion Batteries under High Temperature Environment

Kairi SHIRAISHI[1*], Masaya UEDA[1], Shiori TAGAI[1], Kohta KIKUCHI[1], Yudai FURUHATA[1], Yoshinao KISHIMOTO[1] and Yukiyoshi KOBAYASHI[1]

[1] Tokyo City University, JAPAN

* Corresponding author: g2281033@tcu.ac.jp

ABSTRACT:
Anode materials of lithium-ion batteries are composite structural materials in which active material particles are supported by polymer binders. This study has proposed a simple estimation method of creep properties of the anode materials using the creep properties of the binders. Since the internal temperature of lithium-ion batteries rise to 80℃ during use due to charging and discharging, creep tests in which constant tensile stress is applied were conducted on a carbon-based anode material consisting of carbon powder and polyvinylidene fluoride (PVDF) binder and a bulk material of the PVDF at room temperature and 80℃. Both the anode material and the PVDF exhibited the transition creep region where the creep rate, which is the amount of increase in the tensile strain with respect to time, gradually decreases after reaching the holding stress and the steady-state creep region where the creep rate is constant after the transition creep region. Also the tensile strain of both the anode material and the PVDF at 80℃ was greater than at room temperature when the same stress was applied. Using the creep rate of the PVDF, the proposed method successfully estimated the creep rate of the anode material.

KEYWORDS:
Lithium-ion battery; Anode material; Composite material; Creep test; High temperature

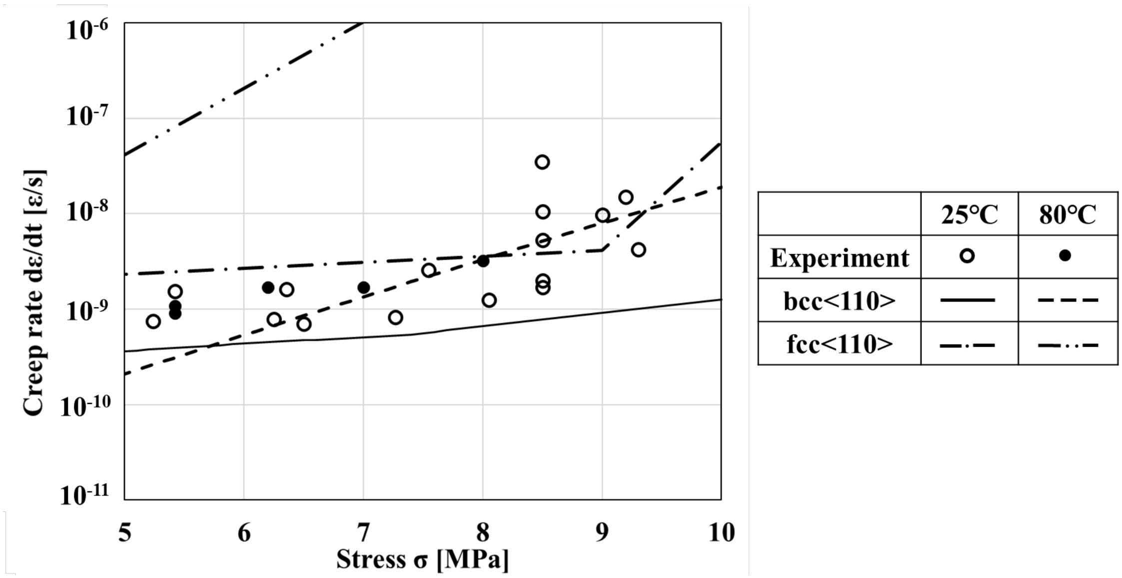


Fig. 1 *Creep rate of anode material under two different temperatures.*

C2-317

Investigation of Simple Mechanical Model for Fatigue Life Prediction of Anode Material for Lithium-ion Batteries

Masaya UEDA[1,*], Kohta KIKUCHI[1], Shiori TAGAI[1], Kairi SHIRAISHI[1], Atsuki TAKEUCHI[1], Yoshinao KISHIMOTO[1] and Yukiyoshi KOBAYASHI[1]

[1] Tokyo City University, JAPAN

* Corresponding author: g2381010@tcu.ac.jp

ABSTRACT:
Lithium-ion batteries mounted on a vehicle body are subjected to repeated load due to vibration. This study conducted tensile and plane bending fatigue tests on a carbon-based anode material for lithium-ion batteries, and proposed a simple mechanical model which easily predicts the fatigue life of the anode material. The test results showed that the anode material dissipated energy under the repeated load in the tensile fatigue test, and the number of cycles at the crack initiation increased with the decrease of the strain amplitude in the bending fatigue test. The proposed model approximates the arrangement of the carbon particles by a body-centered cubic or face-centered cubic lattice. The structure of the anode material was assumed to be supported by the binder as a straight bar. The dissipated energy per one binder and the S-N curve of the anode material with various concentration of the binder and various aspect ratio of the lattice models were calculated using the results of the tensile fatigue tests. The calculated total dissipated energy per one binder was linear to the number of cycles despite of the binder concentration, and the upper limit of the calculated S-N curves agreed with the bending fatigue test.

KEYWORDS:
Lithium-ion battery; Composite material; Fatigue test; Dissipated energy; S-N curve

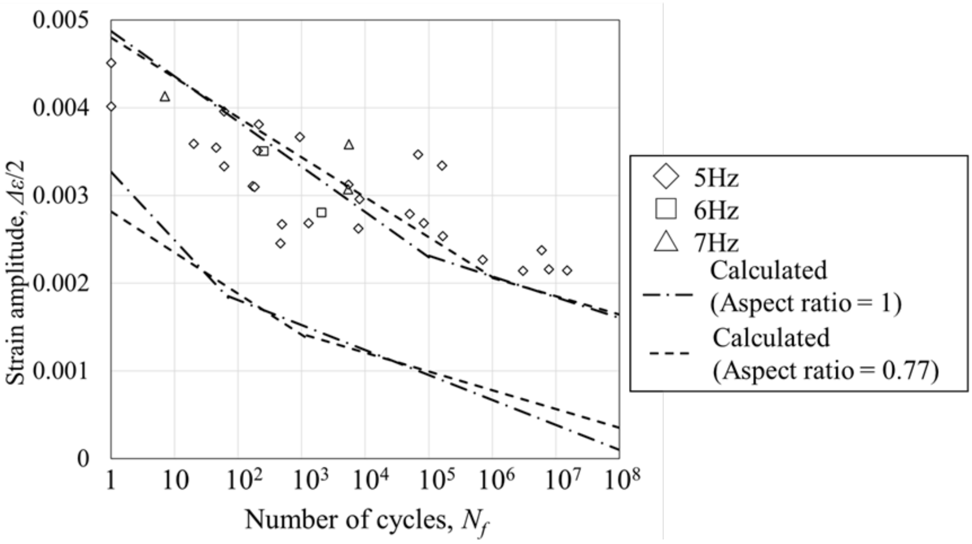


Fig. 1 *S-N curves of anode material by bending fatigue test.*

C2-318

Microstructure-based fatigue life assessment of additively manufactured nickel-based superalloy

Huang YUAN*, Shenzhe JIN and Tinglian ZHANG

Tsinghua University, School of Aerospace Engineering, Beijing, CHINA

* Corresponding author: yuan.huang@tsinghua.edu.cn

ABSTRACT:

The additively manufactured (AM) materials often show anisotropic mechanical properties. In the present paper, a constitutive model for a nickel-based superalloy made by selective laser melting was established to characterize cyclic mechanical behaviors under multi-axial loading conditions. Detailed material tests revealed that the effects from the build orientation decrease with multiaxial cyclic loads. A cyclic constitutive model based on the Hill criterion was introduced for the superalloy and considered the orthotropic mechanical properties depending on the stress triaxiality and loading cycles. The AM materials show additionally significant differences in fatigue performance, which have not been quantified properly, in combination with detailed microstructural analysis. The dendritic columnar microstructures elongated along the building direction are related to macroscopic mechanical properties. The anisotropy in mechanical properties is mainly due to the orientation-dependent columnar structure and the preferential texture with respect to the loading direction. Detailed experiments under multi-axial non-proportional loading conditions revealed that the influence of the build orientation from manufacturing on mechanical property and fatigue performance decreases with loading cycles. The present work confirms that the multi-axial variable loading amplitude fatigue can be reasonably characterized by the modified fatigue model based on the shear strain in combination.

KEYWORDS:

Laser selective melting, nickel-base superalloy, constitutive model, low cycle fatigue, fatigue life model

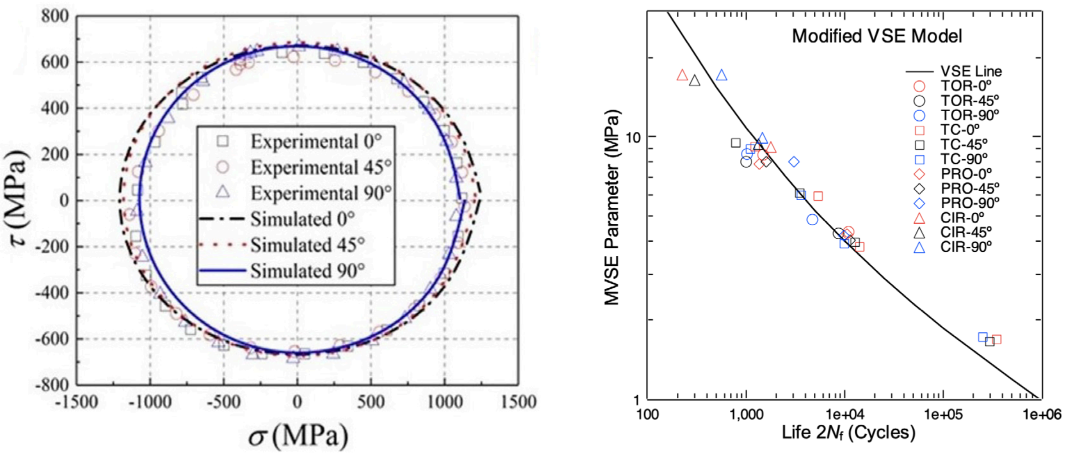


Figure 1 – Mechanical properties of the AM nickel-based superalloy of different orientations, experimental results versus computational predictions. (a) Cyclic non-proportional stress-strain loops. (b) Fatigue life results.

R1-301

Investigation of the torsional fatigue crack initiation mechanisms in the cast AlSi7Mg0.3 aluminum alloy using combined 3D X-ray CT and diffraction contrast tomography in a synchrotron beamline.

Viet Duc LE[1], Jean-Yves BUFFIERE[2], Nicolas SAINTIER[1], Pierre OSMOND[3], Daniel BELLETT[1], Marta MAJKUT[4], Wolfgang LUDWIG[2] and Franck MOREL[1,*]

[1] Arts et Métiers Institute of Technology, FRANCE
[2] INSA de Lyon, FRANCE
[3] CETIM, FRANCE
[4] ESRF, FRANCE

* Corresponding author: franck.morel@ensam.eu

ABSTRACT:
In-situ fatigue tests have been conducted in a synchrotron beamline at the European Synchrotron Radiation Facility (Grenoble, France) in order to understand the effect of the microstructure on the mechanisms of fatigue crack initiation and small crack propagation under torsional loads for the cast AlSi7Mg03 aluminum alloy. These experiments made it possible, on one hand, to obtain high resolution and high contrast 3D tomography images of the microstructure. On the other hand, thanks to the Diffraction Contrast Tomography technique, the 3D grain images have been rendered which include all necessary information related to the grains. Two crack initiation mechanisms were observed. The first one concerns crack initiation inside grains from the PSBs, either with or without the presence of a pore in the neighborhood of the grain. The second mechanism concerns crack initiation from pores. For the first mechanisms, crack initiation occurs in a shear mode and is greatly influenced by the grain orientation. The crack initiation mechanism due to pores occurs in the opening mode. No link to grain orientation was found. In spite of the presence of a large number of pores, the number of cracks initiated in this mode is smaller than the ones initiated from PSBs.

KEYWORDS:
Fatigue, crack initiation mechanisms, microstructure, tomography, synchrotron,

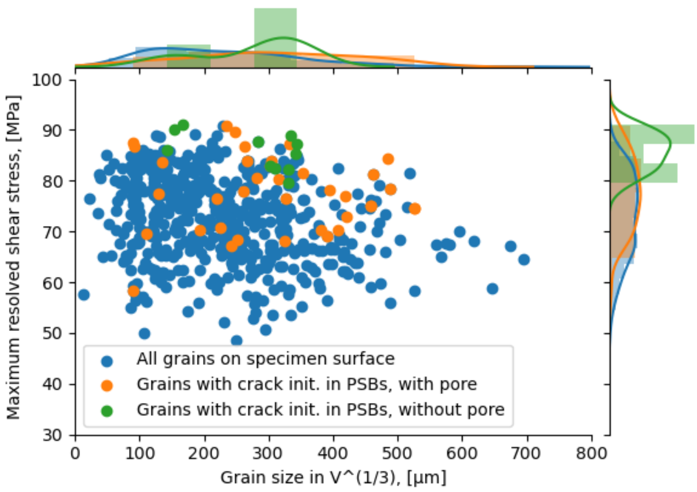


Fig. 1 *Effect of the maximum resolved stress and grain size on the crack initiations dues to PSBs.*

R1-302

Fatigue damage and temperature evolution under anisotropic cyclic deformation in a single crystal Ni-base superalloy using notched specimens

Putt THANAKUN[1,*], Motoki SAKAGUCHI[1], Akira KOSHIO[1] and Hirotsugu INOUE[1]

[1] Department of Mechanical Engineering, Tokyo Institute of Technology, O-okayama 2-12-1 Meguro-ku, Tokyo 152-8552, Japan

* Corresponding author: thanakun.p.aa@m.titech.ac.jp

ABSTRACT:

Evaluating the fatigue limit by measuring temperature changes via infrared thermography has attracted significant interest because of its potential for rapid assessments. However, the physical background and validity of this technique are not yet fully understood. In this study, an experimental study is carried out using notched specimens of a single crystal Ni-base superalloy subjected to cyclic loading through observation of fatigue crack initiation by microscope and measurement of temperature field by infrared thermography. Two types of notched specimens with different crystallographic orientations are subjected to cyclic loading below and above the fatigue limit to investigate fatigue damage accumulation and temperature evolution. Local slip deformation is quantified using crystal plasticity finite element analyses. It is found from the experimental and analytical results that the distribution of the temperature change and the local slip deformation (a plastic shear strain on the most active slip system) are affected by the crystallographic orientation. However, the correlation between the plastic shear strain and the second harmonic amplitude of the temperature signal, as well as the threshold values of these parameters for crack initiation, are independent of the crystallographic orientation.

KEYWORDS:

Fatigue; Temperature evolution; Dissipated energy; Single crystal; Crystal plasticity.

R1-303

Phase-field simulation on the martensitic transformation/reorientation toughening behaviors of single crystal NiTi shape memory alloy

Junyuan Xiong[1], Bo Xu[1], Qianhuha Kan[1], Guozheng Kang[1, *]

[1] Applied Mechanics and Structure Safety Key Laboratory of Sichuan Province, School of Mechanics and Aerospace Engineering, Southwest Jiaotong University, Chengdu 610031, China

* Corresponding author: guozhengkang@swjtu.edu.cn

ABSTRACT: Based on Ginzburg-Landau's theory, a two-dimensional phase-field model coupling martensitic transformation/reorientation (MT/MR) and fracture was established. The crack propagation of single crystal NiTi shape memory alloy (SMA) was studied by the phase-filed simulations. The simulated results show that the proposed phase-field model can reasonably characterize the crack propagation, MT/MR and stress-strain curve of single crystal NiTi SMA with different crystalline orientations and temperatures. The MT/MR toughening behaviors is observed in the simulations, which greatly depend on the crystalline orientation and temperature: when the temperature is higher than the chemical equilibrium temperature, the MT toughening effect decreases with the increase of temperature; when the temperature is lower than the chemical equilibrium temperature, the MR toughening effect decreases with the decrease of temperature. Generally, the closer the temperature to the chemical equilibrium temperature, the better the MT toughening effect and the weaker the orientation dependence are. However, the change of MR toughening with the temperature and crystalline orientation is complex since the twinned martensite phase at the crack tip can not only slow down the crack propagation rate, but also induce the crack bifurcation.

KEYWORDS:
Single crystal NiTi SMA; Martensitic transformation toughening; Martensitic reorientation toughening; Phase-field simulation; Crystalline orientation

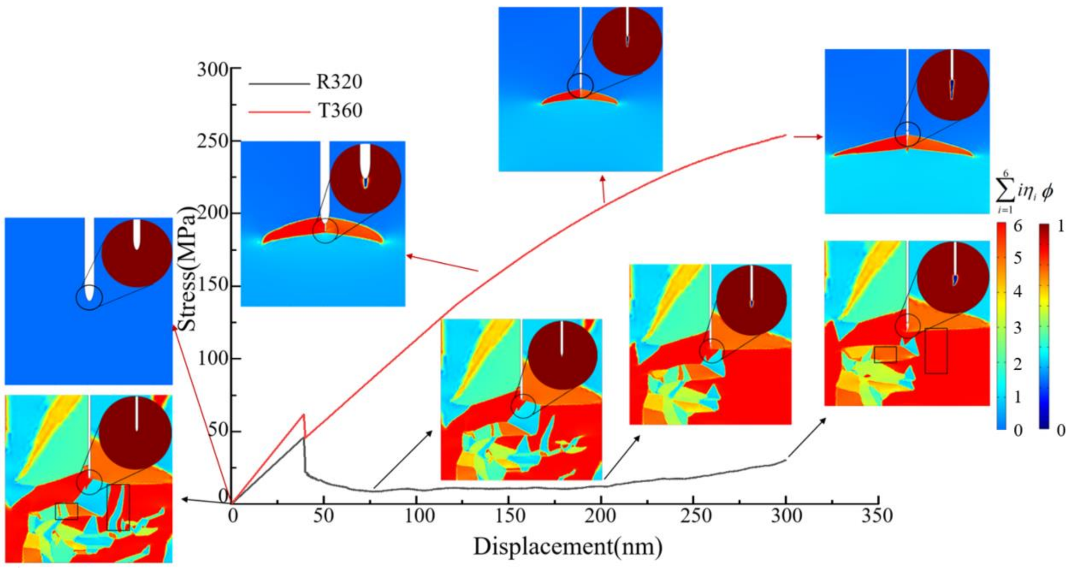


Fig. 1 *Stress-displacement curves and microstructure evolutions in the R320 and T360 systems during the displacement loading.*

R1-304

Analysis and modeling of the strain distribution and evolution during a fatigue test in ULCF and LCF. Application on a friction stir welded specimen from steel and aluminum

Paul Dario TOASA CAIZA[1],* and Yoshihiko UEMATSU[2]

[1]KIT Stahl- und Leichtbau, Versuchsanstalt f¨ur Stahl, Holz und Steine,Karlsruher Institut f¨ur Technologie (KIT). Otto-Ammann-Platz 1, 76131 Karlsruhe, Germany
[2]Department of Mechanical Engineering, Gifu University. 1-1 Yanagido, Gifu 501-1193, Japan
*Corresponding author: paul.toasa@kit.edu

ABSTRACT:

Under cyclic loading in ULCF and LCF regimes the strain variation plays a fundamental role in the analysis of the fatigue resistance and in the estimation of the fatigue life. The Digital Image Correlation (DIC) method, which allows to acquire strain and deformation in large areas is applied in order to obtain the maximum reached strain, strain range, mean strain and SWT parameter during a full reversal fatigue test on a friction stir welded specimen. The materials used to manufacture the specimen are Al alloy A6061-T6 and stainless steel type 304.

On the one hand, since the distribution of these strain related variables in the Region of Interest (ROI) shows a geometry given by symmetric bells, a two peak Gaussian model is applied to model it. On the other hand, the evolution of these variables during the fatigue test up to failure is modeled by applying a third grade polynomial.

The obtained results, show the plausibility of the proposed methods to model the strain distribution and evolution under cyclic loading in ULCF and LCF. Based on the distribution and evolution of the strain acquired during the fatigue tests, an estimation of the fatigue life can be performed.

KEYWORDS:

Strain, Cyclic Loading, Gaussian Model, Lifetime estimation, DIC

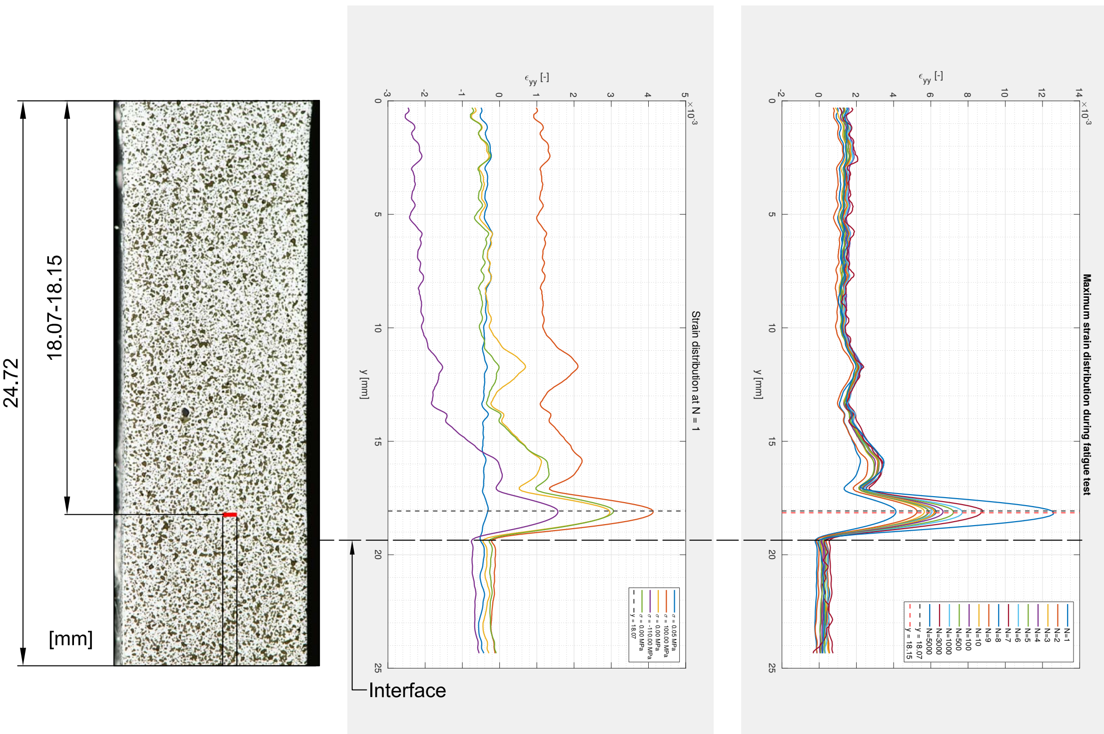


Figure 1: Region where the maximum strain is reached. Position compared with the data of the first loading cycle and of the complete fatigue experiment.

R1-305

A review on the fatigue cracking of twin boundaries: crystallographic orientation and stacking fault energy

Zhefeng ZHANG[1]*, Linlin LI[1,2], Zhejun ZHANG[1] and Peng ZHANG[1]

[1] Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, P.R. China

[2] State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110819, P.R. China

* Corresponding author: zhfzhang@imr.ac.cn

ABSTRACT:

Twin boundaries (TBs) are ubiquitous interfaces of specific structure in metallic materials. They possess special interactions with dislocations and fatigue cracking behaviors distinctive from that of conventional high-angle grain boundaries. A profound understanding on the fatigue cracking mechanisms of TBs achieved over past decades is reviewed here for the first time. The dislocation slips in the matrix and twin grains determined by grain orientations are closely related to the inclinations of coherent and incoherent TBs. The variable TB-dislocation interactions generate tunable fatigue cracking behaviors of TBs. Besides the grain orientations, the stacking fault energy (SFE) also alters the dislocations piling up at TBs by influencing dislocation dissociation. Both factors synergistically affect the fatigue cracking behaviors of TBs with a linear relationship between the difference in Schmid factors and SFE at the threshold of TB cracking. Moreover, the TBs produced by deformation twins in face-centered cubic materials are strong to resist fatigue cracking by promoting deformation homogeneity while those linked with deformation twins in hexagonal-close-packed or body-centered-cubic materials are preferential sites of fatigue cracking with strain localization and stress concentration. These fundamental knowledges of TB fatigue cracking provide important guidance in interfacial design to enhance materials fatigue performance.

KEYWORDS:

Twin boundary; Orientations; Fatigue cracking; Slip bands; Stacking fault energy

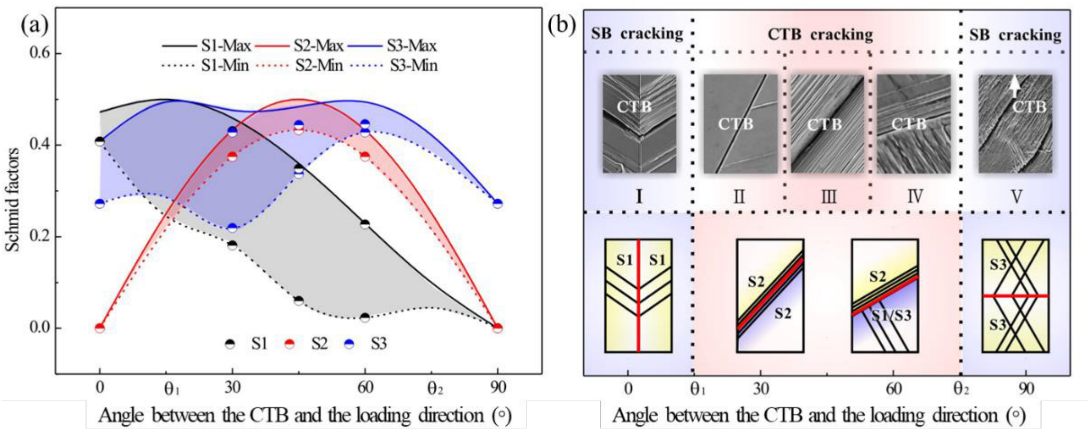


Fig. 1 Fatigue cracking behaviors of twin boundaries with different orientation.

Reference:

L.L. Li, Z.J. Zhang, P. Zhang, and **Z.F. Zhang***, A review on the fatigue cracking of twin boundaries: Crystallographic orientation and stacking fault energy. *Prog. Mater. Sci.*, 131 (2023) 101011.

R1-306

Low-cycle fatigue of CrCoNi medium-entropy alloy with different grain sizes

Yujie Wang[1], Tao Yu[1], Zhiguang Wang[1], Linlin Li[1]*, Guo Yuan[1], Zhefeng Zhang[2],

[1] State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110819, PR China
[2] Shi-changxu Innovation Center for Advanced Materials, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China

* Corresponding authors: lill@ral.neu.edu.cn

ABSTRACT:

Low-cycle fatigue behaviors of CrCoNi medium entropy alloy with different grain sizes were investigated. It is found that grain refinement improved deformation homogeneity to delay fatigue crack initiation by dispersing slip bands and fatigue damage. Yet, the increase in grain size promoted deformation twinning to retard fatigue crack growth by dissipating plastic work and deflecting crack. With enough plastic deformation accumulated, extensive dislocation slip and deformation twinning significantly refined the grains localized near fatigue cracks. The grain refinement could trade off the cyclic softening caused by breaking the short-range order in CrCoNi alloy with fine grains. These findings indicate that refined grains with certain twinning ability would extend the fatigue life of CrCoNi alloy the most and suppress cyclic softening at the same time.

KEYWORDS:

Medium-entropy alloy; Low-cycle fatigue; Grain size; Deformation twinning; Planar slip.

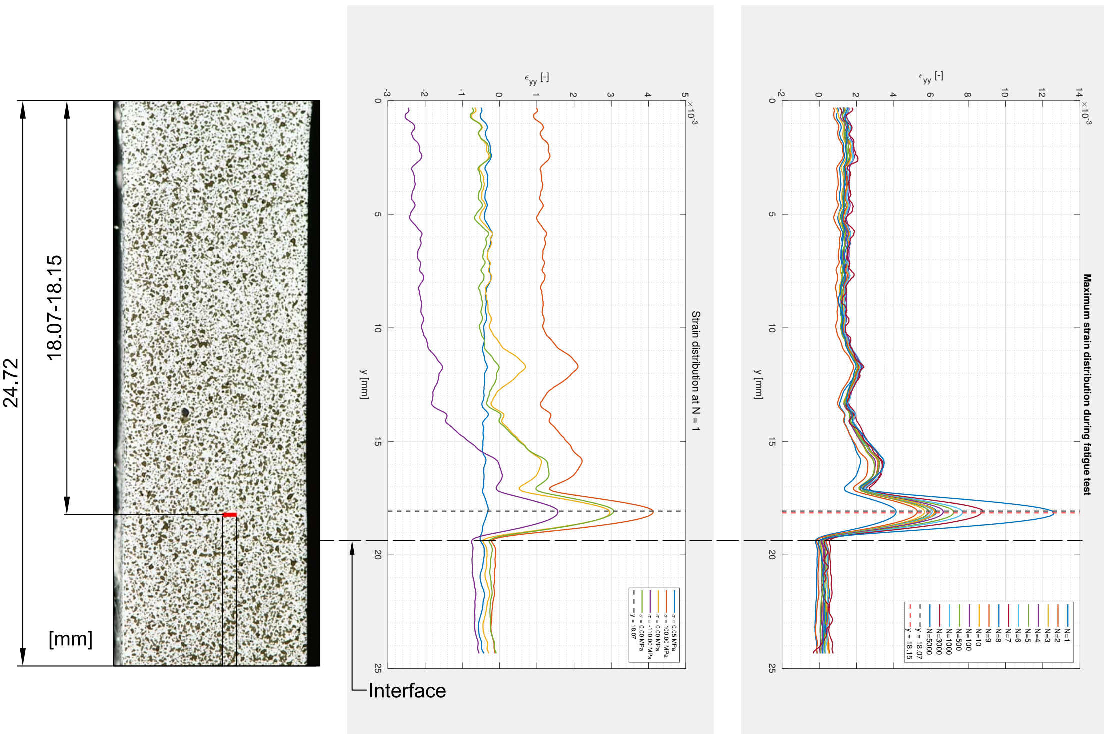


Figure 1: Region where the maximum strain is reached. Position compared with the data of the first loading cycle and of the complete fatigue experiment.

R1-307

Influence of mechanical fatigue on magnetic properties of electrical steels

Constanze BACKES[1,*], Marek SMAGA[1] and Tilmann BECK[1]

[1] Institute of Material Science and Engineering (WKK), RPTU Kaiserslautern-Landau, GERMANY

* Corresponding author: c.backes@mv.rptu.de

ABSTRACT:

Electrical steels are widely used as functional materials in transformers and e-motors. For ensuring high power and efficiency, outstanding soft magnetic properties are required. Since mechanical loading leads to an alteration of the magnetic properties, the understanding of fatigue induced changes of the material's function is of great importance. This study investigates the fatigue behavior of non-oriented (NOES) and grain-oriented (GOES) electrical steels regarding the cyclic deformation behavior and mechanical as well as functional fatigue. Stress controlled fatigue tests were performed with a stress ratio of R = 0.1, f = 5 Hz at ambient temperature. The cyclic deformation behavior is characterized by pronounced ratcheting, where total mean strain reaches max. values between 18 % - 20 % for NOES and GOES. Concerning the magnetic properties, measuring of micromagnetic properties using the micromagnetic, multiparameter, microstructure and stress analysis (3MA) sensor is conducted. Furthermore, changes in crystallographic microstructure and magnetic domain structure are characterized via electron back scattered diffraction (EBSD) and magneto-optical Kerr effect (MOKE), respectively.

KEYWORDS:
electrical steel; high cycle fatigue; cyclic deformation behavior; magnetic properties; magnetic domain structure.

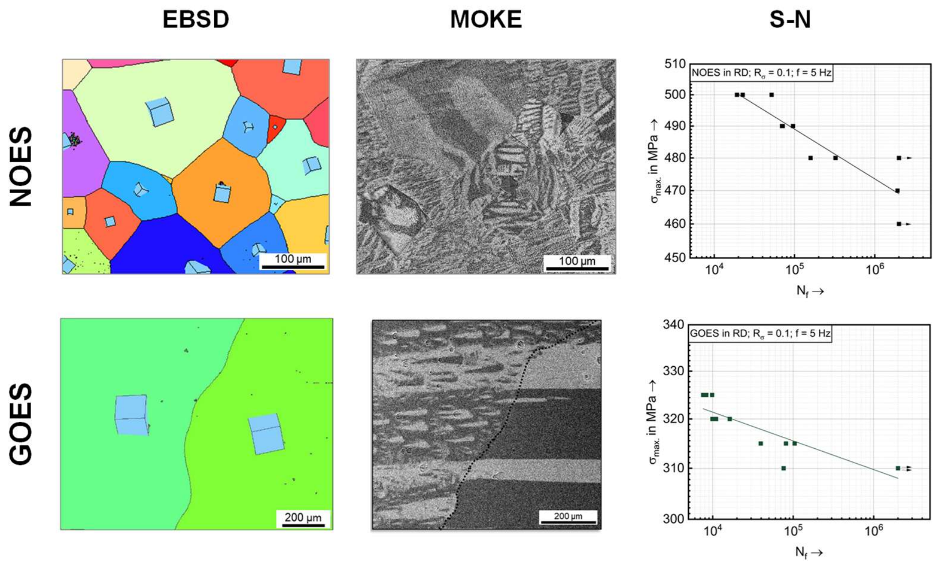


Fig. 1 Crystallographic (EBSD) and magnetic (MOKE) microstructure of non-oriented and grain oriented electrical steel in initial state and S-N-curve for both materials.

R1-308

Influence of different temperatures on the fatigue behavior of fully ferritic high chromium steel

P. Lehner[1]*, T. Fischer[2], B. Blinn[1], B. Kuhn[2], T. Beck[1]
1 Institute of Materials Science and Engineering, RPTU,
2 Institute for Energy and Climate Research IEK-2, Research Center Jülich
* Corresponding author: p.lehner@mv.rptu.de

ABSTRACT:
Since the transition to new energy systems leads to strong fluctuations in power plant operation, materials with enhanced (thermomechanical) fatigue strength are required. Fully ferritic high chromium steels (e.g. HiperFer-17Cr2) exhibit a higher resistance to fatigue crack initiation and growth than conventional advanced ferritic martensitic (AFM) steels, which is mainly caused by the thermomechanically induced precipitation of Laves phase [1]. As this precipitation depends on the thermomechanical load, understanding the relationship between loading condition, precipitation state, and resulting fatigue behavior is indispensable.
Consequently, fatigue tests were performed at temperatures between 600 and 650°C for HiperFer-17Cr2 and AFM steel P91. The P91 reveals a significant decrease in fatigue strength with increasing temperature, while the temperature-induced reduction in fatigue strength of HiperFer-17Cr2 is less pronounced up to 635°C (see Figure 1). This is attributed to the difference in cyclic deformation behavior. While P91 exhibits cyclic softening, HiperFer-17Cr2 shows a strong cyclic hardening, which is assumed to be caused by precipitation hardening due to Laves phase formation, being more pronounced at higher temperatures. According to [2], cyclic indentation tests were used to qualitatively evaluate the influence of the temperature on the change in cyclic hardening potential and precipitation state in intermitted fatigue tests.

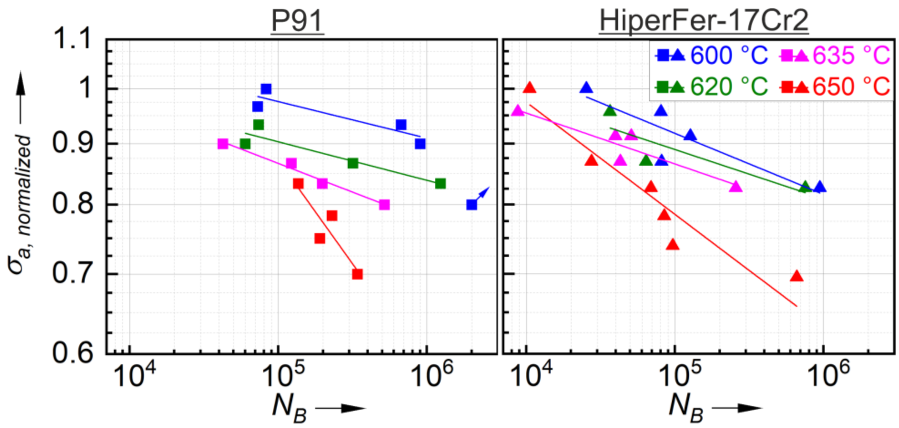


Figure 1. Normalized S-N_f curves of P91 and HiperFer-17Cr2 for different temperatures

KEYWORDS:
fully ferritic high chromium steel; Laves phase strengthening; isothermal fatigue; cyclic softening/hardening; cyclic indentation testing.

[1] Kuhn et al.: Impact of Thermomechanical Fatigue on Microstructure Evolution of a Ferritic Martensitic 9 Cr and a Ferritic, Stainless 22 Cr Steel. 2020. Appl. Sci. 10, 6338
[2] Blinn et al.: Analysis of the Thermomechanical Fatigue Behavior of Fully Ferritic High Chromium Steel Crofer22H with Cyclic Indentation Testing. 2020. Appl. Sci. 10, 6461

R1-309

Cyclic Simple Shear Properties of Single- and Poly-crystalline Fe and Fe–3wt%Si alloys

Mamoru HAYAKAWA[1,*], Eisuke NAKAYAMA[1], Ryota HIGUCHI[1], Kazuo OKAMURA[2], and Kazuyuki SHIZAWA[3]

[1] Nippon Steel Corporation, JAPAN
[2] Osaka University, JAPAN
[3] Keio University, JAPAN

* Corresponding author: hayakawa.e8c.mamoru@jp.nipponsteel.com

ABSTRACT:
Cyclic simple shear tests were performed on single- and poly-crystalline Fe and Fe–3wt%Si alloys to evaluate the effect of solute elements on the activity of slip systems in the low-cycle fatigue deformation of iron. Notched plate specimens with shearing planes of {110}<111> and {112}<111> were prepared to obtain the cyclic shear stress–strain (CSSS) responses of the single crystals. The CSSS curves of the single- and poly-crystalline Fe and Fe–3wt%Si specimens are shown in Fig. 1. The single- and poly-crystalline specimens exhibited different CSSS behaviors. The CSSS behavior of the cross section of the single-crystalline Fe specimen on the (110) plane was higher than that on the (112) plane. In contrast, the single-crystalline Fe–3wt%Si specimen exhibited similar CSSS behaviors on both the (110) and (112) planes. Moreover, the poly-crystalline Fe–3wt%Si specimen exhibited higher cyclic hardening than the poly-crystalline Fe specimen. For the Fe–3wt%Si specimen, large cyclic hardening occurred uniformly in each polycrystalline crystal because the variation in CSSS between the different slip systems is small. This characteristic is effective for improving the cyclic shear yield stress and fatigue limit of the Fe–3wt%Si specimens.

KEYWORDS:
Cyclic stress–strain curve; Shear properties; Single crystal; Solid-solution strengthening; Pure iron.

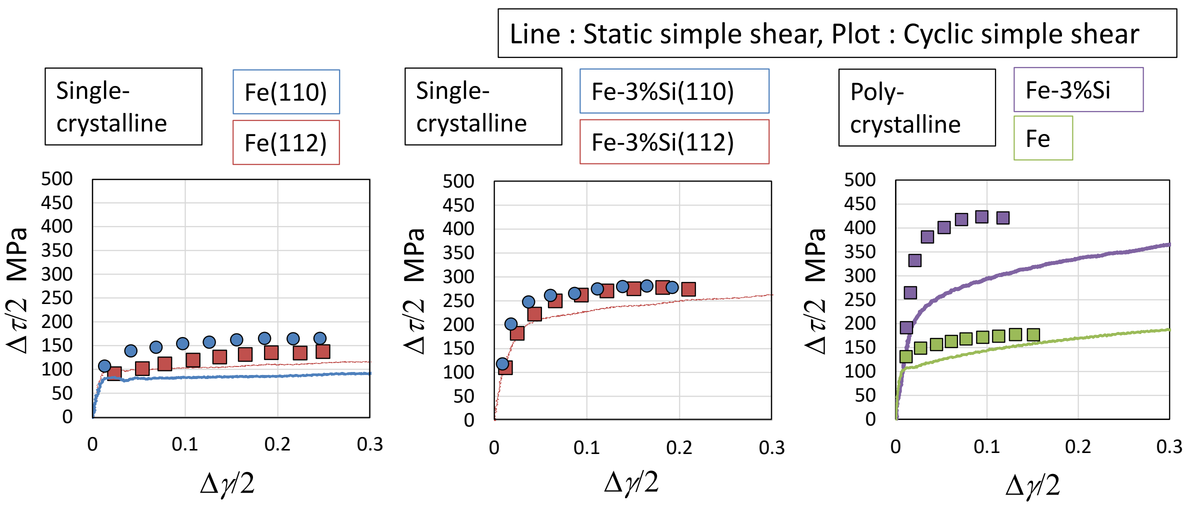


Fig. 1 *Cyclic shear stress–strain curves of single- and poly-crystalline Fe and Fe–3wt%Si specimens.*

R1-310

Effect of Lüders strain localization on notch fatigue of medium manganese steels

Xiangbo Hu[1], Xiaogang Wang[1,*], Chao Jiang[1]

[1] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, College of Mechanical and Vehicle Engineering, Hunan University, 410082 Changsha, China

* Corresponding author: xgwang@hnu.edu.cn

ABSTRACT:

The Lüders strain localization effect is a common phenomenon appearing during tensile tests of medium manganese steels. It results in plastic instability and specimen surface roughening. Nevertheless, regarding notch fatigue cases, the influence and mechanism of the Lüders strain localization effect is yet unclear. In this work, two different kinds of experiments were carried out to analyze the influence of Lüders banding in fatigue behavior of notched specimens of medium manganese steels. First, specimens with different notch sizes and curvatures were deformed under quasi-static tensile tests. The strain localization was identified by the developed digital image correlation (DIC) method. It shows that the Lüders band was prone to nucleate at notches which have lower stress concentration factors and larger notch sizes. Then specimens with pronounced Lüders effect were compared with specimens which have little or no Lüders effect under fatigue loading. The fatigue behaviors of the two different types of specimens demonstrate essential differences, indicating that the Lüders strain localization effect has a significant influence in the application of medium manganese steels under fatigue loading conditions.

KEYWORDS:

Lüders effect; notch fatigue; medium manganese steel; digital image correlation

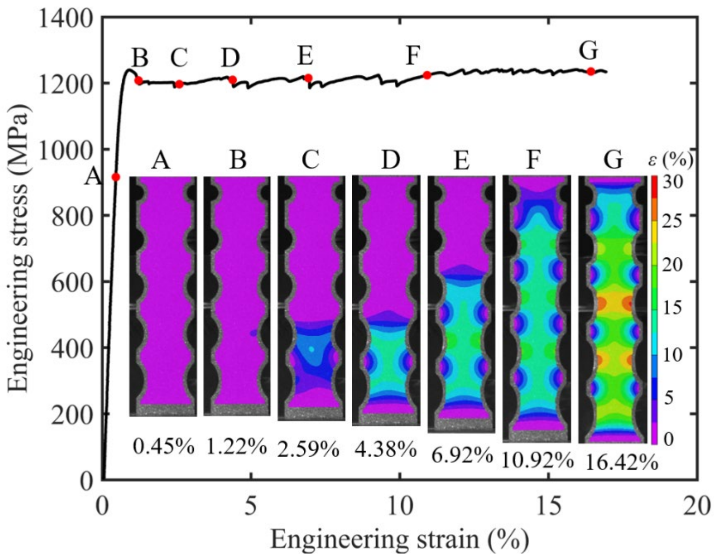


Fig. 1. Macroscopic strain and stress response and full-field strain evolution of notched specimen.

R1-311

Evaluation of Fatigue Properties of CFRF and Experimental Elucidation of Damage Growth Mechanism

Koga Yuta[1], Yusuke Sato[1], Takuto Kikuchi[1] Atsushi Hosoi[1,2,*], Kota Kawahara[3], Yoshiki Takebe[3] and Hiroyuki Kawada[1,2]

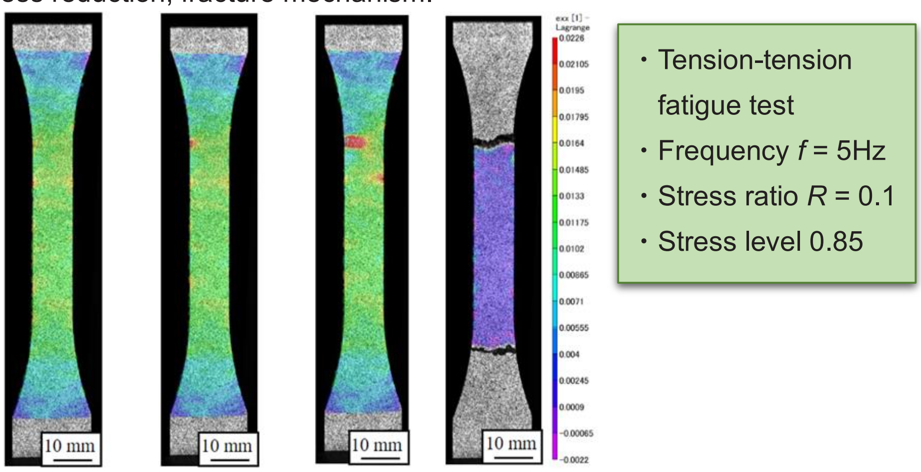
[1] Waseda University, JAPAN
[2] Kagami Memorial Research Institute for Materials Science and Technology, Waseda University, Japan
[3] Composite Materials Research Laboratories, Toray Industries, Inc., Japan
* Corresponding author: hosoi@waseda.jp

ABSTRACT:

Carbon fiber reinforced foam (CFRF) are expanded thermoplastic composite materials reinforced with three-dimensionally discontinuous carbon fibers. In this study, the stiffness reduction of CFRF was measured and evaluated, and the failure mechanism was investigated. The stiffness reduction behavior of CFRF under tension-tension fatigue testing was measured using a digital image correlation method (DIC). The results showed that the strain distribution in the CFRF was scattered, and the strain was locally high at the fracture points. In addition, the stiffness behavior of the entire specimen and gauge length was different. Therefore, it is suggested that the difference in local stiffness reduction behavior affects the scatter of fatigue life. Failure mechanisms were investigated for static and fatigue. For the static fracture mechanism, in-situ observation using scanning electron microscopy (SEM) showed that fracture progressed by interfacial debonding and fiber pullout after microcrack initiation. As for the fatigue fracture mechanism, in the DIC results, the areas of high local strain were cut using a cutter and observed using SEM. The results suggest that the cracks propagated due to changes in the internal structure caused by resin fracture and fiber pullout.

KEYWORDS:

CFRF, foam, stiffness reduction, fracture mechanism.



(a) *N*=2000 (b) *N*=3200 (c) *N*=4400 (d) *N*=4479

Fig. 1 *CFRF's DIC image under fatigue testing.*

R1-312

Achieving superior fatigue strength in a powder-metallurgy titanium alloy via in-situ globularization during hot isostatic pressing

Lei Xu[1,*], Jie Wu[1], and Zhengguan Lu

[1] Institute of Metal Research, Chinese Academy of Sciences, China

* Corresponding author: lxu@imr.ac.cn

ABSTRACT:
Powder-metallurgy (PM) titanium alloys exhibit outstanding quasistatic-mechanical properties, but suffer from low fatigue performance, which severely limits their applications in aerospace. Here, we achieve a superior fatigue strength of 600 MPa in a near-α PM titanium alloy, using a two-step hot-isostatic-pressing scheme, during which more than 80 vol.% (volume fraction) randomly orientated equiaxed grains was obtained. The largely improved fatigue strength (~ 25%) is mainly attributed to the in-situ globularization of the lamella-like microstructure, leading to higher crack nucleation resistance and lower growth rates of short cracks. The present findings offer a useful route for fabricating PM titanium alloys with high fatigue strengths.

KEYWORDS:
Powder metallurgy; hot-isostatic-pressing; fatigue strength;

R1-314

Experimental investigation of early strain localizations on ferrite-pearlite steel under cyclic loading.

Nagesh Narasimha Prasad[1,*], Ahmed El Bartali[1], Jean-François Witz[1], Nathalie Limodin[1] and Denis Najjar[1]

[1] Univ. Lille, CNRS, Centrale Lille, UMR 9013 - LaMcube - Laboratoire de Mécanique, Multiphysique, Multiéchelle, F-59000 Lille, France

* Corresponding author: nagesh.narasimha@centralelille.fr

ABSTRACT:

The use of fatigue-resistant steel grades is crucial for the development of durable and reliable railway components. Ferrite-pearlite steels are commonly used due to their balance between strength and toughness. The application of heat treatments during manufacturing and plastic deformation during operation generates microstructural gradients that can potentially improve the material's mechanical properties. However, the impact of these microstructure gradients on fatigue remains unclear. To address this issue, we developed an experimental methodology employing in-situ optical-based Digital Image Correlation (DIC) to measure local strain during Low Cycle Fatigue loading. A flat specimen with a semi-circular notch was utilized in the experiment, with 70mm length, 5mm thickness, and 10mm width at the notch. A Region of Interest (ROI) was identified and a speckle pattern was applied to the surface. A pixel-wise DIC technique was utilized to analyze displacement fields by capturing images of the speckle at the cyclic load peaks. These fields were then mapped onto the surface microstructure of the ROI to identify strain localization and potential crack initiation sites. Our study aims to investigate the impact of microstructural gradients on fatigue crack initiation mechanisms of ferrite-pearlite steel components and improve prediction models as well as fatigue life management practices.

KEYWORDS:
Ferrite-Pearlite steel; Microstructure gradient; Plasticity; Fatigue damage; Digital image correlation.

R1-315

Multi-mechanism constitutive model for uniaxial ratchetting of extruded AZ31 magnesium alloy at room temperature

Yu Lei[a], Ziyi Wang[a], Qianhua Kan[a], Guozheng Kang[a*]

[a] Applied Mechanics and Structure Safety Key Laboratory of Sichuan Province, School of Mechanics and Aerospace Engineering, Southwest Jiaotong University, Chengdu 611756, China

* Corresponding author: guozhengkang@home.swjtu.edu.cn or guozhengkang@126.com

ABSTRACT:

A multi-mechanism macroscopic phenomenological constitutive model is established to characterize the uniaxial ratchetting of extruded AZ31 magnesium (Mg) alloy at room temperature in the framework of small deformation. Because the uniaxial ratchetting of the alloy depends greatly on the strong basal texture and different deformation mechanisms (i.e., dislocation slipping, twinning and detwinning) and presents apparent tension-compression asymmetry, two separated yield functions and different hardening rules are used in the proposed model regarding to different deformation mechanisms. That is, the traditional von Mises yield criterion and a flow rule in power-law form are used for the plasticity contributed by dislocation slipping, while the Cazacu–Barlat–Plunkett (CPB) yield criterion extended with a back stress tensor and an internal variable f (i.e., twin volume fraction) is employed to express the plastic deformation induced by twinning/detwinning. In addition, the modified Armstrong-Frederick(A-F) kinematic hardening models are adopted to reflect the strain hardening features contributed by different plastic mechanisms, and the interaction among different plastic mechanisms is considered in the developed constitutive model. The reproduced uniaxial ratchetting of extruded AZ31 Mg alloy by the proposed multi-mechanism constitutive model is in a good agreement with the corresponding experimental results obtained at room temperature, which validates the reasonability and capability of the proposed model.

KEYWORDS:

Extruded magnesium alloy; Ratchetting; Multi-mechanism constitutive model; Dislocation slipping; Twinning/detwinning;

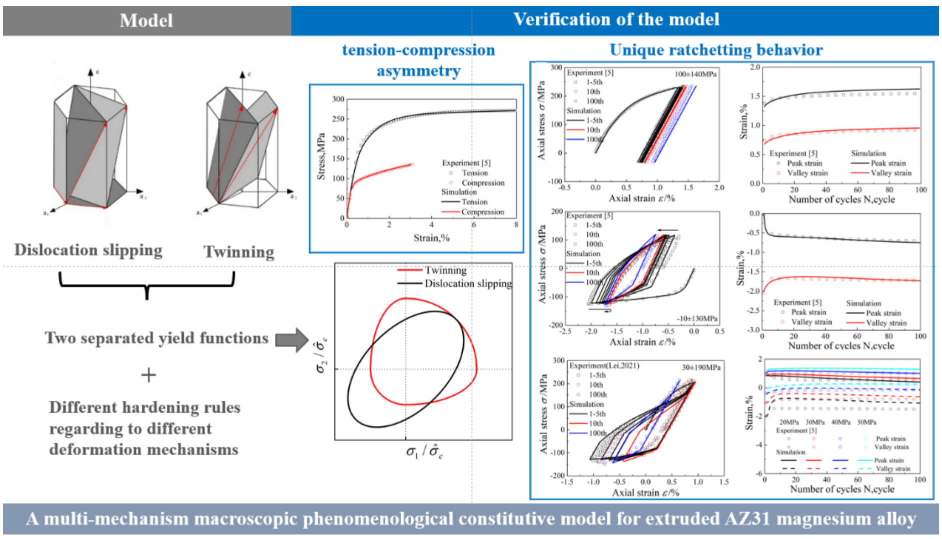


Fig. 1 *Graphical abstract*

R1-316

Cyclic responses and damage evolution of ultra-high strength steel under low-cycle fatigue

Feinong Gao[1], Lijing Xie[2,*], Tongyu Liu[1], Xibin Wang[2]

[1] School of Mechanical Engineering, Beijing Institute of Technology, No. 5 Zhongguancun South Street, Haidian District, Beijing 100081, China

[2] Key Laboratory of Fundamental Science for Advanced Machining, Beijing Institute of Technology, Beijing 100081, China

* Corresponding author: rita_xie2004@163.com

ABSTRACT:

As the mechanical properties are highly dependent on microstructure, the correlation between microstructure evolution and cyclic responses have gained widespread attentions. In this work, the cyclic properties of ultra-high strength steel are first studied with fatigue experiments followed by microstructure characterizations using transmission electron microscope (TEM), and the effects of strain range, strain ratio, and the loading history on the cyclic responses are examined. Based on the characterization of cyclic loops, the evolution of elastic modulus is examined first, the degradation of elastic modulus with cycles and load-dependent variation within cycles are observed. Though nonhardening region as first proposed by Ohno (1982) is also detected in stepwise loading under fully reversed condition, cyclic softening occurs in step II under tensile-tensile loading condition. In order to solve such problems, the elastic hysteresis is first modelled in conjunction with classical cyclic plasticity model with consideration of damage accumulation, and a multi-stage isotropic hardening as long as modified plastic strain range (PSR) model are proposed based on the idea of microstructure evolution, the proposed models are validated with experimental data, which shows the proposed model could predict the cyclic responses under various loading conditions with outstanding precision.

KEYWORDS:

Damage evolution, isotropic hardening, strain range history, cyclic plasticity

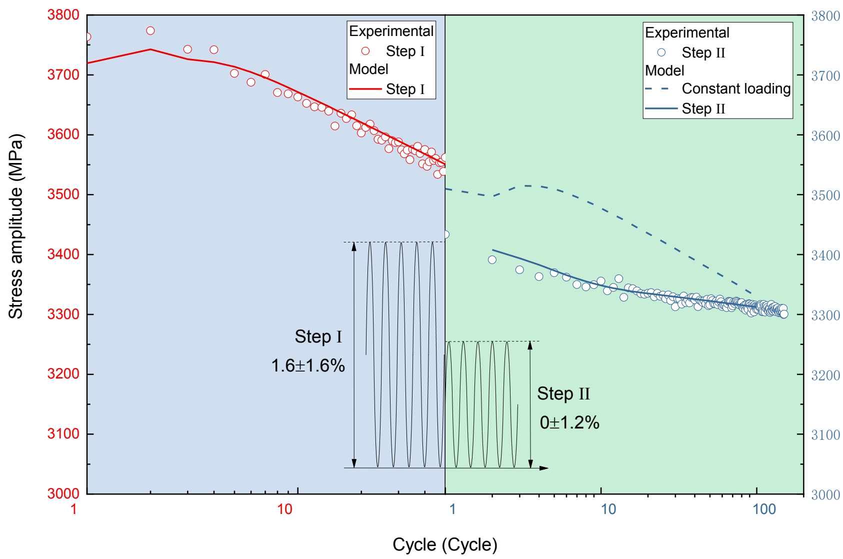


Fig. 1 Simulation and experimental results of stress amplitude evolutions under stepwise loading

R1-317

Mechanism-based assessment of profiles made from directly recycled hot extruded EN AW-6060 aluminum chips

Alexander KOCH*, Sarah LASKOWSKI and Frank WALTHER

TU Dortmund University, Chair of Materials Test Engineering (WPT), Dortmund, Germany

* Corresponding author: alexander3.koch@tu-dortmund.de

ABSTRACT:

The global demand for aluminum is showing steady growth due to the high specific strength, the corrosion resistance and an excellent suitability for forming processes. Recycling aluminum by re-melting can significantly reduce the required energy compared to the production of primary aluminum but recycling still requires a noticeable amount of energy because of the high process temperatures. Solid-state-recycling processes are promising alternatives to energy-intensive re-melting. For the direct recycling without the necessity of re-melting, the chips are pre-compacted and further processed into profiles in a hot extrusion process. The quality of the so-produced profiles depends on the quality of the interface between the single chips, which are bonded by microstructural welding. The investigations clearly show that the process window of hot extruded, directly recycled aluminum chips is restricted. Due to the interaction especially of strain and hydrostatic pressure, ideal conditions for sufficient welding of the chips cannot be achieved for the whole profile by varying the extrusion ratio. If the extrusion ratio is high, the criterion of high shear strain is fulfilled, but the hydrostatic pressure is too low to sufficiently compress the chip surfaces at the simultaneously high strain and vice versa. As a consequence, different zones form during the extrusion process (Fig. 1), all of which have different fatigue properties and can be correlated well with microstructure and associated mechanisms such as recrystallization, strain hardening, and grain refinement.

KEYWORDS:

Aluminum alloys; hot extrusion; solid-state-recycling; microstructural mechanisms; fatigue properties

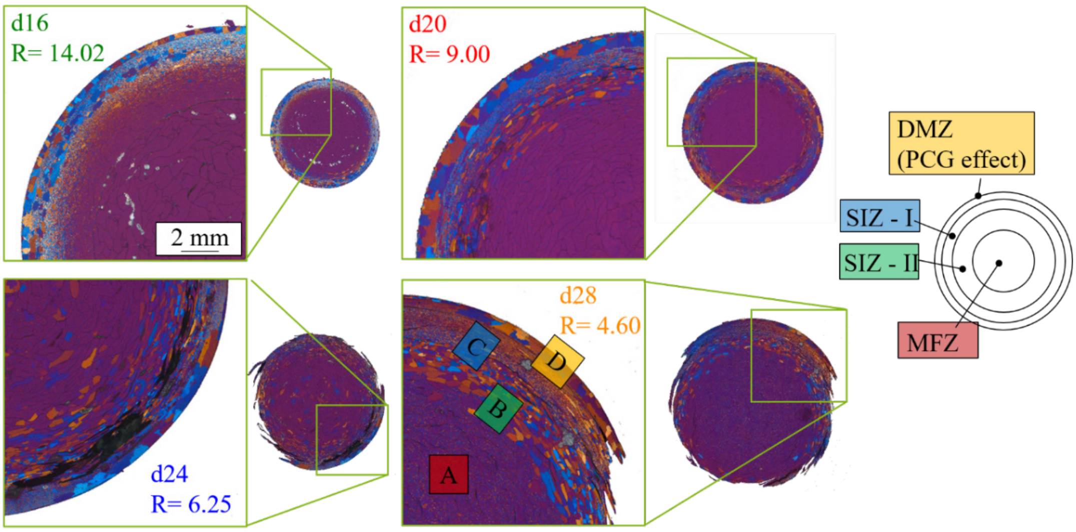


Fig. 1 *Microstructural formation dependent on extrusion ratio R with dead metal zone (DMZ), shear intensive zone (SIZ) and metal flow zone (MFZ)*

R1-318

Phase transformation and ratchetting behavior of medium manganese steel under asymmetrical cyclic stressing: experiments, phase-field simulations and meso-mechanical constitutive model

Shuxin CHANG[1], Juan ZHANG[1,*], Xingmin HUANG[2], Zhiwu ZHU[1], Guozheng KANG[1]

[1] Applied Mechanics and Structure Safety Key Laboratory of Sichuan Province, School of Mechanics and Aerospace Engineering, Southwest Jiaotong University, Chengdu, 610031, China
[2] School of Materials Science and Engineering, Southwest Jiaotong University, Chengdu, 610031, China

* Corresponding author: zhangjuan@swjtu.edu.cn

ABSTRACT:
Medium manganese steel is a representative of third-generation advanced high-strength steel, which has wide application foreground due to its enhanced strength and plasticity. Transformation induced plasticity (TRIP) effect is the main reason for excellent mechanical properties of medium manganese steel. Due to TRIP effect, the deformation behavior and microstructure evolution of medium manganese steel are more complicated than other steels during cyclic loading. Therefore, the present work focuses on the cyclic plasticity of the typical medium manganese steel containing Al content, especially on the phase transformation and ratchetting behavior under asymmetrical cyclic stressing. Fristly, the macroscopic mechanical experiments and microstructural characterizations were systematically developed at room temperature. Furthermore, a phase field-finite element simulation was performed to investigate the microscopic mechanism of the transformation-induced plasticity in response to ratchetting. Through those researches, the cyclic plasticity features of medium manganese TRIP steel and the evolution laws of microstructures, especially the influence mechanism of phase transformation on rarchetting behavior, were revealed. And then, a cyclic constitutive model considering the properties and evolution of each phase was established by mean-field homogenization method, which was proved can reasonably describe and predict the ratchetting of medium manganese steel.

KEYWORDS:
Medium manganese steel; Ratchetting; TRIP; Phase-field; Homogenization

R2-301

Different Axial/Shear Stress Ratios under Tension/Torsion UFT

Luís REIS[1,2,*], Henrique LOPES[2], Francisco PACA[2], Pedro R. da COSTA[1,3], Manuel FREITAS[1,3]

[1] IDMEC, Department of Mechanical Engineering, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais, 1, 1050-099 Lisboa, PORTUGAL
[2] Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais, 1, 1050-099 Lisboa, PORTUGAL
[3] Atlântica, Escola Universitária, Fabrica de Pólvora de Barcarena, 2730-036 Barcarena, PORTUGAL

* Corresponding author: luis.g.reis@tecnico.ulisboa.pt

ABSTRACT:

The necessity for an energy- and time-efficient approach led to the development of ultrasonic fatigue testing (UFT) methodology. In this study, several specimen designs are applied to a state-of-the-art ultrasonic fatigue testing apparatus that can produce a combination of multiaxial and tension/torsion stress states. The higher stress amplitude in the major throat is guaranteed by the new specimens, ensuring that just the region of interest will be studied. All tested designs were subjected to a thorough displacement and stress analysis using both multiaxial and uniaxial horns. Due to rotation's sensitivity to resonant frequencies at closer frequencies, the research revealed shear variability. Lower rotational variability between specimen geometries can be achieved by making both multiaxial horn and specimen simplicity improvements. Three different shear/axial stress ratios were used in the experiments, and the results of tension/torsion fatigue tests performed on ultrasonic fatigue testing machines are presented. These results demonstrate that it is possible to conduct reliable fatigue tests under the Very High Cycle Fatigue regime and under tension/torsion loading for different shear/axial stress ratios.

KEYWORDS:

Ultrasonic fatigue Testing; Biaxial fatigue; VHCF.

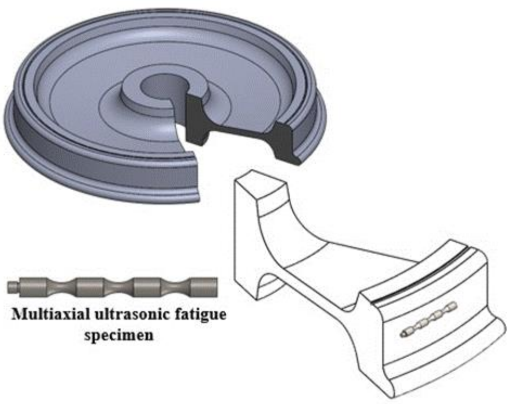


Fig. 1 *UFT specimen.*

R2-302

Effects of microstructure refinement and metallic adhesion on the sub-surface fatigue crack propagation process in Ti6Al4V alloy

Hiroyuki OGUMA[1, *], Fumiyoshi YOSHINAKA[1], Nao FUJIMURA[2], Takuya YAMAZAKI[2] and Takashi NAKAMURA[2]

[1] National Institute for Materials Science, JAPAN
[2] Hokkaido University, JAPAN

* Corresponding author: OGUMA.Hiroyuki@nims.go.jp

ABSTRACT:

Very high cycle fatigue (VHCF) has become an issue of growing concern for mechanical engineers due to the increased use of high-strength metallic materials. The origin of fatigue fracture is usually at the surface in regions under high stress and with lower fatigue life, whereas in regions with low stress and longer fatigue life, the origin is generally subsurface. The region of initial crack propagation, including the fracture origin on the fracture surface in the case of subsurface fractures, has received considerable attention as more than 90% of fatigue life has passed when crack initiation occurs. Furthermore, this region is strongly related to non-propagating cracks and the fatigue limit of subsurface fractures. Observation of fracture surfaces has revealed the formation of a unique fine concave-convex asperity, smaller than grains, on the fracture surfaces in subsurface fractures. Based on microstructure refinement and metallic adhesion, a new model for the formation mechanism of the fine asperity has been proposed for Ti6Al4V alloy. The relation between these phenomena and very high cycle properties will be discussed, with a particular focus on crack closure in the initial fatigue crack propagation.

KEYWORDS:

Subsurface fracture; Microstructure refinement; Metallic adhesion; VHCF; Ti6Al4V

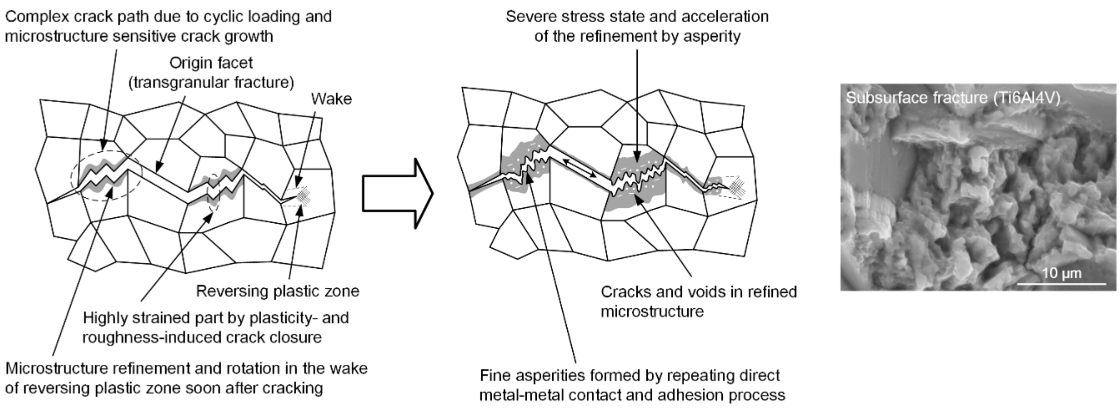


Fig. 1 Formation mechanism of the fine asperity in the initial crack propagation of subsurface fracture.

R2-303

20 kHz cantilever fatigue testing of high strength precision strip steels in different load conditions

Mohamed SADEK[1],* Katerina CHANTZIARA[1], and Jens BERGSTRÖM[1]

[1] Karlstad University, SWEDEN

* Corresponding author: mohamed.sadek@kau.se

ABSTRACT:
High strength strip steels are used in demanding applications with the requirement long fatigue lifes (>10^7 cycles). For that, fatigue testing for long lifes is required which is conveniently achieved by high frequency testing. However, high frequency bending fatigue of thin strip steels is a difficult task and not commonly performed. In the present study, further development of an existing cantilever bending fatigue test setup using an ultrasonic 20 kHz fatigue testing system (Figure 1) was conducted. With regard to design in technical strip applications, an investigation of the effects of a notch (a hole in the middle part of the specimen), varied load ratio (by manipulating the boundary conditions) and specimen thickness was carried out. The new setups were simulated using FEM to compute the stress/strain distribution in the specimen. The FEM analysis was confirmed by experimental measurements of the displacement distribution along the length of the specimen. Fatigue test series were run to determine the VHCF bending fatigue strength of a high strength precision strip steel grade in the different load conditions. Mechanical analysis of failure criteria and evaluation of failure mechanisms using scanning electron microscopy were accomplished in consideration of the different load conditions.

KEYWORDS:
VHCF; Strip steels; cantilever; Fatigue strength

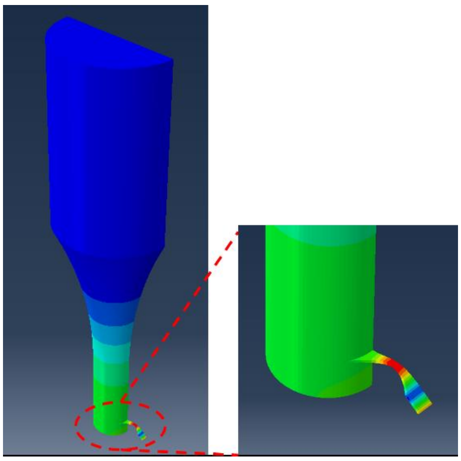


Fig. 1 *FEM modal analysis of ½ symmetry of the existing setup with the ultrasonic horn and the cantilever specimen.*

R2-304

Fatigue assessment in the HCF and VHCF regimes of PM-HIPed Inconel 625

Faezeh Javadzadeh Kalahroudi[1,*], Mohamed Sadek[1], Jens Bergström[1], Tomas Berglund[2], Mikael Grehk[1]

[1] Karlstad University, Sweden
[2] MTC Powder Solutions AB., Sweden

* Corresponding author: faezeh.javadzadehkalahroudi@kau.se

ABSTRACT:

In this study, Inconel 625 has been manufactured by hot isostatic pressing technique, which is one of the advanced near net-shape manufacturing methods. This technique has gained attention for its ability to produce complex components while eliminating the need for costly forging and machining operations, all while maintaining high-performance standards. Understanding the very high cycle fatigue behavior of these HIPed samples is an important step towards their qualification processes. In order to achieve this goal, uniaxial fatigue tests were conducted using ultrasonic test equipment operating at 20 kHz with stress ratios of 0.1 and -1. The fatigue strengths were obtained using the staircase method and S-N curves were plotted in the fatigue life range of 10^6-10^9 cycles (Fig. 1). Detailed fractography of the failed samples revealed that crystallographic features like transgranular facets and triple junctions were the dominant failure initiation mechanisms at R=-1. On the other hand, the majority of failures at R=0.1 initiated at Mo-Nb rich carbonitrides and transgranular crystallographic facets. A comprehensive analysis including the fracture surface features, crack initiation mechanisms, associated microstructural properties, and crack growth was carried out.

KEYWORDS:

Inconel 625; hot isostatic pressing; very high cycle fatigue; fractography.

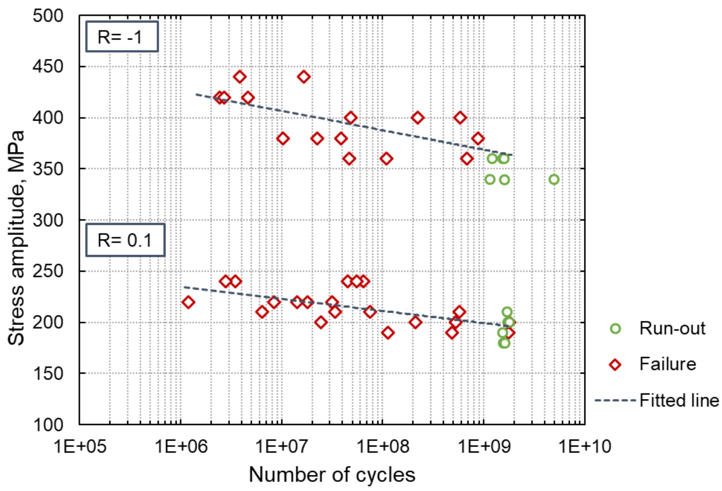


Fig. 1 *S-N curves at stress ratios of -1 and 0.1 indicating different crack initiation points in PM-HIPed Inconel 625 samples.*

R2-305

High and very high cycle fatigue properties of pearlitic rail steel R350HT

Bernd M. SCHÖNBAUER[1,*], Mahjoubeh SISTANINIA[2], Jürgen MAIERHOFER[2], Hans-Peter GÄNSER[3], Reinhard PIPPAN[3] and Herwig MAYER[1]

[1] University of Natural Resources and Life Sciences (BOKU), Vienna, AUSTRIA
[2] Materials Center Leoben Forschung GmbH (MCL), Leoben, AUSTRIA
[3] The Erich Schmid Institute of Materials Science (ESI), Leoben, AUSTRIA

* Corresponding author: bernd.schoenbauer@boku.ac.at

ABSTRACT:

Conventional servo-hydraulic as well as ultrasonic fatigue tests were performed to study the high and very high cycle fatigue (HCF/VHCF) properties of pearlitic steel R350HT, which is standard material for rails. Tests were performed up to more than 10^{10} cycles at different load ratios. At fully reversed loading, i.e. at $R = -1$, crack initiation occurred solely at the surface in the HCF regime (below 10^7 cycles). At $R = 0.1$, in contrast, failure was also observed from the interior in the VHCF regime between 10^6 and 10^9 cycles. The origin of fracture in the interior was identified as ferritic phases where fatigue cracks can more easily initiate than in the harder pearlitic microstructure. Compared with servo-hydraulic test results, that were obtained at cycling frequencies between 15 and 60 Hz, slightly higher fatigue strengths were found when tests were performed with the ultrasonic fatigue testing equipment at approx. 19 kHz. This might be explained by the strain-rate sensitivity of ferrite where fatigue cracks preferentially initiate. Furthermore, tests with specimens containing artificially introduced micro-holes were conducted to systematically study material's defect sensitivity as well as the effects of cycling frequency and mean load.

KEYWORDS:

Very high cycle fatigue; mean-stress sensitivity; paralic steel R350HT; defect tolerance; fracture mechanics

R2-306

Crack Initiation and Propagation of Cruciform Specimens in Ultrasonic Fatigue Testing

Pedro COSTA[1], Diogo MONTALVÃO[2], Luis REIS[3] and Manuel FREITAS[1,3]*

[1] Atlântica, Instituto Universitário, Barcarena, PORTUGAL
[2] Faculty of Science and Technology, Bournemouth University, UNITED KINGDOM
[3] IDMEC, Instituto Superior Técnico, Lisboa, PORTUGAL

* Corresponding author: manuel.freitas@tecnico.ulisboa.pt

ABSTRACT:
The need for more efficient, complex and safe component/system design drives the need for extensive and comprehensive fatigue research, as it remains one of the main concerns regarding mechanical failures in a wide range of industries. As such, it is essential to carry out experimental studies that cover different stress states, from uniaxial to multiaxial or service lives from low to high cycle fatigue and more recently to very number of cycles. With respect to longer service lives, the development of ultrasonic fatigue testing machines has enabled research studies for very high cycle fatigue (VHCF) tests to be performed within a reasonable time interval since ultrasonic fatigue tests (UFT) are carried out at 20 kHz. However, new challenges arise for UFT such as adequate specimen design and test conditions. An interesting solution to the design of a cruciform specimen has been previously studied by the authors where an in-plane axial-axial (biaxial) stress state is applied to a special designed cruciform specimen. The specimens were designed to have a desired resonance mode within the working frequency range of the ultrasonic fatigue test machine, Figure 1.
The scope of the present work is to explore the fatigue crack behavior of cruciform specimens subjected to a biaxial stress state, tension/tension or tension/compression, in an ultrasonic fatigue testing machine within the VHCF regime (10E6 to 10E9 cycles). The fatigue tests were carried out on cruciform specimens manufactured from Aluminum alloy 6082-T651 and crack initiation angles and fracture surfaces were analyzed.

KEYWORDS:
Multiaxial fatigue; Cruciform Specimens; Ultrasonic Fatigue Testing; Crack Paths

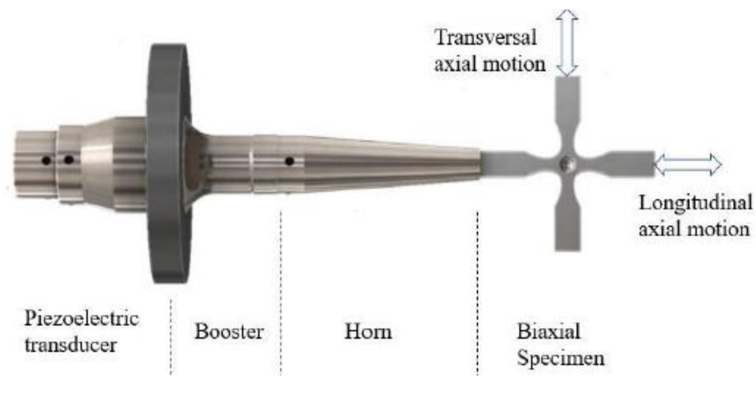


Fig. 1 *Ultrasonic fatigue testing assembly with cruciform specimen.*

R2-307

Effect of Mean Torsional Stress on Torsional Fatigue Strength in the Very High Cycle Regime for Spring and Bearing Steels

Yoshinobu SHIMAMURA[1,*], Yusuke HAYASHI[2], Masao KINEFUCHI[2], Ryota TANEGASHIMA[3], Kazuya SUGITANI[2], Yusuke SANDAIJI[2], Tomoyuki FUJII[1], Shoichi KIKUCHI[1] and Keiichiro TOHGO[1]

[1] Shizuoka University, JAPAN
[2] Kobe Steel, Ltd., JAPAN
[3] Kobelco Research Institute, Inc., JAPAN

* Corresponding author: shimamura.yoshinobu@shizuoka.ac.jp

ABSTRACT:
Mean torsional stress is considered to less affect torsional fatigue strength of steels, but several experimental results have been recently reported that mean torsional stress caused significant reduction in torsional fatigue strength in the very high cycle region for shot-peened spring steel. To investigate the effect of mean torsional stress on the very high cycle fatigue strengths of spring and bearing steels, ultrasonic torsional fatigue tests were conducted. Torsional fatigue strength up to 10^9 cycles were obtained for fully reversed torsional loading to pulsating torsional loading. The results revealed that mean torsional stress caused reduction in very high cycle fatigue strengths of spring and bearing steels, and applying higher mean shear stress would result in transition of the fracture origin from surface to an internal inclusion. The reduction in very high cycle torsional fatigue strength was discussed from the viewpoint of the transition of fatigue origin, and applicability of a $\sqrt{area}$ parameter model was discussed for predicting the reduction in the very high cycle torsional fatigue strength.

KEYWORDS: High strength steel, Torsional fatigue, Mean torsional stress, Very high cycle fatigue, Ultrasonic fatigue test

R2-308

Study and modeling of Fatigue Properties at Very Large Cycles from Self-heating Tests under Cyclic Loads

Théo SEVEDE[1*], Younes DEMMOUCHE[1], Shabnam ARBAB CHIRANI[2], and Sylvain CALLOCH[1]

[1] IRDL – UMR CNRS 6027 – ENSTA Bretagne, FRANCE
[2] IRDL – UMR CNRS 6027 – Ecole Nationale d'Ingénieurs de Brest, FRANCE
* Corresponding author: theo.sevede@ensta-bretagne.org

ABSTRACT:
For several years, research teams have been interested in characterizing HCF properties from self-heating tests. This method reduces the time and cost of characterizing the fatigue properties of materials. It is based on temperature monitoring of the specimen during cyclic loading.
This method has been widely studied and validated at room temperature and at low frequency on many materials. However, the application of this method to high frequency tests requires the development of a new approach. Indeed, the conditions of the high frequency test at the geometrical, thermal, and mechanical level makes the classical 0D approach impossible and forces to use a 1D approach.
An experimental protocol was therefore set up to perform self-heating tests on a high frequency VHCF machine as well as a numerical model of the test to try different virtual test configurations. The objective of the study is to adapt the self-heating method for high frequency solicitations to determine the VHCF properties of different metals, to be able to relate these measurements to failure mechanisms and to know how the high frequency thermal signature can help us to better understand and model the VHCF properties of metals.

KEYWORDS:
VHCF; Self-Heating; Thermal Measurement; Metals

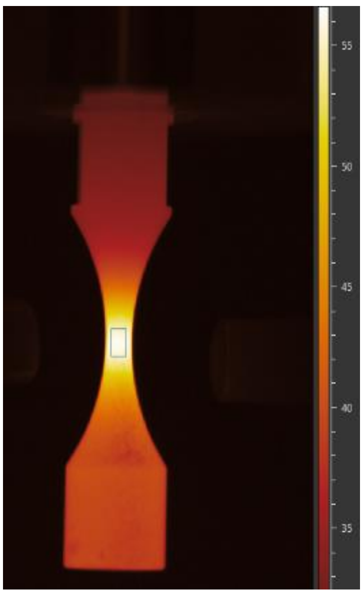


Fig. 1 *Thermographic image of a specimen during a VHCF Self-Heating test*

R2-309

A naturally initiated internal fatigue crack growth process in beta titanium alloy using in situ synchrotron radiation multiscale computed tomography

Gaoge Xue[1,*], Nao Fujimura[2], Takashi Nakamura[2], Kosuke Takahashi[2], Hiroyuki Oguma[3], Akihisa Takeuchi[4], Masayuki Uesugi[4], and Kentaro Uesugi[4]

[1]Division of Mechanical and Space Engineering, Hokkaido University, JAPAN

[2]Division of Mechanical and Aerospace Engineering, Hokkaido University, JAPAN

[3]Research Center for Structural Materials, National Institute for Materials Science, JAPAN

[4]Japan Synchrotron Radiation Research Institute, SPring-8, JAPAN

*Corresponding author: setsu.gaogexue@gmail.com

ABSTRACT:

This study nondestructively monitored the full-life growth behavior of a naturally initiated internal fatigue crack in a beta titanium alloy Ti-22V-4Al using in situ synchrotron radiation multiscale computed tomography, which is a combination of microtomography and nanotomography (Fig. 1). After the fracture, the crack fronts at various cycles were superimposed on the fracture surface. The crack propagated at 45 degrees and perpendicular to the loading direction, corresponding to fracture surface features of multiple facets and smooth area, respectively. The crack propagation related to multiple facets represented 95% of the crack propagation life, which was dominant in the internal crack propagation in the beta titanium alloy. Moreover, the factor that triggered crack growth associated with facets to the surrounding matrix was examined based on the crack opening and blunting behavior. In addition, the internal crack propagation rate of Ti-22V-4Al was slower than that of the surface crack and was analyzed with respect to crack growth stages.

KEYWORDS:

Non-destructive inspection; internal fatigue crack; crack propagation rate; beta titanium; fractography

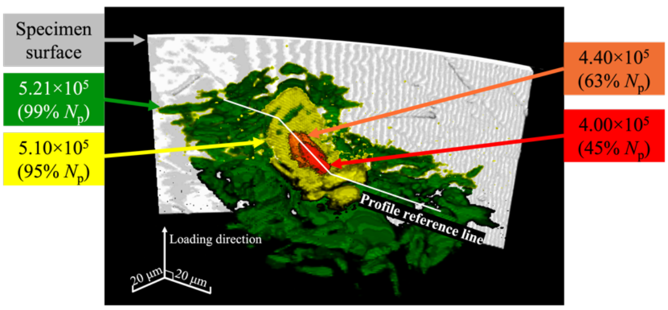


Fig. 1 Crack fronts obtained by synchrotron radiation multiscale computed tomography

R2-310

Physics-informed neural networks for very high cycle fatigue

Jia-Le Fan, Gang Zhu, Ming-Liang Zhu*, Fu-Zhen Xuan*

Key Laboratory of Pressure Systems and Safety, Ministry of Education, School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, CHINA

*Corresponding author: mlzhu@ecust.edu.cn; fzxuan@ecust.edu.cn

ABSTRACT:

In this work, by taking stress level, defect size and location into account, the physical *Z*-parameter fatigue life prediction model was combined with artificial neural network. The fatigue life data were expanded based on the *Z*-parameter, and the physics-informed loss function was integrated into artificial neural network as constraint. A new data-physics integrated approach, based on physics-informed neural network modeling, was established and verified for prediction of fatigue life of 15Cr and FV520B-I steels. It is shown that the new approach was able to predict fatigue life up to the very high cycle fatigue regime, and had better performance than the traditional physical *Z*-parameter model, and even the Murakami model.

KEYWORDS:

Very high cycle fatigue; Fatigue life prediction; Physics-informed neural networks; Micro-defect; *Z*-parameter

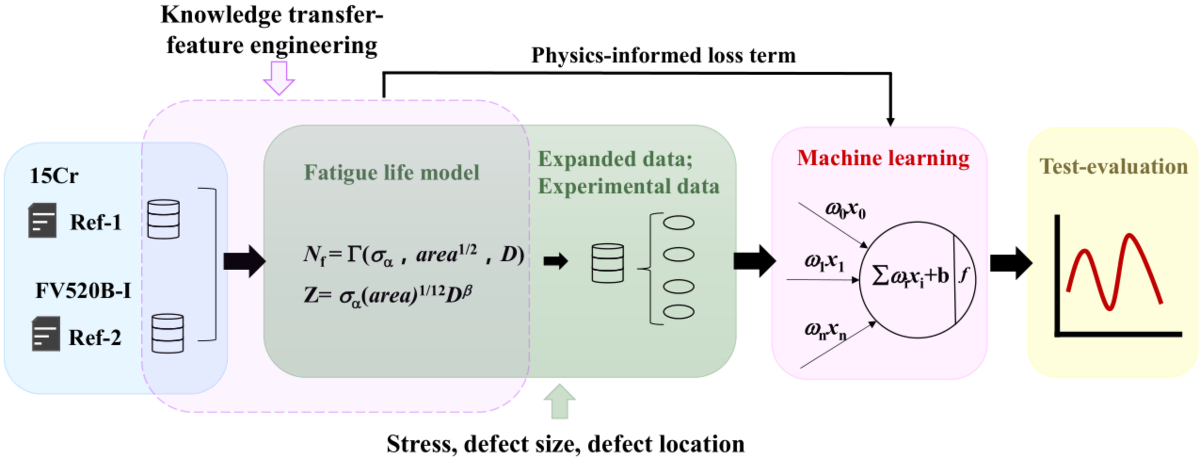


Fig. 1 Schematic diagram for predicting fatigue life of engineering structures by combining physical information with artificial neural network

R2-311

Interior microstructure induced cracking of a NiCr20TiAl alloy at elevated temperature

Gang Zhu, Ming-Liang Zhu* and Fu-Zhen Xuan*

Key Laboratory of Pressure Systems and Safety, Ministry of Education; School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, CHINA

*Corresponding author: mlzhu@ecust.edu.cn; fzxuan@ecust.edu.cn

ABSTRACT:

Axially loaded cyclic tests of a NiCr20TiAl Nickel based alloy at different elevated temperatures and stress ratios were conducted up to high cycle fatigue regime. In-depth fracture surface observation and quantitative characterization of microstructural damage were carried out to illustrate the physics and mechanics of interior microstructure induced cracking. Results showed obvious effects of elevated temperature and mean stress on fatigue strength and crack initiation morphology. The fatigue strength depended on low- angle grain boundary content in the current range of temperature and loading modes. The formation of facet in crack initiation zone was confirmed as a result of dislocation slip and short crack growth with significant contribution from cyclic shear stress. A new mechanistic model of interior microstructure induced cracking was finally established where the high cycle fatigue damage of Nickel based alloy was believed as a process of crack nucleation and short crack growth. All these are promising for material development and design against fatigue of engineering structures for long life.

KEYWORDS:
Nickel based alloy; Elevated temperature; Mean stress; Fatigue strength; Facet

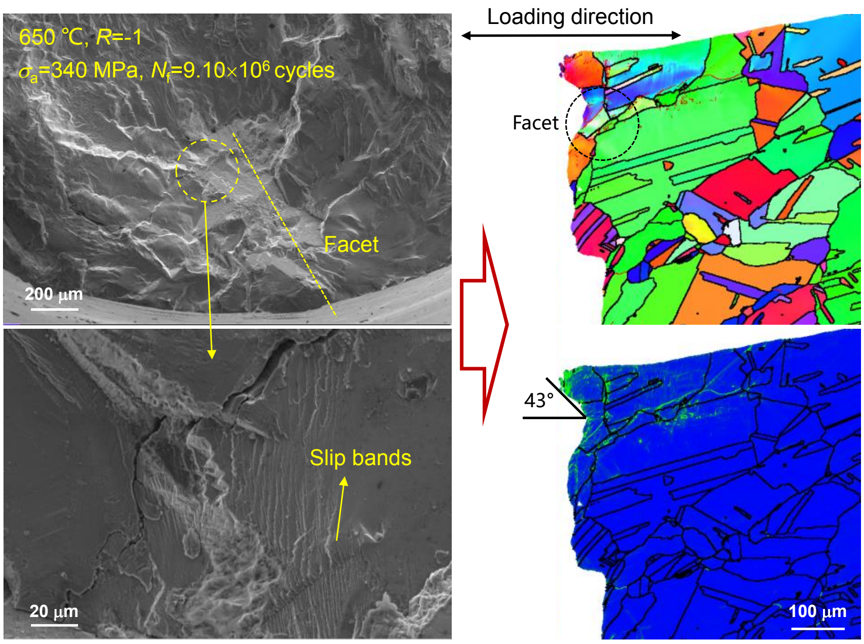


Fig. 1 Microstructural morphologies of facet in crack initiation zone

R2-312

A VHCF Life Prediction Method Based on Surface Crack Density for FRP

Tao Wu[1]*, Weixing Yao[2], Chao Xu[1]

[1] Key Laboratory of Fundamental Science for National Defense-Advanced Design Technology of Flight Vehicle, Nanjing University of Aeronautics and Astronautics, Nanjing 210016,China
[2] State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

* Corresponding author: Taowu017@nuaa.edu.cn

ABSTRACT:

In order to solve the difficulty of fiber reinforced plastic (FRP) very high cycle fatigue (VHCF) life prediction, a very high cycle fatigue life prediction method based on surface crack density is presented in this paper. According to the general rule of FRP fatigue damage evolution, the crack density is used to characterize the damage state of FRP and the matrix crack density-life evolution model is established in this method. And the very high cycle fatigue life can be predicted when the parameters of the evolution model under different load levels are obtained through fatigue test. Also the threshold value of FRP fatigue is assumed to exist. If the working strain level is lower than this strain threshold value, there will be no new damage after the matrix crack density reaches the characteristic damage state (CDS). Therefore, FRP under these kinds of loads has an infinite life. In this paper, the very high cycle fatigue test of single-layer orthotropic woven CFRP has been completed. The matrix crack density-life curve and the strain threshold value of fatigue have been obtained, which proves the rationality of this method.

KEYWORDS:

Composite, Very high cycle fatigue, Characteristic damage state, Fatigue life prediction

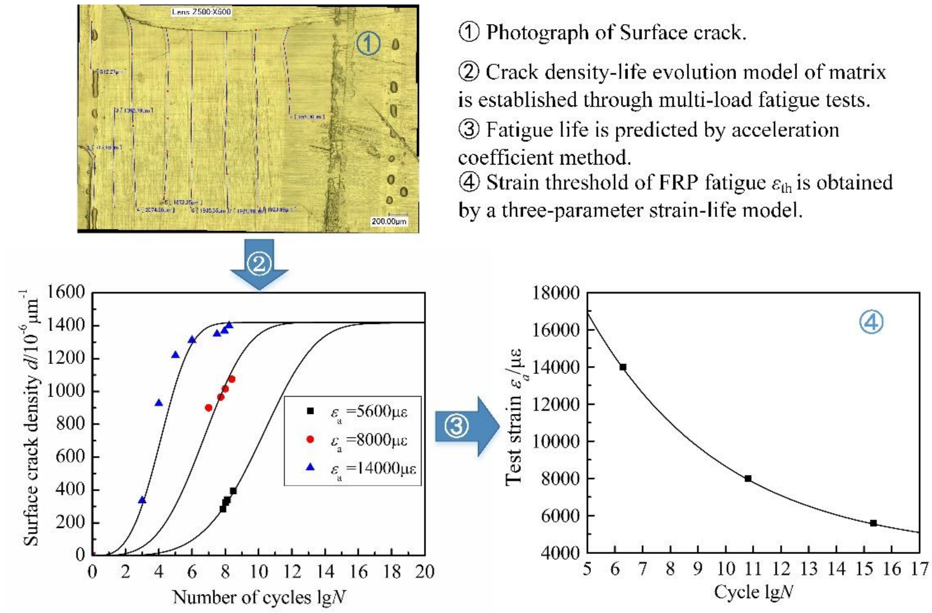


Fig. 1 *The VHCF Life Prediction procedure Based on Surface Crack Density for FRP.*

D1-501

Anisotropic thermomechanical fatigue assessment of nickel-base single crystal alloys

Huang YUAN[1,2,*], Luo CHENG[1] and Jiawei XU[2]

[1] Tsinghua University, School of Aerospace Engineering, Beijing, CHINA
[2] Tsinghua University, Institute for Aero Engine, Beijing, CHINA

* Corresponding author: yuan.huang@tsinghua.edu.cn

ABSTRACT:

In the present work, tubular specimens were experimentally and computationally investigated under different temperature-gradient mechanical fatigue (TGMF) loading conditions. The inverse heat conduction (IHCP) method was improved to predict the inner boundary from external measurements to quantify thermomechanical loads with significant temperature gradients. TMF behavior and life of a second-generation single crystal alloys were investigated. IP and OP TMF tests were conducted along three distinct crystal orientations under strain control and a temperature range of 400-980°C. The fatigue lives were reduced by 70-90% under the same mechanical strain range when compared with isothermal LCF. The OP-TMF was found to be more detrimental than IP-TMF in the investigated crystal orientation. For the investigated strain ranges, the [001] specimens cycled in the elastic regime while the [011] and [111] specimens presented plastic deformation under higher strain ranges. The material presented cyclic stability in TMF tests in specimens of all crystal orientations. A modified model considers temperature gradient effects and thermal-mechanical phase angle and can describe the TGMF lifetime of the single-crystal superalloy reasonably.

KEYWORDS:

Temperature-gradient mechanical fatigue (TGMF), temperature gradients, thermal-mechanical fatigue, single crystal superalloy, fatigue life model

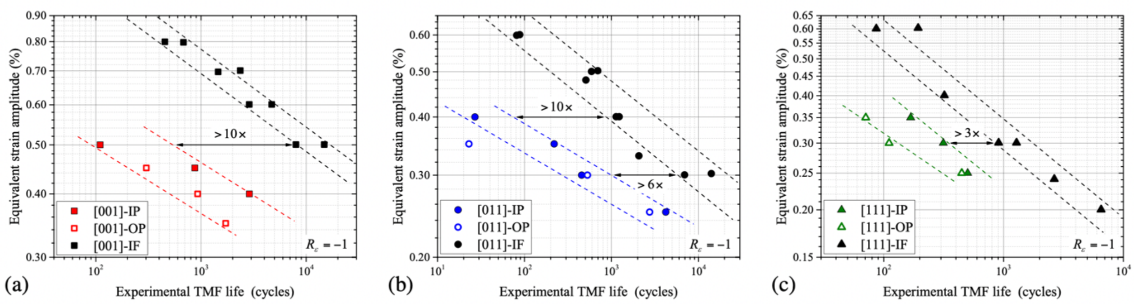


Fig. 1 – Comparison between TMF life and IF life with crystal orientations (a) [001], (b) [011] and (c) [111].

D1-502

Role of temperature gradient in thermo-mechanical fatigue analyzed through micro-cracks growth

Vincent Maurel[1], Nicolas Leost[1,2], Djamel Missoum-Benziane[1]

[1] MINES Paris, PSL Research University, MAT - Centre des Matériaux, CNRS UMR 7633, BP 87 91003 Evry, France
[2] Safran Aircraft Engines Villaroche, Rond-Point René Ravaud, 77550 Moissy-Cramayel, France
* Corresponding author: vincent.maurel@minesparis.psl.eu

ABSTRACT:

Many authors have studied crack initiation under thermo-mechanical fatigue (TMF) loading. Due to significant improvements in both experimental field acquisition and finite element analysis of crack behaviour, we propose here to focus on short crack analysis under TMF loading. This study combines infrared thermography, digital image correlation (DIC) and machine learning techniques to investigate TMF behaviour and damage evolution under severe temperature gradients. Out-of-phase loading conditions are investigated, particularly in thin sheets where high temperature compression can induce buckling. Using a Co-based superalloy (Haynes 188) as a case study, full field identification and validation of behaviour and damage models are achieved. Different thermal gradients are investigated to evaluate their potential on fatigue crack growth rate (FCGR). The combination of machine learning and DIC allows the assessment of FCGR by analysing micro-crack displacement jumps. FEA validates the overall model framework for TMF loading and damage within fatigue loading inducing large scale yielding. This research extends the analysis to include long crack growth and investigates the role of crack closure. This integrated approach improves fatigue life predictions and has implications for optimising material design and durability under TMF conditions.

KEYWORDS:

TMF, micro-crack, gradients, conform remeshing, large scale yielding

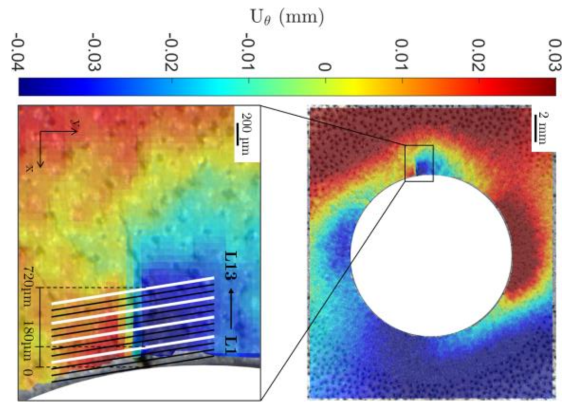


Fig. 1 *micro-crack analysis (left) and global displacement field (right) – 300-900 °C OP-TMF testing (from Leost et al, International Journal of Fatigue (2023): 107513).*

D1-503

Crack Growth Behavior of 316LN Stainless Steel under Thermomechanical and Isothermal Fatigue Loading

Yiming Zheng[1], Bingbing Li[1], and Xu Chen[1 2] *

[1] TianUniversity, China
[2] Zhejiang Institute of Tianjin University, China
* Corresponding author: xchen@tju.edu.cn

ABSTRACT:
The problem of thermomechanical fatigue crack propagation is becoming a research focus for nuclear power safety. In this study, the crack growth tests of 316LN under force control and strain control were carried out. The differences of crack propagation behavior under different phases (in-phase tests, out-phase test and isothermal test) and loading conditions (strain control and stress control) are compared. It can be seen from the results that a significant difference exists between the crack growth rate under stress control and strain control tests. In addition, the crack growth rates under isothermal fatigue and in-phase conditions are similar in stress control tests, which are slightly higher than those under out-of-phase (OP) condition. In the tests of strain control, the crack growth rate of TMF is higher than that under IF condition and the crack growth rate of OP is higher than that of IP. At the same time, a DIC method which can be used to monitor the crack length and calculate the strain field at the crack tip is proposed.

KEYWORDS:
Crack growth;TMF;316LN;DIC.

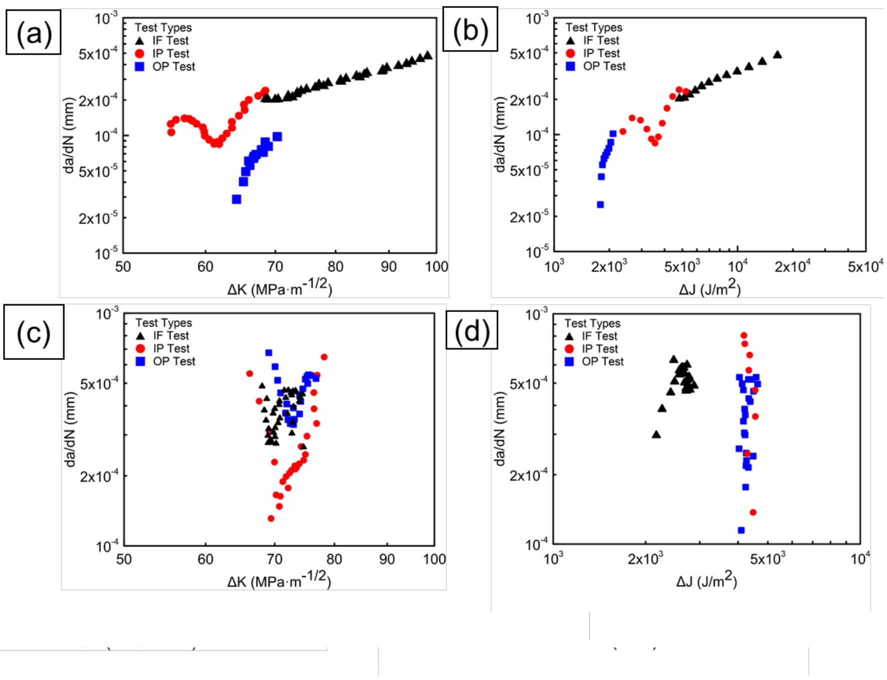


Fig. 1 *Crack growth rate under different loading conditions.*

D1-504

Material characterization of pearlitic railway steels exposed to simultaneous thermal and mechanical cycling

Erika STEYN[1,*] and Johan AHLSTRÖM[1]

[1] Chalmers University of Technology, SWEDEN

* Corresponding author: erika.steyn@chalmers.se

ABSTRACT:

Railway steels can be exposed to high temperatures during operation and maintenance activities, such as severe block braking, rail grinding or repair welding. This can result in microstructural changes, and the subsequent deterioration of the mechanical properties, fatigue properties and component life. In pearlitic railway steel, two types of microstructural changes can significantly affect the material behavior: pearlitic spheroidization (at ca 500-700 °C) and austenitic transformation (above ca 700 °C). In this study the material behavior has been investigated during thermo-mechanical loading, where the peak temperature and the degree of thermal dilatation restriction has been varied. The stress induced during this cycling for a peak temperature of 650 °C is shown in Figure 1. Our study aims at understanding the effect of material transformations during thermo-mechanical loading on the mechanical behavior when compared to the behavior during isothermal cycling.

KEYWORDS:

Railway, pearlite, spheroidisation, austenite, thermo-mechanical fatigue.

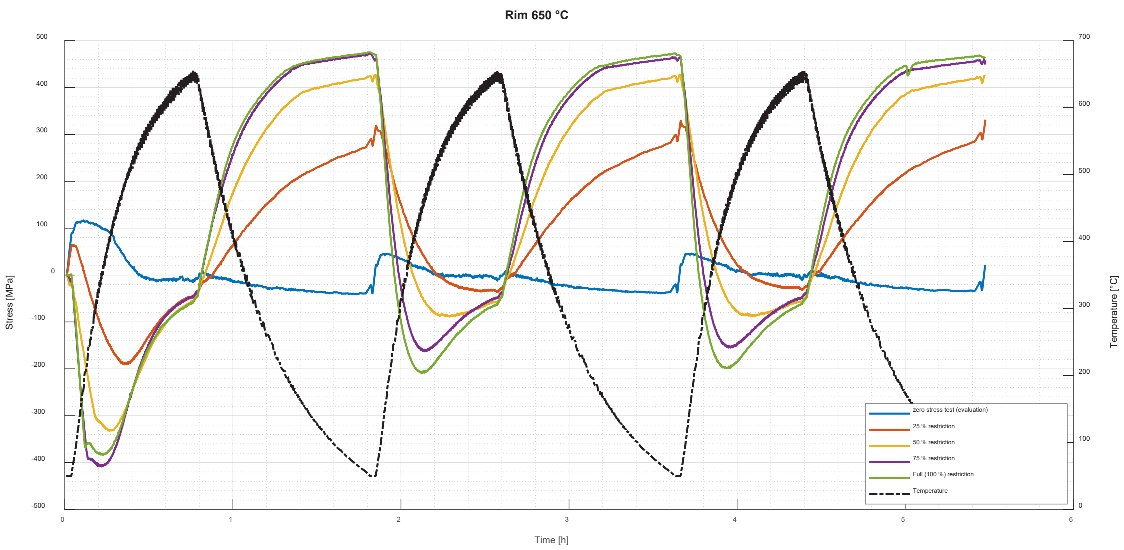


Fig. 1 *Influence of thermal dilatation restriction (in %) on stress during thermal cycling for R7T railway wheel rim samples with a peak temperature of 650 °C*

D1-505

Thermomechanical fatigue behavior of 316LN stainless Steel

Bingbing Li, Xu Chen*

School of Chemical Engineering and Technology, Tianjin University, Tianjin, 300350, CHINA

* Corresponding author: xchen@tju.edu.cn

ABSTRACT:
A series of comprehensive and systematic study on the uniaxial/multiaxial high temperature and thermomechanical fatigue properties of the nuclear-grade 316LN stainless steel was carried out based on the self-developed tension-torsional multiaxial thermomechanical fatigue testing system. The change of dominant damage mechanism leads to the difference in the relationship between the isothermal fatigue life at 550℃(IF-550℃) and the thermomechanical fatigue (TMF) life within the temperature range of 350℃– 550℃ in different strain ranges. DSA plays the dominant role in fatigue failure at the relatively high strain amplitudes (>0.4%), correspondingly, the TMF life is about two times of the IF-550℃ life. High temperature oxidation becomes the dominant damage mechanism when the strain amplitude is low (≤0.4%), which results in an approximately equal fatigue life in IF-550℃ and TMF tests. Further, the result of shorter TMF life comparing to the IF-550℃ life is likely to occur when the strain amplitude is small enough (<0.2%).

KEYWORDS:
Thermomechanical fatigue, Dynamic strain aging, Microcrack nucleation, Fatigue life prediction

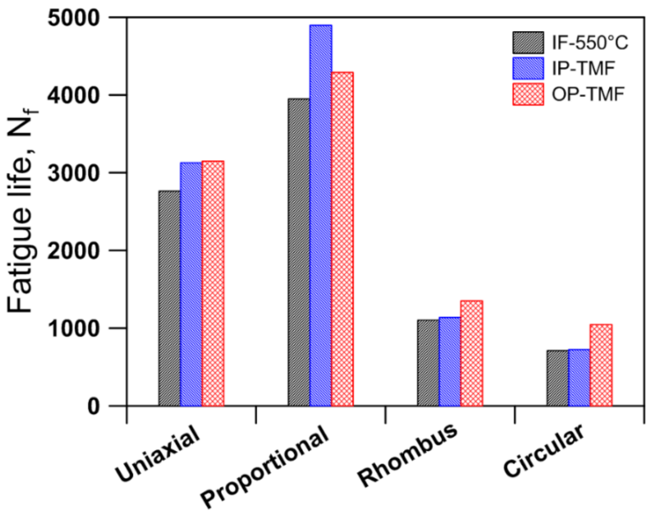


Fig. 1 *Fatigue life under different loading paths at the equivalent strain amplitude of 0.4%.*

D1-507

A CTOD-based fatigue crack growth model under high temperature and dwell time

Mi Wang[1], Yunpeng Gao[1], Yubin Tang[2] and Wei Zhang[1,*]

[1] Beihang University, CHINA
[2] Aerospace Science and Technology Defense Technology Research and Experimental Center, CHINA

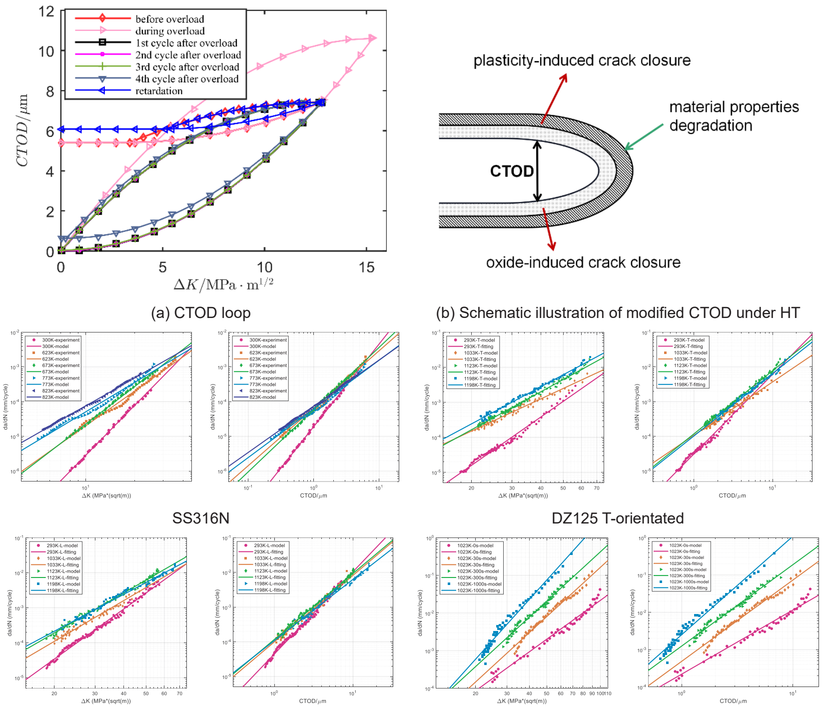
* Corresponding author: zhangwei.dse@buaa.edu.cn

ABSTRACT:

In this study, a fatigue crack growth (FCG) model based on crack tip opening displacement (CTOD) is proposed for high temperature (HT) and dwell time (DT) conditions. Firstly, an in-situ fatigue crack growth experiment under single overload is performed, which demonstrates that CTOD can be a superior driven parameter compared to stress intensity factor (SIF). Subsequently, the CTOD model under HT condition is established considering the degradation of material mechanical properties and oxide-induced crack closure. Then, the HT FCG model driven by CTOD is proposed. Additionally, many studies indicate that creep damage leads to the increased plastic deformation at the crack tip, resulting in a progressive increase in CTOD with prolonged load retention time. Consequently, a CTOD-based model for creep-fatigue crack growth (CFCG) with different DT is developed, incorporating the crack growth rate component solely due to fatigue. Finally, several datasets of various materials are used to validate the proposed model, and the model predictions agree well with the experimental data. Overall, valuable insights are provided for assessing material durability and structural integrity under HT and DT conditions.

KEYWORDS:

High temperature; Dwell time; Crack growth model; Crack tip opening displacement



(a) CTOD loop (b) Schematic illustration of modified CTOD under HT

SS316N DZ125 T-orientated

DZ125 L-orientated ATGP3

(c) Comparison of driven parameter ΔK and CTOD under different HT or DT

Fig. 1 Modeling and main results

D1-508

A comparison of the thermomechanical fatigue behavior of electron-beam-melted and conventional Inconel 718

Stefan GUTH[1,*], Tomáš BABINSKÝ[2], Steffen ANTUSCH[1], Alexander KLEIN[1], Daniel KUNTZ[1], and Ivo ŠULÁK[2]

[1] Karlsruhe Institute of Technology, Institute for Applied Materials, GERMANY
[2] Institute of Physics of Materials, Czech Academy of Sciences, CZECH REPUBLIC

* Corresponding author: stefan.guth@kit.edu

ABSTRACT:

Electron beam melting (EBM) of Ni-base superalloy Inconel 718 allows producing a microstructure with elongate grains and pronounced texture resembling directionally solidified (DS) alloys. Similar to the DS alloys, the EBM microstructure may outperform conventional equiaxed microstructures under high temperature loading. The goal of this study is to evaluate the potential of EBM Inconel 718 for applications with severe creep-fatigue interaction. Therefore, we conducted strain-controlled thermomechanical fatigue (TMF) tests in the temperature range of 300 to 650 °C on both EBM and conventionally forged Inconel 718 specimens. Several cycle forms including dwell times and slow tensile loading ramps were applied to realize varying amounts of creep-fatigue interaction. The EBM specimens show exceptional resistance against creep-fatigue interaction, which is exemplified by the influence of tensile dwell times on the TMF lifetime (Fig. 1). While at lower strain amplitudes dwell times reduce the lifetime moderately, there is even a positive effect at higher strain amplitudes due to lower stresses under dwell time cycling. In terms of strain-life behavior, EBM specimens significantly outperform conventional ones. The behavior is discussed based on microstructural and damage observations. Further, we illustrate optimization potential for the EBM material based on the observed damage mechanisms.

KEYWORDS:

Inconel 718, thermomechanical fatigue, additive manufacturing, creep-fatigue interaction, damage mechanisms

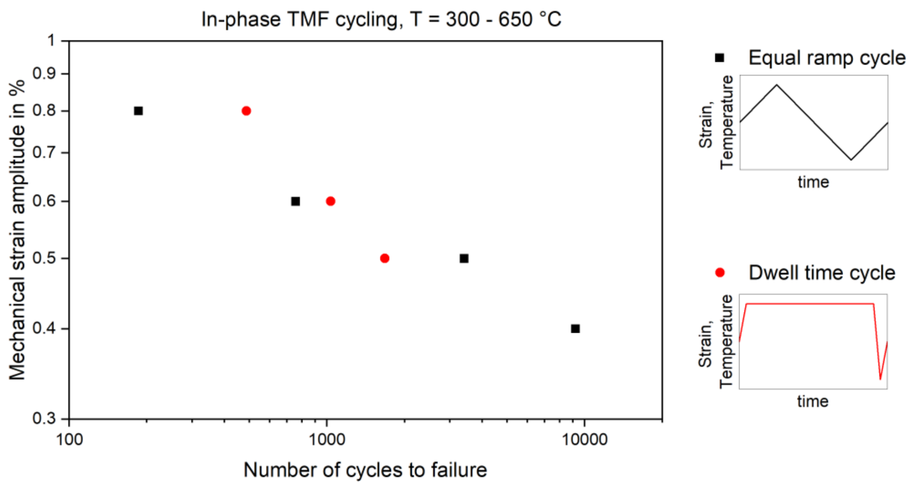


Fig. 1 *Influence of cycle form on TMF-lifetime of EBM-manufactured Inconel 718*

D1-509

Development of a thermal fatigue characterization protocol for metal alloys, adapted to characterize the strength of repaired structures.

Grégoire WISDORFF[1,2], Baris TELMEN[1], Nicolas THURIEAU[1], Fabien SZMYTKA[1,*]

[1] ENSTA Paris, IMSIA UMR 9219, Institut Polytechnique de Paris, 91120 Palaiseau, FRANCE
[2] ONERA, 29 Av. de la Division Leclerc, 92320 Chatillon, FRANCE

* Corresponding author: fabien.szmytka@ensta-paris.fr

ABSTRACT:

Thermal fatigue remains a critical damage mechanism for various structures undergoing high temperature gradients particularly in the energy and aerospace fields. Most of the existing thermal fatigue benches require the use of specific clamping systems and are therefore difficult to transfer from a laboratory: this leads to problems of reproducibility and ease of implementation. A new thermal fatigue test protocol is therefore proposed, based on a conventional tensile test rig, which allows precise and continuous control of the clamping conditions. The development of a specific specimen geometry makes it possible to generate strong thermal gradients using an inductor controlled by a bichromatic pyrometer for heating and forced air flow for cooling to concentrate crack initiation in a dedicated zone, monitored by a camera. The geometry is moreover designed to allow the analysis of specimens that have been damaged and then repaired using additive manufacturing processes.

After validation of this geometry and the complete protocol by numerical modeling, fatigue tests were carried out between 300°C and 700°C on ferritic steels to validate the set-up, while an analysis of the results is finally proposed by observing the cracked zones and their propagation in relation to the measured temperatures.

KEYWORDS:

Thermal Fatigue, Thermal cracks, Experimental set-up

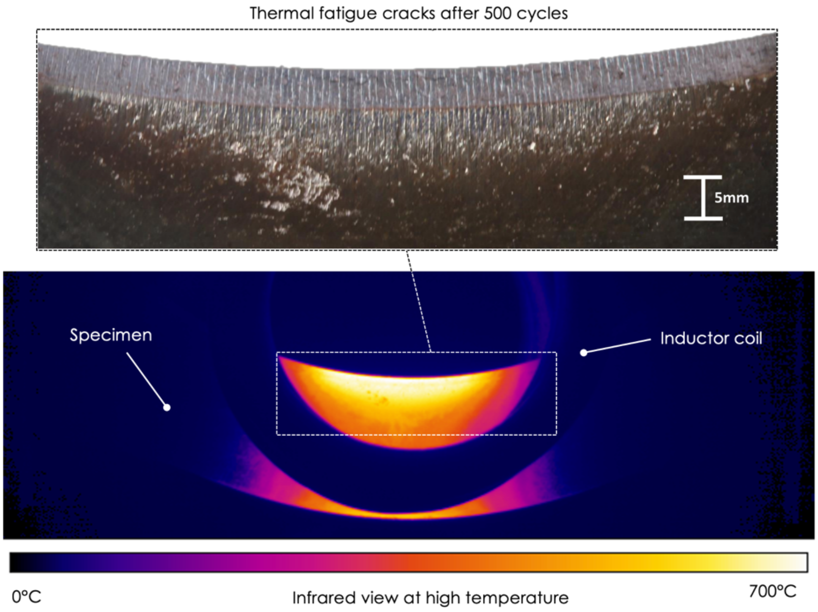


Fig. 1 *Thermal load and resulting cracks observed on the proposed set-up*

D1-510

Cyclic deformation and fracture mechanisms of powder-metallurgy nickel-based superalloy under thermo-mechanical fatigue

Lu ZHANG[1,2,*], Zhiwei YU[1,2], Leicheng ZHANG[1,2], Rong JIANG[1,2], Yingdong SONG[1,2,3]

[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, Nanjing, 210016, PR CHINA

[2] Jiangsu Province Key Laboratory of Aerospace Power System, College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, PR CHINA

[3] State Key Laboratory of Mechanics and Control Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, PR CHINA

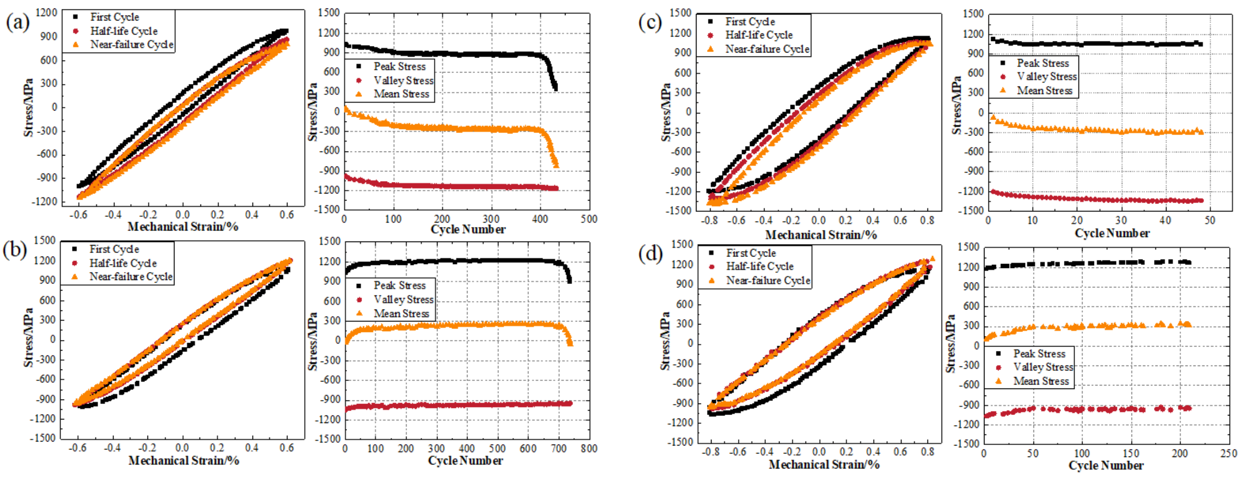
* Corresponding author: Luzhang@nuaa.edu.cn

ABSTRACT:

Thermo-mechanical fatigue (TMF) failure is one of the major concerns for aero-engine turbine discs under complex service loading conditions. By conducting both in-phase (IP) and out-of-phase (OP) TMF tests, the stress-strain hysteresis loops and the cyclic stress responses were analyzed for the third-generation powder-metallurgy (P/M) nickel-based superalloy. To reveal the failure mechanisms, advanced microscopic analysis was carried out to investigate the fracture surface and microstructure of the alloy after complete fracture. The phase angle between the alternating mechanical and thermal loads results in tension-compression asymmetry for the TMF stress-strain responses. According to SEM fractography, the fatigue crack exhibits intergranular growth under IP TMF, while it shows transgranular fracture under OP TMF. By EBSD and TEM characterizations, the geometrically necessary dislocation density is higher for IP TMF, indicting more plastic deformation. The material exhibits cyclic softening behavior during the high-temperature half cycle, while the low-temperature half cycle undergoes cyclic hardening. The cyclic deformation under IP loading conditions is mainly affected by dislocation motions and final failure caused by fatigue and creep damage, while the cyclic deformation under OP is dominated by stacking layer faults and the failure contributed by the combination of fatigue and oxidation damage.

KEYWORDS:

Thermo-mechanical fatigue; powder-metallurgy superalloy; cyclic deformation; fracture mechanisms; microscopic characterization



g. 1 *TMF stress-strain responses: (a) IP 0.6%, (b) OP 0.6%, (c) IP 0.8%, (d) OP 0.8%*

D1-511

Constitutive Modelling of alloys under high temperature low-cycle and thermal- mechanical fatigue: a key issue in component design

Luc REMY[1,*], Fabien SZMYTKA[2] and Pierre OSMOND[3]

[1] Mines Paris, PSL* University, Centre des Matériaux CNRS UMR 7633, Evry, FRANCE
[2] ENSTA Paris Institut Polytechnique de Paris, IMSIA UMR 9219, Palaiseau, FRANCE
[3] Stellantis, Carrières Sous Poissy, now with CETIM, Nantes, FRANCE

* Corresponding author: luc.remy@minesparis.psl.eu

ABSTRACT:

Hot section automotive components are exposed to high temperature operation and thermal transients. Environmental rules required cleaner and lighter engines, which increases the risk of thermal fatigue crack initiation. Part design optimization relies on tests on structures and numerical protocols using energy-based fatigue criteria. However, thermal mechanical fatigue testing has shown that traditional assumptions on constitutive behavior were defaulted in some loading cases.

Physically based models could improve current design process, but cost-effective modelling is mandatory. A better description of deformation mechanisms at work, or microstructure sensitive modelling have been used during the last decade. A compromise is proposed using mean field models with dislocation density taken as internal variable and considering the interaction with precipitate microstructure. Examples are shown on (cast or welded) iron-based and cast aluminum alloys used respectively for exhaust manifolds and cylinder heads. Static recovery or aging during high temperature exposure can be described more easily than in pure phenomenological models. Reduced number of adjustable parameters, combined with dedicated identification procedure results in an increased robustness, required for component design. Substantial achievements are presented and directions for further progress are briefly discussed.

This work was partly supported by Groupe PSA now Stellantis and Aperam over years.

KEYWORDS:

Constitutive modelling; thermal-mechanical fatigue; life prediction; microstructure sensitive models.

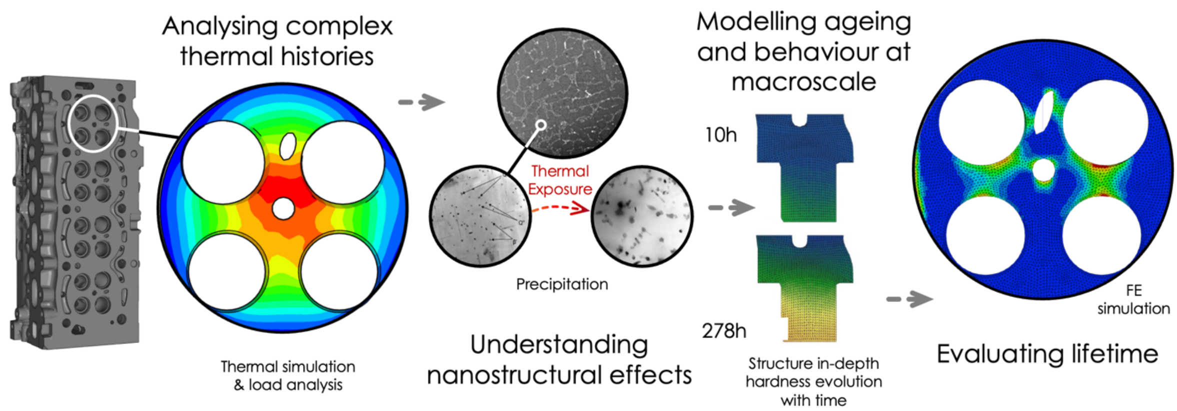


Fig. 1 *Design protocol for cylinder heads including microstructure sensitive models.*

D1-513

Quantitative Evaluation of the Sliding-mode Crack-closure Affecting the Shea-mode Fatigue Crack-growth Threshold in Ni-based Superalloy 718

Yuta TANAKA[1,2,3]*, Masahiro ENDO[1,3] and Hisao Matsunaga[2,4]

[1] Department of Mechanical Engineering, Fukuoka University, JAPAN
[2] Research Center for Hydrogen Industrial Use and Storage (HYDROGENIUS), Kyushu University, JAPAN
[3] Institute of Materials Science and Technology, Fukuoka University, JAPAN
[4] Department of Mechanical Engineering, Kyushu University, JAPAN

* Corresponding author: y.tanaka.vu@fukuoka-u.ac.jp

ABSTRACT:

Ni-based superalloy 718 (Alloy 718) is widely used as the main structural material for rocket engines owing to its excellent characteristics under wide-range temperatures. However, the fatigue limit evaluation method for Alloy 718 has yet to be established because of its peculiar fracture process related to shear-mode fatigue crack-growth. The shear-mode growth threshold, $\Delta K_{\tau th}$, is affected by friction, wear, mechanical locking of surface asperities, *etc.* (*i.e.*, sliding-mode crack-closure), which renders the fatigue limit evaluation for Alloy 718 complex. In this study, three types of fatigue tests (tension-compression, pure-torsion and torsion superposed a static tension) were conducted for the alloys with various microstructures, aiming to quantitate the impact of crack-opening/-closing stresses, which alter the degree of the sliding-mode crack-closure. The results indicated that $\Delta K_{\tau th}$ has a monolithic crack-size dependency, irrespective of loading conditions, heat-treatment conditions and/or microstructural morphologies (*cf.* Fig. 1). Based on these experimental findings, a shear-mode threshold-based criterion is proposed for the comprehensive fatigue limit evaluation.

KEYWORDS:

Ni-based superalloy; Shea-mode fatigue cracks; Fatigue thresholds; Sliding-mode crack closure

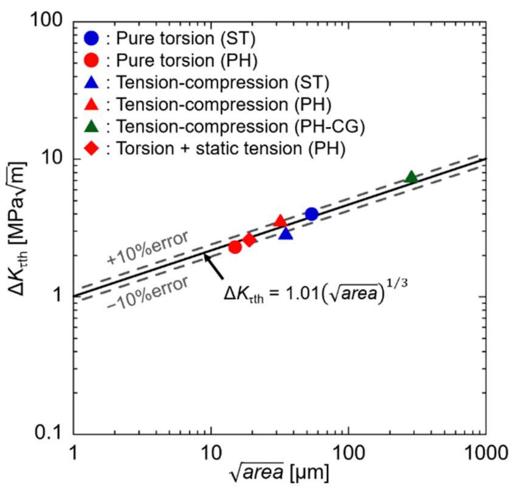


Fig. 1 $\Delta K_{\tau th}$ of Alloy 718 as a function of square-root of area of non-propagating crack under various loading conditions. The black solid line is defined using the least-squares fitting for all experimental plot-points.

D1-514

Fatigue crack propagation behavior of Inconel 718 superalloy aged with different temperature/stress coupled fields

Lei WANG[1]*, Hanzhong DENG[2], Yang LIU[1], Xiu SONG[1] and Fanqiang MENG[3]

[1] Northeastern University, CHINA
[2] Liaoning Technical University, CHINA
[3] Sun Yat-Sen University, CHINA

* Corresponding author: wanglei@mail.neu.edu.cn

ABSTRACT:
Fatigue crack propagation behavior of Inconel 718 superalloy aged at different temperatures with a stress of 300 MPa was investigated. Fatigue crack propagation rate (FCGR) tests were carried out with compact tensile specimens at 650 ℃, 700 ℃ and 730 ℃. Both microstructural characteristics and fracture surface morphology were examined with an optical microscopy (OM), scanning electron microscope (SEM) and confocal laser scanning microscope (CLSM). The results show that the threshold value and FCGR of alloy aged at 650 ℃ for 1000 h with 300 MPa stress are the highest, while the FCGR is the slowest. It is mainly caused by the transition of dislocation approaching the γ" phase from the cutting to the by-pass where there is a critical size of γ" phase during ageing. However, the FCGR of alloys aged at 700 ℃for 1000 h with 300 MPa stress is lower than that of alloy aged at the same temperature and time without stress, which is considered due to the high bearing capacity of δ phase exceeding the critical length to diameter ratio during the ageing. The detail mechanism also deeply discussed with quantitative analyzing from the view point of both microstructure and fracture surface.

KEYWORDS: FCPR temperature/stress coupled field; IN718 alloy; γ″ phase; δ phase

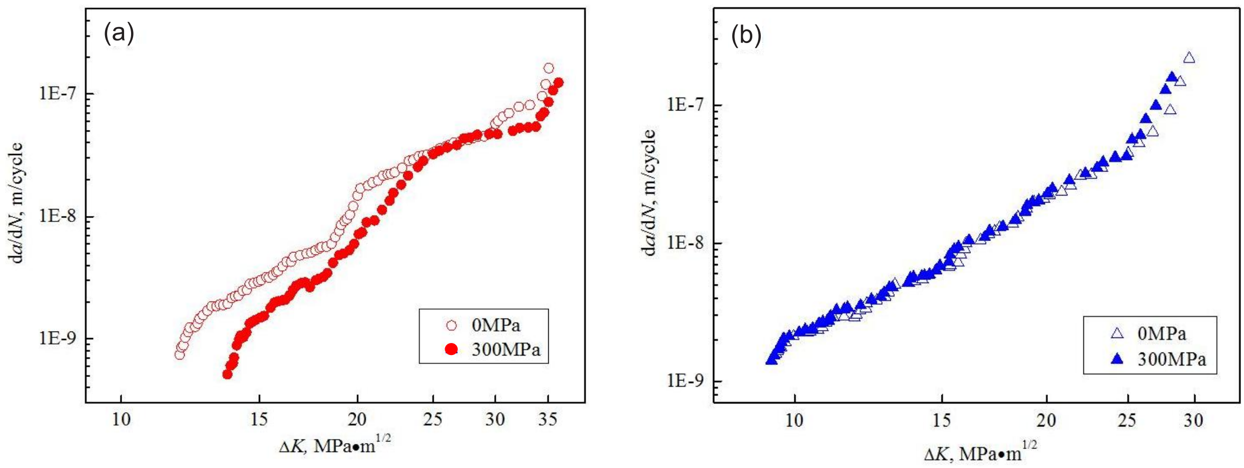


Fig. 1 *da/dN curves of the alloy aged at (a) 650 ℃ and (b) 700 ℃ for 1000 h without or with stress.*

D1-515

In-situ scanning electron microscopy observation of crack closure of non-propagating fatigue crack in Fe alloy

Atsushi TAKAYAMA[1,*], Mamoru HAYAKAWA[1], Eisuke NAKAYAMA[1], Takanori KATO[1], Taizo MAKINO[1], Naoki MARUYAMA[2] and Miyuki YAMAMOTO[2],

[1] Nippon Steel Corporation, JAPAN
[2] Osaka University, JAPAN

* Corresponding author: takayama.8a8.atsushi@jp.nipponsteel.com

ABSTRACT:
The purpose of this research was to clarify the crystal orientation dependence of near-threshold fatigue crack propagation in Fe alloy. In order to investigate the crack closure and strain distribution around non-propagating fatigue crack tips, a miniature compact tension (CT) stage for the in-situ observation of fatigue crack tips using scanning electron microscopy was developed. First, a non-propagating fatigue crack was induced in a CT specimen using the stress intensity factor range (ΔK) decreasing test method. Then, the crack closure and strain distribution were evaluated at the crack tip of the specimen using this apparatus. Fig.1 shows the crack shape and strain (ε_{YY}) map obtained from digital image correlation measurements. The crack path (dash-dotted line) was oriented at 72° from the width direction. However, the direction of the large strain area (dotted line) was oriented at 51° from the crack path. To explain these angles, a fracture mechanics model that considered the singular stress field and crystallographic slip systems was applied.

KEYWORDS
Fatigue crack propagation; Non-propagating fatigue crack; In-situ observation; Digital image correlation; Crack closure

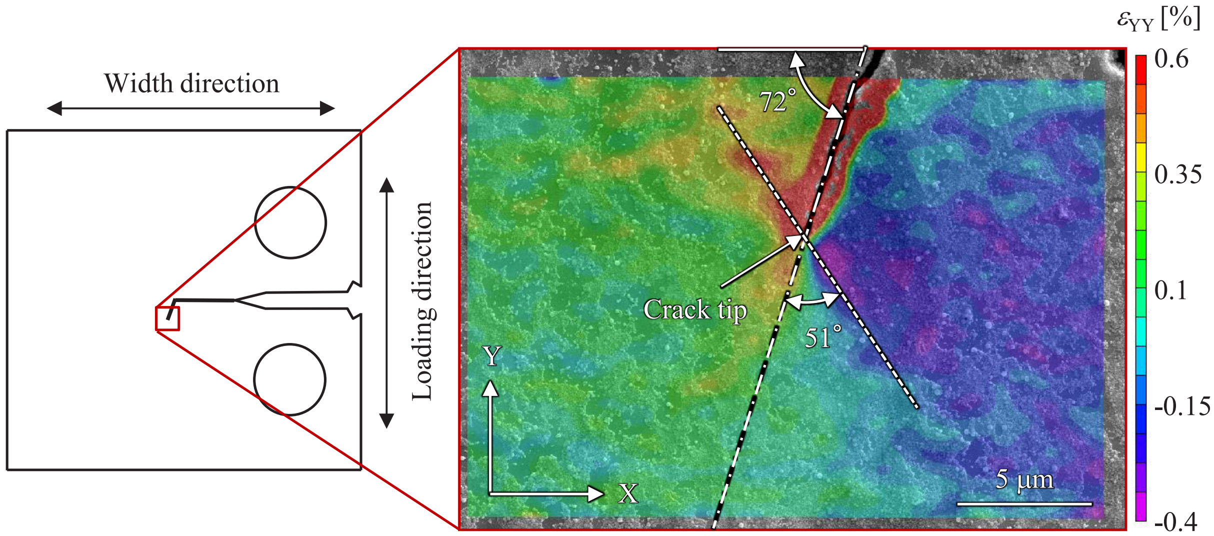


Fig. 1 *Crack shape and strain map.*

D1-516

Fatigue Limit Evaluation of Ni-based Superalloy 718, Considering the Competition between Opening- and Shear-mode Fatigue Crack-growth

Yuya TANAKA[1,2,3]*, Sungcheol PARK[4], Saburo OKAZAKI[5] and Hisao MATSUNAGA[2,6]

[1] Department of Mechanical Engineering, Fukuoka University, JAPAN
[2] Research Center for Hydrogen Industrial Use and Storage (HYDROGENIUS), Kyushu University, JAPAN
[3] Institute of Materials Science and Technology, Fukuoka University, JAPAN
[4] Graduate School of Engineering, Kyushu University, JAPAN
[5] Kobe Material Testing Laboratory Co., Ltd., JAPAN
[6] Department of Mechanical Engineering, Kyushu University, JAPAN

* Corresponding author: y.tanaka.vu@fukuoka-u.ac.jp

ABSTRACT:

The determination mechanism of the fatigue limit of Ni-based superalloy 718 associated with small-crack arrest has not been reached consensus. In order to comprehensively evaluate the alloy's fatigue limit as a small-crack problem, three types of fatigue tests (ΔK_I-decreasing fatigue crack-growth test, torsional fatigue tests and tension-compression fatigue tests) were conducted at the stress ratio, R, of −1. In addition, elastic, crack-tip stress fields were analyzed for cracks under various loading conditions. All experimental and analyses results indicate that the alloy's arresting mode (*i.e.*, opening or shear modes) at the fatigue limit is governed by complex conditions, in which the ratio of the driving force for crack-extension, R_D, and fatigue crack-growth thresholds in the opening- and shear-modes (ΔK_{Ith} and $\Delta K_{\tau th}$) are all implicated (*cf*. Fig. 1). In this study, based on the above findings, a novel strategy for evaluating the alloy's fatigue limit in a systematic fashion is proposed after consideration of two crack-arresting modes.

KEYWORDS:

Ni-based superalloy; Fatigue crack-growth threshold; Driving force; Opening-mode crack; Shear-mode crack

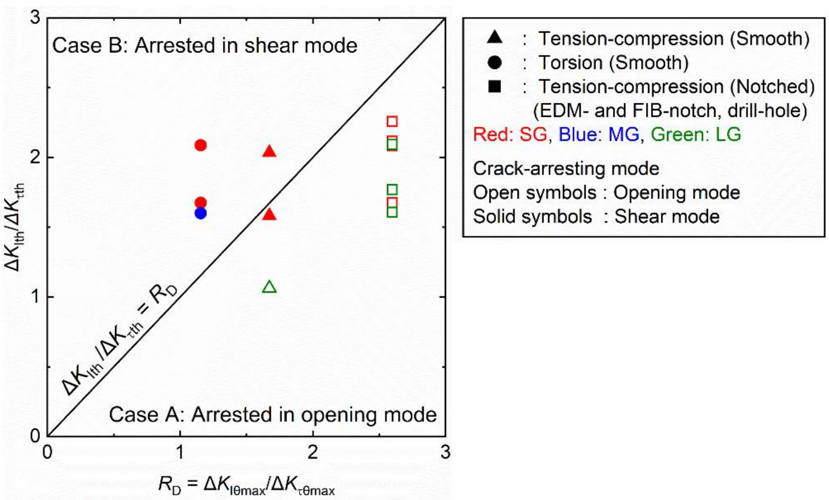


Fig. 1 $\Delta K_{Ith}/\Delta K_{\tau th}$ as a function of R_D. The conditions plotted below the solid black line (which indicates $\Delta K_{Ith}/\Delta K_{\tau th} = R_D$) are categorized as Case A, in which the crack arrests in opening mode. The opposite situations correspond to Case B, in which the crack arrests in shear mode.

D1-517

Investigation of failure analysis for AISI 4340 steels on near threshold region

Salim ÇALIŞKAN[1]

[1] Turkish Aerospace, TÜRKİYE

* Corresponding author: salim.caliskan@tai.com.tr

ABSTRACT:

Fractography investigations may unveil the pathway behind the failure by examining the fracture surfaces, and it is a subject that requires careful consideration, particularly in aircraft structures. Fractography can identify crack initiation sites, the direction of crack growth, any associated defect on the microstructure, the environmental effect on fracture, and the type of stress to which the material is applied. Proper investigations are needed to identify the origin of the failure, the direction of crack propagation, and the relating fracture mechanism. This is achieved by assessing the marks on the fracture surface under the microscope. Most of the failures are the result of multiple influences and are rarely single in metallic alloys. Fatigue striations are the most prevalent indicator on the fracture surface of ductile metal alloys in Paris region of crack growth curve. In this study, failure analysis was performed after performing crack growth tests for different microstructures for AISI 4340 steels, especially in the near threshold region, and root causes of failure were compared for each case. Crack propagation and morphological changes up to fracture have been observed in AISI 4340 steel. Under SEM and stereomicroscope examination, each stage of crack propagation was detailed with failure analysis.

KEYWORDS:

Failure Analysis; Fatigue; Heat Treatment; Steel; Threshold

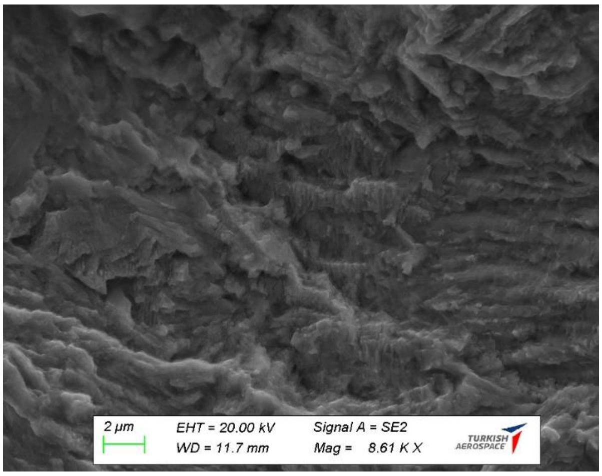


Fig. 1 Striation marks for annealed specimen

D2-501

Investigation on Fatigue Life Estimation of GH4169 Superalloy at Elevated Temperature Based on Thermodynamic Entropy Generation

Shuiting DING[1,2], Liangliang ZUO[1], Zhenlei LI[3], Guo LI[1,4,*], Shuyang XIA[1], Shaochen BAO[3] and Bolin LI[1]

[1] School of Energy and Power Engineering, Beihang University, Beijing 102206, CHINA
[2] Civil Aviation University of China, Tianjin 300300, CHINA
[3] Research Institude of Aero-Engine, Beihang University, Beijing 102206, CHINA
[4] Tianmushan Laboratory, Hangzhou 310023, CHINA

* Corresponding author: 09869@buaa.edu.cn

ABSTRACT:

According to the second law of thermodynamics, a life estimation model for crack propagation of GH4169 superalloy at elevated temperature is investigated based on thermodynamic entropy generation. A thermodynamic system was defined to conduct the thermodynamic analysis for specimen with an initial crack. The crack propagation process was simulated using commercial finite element software to obtain the local stress and strain, which was the input to calculate the cyclic entropy generation rate (CEGR). The fatigue damage of the specimen was defined by thermodynamic entropy generation, and the relationship between fatigue damage and cyclic number was analyzed. Results indicated that the CEGR at fracture point increases firstly and then decreases with the increases of loading amplitude. The increase of temperature leading to higher CEGR under constant loading amplitude. The entropy generation accumulates linearly with crack length, and the fatigue fracture entropy is almost a constant for different loading amplitudes when the temperature remains unchanged. A fatigue life estimation model was established to predict the crack propagation life for GH4169 superalloy based on thermodynamic entropy generation. The comparison with literature indicates that the proposed life estimation model is valid.

KEYWORDS:

Fatigue life estimation; Crack propagation; Elevated temperature; Thermodynamic entropy generation; Fatigue fracture entropy

D2-502

Modelling the effect of a superficial defect over the fatigue-life structural steels: a modified version of the S-N curve

Marcos PEREIRA[1], Tiago CASTRO[1,*] and Thiago PEIXOTO[1]

[1] Pontifical Catholic University of Rio de Janeiro, BRAZIL

* Corresponding author: tiagocastrobl@gmail.com

ABSTRACT:
S-N curves are typically determined for smooth specimens, which only present a limited number of internal imperfections and are usually thoroughly polished to avoid superficial defects. Nevertheless, while in service, large mechanical components subjected to cyclic loads often present numerous imperfections such as cracks, macroscopic inclusions or welding defects from which fatigue cracks are prone to nucleate, leading the components to failure. The present work aims to propose a modification to the Basquin equation, including in its expression the effect of a superficial defect over the fatigue-life of an hourglass specimen. The approach consists of adjusting experimental residues as function of the $\sqrt{area}$ parameter, which is related to the defect's dimensions. The obtained expression is thus incorporated into Basquin's equation, therefore modelling the influence of the size of the defect over the fatigue-life of a specimen. Finally, ultrasonic testing allows one to verify the validity of this approach when fatigue-life is extended to the very high cycle fatigue regime.

KEYWORDS:
Murakami; Wöhler plot; very high cycle fatigue; ultrasonic testing; notched specimen

D2-503

COMPARISON OF CUMULATIVE USAGE FACTORS USING VARIOUS FATIGUE EVLUATION RULES FOR SPECIMEN AND PIPE TESTS UNDER LOW CYCLE FATIGUE CONDITION

Kyoung-Chan Yoo[1†], Hyun-Seok Song[1], Jong-Min Lee[1], Yun-Jae Kim[1*] and Jin-Weon Kim[2]

[1] Korea University, KOREA
[2] Chosun University, KOREA

* Corresponding author: kimy0308@korea.ac.kr

ABSTRACT

There are various methods to evaluate fatigue lives under low cycle loading, for instance, the method presented in ASME Sec. III and JSME Code Case and Cyclic Void Growth Model (CVGM). Although these methods have been extensively used, comparison with pipe test data would be desired to quantify conservatism (and possibly non-conservatism) and thus to propose the most appropriate low cycle fatigue life evaluation model.

In this presentation, Cumulative Usage Factor values (CUF) are calculated for low cycle fatigue test data using notched C(T) specimens and pipe elbows using the three low cycle fatigue life evaluation methods. Low cycle fatigue test was performed by considering cyclic loading amplitude, temperature and pipe size. In notched C(T) test, SA508 Gr.3 C1.1 and SA312 TP316 materials were used. In quasi-static pipe elbow test, SA234 WPB CS and SA403 WP316 SS were used.

CUF values were calculated using three methods, ASME, JSME and CVGM. In the ASME Sec. III, a simplified elastic analysis using the fatigue curve is presented. For the simplified elastic analysis, finite element (FE) analysis was performed and alternating stress intensity (S_{alt}) by multiplying strain distribution factor (K_e) was calculated. In the analysis, two fatigue life curves were used. The ASME design fatigue curve and best-fit curve in NUREG/CR-6909. In JSME code case, elastic-plastic analysis using the fatigue curve is presented. For elastic-plastic analysis, finite element (FE) analysis was performed, and the extreme value occurrence time based on the strain component with the largest amplitude was extracted. Then the equivalent strain range ($\Delta\varepsilon$) was calculated. The same fatigue curves used in the simplified elastic analysis were used. Finally, the CVGM is a method considering the void growth for tensile stressing and void shrinkage for compressive stressing. Damage is calculated by subtracting the accumulated damage considering void shrinkage ratio (k) in compression from the amount of damage accumulated in tension. For CVGM, the multi-axial fracture strain presented in ASME Sec. VIII was used. The void shrinkage ratio (k) was determined using the fatigue curve of the material. Based on the calculated CUF, the conservatism of each evaluation method is discussed.

KEYWORDS:
Low cycle fatigue life evaluation methods, Cumulative Usage Factor (CUF), Notched C(T) specimen test, Pipe elbow test

D2-504

A Physics-informed Neural Network for Probabilistic Fatigue Life Prediction under Constant Amplitude Loading with Overloads

Shan JIANG[1], Ying-Chun ZHANG[1] and Wei ZHANG[2,*]

[1] School of Information Engineering, Minzu University of China, Beijing, CHINA
[2] School of Reliability and Systems Engineering, Beihang University, Beijing, CHINA

* Corresponding author: zhangwei.dse@buaa.edu.cn

ABSTRACT:

In this paper, a physics-informed neural network (PINN), combining the fatigue life prediction model and neural network, is proposed for calculating the probabilistic fatigue life under constant amplitude loading (CAL) with periodic overloads. First, the equivalent stress level is computed, which takes the crack closure as the main parameter to account for the interaction effects. Furthermore, the fatigue life prediction model is derived using linear elastic fracture mechanics. Then, the above fatigue model and the mean squared error are integrated into the loss function of a neural network to build the PINN (Fig.1). A three-layer backpropagation neural network is utilized. The inputs are the feature parameters, including the material coefficients, the equivalent stress level, the equivalent initial crack length and the critical crack length. The outputs are the mean and standard deviation of fatigue life. Eventually, the probability distribution of fatigue life under CAL with overloads can be achieved and P-S-N curves can be drawn. The fatigue testing data under CAL are employed to train the PINN. A fatigue experiment of aluminum alloy 7075-T6 under CAL with overloads is conducted to obtain the testing dataset, which is used to verify the extrapolation capability of the PINN. Good agreements are observed.

KEYWORDS:

Fatigue life prediction; Crack closure; Interaction effects; Physics-informed neural network; Overloads

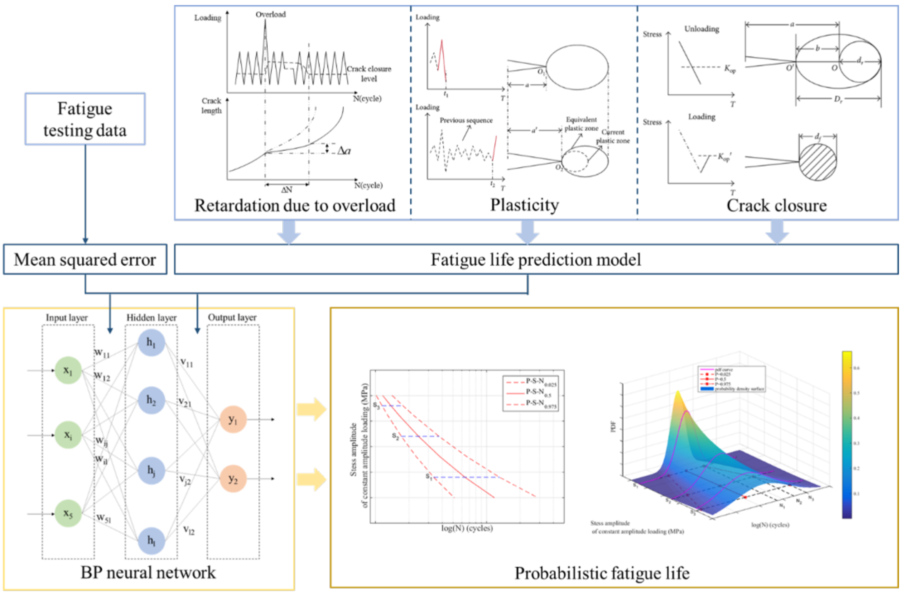


Fig. 1 *Physics-informed neural network architecture.*

D2-505

Probabilistic estimation of the W¨ohler and Goodman-Haigh curves by considering the stress ratio effect

Paul Dario TOASA CAIZA[1],*, Stéphane SIRE[2], Thomas UMMENHOFER[3], and Yoshihiko UEMATSU[4]

[1,3]KIT Stahl- und Leichtbau, Versuchsanstalt für Stahl, Holz und Steine, Karlsruher Institut für Technologie (KIT). Otto-Ammann-Platz 1, 76131 Karlsruhe, Germany
[2]University of Brest, UMR CNRS 6027 IRDL, 29200, Brest, France
[4]Department of Mechanical Engineering, Gifu University. 1-1 Yanagido, Gifu 501-1193, Japan
* Corresponding author: paul.toasa@kit.edu

ABSTRACT:

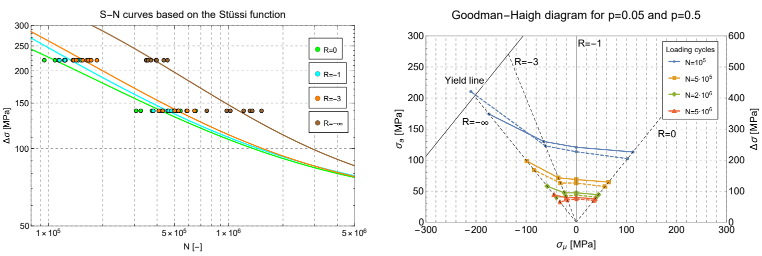
The stress ratio plays a relevant and complex role on the fatigue life estimation. Usually, two deterministic approaches are applied to study this phenomenon. On the one hand, based on the Wöhler curves obtained from tests performed under a particular stress ratio, the corresponding fatigue life under a particular stress range is estimated. On the other hand, the stress amplitude corresponding to a constant fatigue life is estimated by applying the failure criteria for fluctuating stress like the Goodman-Haigh relationship. Additionally, if a suitable statistical distribution is included, these approaches allow to make estimations with certain probability.

Based on the Stüssi function and on a Weibull distribution, a model to estimate W¨ohler curves and constant fatigue Goodman-Haigh diagrams is presented. This procedure requires data corresponding to tests performed from LCF to HCF under a particular stress ratio, and data from one stress range in LCF and one stress range in HCF for each subsequent stress ratio.

Afterwards, this model is applied on data from a) welded specimens made of St 52-3 subjected to tension and compression dominated cyclic loading, b) specimens manufactured of Ti-6Al-4V and c) double shear mono rivet specimens made of S235, both of them subjected to pure tension cyclic loading.

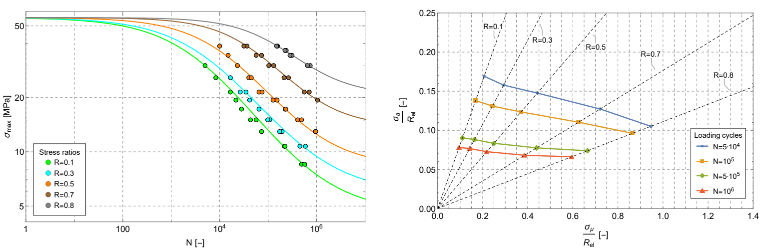
KEYWORDS:

Stress Ratio , Mean Stress , Lifetime Estimation , Stüssi, Weibull,Goodman-Haigh , Wöhler



(a) $\Delta\sigma$-N curves (b) Prob. Goodman-Haigh diagram

Figure 1: Fatigue life estimation of welded specimens made of St 52-3



(a) σ_{max}-N curves (b) Goodman-Haigh diagram

Figure 2: Fatigue life estimation of specimens made of Ti-6Al-4V

D2-506

High Temperature Fatigue Tests on Small-scale Specimens Extracted from High Pressure Turbine Blades for Calibrating an Efficient Lifetime Model

Christian DRESBACH[1], Janine WISCHEK[2], Beruktayet FEKADU[2], Yasuko BESEL[2], Rizviul KABIR[2], Liudmila CHERNOVA[2], Thiemo PRIEN[3], and Marion BARTSCH[2,*]

[1] University of Applied Sciences Bonn-Rhein-Sieg, Rheinbach, GERMANY
[2] German Aerospace Center, Institute of Materials Research, Cologne, GERMANY
[3] Lufthansa Technik AG, Hamburg, GERMANY

* Corresponding author: marion.bartsch@dlr.de

ABSTRACT:
Small scale low cycle fatigue (LCF) experiments were performed in a temperature range between 20 °C and 950 °C for calibrating a beforehand developed lifetime assessment model, which is based on fracture strength data of the used alloy René 5 combined with LCF data reported in the literature for the well described reference alloy CMSX®-4. Test samples were extracted from high pressure turbine blades to capture the influence of the microstructure, which developed during solidification of thin walled blade structures. To keep the costs within reasonable limits, small-scale samples were extracted from the cooling channel walls of used turbine blades, which have a microstructure close to the pristine state, since they were exposed to moderate temperatures. All fracture surfaces were examined with respect to the origin of lifetime limiting fatigue cracks. Main results of this study were (1) the predictive power of the lifetime model is not sufficient if based on LCF data from reference material, (2) if calibrated with LCF data from the actual material, the model fits well for all temperatures, (3) the observed lifetime scatter discourages extrapolating the model to longer lifetimes, and (4) the lifetime scatter is mainly related to the size distribution of solidification pores.

KEYWORDS:
Nickel-based superalloy; lifetime prediction; fatigue; gas turbine blade; miniaturized high temperature testing

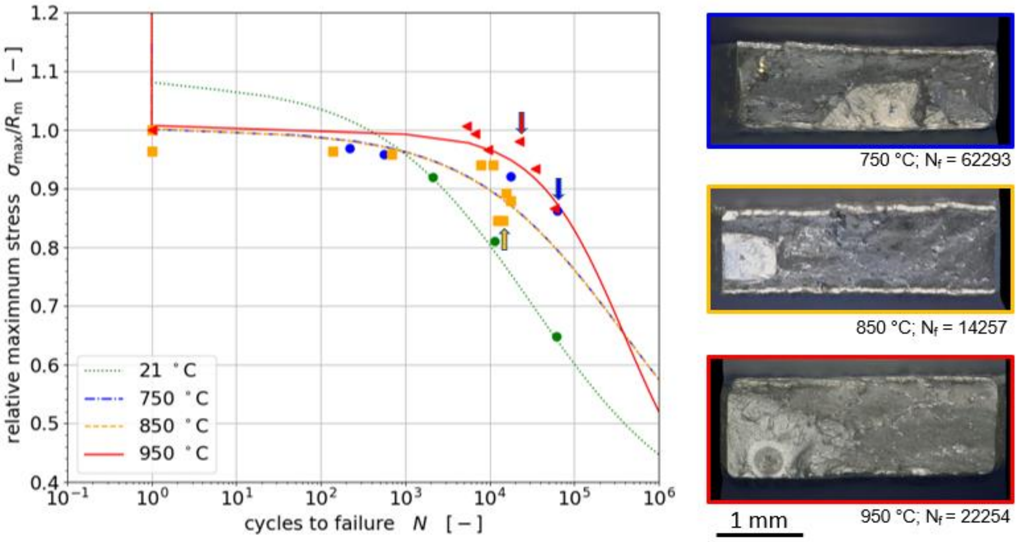


Fig. 1 *Experimental lifetime data for René 5 with modeled S-N curves (LCF-tests, sinusoidal with 5 Hz, stress ratio 0.1) and exemplary fracture surfaces associated to marked lifetime data*

D2-507

On the influence of mean stresses on the predictive capability of the elliptical curve method

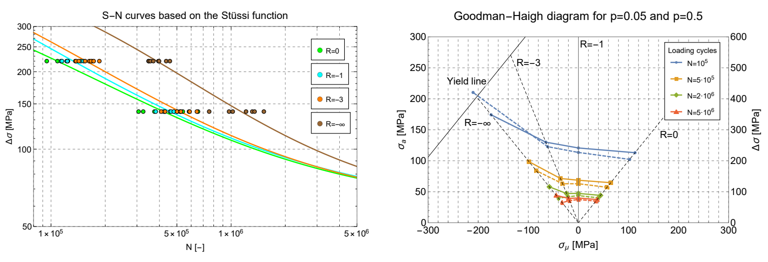
Tiago CASTRO[1,*], Marcos PEREIRA[1], Lucas ARAUJO[2], Fathi DARWISH[3] and José ARAÚJO[2]

[1] Pontifical Catholic University of Rio de Janeiro, BRAZIL
[2] University of Brasília, BRAZIL
[3] Fluminense Federal University, BRAZIL

* Corresponding author: tiagocastrobl@gmail.com

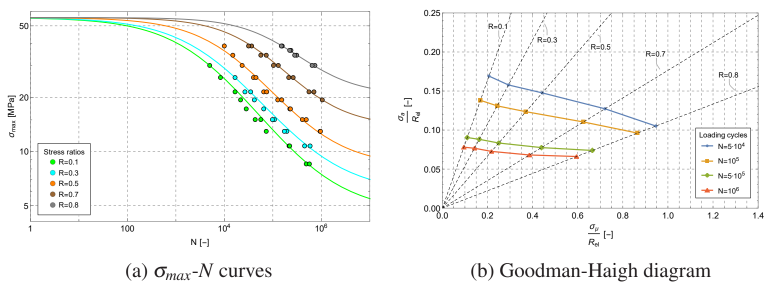
ABSTRACT:
The elliptical curve method establishes a simple relation where fatigue-life can be determined as a direct function of the normal and shear stresses applied to a specimen, being thus independent of critical plane determination. A slight bias towards conservativeness is attenuated with the introduction of an adjustment function, which is also seen to exert a positive influence on the predictions relative to out-of-phase loadings. As such, the present work approaches the influence of mean stresses and different stress trajectories upon the predictive capability of the elliptical curve method relative to both in-phase and out-of-phase loading conditions. Assessment of the predictive capability is carried out by comparing its predictions with experimental observations, as well as with predictions obtained from adapted versions of popular multiaxial fatigue criteria.

KEYWORDS:
Multiaxial high-cycle fatigue criteria; combined bending and torsion; critical plane-based models; non-proportional loadings; structural steels



(a) $\Delta\sigma$-N curves (b) Prob. Goodman-Haigh diagram

Figure 1: Fatigue life estimation of welded specimens made of St 52-3



(a) σ_{max}-N curves (b) Goodman-Haigh diagram

Figure 2: Fatigue life estimation of specimens made of Ti-6Al-4V

D2-508

Machine learning-based fatigue life prediction of metal materials: Perspectives of physics-informed and data-driven hybrid methods

Haijie WANG[1], Bo LI[1,3]* and Fuzhen XUAN[1,2,3]*

[1] School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, PR China
[2] Key Laboratory of Pressure Systems and Safety, Ministry of Education, East China University of Science and Technology, Shanghai 200237, PR China
[3] Shanghai Collaborative Innovation Center for High-end Equipment Reliability, Shanghai 200237, PR China

* Corresponding author: libo@ecust.edu.cn (Bo Li); fzxuan@ecust.edu.cn (Fu-Zhen Xuan)

ABSTRACT:
Fatigue life prediction is critical for ensuring the safe service and the structural integrity of mechanical structures. Although data-driven approaches have been proven effective in predicting fatigue life, the lack of physical interpretation hinders their widespread applications. To satisfy the requirements of physical consistency, hybrid physics-informed and data-driven models (HPDM) have become an emerging research paradigm, combining physical theory and data-driven models to realize the complementary advantages and synergistic integration of physics-based and data-driven approaches. This paper provides a comprehensive overview of data-driven approaches and their modeling process, and elaborates the HPDM according to the combination of physical and data-driven models. Then, the fatigue life of additive manufactured as-built parts is predicted based on HPDM.

KEYWORDS:
Fatigue life; Machine learning; Physical theory; Data-driven; Hybrid models

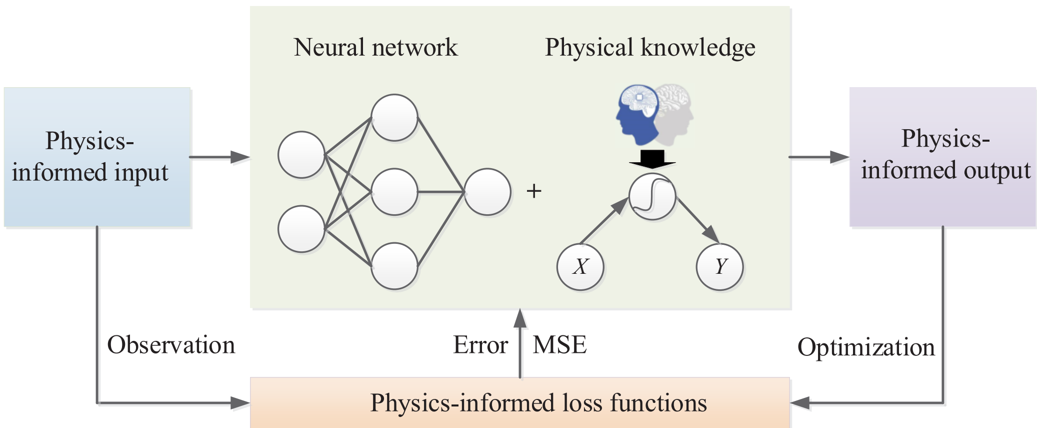


Fig. 1 *Structure of hybrid physics-informed and data-driven models.*

D2-509

Prediction of fatigue crack growth life under complex environmental loads via cycle-by-cycle algorithm and XFEM

Zhiying Chen[1,*], Yanwei Dai[2], Yinghua Liu[1]

[1] Tsinghua University, CHINA
[2] Beijing University of Technology, CHINA

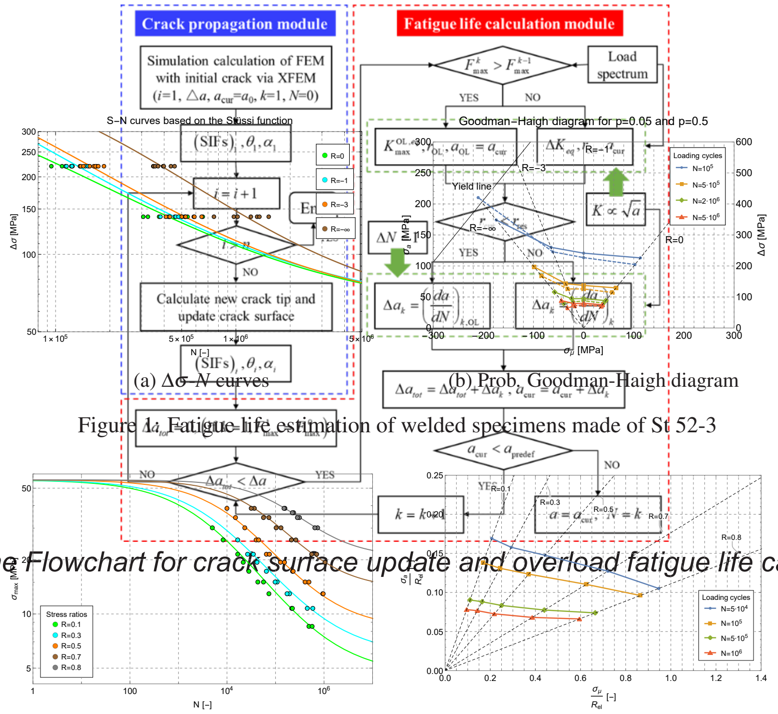
* Corresponding author: chenzy21@mails.tsinghua.edu.cn

ABSTRACT:

In order to accurately predict the fatigue crack growth life of structures under complex environmental loads via the extended finite element method (XFEM), a simple crack surface update method is developed. This method not only makes full use of the advantages of XFEM, but also avoids the level set marching algorithm, which can ensure good robustness and high efficiency. Combined with the interaction integral and the piecewise interpolation methods, the stress intensity factors at crack tip with arbitrary crack length can be accurately calculated, which ensures the accurate simulation of mixed-mode crack path for complex configuration structure and is suitable for the case of multiple crack tips. Then, aiming at the crack growth rate model under complex environmental loads, a high-cycle fatigue life algorithm based on the cycle-by-cycle concept is developed. Based on this algorithm, the fatigue crack growth life considering retardation effect is accurately predicted when structure is under the cyclic overload spectrum. Based on this algorithm, the corrosion damage increment produced in each load cycle is calculated and the corrosion-fatigue life is accurately predicted when structure is in a corrosion environment. This method has also been well applied in practical engineering structures.

KEYWORDS:

Extended finite element method (XFEM); Crack surface update; Cycle-by-cycle algorithm; Cyclic overload; Corrosion-fatigue life



(a) Δσ-N curves (b) Prob. Goodman-Haigh diagram

Figure 1: Fatigue life estimation of welded specimens made of St 52-3

Fig. 1 *The Flowchart for crack surface update and overload fatigue life calculation.*

(a) σ_{max}-N curves (b) Goodman-Haigh diagram

Figure 2: Fatigue life estimation of specimens made of Ti-6Al-4V

D2-510

On the integration of domain knowledge and branching neural network for fatigue life prediction with small samples

Lei GAN[1], Hao WU[2], Zheng ZHONG[1,*]

[1] School of Science, Harbin Institute of Technology (Shenzhen), CHINA
[2] School of Aerospace Engineering and Applied Mechanics, Tongji University, CHINA

* Corresponding author: zhongzheng@hit.edu.cn

ABSTRACT:
A versatile data-driven model integrating domain knowledge and deep neural networks (DNNs) is proposed for fatigue life prediction with small samples. In the model, traditional fatigue life models, like the Fatemi-Socie model, are regarded as comprehensive reflections of domain knowledge, and are used to generate pseudo labels for data augmentation. Meanwhile, a new DNN typology, called Branching neural network, is devised to distill useful training information without theoretical biases contamination. Further model improvement is achieved by the introduction of a subtractive clustering-based procedure for training data collection. The proposed model is experimentally validated in three distinct case studies, and shows better prediction performance against traditional models and conventional DNNs under small sample conditions.
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KEYWORDS:
Fatigue life prediction; Small samples; Fatigue domain knowledge; Branching neural network; Subtractive clustering

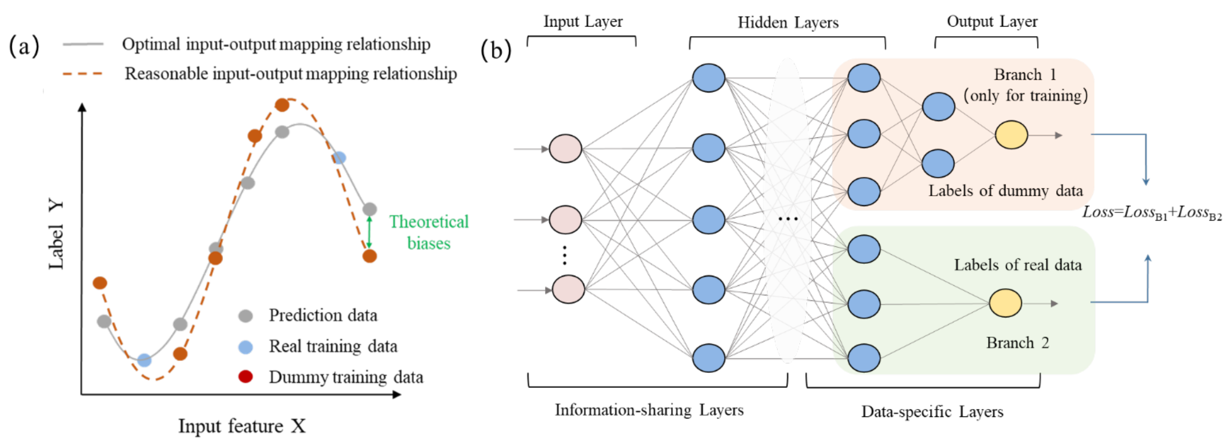


Fig. 1 (a) Data-driven modeling of the input-output mapping relationship with dummy training data; (b) Illustration of the newly presented BNN.

D2-511

Methodology for pore detection and classification with regard to fatigue of PBF-LB/M-manufactured 316L using µCT and machine learning algorithms

Johannes Diller[1]*, Ludwig Siebert[1] Christina Radlbeck[1] and Martin Mensinger[1]

[1] Chair of Metal Structures, Technical University of Munich, Germany

* Corresponding author: Johannes.diller@tum.de

ABSTRACT:

The fatigue behaviour of parts manufactured by powder bed fusion of metals using a laser (PBF-LB/M) is still one of the major obstacles in achieving the goal of safe and reliable use of structural components. The main geometric defects affecting the fatigue resistance of PBF-LB/M-manufactured components are porosity and the surface topology. They lead to a reduction in fatigue strength due to high stress intensities. Micro-computed tomography scans (µCT) generate a high amount of data which is an unused potential for machine learning. Many geometrical features can be extracted from µCT-data and used to gain more information about the severity of geometrical defects with regard to fatigue. This work seeks to automate the detection and analysis of internal defects in PBF-LB/M-manufactured components. The ultimate objective is to evaluate how these defects impact the fatigue behaviour of the components. Therefore, image processing of µCT-scans, fatigue testing, and machine learning have been applied. The generation of a workflow contributes to the non-destructive assessment of component quality and mechanical properties. In Fig. 1, the approach to a machine learning task is illustrated with a classification problem by developing a model to classify pores into gas pores and lack of fusion pores.

KEYWORDS:

Additive manufacturing, µCT, life prediction methodology, machine learning, statistical and durability aspects

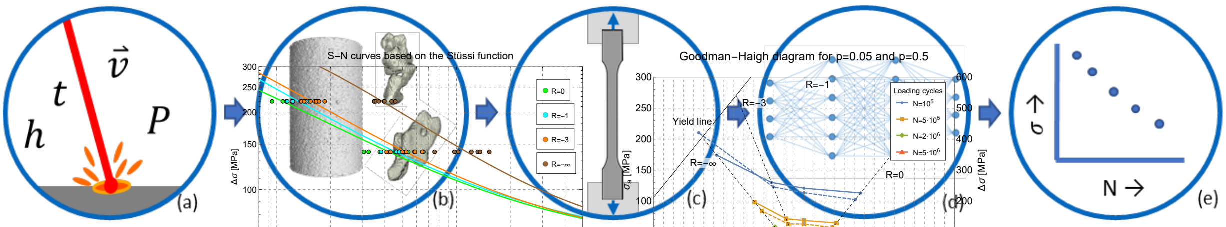
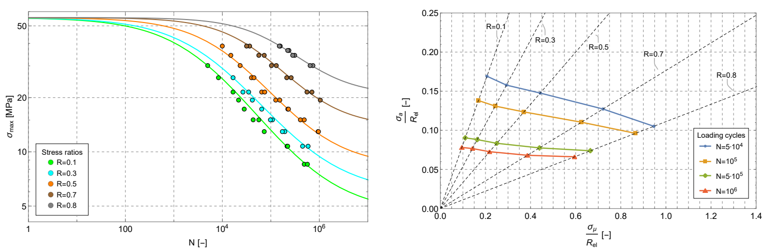


Fig. 1: Workflow to predict the fatigue life of PBF-LB/M-manufactured components. (a): Manufacturing, (b): µCT-scanning and feature extraction, (c): fatigue testing, (d): machine learning, and € final prediction of the fatigue life of individual components.

(a) $\Delta\sigma$-N curves (b) Prob. Goodman-Haigh diagram

Figure 1: Fatigue life estimation of welded specimens made of St 52-3



(a) σ_{max}-N curves (b) Goodman-Haigh diagram

Figure 2: Fatigue life estimation of specimens made of Ti-6Al-4V

D2-512

Prediction of Corrosion Fatigue Crack Growth Rate in Alloys Based on Quantitative Expression of Data Nonlinear Correlation

Yongzhen ZHANG[1,2,3,*], Leijiang YAO[1,2,3], Xiaoyan TONG[1,2,3], Jiachuan XIE[1,4] and Bin LI[2,3]

[1] Institute of Corrosion Science and Technology, CHINA
[2] Northwestern Polytechnical University, CHINA
[3] Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), CHINA
[4] Guangzhou University, CHINA

* Corresponding author: yzzhang@icost.ac.cn

ABSTRACT:

The data of aluminum alloys corrosion fatigue crack growth including material, environment, mechanical load, and crack growth rate were collected, forming the data basis for the prediction of aluminum alloy corrosion fatigue crack growth rate. Combining the contribution rate of data features to crack growth rate prediction, a nonlinear correlation quantitative characterization method for high-dimensional corrosion fatigue data features of aluminum alloys was proposed, which realizes effective dimensionality reduction of high-dimensional nonlinear data. Finally, using a 5-layer deep neural network, Adam optimizer, and data after dimension reduction, the prediction model of corrosion fatigue crack growth rate of aluminum alloy was obtained, and the effective prediction of crack growth rate was realized. The results show that (Fig.1): the maximum relative error and the average relative error of aluminum alloy corrosion fatigue crack growth rate's predicted values, based on the deep neural network and effective data dimension reduction, are 18.59% and 6.96%, respectively. Compared with the prediction results using data before dimensionality reduction, the maximum and average relative error decreased by 10.17% and 1.61%, respectively.

KEYWORDS:

Aluminum alloys; Corrosion fatigue; Crack growth; Data dimension reduction; Prediction

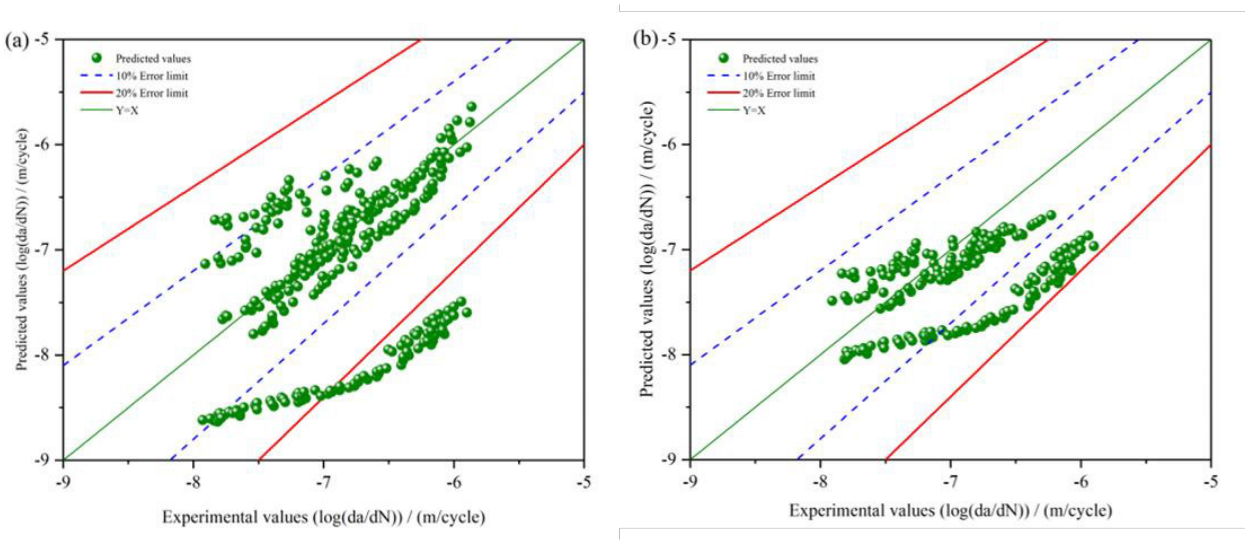


Fig. 1 Prediction results of Aluminum alloys corrosion fatigue crack growth rate: (a) Data before dimensionality reduction was used; (b) Data after dimensionality reduction was used.

D2-513

Separate Effects of Surface Roughness and Residual Stress on Fatigue Limit of Austenitic Stainless Steels

Masatoshi KURODA[1,3,*] and T. James MARROW[2,3,*]

[1] Kumamoto University, JAPAN
[2] University of Oxford, UK
[3] University of Manchester, UK[i]

* Corresponding author: mkuroda@mech.kumamoto-u.ac.jp, james.marrow@materials.ox.ac.uk

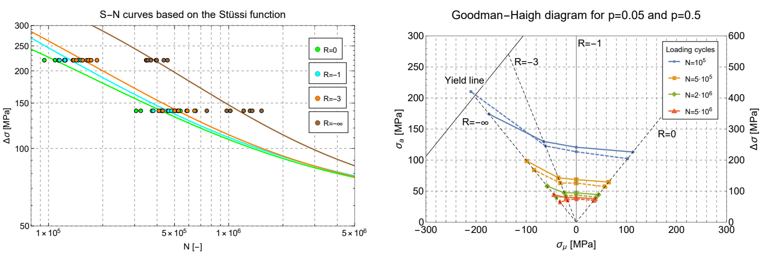
ABSTRACT:

The separate effects of surface roughness and residual stress on the fatigue limit of Type 304 austenitic stainless steels with fine (8 μm) and coarse (40 μm) grain size have been examined using rotating bending fatigue tests, performed with specimens prepared on a numerically controlled lathe to obtain reproducible surface characteristics: (Type-I) as-machined (fine and rough); (Type-II) annealed (900 °C); and (Type-III) electropolished.

The contribution of the surface roughness to the fatigue limit was extracted by comparing the observed fatigue limits of the Type-II and Type-III specimens; the contribution of the residual stress was examined by comparing the Type-I and Type-II specimens. Both the effects of the roughness and the residual stress on the fatigue limits were negligible in the fine-machined coarse-grain material. In the rough-machined fine-grain material, it was not the roughness but the residual stress that significantly affected the fatigue limit. It is concluded that the residual stress can be a dominant surface characteristic affecting the fatigue limit of Type 304 austenitic stainless steels rather than the roughness, depending on the cutting condition.

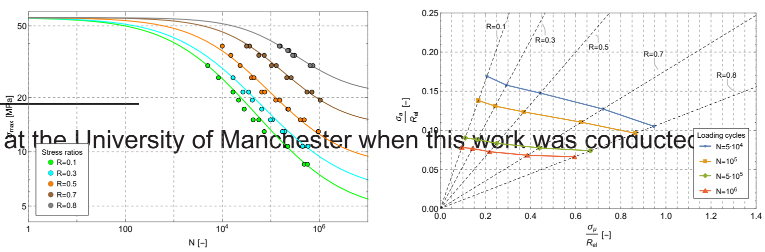
KEYWORDS:

Fatigue; Surface roughness; Residual stress; Fatigue limit; Austenitic stainless steel



(a) $\Delta\sigma$-N curves (b) Prob. Goodman-Haigh diagram

Figure 1: Fatigue life estimation of welded specimens made of St 52-3



(a) σ_{max}-N curves (b) Goodman-Haigh diagram

Figure 2: Fatigue life estimation of specimens made of Ti-6Al-4V

[i] Both authors were at the University of Manchester when this work was conducted

D2-514

Influence of manufacturing process, heat treatment and microstructure on fatigue properties of carbide-rich high-speed steels

Lennart Mirko SCHOLL[1,*], Alexander BEZOLD[1] and Christoph BROECKMANN[1]

[1] RWTH Aachen University, Chair and Institute for Materials Applications in Mechanical Engineering (IWM), Augustinerbach 4, 52062 Aachen, Germany

* Corresponding author: L.Scholl@iwm.rwth-aachen.de

ABSTRACT (max. 200 words + max. 1 Figure):

Effects of microstructural factors like carbide/inclusion size or content on fatigue in carbide-rich HSS have hardly been investigated. Manufacturing including hot forming and heat treatment fundamentally determine the resulting microstructure and thus fatigue strength. Influencing factors have been investigated sporadically and usually considered individually, making it practically impossible to develop a fundamental, in-depth understanding of underlying relationships. In this work a comprehensive fatigue strength database with systematic microstructure variation is presented.

Rotating bending tests (HCF, NG=10^7) in quenched and tempered condition were performed in longitudinal (for HS6-5-3-8/HS6-5-2 also in transversal) direction for the powder metallurgical (PM) grades HS15-3-5-11, HS6-5-3, HS6-5-3-8 and ingot cast HS6-5-2. The hardness was systematically varied by tempering. The results indicate that a reverse hardness effect (RHE) exists leading to a fatigue strength decrease when exceeding a critical hardness. Hot working leads to pronounced anisotropy. Carbide size and cleanliness are the most important factors.

Significantly increasing the carbide content in very clean PM grades does not decrease fatigue strengths or change the (linear) hardness influence. The RHE is shifted and not occurring, allowing combinations of maximum hardness, fatigue strength and carbide content. Highest fatigue strengths can be achieved by maximum cleanliness combined with smallest, finely distributed carbides.

KEYWORDS (max. 5 tags): Carbide-Rich High-Speed Steels; HCF Strength; Microstructure; Statistical Fractography of Critical Defects; Heat Treatment

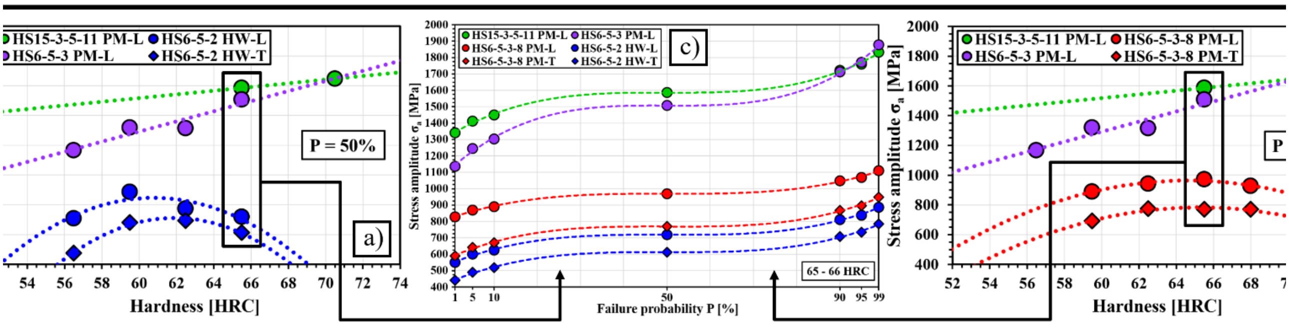


Fig. 1: *Effects of various microstructural fatigue influencing factors in carbide-rich HSS: Comparison of hardness effects in HS15-3-5-11 PM and HS6-5-3 PM with those in a) ingot cast + hot worked HS6-5-2 HW-L and -T, b) HS6-5-3-8 PM-L and -T, and c) fatigue strengths over failure probability P*

D2-515

Bidirectional Transformation: A Novel Approach to Enhance Fatigue Durability of Steel

Fumiyoshi YOSHINAKA[1,*], Takahiro SAWAGUCHI[1], Susumu TAKAMORI[1] and Satoshi EMURA[1]

[1] National Institute for Materials Science, JAPAN

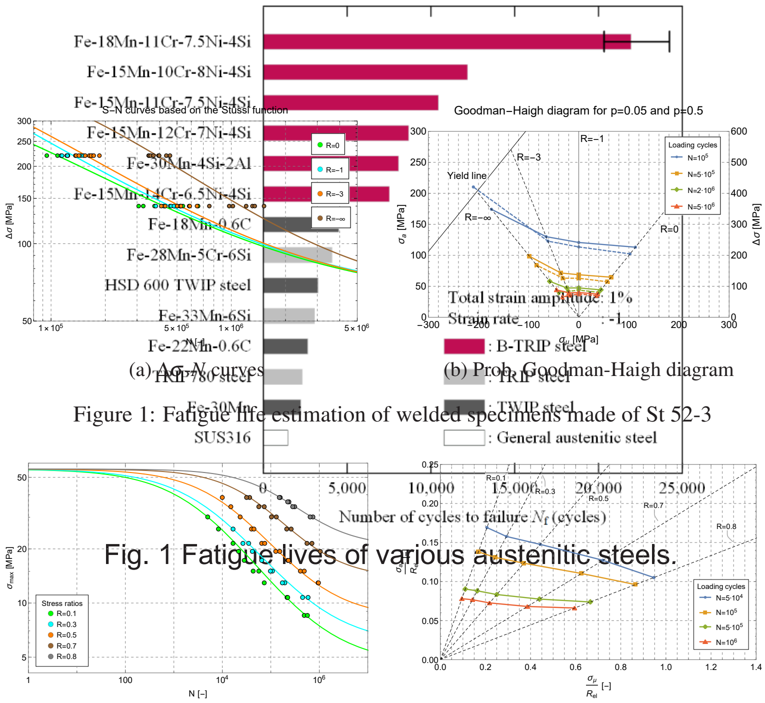
* Corresponding author: YOSHINAKA.Fumiyoshi@nims.go.jp

ABSTRACT:

Bidirectional transformation between γ-austenite and ε-martensite is a promising novel deformation mechanism, known as Bidirectional-TRansformation Induced Plasticity (B-TRIP), for developing fatigue-resistant steel due to its high reversibility in dislocation motion. The relationship between the deformation mechanisms and fatigue life was characterized using a Gibbs free energy difference between γ-austenite and ε-martensite $\Delta G^{\gamma\rightarrow\varepsilon}$. An optimum thermodynamic condition for B-TRIP is $\Delta G^{\gamma\rightarrow\varepsilon} \approx 0$ J/mol, which has been shown to result in improved fatigue life. However, the two-stage γ→ε→α'-martensitic transformation is another important deformation mechanism that can harmfully affect the fatigue life of B-TRIP steel. The enhanced irreversible α'-martensitic transformation around a fatigue crack locally inhibits B-TRIP, leading to a decrease in fatigue life. Therefore, to benefit from B-TRIP to improve fatigue durability, in addition to the condition that the $\Delta G^{\gamma\rightarrow\varepsilon}$ is set to around 0, the mechanical stability of the ε-martensite should be significantly higher against α'-martensite so that the γ→ε→α'-martensitic transformation hardly occurs even at the stress/strain field at the crack tip. The developed B-TRIP steel based on this design concept has achieved twentyfold fatigue life compared to general steel.

KEYWORDS:

Alloy design, Martensitic transformation, Steel, Fatigue life, Low cycle fatigue



(a) Δσ-N curves (b) Prob. Goodman-Haigh diagram

Figure 1: Fatigue life estimation of welded specimens made of St 52-3

Fig. 1 Fatigue lives of various austenitic steels.

(a) σ_{max}-N curves (b) Goodman-Haigh diagram

Figure 2: Fatigue life estimation of specimens made of Ti-6Al-4V

D2-516

Fatigue crack growth behavior of metallic plates reinforced with bonded and prestressed retarders

Wandong WANG[1*], Yu'e MA[1]

[1] Northwestern Polytechnical University, CHINA

* Corresponding author: w.wang@nwpu.edu.cn

ABSTRACT:

Bonded crack retarders are extensively applied to enhance the damage tolerance of metallic structures. This paper investigates the effect of bonded and prestressed retarders on the crack growth behavior of metallic plates containing central cracks. Iron-based shape memory alloy (Fe-SMA) strips were first pretrained to 2% and then bonded to cracked metallic plates as retarders in order to reduce the fatigue crack growth rate. The bonded Fe-SMA retarders were subjected to an activation process in order to achieve self-prestressing and to generate desirable compressive stresses in the cracked metallic plates. A series of fatigue tests were conducted and their crack growth behavior were analyzed. Experimental results show that the bonded prestressed Fe-SMA retarders is very favorable in terms of reducing the crack growth rate. The fatigue life results show that the distance between the retarder and the initial crack tip also affect the crack growth behavior, the closer the better in term of fatigue performance.

KEYWORDS:

Shape memory alloy; Crack growth retardation; Prestressing; Fatigue life extension; Crack growth behavior.

D2-517

An analytical approach to evaluate fatigue behaviour of notched specimens in VHCF: challenges, accomplishments and limitations

R. Dantas[a,b,c*], M. Gouveia[b], F.G.A. Silva[b], F.Fiorentin[a,b], J.A.F.O. Correia[a,b,c], G. Lesiuk[d], A. Reis[a,b], A. de Jesus[a,b]

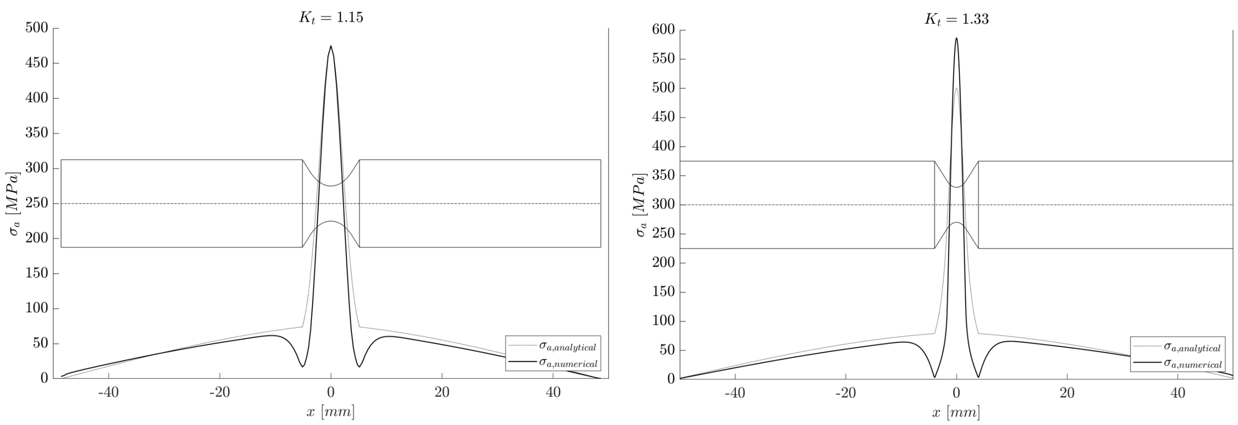
[a] *Faculty of Engineering of the University of Porto, Rua Dr. Roberto Fria, 4200-465, Porto, Portugal*
[b] *INEGI, Faculty of Engineering of the University of Porto, Porto, Portugal*
[c] *CONSTRUCT, Faculty of Engineering of the University of Porto, Porto, Portugal*
[d] *Faculty of Mechanical Engineering, Wroclaw University of Science and Technology, ul. Smoluchowskiego 25, PL-50370 Wrocław, Poland*
**Corresponding author: rdantas@inegi.up.pt*
Keywords: very high cycle fatigue; steel; notch effect;

Abstract

In the last decades, ultrasonic fatigue testing became a topic of interest due to the need of characterizing the fatigue behaviour of engineering components and structures in the very high cycle region, since some of them achieve 10^9 number of cycles during their service lives [1]. The notch effect in VHCF regime was addressed by some authors, but the procedure to design specimens to be tested in ultrasonic fatigue tests, which require particular considerations, is not well described and there is no analytical methodology well established for that [2].

Therefore, the authors developed and proposed an analytical model based on the elastic wave theory to design and assess blunt notched specimens to be tested in an ultrasonic fatigue machine. Thus, an experimental campaign with blunt v-notched specimens of S690 QL steel, a structural steel with application in offshore industry, was planned and performed to verify the analytical model and delineate limitations. Two different notched geometries were defined, which resulted into two different stress concentration factors: $K_T = 1.15$ and $K_T = 1.33$.

As first step, the specimen's geometries were defined based on the analytical model proposed. Then, a numerical model was developed in a commercial software to evaluate the accuracy of analytical approach. Figures 1 (a) and (b) establishes a comparison between analytical and numerical maximum stress amplitudes along notched specimen during the fatigue test for the two stress concentration factors under analysis. The analytical model seems to estimate the stress amplitude with better precision for the lower stress concentration factor.



(a) (b)

Figure 1. Comparison between analytical and numerical maximum stress amplitudes along notched specimen

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[2] Y. Akiniwa, N. Miyamoto, H. Tsuru, and K. Tanaka, "Notch effect on fatigue strength reduction of bearing steel in the very high cycle regime," *Int. J. Fatigue*, vol. 28, no. 11, pp. 1555–1565, 2006, doi: 10.1016/j.ijfatigue.2005.04.017.

Acknowledgments

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D2-518

Influence of Metallurgical Variables on Corrosion Fatigue Strength of Structural Steels

Ryuichiro Ebara[1]

[1] Institute of Materials Science and Technology, Fukuoka University, JAPAN

* Corresponding author: ebara@fukuoka-u.ac.jp

ABSTRACT:

Corrosion fatigue strength of structural stees is indispensable to determine the design stress of structural components working under corrosive environments. This paper aims to present the effect of metallurgical variables controlling corrosion fatigue strength of structural steels such as carbon steels, high strength steels, low alloy steels and various kinds of stainless steels. The emphasis is focused upon the effect of metallurgical variables such as chemical compositions, heat treatment and microstructure on long term corrosion fatigue strength of stainless steels. It can be concluded that corrosion fatigue strength of structural steels is strongly influenced by chemical compositions and heat treatment controlling corrosion pit initiation at corrosion fatigue crack initiation area.

Finally, a couple of remaining issues on research on corrosion fatigue of structural steels are touched on brief.

KEYWORDS:

Corrosion fatigue, structural steels, metallurgical variables, long term corrosion fatigue strength, corrosion pit

13th International Fatigue Congress (FATIGUE2022+1) November 6th to 10th, 2023– Hiroshima, JAPAN

C1-501

Very high cycle fatigue at RT and elevated temperatures on additively manufactured materials

Anja WEIDNER[1,*], Horst BIERMANN[1]

[1] Institute of Materials Engineering, TU Berhakademie Freiberg, GERMANY

* Corresponding author: weidner@ww.tu-freiberg.de

ABSTRACT:
Additive manufacturing (AM) gained an increased interest during the last decade due to unprecedented design freedom arising from the related novel production technologies. However, drawbacks of the layerwise processing of three-dimensional components via several AM techniques are both the anisotropic microstructure with columnar grains and strong textures as well as several building defects such as lack of fusion and porosity. Fatigue properties of materials processed by additive manufacturing are of high interest, in particular both for components designed for high-temperature applications as well as in the range of high fatigue lives. The talk gives an overview on investigations of the very high cycle fatigue (VHCF) lives of titanium alloys (Ti6Al4V, γ-TiAl) and the nickel-base superalloy IN718 at RT as well as application-relevant high temperatures up to 700°C by ultrasonic fatigue. The analysis of the fatigue fracture surfaces provides the failure-relevant microstructural features of AM states and conventionally manufactured reference materials.

KEYWORDS:
Additive manufacturing, Very high cycle fatigue

C1-502

Contribution of self-heating measurements under cyclic loading to the study of VHCF properties at high temperature of nickel-based superalloys

Alexis MION[1,3,*], Cédric DOUDARD[1], Jonathan CORMIER[2], Vincent ROUÉ[3], Dimitri MARQUIÉ[3], and Sylvain CALLOCH[1]

[1] ENSTA Bretagne, IRDL – UMR CNRS 6027, 2 rue François Verny, 29200 Brest, France
[2] ISAE-ENSMA, Institut Pprime – UPR CNRS 3346, 1 Avenue Clément Ader, BP 40109, 86961 Futuroscope Chasseneuil Cedex, France
[3] Safran Aircraft Engines, Rond-Point René Ravaud - Réau, 77550 Moissy-Cramayel, France

* Corresponding author: alexis.mion@ensta-bretagne.org

ABSTRACT:

Components used for the hot sections of aero-engines are subjected to high thermomechanical stresses, particularly of the vibratory type. The improvement in the efficiency of aeronautical engines, which involves an increase in operating temperatures, as well as the need to reduce mass, means that these parts have to withstand severe mechanical and thermal stresses. It is therefore critical to improve the fatigue design methods of these parts, especially in the HCF and VHCF domains. However, the implementation of predictive models is time-consuming as the fatigue behavior depends on many parameters.

The self-heating method, which is based on the measurement of the temperature evolution of a specimen during cyclic stresses, makes it possible to considerably reduce characterization times.

High temperatures self-heating tests are conducted on two nickel-based superalloys: INCONEL 718 (polycrystalline forged alloy), and AM1 (single crystal cast alloy). Low frequency tests (20 Hz) are carried out on a hydraulic machine. We also propose a test protocol using an ultrasonic fatigue machine (20 kHz), as well as an adapted data analysis method. The objective is to identify the dissipative mechanisms of these alloys, since their understanding will be useful for the study of fatigue properties.

KEYWORDS:

VHCF ; Self-heating ; High temperatures ; Nickel-based superalloys ; dissipative mechanisms

Figure 1 : Ultrasonic fatigue machine and inductive specimen heating system

C1-503

Nanograin formation mechanism under fatigue loadings in additively manufactured Ti-6Al-4V alloy

Weiqian CHI[1], Wenjing WANG[1,*] and Chengqi SUN[2]

[1] Beijing Jiaotong University, CHINA
[2] Institute of Mechanics, Chinese Academy of Sciences, CHINA

* Corresponding author: wjwang@bjtu.edu.cn

ABSTRACT:

Quasi in-situ electron backscatter diffraction (EBSD) observation during fatigue loading was conducted at of additively manufactured (AM) Ti-6Al-4V alloy to investigate the microstructure evolution before the crack initiation. The research indicates that the basal slips, prismatic slips and pyramidal <*a*> slips are main slip types in α grains at low cycle fatigue. The deformation twinning all occurs in the α grains with the *c*-axis nearly parallel to the applied stress i.e., hard grains. Further transmission electron microscopy (TEM) and high resolution transmission electron microscopy (HRTEM) observations show that the twinning part of α grains is more conducive to prismatic slip, and the $\{10\bar{1}2\}$ twin boundaries presented serrated character, splitting the original α hard grains into nanograins. The results suggest that the slip-induced dislocation cells or dislocation walls and thus subgrain generation, and the interaction of twin variants ($\{10\bar{1}2\}$ $<10\bar{1}1>$) with large orientation (~85°) generated by deformation twinning together results in the nanograin formation.

KEYWORDS:

Additively manufactured titanium alloy; Very high cycle fatigue; Crack initiation; Twinning; Nanograin formation

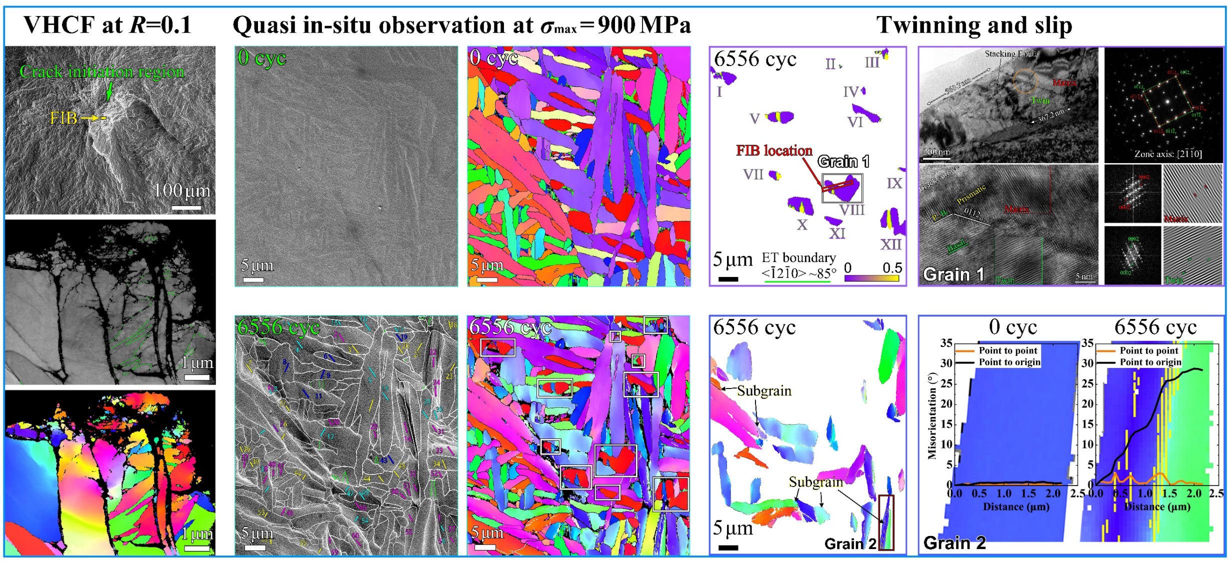


Fig. 1 *Microstructure evolution during ultrasonic frequency fatigue loading and conventional fatigue loading at R=0.1.*

C1-504

Very high cycle fatigue properties of bearing steels at elevated temperatures

Suraj S. MORE[1], Guillermo E. MORALES-ESPEJEL[2], Herwig MAYER[1] and Bernd M. SCHÖNBAUER[1,*]

[1] University of Natural Resources and Life Sciences (BOKU), Vienna, AUSTRIA
[2] SKF Research & Technology Development, Houten, THE NETHERLANDS

* Corresponding author: bernd.schoenbauer@boku.ac.at

ABSTRACT:

In this study, the effect of temperature on the high and very high cycle fatigue (HCF/VHCF) properties of three high carbon chromium bearing steels is investigated. Ultrasonic fatigue tests up to more than 10^{10} cycles were performed with 52100, 52100-VIM/VAR (i.e. vacuum induction melting (VIM) followed by vacuum arc remelting (VAR)) and M50-VIM/VAR at room temperature, 200 °C and 300 °C. Furthermore, hardness measurements were conducted after different exposure times to elevated temperature. It is found that the fatigue strength significantly decreases with increasing temperature – which is more pronounced for 52100 steels due to softening at elevated temperature. The fracture mechanism in the VHCF regime is identified as interior crack initiation at non-metallic inclusions (52100) and carbides (52100-VIM/VAR and M50-VIM/VAR), independent of temperature. Considering the sizes of crack-initiating inclusions/carbides, the results are evaluated applying fracture-mechanics principles. An equation based on the $\sqrt{area}$-parameter model is proposed which successfully predicts the fatigue limit in the VHCF regime at different temperatures.

KEYWORDS:

Bearing steel; very high cycle fatigue; elevated temperature; fatigue limit; fracture mechanics

C1-505

Factors in ODA-like Morphology on the Fracture Surface in Beta Titanium Alloys

Rajshree AWASTHI[1], Gaoge XUE[1], Nao FUJIMURA[2], Kosuke TAKAHASHI[2] and Takashi NAKAMURA[2,*]

[1] Division of Mechanical and Space Engineering, Hokkaido University, JAPAN

[2] Division of Mechanical and Aerospace Engineering, Hokkaido University, JAPAN

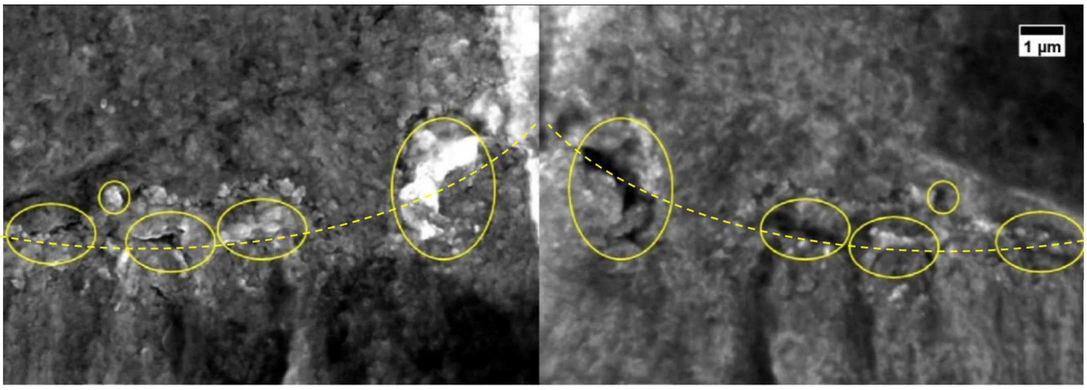
* Corresponding author: nakamut@eng.hokudai.ac.jp

ABSTRACT:

Internal fatigue fracture in high-strength steels, usually reported in the very high cycle fatigue (VHCF) regime at over 10^7 cycles, reveals a characteristic concavo-convex feature known as the optically dark area (ODA) on the fracture surface. However, internal fractures in beta titanium alloys can occur at as low as 10^5 cycles and are characterized by the absence of ODA. The objective of the current study is to investigate the contributing factors of ODA formation in beta titanium alloy, based on the idea that internal cracks can be simulated by the surface crack in a vacuum environment. A repeated contact experiment of the crack surfaces was performed on a pre-fatigued crack in Ti22V4Al up to VHCF regime at a negative load ratio in air and vacuum environments, followed by fracture surface observation using scanning electron microscopy. As a result, an ODA-like morphology was observed only in a vacuum dispersed on the crack front region (Fig. 1). Thus, a vacuum environment and a sufficient number of cycles are considered essential factors in ODA formation. The fact that the ODA-like morphology appeared mainly on the crack front can be explained by the heavy repeating compression produced by the crack front's plasticity-induced crack closure.

KEYWORDS:

Internal fracture; vacuum; beta titanium alloy; VHCF; ODA



(a) (b)

Fig. 1 *ODA-like morphology encircled in yellow on the crack front (dotted lines) on the mating fracture surfaces in Ti22V4Al after the repeated contact experiment in a vacuum (number of repeating contacts = $3x10^7$ cycles; load ratio = -1; vacuum pressure = $1.3x10^{-5}$ Pa). (a) The upper and (b) lower parts of the fractured specimen, respectively.*

C1-506

Thermodynamic Investigation on the Crack Growth Behavior at Very High Cycle Fatigue Regime

Yujia Liu[1], Bo Xu[1], Sen Tang1,[2], Lang Li[1], Chao He[1], Chong Wang[1,*], and Qingyuan Wang[1,2]

[1] Sichuan University, China
[2] Chengdu University, China

* Corresponding author: chongwang@scu.edu.cn

ABSTRACT:
This paper presents a thermodynamic characterization method for estimating the internal crack growth rate, which has been a puzzle in very high cycle fatigue research. A theoretical approach of surface temperature is discussed with crack size, initiation site, and time for thin sheet material. Infrared thermography is used to study the inner crack behavior and the heat dissipation phenomenon under 20 kHz vibration loading on high-strength stainless steel. A numerical simulation reveals the consequent temperature elevation on the surfaces by the heat generation at the crack tip and the heat conduction. Ultimately, the internal crack growth rate and final fatigue failure prediction are obtained by combining the calculation of heat dissipation and the observed evolution of the surface temperature field.

KEYWORDS:
Very high cycle fatigue; Internal crack; Fatigue crack propagation; Infrared thermography; Thermal dissipation

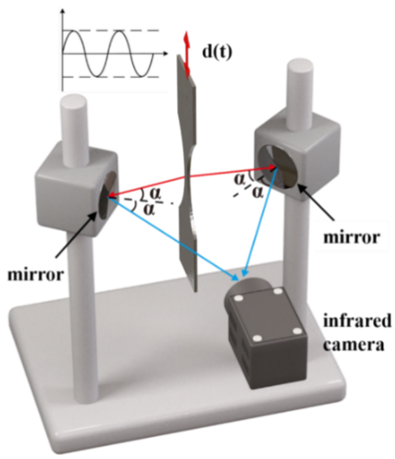


Fig. 1 *Device schematic for surface temperature based on synchronous monitoring.*

C1-507

Construction of Probabilistic Model on Interior Crack Nucleation and Propagation in Very High Cycle Fatigue of High Strength Steels

Yuki NAKAMURA[1]*, Akiyoshi NAKAGAWA[2], Noriyasu OGUMA[3], Seiichiro TSUTSUMI[4] and Tatsuo SAKAI[5]

[1] National Institute of Technology, Toyota College, JAPAN
[2] Hitachi Industrial Products, Ltd., JAPAN
[3] University of TOYAMA, JAPAN
[4] Osaka University, JAPAN
[5] Ritsumeikan University, JAPAN

* Corresponding author: nakamura@toyota-ct.ac.jp

ABSTRACT:

In case of the high strength steel, fatigue crack tends to occur around the interior inclusion in very high cycle regime. The fine granular area (FGA) is usually formed in the vicinity around the inclusion as shown in Fig.1. Within the FGA, a lot of fine grains having the size of 1 μm can be observed, while the fracture surface outside the FGA is very smooth. It is well known that the stress cycles to nucleate the FGA occupies more that 99% of the total fatigue life of the material. Thus, the nucleation and the propagation behaviors of high strength steel is an important subject to ensure the safety of the mechanical structures. From this viewpoint, probabilistic model was constructed on the crack nucleation and propagation behaviors based on the intermittent debonding of fine cells and their coalesces along the long sequence of the stress cycling. Analytical results thus obtained is in good agreement with the experimental results reported by several researchers.

KEYWORDS:

Very High Cycle Fatigue, Interior Crack Nucleation, FGA, Probabilistic Model, Crack Growth Law

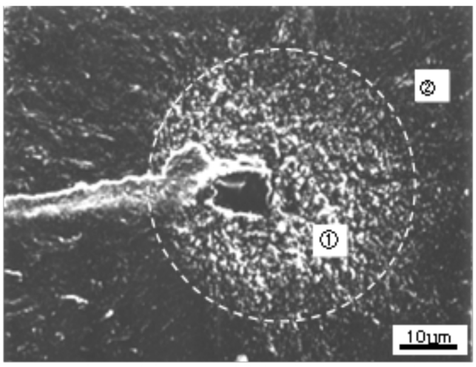


Fig. 1 *FGA formed around inclusion.*

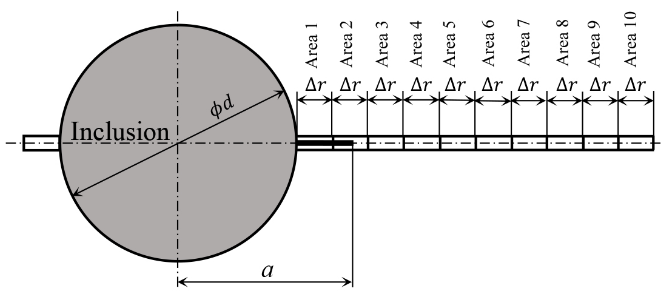


Fig.2 *Concept of probabilistic model.*

C1-508

Fatigue Mechanism for an Additively Manufactured Aluminium Alloy up to Very-High-Cycle Regime

Xiangnan PAN and Youshi HONG*

LNM, Institute of Mechanics, Chinese Academy of Sciences, CHINA

* Corresponding author: hongys@imech.ac.cn

ABSTRACT:

Fatigue failures of aluminium alloys still occur beyond 10^7 cycles, i.e. very-high-cycle fatigue (VHCF). Generally, the S-N curves and the related fractography of conventional aluminium alloys are different from high-strength steels and titanium alloys. Here, we prepared an additively manufactured (AM) AlSi10Mg and conducted fatigue tests of axial cycling with electromagnetic resonance (110 Hz) and ultrasonic vibration (20 k ± 500 Hz) up to very-high-cycle regime. We proposed a mechanism to describe fatigue behavior of the AM alloy, and discussed the effects of loading frequency, mean stress or stress ratio *R* on the fatigue behavior. The loading frequency does not affect the S-N values and fracture modes. The AM pores play a key role in fatigue crack initiation similar to the inclusions in high-strength steels, which presents almost identical crack initiation behavior with a characteristic region of fine granular area (FGA) under different mean stresses with a stress ratio at $R < 0$ or $R > 0$. The FGA profile microstructure is identified as a nanograin layer with Si rearrangement and grain boundary transition. This process consumes a large amount of cyclic plastic energy making FGA to undertake a vast majority of VHCF life.

KEYWORDS:

very-high-cycle fatigue (VHCF); crack initiation; mean stress; additive manufacturing; aluminium alloy

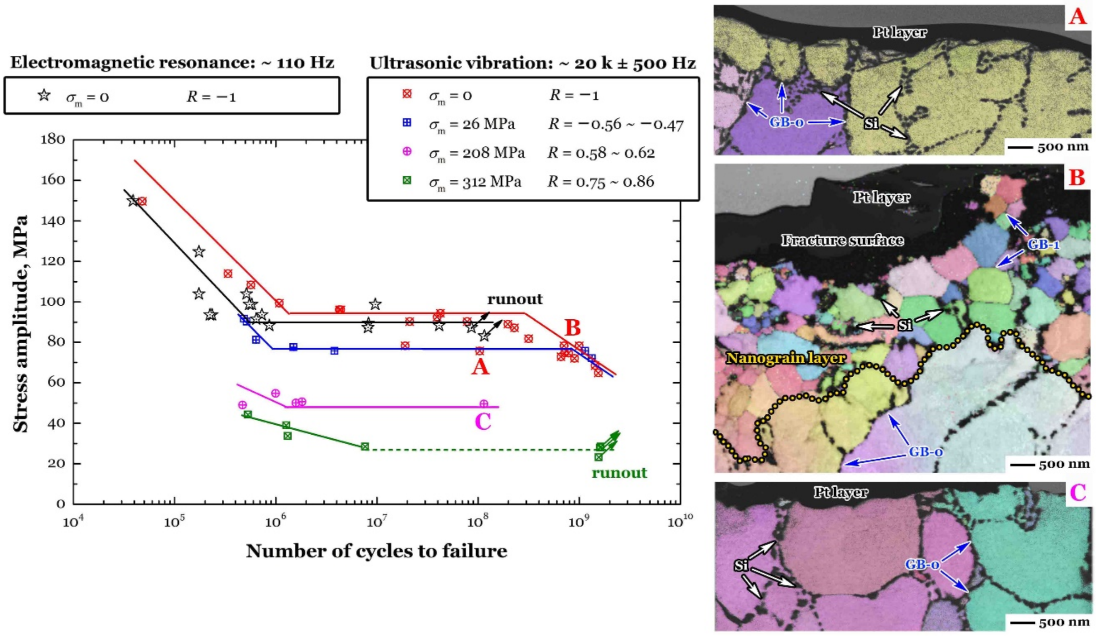


Fig. 1 *S-N curves and microstructure features of representative specimens.*

C1-509

Localized oxidation assisting microcrack initiation in a LPSO-reinforced Mg-RE alloy up to very-high-cycle-fatigue regime

Yao Chen[1,2,*], Fulin Liu[2], Chao He[2], Yongjie Liu[2], Qiang Chen[1], Qingyuan Wang[2]

[1] Kyushu University, JAPAN
[2] Sichuan University, CHINA

* Corresponding author: chen.yao.632@m.kyushu-u.ac.jp & yaochen@scu.edu.cn

ABSTRACT:
The transition from a crack-free to a cracked state in very-high-cycle-fatigue regime is a complex phenomenon that remains difficult to understand. Mg-rare earth alloys, containing the long-period stacking ordered (LPSO) phase, exhibit superior mechanical properties. According to the present study, microcracks tend to nucleate from the thick α-Mg layers, which are located away from the dense LPSO lamellae. Interestingly, microcrack nucleation occurred within the highly localized oxides that were orders of magnitude thicker than the native oxide. This study highlights the critical role that these localized oxides play in the process of microcrack nucleation. The proposed model suggests that the extrusion/intrusion process is important, but that the oxidation that occurs during fatigue plays a key role in the embrittlement of the extrusion/intrusion structure. This, in turn, affects the nucleation of microcracks. The 'fatigue-induced oxidation' and 'oxygen embrittlement' process for microcrack nucleation is distinct from the existing fatigue mechanisms for metals.

KEYWORDS:
Mg-RE alloy; Very high cycle fatigue; Fatigue crack initiation; Fatigue-induced oxidation; Oxygen embrittlement

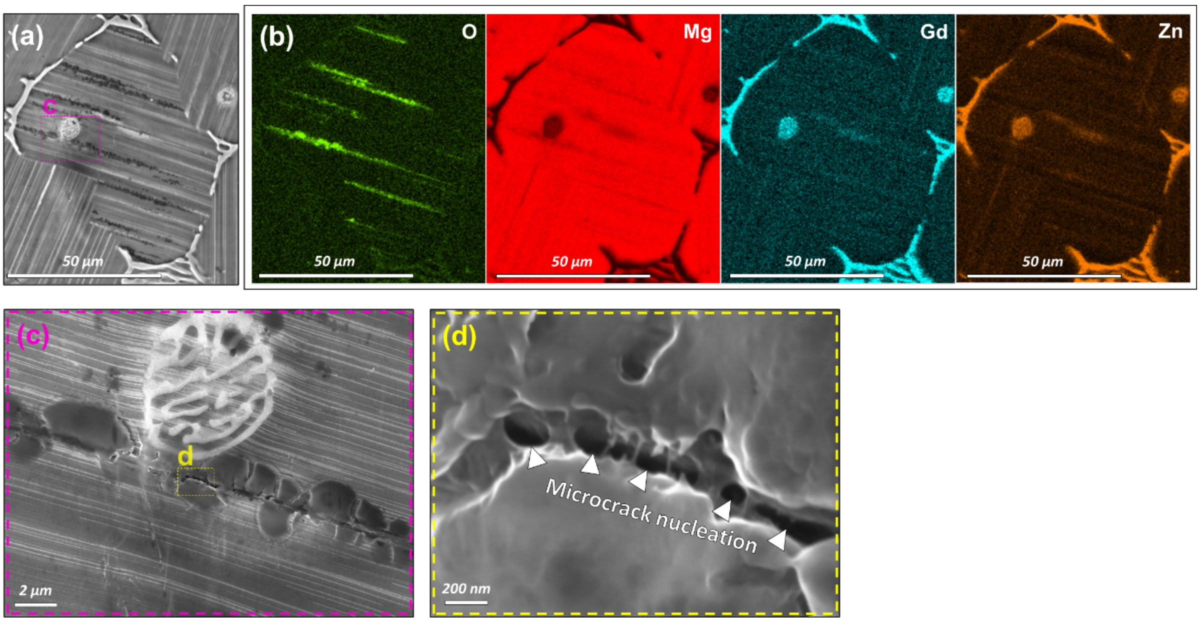


Fig. 1 *Highly localized oxide assisting microcrack nucleation.*

C1-510

Characterizing the very high cycle fatigue behavior of CF-PEKK material under ultrasonic cyclic bending loads

Aravind PREMANAND[1*] and Frank BALLE[1,2,3]

[1] Department for Sustainable Systems Engineering (INATECH), University of Freiburg, Germany
[2] Freiburg Material Research Center (FMF), Germany
[3] Fraunhofer Institute for High Speed Dynamics Ernst-Mach-Institute (EMI), Germany

* Corresponding author: aravind.premanand@inatech.uni-freiburg.de

ABSTRACT:
Accelerated cyclic loading using an ultrasonic fatigue testing system is one potential solution to evaluate the very high cycle behavior of composite materials within a reasonable time. Insufficient sampling rate and accuracy of non-contact measurement devices pose a critical challenge in realizing fatigue experiments with the currently available online damage monitoring techniques. This study aims to overcome these challenges by correlating different damage characterization techniques to capture the damage evolution in a carbon fabric-reinforced poly-ether-ketone-ketone (CF-PEKK) composite material system. Fatigue experiments were carried out under three-point bending loading conditions at a cyclic frequency of 20 kHz. Various parameters, such as the surface temperature, the cyclic displacement, and the input resonance parameters of the ultrasonic generator, were recorded during these experiments. The VHCF behavior of the CF-PEKK material system was characterized based on these results and the digital light optical microscopy.

KEYWORDS:
Ultrasonic fatigue testing; Online monitoring techniques; very high cycle fatigue; carbon fiber reinforced polymers; infra-red thermography.

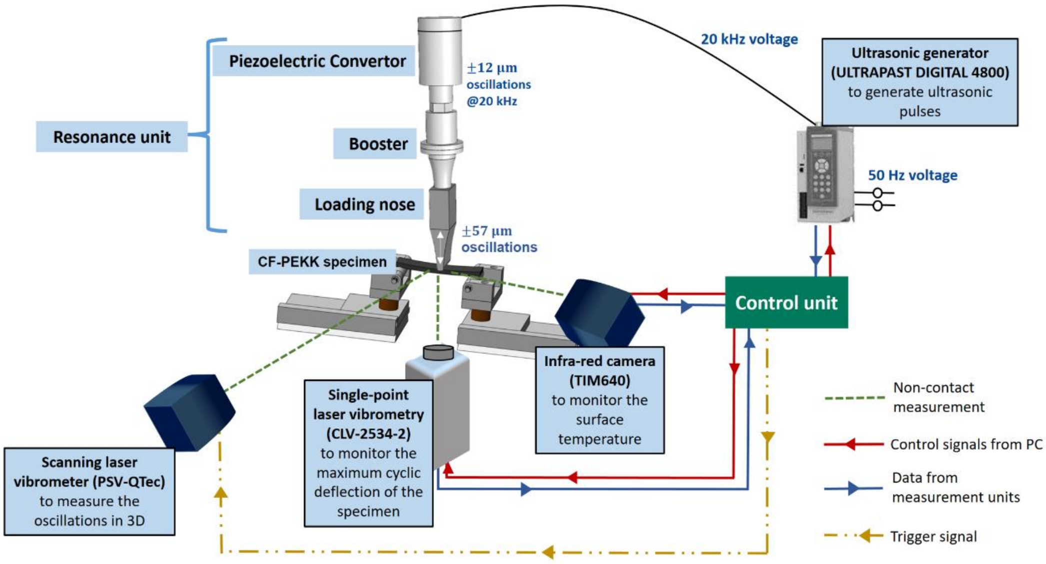


Fig. 1 *Description of the ultrasonic fatigue test system with different online monitoring techniques*

C1-511

New fatigue limits in gigacycle fatigue of high-strength steels

Yoshiyuki FURUYA[1, *]

[1] National Institute for Materials Science, JAPAN

* Corresponding author: FURUYA.Yoshiyuki@nims.go.jp

ABSTRACT:

Gigacycle fatigue tests were conducted up to 10^{11} cycles to confirm the presence of the new fatigue limit in high-strength steels. The 10^{11}-cycles fatigue test took 2 months even by using ultrasonic fatigue testing at 20 kHz. 3 specimens were tested beyond 10^{10} cycles. A test of a specimen was terminated at around 5 x 10^{10} cycles, while 2 specimens reached 10^{11} cycles. Namely, no specimen failed above 10^{10} cycles, demonstrating the presence of the new fatigue limit. The runout specimens were forcibly fatigue-fractured in short lives to observe ODAs (Optically Dark Areas). As the result, the ODAs was observed, meaning that small internal cracks existed in the runout specimens. Non-propagating cracks were thus the mechanism of the presence of the new fatigue limit.

KEYWORDS:

Very high cycle fatigue, internal fracture, high-strength steel, inclusion, internal crack

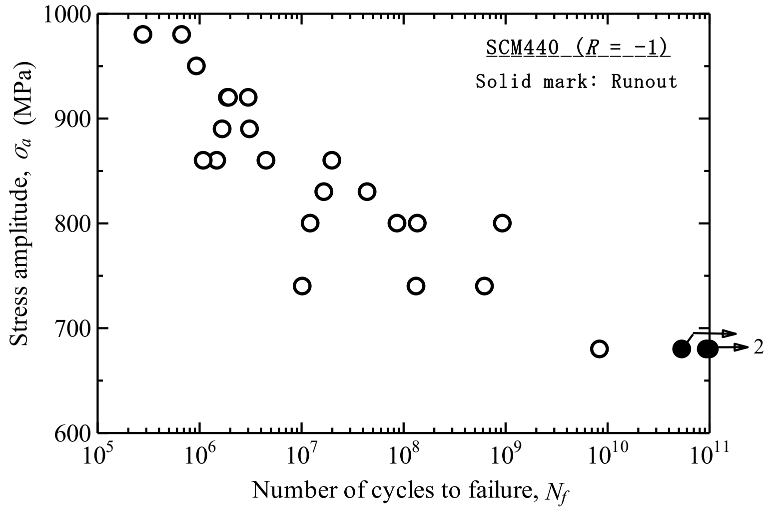


Fig. 1 10^{11}-cycles fatigue test results.

C1-513

Microstructural changes during fatigue loading in the very high cycle regime of the metastable austenitic steel AISI 347 at 573 K

Elen REGITZ[1*], Marek SMAGA[1], Yuliya HANESCH[2], Magdalena SPEICHER[2], Tilmann BECK[1],

[1] Institute of Material Science and Engineering (WKK), RPTU Kaiserslautern-Landau, GERMANY
[2] Materials Testing Institute, University of Stuttgart, GERMANY

* Corresponding author: e.regitz@mv.rptu.de

ABSTRACT:
During the operation of nuclear power plants, reactor internals made of austenitic stainless steels (ASSs) undergo various loadings in different fatigue regimes, including low cycle fatigue (LCF), high cycle fatigue (HCF) and very high cycle fatigue (VHCF). While the LCF and HCF behavior of ASSs is well studied, VHCF remains a subject of ongoing research. This contribution focuses on the fatigue behavior of the metastable austenitic stainless steel AISI 347 in the VHCF regime at 573 K. The material behavior was investigated using both an ultrasonic fatigue testing system with a load frequency of 20 kHz and a high frequency servo-hydraulic testing system with a load frequency of 980 Hz. The study revealed a discontinuity in the fatigue life, where some specimens broke, while others reached the endurance limit at the same load level when entering the VHCF regime. Therefore, the microstructural changes in the respective specimens, such as the dislocation density and arrangement, stacking faults and twin formation as well as the formation of α´-martensite at the specimen´s surface and in the bulk material were investigated using transmission electron microscopy (TEM), scanning electron microscopy (SEM) and X-ray diffraction. These findings contribute to a better understanding of the VHCF behavior of ASSs at elevated temperature.

KEYWORDS: Austenitic stainless steels; VHCF; 573 K; TEM; REM

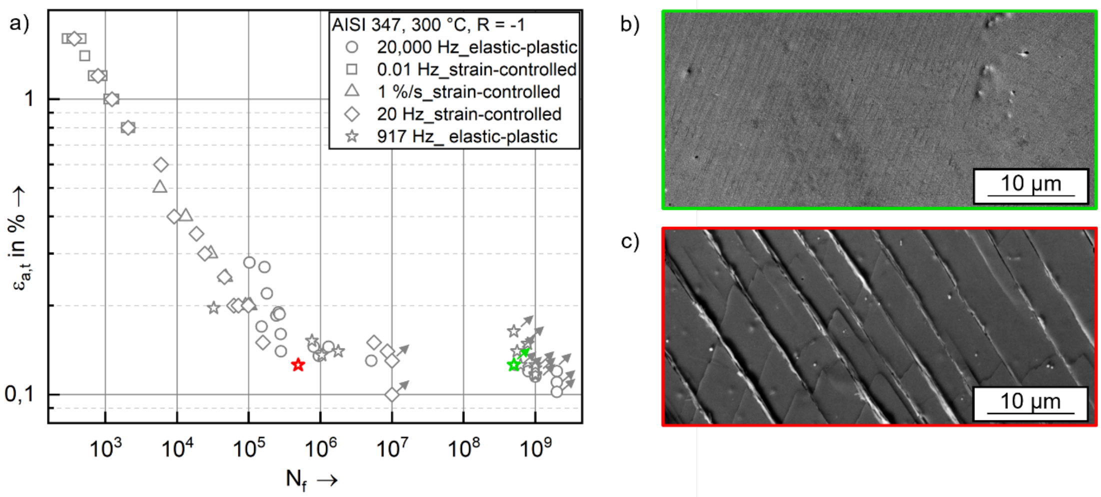


Fig. 1 *S-N curve of AISI 347 at 573 K (a) and comparison of SEM micrograph of a specimen´s surface reaching the endurance limit in VHCF range (b) and failed in HCF regime (c) tested at the same load level of 0.126 %.*

C1-514

Mechanism of nanograin formation and crack initiation for very high cycle fatigue of titanium alloys

Chengqi SUN* and Han WU

State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, CHINA

* Corresponding author: scq@lnm.imech.ac.cn

ABSTRACT:
Extensive results have shown that nanograins usually form in the initial coarse grains during crack initiation and early growth of metals in very high cycle fatigue (VHCF) regime. However, a pending issue is how these nanograins form to cause fatigue cracking in metals. In this paper, VHCF behavior of a TC17 alloy was investigated at room temperature and in air. It shows that nanograins form in a locally high-stress concentration region during fatigue loadings, and twinning is an important contributor to the nanograin formation. The locally high-stress concentration results in the twinning or slip in preferentially oriented α grains. Then, the interaction between twin systems or dislocations induces the formation of dislocation cells or walls, the nucleation of microbands, and finally the nanograins. As a result, the nanograin regions and the boundaries between the nanograin and the coarse grain regions become preferential sites for crack initiation and early growth. The findings give a new insight into the crack initiation mechanism in the fatigue of metals.

KEYWORDS:
Very high cycle fatigue; titanium alloy; twinning; nanograin deformation; crack initiation mechanism

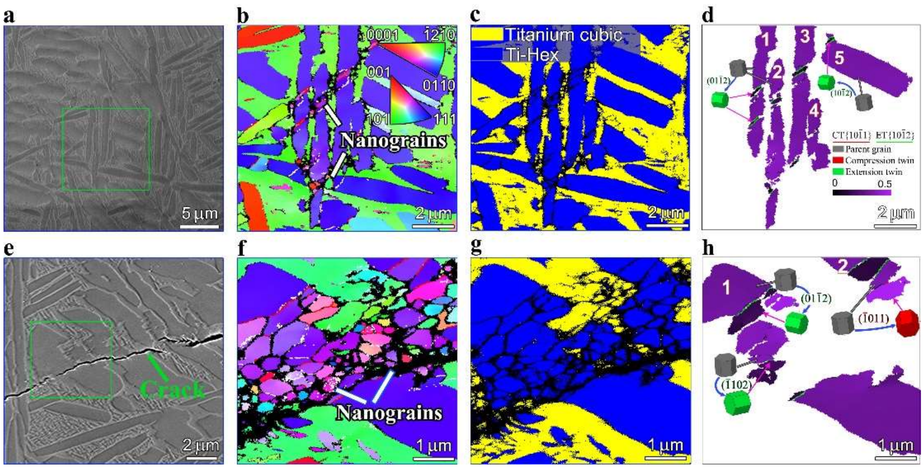


Fig. 1 *SEM and EBSD results of a fatigued specimen experiencing 1.4×10⁸ cycles under σ_a=588 MPa and R=-1. a: SEM image of a non-cracking region. b-d: inverse pole figure, phase map and Schmid factor for basal slip system of α grains in the rectangular region in a, respectively. e: SEM image of a region with a small crack. f-h: inverse pole figure, phase map and Schmid factor for basal slip system of α grains in the rectangular region in e, respectively. Loading direction is up and down along the paper.*

C1-516

Effects of Induction hardening and Press-Fitting on Very High Cycle Fatigue Properties of Railway Axle Steel

Makoto AKAMA[1,*], Wutong WANG[1], Masahiro TSUKAHARA[2], Yoshitaka MISAKA[2], Shinya MATSUDA[3], Benjamin GUENNEC[4] , Noriyo HORIKAWA[4] and Tatsuo SAKAI[5]

[1] Osaka Sangyo University, JAPAN
[2] Neturen Co., Ltd., JAPAN
[3] Kagawa University, JAPAN
[4] Toyama Prefectural University, JAPAN
[5] Ritsumeikan University, JAPAN

* Corresponding author: akama@tm.osaka-sandai.ac.jp

ABSTRACT:
Rotating bending fatigue tests were performed to investigate the effects of induction hardening (HQI) and press-fitting (PF) on the very high cycle fatigue (VHCF) properties of the axle steel. In addition, finite element analyses (FEA) and scanning electron microscope (SEM) observations were conducted to elucidate the phenomenon. The results obtained are summarized as follows; (1) It was found that the fatigue strength of the axle steel was improved by almost 300 MPa by HQI; (2) A lot of specimens of the HQI had fractured in VHCF region, therefore, the consideration of VHCF properties should be taken into account in the design of railway axles; (3) Crack initiation sites can be classified into three forms; the surface of the HQI layer in the minimum section, the base metal beyond the HQI layer in the axial direction, and the internal base material in the minimum section; (4) These can be reconfirmed through the comparison between the local fatigue strength distribution and the bending stress distribution obtained by FEA; (5) The fatigue strength was decreased by almost 200MPa by PF; (6) FEA showed that high stresses occur at the edge of the PF due to the stress concentration.

KEYWORDS:
Very high cycle fatigue; Railway axle; Induction hardening; Press-fitting; Finite element analysis

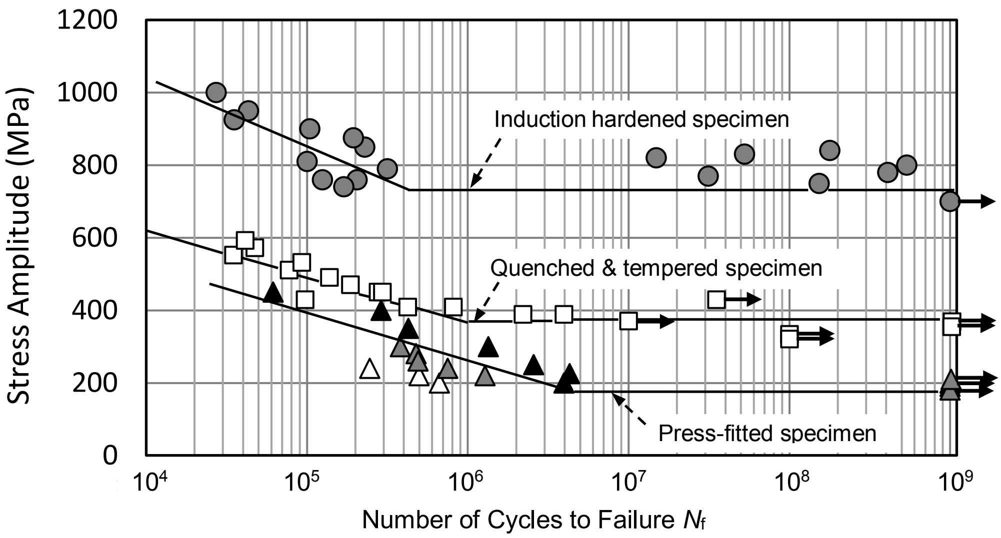


Fig. 1 *S-N curve.*

C2-501

Modelling Cyclic Deformation and Fatigue Crack Growth through Coupling of Phase Field and Viscoplasticity

Jianan SONG[1] and Liguo ZHAO[2,*]

[1] Central South University, China
[2] Nanjing University of Aeronautics and Astronautics, China

* Corresponding author: L.Zhao@nuaa.edu.cn

ABSTRACT:
For metals, especially at elevated temperatures, the viscoplastic behavior plays an important role in cyclic deformation and fatigue crack propagation. In this paper, a coupled phase field-viscoplasticity approach was developed to model the time-dependent deformation and crack growth in a nickel-based superalloy under fatigue. The coupled approach was further applied to study 2D crack growth in CT specimens under different model I cyclic loading conditions, focusing on the effect of dwell periods imposed at peak loads. In addition, 3D crack growth was also studied using the coupled approach, aiming to clarify the effect of varied multiaxial stress state along the 3D crack front. The coupled model has an advantage in predicting the cyclic softening behavior of the alloy caused by fatigue damage, overcoming a major limitation of the original cyclic viscoplasticity model. The coupled approach is also highly effective in predicting fatigue crack propagation under varied dwell times at peak load, an important behavior for crack growth under dwell fatigue. By incorporating the stress triaxiality factor, the coupled model was also able to capture both the geometrical feature of the 3D crack front and the overall crack growth rate, confirming the predicative capability of the coupled model.

KEYWORDS:
Phase field; Viscoplasticity; Coupled model; Cyclic softening; Fatigue crack propagation.

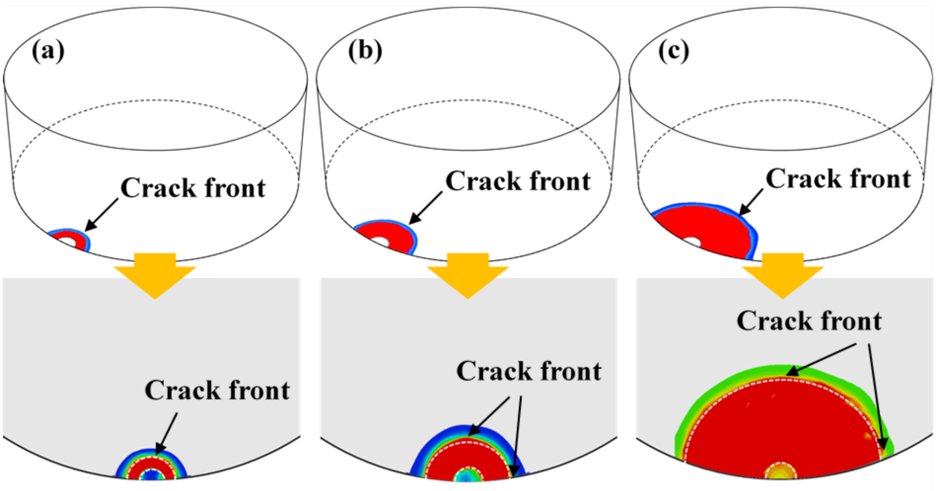


Fig. 1 *Growth path of 3D surface crack at (a) 10 cycles, (b) 18 cycles and (c) 20 cycles.*

C2-502

Process-performance-prediction integration oriented to fatigue life improvement: implementation in high-temperature structures based on dual-scale modeling approach

Kai-Shang LI[1], Run-Zi WANG[2,*], Xian-Cheng ZHANG[1,*], Shan-Tung TU[1]

[1] East China University of Science and Technology, CHINA
[2] Tohoku University, JAPAN

* Corresponding author: runzi.wang@rift.mech.tohoku.ac.jp & xczhang@ecust.edu.cn

ABSTRACT:

Advanced surface strengthening processes (SSPs) can effectively improve fatigue performance of polycrystal materials. However, how to quantitatively reveal life improvement mechanisms and address dominant role in life improvement still remain great challenge. In this work, the process-performance-prediction integration (3P integration) is developed to improve the fatigue life and reveal the underlying strengthening mechanisms of high-temperature structures after a novel SSP, where a specific dual-scale modeling approach is proposed to refine the close-loop system. In the macro-scale simulation, the cyclic deformation behavior is addressed by a phenomenological constitutive model. The local deformation histories in weak region calculated from the macro-scale simulation are supplied to the micro-scale simulation as boundary conditions. The micro-scale simulation solves the local damage evolution of holed structures after SSP by using a modified crystal plasticity theory. Excellent agreements between experimental data and predicted results in terms of fatigue life and damage mechanisms prove the robustness and accuracy of the proposed dual-scale modeling approach. Finally, a feedback link in the 3P integration is established by the proposed approach combined with different residual stresses and plastic layers. The significant fatigue life improvement is mainly ascribed to residual stress, while plastic layer plays a synergistic role in the life performance.

KEYWORDS:

Process-performance-prediction; Dual-scale modeling; Cold expansion; Crystal plasticity; Fatigue life improvement prediction

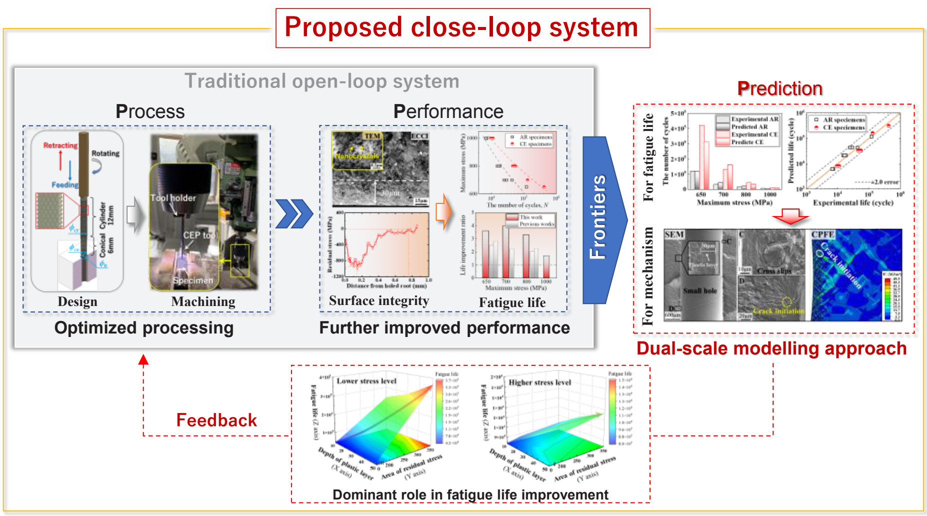


Fig. 1 *A 3P close-loop integration system for holed structures after cold expansion process.*

C2-503

Physics-based modelling of HCF variability in carburized steels

Vincent ARGOUD[1,2], Franck Morel[1], Etienne Pessard[1], Daniel BELLETT[1]

[1] *Arts et Metiers Institute of Technology, LAMPA, HESAM Université, F-49035 Angers, France*
[2] *Safran Tech, Materials and Processes Department, Rue des Jeunes Bois, Châteaufort, 78114 Magny-Les-Hameaux, France*

* Corresponding author: franck.morel@ensam.eu

ABSTRACT:

Several works conducted during the 90's and 00's demonstrate that for some metallic materials VHCF can leads to a "duplex S-N curve". In this work, from a large fatigue testing campaign carried out in the HCF and VHCF regimes, a significant variability in fatigue life – ranging from 10^4 to 10^9 cycles – is observed on two low pressure case-hardened steels, leading to a duplex S-N curve. Thanks to detailed fracture surface observations and analyses, part of the variability can be explained by the competition between several initiation mechanisms leading to the formation of a bimodal distribution of the fatigue life. A probabilistic model based on the weakest link concept is proposed to predict the macroscopic behaviour (duplex S-N curve) while taking into account the physical phenomena leading to initiation. This model is identified on the one hand by means of crack propagation test results and on the other hand, by using a maximum likelihood estimator based on the fatigue test results. The ability of the model to predict the macroscopic behaviour is then discussed. Finally, the sensitivity of the model parameters is analysed to discuss the capacity of the model to predict other data sets.

KEYWORDS:

Steel ; carburizing ; VHCF ; bimodality ; probabilistic model

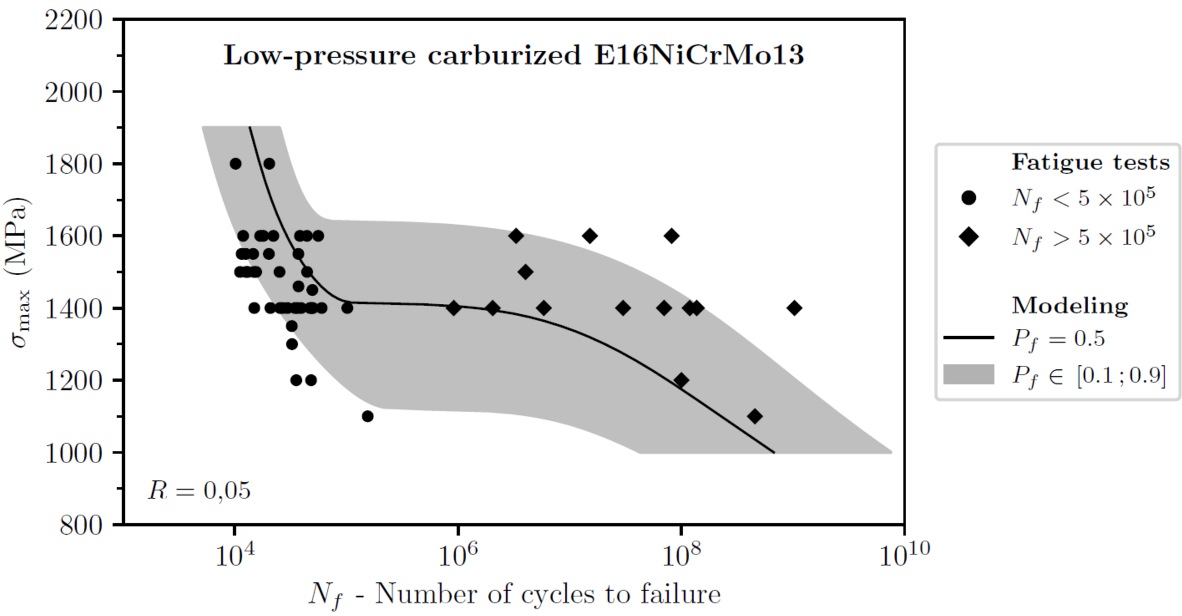


Fig. 1 *: Duplex S-N curve for the low-pressure carburized E16NiCrMo13 steel.*

C2-504

Phase-Field and Crystal Plasticity Coupling Model Investigation of Grain Growth under Fatigue Loading

Wei Peng[1], Jianbao Gao[2], Xiancheng Zhang[1,*], Lijun Zhang[2], Shantung Tu[1]

[1]Key Laboratory of Pressure Systems and Safety, Ministry of Education, School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai, 200237, China

[2]State Key Laboratory of Powder Metallurgy, Central South University, Changsha, 410083, China

Corresponding authors: xczhang@ecust.edu.cn (X.C. Zhang)

ABSTRACT:

The mechanical properties of materials are strongly influenced by microstructural features. It is crucial to accurately capture the heterogeneities and incorporate them into a continuum-scale framework to investigate microstructural evolutions under complex loading conditions. In this study, a phase-field and crystal-plasticity coupled model is built to investigate the interaction between mechanical behavior and grain growth in pure cp-Ti under fatigue loading. First of all, bi-crystal cases are simulated to present the basic idea that stress distribution and grain growth exhibit both anisotropy and periodicity under fatigue loading. Further for polycrystalline, the competing relationships of two grain-growth mechanisms, including grain rotation and grain boundary migration, are well revealed. Macroscopically, results show that the dominant mechanism for grain growth changes with the increase of loading frequency within high-cycle fatigue domain. Specifically, stored energy-driven grain boundary migration is the dominant factor at lower frequency, while grain merging induced by grain rotation takes the primary role at higher one. This study gives us a new computational pathway to explore microstructure evolutions under fatigue loading.

KEYWORDS: Fatigue; Titanium; Grain growth; Crystal plasticity; Phase field method.

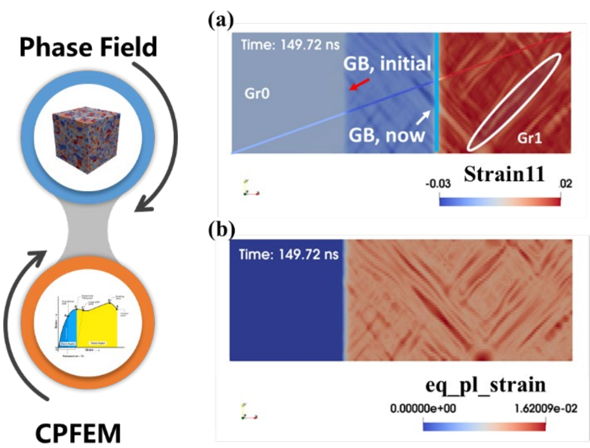


Fig.1. Schematic representation of the coupling model and stress/ equivalent plastic strain distribution.

C2-505

Molecular Dynamics Analysis of the Effect of Strain Rate on the Acceleration of the Degradation of the Crystallinity of a Grain Boundary under Creep-Fatigue Loads at Elevated Temperature

Takuma YAMAWAKI[1*], Ken SUZUKI[2], and Hideo MIURA[3]

[1] Department of Finemechanics, Graduate School of Engineering, Tohoku University, JAPAN
[2] Green X-Tech Center, Green Goals Initiative, Tohoku University, JAPAN
[3] Fracture and Reliability Research Institute, Graduate School of Engineering, Tohoku University, JAPAN

* Corresponding author: takuma.yamawaki.s1@dc.tohoku.ac.jp

ABSTRACT:
The crystallinity of heat-resistant alloys used in thermal power turbine blades are subjected to random change of creep-fatigue loading at elevated temperature, and it causes the drastic decrease in the fracture life of the alloys. Acceleration mechanism of the creep-fatigue damage at elevated temperature, therefore, was analyzed by molecular dynamics analysis. Since the crystallinity around grain boundaries are found to be degraded seriously, bicrystal structures were modeled for the damage analysis. Uniaxial creep-fatigue loads with different strain rate were applied to the structures with different combination of crystallographic orientations at 1073 K. Under the strain-controlled condition, it was found that the internal stress in the structure shifted to compressive stress side even under the strain ratio was zero (tensile side). The reason for this shift was attributed to the local plastic deformation around the grain boundary. In addition, the acceleration of the shift was clearly observed under faster strain rate as shown in Fig. 1. The acceleration was attributed to the activation of viscoelasticity of the alloy at elevated temperature. The insufficient relaxation during the fast-unloading condition due to viscoelasticity and further fluctuation of the local stress led to the acceleration of the crystallinity degradation of grain boundaries.

KEYWORDS:
Creep-fatigue damage, Strain rate, Crystallinity, Molecular Dynamics, Viscoelasticity

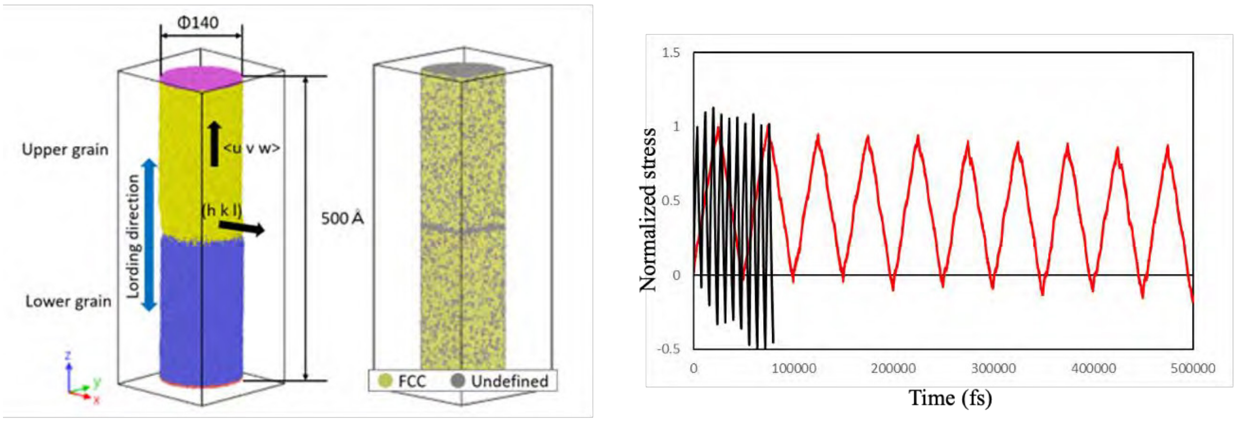


Fig. 1 *Bicrystal model for the molecular dynamics analysis and strain-rate-induced change in the internal stress under a strain-controlled load*

C2-506

Spectral method for fatigue life estimation of notched metallic structures under broad-band random vibration loadings

Daiyang Gao[1*]

[1] School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China

* Corresponding author: dygao@njust.edu.cn

ABSTRACT:

A critical distance parameter is proposed for the fatigue life analysis of notched specimens of metallic material under random vibration loadings, which is the equivalent Power Spectral Density(PSD) function of the line method stress given by the Theory of Critical Distance(TCD). The fatigue life of notched structures under random vibration loadings in the frequency domain could be estimated based on this damage parameter at the fatigue critical location with the spectral method for random vibration fatigue life calculation. The fatigue experiment under random vibration loadings is conducted on 2 types of notched plate specimens of 7075-T6 aviation grade aluminum alloy, where both circumstances of large and small stress gradients in the notch region are investigated. The experimental fatigue lives are compared to those calculated by the proposed method, where satisfactory prediction capability on random vibration fatigue life of the model is demonstrated for notch conditions of both steep and mild stress distribution variations.

KEYWORDS:

random vibration fatigue, notched fatigue, stress gradient, power spectral density, theory of critical distance

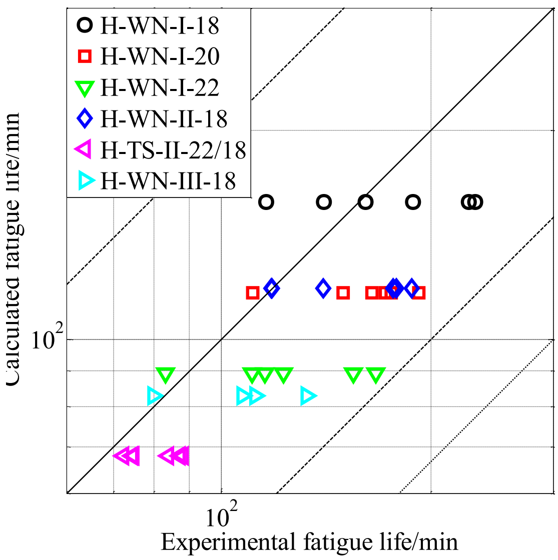


Fig. 1 *Fatigue life prediction results for hole specimens.*

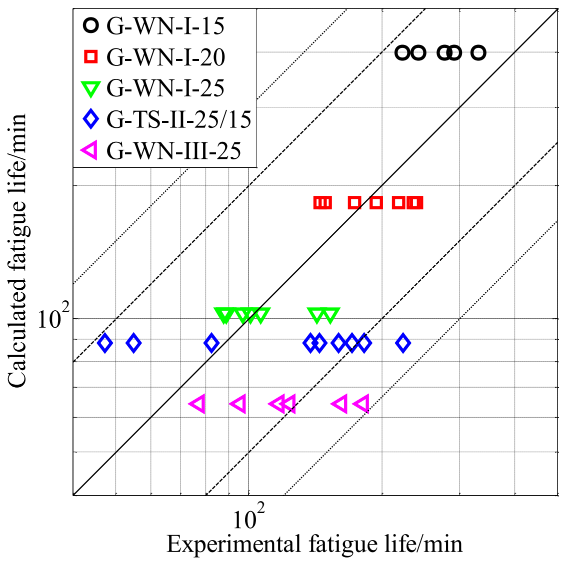


Fig. 1 *Fatigue life prediction results for groove specimens.*

C2-507

Multiscale Modeling Strategy for Accurately Predicting Fatigue Life of Steels

Kazuki SHIBANUMA[1,*], Hongchang ZHOU[1] and Masao KINEFUCHI[2]

[1] The University of Tokyo, JAPAN
[2] Kobe Steel, JAPAN

* Corresponding author: shibanuma@struct.t.u-tokyo.ac.jp

ABSTRACT:
This study presents a multiscale modelling strategy for accurately predicting the high-cycle fatigue strengths of steels. The required input data are only microstructural information, tensile properties, and loading conditions, without any adjustable material constants. In the proposed strategy, total fatigue life is estimated from crack growth life alone. The entire model comprises three sub-models, for: (i) a macroscopic finite element analysis, (ii) microstructure, and (iii) crack growth. The model was strictly validated against the results of experiments performed on three different steels under various loading conditions. Although the experimental fatigue life results exhibited wide variation, the predicted and experimental data were accurately matched over the entire range. The notch sensitivity of the fatigue limits depending on the material strength were successfully reproduced by the proposed model. The transition of the crack growth rate was also accurately predicted compared with the experimental results. The results demonstrate that the fatigue life of steels under high-cycle fatigue can be accurately predicted from crack growth life alone. Furthermore, the proposed strategy is capable of effectively explaining the dependence of fatigue strength on microstructure and loading conditions based on the fracture mechanics.

KEYWORDS:
Multiscale model; Fatigue life prediction; Small crack growth; Microstructure; Steels

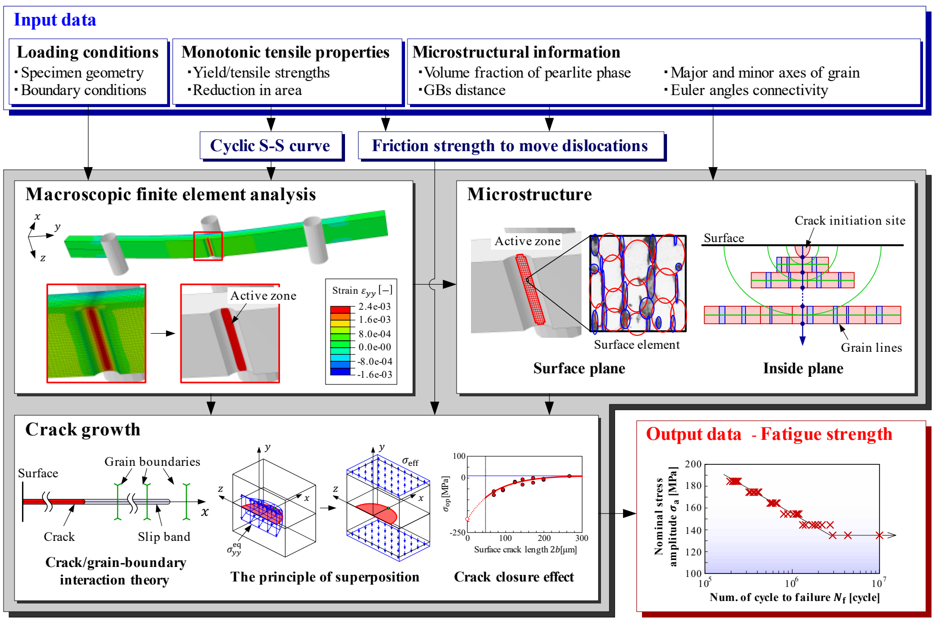


Fig. 1 *Outline of the proposed multiscale modelling strategy.*

C2-508

A Bridging Strategy between Microscopic and Macroscopic Crack Growth Simulations for Predicting Fatigue Strength of Steels

Hongchang ZHOU[1]*, Yuta SUZUKI[1], Masao KINEFUCHI[2], Siegfried SCHMAUDER[3], Kiarash DOGAHE[3] and Kazuki SHIBANUMA[1]

[1] The University of Tokyo, JAPAN
[2] Kobe Steel, Ltd., JAPAN
[3] University of Stuttgart, GERMANY

* Corresponding author: zhouhongchang@g.ecc.u-tokyo.ac.jp

ABSTRACT:

A strategy is proposed for bridging microscopic and macroscopic crack-growth simulations to efficiently and accurately predict the fatigue strength of steels. This strategy integrates a multiscale model with the concept of the bridging method. Validation is conducted by comparing experimental results of macro-crack specimens with numerical results of the multiscale model. The findings demonstrate a significant reduction of over 90% in numerical costs when employing the proposed strategy, as opposed to the multiscale model. Moreover, the proposed strategy achieves minimal errors of only 4.2% and 2.7% in fatigue life for the two macro-crack specimens under maximum loading conditions. Importantly, no errors in fatigue limits are observed with the proposed strategy when compared to the multiscale model. The accuracy and efficiency of the predicted results indicate that the proposed strategy can serve as a robust foundation for evaluating the fatigue failure behavior of thick components/structures in engineering applications.

KEYWORDS:

Fatigue life prediction; Multiscale model; Crack growth law; Steel.

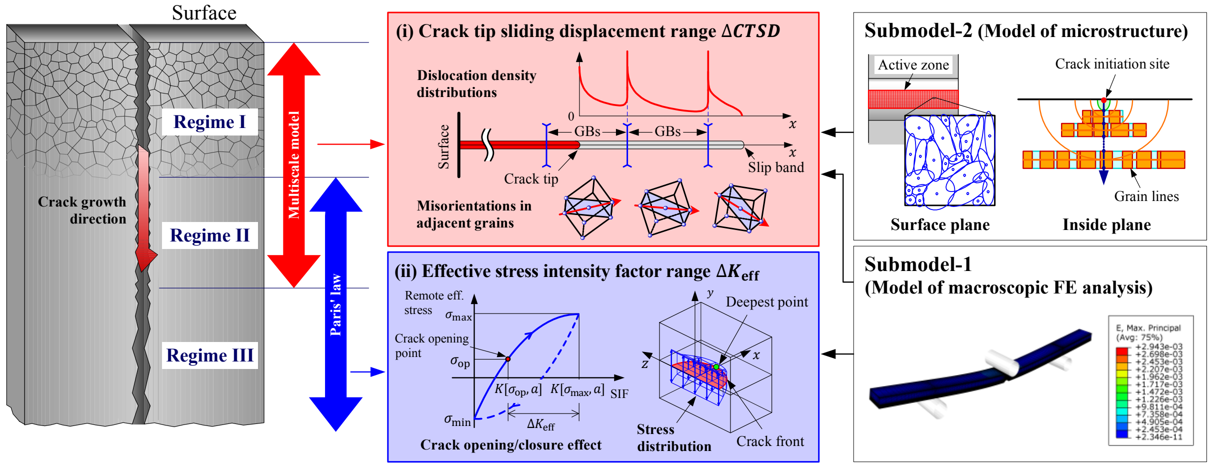


Fig.1 Outline of the proposed strategy for bridging microscopic and macroscopic crack-growth simulations.

C2-509

An elastoplastic constitutive model for effect of loading history on ratcheting and cyclic hardening behavior

Jiawei Bai[1,2,3,*] and Ke Jin[1,2,3]

[1] School of Aerospace Science and Technology, Xidian University, Xi'an, 710126, China
[2] Shaanxi Key Laboratory of Space Extreme Detection, Xi'an, 710126, China
[3] Key Laboratory of Equipment Efficiency in Extreme Environment, Ministry of Education, Xi'an, 710126, China

* Corresponding author: 18391982778@163.com

ABSTRACT:

The ratcheting or cyclic hardening/softening behavior of alloy steel structures often occurs due to complex cyclic loading in service, which affects the structure life. In this work, an elastoplastic constitutive model is developed to describe the effect of loading history on the cyclic plastic behavior of alloy steels under uniaxial loading. Based on the Abdel-Karim-Ohno model, a new kinematic hardening rule is proposed to simulate the ratcheting behavior by introducing the loading history variable and the nonlinear equation of ratcheting parameter. A new isotropic hardening rule is proposed to describe cyclic hardening/softening behavior. The isotropic hardening variable are decomposed into hardening and softening terms by considering the formation of different dislocation structures under cyclic loading. The magnitude and rate of hardening term depend on the plastic strain range memory space. The softening term is only related to the accumulated plastic strain. Compared with experiments and existing models, this study can better capture ratcheting and cyclic hardening/softening behavior with loading history, as shown in Fig. 1.

KEYWORDS:

Loading history, Ratcheting, Cyclic hardening, Kinematic hardening, Isotropic hardening

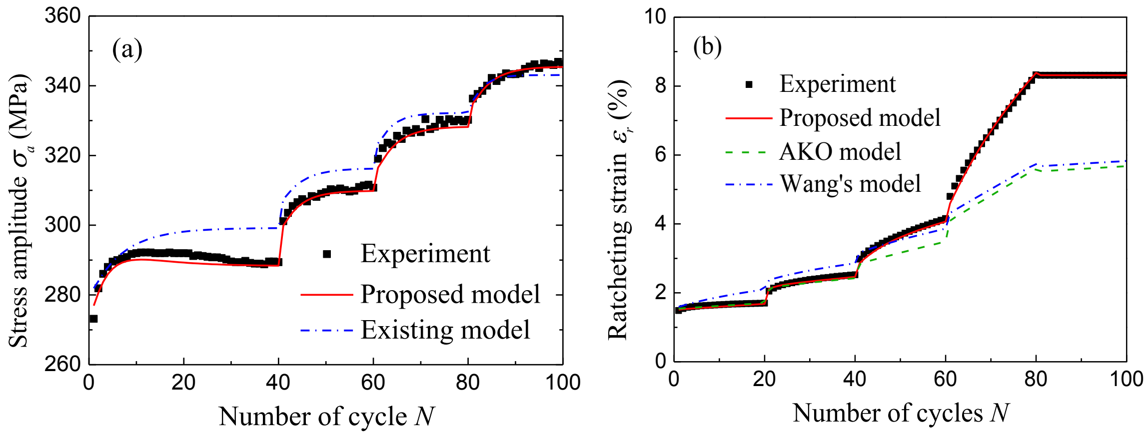


Fig. 1 *(a) Multi-step cyclic hardening/softening behavior. (b) Multi-step ratcheting behavior.*

C2-510

Fatigue behavior and cyclic slip irreversibility of AlCoCrFeNi high entropy alloys: A molecular dynamics simulation study

Dongxing Pan[1], Xiaogang Wang[1,*], and Chao Jiang[1]

[1] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, College of Mechanical and Vehicle Engineering, Hunan University, 410082 Changsha, China

* Corresponding author: xgwang@hun.edu.cn

ABSTRACT:

The severe lattice distortion effect of high entropy alloys (HEAs) at atomic scales is regarded as a vital element for its excellent mechanical properties such as superior strength and high toughness. However, there are still some controversies regarding the performance of HEAs with respect to its fatigue properties. The dynamic and continuous microstructural evolution of metal materials are difficult to be observed by existing characterization techniques, which results in a lack of in-depth understanding on the fatigue behavior of HEAs from a microscopic viewpoint. Based on molecular dynamics simulation and cyclic slip irreversibility theories, the fatigue behavior of AlCoCrFeNi HEA was explored and an evaluation index for cyclic slip irreversibility was established in this work. The results show that the fatigue process of AlCoCrFeNi HEA can be divided into two stages: development stage and stabilized stage. Lattice distortion promotes plastic shear strain localization and the formation and intensification of dislocation tangles in the studied HEA. This study assists in further understanding the fatigue mechanism of HEAs at the atomic scale and provides a feasible method for fatigue life prediction of such alloys.

KEYWORDS:

High entropy alloys; Molecular dynamics simulation; Fatigue behavior; Microstructural evolution; Cyclic slip irreversibility

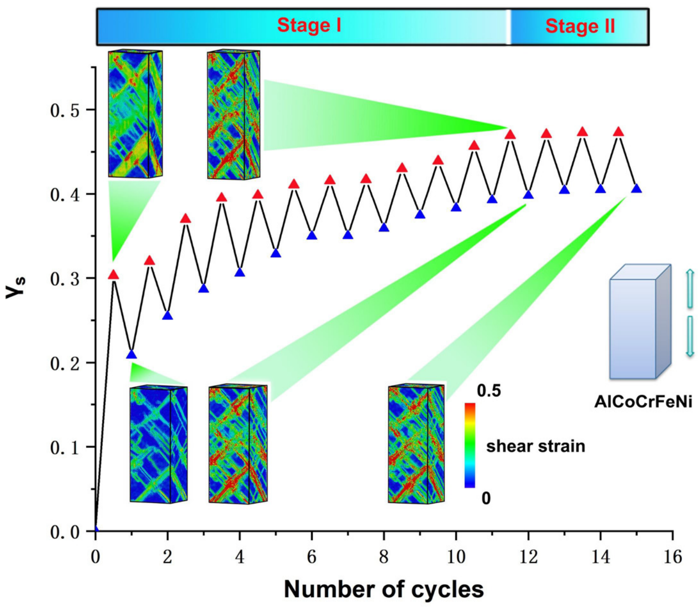


Fig. 1 *Evolution of shear strain(γ_s) in slip bands with increasing number of cycles of tensile and compressive loading.*

C2-511

VERY LOW CYCLE FATIGUE CRACK GROWTH MODELLING AND EXPERIMENTAL VALIDATION USING CRACKED PIPE TEST DATA

Yun-Jae Kim[1†*], Jin-Ha Hwang[2], Hyun-Seok Song[1], and Jin-Weon Kim[3]

[1] Korea University, KOREA
[2] Korea Military Academy, KOREA
[3] Chosun University, KOREA

* Corresponding author: kimy0308@korea.ac.kr

ABSTRACT

The fracture behaviour for cracked pipes under large-amplitude cyclic seismic loading is an important part of the structural integrity. Many institutions performed the full-scale cracked pipe tests under very low cycle fatigue loading. The full-scale cracked pipe test could accurately observe complicated pipe fracture behaviour, but had limitations of time and cost. The finite element (FE) damage analysis is numerical method that can simulate the crack growth under very low cycle fatigue loading using minimal experimental data.

In this presentation, a modeling method to simulate very low cycle fatigue crack growth in a pipe is presented. Ductile crack growth simulaton was performed using the multiaxial fracture strain energy damage model having two parameters, multiaxial fracture strain energy and critical damage value. They were determined by analyzing standard tensile test and monotonic fracture toughness test data using FE analyses. The load amplitude and load ratio effect on the plastic strain energy under low cycle fatigue loading was incorporated in the multiaxial fracture strain energy density, of which parameters were determined by analyzing the fatigue curve of the material. The load amplitude effect (failure cycle) was included from the relationship between the plastic strain energy per cycle and the failure cycle. The load ratio effect was included from the Coffin-mason fatigue curve considering the mean stress correction factor based on the Walker model. The proposed damage model was applied by simulating the crack growth for through-wall cracked pipe under very low cycle fatigue loading with different load amplitudes and load ratios.

The proposed modelling method was applied to fracture tests of circumferential and surface cracked pipes under four-point load-controlled cyclic load condition. The cyclic hardening model used the Chaboche combined hardening model was used. The predicted results compared with the experimental crack growth and fracture surface data and were in good agreements.

KEYWORDS:
Experimental valuation using cracked pipe test data, Multi-axial fracture strain energy model, Very low cycle fatigue crack growth modeling

C2-512

Fatigue assessment procedure based on effective crack propagation data and cyclic R-curve

Larissa DUARTE[1,*], Mauro MADIA[1] and Uwe ZERBST[1]

[1] Bundesanstalt für Materialforschung und -prüfung, GERMANY
* Corresponding author: larissa.duarte@bam.de

ABSTRACT:
Fracture mechanics-based methods can be applied to the fatigue assessment of mechanical components containing defects or cracks subjected to cyclic loading. The knowledge of the crack growth behavior for short and long cracks enables the determination of both finite and infinite life regimes. Nevertheless, a first problem arises from the empirical determination of the fatigue data, which vary according to the test conditions, e.g., the test method, frequency and the stress ratio R. This is due to crack closure and further environmental phenomena affecting crack propagation behavior. A second issue regards the lack of standard experimental procedures for the determination of the fatigue crack propagation threshold ΔK_{th} dependency on the crack size. This is problematic, since ΔK_{th} increases with the build-up of the closure effects in the short crack regime and its inaccurate experimental determination leads to large deviations in the assessment and, even more critical, to non-conservative predictions. Aiming at providing more reliable and safer assessment procedures, the present work proposes a method based on effective crack growth data obtained at high stress ratios ($R \approx 0.8$). A short-crack model based on the cyclic R-curve and CPLR data is employed for describing the development of the closure effects. The predictions are compared to established methods and validated by experimental tests.

KEYWORDS:
Component assessment, fatigue crack propagation, fatigue threshold, crack closure, cyclic R-curve

C2-513

A unified approach for the fatigue categorization of cold-formed mild steel details

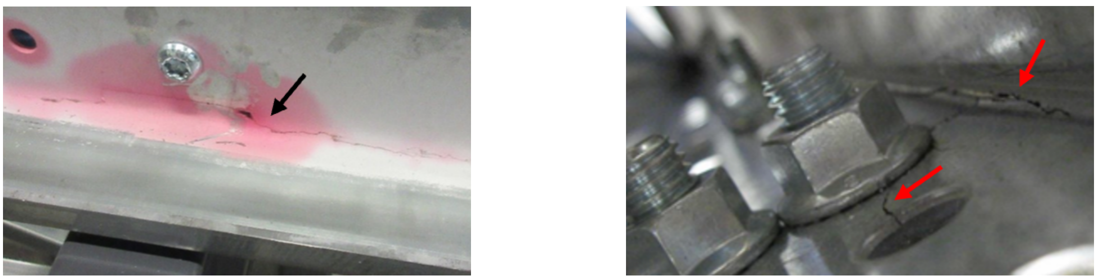
A. M. P. de Jesus[1], C. D. S. Souto[1], V. M. G. Gomes[1], J. A. F. O. Correia[1], M. A. V. Figueiredo[1], A. D. Santos[1], F. Morelli[2], A. Piscini[2], B. Hoffmeister[3], T. Geers[3], H. Degée[4], A. Menghini[5], C. A. Castiglioni[5]

[1]*Department of Mechanical Engineering, Faculty of Engineering of the University of Porto, Porto, Portugal*
[2]*Department of Civil and Industrial Engineering, University of Pisa, Pisa, Italy*
[3]*Institute of Steel Construction, RWTH Aachen University, Aachen, Germany*
[4]*Faculty of Engineering Technology, Hasselt University, Hasselt, Belgium*
[5]*Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Milano, Italy*

Rack structures represent the structural framework for automated storage-and-retrieval (S&R) solutions used in warehouse logistics, e.g., pallet carrier shuttles and stacker cranes, which offer an efficient and continuous operation. These structures are subjected to fatigue loads arising from the cyclic storage of heavy palletized goods combined with the dynamic action of moving S&R systems. This eventually leads to fatigue cracking, as shown in Figure 1, which raises safety concerns and is responsible for expensive maintenance downtimes. Nevertheless, considerations for rack structures, which are characterized by the usage of cold-formed thin-walled mild steel profiles joined via non-preloaded bolted connections that are associated with a limited shear slip resistance, are completely missing from current versions of European standards for fatigue design, e.g., EN 1993-1-9 (Eurocode 3). Answering to an industrial need, the FASTCOLD research project financed by the Research Fund for Coal and Steel (RFCS) of the EU (project ID 745982), aimed the development of new fatigue design rules for constructional cold-formed mild steel details commonly found in the rack industry, filling the identified gap in currently available fatigue design guidelines.

The current objective is to present a global summary of the main fatigue data generated during the FASTCOLD project in a unifying manner. This data is derived from several fatigue testing campaigns, which include the testing of both full-scale profiles and small-scale specimens extracted from those profiles. Based on a large dataset, the aim is to develop fatigue design rules via the categorization of distinct structural details. The categorization is accomplished via regression-based S-N approaches; however, fatigue actions are evaluated numerically via finite element analysis, allowing for the assessment of general multiaxial cases that are generally not foreseen by design standards. The finite element modelling component also allows for the inclusion of advanced considerations, such as friction and bolt preload levels, which directly influence the fatigue behaviour. Additionally, the models may also include the actual geometry of the components, as it is shown that the consideration of geometrical deviations found at the cold-formed corners due to manufacturing tolerances is of paramount importance in regard to fatigue. Furthermore, the numerical modelling aspect also aims to modernize current fatigue design approaches: it is shown that currently adopted fatigue detail categorization systems, which are becoming increasingly more convoluted in order to account for new and special cases, can be simplified by following a more rigorous numerical stress evaluation.

Finally, these results arrive at an opportune time due to the ongoing Eurocode 3 revision process, where a final draft, denoted prEN 1993-1-9, is currently under enquiry. In short, considerations for non-preloaded bolted connections and rolled products are underway, and, in general, this research shows results that tend to agree with the proposed Eurocode 3 changes.



(a) (b)

Figure 1: Fatigue cracking on cold-formed corners: cracking on a guide rail for pallet carrier shuttles (a) and on a structural bolted beam-to-upright connection (b).

C2-514

A continuum damage mechanics-based machine learning approach for thermal fatigue life prediction of aluminum alloy

Zhixin ZHAN*, Ao LI, Weiping HU, and Qingchun MENG

School of Aeronautic Science and Engineering, Beihang University, CHINA

* Corresponding author: zzxupc@163.com

ABSTRACT:

Aluminum alloys are widely used in aviation industries, whose thermal fatigue performance is an important issue. In this study, a machine learning (ML) method combing with continuum damage mechanics (CDM) framework is developed to accurately predict the thermal fatigue life of aluminum alloy. First, temperature terms are introduced into the damage evolution equations, and a novel thermal elastic-plastic fatigue damage model is established. The good capability of the model is then verified by the experimental data. After that, a large database of fatigue lives of three notched specimens at different stress levels and different temperatures is acquired through the numerical calculation, which is employed to train ML models. Then, the trained ML models with inputs including maximum stress, stress ratio, temperature and notch stress concentration factor are utilized to predict the thermal fatigue lives of different notched specimens at different loading conditions. The predicted results agree well with the experimental data. The proposed framework is with high efficiency and high predicted accuracy. Finally, detailed parametric studies are conducted to investigate the predicted performance of ML models.

KEYWORDS:

Machine learning; Continuum damage mechanics; Thermal fatigue life prediction; Aluminum alloy

C2-515

Studying the Fatigue Strength in the VHCF Regime of an Epoxy used for Fiber-Reinforced Polymers

Malo ROSEMEIER[1,*] and Paul Dario TOASA CAIZA[2]

[1] Fraunhofer Institute for Wind Energy Systems IWES, GERMANY
[2] Karlsruhe Institute of Technology KIT, GERMANY

* Corresponding author: malo.rosemeier@iwes.fraunhofer.de

ABSTRACT:
The fatigue life of structures composed of fiber-reinforced polymers (FRPs), such as wind turbine blades, is significantly influenced by the polymer matrix behavior. These matrices are exposed to over 100 million loading cycles with diverse combinations of mean stresses and stress amplitudes throughout the blades' operational life of at least two decades. For this purpose, experimental data of an epoxy polymer, commonly utilized as the matrix material in FRPs, have been studied and evaluated. The data set includes stress ratios of R=−1 and R=0.1 (Fig. 1). The epoxy's stress-life was estimated by using different approaches: the Weibull model suggested by Castillo and Fernández-Canteli [1], the Stüssi model proposed by Toasa Caiza *et al.* [2] and the Stüssi-Boerstra model as proposed by Rosemeier and Antoniou [3]. The first model allows to estimate the fatigue limit, even though it does not allow to describe the fatigue behavior in the LCF regime. The last two models are suitable to take into account the stress ratio influence. Despite the acceptable and sometimes similar results within the experimental frame, the emphasis of applying these models is on predicting the fatigue behavior in the VHCF regime, where their outcomes diverge considerably. These results deserve to be analyzed and discussed properly.

KEYWORDS:
Cyclic loading; Lifetime estimation; Weibull; Stüssi; Stress ratio

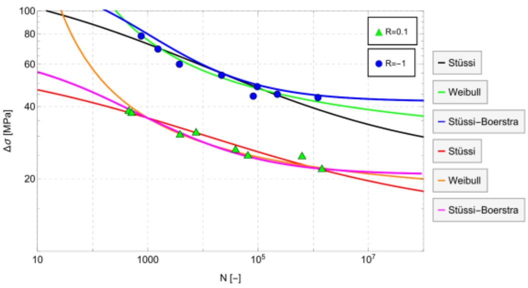


Fig. 1 $\Delta\sigma$ -*N* curves according to Weibull, Stüssi and Stüssi-Boerstra.

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C2-516

Comprehensive Comparison between two different fatigue modeling methods for welded hollow spherical joints

Yongtao Bai[1], Cheng Xie[1,*], Mizero Racine[1] and Julio Flórez-López[1]

[1] Chongqing University, CHINA

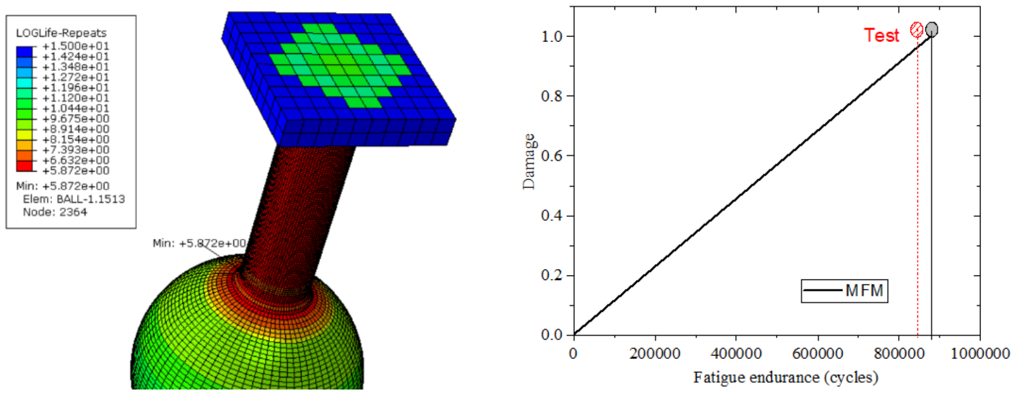
* Corresponding author: xiecheng0913@gmail.com

ABSTRACT:

Different from the accurate analysis for structural capacity, high cycle fatigue (HCF) simulation is considered as uncertain, time-assuming and unquantified for damage in the process. Aimed to improve HCF simulation, two different fatigue modeling methods are presented and compared in this paper, where one is finite element analysis (FEA) followed by life prediction using FE-safe software, and the other is mesh free method (MFM) based on lumped damage mechanics. Firstly, the frameworks of above two methods are built up with the fatigue damage mechanics introduced. Secondly, welded hollow spherical joints (WHSJs) prone to fatigue crack at the intersection area of pipe and ball are selected as modeling objects. Static test and fatigue test are also used for validation of fatigue simulations. Finally, from the aspects of life prediction accuracy, damage quantitation and parameter determination, the comprehensive comparison between two methods of FEA and MFM is conducted. The results show that the errors predicted fatigue life of both are 12.7% and 2.7% respectively. Therefore, MFM is quite accurate as FEA and more efficient. This research provides an alternative HCF simulation method of MFM, which could be a promising application in structural health monitoring and damage real-time evaluation.

KEYWORDS:

High cycle fatigue; lumped damage mechanics; mesh free method; life prediction; fatigue simulation



(a) Life (FEA): $10^{5.872}$=744732 (b) Life (MFM): 876000; Test: 853150

Fig. 1 *Life prediction of two models (unit: cycles).*

C2-517

Incorporation of Notch Size Effect Correction Factors into the Correlation Parameter between Fatigue Strength Diagrams of Smooth and Notched Specimens and Induction of Master Diagrams as Base Data for Estimation of Fatigue Strength of Machine Parts and Structural Elements

Hiroshi MATSUNO[1,*]

[1] Sojo University, JAPAN

* Corresponding author: hi-matsuno@par.odn.ne.jp

ABSTRACT:

In the previous studies, two ideas were proposed to correlate the fatigue strength diagrams of smooth and notched specimens. One is a main parameter “Equivalent Cyclic Stress Ratio (symbol R_{EQ})” and the other is a complementary parameter “Notch Size Effect Correction Factor (symbol F_{S1})”. R_{EQ} is expressed by using a “Nominal Cyclic Stress Ratio R_N” and a “Stress Concentration Factor K_t”. Applicability of R_{EQ} alone is limited to the case of large size notch, but applications to small size notch require F_{S1}. F_{S1} is derived from a “Yield Zone Growth Curve” expressed as the function of the maximum depth of yield zone normalized by notch size and applied stress normalized by yield stress, based on FEM elastic-completely plastic analyses. In the present study, accuracy of F_{S1} is improved by setting the elastic-plastic transition point of the yield zone growth curve on the critical notch size line of $(\sqrt{t\rho})_{REQ\text{-}critical}$ = material constant, which R_{EQ}-proper and R_{EQ}-plus-F_{S1} region are partitioned with, as illustrated on the “Notch Behavior Map” of Fig.1. As the result, uniaxial fatigue strength diagrams of smooth specimens (termed “Master Diagrams of Materials”) are induced from laboratory fatigue tests of in-/out-plane and rotating bending and torsion as well as tension-compression.

KEYWORDS:

Smooth/notched specimen; Fatigue strength diagram; Equivalent cyclic stress ratio; Notch size effect correction factor; Master diagram of material.

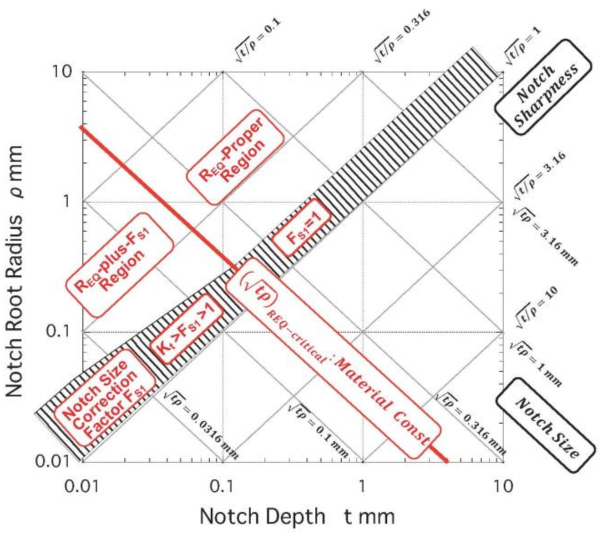


Fig. 1 Illustration of dependence of the yield zone initiation stress at a notch root upon the notch sharpness $\sqrt{t/\rho}$ and the notch size $\sqrt{t\rho}$, and diagraming of notch size effect correction factor F_{S1}. The elastic-plastic transition point of F_{S1} is set on the line of $(\sqrt{t\rho})_{REQ\text{-}critical}$ whose value depends on material.

R1-501

Fatigue Properties of Short Fiber Reinforced Polyamides exposed to acid environment

Florent ALEXIS[1], Sylvie CASTAGNET[1,*], Carole NADOT-MARTIN[1], Peggy HAVET[2] and Gilles ROBERT[3]

[1] Institut Pprime (UPR 3346 CNRS – ISAE-ENSMA – University of Poitiers), FRANCE
[2] Valeo Thermal Systems – BG Material Laboratory, FRANCE
[3] Polytechnyl sas (DOMO Chemicals), FRANCE

* Corresponding author: sylvie.castagnet@ensma.fr

ABSTRACT:

The effect of acid aqueous environment on the fatigue lifetime of Short Fiber Reinforced Thermoplastics (SFRP) was investigated. The global framework is that of automotive components.
Two polyamides (PA6 and PA66) containing 35% weight ratio of short glass fibers were aged for 1000h at pH=2,5 and T=60°C and compared with unaged materials.
The effect of pre-aging was characterized first from Scanning Electronic Microscopy and Differential Scanning Calorimetry. Monotonic tests evidenced a slight embrittlement of the aged materials and no stiffening, consistently with the molecular chain breakage due to hydrolysis and with the unaffected crystallinity ratio. Through a 200µm external layer fibers were highly debonded from the matrix.
Stress-controlled fatigue tests were performed at constant amplitude, frequency (1Hz) and load ratio (R=0.1), for three main orientations of short fibers (0°, 45° and 90°). An in-situ device was specifically developed to test immersed samples in acid solution, with the challenge to ensure stability and homogeneity of the solution and of the strain measurement all along fatigue tests.
A slight decrease of fatigue lifetime was observed after acid aging, especially when fibers were mainly aligned with the tensile direction (0°). Such decrease was not observed in samples aged and tested in water.

KEYWORDS:
Short fiber-reinforced thermoplastic; acid solution; hydrolysis; in-situ fatigue testing

R1-502

Evaluation of Fatigue Properties of Injection Molded Plates of Short Glass Fiber Reinforced Composites Based on Matrix Phase Stress

Kenichi SHIMIZU[1], Koji KAMEYAMA[2], Miori SAITO[2], Masatoshi TSUDA[3], Keiji KIMURA[3], Etsuo KOKURYU[3] and Keisuke TANAKA[4]

[1] Meijo University, JAPAN
[2] Graduate Student, Meijo University, JAPAN
[3] Denso Corporation, JAPAN
[4] Professor Emeritus, Nagoya University, JAPAN

* Corresponding author: kshimizu@meijo-u.ac.jp

ABSTRACT:

Fatigue tests were conducted to evaluate the lifespan of injection-molded plates made of PPS resin filled with short glass fibers, known as short-fiber GFRP (SGFRP). Three types of specimens were prepared to investigate the effect of fiber orientation: Molding Direction (MD) specimens cut parallel to the injection direction, Transverse Direction (TD) specimens cut orthogonally to the injection direction, and a PPS specimen without fibers. Compared to the PPS specimens, the MD specimens exhibited an increase in fatigue strength, while the TD specimens showed no improvement. X-ray CT analysis of the short fiber orientation revealed that the SGFRP injection-molded plate has a three-layer structure, with fibers oriented in the molding direction in the surface layer and in the transverse direction in the core layer. The elastic constants of each layer were calculated using micromechanics, considering the fiber orientation, and the stress in the PPS phase was analyzed using FEM (finite element method). By plotting the S-N diagram based on the stress in the PPS phase, it was observed that the MD and TD specimens closely resembled the behavior of the PPS specimens. This indicates that the fatigue failure of SGFRP is primarily influenced by the stress in the PPS phase.

KEYWORDS:

Short-fiber reinforced plastics, Fiber orientation, Fatigue properties, Micromechanics, Matrix Phase Stress

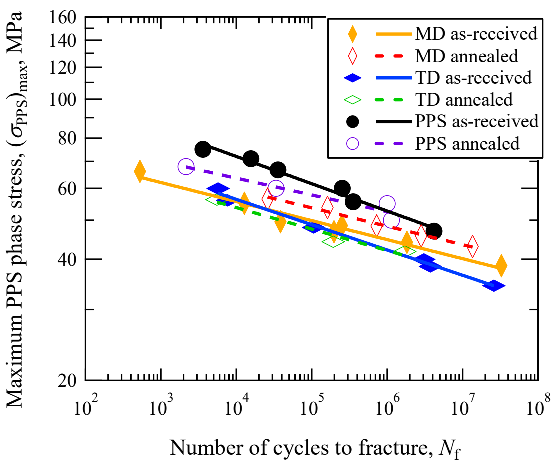


Fig. 1 *Relationship between maximum PPS phase stress and number of cycles to fracture.*

R1-503

Fatigue crack evolution of thermoplastic-based fiber metal laminates under application-related temperatures

Selim MRZLJAK[1,*], Maik TRAUTMANN[2], Guntram WAGNER[2], Frank WALTHER[1]

[1] TU Dortmund University, Chair of Materials Test Engineering (WPT), Dortmund, Germany
[2] Chemnitz University of Technology, Institute of Material Science and Engineering (IWW), Group of Composites and Material Compounds, Chemnitz, Germany
* Corresponding author: selim.mrzljak@tu-dortmund.de

ABSTRACT:
Fiber metal laminates (FML) were introduced to decelerate crack development and extend fatigue life compared to monolithic metals, e.g. aluminum in the aerospace industry. Not only is the high performance of such materials relevant, but the ever-increasing demand for sustainability (including recyclability and long-term use) is also important. Therefore, thermoplastic-based FML was introduced, enabling improved possibilities in formability and shorter production times compared to thermoset FML. However, knowledge about the mechanical properties, especially regarding fatigue, is yet not sufficiently acquired, which is indispensable for fatigue life estimation and thus part design. In this study, the fatigue properties of thermoplastic-based FML, consisting of unidirectional glass and carbon fiber-reinforced polyamide 6 and AA6082 aluminum alloy sheets, are investigated within a variety of temperature environments (within -35 up to 80 °C). The fatigue-induced crack evolution is investigated under tension-tension loading up to the VHCF range of 1E8 cycles using 3D digital image correlation for crack and deformation measurements and monitoring of the change in electrical resistance (see Fig. 1). The results show that the fatigue life of the thermoplastic-based FML depends significantly on the temperature environment present, resulting in decreased interfacial strength with increasing temperature, leading to accelerated crack initiation and propagation in the aluminum sheets.

KEYWORDS: Fiber metal laminate, thermoplastic, temperature, instrumented fatigue testing, crack evolution

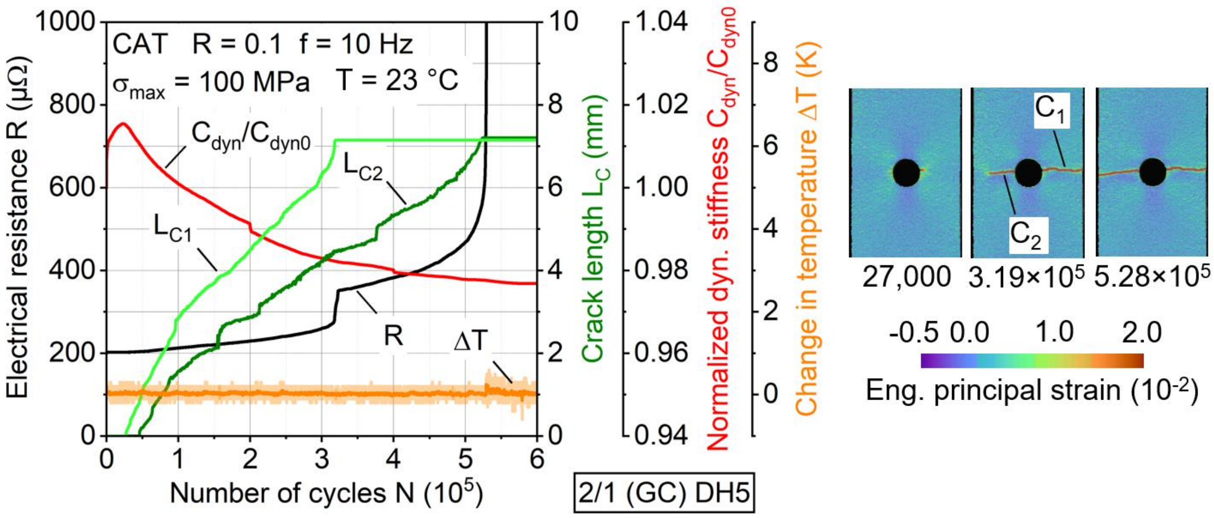


Fig. 1 *Constant amplitude test for thermoplastic-based FML specimen: Crack length and electrical resistance evolution, digital image correlation deformation for selected load cycles*

R1-504

Fatigue damage evolution and damage tolerance of composite structures

Selim MRZLJAK, Lars GERDES, Alexander DELP, Ramon HELWING, Pascal FRANCK, Ronja SCHOLZ, Frank WALTHER*

TU Dortmund University, Chair of Materials Test Engineering (WPT), Dortmund, Germany

* Corresponding author: frank.walther@tu-dortmund.de

ABSTRACT:
Modern composite structures are widely applicated in various industrial structures nowadays because of their beneficial properties, i.e. lightweight and high-performance potential. The design of composite structures relies on reliable lifetime estimation, pinpointing the need for the characterization of fatigue behavior and respective damage mechanisms. Characterization techniques and procedures are presented for materials used within today's prospects, which fulfill the demand for high-performance applications and suitability for sustainable approaches. These include classical as well as natural fiber-reinforced polymers, cellulose-based composites, and hybrid structures like thermoplastic-based fiber metal laminate (see Fig. 1a). The used characterization techniques focus on investigating damage mechanisms under laboratory scale application scenarios using metrology, e.g. like digital image correlation and thermography. Due to the complexity of such composites, critical ambient conditions, including temperature and humidity conditions, are investigated using climatic chambers to generate a comprehensive overview of their mechanical and structural properties. To gather essential information about damage initiation and evolution, leading techniques for true damage state characterization (see Fig. 1b), i.e. in situ testing during scatter electron microscope and computed tomography analysis, are used alongside intermittent fatigue testing. This way the composites can be qualified for various applications within the automotive, aerospace, and building industries.

KEYWORDS: Fatigue, characterization, fiber reinforced polymer, cellulose, fiber metal laminate

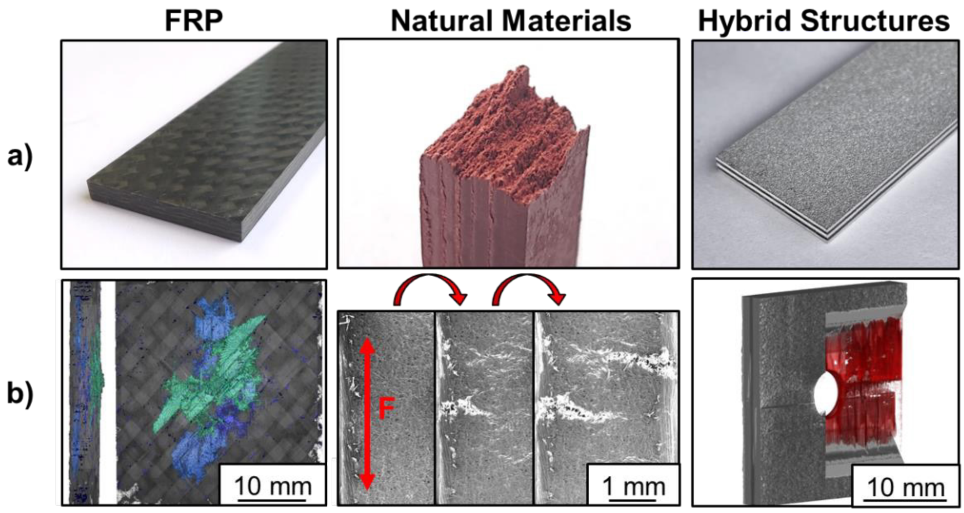


Fig. 1 *a) Composite materials and b) related damage characterization techniques*

R1-505

Correlating composite fatigue to its matrix properties

Andreas Baumann[1], Joachim Hausmann[1]

[1] Leibniz-Institut für Verbundwerkstoffe GmbH, GERMANY

* Corresponding author: andreas.baumann@ivw.uni-kl.de

ABSTRACT:
Fiber reinforced polymers (FRP) offer excellent fatigue resistance in combination with low specific weight. However this is only fully true for loading along the reinforcement fibers. Despite processing technologies like tailored fiber placement it is common that fiber orientation and loading direction mismatch. Especially under those conditions it is desirable to find matrix materials with the right set of properties to sustain cyclic loading.
This research is concerned with the investigation on how the matrix polymer's properties in continuous fiber reinforced material affect the fatigue performance of the laminate as whole. It was the expressed aim of this research to modify solely the matrix polymer and keep all other composite parameters like fiber sizing, geometry and alike constant. This is achieved by high energy radiation (see Fig. 1 for induced changes). Mechanical experiments on both the neat polymer (epoxy and Polycarbonate) and its composites (carbon and glass -FRP) are used to correlate matrix properties and composite fatigue performance. Tensile tests, relaxation experiments and fatigue tests reveal that despite a high matrix ductility during monotonic loading this property is lost for repeated loading or long-term loading. This effect is also documented in terms of laminate damage by edge microscopy.

KEYWORDS: Composite; Polymer; Fatigue; Matrix properties

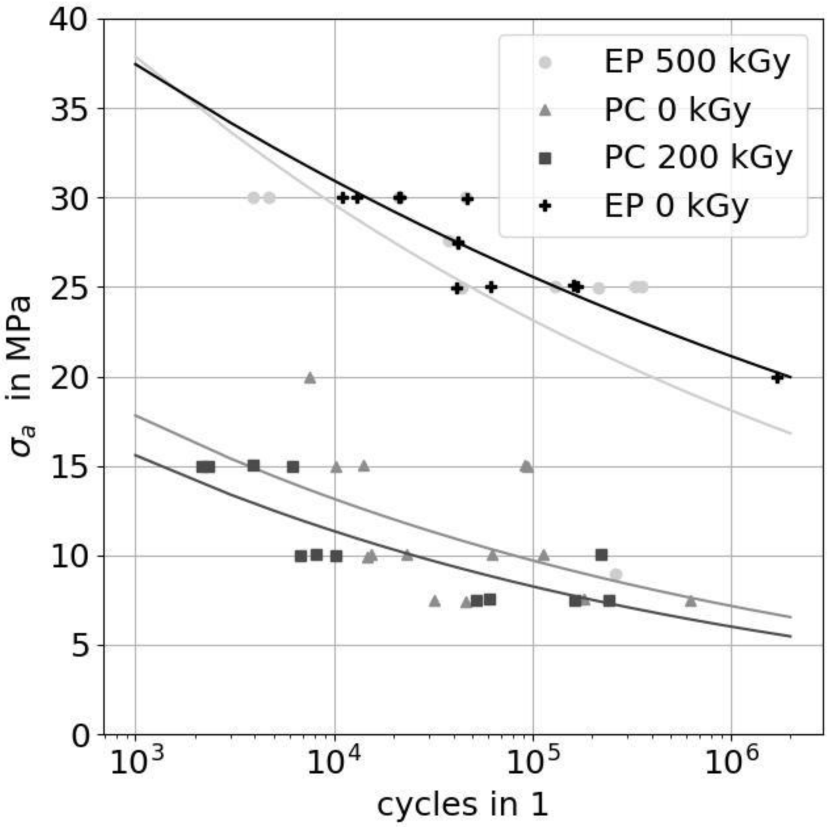


Fig. 1 Irradiation modified polymers *S-N curve.*

R1-507

Effect of thermal induced porosity on high-cycle fatigue and very high-cycle fatigue behaviors of hot-isostatic-pressed Ti-6Al-4V powder components

Zhengguan Lu[1,*], Ruipeng Guo[2] , Jie Wu[1], Lei Xu[1] and Rui Yang[1]

[1] Institute of Metal Research, Chinese Academy of Sciences, China
[2] Taiyuan University of Technology, China

* Corresponding author: zglu@imr.ac.cn

ABSTRACT:

The present work reports the effect of thermal induced porosity (TIP) on the high-cycle fatigue (HCF) and very high-cycle fatigue (VHCF) behaviors of hot-isostatic-pressed (HIPed) Ti-6Al-4V alloy from gas- atomized powder. The results show that the residual pores in the as-HIPed powder compacts present no obvious effect on the HCF life. The regrowth of the residual pores can be observed after solution heat treatment. The pore location ranks the most harmful for the fatigue life compared with the other initiat- ing defects. The maximum stress intensity factors were calculated. The plastic zone size of fine granular area (FGA) is much less than the characteristic size of the microstructure, and the crucial size of the inter- nal pores in this study is about 40 μm. The failure types of fatigue specimens in the VHCF regime were classified, and the competition of different failure types was described based on the modified Poisson distribution.

KEYWORDS:

Ti-6Al-4V; thermal induced porosity; high-cycle fatigue; very high-cycle fatigue;

R1-508

Effect of powder size on fatigue properties of Ti-6Al-4V powder compact using hot isostatic pressing

Jie Wu[1], Xiaoxiao Cui[1], Zhengguan Lu[1], Lei Xu[1,*] and Yiping Li[1]

[1] Institute of Metal Research, Chinese Academy of Sciences, China

* Corresponding author: lxu@imr.ac.cn

ABSTRACT:
Ti-6Al-4V powder compacts were prepared using hot isostatic pressing (HIP), and the effect of powder size on microstructure and fatigue properties of HIPed powder compacts was investigated. The results show that the microstructure of powder compacts is fine and homogeneous. The volume fraction of equiaxed a phase in the powder compact decreases with the increase of powder size. The powder compact HIPed from powder with a full size range (5–250 μm) achieves excellent tensile properties and the best fatigue strength compared with the HIPed fine and coarse powders. The relevant mechanisms are discussed based on the powder surface quality and as-HIPed microstructure.

KEYWORDS:
Ti-6Al-4V; hot-isostatic-pressing; powder size; tensile properties

R1-509

Creep-fatigue crack initiation criterion for crystallographic evolutions based on damage mechanics descriptions

Run-Zi Wang[1,*], Le Xu[1], Xian-Cheng Zhang[2], Shan-Tung Tu[2], Hideo Miura[1]

[1] Fracture and Reliability Research Institute, Graduate School of Engineering, Tohoku University, Sendai, Miyagi 980-8579, Japan
[2] Key Laboratory of Pressure Systems and Safety, Ministry of Education, East China University of Science and Technology, Shanghai 200237, P.R.China

* Corresponding author: runzi.wang@rift.mech.tohoku.ac.jp

ABSTRACT:
Crystallographic evolutions based on Electron Back-Scatter Diffraction (EBSD) techniques provide a solid physical basis for advancing the multiscale links between the mesoscale and macroscale, where typical local misorientation parameters over multiple grains promote the development of diffraction-based misorientation mapping in polycrystalline alloys. This research proposes a multiscale crack initiation criterion under typical creep-fatigue loading conditions. The principle of this criterion is to establish the continuum damage descriptions of the stored energy dissipation theory, enabling quantified assessment of damage evolutions until crack initiation. The feasibility and robustness of this criterion were validated through ex-situ creep-fatigue tests combined with EBSD observations. From a quantitative perspective, a mathematical relationship was constructed between mesoscopic crystallographic evolutions and macroscopic damage accumulations during the creep-fatigue progress using a square root power law of Kernel Average Misorientation (KAM) or other dislocation-related parameters to the final status. This relationship serves as an excellent indicator to reflect material degradation with clear physical meaning. For a larger generality of strong creep-fatigue interactions where microcavities and microcracks interact seriously, a subsequent generalized criterion was discussed to exclude external disturbances and achieve lognormal domain averaging.

KEYWORDS:
Creep-fatigue; Ex-situ tests; Multiscale; EBSD technique; Damage mechanics

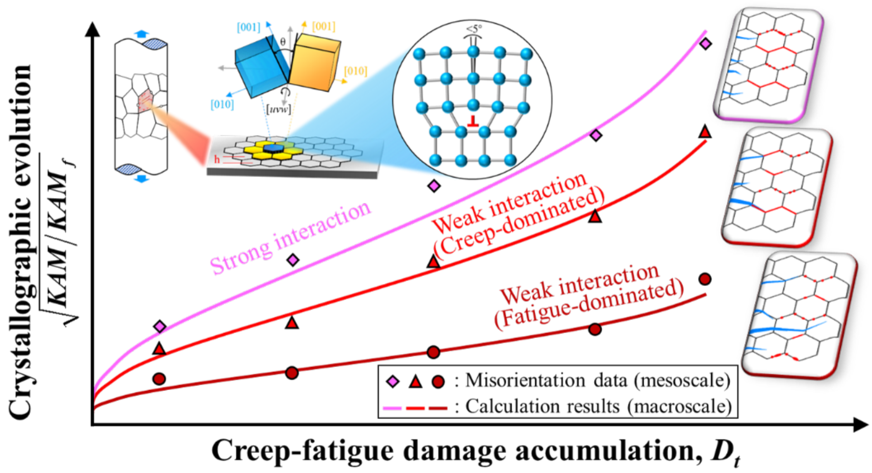


Fig. 1 Multiscale link between crystallographic evolution and damage accumulation under creep-fatigue loads

R1-510

Dynamic Evolution and Crystal Plasticity Study of GCr15 Bearing Steel Damage under Cyclic Loading

Tengyuan Liu[1,2], Yonghan Li[1,2], Yifan Xia[1,2], Guangcai Ma[1], Pei Wang[1]*, Dianzhong Li[1]*

[1] Institute of Metal Research, Chinese Academy of Sciences, CHINA
[2] University of Science and Technology of China, CHINA

* Corresponding author: pwang@imr.ac.cn

ABSTRACT:

This paper combines in-situ fatigue experiments and crystal plasticity models to investigate the effects of different microstructural features on local damage evolution in GCr15 bearing steel, and reveals the nonlinear evolution of dislocation density influenced by microstructure. The results show that cracks mainly initiate at phase/grain boundary intersections or near carbides, due to the stress concentration that causes rapid dislocation accumulation at these locations. It is also found that higher carbide content leads to smaller grain size and more phase/grain boundary intersections, which aggravates damage evolution. Microstructure has a significant impact on the nonlinear evolution of dislocation density. As the load cycle number increases, the increment of dislocation density gradually decreases, and it weakens from phase/grain boundary intersections to grain boundaries and then to grain interiors. Therefore, reasonably controlling the uniformity of carbide distribution and grain size can reduce weak points and improve the fatigue performance of bearing steel.

KEYWORDS:

Bearing steel; Microstructure; In-situ experiment; Crystal plasticity; Dynamic damage evolution

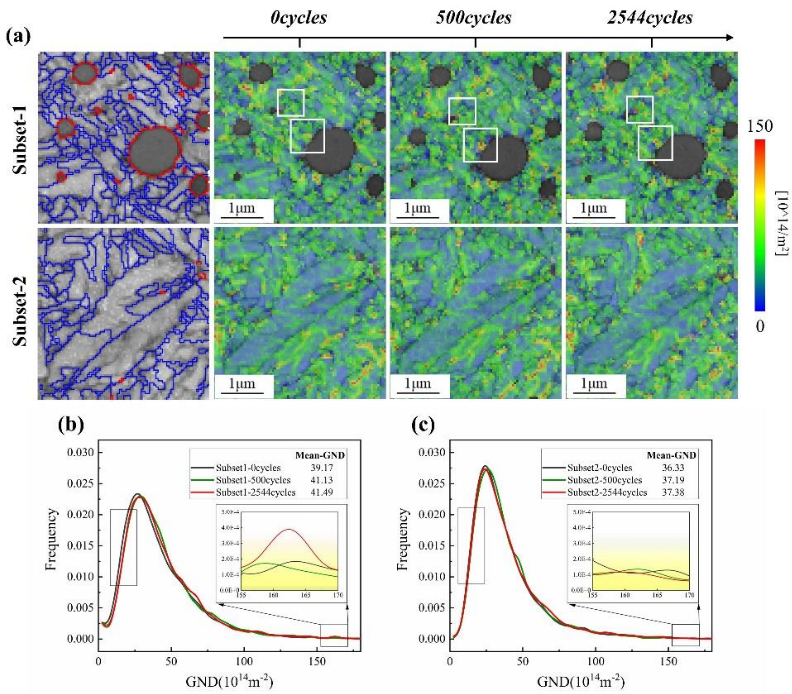


Fig. 1 *The evolution process of GND density in different micro-regions within the same sample: (a) evolution process of GND dislocation density after 0-500- fracture; (b-c) distribution diagram of GND density in two subsets.*

R1-511

Non-uniform cyclic temperature field induced deformation behavior of IN718 in thermal gradient mechanical fatigue

Guo LI[1], Shaochen BAO[2], Shuiting DING[3], Zhenlei LI[2],*, Wenhao Ma[1], Shuyang XIA1

[1]School of Energy and Power Engineering, Beihang University, 37 Xueyuan Road, Beijing, 100191, China
[2]Research Institute of Aero-Engine, Beihang University, 37 Xueyuan Road, Beijing, 100191, China
[3]Civil Aviation University of China, 2898 Jinbei Road, Tianjin, 300300, China

* Corresponding Author: Zhenlei LI. Email: lizhl@buaa.edu.cn

ABSTRACT:

Hot-section rotator components in advanced gas turbine need protection of efficiency cooling technologies, which induce additional thermal stress and complicate the fatigue behavior of components. In the present work, a series of fluid-thermal-solid coupling analysis have been conducted on a tabular specimen to study the effect of non-uniform cyclic temperature field on Inconel 718 deformation behavior. Because of the non-monotonic distribution of heat transfer coefficient along the axial direction, the cyclic temperature field which peak value varies from 300℃ and 650℃ is heterogeneous both in radial and axial. Through visco-plastic finite element analysis, cyclic strain accumulation can be found even if the mechanism load is controlled by strain amplitude. Comparing with radial gradient, axial temperature gradient has more impact on radial and axial strain accumulation. Therefore, the dramatical decline of fatigue life, observed in recent thermal gradient mechanical fatigue experiment comparing with thermomechanical fatigue, can be partially explained by greater damage caused by the higher accumulated plastic deformation.

KEYWORDS:

Accumulated plastic deformation, Thermal stress, Thermal gradient mechanical fatigue, Non-uniform cyclic temperature field, Fluid-thermal-solid coupling

R1-512

Fatigue behavior of metastable Fe-based austenites

Marek SMAGA*, Dietmar EIFLER and Tilmann BECK

Institute of Material Science and Engineering (WKK), RPTU Kaiserslautern-Landau, GERMANY

* Corresponding author: m.smaga@mv.rptu.de

ABSTRACT:

Metastable Fe-based austenites exhibit a local minimum of Gibb's free energy and can, hence, transform into a more stable structure. Besides temperature, the mechanical loading belongs to the most important parameters, which provide a driving force for this transformation. Consequently, during fatigue a complex change in the microstructure associated with formation and slip of dislocations, formation of stacking faults, twinning and phase transformations takes place. Furthermore, in some metastable austenites, back transformation from ε-martensite into γ-austenite can occur, which results in the shape memory effect. The talk gives an overview on the investigations of the fatigue behavior of three different types of metastable austenite: austenitic stainless steels, high manganese twinning induced plasticity steels and shape memory alloys. LCF, HCF and VHCF tests were made under uniaxial fully reversed tension-compression loading on servo-hydraulic and ultrasonic fatigue systems at ambient temperature. Using mechanical stress-strain, magnetic and electrical resistance measurements as well as EBSD, ECCI, TEM and XRD methods the cyclic deformation and phase transformation behavior were characterized in detail.

KEYWORDS:

Austenitic stainless steels; high manganese steels; shape memory alloys; LCF; HCF; VHCF.

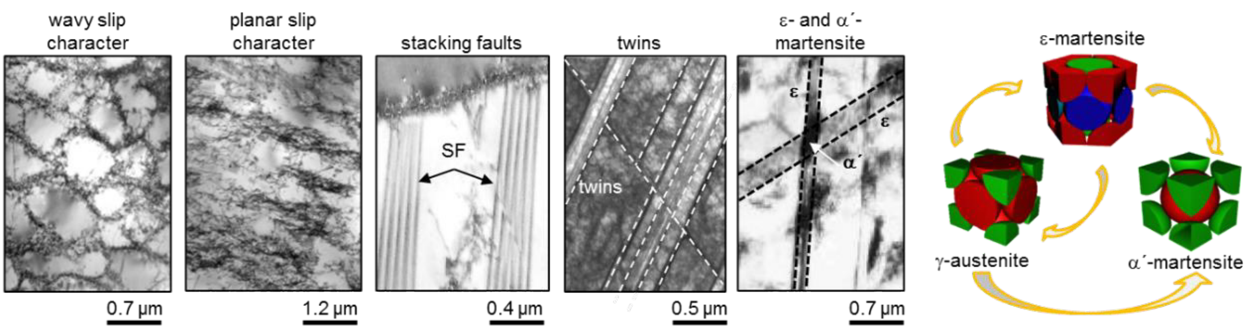


Fig. 1 *Fatigue induced microstructural changes in metastable Fe-based austenite.*

R1-514

In-site Mesoscopic Tension and Fatigue Properties of Proton Exchange Membrane for Fuel Cell

Wei Li[1]*, Zhenlin Mo[1] and Liang Cai[1]

[1] Beijing Institute of Technology, CHINA

* Corresponding author: lliw@bit.edu.cn

ABSTRACT:

The mechanical and fatigue properties greatly determine the durability of proton exchange membrane for fuel cell. In this study, In-site tension and fatigue tests were performed to investigate the fundamental constitutive relation and crack growth behavior of a perfluorosuphonic acid membrane (Nafion 115) in room temperature and dry air, and the variation of strain and displacement fields at the crack tip were discussed in combined with the measurement of digital correlation technology. Results show that the monotonic mesoscopic stress-strain curve exhibits the typical characteristics with strain softening, necking and orientation hardening after yielding, and a viscoelastic-plastic constitutive model is proposed to characterize the time-dependent stress/strain response. Based on the obtained crack growth rate curves, it can be found that the increased stress ratio has a tendency to increase the crack growth rates in all portions of the sigmoidal curve. At a given crack size, moreover, the morphologies of plastic zone at the crack tip with the change of load are observed and the relationship between the strain and the distance away from the crack tip was established. Compared with the effect of stress ratio, the effect of crack size on the strain variation at the crack tip is more significant.

With the increasing of stress ratio, the crack growth

KEYWORDS:

Perfluorosuphonic acid membrane, Fatigue, Stress-strain relationship, Crack growth behavior, Plastic zone variation

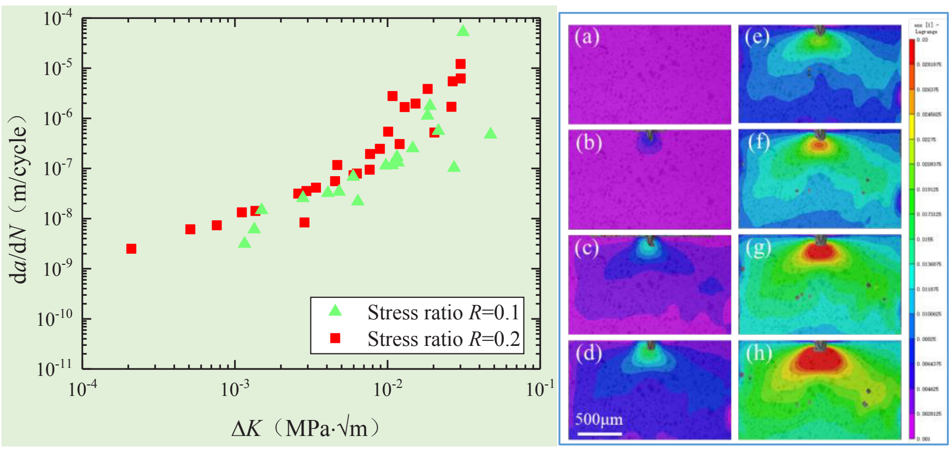


Fig. 1 Crack growth behavior.

R1-515

Fatigue behavior of metastable Fe-based austenites

Marek SMAGA*, Dietmar EIFLER and Tilmann BECK

Institute of Material Science and Engineering (WKK), RPTU Kaiserslautern-Landau, GERMANY

* Corresponding author: m.smaga@mv.rptu.de

ABSTRACT:
Metastable Fe-based austenites exhibit a local minimum of Gibb's free energy and can, hence, transform into a more stable structure. Besides temperature, the mechanical loading belongs to the most important parameters, which provide a driving force for this transformation. Consequently, during fatigue a complex change in the microstructure associated with formation and slip of dislocations, formation of stacking faults, twinning and phase transformations takes place. Furthermore, in some metastable austenites, back transformation from ε-martensite into γ-austenite can occur, which results in the shape memory effect. The talk gives an overview on the investigations of the fatigue behavior of three different types of metastable austenite: austenitic stainless steels, high manganese twinning induced plasticity steels and shape memory alloys. LCF, HCF and VHCF tests were made under uniaxial fully reversed tension-compression loading on servo-hydraulic and ultrasonic fatigue systems at ambient temperature. Using mechanical stress-strain, magnetic and electrical resistance measurements as well as EBSD, ECCI, TEM and XRD methods the cyclic deformation and phase transformation behavior were characterized in detail.

KEYWORDS:
Austenitic stainless steels; high manganese steels; shape memory alloys; LCF; HCF; VHCF.

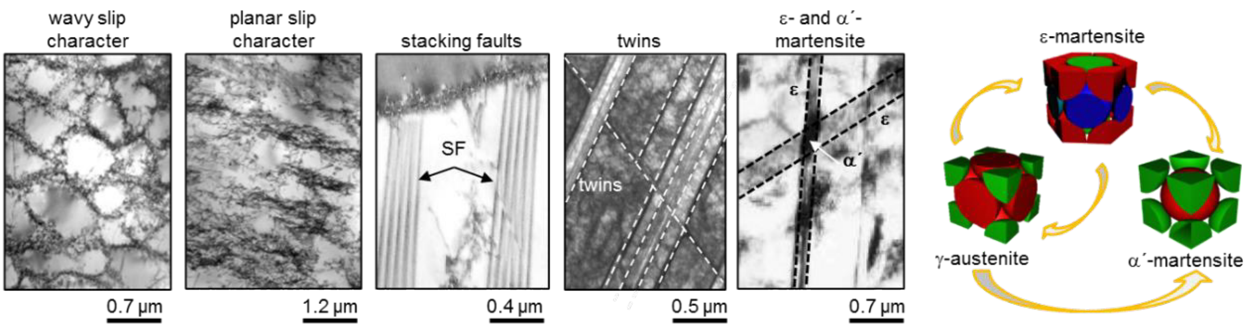


Fig. 1 *Fatigue induced microstructural changes in metastable Fe-based austenite.*

R1-516

Crystallographic mechanism of fatigue failure of zirconium alloys

Conghui Zhang[1,*], Xiangkang Zeng[1], Mingliang Zhu[2], and Tongguang Zhai[3]

[1] Xi'an University of Architecture and Technology, CHINA
[2] East China University of Science and Technology, CHINA
[3] Shandong Jianzhu University, CHINA

* Corresponding author: zhangconghui@xauat.edu.cn

ABSTRACT:
Fully-reversed cyclic deformation of Zr was conducted at strain amplitudes of 0.4% and 0.8% to investigate the deformation and crack initiation behaviors based on slip trace analysis. Results show that prismatic <a> slip with higher Schmid Factor (m >0.4) was the dominant deformation mode. The grains containing persistent slip bands (PSBs) tended to go towards $[\bar{1}2\bar{1}0]$ pole, and the SF had a critical value of 0.4 above. PSB cracks were mainly parallel to prismatic <a> slip with higher SF while some cracks tended to be initiated at GBs with higher misorientation angles. Quantitative investigation of short fatigue crack growth (SFCG) shows that the SFCG was mainly transgranular, sensitive to crystallographic orientation which determined the slip systems within grains and often deflected at GBs. The cracks propagated preferentially on prismatic and pyramidal slip planes due to higher SF for each grain. A set of crack deflections at GBs was quantitatively analyzed. A combination of the geometrical compatibility factor, m', and twist angle, α, as well as the SF, m, were proposed to evaluate SFCG across GBs. The SFCG could cross GBs on the conditions of m > 0.3, α < 40°, and m'> 0.3.

KEYWORDS:
Fatigue crack initiation; Short fatigue crack growth; Grain boundary; persistent slip bands; crystallographic orientation.

R1-517

High Frequency High Cycle Bending Fatigue Failure Mechanism of Blade-like Specimen at High Stress Ratio under Biaxial Tension-bending Load

Zhenlei LI [1], Hao XU [2], Nina LI [3], Guo LI [4, 5], Shuiting DING [6], Duoqi SHI [4, *]

[1] Research Institude of Aero-Engine, Beihang University, Beijing 102206, CHINA
[2] Sichuan Tengden Technology Co., Ltd., Chengdu 610036, CHINA
[3] AECC Guiyang Aero-Engine Design Institute, Guiyang 550081 , CHINA
[4] School of Energy and Power Engineering, Beihang University, Beijing 102206, CHINA
[5] Tianmushan Laboratory, Hangzhou 310023, CHINA
[6] Civil Aviation University of China, Tianjin 300300, CHINA

* Corresponding author: shdq@buaa.edu.cn

ABSTRACT:
This study aims to experimentally investigate the failure mechanism of high cycle bending fatigue (HCBF) with high stress ratio at high temperature. A blade-like specimen was designed and manufactured to represent the structural details between the airfoil and the platform of turbine blade. Then, a novel test rig was developed to apply the axial loading and the transversal high-frequency-vibration. Biaxial tension-bending test system was constructed, including the axial loading, transverse excitation, electromagnetic induction heating, water cooling, control and on-line measurement subsystems. HCBF experiments were performed on the blade-like specimen at 850ºC, using the proposed biaxial experimental methodology. Test results show that the HCBF life was significantly shorter than axial high cycle fatigue (AHCF) in Haigh diagram. Compared with the conventional AHCF, bending stress gradient and high stress ratio in HCBF lead to a different failure mechanism. Scanning electron microscopy (SEM) observations reveal that creep-induced microstructure degradation and voids accelerate the damage process of HCBF.

KEYWORDS: high cycle bending fatigue; high frequency; failure mechanism; blade-like specimen

R1-518

Improving the fatigue defect tolerance of steels by Cu precipitates

David GÖRZEN, Hendrik KRAMER, Bastian BLINN, Tilmann BECK, Dietmar EIFLER*

Institute of Materials Science and Engineering (WKK), RPTU Kaiserslautern-Landau, GERMANY

*Corresponding author: d.eifler@mv.rptu.de

ABSTRACT:

Aging of Cu-alloyed steels leads to the formation of nano-scaled Cu-precipitates, which significantly influence the mechanical properties. However, the specific effect of Cu-precipitates on the fatigue behavior, especially the defect tolerance, has not yet been investigated adequately. Therefore, the influence of Cu-precipitates on the cyclic deformation behavior of 18CrNiMo7-6 steel was analyzed in this work. A higher fatigue defect tolerance for a Cu-alloyed variant was observed in relation to a conventional 18CrNiMo7-6. Since microstructural defects significantly impact the fatigue performance of high-strength steels, an increased defect tolerance can be beneficial for their fatigue strength. However, due to additional alloying elements, the increase in defect tolerance could not be assigned solely on the effect of Cu-precipitation hardening. Thus, the interrelation between the Cu-precipitation state and the cyclic properties was analyzed in more detail using the fully ferritic steel X0.5CuNi2-2. Based on 3D-Atom Probe Tomography (3D-APT) and cyclic indentation testing, it was shown that a change in Cu-precipitation state correlates with a change in Martens hardness *HM* and cyclic hardening potential, represented by $|e_{II}|$ (Fig.1a). Moreover, in fatigue tests it was demonstrated that Cu-precipitates increase both, the fatigue strength (Fig.1b) and the defect tolerance, the latter correlating with the cyclic hardening potential.

KEYWORDS:

Cu-precipitates; precipitation hardening; defect tolerance; cyclic hardening potential; cyclic indentation test

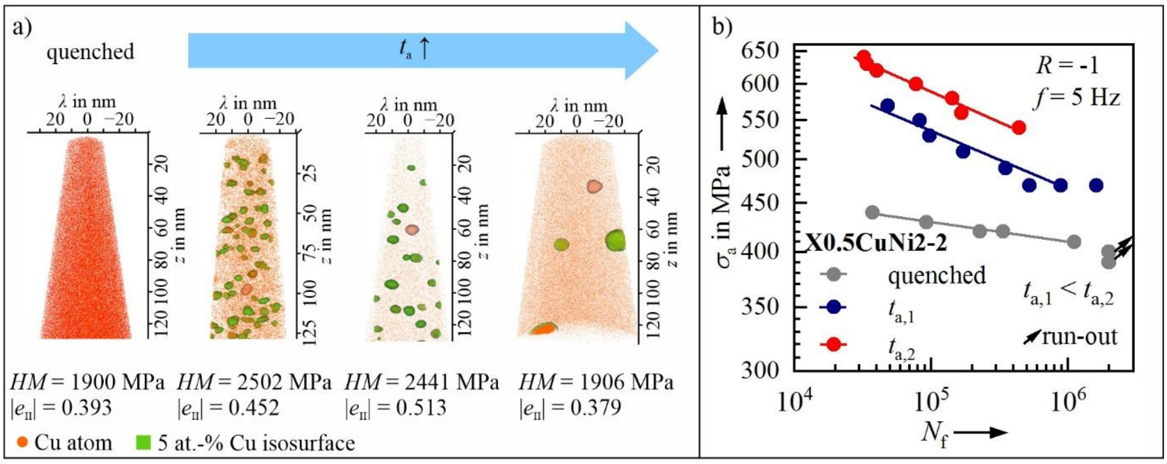


Fig. 1 *a) 3D-APT tips of X0.5CuNi2-2 obtained from IEHK of RWTH Aachen in different heat treatment states with Martens hardness HM and cyclic hardening exponent*$_{CHT}$ $|e_{II}|$*; b) S-N curves of different heat treatment states of X0.5CuNi2-2.*

R2-501

Application of energy-based damage accumulation rule for fatigue monitoring of structure under variable amplitude loading

Matus MARGETIN[1,*], Vladimir CHMELKO[1] and Tomas KOSCO[1]

[1] Slovak University of Technology in Bratislava – Faculty of Mechanical Engineering, SLOVAKIA

* Corresponding author: matus.margetin@stuba.sk

ABSTRACT:
Fatigue lifetime estimation of engineering structures loaded by 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 paper 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.

KEYWORDS:
Damage accumulation rule, fatigue monitoring, variable amplitude loading

R2-502

Micromechanical study of low-cycle fatigue behavior of additively manufactured Inconel 718 superalloy at ambient and elevated temperatures

Xin Zhang[1], Chao Ling[1], Dongfeng Li[1,*], and Hailong Qin[2]

[1] Harbin Institute of Technology, Shenzhen 518055, China
[2] Central Iron and Steel Research Institute, Beijing 10081, China
* Corresponding author: lidongfeng@hit.edu.cn

ABSTRACT:
In the present work, defect- and microstructure-sensitive fatigue behavior of additively manufactured Inconel 718 superalloy (IN718) have been investigated, with an emphasis on the effects of heat treatment conditions and fatigue test temperature. Low cycle fatigue tests have been conducted at room temperature and 650 ^{o}C with a strain ratio of R=-1 and at a fixed strain rate of 10^{-3} s^{-1} for the IN718 alloys undergone different heat treatments. Defects and microstructures of the materials were characterized via electron backscatter diffraction and X-ray computed tomography. Representative volume elements were then constructed based on the key features of the defects and the grain morphology characterized. Finally, crystal plasticity finite element simulations were performed to study the development of cyclic plasticity and the low-cycle fatigue life of the materials. The present work aims to provide deep understanding into the fatigue failure mechanisms of the additively manufacture IN718 and to quantify the effects of the specific microstructure and pores generated during the additive manufacturing process on the fatigue response, which are relevant in order to accurately assess the fatigue life of the IN718 components.

KEYWORDS:
Low-cycle fatigue; Microstructure characterization; Microstructure sensitive modeling; Crystal plasticity; Finite element method

R2-503

Strain distribution of a fir-tree tenon/mortise structure under combined high and low cycle fatigue loads

Han Yan[1], Xin Ding[1], Dawei Huang[1,2,3]*, Xiaojun Yan[1,2,3,4], Xingyu Yang[1], Weifeng Wan[1]

[1] School of Energy and Power Engineering, Beihang University, Beijing 100191, China
[2] National Key Laboratory of Science and Technology on Aero-Engine Aero-thermodynamics, Beijing 100191, China
[3] Beijing Key Laboratory of Aero-Engine Structure and Strength, Beijing 100191, China
[4] Collaborative Innovation Center of Advanced Aero-Engine, Beijing 100191, China

* Corresponding author: huangdawei@buaa.edu.cn

ABSTRACT:
The fir-tree tenon/mortise structure in areo-engine suffers from the combined high and low cycle fatigue (CCF) loads during service, including the low cycle fatigue (LCF) loads (the centrifugal force and the temperature gradient) and the non-coaxial high cycle fatigue (HCF) loads (the aerodynamic force and vibration). The structural integrity of the tenon/mortise structure is significantly affected by the local strain distribution, while the strain value under CCF loads is difficult to acquire. In this study, a simulated specimen of tenon/mortise structure is designed and the CCF test is carried out using a divided-path loading fixture to avoid interference between HCF loads and LCF loads. The amplitude of LCF load is 12kN, while the maximum amplitude of HCF load is 0.5mm and its frequency is 65Hz. The high speed digital image correlation (DIC) method is adopted to acquire the real-time strain distribution during CCF test. According to the strain results, the critical position of the mortise and its strain variation are determined. The high cycle strain of the mortise is proportional to the vibration amplitude of the tenon. The experimental results can provide basis for strength and life assessment.

KEYWORDS:
CCF test, high speed DIC, strain measurement, tenon/mortise

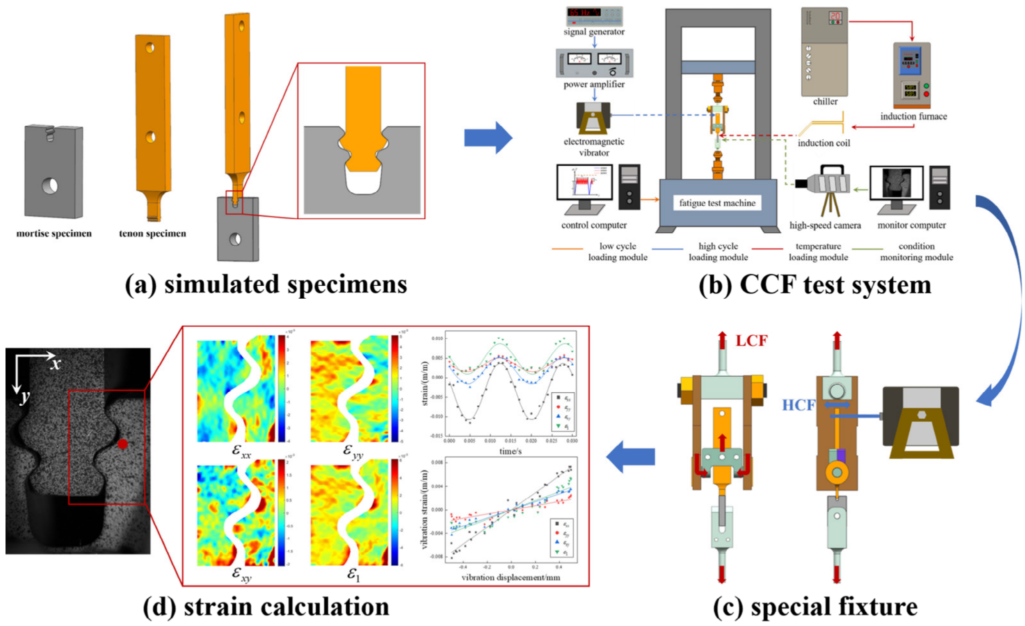


Fig. 1 *Strain measurement process.*

R2-504

An in-situ SEM investigation on fatigue crack growth mechanism under single overload

Lindong Chai[1], Lu Han[1], Yihai He[1] and Wei Zhang[1,*]

[1] Beihang University, CHINA

* Corresponding author: zhangwei.dse@buaa.edu.cn

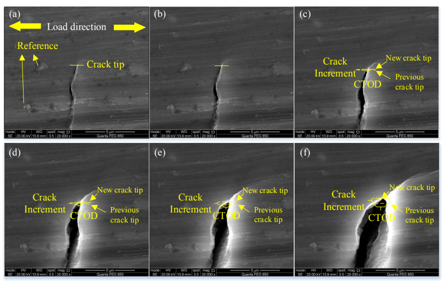
ABSTRACT:

In this study, the fatigue crack growth mechanism under single overload is investigated in a small-time scale by the in-situ scanning electronic microscope (SEM) testing. Firstly, each load cycle is divided into multiple steps. At each step, the crack tip morphology is observed and captured by SEM. Subsequently, the crack increment and crack tip opening displacement (CTOD) are measured, and the correlation between crack growth behavior and CTOD is analyzed. Some typical crack growth behaviors can be directly observed, including crack closure, transient acceleration and retardation. It is found that CTOD is double-log-linear with the crack growth rate in the stable growth stage before and after the overload, which indicates that crack closure is an important mechanism. However, the transient acceleration phenomenon after the overload cannot be solely explained by crack closure. Inspired by the strain memory effect, the CTOD model in the transient acceleration stage is modified by considering the evolution of crack closure and yielding condition simultaneously. The predicted crack increment is very close to the experimental data. It is shown that CTOD can well describe the stable crack growth behavior before and after the overload, and provides a promising explanation for the transient acceleration phenomenon.

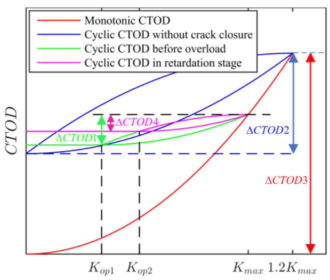
KEYWORDS:

In-situ SEM testing; Crack growth mechanism; Single overload; Crack tip opening displacement

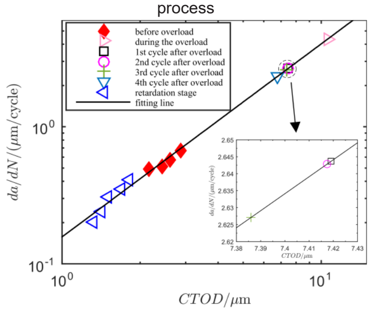
(a)Experimental setup



(b) CTOD and crack increment measurements during loading process



(c)Schematic illustration of CTOD variation under the monotonic and cyclic loading before and after overload(R=0)



(d) Calculated CTOD and FCG rate in transient acceleration stage

Fig. *1 Experimental setup and main results*

R2-505

Fatigue of metallic glasses after an overload as a first step to fatigue under variable amplitude loading

Michael MARX[1,*], Ralf BUSCH[2] and Christian MOTZ[1]

[1] Saarland University, Materials Science and Methods, GERMANY
[2] Saarland University, Metallic Materials, GERMANY

* Corresponding author: m.marx@matsci.uni-sb.de

ABSTRACT:
Describing variable amplitude loading and its influence on crack growth behavior is very complex because of residual stresses and plasticity induced crack closure in front of the crack tip after high tensile loading steps. Typically, this results in a reduced crack propagation rate and accordingly in an increased lifetime. On the other hand, high compressive loads can reduce the effect.
The ductile deformation behavior in metallic glasses differs on the atomic scale from that of crystalline metals due to changing mechanisms from dislocation induced plasticity to shear band induced plastic deformation. Therefore, this might also influence the fatigue behavior at variable load spectra. This effect is investigated for single overloads at a first step. As shown in figure 1, the plastic zone in front of the crack is clearly visible. The crack opening after the overload is comparable to that of a crystalline material and the crack propagation path formerly perpendicular to the loading axis splits in two ways in the direction of the highest shear stresses. As in "normal" metals, the crack propagation rate is reduced as well.

KEYWORDS:
metallic glasses, overload, plastic zone, crack tip opening

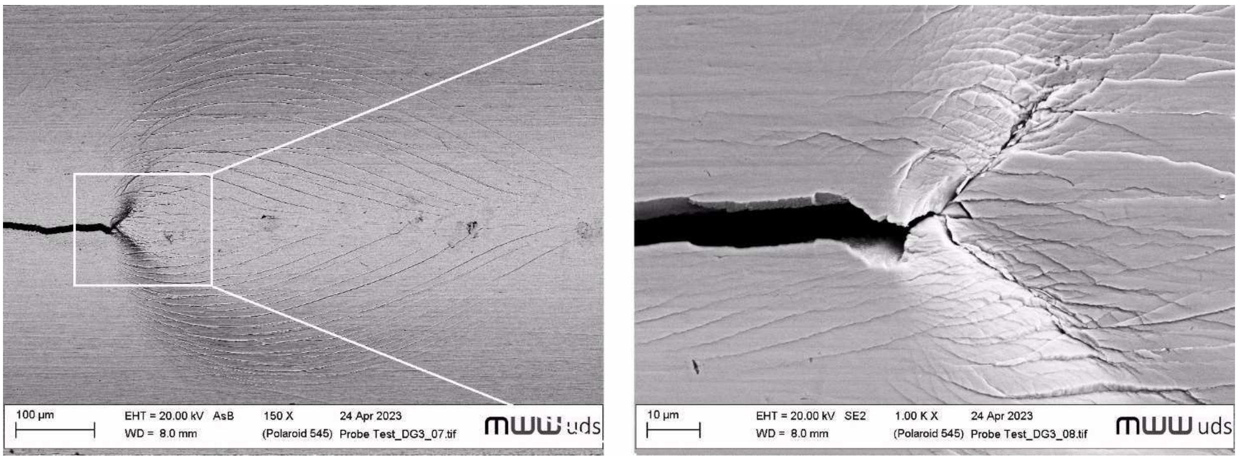


Fig. 1 *Fatigue crack with plastic zone after an overload and additional 1000 cycles (left) and enlarged view of the crack tip (right).*

R2-506

An iso-damage model based on residual *S-N* curves to consider fatigue damage accumulation under HCF-VHCF loads

Tao Liang[1], Songsong Lu[1,*] and Rui Bao[1]
[1] Beihang University, CHINA
* Corresponding author: b21086@buaa.edu.cn

ABSTRACT:

The cumulative fatigue damage (CFD) analysis is necessary for various engineering components, such as aircraft wings, to ensure the structural integrity. The Miner's rule and other isodamage curve-based models are the basis for CDF analysis to calculate and accumulate the fatigue damage (FD) caused by cyclic loads. These models work well in the high cycle fatigue (HCF) regime, but cannot calculate the FD of cyclic loads lower than the fatigue endurance limit of original material (σ_{e0} at 10^7 cycles). This results in the significant error in the CFD analysis of some loading cases with smaller cyclic loads (lower than σ_{e0}), such as loads history contains both HCF and very high cycle fatigue (VHCF) loads. In terms of this issue, a new definition of iso-damage status is put forward based on residual fatigue performance, where the iso-damage status is defined as the FD status with the same remaining *S-N* curve. Under this definition, iso-damage curves can be determined by fatigue experiments directly. They are the remaining *S-N* curve at different FD status. These iso-damage curves (remaining *S-N* curves) can be used to conduct CFD in an innovative way. Fig. 1 schematically shows the procedure for analyzing CFD under a four-stage load history in this way. The detailed procedure is: 1) finding the start point on the original *S-N* curve; 2) from this point, drawing a N_1-length horizon line at the load level of σ_1 to determine the next FD status D_1 (see red arrow marked by (σ_1, N_1)); 3) finding the point of the cyclic load level of σ_2 on the iso-damage curve at FD status D_1 ; 4) from this point, drawing a N_2-length horizon line at the load level of σ_2 to determine the next FD status D_2 (see blue arrow marked by (σ_2, N_2)); 5) repeating procedure 3) and 4) to determine the FD status after each stage of cyclic loads until the horizon arrow reaching the y axis; 6) the interaction between the horizon arrow and axis means the FD reaching 100% and the interaction point is the final failure point (marked by pink color). It should be noted that the value of σ_e on remaining S-N curve decreases with the increase of the pre-FD (see $\sigma_{e0}>\sigma_{e1}>\sigma_{e2}>\sigma_{e3}$ in Fig. 1). This indicates that the FD of cyclic loads lower than the initial σ_{e0} can be calculated at some FD status. Therefore, the new CDF model has the ability to accumulate the FD of cyclic loads lower thanσ_{e0}, thus providing an effective way to conduct the CFD analysis for HCF-VHCF loads.

KEYWORDS:

Fatigue; Cumulative damage; Iso-damage; Fatigue endurance limit.

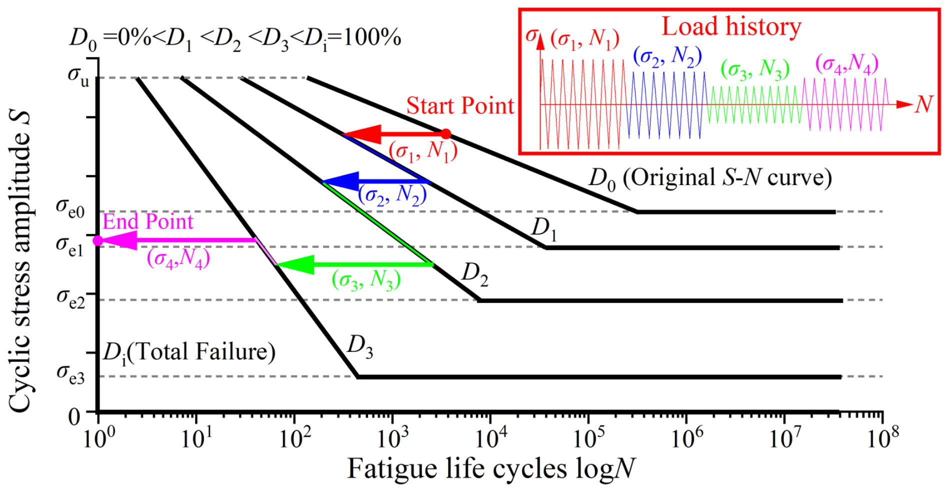


Fig. 1 *Schematic diagram of S-log N lines after prestressing and CDF analysis based on it.*

R2-507

Crack Initiation and Relaxation Behavior of a 1Cr-Cast Steel under Multiaxial High Temperature Loading

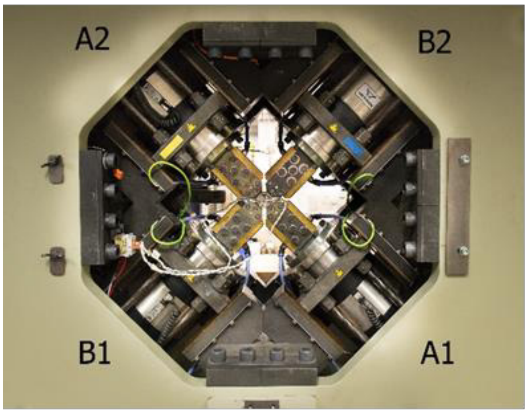
Christian KONTERMANN[1,*], Fabian CONRAD[1], Stefan LINN[1], Massimiliano BIANCHINI[2], Dirk KULAWINSKI[2] and Matthias OECHSNER[1]

[1] Chair and Institute of Materials Technology, TU Darmstadt, GERMANY
[2] Siemens Energy Global GmbH & Co. KG, Muelheim a. d. Ruhr, GERMANY

* Corresponding author: christian.kontermann@tu-darmstadt.de

ABSTRACT:
Rising demands on material performance at high temperature in components under complex loading such as steam- and gas turbine housings require an increase in versatility and precision of component fatigue life modelling approaches. However, the database to calibrate those models is commonly derived from uniaxial testing. The impact of multiaxial loading is usually addressed theoretically by the use of equivalent stress/strain formulations or reduction ratios derived from few specific validation tests. Therefore, a research program which systematically investigates the fatigue life of a 1Cr-cast steel under multiaxial cyclic loading conditions both experimentally and theoretically has been recently conducted. For the experimental part, cruciform specimens are tested by using a servo-hydraulic biaxial test rig equipped with an induction heating device. Each experiment is accompanied by finite element simulations to parametrize the loading condition and derive various equivalent loading parameters at hot-spot locations. In this paper the resulting cycles until crack initiation in the experiments as function of the multiaxiality using different lifetime parameters are summarized. Beside the fatigue life in terms of cycles to crack initiation, the multiaxial loading conditions may also affect the stress relaxation behavior for performed biaxial LCF-testing with hold-time. This is as well summarized in detail both on an experimental and theoretical basis.

KEYWORDS:
Biaxial Testing, Multiaxiality, Elevated Temperature, Crack Initiation, Relaxation



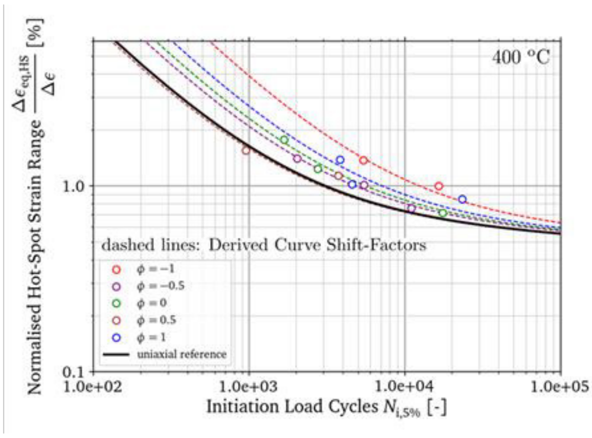


Fig. 1 Servo-hydraulic planar-biaxial test-rig (left), crack initiation curves using hot-spot strain range and derived curve-shift factors for a 1Cr-cast steel (right)

R2-508

Fatigue behaviors and life evaluation of AISI 304 under multiaxial non-proportional random loading

Yu-Chen WANG[1], Le XU[2], Lv-Yi CHENG[3], Lei HE[4,*], Takamoto ITOH[4]

[1] Graduate School of Science and Engineering, Ritsumeikan University, 1-1-1 Nojihigashi, Kusatsu-shi, Shiga, 525-8577, JAPAN
[2] Fracture and Reliability Research Institute, Graduate School of Engineering, Tohoku University, Sendai, Miyagi, 980-8579, JAPAN
[3] Key Laboratory of Pressure Systems and Safety, Ministry of Education, East China University of Science and Technology, Shanghai 200237, PR CHINA
[4] College of Science and Engineering, Ritsumeikan University, 1-1-1 Nojihigashi, Kusatsu-shi, Shiga, 525-8577, JAPAN

* Corresponding author: lei-he@fc.ritsumei.ac.jp

ABSTRACT:

This study focuses on the fatigue behaviors and life of AISI 304 stainless steel under multiaxial non-proportional random loading. Strain-controlled uniaxial and multiaxial random loading low cycle fatigue tests were conducted at room temperature using hollow cylinder specimens. The hollow specimen has an inner diameter of 9 mm, an outer diameter of 12 mm, and a gauge length of 8 mm. The effects of strain range and the intensity of non-proportionality on fatigue life were investigated, and microstructure analysis was carried out to study the failure mechanism. Results indicated that the non-proportional test life was lower than the uniaxial and proportional test life due to cyclic additional hardening. Existing life prediction methods were used to evaluate the fatigue life under random loading, and the results indicate that these methods can effectively predict fatigue life under uniaxial and proportional random loading. However, their evaluation ability for multiaxial non-proportional random loading fatigue life is limited. To address this, a new life evaluation method based on test data is proposed, which can effectively predict uniaxial and multiaxial non-proportional fatigue life under random loading.

KEYWORDS:

Low cycle fatigue; Life evaluation; Multiaxial non-proportional loading; Random loading.

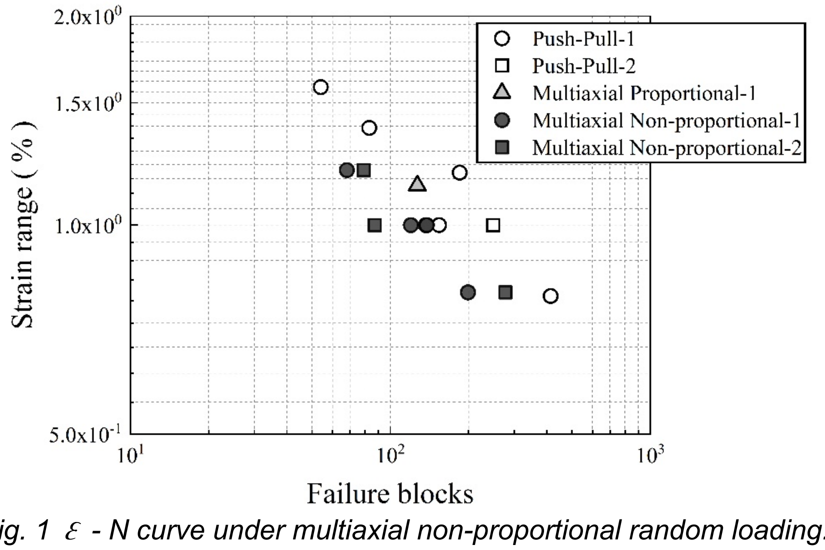


Fig. 1 ε - N curve under multiaxial non-proportional random loading.

R2-509

Fatigue Life Estimation Method Using Equivalent Stress Amplitude by Smith-Watson-Topper Method for SCM440

Naoki HASHIMOTO[1,*], Miu HAYASHI[1], Jinta ARAKAWA[2], Hiroyuki AKEBONO[1] and Atsushi SUGETA[1]

[1] Hiroshima University, JAPAN
[2] Okayama University, JAPAN

* Corresponding author: m223423@hiroshima-u.ac.jp

ABSTRACT:
In this study, repeated two-step variable loading tests were conducted on SCM440 chrome molybdenum steel. The influence of the mean stress effect on the fatigue life evaluation was examined. The modified Goodman method, which is now commonly used, and the Smith-Watson-Topper method, which has attracted attention in recent years, were used as correction methods for the mean stress effect. As a result, it was found that the accuracy of fatigue life prediction was greatly improved by considering the mean stress effect in fatigue life evaluation. It was also found that the SWT method is more accurate than the modified Goodman method in fatigue life evaluation by using the unified *S*-*N* curves with mean stress correction.

KEYWORDS:
Smith-Watson-Topper method, Modified Goodman method, Average stress, Fatigue test, *S*-*N* curves.

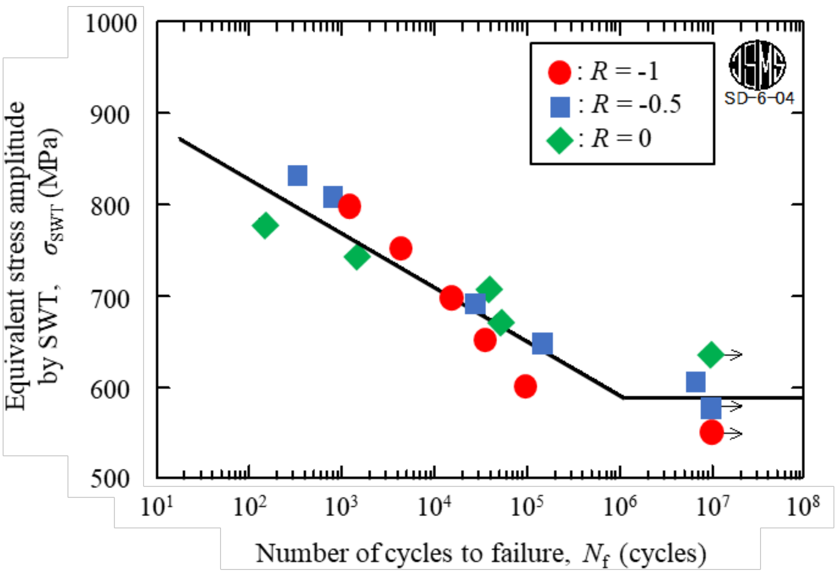


Fig. 1 *S*-*N* curves (SWT).

R2-510

Investigation of the test evaluation for the determination of multiaxial material properties

Alexander LINN[1,*], Michael WÄCHTER[1] and Alfons ESDERTS[1]

[1]Clausthal University of Technology, GERMANY

*Corresponding author: alexander.linn@tu-clausthal.de

ABSTRACT:

An essential aspect of a structural engineer's daily routine is the design of safety-relevant components, with a specific focus on secure fatigue assessment. To achieve the most accurate fatigue assessment possible, it is crucial to accurately describe the material behavior. This poses a significant challenge for engineers, particularly when dealing with non-proportional loads, as additional material effects such as non-proportional hardening become evident.

One approach that addresses non-proportional hardening is the Socie and Marquis method, which adjusts the cyclical hardening coefficient K' of the Ramberg-Osgood approach. The adjustment is based on the degree of non-proportionality of the load sequence and a parameter that describes the non-proportional hardening capacity.

Determining this parameter requires conducting experiments. However, currently, there is no standardized evaluation of these experiments, making it difficult to compare the parameters found in the literature.

In tests on thin-walled tube specimens under non-proportional loading, rounded hysteresis occur (see Fig. 1). The amplitudes are determined on these hysteresis. However, so far, there is no standardized method that specifies the exact point on the hysteresis from which the amplitudes are determined.

This article aims to address and discuss this specific aspect of the evaluation. Through the use of elastic-plastic finite element simulations, this aspect is examined, leading to a proposed standardized evaluation method.

KEYWORDS:

multiaxial fatigue, non-proportional hardening, material behavior, material characterization, finite element analysis

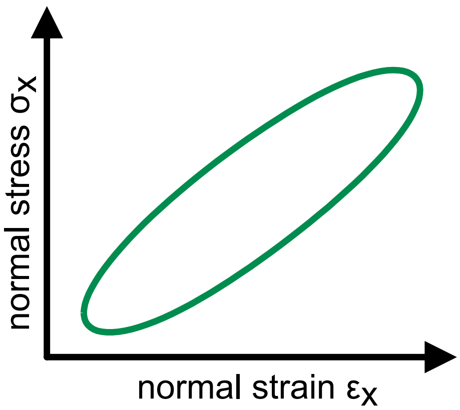


Fig. 1 *Rounded hysteresis with a 90°-phase-shifted load.*

R2-511

Influence of cut edge and notch on electric steel strip under constant and variable amplitude loading

Patrick SCHWARZ[1], Tobias LANGLOIS[1] and Peter HAEFELE[1]

[1] University of Applied Sciences Esslingen, Faculty of Mobility and Technique, Germany

ABSTRACT:
Thin electrical sheets are used to improve the efficiency of electric motors. In packages of laminations (t < 1 mm), the sheets form the rotor of an electric machine. The characteristics of this material group are high grain sizes and high silicium contents. Due to centrifugal forces the laminations are exposed to cyclic loads. In order to determine edge and notch influences, cyclic tests are carried out on unnotched and notched specimens with different edge conditions (milled/polished and shear cut). The cyclic tests are carried out with constant and variable amplitude loading. While in unnotched specimens the edge condition has a significant influence in the limit life time regime and fatigue strength, no edge influence occurs for notched specimens. This behaviour is observed under constant and variable amplitude loading. The cut edge influence of unnotched specimens under variable amplitude loading is lower than under constant amplitude loading. The dynamic support effect is higher for the shear-cut specimens than for the milled and polished edges. The influence of geometric notches is more pronounced under constant amplitude than under variable amplitude loading. The middle damage sum $D_{50\%}$ is higher for notched specimens than for unnotched ones.

KEYWORDS:
Electrical steel strip, fatigue test, notches, cut edge influence, variable amplitude loading

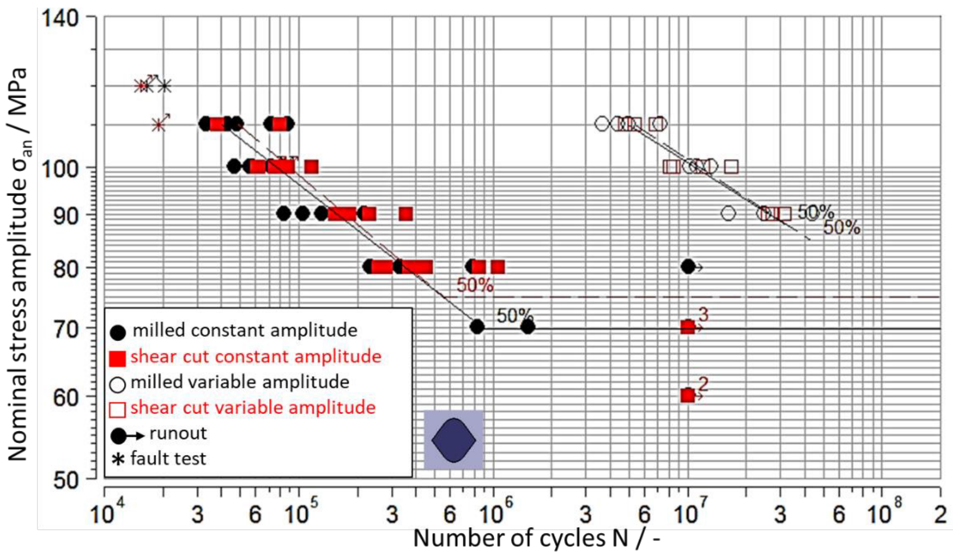


Fig. 1 *SN-curves and lifetime curves for electric strip NO30-15, t = 0.3 mm, K_t = 5.8, R = 0.1, P_F = 50 %, load along the rolling direction*

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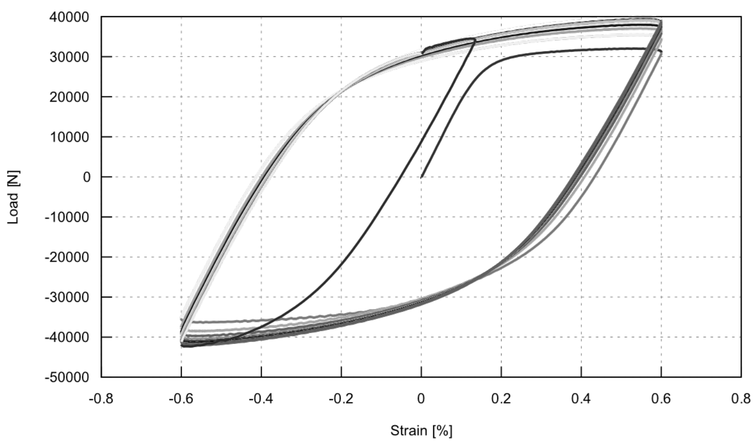
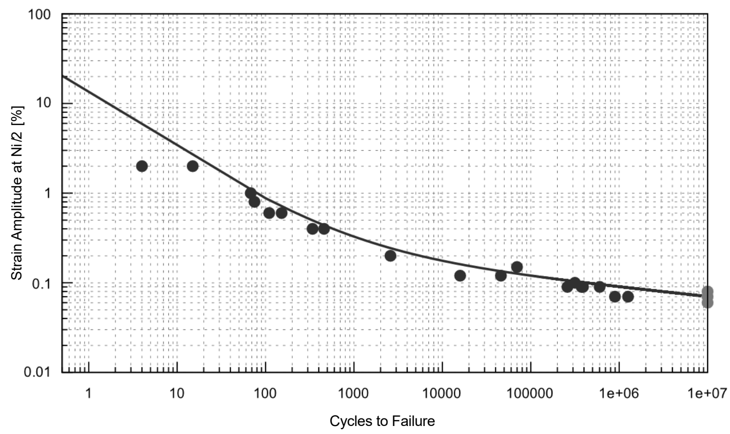
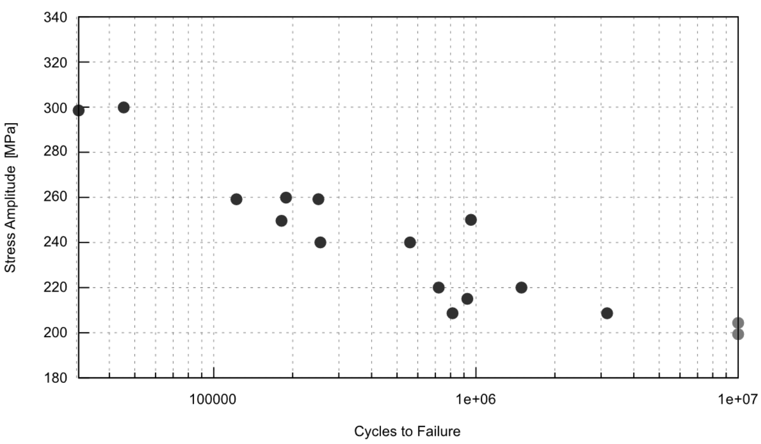
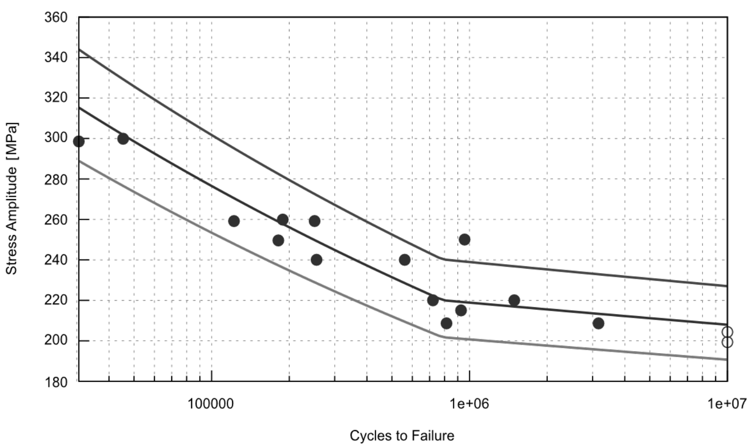




From raw test data to lifetime prediction using advanced statistical functions (maximum likelihood)





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