SUPERALLOYS 2021

14TH INTERNATIONAL SYMPOSIUM ON SUPERALLOYS

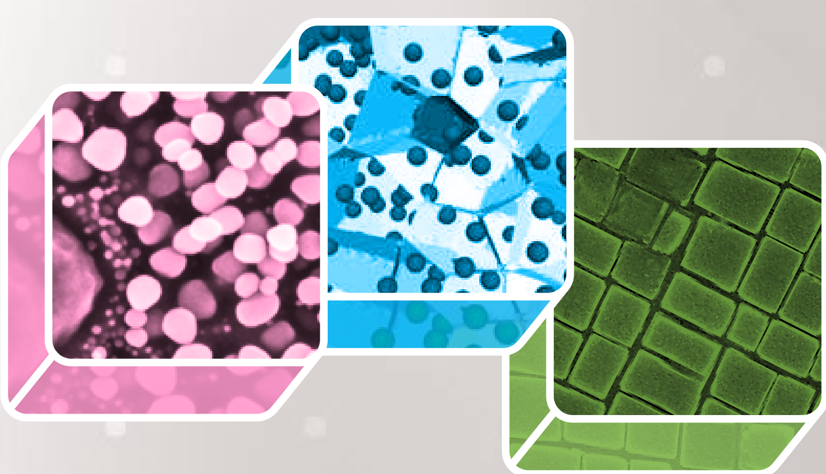
VIRTUAL EVENT

September 13–16, 2021

Pre-Conference Live Talks on September 8

FINAL PROGRAM

Current as of 9/2/2021



SPONSORED BY: TMS The International Seven Springs Symposium Subcommittee of the TMS International Affairs Committee, the TMS Structural Materials Division (SMD), and the TMS High Temperature Alloys Committee.

www.tms.org/Superalloys2021

SCHEDULE

Tuesday, September 7, 2021		
Virtual platform access opens for registrants.		On-demand
Wednesday, September 8, 2021		
8:30 - 9:45 a.m. EDT	Pre-Conference Live Talks	Live
9:45 - 10:10 a.m. EDT	Q&A with Presenters	Live
10:30 a.m. - 12:00 p.m. EDT	Short Course: A Review of Vacuum Precision Investment Casting	Live
Monday, September 13, 2021		
8:30 - 9:30 a.m. EDT	Opening Keynote Session and Keynote Q&A	Live
9:30 - 11:00 a.m. EDT	Interactive Session Honoring Pierre Caron*	Live
11:10 a.m. - 12:50 p.m. EDT	Technical Session: Alloy Development I	Live
12:50 - 1:15 p.m. EDT	*Alloy Development I Q&A*	Live
1:30 - 2:45 p.m. EDT	Technical Session: Alloy Development II	Live
2:45 - 3:10 p.m. EDT	*Alloy Development II Q&A*	Live
3:10- 4:10 p.m. EDT	Interactive Session on Alloy Design*	Live
4:10 - 5:25 p.m. EDT	Technical Session: Blade Alloy Behavior	Live
5:25 - 5:50 p.m. EDT	*Blade Alloy Behavior Q&A*	Live
Tuesday, September 14, 2021		
8:30 - 9:45 a.m. EDT	Technical Session: Disk Alloy Manufacture	Live
9:45 to 10:10 a.m. EDT	*Disk Alloy Manufacture Q&A*	Live
10:10 to 11:10 a.m. EDT	Interactive Session on Disk Alloy Manufacture and Behavior*	Live
11:10 a.m. - 12:25 p.m. EDT	Technical Session: Disk Alloy Behavior	Live
12:25 -12:50 p.m. EDT	*Disk Alloy Behavior Q&A*	Live
1:30 - 2:45 p.m. EDT	Technical Session: Blade and Disk Alloy Behavior	Live
2:45 - 3:10 p.m. EDT	*Blade and Disk Alloy Behavior Q&A*	Live
3:10- 4:10 p.m. EDT	Interactive Session on Disk Alloy Behavior*	Live
4:10 - 5:25 p.m. EDT	Technical Session: Environmental Behavior	Live
5:25 - 5:50 p.m. EDT	*Environmental Behavior Q&A*	Live
Wednesday, September 15, 2021		
8:30 - 9:45 a.m. EDT	Technical Session: Blade Alloy Manufacture	Live
9:45 to 10:10 a.m. EDT	*Blade Alloy Manufacture Q&A*	Live
10:10 to 11:10 a.m. EDT	Interactive Session on Blade Alloy Behavior*	Live
11:10 a.m. - 12:25 p.m. EDT	Technical Session: Alternative Materials	Live
12:25 -12:50 p.m. EDT	*Alternative Materials Q&A*	Live
1:30 - 2:45 p.m. EDT	Technical Session: Additive	Live
2:45 - 3:10 p.m. EDT	*Additive Q&A*	Live
3:10- 4:10 p.m. EDT	Interactive Session on Alternative Materials and Additive*	Live
4:10 - 5:25 p.m. EDT	Technical Session: Alloy Development and Component Manufacture and Repair	Live
5:25 - 5:50 p.m. EDT	*Alloy Development and Component Manufacture & Repair Q&A*	Live
5:50 - 6:00 p.m. EDT	Concluding Comments	Live
Thursday, September 16 to Sunday, October 31, 2021		
Virtual platform access remains open for registrants through October 31, 2021.		On-demand
Discussion and networking via conference platform.		

** Interactive sessions are presentations of graphical abstracts followed by discussion of results and research.*

The schedule is in Eastern Daylight Time (UTC-4:00).
Use the Time Zone Converter to translate event times into your local time zone.

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FINAL PROGRAM

The 14th International Symposium on Superalloys (Superalloys 2021) aims to highlight technologies for lifecycle improvements. In recent years, the superalloys community has benefited greatly from advances in the development of property models, computational tools, processing methods, and innovative characterization techniques that have contributed to and improved the processing and performance of existing materials while accelerating the development of new alloys. In addition to the traditional focus areas of alloy development, processing, mechanical behavior, coatings, and environmental effects, this symposium includes papers from academia, supply chain, and product-user members of the superalloy community that highlight technologies that contribute to improving manufacturability, affordability, life prediction, and performance of superalloys.

For the first time, the symposium takes place virtually and offers a contactless format for inspiring conversations and collaborations, as the COVID-19 pandemic continues to prevent in-person meetings. Your focused participation is appreciated as we present topics for discussion, explore new ways to engage with each other, and encourage networking among attendees. Thank you for joining us. You are an essential part of Superalloys 2021.

TIPS FOR PARTICIPATING IN THE VIRTUAL EVENT

1) **Remove Distractions.** Notify others that you are at a conference. Set your out-of-office message in your e-mail client. Actively listen and take notes during the presentations, as if you were attending in person.

2) **Attend in Real Time.** Whenever possible, listen to presentations at their scheduled time so that you are able to ask questions and engage in discussions.

3) **Relax, and Enjoy!** If you miss something, don't worry. One of the benefits of a virtual event is the ability to access recordings of the presentations. You have access to the recordings and the proceedings through the end of October 2021.

ORGANIZING COMMITTEE

CHAIR:

Sammy Tin, University of Arizona

CONFERENCE ORGANIZERS:

- **Chris O'Brien**, ATI Specialty Materials
- **Justin Clews**, PCC Structurals
- **Jonathan Cormier**, ISAE-ENSMA
- **Qiang Charles Feng**, University of Science and Technology Beijing
- **Mark Hardy**, Rolls-Royce plc
- **John Marcin**, Collins Aerospace
- **Akane Suzuki**, GE Research

SUPERALLOYS 2021 AWARDS COMMITTEE:

- **Eric Huron**, GE Aviation
- **Gern Maurer**
- **Tresa Pollock**, University of California at Santa Barbara
- **Roger Reed**, University of Oxford

CONFERENCE DETAILS

KEYNOTE PRESENTATIONS, TECHNICAL SESSIONS, AND INTERACTIVE SESSIONS

Keynote presentations, technical sessions, and interactive sessions will be live talks with webinar-style question-and-answer sessions. Refer to the schedule to participate.

ADDITIONAL PRE-RECORDED TALKS

Additional pre-recorded talks are available on demand starting September 13, 2021. Access ends on October 31, 2021.

VIRTUAL MEETING SETTINGS

The following practices are recommended for optimal participation:

- Google Chrome browser; use the latest version.
- Mute your audio settings before joining a session.
- Minimize distractions; consider an out-of-office response for e-mail.

For additional technical support, contact **support@whova.com**. For questions about programming, contact programming@tms.org.

CLOSED CAPTIONING

Access closed captioning by using Google Live Caption in the Chrome browser.

Open Settings >> Advanced >> Accessibility. Toggle Live Caption to **On**. Open a new tab with video content and play a video. Captions should appear once speaking begins.

To stop Live Caption, open Settings >> Advanced >> Accessibility and toggle Live Caption **Off**.

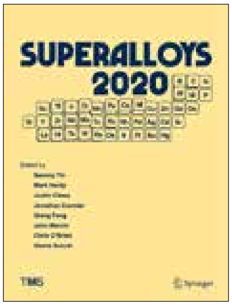
GETTING STARTED

To participate in Superalloys 2021, you will need to log on to the virtual conference platform. Upon registering, you will be e-mailed a link. Use the link to log on with your e-mail address and create a password. Enter your e-mail address and password to access the virtual platform.

TECHNICAL SUPPORT

Superalloys 2021 is hosted on the Whova virtual event platform. If you need assistance using the virtual platform, contact the Whova support team by emailing **support@whova.com**.

DOWNLOAD PROCEEDINGS



All registrants receive free electronic access to the Superalloys 2020 proceedings publication until October 31, 2021.

To download the proceedings, go to the proceedings publications login page at **www.tms.org/Superalloys2020proceedings**. Enter your name and your order number, found at the top of your registration confirmation.

TMS WOULD LIKE TO THANK THE FOLLOWING SPONSORS FOR THEIR SUPPORT OF THE EVENT:

GE Research
https://www.ge.com/research/

ATI
https://www.atimetals.com/

MEETING POLICIES

By registering for this meeting, attendees accept the terms of the **TMS Privacy Policy** and agree to abide by TMS policies, including the **Meetings Code of Conduct** and the **TMS Anti-Harassment Policy.** For additional information on policies related to TMS events, visit the **TMS Meetings Policies** page and the **Code of Conduct portal.** A complete listing of Society policies can be accessed through the **Society Bylaws & Policies** section of the TMS website.

REFUNDS

The deadline for all refunds was August 9, 2021.

TIME ZONES

Unless otherwise noted, all times for this conference and related events will take place in the local time zone, EDT (UTC/GMT -4:00 hours). This is the local time for TMS headquarters in Pittsburgh, Pennsylvania, USA. Use a tool like the **Time Zone Converter** to translate event times into your local time zone.

LANGUAGE

The meeting and all presentations and program materials will be in English.

CURRENCY

All meeting fees are expressed in U.S. dollars (USD).

ACCESS TO RECORDED PRESENTATIONS AFTER THE CONFERENCE

Please note that registrants will have access to all recorded presentations from Superalloys 2021 through October 31, 2021. Log in to the conference platform at any time after the conference has ended to view content.

SHORT COURSE (Included in your registration fee)

A REVIEW OF VACUUM PRECISION INVESTMENT CASTING

Wednesday, September 8, 2021
10:30 a.m. to 12:00 p.m. EDT

This course will provide a review of the investment casting process for superalloys. The instructors will begin with an overview for those new to the topic and will cover more advanced topics on process control, solidification and defects later in the session. The focus will be on production-oriented vacuum investment casting furnaces and the casting process itself. Wax pattern and ceramic shell making will be discussed for context.

Major topics will be:

- Introduction to the investment casting process
- Production furnace basic configuration and main components
- Vacuum precision investment casting (VPIC) process steps
- Common VPIC defects, causes, and remedies
- Participants will leave with a deeper understanding of the state-of-the-art Vacuum Precision Investment Casting (VPIC) equipment, the VPIC process and how it is controlled, as well as an overview of common defects and their causes.

INSTRUCTORS:

- **Andrew Elliott**
  Vice President Technology, Consarc Corporation
- **Iñaki Vicario**
  Casting Technology Specialist, Consarc Engineering

FINAL PROGRAM

SUPERALLOYS 2021

B C N Al Si P Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In La Hf Ta W Re Os Ir Pt Au Hg

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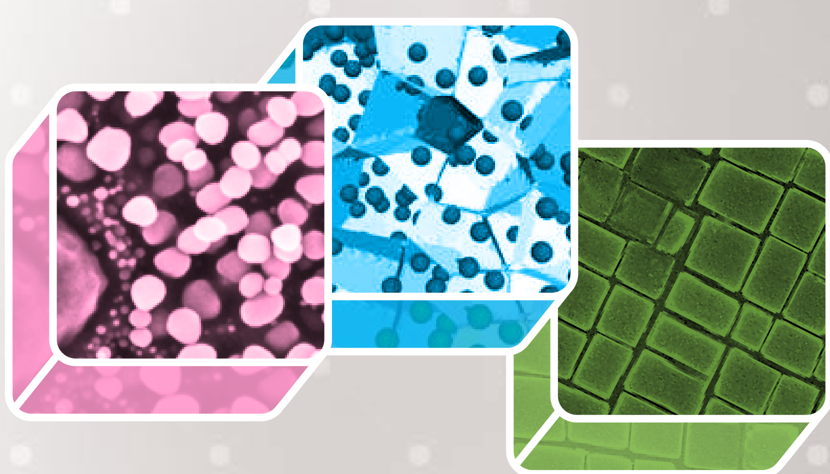

www.tms.org/Superalloys2021

Pre-Conference Live Talks

Begins Wednesday at 8:30 AM EDT
September 8, 2021

Session Chairs: A. Suzuki, GE Research; V. Saraf, ATI Ladish

8:30 AM

Evaluation and Comparison of Damage Accumulation Mechanisms during Non-isothermal Creep of Cast Ni-based Superalloys: *Stoichko Antonov*[1]; Wenrui An[1]; Satoshi Utada[2]; Xiaotong Guo[1]; Caspar Schwalbe[3]; Weiwei Zheng[1]; Cathie Rae[3]; Jonathan Cormier[2]; Qiang Feng[2]; [1]University of Science and Technology Beijing; [2]ISAE-ENSMA; [3]University of Cambridge

The creep behavior under non-isothermal and isothermal creep conditions was studied for a single crystal, a directionally solidified, and a polycrystalline superalloy. Regardless of the alloy type, the non-isothermal creep life of the alloy was much lower than that under isothermal conditions, yet the samples ruptured at higher plastic strains. Irregular interfacial network formation and early (but homogeneously distributed) shearing of the ã' phase was identified as the main source of damage for all three alloys. Additionally, secondary precipitates with thermal expansion coefficients different from the surrounding matrix, led to the formation of creep voids, especially under thermal cycling. In that respect, surface carbides were seen as particularly damaging due to their selective oxidation, which resulted in the extension of secondary cracks. The higher plastic strains exhibited by the non-isothermal creep samples were correlated to the more homogeneously distributed damage accumulation, in comparison to the more localized deformation during isothermal creep. This study provides an overview of the damage accumulation sources in the three types of available superalloys, and highlights areas which need to be further considered when designing future alloys for the non-isothermal creep regime.

8:55 AM

Precipitate Phase Stability and Mechanical Properties of Alloy 263 and Variants in Wrought or Cast Form: *Martin Detrois*[1]; Paul Jablonski[1]; Jeffrey Hawk[1]; [1]National Energy Technology Laboratory

Alloy 263 is a candidate Ni-based superalloy for use in advanced ultra-supercritical (AUSC) power plants that are targeted to operate above 700 ˚C. Exposure times in this type of environment are considerable with target creep properties specified at 100,000 h making phase stability an important parameter in the alloy selection process. In this investigation, the microstructure of alloy 263 and two modified compositions in both cast and cast/wrought forms were investigated after exposure at 800 ˚C for various times ranging from 1,000 h to 10,000 h. Tension and creep properties were assessed for all alloys in both forms. Modification to the Ti and Al concentrations successfully slowed down the ã' to ç transformation while doubling the ã' fraction. Thin elongated ç needles or platelets formed in the wrought products while thicker, plate-like, ç precipitates were found in the castings. The effect of the various microstructures on the creep properties were determined using isothermally aged specimens aged at 800 ˚C for 3,000 h and 10,000 h prior to creep screening. Strong precipitation of the ç phase was found to considerably decrease creep life and increase minimum creep rate. By modifying the Ti and Al content, the creep life and ductility of the new formulation tested on specimens isothermally aged for 3,000 and 10,000 h were near that of the nominal alloy in its standard aged condition.

9:20 AM

Effect of Carbide Inoculants Additions in IN718 Fabricated by Selective Laser Melting Process: Tzu-Hou Hsu[1]; Kai-Chun Chang[1]; Yao-Jen Chang[1]; I-Ting Ho[2]; Sammy Tin[2]; Chen-Wei Li[3]; Koji Kakehi[3]; Chih-Peng Chen[4]; Kuo-Kuang Jen[4]; Ho-Yen Hsieh[5]; *An-Chou Yeh*[1]; [1]National Tsing Hua University; [2]Illinois Institute of Technology; [3]Tokyo Metropolitan University; [4]National Chung-Shan Institute of Science and Technology; [5]Gloria Material Technology Corp.

This article presents the effect of carbide inoculants additions on microstructure evolution and mechanical properties of Inconel 718 superalloy fabricated by selective laser melting (SLM) process. Flakes of titanium carbide (TiC) and niobium carbide (NbC) were mixed with the Inconel 718 powder and acted as nucleating agents to induce heterogenous nucleation in order to eliminate anisotropic grain structure. By increasing fraction of carbide inoculants, more isotropic grain texture was detected. Furthermore, significant improvements on creep properties have been observed with minor carbide additions. With 0.5 wt % TiC and NbC addition, creep rupture life could be increased from 198.5 hours to 449.5 hours and 371.8 hours, respectively. Moreover, creep strain rate was dramatically decreased from 0.513 10-8 s-1 to 0.12 10-8 s-1 by 0.5 wt % TiC additions. This study has demonstrated that minor carbide addition can have profound impact on the microstructure and property of Inconel718 processed by SLM.

9:45 AM Question and Answer Period

Opening Keynote Session

Begins Monday at 8:30 AM EDT
September 13, 2021

Session Chairs: M. Hardy, Rolls-Royce Plc; S. Tin, University of Arizona

8:30 AM Introductory Comments

8:40 AM Keynote

Advanced Modeling Tools for Processing and Lifing of Aeroengine Components: *Christian Dumont*[1]; Arnaud Longuet[1]; [1]AUBERT & DUVAL

Lifing is one of the main challenges for aeroengine manufacturers. For fatigue prediction, attention has been focused on the crack initiation mode depending on stress level and initial microstructure. Microstructure prediction during the component manufacturing, especially for final heat treatments and final forging operations is required if it is to be included in fatigue analysis. Reliable tools are now available for basic nickel-based alloys such as Inconel 718. For other alloys, notably ã/ã' alloys, research is still being performed in close partnership with academia. Globally, two main trends are emerging; first, one of our main interests is to develop the modeling capability for the entire manufacturing process, including ingot conversion and billet forging. Second, new approaches are still under development by introducing more physical considerations through full field models, which are very useful for a better understanding of specific issues such as heterogeneous grain growth. From a component lifing point of view, the initial state of stress is also a key parameter to be considered. One method for the control of residual stresses is application of a pre-spinning process. Finally, a standard lifing methodology is explained and improvements are proposed, in particular, size effect is used to model notch specimen life considering surface or internal initiation.

Question and Answer Period to Follow.

Monday Interactive Session - Celebration of Pierre Caron's Contributions

Begins Monday at 9:30 AM EDT
September 13, 2021

Session Chairs: J. Cormier, ENSMA - Institut Pprime - UPR CNRS 3346; N. Bozzolo, MINES ParisTech; T. Pollock, University of California, Santa Barbara

Check the virtual conference platform for links to the honorary presentations and the celebration session.

Monday Part I - Alloy Development I

Begins Monday at 11:10 AM EDT
September 13, 2021

Session Chairs: R. Reed, University of Oxford; T. Pollock, University of California, Santa Barbara

11:10 AM
Developing Alloy Compositions for Future High Temperature Disk Rotors: *Mark Hardy*[1]; [1]Rolls-Royce Plc
Two new alloy compositions for possible disk rotor applications have been examined. Both were intended to have higher ' content than the existing alloy, RR1000, and be produced using powder metallurgy and isothermal forging to enable forgings to show a consistent coarse grain microstructure. Small pancake forgings of the new alloys and RR1000 were made and from these, blanks were cut, solution heat treated, cooled at measured rates and aged. Results of screening tests to understand the tensile, creep and dwell crack growth behavior, oxidation resistance and phase stability of these new alloys and coarse grain RR1000 are reported. The development alloys were similar in composition but exhibited different tensile and creep properties, phase stability and resistance to oxidation damage. Despite attempts to minimize variation in microstructure from heat treatment, differences in ' size distribution were found to influence tensile and creep behavior. One of the new alloys (Alloy 2) showed improved yield and tensile strength compared to RR1000. Alloy 2 displayed similar initial creep strain behavior to RR1000 but superior resistance to subsequent creep damage, producing longer creep rupture lives. All of the alloys showed crack retardation at low stress intensity factor ranges (K) from 3600 s dwell cycles at 700 ˚C in air. This occurred whilst crack growth was intergranular. Alloy 1 was found to precipitate C14 Laves phase from long term exposure at 800 ˚C. Like RR1000, σ phase was not detected in the new alloys after 750 hours at 800 ˚C.

11:35 AM
Ni-Co-based Wrought Superalloys Containing High W – Microstructure Design for a Balance of Properties: *Akane Suzuki*[1]; Steve Buresh[2]; Richard DiDomizio[2]; Scott Oppenheimer[2]; Soumya Nag[2]; Ian Spinelli[2]; PR Subramanian[2]; Stephen Pope[3]; Jon Schaeffer[3]; [1]GE Global Research; [2]GE Research; [3]GE Gas Power
Ni-Co-based $\gamma+\gamma'$ superalloys were explored in a wide range of Co/Ni ratios for designing a wrought superalloy with a combination of superior high temperature strength and environmental resistance at temperatures above 927 ˚C (1700 ˚F). While alloys with high Co/Ni ratios possess superior creep resistance, reductions of the Co/Ni ratio and additions of Fe and B are effective in improving ductility in the intermediate temperature range and hold-time low cycle fatigue resistance. A formation of fine, discrete Co2W Laves precipitates covering a large fraction of grain boundaries is responsible for the improvements. The experimental alloys exhibited excellent oxidation resistance at 982 ˚C (1800 ˚F) by forming a protective alumina scale during cyclic exposure.

12:00 PM
Development of AGAT, a 3rd Generation Nickel Based Superalloy for Single Crystal Turbine Blade Applications: *Jeremy Rame*[1]; Pierre Caron[2]; Virginie Jaquet[3]; Didier Locq[2]; Odile Lavigne[2]; Mikael Perrut[2]; Joël Delautre[1]; Lorena Mataveli Suave[3]; Amar Saboundji[3]; Jean-Yves Guedou[1]; [1]Safran Aircraft Engines; [2]ONERA; [3]SAFRAN Tech
The new third generation single crystal superalloy AGAT has been developed for aircraft engine turbine blade applications. Alloy design procedure is described and AGAT alloy properties are presented and compared with those of respectively 1st, 2nd and 3rd generation AM1, CMSX-4 and CMSX-10 alloys. AGAT alloy exhibits high creep resistance at very high temperature (1200 ˚C) compared with 1st and 2nd generation superalloys while maintaining moderate density (8870 kg·m-3) and stable microstructure unlike the 3rd generation superalloy. High cycle fatigue (HCF) and low cycle fatigue (LCF) properties of AGAT alloy are similar to 2nd generation CMSX-4 alloy. AGAT solution heat treatment allows suppressing the ã/ã' interdendritic eutectic pools at a temperature 30 ˚C lower than for CMSX-10 with a shorter duration. Oxidation resistance of AGAT alloy at 1150 ˚C is lower than that of 2nd but higher than that of 3rd generation reference superalloys. AGAT shows low sensitivity to secondary reaction zone (SRZ) formation under b-NiPtAl bond coat (BC) and great spallation resistance of YPSZ EB-PVD thermal barrier coating (TBC) compared with reference alloys. Finally, single crystal turbine blades were successfully manufactured through industrial processes to be tested in engine conditions.

12:25 PM Invited
Enhancing the Creep Strength of Next Generation Disk Superalloys via Local Phase Transformation Strengthening: *Timothy Smith*[1]; Timothy Gabb[1]; Katelun Wertz[2]; Joshua Stuckner[1]; Laura Evans[1]; Ashton Egan[3]; Michael Mills[3]; [1]NASA Glenn Research Center; [2]AFRL; [3]The Ohio State University
A new disk superalloy has been developed by NASA to improve high temperature creep performance utilizing the recently discovered local phase transformation strengthening mechanism. Creep tests were performed at 760˚C and 552MPa, to approximately 0.3% plastic strain, a regime where the formation of ã' shearing modes such as superlattice extrinsic and intrinsic stacking faults are active. The new alloy exhibited superior creep performance over the current state-of-the-art superalloys, ME3 and LSHR. High resolution characterization confirmed the formation of the strengthening ç phase along superlattice extrinsic stacking faults and ÷ phase along superlattice intrinsic stacking faults. In addition, creep deformation analysis via scanning transmission electron microscopy appears to show a significant reduction in microtwin formation as compared to LSHR and ME3. This improvement in creep performance was also accompanied by an improvement in both room temperature and high temperature strength.

12:50 PM Question and Answer Period

FINAL PROGRAM

Monday Part II - Alloy Development II

Begins Monday at 1:30 PM EDT
September 13, 2021

Session Chairs: J. Marcin, Collins Aerospace; E. Huron, GE Aviation

1:30 PM
Segregation of Solutes at Dislocations: A New Alloy Design Parameter for Advanced Superalloys: Lola Lilensten[1]; Philipp Kürnsteiner[1]; Jaber Mianroodi[1]; Alice Cervellon[2]; Johan Moverare[3]; Mikael Segersäll[3]; Stoichko Antonov[4]; *Paraskevas Kontis*[1]; [1]Max-Planck-Institut für Eisenforschung GmbH; [2]University of California Santa Barbara; [3]Linköping University; [4]University of Science and Technology Beijing
The interactions of solutes with crystal defects at near atomic level were investigated in five single crystal Ni-based superalloys deformed at temperatures between 850 and 1160 ˚C and various deformation conditions. These interactions, and consequently the composition of a particular solute that segregates at a crystal defect, are controlled by the type of the crystal defect, the deformation conditions, i.e. temperature and stress, and the overall alloy composition. Atomistic phase field simulations also reveal the effect of dislocation velocity on the amount of solutes that can segregate on dislocations. The observed plasticity-assisted redistribution of interacting solutes phenomena result in microstructural and chemical alterations, which are associated with recrystallization, rafting and the formation of topologically close-packed phases. Deciphering these interactions by enabling quantitative three-dimensional imaging of solutes at crystal defects with high sensitivity and spatial resolution, will allow to develop a solute-defect database that can be used as a key-design parameter for advanced superalloys.

1:55 PM
A New Co-free Ni Based Alloy for Gas Turbine and Exhaust Valve Applications: Karl Heck[1]; *Ning Zhou*[1]; Samuel Kernion[1]; Danielle Rickert[1]; Filip Van Weereld[1]; [1]Cartech
A new Ni-based cast-and-wrought alloy designed for high temperature strength, stability, notch ductility and minimal elevated temperature dwell fatigue crack growth rate has been laboratory developed and scaled up in the mill. Based on studies of a relatively wide compositional space, a Co-free composition was selected. Other properties, including tensile strength, stress rupture, creep, low cycle fatigue, oxidation and sulfidation resistance, as well as hot workability were also studied. Several heat treatments were developed to achieve property balances as appropriate for various end-user applications such as those limited by damage tolerance, creep, fatigue or tensile strength. Microstructural stability after extended exposure at temperatures ranging from 704 ˚C to 871 ˚C was studied. Multiple 12-tonne heats have been successfully processed as VIM/VAR and VIM/ESR ingots converted into forged billets, rolled bar and strip products. Potential applications for this alloy include turbine disks, gas turbine engine casings, high temperature fasteners, heavy duty diesel engine exhaust valves and high temperature gaskets. This paper discusses alloy and process development as well as microstructure-property relationships of the alloy.

2:20 PM
Alloying Effects on the Competition between Discontinuous Precipitation vs. Continuous Precipitation of δ/η Phases in Model Ni Based Superalloys: *Satoru Kobayashi*[1]; [1]Tokyo Institute of Technology
Alloying effects on the competition between discontinuous and continuous precipitation of d-Ni3Nb (D0a) phase and h-Ni3Ti (D024) phase were investigated in model Ni-Cr-Fe-Nb and Ni-Ti based alloys, respectively, to aim at designing polycrystalline Ni based superalloys with better temperature capability. Discontinuous precipitation tends to occur at lower temperatures while continuous precipitation dominates at higher temperatures in the two alloy systems. The addition of Mo promotes continuous precipitation with respect to discontinuous precipitation while that of Ti promotes discontinuous precipitation rather than continuous precipitation in d phase precipitation alloys. A replacement of Ti with Mo promotes continuous precipitation with respect to discontinuous precipitation in h phase precipitation alloys at 800 C. The observed alloying effects are discussed in terms of chemical driving force, interfacial energy between the matrix phase and the d(h) phases, and coherency strain caused by the formation of the metastable phases prior to the formation of d/h phases.

2:45 PM Question and Answer Period

Monday Interactive Session on Alloy Design

Begins Monday at 3:10 PM EDT
September 13, 2021

On the Influence of Alloy Composition on Creep Behavior of Ni-based Single Crystal (SX) Superalloys: Oliver Horst[1]; Sadaf Ibrahimkhel[1]; Jonathan Streitberger[1]; Nick Wochmjakow[1]; Paul Git[2]; Felicitas Scholz[1]; Pascal Thome[1]; Robert Singer[3]; Jan Frenzel[1]; Carolin Körner[3]; Gunther Eggeler[1]; *Marc Sirrenberg*[4]; [1]Ruhr-Universitaet Bochum; [2]Friedrich-Alexander-Universitaet ; [3]Friedrich-Alexander-Universitaet; [4]Ruhr-University Bochum
In the present work, three Ni-based single crystal superalloys (SXs) were investigated, a Re-containing alloy ERBO/1 (CMSX-4 type) and two Re-free SXs referred to as ERBO/15 and ERBO/15-W, which differ in W content. The microstructural evolution of the three alloys during heat-treatment and their creep behavior is investigated. When one applies one heat-treatment to all three alloys, one obtains different γ/γ' -microstructures. Subjecting these three alloys to creep in the high temperature low stress creep regime, ERBO/15 outperforms ERBO/1. In order to separate the effects of alloy chemistry and microstructure, the kinetics of the microstructural evolution of the three alloys was measured. The results were used to establish similar microstructures in all three alloys. Comparing ERBO/15 with ERBO/15-W it was found that in ERBO/15-W particles grow faster during the first precipitation heat-treatment and that ERBO/15-W creeps significantly faster. At constant microstructure, ERBO/15 and ERBO/1 show similar creep behavior. In the high temperature and low stress creep regime, ERBO/15 shows lower minimum creep rates but ERBO/1 features a slower increase of creep rate in the tertiary creep regime. It was also found that in the high temperature low stress creep regime, ERBO/1 shows a double minimum creep behavior when particles are small.

Development and Application of New Cast & Wrought Ni-base Superalloy M647 for Turbine Disk: *Naoya Kanno*[1]; Masaya Higashi[1]; Ryosuke Takai[1]; Shigehiro Ishikawa[1]; Kota Sasaki[1]; Kenji Sugiyama[2]; Yoshinori Sumi[2]; [1]IHI Corptation; [2]Daido steel Co.

The cast and wrought nickel base superalloy M647 has been developed with high mechanical performance and deformability. This study describes an overview of the microstructure and the properties of M647. A full scale forging process has been developed with uniform fine grain distribution. The detrimental effect of thermal exposure at 700 ˚C ~ 800 ˚C on mechanical properties was evaluated. M647 showed good mechanical properties and equivalent thermal stability to conventional turbine disk alloys. M647 offers good balance of deformability and mechanical properties with lower cost than powder metallurgy alloys.

Alloy Design and Microstructural Evolution during Heat Treatment of Newly Developed Cast & Wrought Ni-base Superalloy M647 for Turbine Disk Application: *Kenji Sugiyama*; Yoshinori Sumi[1]; Naoya Kanno[1]; Masaya Higashi[1]; Ryosuke Takai[1]; Shigehiro Ishikawa[1]; Kota Sasaki[1]; [1]IHI

A new Cast & Wrought Ni-base superalloy, M647, has been developed for turbine disk application with high mechanical properties at elevated temperatures and reasonable hot deformability. Conventional Ni-base superalloys are known to be strengthened by primary, secondary and tertiary ã', but optimal heat treatment is dependent upon specific chemical composition. For optimal mechanical properties, microstructural evolutions including austenitic grain size and ã' morphology were identified for M647. To evaluate these properties, a full-scale low pressure turbine disk was manufactured. This was subjected to a sub-solvus solution heat treatment, such that primary ã' remained to prevent grain growth, enabling required mechanical properties, especially proof stress and low-cycle fatigue, to be achieved. As for secondary ã', precipitation behavior was controlled intentionally by changing cooling rate after solution treatment, and this also resulted in modifying the precipitation behavior of tertiary ã' during aging. In this study, microstructural evolution and tensile properties at 650 ˚C were investigated to clarify the relationship between them, and to identify the strengthening mechanisms. From the result of SEM observation, size distributions of secondary ã' had a clear relationship with cooling rate. Moreover, the mean diameter of secondary ã' was unchanged during aging and this suggested that only tertiary ã' was precipitated during aging. Finally, critical resolved shear stress was calculated using both weakly and strongly coupled dislocation models, and it was clear that M647 was strengthened by a high volume fraction of secondary ã' and a small volume fraction of fine tertiary ã' precipitates.

Thermodynamic Simulation and Experimental Validation of Phase Stability in Ni-based Superalloys: *Kyle Ventura*[1]; David Beaudry[1]; Alex Aviles[1]; Anna Kapustina[2]; Phillip Draa[2]; Kirtan Patel[2]; Raymond Snider[2]; Gerhard Fuchs[1]; [1]University of Florida; [2]Siemens Energy, Inc.

There is a constant push for higher efficiencies, lower cost and increased power in power generating and propulsion gas turbines. In order to meet these requirements, hot section materials with higher temperature capabilities are needed. Ni-base superalloys are selected for these applications. In this study, commercially available and model Ni-based superalloy compositions were simulated with thermodynamic calculations using Thermo-Calc software, which were then experimentally evaluated. Previously, alloy development campaigns have relied heavily on preparing many heats of alloys to examine the effect of various alloying additions and various levels to down-select a single alloy. Methods like PHACOMP have used understanding of partitioning behavior for alloy design. More recent studies have utilized regression analysis of empirical data to inform new alloy design. Physical models can be used to improve upon these methods. The ability to use computational materials science approaches to reduce the number of heats processed in an alloy development program was explored. By validating database sensitivity to compositional changes, future alloy development work can be performed precisely, leading to faster alloy development, validation, and implementation. Model alloys were optimized for phase stability, cost, and density. Continued experimental validation of thermodynamic prediction databases will create a more robust system for alloy property prediction and development.

Suppression of Sulfur Segregation at Scale/Substrate Interface for 6th Generation Single Crystal Ni-base Superalloy: Kyoko Kawagishi[1]; *Chihiro Tabata*[2]; Takuya Sugiyama[2]; Tadaharu Yokokawa[1]; Jun Uzuhashi[1]; Tadakatsu Ohkubo[1]; Yuji Takata[1]; Michinari Yuyama[1]; Shinsuke Suzuki[2]; Hiroshi Harada[1]; [1]National Institute for Materials Science; [2]Waseda Unversity

It is known that a single-crystal Ni-base superalloy containing a trace amount of sulfur has reduced high-temperature oxidation resistance. Our previous study has shown that melting of Ni-base superalloys in a CaO crucible can eliminate the effect of sulfur on oxidation resistance, but the mechanism was not completely clear. In this study, we finally succeeded in detecting the segregation of sulfur at the oxide / substrate interface of 6th generation single-crystal superalloys using STEM-EDS analysis, and confirmed that segregation could be suppressed by melting in the CaO crucible. As a result, it was found that melting in the CaO crucible can improve the oxidation resistance while maintaining the creep characteristics of 6th generation single-crystal Ni-base superalloy.

Composition and Temperature Stability of η and δ Phases for Future Nickel-base Superalloys for Turbine Discs Application: *Laurane Finet*[1]; Vladimir Esin[2]; Vincent Maurel[2]; Loïc Nazé[2]; [1]R&D Department, Aubert & Duval, BP1, 63770 Les Ancizes, France; [2]Centre des Matériaux, MINES ParisTech

To provide precipitation hardening of nickel-base superalloys, ã' and ã'' phases can be partially replaced by phases like eta (ç) and delta (ä), which may be stable up to temperatures higher than 800 °C. Nevertheless, there is still a lack of information about these phases in terms of crystal structure, composition, thermodynamic stability and precipitate morphology. Therefore, the present study focuses on the composition and temperature stability of ç and ä phases in alloys with high Nb and Ta contents. Various experimental nickel-base alloys were designed using literature and thermodynamic calculations. After solution and aging treatments, they were characterized using SEM to determine precipitate morphology and distribution, and TEM-EDS to determine crystal structure and composition of precipitated phases. Combined in situ HE-XRD experiments followed by metallographic analysis were performed to determine the solvus temperature of ç phase in several alloys. Results on the nature of the precipitated phases show that thermodynamic calculations (TCNI7 database) and composition criteria are not always consistent with experimental data. The investigation also reveals that Ta is more favorable to form ç phase than Nb and that other elements than Nb, Ta, Al and Ti have an effect on ç and ä phases, such as Cr, Co and Fe. Hence the composition criteria for the formation of ç and ä phases in alloys with high Ta content are discussed.

Advanced Alloy Design Program and Improvement of 6th Generation Ni-base Single Crystal Superalloy TMS-238: *Tadaharu Yokokawa*[1]; HIroshi Harada[1]; Kyoko Kawagishi[1]; Toshiharu Kobayashi[1]; Michinari Yumaya[2]; Yuji Takata[1]; [1]National Institute for Materials Science; [2]National Institute for Materials Sci

This paper describes the advanced alloy design program (AADP) and improvement of a 6th generation single crystal superalloy, TMS-238, using this AADP. Creep rupture life prediction equations for five different creep conditions, 800 °C /735 MPa, 900 °C /392 MPa, 1000 °C /245 MPa, 1100 °C /137 MPa, and 1150 °C /137 MPa, were obtained with excellent determination coefficients from 0.95 to 0.98. Using the AADP, we successfully developed three alloys, TMS-238mod-A, TMS-238mod-B, and TMS-23mod-C, which have 10 °C to 22 °C higher temperature capabilities than those of the TMS-238 alloy. The AADP successfully predicted that the creep life was maximized when the volume fraction of g' phase was approximately 65% at low-temperature and high-stress conditions, such as 900 °C/392 MPa, compared to that of approximately 60% under high-temperature and low-stress conditions, such as 1100 °C/137 MPa. This prediction enables us to precisely optimize the creep property. Moreover, the prediction equation of the weight change after 1100°C/1h oxidation was also updated. The determination coefficient of this equation was R2=0.90.

Development of a New Coating Compatible with 3rd Generation Nickel Based Superalloys and Thermal Barrier Coatings: *Amar Saboundji*[1]; Virginie Jaquet[1]; Lorena Mataveli Suave[1]; Jeremy Rame[1]; [1]Safran

A new coating has been developed for single-crystal-alloy-coating system (SXS) (single crystal (SX) superalloy/g/g' bond coat (BC) /thermal barrier coating (TBC)) for aircraft engine turbine blade applications. Design procedure of the new SXS, mechanical and environment characterizations are presented and compared with other reference systems composed of AM1, CMSX-4 SLS and CMSX-4 Plus superalloys with -NiPtAl (BC) and TBCs. Targeted coating compositions were optimized for extending TBC lifetime and avoiding secondary reaction zone (SRZ) formation while maintaining satisfactory level of oxidation resistance. In order to avoid the formation of SRZ, the strategy chosen was to develop new g/g' structural coatings close to the substrate composition. This new SXS exhibits high creep resistance at high temperature compared with the other reference systems while exhibiting high oxidation resistance. Indeed, oxidation resistance of the new SXS with CMSX-4 Plus alloy (CMSX-4 Plus/g/g' coating) at 1100 °C is similar to that of the other reference systems. Otherwise, oxidation resistance of the new SXS with AGAT-3 alloy (AGAT-3 /g/g' coating) at 1100 °C is higher than that of the other reference systems. The new coating (g/g') does not generate SRZ even after aging or creep testing at high temperature and ensures high lifetime of thermal barrier coatings (TBCs) (YPSZ- Electron beam physical vapor deposition (EB-PVD) and YPSZ- Suspension plasma spraying (SPS)). Finally, turbine blades with such a new system were successfully manufactured and will be tested in engine conditions.

Computational Methods to Accelerate Development of Corrosion Resistant Coatings for Industrial Gas Turbines: *Rishi Pillai*[1]; Kenneth Kane[1]; Michael Lance[1]; Bruce Pint[1]; [1]Oak Ridge National Laboratory

Oxidation resistant overlay coatings protect the underlying superalloy component in industrial gas turbines from oxidation attack. Rate of depletion of the Al-rich b-phase in the bond coat governs the lifetime of these coatings. The applicability of a computational method in accelerating the development of corrosion resistant coatings and significantly reducing the extensive experimental effort to predict coating lifetimes and microstructural changes in three coated Ni-base superalloys for real operational durations (20-40 kh) was undertaken in the present study. Scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX) and electron microprobe analysis (EPMA) were employed to characterize MCrAlY coated superalloy substrates (1483, 247 and X4) after exposure at 900 °C in air + 10% H2O for up to 20,000 h. The model predicted the longest coating lifetime for the coating on X4 substrate. Precipitation of g in the coatings was correctly predicted for all three coating systems. Additionally, the model was able to predict the formation of topologically close packed (TCP)-phases in the investigated coating systems.

The Yield Strength Anomaly in Co-Ni Design Space: *K V Vamsi*[1]; Sean Murray[1]; Tresa Pollock[1]; [1]University of California Santa Barbara

A new computational approach to model precipitate compositions and properties in the CoNi-design space for yield strength anomaly prediction is presented. The antiphase boundary (APB) energies on {111} and {010} and the degree of elastic anisotropy are known to influence the yield strength anomaly. APB energies were estimated by a diffuse multi-layer fault (DMLF) model using the structural energies of proximate structures: L12, and D023. The elastic moduli were calculated via the energy-strain approach using density functional theory calculations. (Ni1-xCox)3(Al1-yWy) was chosen as the model system and Yoo's criterion is evaluated over the entire range of compositions to identify regions that exhibit the yield strength anomaly. (Ni0.65Co0.35)3(Al0.5W0.5) has the maximum APB(111) and any two-phase alloy (ã+ã') in Ni-Co-Al-W system with this precipitate composition might exhibit higher strength upon shearing by a matrix dislocation. ThermoCalc was employed to identify stable L12 regions in (Ni1-xCox)3(Al1-yWy). The effect of Co on the yield strength anomaly was investigated experimentally in three (Ni1-xCox)3Al alloys with L12 structure. All three alloys exhibited the yield strength anomaly, validating the computational approach. The addition of Co provides solid solution strengthening to Ni3Al at room temperature, however this contribution to the overall strength diminished as a function of temperature. CoNi-alloys displayed strengths similar to Ni3Al at elevated temperatures with Co addition resulting in a marginal increase in strength at the peak temperature. The present study elucidates that APB energies from a DMLF model combined with elastic moduli can be employed to predict yield strength anomaly using Yoo's criteria.

Phase Equilibria Among A1/TCP/GCP Phases and Microstructure Formation in Ni-Cr-Mo System at Elevated Temperatures: *Ryota Nagashima*[1]; Ryosuke Yamagata[1]; Hirotoyo Nakashima[1]; Masao Takeyama[1]; [1]Tokyo Institute of Technology

Phase equilibria among the A1 (g-fcc), Ni2Cr (oP6) and TCP phases in Ni-Cr-Mo system at temperatures above 973 K have been investigated, in order to evaluate the possibility for utilizing a novel microstructure design principle for Ni-based alloys having TCP phase at grain boundaries and GCP phase other than g' phase within grain interiors. Unlike the phase diagram calculated based on commercially available thermodynamic databases, the Ni2Cr phase in the binary system becomes stabilized by the presence of Mo solute atoms in solution at temperatures greater than 200 K, and the Ni2(Cr, Mo)-oP6 single-phase region exists as an island at around the composition of Ni-20Cr-15Mo (at.%) at temperatures above 973 K. The oP6 phase decomposes to g and P (oP56) phase at temperatures above 1073 K. Two distinct three-phase regions of g+oP6+P and g+oP6+NiMo (oP56) were found to exist around the oP6 single-phase region. In case of the decomposition of high temperature g phase to the three-phase mixture comprised of g+oP6+P, very fine coherent particles of oP6 phase that are only a few hundred nanometers in size form in the g matrix with a tweed-like morphology. These precipitates possess an orientation relationship of {10}g//(100)oP6, <001>g//[010]oP6, just like precipitation behavior of g' particles in Ni-base superalloys. In contrast, the TCP phase preferentially precipitates at the g grain boundaries. The novel phase transformations and microstructures occurring in this class of alloys may potentially lead to advances in the design of novel Ni-based alloys.

Monday Part III - Blade Alloy Behavior

Begins Monday at 4:10 PM EDT
September 13, 2021

Session Chairs: J. Clews, PCC Structurals; A. Elliott, Consarc Corporation

4:10 PM
Rationalisation of the Micromechanisms Behind the High-temperature Strength Limit in Single Crystal Nickel-based Superalloys: *Daniel Barba*[1]; Ashton Egan[2]; Yilun Gong[1]; Michael Mills[1]; Roger Reed[1]; [1]University of Oxford; [2]The Ohio State University

The peculiar atomic structure of $\gamma'\gamma'$ precipitates [Ni33(Al/Ti)-L122] in Ni-based superalloys produces high-energy faults when dislocations glide them, giving their significant strength at high temperatures. The mechanisms behind the strength failure of these alloys above 700–800 ˚ C are still controversial. Recent advances in atomic resolution microscopy have allowed to study these mechanisms with unprecedented detail. In our study, we have characterised in a careful systematic study a SX-[001] superalloy from RT to 1000 ˚ C. Multiscale microscopy (TEM and SEM) has been combined with physical metallurgy and atomistic modelling to fully understand the correlation between the strength drop and the observed changes in the $\gamma'\gamma'$ shearing mechanism. Our results show that, far from previous beliefs, the initial failing of alloy strength is not a consequence of the activation of dislocation climbing. Instead, there is a transition between three different mechanisms: (T<750 ˚ T<750 ˚ C) continuous planar stacking faults below, (T = 750 ˚ C) APB shearing at the strength peak anomaly and (T>800 ˚ T>800 ˚ C) extensive twin deformation after the yield drop. Local chemical changes around the $\gamma'\gamma'$ shearing dislocations boost these changes, thus producing the sudden drop of strength.

4:35 PM
Local Mechanical Properties at the Dendrite Scale of Ni-base Superalloys Studied by Advanced High Temperature Indentation Creep and Micropillar Compression Tests: *Lukas Haussmann*[1]; Steffen Neumeier[1]; Markus Kolb[1]; Johannes Ast[2]; Gaurav Mohanty[2]; Johann Michler[2]; Mathias Göken[1]; [1]FAU Erlangen; [2]EMPA Thun

Chemical inhomogenities due to dendritic solidification of Ni base superalloys result in different local microstructures with varying mechanical properties. New indentation creep test methods allow probing of the local creep properties at the dendrite scale at high temperatures. The as-cast single crystalline Ni-base superalloy ERBO1A (a derivative alloy of CMSX-4) was investigated and electron-probe microanalysis (EPMA) measurements revealed strong segregation of e.g. Re and W in the dendritic region and e.g. Ta in the interdendritic region. Indentation creep experiments at 750 ˚C and micropillar compression tests at 785 ˚C were conducted in both regions and a higher creep strength was found in the dendritic region compared to the interdendritic region. Theoretical models for solid solution hardening as well as ' precipitation hardening confirm these results, since they predict a higher strength in the dendritic region than in the interdendritic region. Compared with the fully heat treated state, a smaller difference in the local mechanical properties or even a reverse strength ratio of the dendritic and interdendritic region can be expected.

5:00 PM
Creep, Fatigue, and Oxidation Interactions during High and Very High Cycle Fatigue at Elevated Temperature of Nickel-base Single Crystal Superalloys: *Alice Cervellon*[1]; Jianzhang Yi[2]; Fabien Corpace[3]; Zéline Hervier[4]; Joe Rigney[5]; P. Wright[5]; Chris Torbet[1]; Jonathan Cormier[6]; J. Jones[2]; Tresa Pollock[1]; [1]University of California Santa Barbara; [2]The University of Michigan; [3]Safran Aircraft Engines; [4]Safran Helicopter Engines; [5]GE Aviation; [6]Institut Pprime

High-temperature fatigue of Ni-based single crystal superalloys is studied at 1000 ˚C in a wide range of loading conditions (-1 = R = 0.8) and number of cycles (103 – 109). Under fully reversed conditions, a competition between crack initiation from the surface – assisted by oxidation – and from internal metallurgical defects – mostly large casting pores – is observed. Increasing the testing frequency shifts the competition to a higher number of cycles. Conversely, decreasing the casting pore size or coating the specimen promotes surface initiations. When a positive mean stress is added (R = 0), a creep deformation/damage mechanism mainly controls fatigue life, despite fracture surfaces presenting a variety of initiation types. Fatigue life can be predicted by a simple creep law if the contribution of the alternating stress is considered. A linear damage summation method that considers pure fatigue and pure creep damage is used to predict the fatigue lives and Haigh diagrams for different alloys are presented.

5:25 PM Question and Answer Period

FINAL PROGRAM

Tuesday Part I - Disk Alloy Manufacture

Begins Tuesday at 8:30 AM EDT
September 14, 2021

Session Chairs: C. O'Brien, ATI Specialty Materials; Z. Bi, Central Iron and Steel Research Institute

8:30 AM
Gamma Prime Precipitate Evolution during Hot Forging of a γ- γ' Ni-based Superalloy at Subsolvus Temperatures: *Marcos Perez*[1]; Christian Dumont[2]; Sebastien Nouveau[2]; [1]AFRC; [2]Aubert & Duval
Nickel superalloys are used to manufacture high temperature rotating engine parts such as high pressure disks in gas turbine engines. Alloy 720Li (720Li) is a precipitation-hardened Ni-based superalloy commonly produced by cast and wrought processes. Conventional ingot-to-billet conversion is an expensive and very complex process, requiring multiple open die forging operations and reheating steps in order to achieve a homogeneous microstructure. The present work studies the microstructural evolution of 720Li billet material with the presence of large unrecrystallized structures. The interaction of ' precipitates with recrystallization during hot forging at subsolvus temperatures was investigated. Double truncated cones were forged at subsolvus temperatures following two forging approaches: single blow and double blow with an intermediate heat treatment. Combined EBSD-EDX analysis was employed to characterize the microstructural evolution of 720Li during hot forging operations. Primary ' precipitates promote heteroepitaxial recrystallization during slow cooling, whereas secondary precipitates, formed during slow cooling are not dissolved during reheating, prior to the forging operations. The presence of undissolved secondary ' promotes strain accumulation and the occurrence of continuous dynamic recrystallization (CDRX). Intermediate heat treatment plays an instrumental role on the recrystallization behaviour for the alloy 720Li. Dissolution of the secondary ' precipitates results in a strong preconditioning of the 720Li microstructure prior to the second blow of deformation, promoting the formation of fully recrystallized structures and removing the undesired large unrecrystallized regions. The coalescence of intragranular ' precipitates into clusters of coalesced ' precipitates represents a clear transition from the apparent unrecrystallized regions to the fully recrystallized structures.

8:55 AM
Dynamic and Post-dynamic Recrystallization during Supersolvus Forging of the New Nickel-based Superalloy – VDM Alloy 780: *Juhi Sharma*[1]; Masood Hafez[2]; Bodo Gehrmann[2]; Charbel Moussa[1]; Nathalie Bozzolo[1]; [1]MINES ParisTech - CEMEF; [2]VDM Metals International GmbH
The need of developing new high temperature materials has increased significantly in the last decades owing to the demand of higher aerospace engine operating temperatures. This requires improved microstructural stability of the polycrystalline nickel-based superalloys used for turbine disks. The microstructure of VDM Alloy 780 consists of ??' strengthening precipitates in addition to the needle/plate-shaped particles (of ä and/or ç phase) to pin the grain boundaries. The present article aims at discussing the recrystallization behavior of the new VDM Alloy 780 in the supersolvus domain. Both dynamic and post-dynamic microstructural evolutions are reported. The dynamic recrystallization (DRX) kinetics was found to be rather sluggish. For a plastic strain of 1.3 at 1050 ˚C applied at a strain rate of 0.01 s-1, the microstructure of VDM Alloy 780 is only 50 % recrystallized. The DRX grain sizes are quite close for the two applied strain rates - 0.01 s-1 and 0.1 s-1. Despite slow DRX kinetics, the fast post-dynamic evolutions allowed to achieve fully recrystallized microstructures with a grain size of 26 ìm within 5 minutes of post-deformation holding at 1050 ˚C. The post-dynamically recrystallized grain sizes were predominantly temperature dependent and were not sensitive to strains and strain rates within the applied range. Deformation followed by 5 minutes holding at temperatures below 1050 ˚C but still in the single phase domain could eventually generate finer grain sizes (< 20 ìm). The low sensitivity of the grain size obtained after post-dynamic evolution to the applied strain and strain rates is an advantage for the industrial forging routes wherein the deformation conditions can vary over the piece. Another advantage of this alloy is the relatively slow grain growth kinetics which makes possible to obtain homogenous and reasonably fine microstructures after supersolvus forging.

9:20 AM
Aspects of High Strain Rate Industrial Forging of Inconel 718: Aleksey Reshetov[1]; Nicola Stefani[1]; *Olga Bylya*[1]; Bhaskaran Krishnamurthy[1]; Paul Blackwell[1]; [1]University of Strathclyde
The major part of all material and microstructural data used for the modelling of nickel superalloy forgings are obtained from uniaxial laboratory tests with limited plastic strain and very simple thermo-mechanical history. At the same time, new challenges in near-net shape industrial forging require a high level of reliability of modelling prediction of metal flow, for predicting the risk of defects and microstructural transformation. A few recently conducted benchmarking studies have shown that despite the availability of various material models (including microstructural ones) embedded in commercial FE software, in many cases, the level of prediction remains unsatisfactory. This is especially true for Fast Industrial Forging Processes (like screw press or hammer forgings). This paper suggests a methodology for processing the results from industrial forgings for obtaining robust data for calibration, validation and improvement of material and microstructural models. This also can provide additional information on the material science behind the microstructural phenomena, which are problematic to capture and study using simple uniaxial tests.

9:45 AM Question and Answer Period

Tuesday Interactive Session on Disk Alloy Manufacture & Behavior

Begins Tuesday at 10:10 AM EDT
September 14, 2021

Phenomenological Modeling of the Effect of Oxidation on the Creep Response of Ni-based Single-crystal Superalloys: *Jean-Briac le Graverend*[1]; Seungjun Lee[1]; [1]Texas A&M University
A new constitutive equation predicting the evolution of oxide thickness is proposed and implemented in a crystal plasticity framework with a hardening-based damage density function. The oxidation model depends on the initial surface roughness as well as the amount of accumulated plastic strain and stress triaxiality. The effect of oxidation on the mechanical behavior and damage is considered at the flow stress level by modifying the amplitude of the kinematic hardening. The oxidation-altered kinematic hardening is able to predict the effect of oxidizing environments on the mechanical behavior, specifically the plastic strain rate in the secondary creep stage, and lifetime. In addition, the oxidation model has also been tested in 3D by performing a finite-element simulation on a notched specimen subjected to a creep load. It revealed that the model is able to predict surface roughness and oxide thickness distributions in 3D and for multiaxial stresses.

Microstructural Effects on Creep Properties in a Co-base Single Crystal Superalloy: *Haijing Zhou*[1]; Longfei Li[2]; Stoichko Antonov[2]; Qiang Feng[2]; [1]Central Iron & Steel Research Institute; [2]University of Science and Technology Beijing

In our previous study, Co-Al-W-Ta-Ti quinary alloys were found to show excellent creep resistance at elevated temperature. In order to clarify the influence of the initial microstructure on the creep behavior of a Co-base single crystal superalloy, the tensile creep behavior of the Co-base alloy with different initial microstructures was investigated at 900 ˚C and 420 MPa and the relationships between the initial microstructures and the creep properties, such as the rupture life and the minimum creep rate, were analyzed. It is suggested that the ã' size increased with increasing aging time or temperature, while the volume fraction of this Co-base alloy remained similar through heat treatments at 900 and 1000 ˚C for 50 - 1000 h. Moreover, the initial dislocation density also increased with increasing aging time, but varied negligibly with higher aging temperature. On the other hand, four distinct creep stages were observed during the creep process, and the rupture life exhibited an optimum peak as a function of ã' size, which was also influenced by the initial ã/ã' lattice misfit. Meanwhile, the minimum creep rate increased with an increase of the initial dislocation density. This study can serve as a guide for future microstructural design and optimization of Co-Al-W-base superalloys.

Tensile, Low Cycle Fatigue and Very High Cycle Fatigue Characterizations of Advanced Single Crystal Nickel-based Superalloys: *Luciana Maria Bortoluci O*[1]; Satoshi Utada[1]; Jérémy Rame[2]; Lorena Mataveli Suave[3]; Kyoko Kawagishi[4]; Hiroshi Harada[4]; Patrick Villechaise[1]; Jonathan Cormier[1]; [1]Ensma/Pprime; [2]Safran Aircraft Engines; [3]Safran Tech; [4]National Institute for Materials Science (NIMS)

Tensile and fatigue life variabilities are investigated for new-generation single crystal Ni-based superalloys: the 3rd generation CMSX-4 Plus, the 6th generation TMS-238, and a newer Ni-based superalloy, TROPEA containing Pt. Consistently from the results of previous research, very high cycle fatigue (VHCF) properties at the chosen condition of T = 1,000 ˚C/ Rå = -1/f = 20 kHz, are mainly influenced by the solidification/homogenization pore size and position. TROPEA alloy has the best low cycle fatigue (LCF) life among all tested alloys at 650 ˚C and Ró = 0.05/f = 0.5 Hz. To better understand the influence of chemical composition on the LCF endurance, tensile properties were investigated using nine different single crystalline alloys at 650 ˚C with the strain rate of 5×10-4 s-1. The yield stress is directly affected by the chemical composition of the Ni-based superalloys, and alloys with high contents of Ti and Ta have a higher yield stress, due to an increased shearing resistance of g' precipitates. Hence, the yield stress is the main control parameter of LCF at the selected condition. No influence of chemical composition on VHCF life durability has been observed, in good agreement with previous studies.

Competing Mechanism of Creep Damage and Stress Relaxation in Creep-fatigue Crack Propagation in Ni-base Superalloys: *Shiyu Suzuki*[1]; Motoki Sakaguchi[1]; Ryota Okamoto[1]; Hideaki Kaneko[2]; Takanori Karato[2]; Kenta Suzuki[2]; Masakazu Okazaki[3]; [1]Tokyo Institute of Technology; [2]Mitsubishi Heavy Industries, ltd.; [3]Nagaoka University of Technology

Effect of creep deformation at crack tip on fatigue crack propagation behavior in a single crystal and a directionally solidified superalloys at 900 ˚C was investigated. Creep-fatigue crack propagation tests with single tension hold introduced into cyclic fatigue loading were conducted. In specimen extracted from the single crystal superalloy, ICMSX-4, when the cyclic fatigue loading was restarted after the tension hold, nascent crack was immediately initiated followed by significant crack retardation. This crack propagation behavior was ascribed to mechanisms based on two different concepts of residual compressive stress and crack closure. From the viewpoint of mechanism based on the residual stress concept, material degradation at crack tip induced by the tension hold was investigated using scanning electron microscope, while stress relaxation and the resultant residual compressive stress at crack tip were quantified by elastic-plastic-creep finite element analysis coupled with digital image correlation technique. Finally, crack propagation behavior in polycrystalline specimen extracted from the directionally solidified superalloy, MGA1400, was investigated focusing on effect of grain boundary. An insight into criteria of a transition from crack retardation to accelerated intergranular cracking was suggested based on a relative grain size to "creep affected zone".

An Integrated Hip Heat-treatment of a Single-crystal Ni-base Superalloy: *Benjamin Ruttert*[1]; Inmaculada Lopez-Galilea[1]; Werner Theisen[1]; [1]Ruhr-Universität Bochum

The heat-treatment of a 2nd generation single-crystal Ni-base superalloy was implemented in a hot isostatic press providing fast quenching rates. Thus it is possible to homogenize chemical heterogeneities, close porosity, and to set a fine and uniform ã/ã'-microstructure via fast quenching and subsequent aging in one processing step. The microstructural evolution in dependence of parameters such as temperature, pressure, and quenching is investigated on different length scales using diverse characterization methods. A virtually defect-free microstructure is the outcome of this unique integrated supersolvus HIP heat-treatment.

3 Ton Melting with CaO Desulfurization of Ni-base Single Crystal Superalloy TMS-1700, Simulating a Recycling of Used Turbine Blades: *Tadaharu Yokokawa*[1]; Hiroshi Harada[1]; Kyoko Kawagishi[1]; Makoto Osawa[1]; Michinari Yumaya[1]; Toshiharu Kobayashi[1]; Takuya Sugiyama[1]; Shinsuke Suzuki[1]; Masao Sakamoto[1]; [1]National Institute for Materials Science

In order to investigate the applicability of a direct and complete recycling method to commercial-scale ingot production, 3 tons of a Ni-base single crystal (SC) superalloy, TMS-1700(MGA1700) was melted and desulfurized by CaO during the melting. Sulfur content in the molten alloy was reduced from about 23 ppm to about 2 ppm 60 min after adding granular CaO to the molten alloy. Microstructural observations using SEM and EPMA showed no presence of inclusions caused by CaO addition. Creep rupture lives of the recycle-simulated TMS-1700 were equivalent to that of the standard TMS-1700 under the conditions from 800 ˚C/735 MPa to 1100 ˚C/137 MPa. The recycle-simulated TMS-1700 exhibits even better oxidation resistance compared with the standard TMS-1700, which has better oxidation resistance than CMSX-4TM. Thus, it became clear that the CaO desulfurization improves the oxidation resistance of Ni-base superalloys. High cycle fatigue (HCF) properties of the standard and the recycle-simulated TMS-1700 were equivalent. From the results described above, it has been suggested that the application of direct and complete recycling method to commercial-scale ingot production is feasible.

Prediction of Rafting Kinetics of Practical Ni-based Single Crystal Superalloys: *Yusuke Matsuoka*[1]; Yuhki Tsukada[1]; Toshiyuki Koyama[1]; [1]Nagoya University

Directional coarsening of ' phase (rafting) in Ni-based single-crystal superalloys during tensile creep at 1273 K is simulated by the phase-field (PF) method. A number of PF simulations are performed with various values of PF model parameters. The obtained results are used to train a neural network (NN) to enable fast and accurate prediction of the rafting time (trafttraft) from the values of model parameters. Material parameters of first-, second-, third-, and fourth-generation superalloys are estimated from their chemical compositions for predicting trafttraft using the trained NN. The trafttraft of several practical superalloys are predicted in the tensile stress range of 130–190 MPa. The NN prediction results show that trafttraft tends to be longer along with the order of alloy generation. Furthermore, creep rupture time (truptrup) of practical superalloys is estimated based on the Larson–Miller parameter method. It is found that there is a positive correlation between trafttraft and truptrup, and the correlation becomes stronger with increasing the magnitude of external tensile stress.

Creep Anisotropy in Single Crystal Superalloy DD6 Near the [001] Orientation: *Jian Yu*[1]; Jiarong Li[1]; Shizhong Liu[1]; Mei Han[1]; [1]Beijing Institute of Aeronautical Materials

This paper has studied the anisotropy in the creep properties of DD6 alloy under different temperatures and applied stresses. The results reveal that the anisotropic creep of DD6 alloy near the [001] orientation is strongly influenced by the temperature in the range of 650 ˚C to 980 ˚C. The anisotropy in the primary creep strain and rupture lifetime at an intermediate temperature of 760˚C is dependent on the applied stress. Compared with the specimens oriented close to the [001]–[111] boundary, the specimens oriented close to the [001] direction and the [001]–[011] boundary exhibit lower primary creep strains and longer rupture lifetimes at intermediate temperatures and high applied stresses. With the increase in the testing temperature or the decrease in the applied stress, the anisotropic creep behavior of the alloy near the [001] orientation disappears. The mechanism of anisotropic creep is attributed to heterogeneous ã' precipitate deformation by <112>{111} slip.

High-resolution Diffraction Imaging of Misorientation in Ni-based Single Crystal Superalloys: *Robert Albrecht*[1]; Maciej Zubko[1]; [1]University of Silesia

In the present work, the novel high-resolution X-ray diffraction technique for imaging misorientation and mosaicity in single crystal superalloys is introduced. The technique is based on classical X-ray diffraction topography geometries combined with high-resolution diffraction and post-processing of obtained data including color coding and 3D projections of each diffraction images. For the investigations, the single crystal rods were produced from CMSX-4 superalloy at a withdrawal rate of 1, 3, 5 and 7 mm·min-1. The high spatial and angular resolution of the method allows to visualize the complex nature of mosaicity present in single crystal superalloys. It was observed that mosaics blocks differ in size and misorientation on the multi-scale level from the small present in dendrite arms, through single dendrites, group of dendrites, up to subgrains. Measurements of misorientation were done on cross and longitudinal sections of the castings. It was proved that increasing withdrawal rate influences the mosaicity structure and mechanisms of its evolution. Solidification at withdrawal rates from 1 to 5 mm·min-1 possesses higher misorientation between dendrites. With higher misorientation between dendrites, when the widening of solidification front occurs, the mosaicity spread across the casting in the form of misoriented dendrite lines as the solidification progress by growing long secondary dendrite arms. Also, it was stated that 3-5 mm·min-1 rates possess a higher possibility of creation of subgrains or selector grains defects in the casting.

Equations to Predict the Elastic Modulus of the Individual Gamma and Gamma-prime Phases in Multi-Component Ni-base Superalloys: *Takuma Saito*[1]; Makoto Osawa[2]; Tadaharu Yokokawa[2]; Hiroshi Harada[2]; Toshiharu Kobayashi[2]; Kyoko Kawagishi[2]; Shinsuke Suzuki[1]; [1]Waseda Univesity; [2]National Institute for Materials Science

Strength of Ni-base single-crystal superalloys under high temperature and low stress creep usually is enhanced by formation of ã/ã' raft structure and larger aspect ratio of ã' phase in the ã/ã' raft structure. Elastic misfit between ã and ã' phases is one of the most important factors to control the aspect ratio of the ã' phase in the ã/ã' raft structure formed under external stress. The aspect ratio of the ã' phase is controlled by kinetics for the ã/ã' raft structure formation, which is affected by a strain inhomogeneity caused by this elastic misfit between the ã and ã' phases under external stress. To realize a new alloy design approach to control the aspect ratio of the ã' phase in the ã/ã' raft structure, this research aimed to obtain the regression equations which can predict elastic modulus of the individual ã and ã' phases for multi-component Ni-base single-crystal superalloys based on measurements of elastic modulus of Ni-base single-crystal alloys. Elastic modulus of the individual ã and ã' phases of various kinds of Ni-base single-crystal alloys were measured by using Rectangular Parallelepiped Resonance (RPR) method. Using the analyzed and referenced elastic modulus, regression equations for predicting <100> longitudinal elastic modulus of the individual ã and ã' phases and its temperature and composition dependence were obtained. Detailed analysis of the elastic modulus and its composition dependence was executed to clarify the contribution of each element on the elastic modulus. At 900 ˚C, Re, Ta, Ti, Al, and Mo reduce the <100> longitudinal elastic modulus in the ã phase. On the other hand, Ru, Re, Ta, Ti, Al, W, and Mo enlarge the elastic modulus in the ã' phase.

Crystal Plasticity Mechanism of Temperature Dependent Crack Propagation in a Single Crystal Nickel Based Superalloy: Xiaosheng Chen[1]; *Motoki Sakaguchi*[1]; Shiyu Suzuki[1]; Hirotsugu Inoue[1]; Masakazu Okazaki[2]; [1]Tokyo Institute of Technology; [2]Nagaoka University of Technology

Temperature dependent fatigue crack propagation in a Ni-based single crystal superalloy was experimentally and numerically investigated in a single crystal Ni-base superalloy. Fatigue crack propagation tests at room temperature, 300 ˚C, 450 ˚C and 700 ˚C were conducted using four types of compact specimens with different combinations of crystal orientations in loading and crack propagation directions. It was revealed in the experiments that the crack propagated along slip planes in crystallographic cracking manner at room temperature, while the cracking mode transitioned from the Mode I to crystallographic cracking at 300 ˚C, 450 ˚C and 700 ˚C. Mode I stress intensity factor range ÄKI values at the transitions depended on the testing temperature as well as crystal orientation. To interpret these temperature dependent crack propagation, a crystal plasticity finite element analysis was conducted by taking into account the 3D inclined crack plane and the activity of slip planes in front of the crack. Slip plane activity, proposed as a damage parameter, could rationalize the fatigue crack propagation rates both during the crystallographic and Mode I cracking. It has been found that crack propagation resistance for crystallographic cracking is more or less the same at low temperature, while that for Mode I cracking decreases with the increase of the temperature. This damage parameter also provided an explanation of the critical condition that induces the transition from Mode I to crystallographic cracking.

Metallurgical Mechanisms Upon Stress Relaxation Annealing of the AD730™ Superalloy: *Malik Durand*[1]; Jonathan Cormier[2]; Patrick Villechaise[2]; Jean-Michel Franchet[3]; Christian Dumont[4]; Nathalie Bozzolo[1]; [1]Mines ParisTech - CEMEF; [2]Institut P'; [3]SafranTech; [4]A&D Ancizes

Fine microstructural analyzes have been performed to identify the microstructural mechanisms controlling stress relaxation during aging heat treatment of AD730TM disk superalloy. Morphological evolution of the hardening g' precipitates and plastic activity occur during relaxation tests. For a 500 MPa initial stress, the relaxation test shows atypical behavior with sluggish relaxation in the first hours, and then a faster one. To understand this atypical behavior, isothermal dilatometry tests were used to decouple the effects of stress and temperature. The later revealed a contraction of the specimen when subjected to a constant temperature. This contraction induces a tendency for an increase in stress during the relaxation test to meet the imposed condition of constant total deformation. Relaxation is then controlled by the competition between the classical relaxation mechanisms (vacancies diffusion and/or dislocation gliding) which tend to lower the stress and the contraction of the specimen which tends to increase the stress during the test.

FINAL PROGRAM

Metallurgical Analysis of Direct Aging Effect on Tensile and Creep Properties in Inconel 718 Forgings: *Alexis Nicolaÿ*[1]; Jean-Michel Franchet[2]; Nathalie Bozzolo[1]; Jonathan Cormier[3]; [1]CEMEF - Mines-ParisTech; [2]Safran SA; [3]Institut Pprime
Performing the double aging thermal treatment on Inconel 718 forged components directly after forging instead of the standard thermal treatment sequence including a solution annealing step before the double aging is known to be beneficial to mechanical properties. In this work, this so-called direct aging (DA) effect has been assessed for tensile properties at room temperature and for creep properties at 650 °C/750 MPa. Mechanical characteristics obtained on direct aged specimens are compared to those obtained on specimens submitted to the standard thermal treatment sequence (i.e. including a solution heat treatment) and tested in the same conditions. The classical effect of direct aging thermal treatment is obtained, better tensile and creep properties are reached for DA specimens. However, contrary to what is generally assumed, fine microstructural characterizations in specimen heads reveal that the direct aging effect cannot be attributed to a higher residual strain hardening level preserved in the microstructure. It is actually shown that its beneficial effect on mechanical properties is due to a lower d phase content obtained in microstructures having undergone such a treatment rather than the standard sequence. On the one hand, it has indeed been demonstrated that, counter-intuitively, the d phase content actually increased during the "solution" treatment performed at 955 °C for 1h. On the other hand, the relationship between mechanical properties and microstructural features (grain size, d phase content, residual forging strain hardening level) has been analyzed in detail and differences in mechanical behavior are mainly controlled by this increased amount of d phase which deteriorates the mechanical properties. On the contrary, no significant effect of residual forging strain hardening on tensile and creep properties has been found for the investigated conditions.

Tuesday Part II - Disk Alloy Behavior

Begins Tuesday at 11:10 AM EDT
September 14, 2021

Session Chairs: C. Rae, University of Cambridge; N. Bozzolo, MINES-ParisTech

11:10 AM
The Effect of Shot Peening on the Ductility and Tensile Strength of Nickel-based Superalloy Alloy 720Li: *Thomas Jackson*[1]; James Rolph[1]; Ross Buckingham[1]; Mark Hardy[1]; [1]Rolls Royce Plc
Alloy 720Li with a polished surface and with a 1000% coverage shot peened surface has been tensile tested at 200-650°C and two loading rates. Shot peened specimens had lower ductility than unpeened specimens across the temperature range, but the effect was greatest at 450 and 500°C. This reduction in ductility resulted in reduced tensile strength (TS) or fracture stress at 300-500°C. The shot peening effect was present at both loading rates. Shot peened specimens showed surface micro cracking all over the gauge length of tested specimens and at the point of fracture which explains their reduced ductility. The micro-cracks started at the surface and propagated along strain bands in the material. In contrast, unpeened specimens showed no surface micro-cracks. Interrupted testing on peened surfaces at 500°C 300 MPa/sec showed that the micro-cracks formed first at 2.3% plastic strain. The application of further strain caused new cracks to form and existing cracks to grow deeper until the specimen fractured at ~9% elongation. Further specimens were tested with different peening coverage levels of 125%, 200%, 400%, 600% and 1000%. Peening coverage of 125% caused a large reduction in ductility and small reduction in TS relative to the unpeened state. Higher coverage caused further reductions in ductility and TS. The reduced ductility of shot peened specimens is attributed to the low ductility of the shot peened layer which is heavily strained and work hardened.

11:35 AM
Experimental and Simulation Study of the Effect of Precipitation Distribution and Grain Size on the AD730TM Ni-based Polycrystalline Superalloy Tensile Behavior: *Marco Panella*[1]; Loïc Signor[1]; Jonathan Cormier[1]; Marc Bernacki[1]; Patrick Villechaise[1]; [1]Institut Pprime, ISAE-ENSMA, University of Poitiers
The mechanical properties of nickel-based superalloys depend strongly on their microstructure, namely the grain size and the state of precipitation. Main design criteria in aeronautical turbine disks are the resistance to disk burst and low cycle fatigue in the bore, but also to creep in the rim part due to higher temperatures. The chosen microstructures result from a compromise between these contradictory requirements. Indeed, creep durability is improved using a coarse grain microstructure while the increase of static and fatigue strength requires a fine grain microstructure. Moreover, the volume fraction and the size distribution of ã' precipitates are the predominant parameters controlling mechanical properties at lower temperatures. A spatial optimization of the microstructure is reachable using specific technologies, e.g. dual microstructure heat treatment. The development of microstructure sensitive models is thus a major concern for the optimal design of these components including gradient of grain size and / or precipitate size. Full-field finite element simulations may be employed to predict the macroscopic behavior of polycrystalline aggregates using crystal plasticity constitutive equations whose parameters depend explicitly on the microstructural attributes. In this framework, the present study is devoted to the evaluation of the yield stress of polycrystalline AD730TM nickel-based superalloy, chosen as a model material. This work includes microstructural characterization and mechanical tests carried out on single crystals and polycrystalline specimens with well-controlled microstructures. Predictions of the macroscopic yield stress are provided by preliminary simulations carried out in the elastic regime combined with a specific post-processing.

12:00 PM
Modeling Creep of Ni-base Superalloys for Applications in Advanced Ultra-supercritical Power Generation: Chen Shen[1]; *Monica Soare*[2]; Vito Cedro[3]; [1]GE Research; [2]GE Global Research; [3]National Energy Technology Laboratory
Steam turbine and boiler materials for Advanced Ultra-Supercritical (A-USC) coal-fired power plants are required to withstand steam conditions up to 760°C and 35MPa for a typical service life of over 100,000 hours. Long-term creep evaluation of these materials is challenging and relies on extrapolation of data from accelerated tests under steady-state conditions and increased temperatures and/or stresses. This study is focused on improving accuracy of creep property predictions by using a microstructurally informed constitutive creep model. The model was recently developed within the framework of continuum damage mechanics (CDM) for ã' precipitation strengthened alloys Haynes 282, Inconel 740H, and Nimonic 105 at stresses between 100 and 400MPa, and temperatures between 700 and 850ºC. The model incorporated physical mechanisms including (1) growth of micro-voids and cracks to macroscopic cavities, (2) accumulation of dislocations toward excessive inelastic deformations, (3) microstructural changes (e.g., ã' coarsening). The model was validated by comparing creep strain evolution in time and rupture times to data from uniaxial creep tests. As damage mechanisms are captured by specific damage variables, the model aims at making predictions beyond the secondary creep regime, well into the tertiary regime by tracking evolution of the damage variables, eliminating the typical need of linear extrapolation.

12:25 PM Question and Answer Period

Tuesday Part III - Blade and Disk Alloy Behavior

Begins Tuesday at 1:30 PM EDT
September 14, 2021

Session Chairs: S. Forsik, Carpenter Technology Corporation; I. Dempster, Wyman Gordon /PPC

1:30 PM
An Approach Towards Understanding Unstable Gamma Prime Precipitate Evolution and Its Effect on Properties: *Nicholas Krutz*[1]; Chen Shen[2]; Mallikarjun Karadge[2]; Ashton Egan[1]; Justin Bennett[3]; Timothy Hanlon[2]; Michael Mills[1]; [1]Ohio State University; [2]GE Research; [3]GE Aviation
The evolution of gamma prime precipitates generated from supersolvus solution heat treatment and controlled continuous cooling of two powder metallurgy (PM) disk superalloys are characterized and modeled. Variation in cooling rate for these alloys shows a tendency for unstable precipitate growth with slower rates. The degree to which this variation is observed in terms of its effect on particle spacing and deformation-induced defect interaction has not been well characterized previously. To better understand this effect, a series of lab heat treatments of varied cooling rates have been carried out and the mechanical response quantified via elevated temperature tensile tests followed by characterization. A phase-field based approach is used to simulate the growth instability of gamma prime precipitates during slow continuous cooling, the simulated particle morphologies are compared to post-mortem characterization of lab-scale coupons using Focused Ion Beam (FIB) serial sectioning and volumetric reconstruction. Phase-field modeling is then used to interrogate the interaction of the particle morphology with planar dislocation evolution. It was determined that the incipient stages of particle evolution are dictated by interface growth instability more so than elastic anisotropy effects. Planar deformation in the presence of these larger, more evolved particles tended to promote Orowan looping, while smaller particles with smaller gamma channel widths showed a tendency for stacking fault formation under the conditions characterized. These observations suggest that particle morphology is a secondary effect to the overall alloy strengthening mechanism.

1:55 PM
High-temperature Pre-deformation and Rejuvenation Treatment on the Microstructure and Creep Properties of Ni-based Single Crystal Superalloys: *Satoshi Utada*[1]; Jérémy Rame[2]; Sarah Hamadi[2]; Joël Delautre[2]; Lorena Mataveli Suave[3]; Patrick Villechaise[4]; Jonathan Cormier[4]; [1]Institut Pprime/Safran Aircraft Engines; [2]Safran Aircraft Engines; [3]SAFRAN Tech; [4]Institut Pprime
Unintentional plastic deformation during production of turbine blades made from Ni-based single crystal superalloy has a huge risk on its durability. In the present study, a plastic deformation was applied at various temperatures to AM1 alloy and its effect on the alloy's microstructure and creep properties were analyzed. Microstructure evolution during aging treatment was different for plastic deformation at lower temperature (= 750 °C) and higher temperature (950 °C) because of different deformation mechanisms. AM1 with mild ã' directional coarsening after plastic deformation at 950 °C and following aging treatments performed well in creep test at 1050 °C/140 MPa, but poorly at 850 °C/500 MPa. Rhenium containing CMSX-4 Plus was tested similarly to AM1. Pre-deformation has huge impact on creep durability of CMSX-4 Plus at 1150 °C/110 MPa, however, the creep life debit at 1050 °C/200 MPa was minor. In order to restore properties of pre-deformed single crystal superalloys, rejuvenation heat-treatment process was added after pre-deformation. Rejuvenation treatment successfully restored microstructure after room-temperature plastic deformation, and creep properties of rejuvenated specimens are equivalent to that of original AM1 and CMSX-4 Plus.

2:20 PM
Tuning Strain Localization in Polycrystalline Nickel-based Superalloys by Thermomechanical Processing: *Marie Charpagne*[1]; Jean-Charles Stinville[1]; Andrew Polonsky[1]; McLean Echlin[1]; Sean Murray[1]; Zhe Chen[1]; Nathalie Bozzolo[2]; Jonathan Cormier[3]; Valery Valle[3]; Tresa Pollock[1]; [1]University of California, Santa Barbara; [2]CEMEF Mines ParisTech; [3]Institut Pprime
Thermomechanical processing routes are used to produce microstructures that minimize plastic strain localization at the sub-grain scale in a polycrystalline γ–γγ–γ' nickel-based superalloy. This novel approach is made possible by the use of innovative experimental tools and statistical data analysis that capture slip events over large representative fields of view. Results are correlated to conventional observations of fatigue crack initiation and early stage of propagation. The effect of coherent twin boundaries and primary γ'γ' precipitates on fatigue properties and plastic localization is detailed.

2:45 PM Question and Answer Period

Tuesday Interactive Session on Disk Alloy Behavior

Begins Tuesday at 3:10 PM EDT
September 14, 2021

Is the Carbon Content Really an Issue for the LCF Durability of Forged γ/γ' Ni-based Disk Alloys?: *Adele Govaere*[1]; Anne-Laure Rouffié[2]; Jean-Michel Franchet[2]; Daniel Galy[2]; Alexandre Devaux[3]; Coraline Crozet[3]; Paraskevas Kontis[4]; Patrick Villechaise[5]; Jonathan Cormier[5]; [1]Ensma / Pprime Institute - Safran Tech; [2]Safran Tech; [3]Aubert & Duval; [4]Max Planck Institute; [5]Pprime Institute
The Non Metallic Inclusions (NMIs) population of two versions of AD730™ (the standard one and a high carbon doped one) alloy were studied in terms of oxidation and low-cycle fatigue behavior at 450°C and 700°C. Cracking of NMIs was observed in the early stages of oxidation without any applied load, even at intermediate temperature. It is assisted by volume expansion and thermal mismatch between the NMIs and the surrounding g/g' matrix. It was observed that the cracking took place in the Nb-rich part of the inclusions. However, the presence of pre-cracked inclusions does not have a detrimental effect on the fatigue lifetimes. The mechanical behaviors and mechanisms were investigated. Moreover, addition of carbon may lead to a debit in LCF life depending on the loading direction with respect to the NMIs cluster alignments. The observation of the fracture surfaces showed that no cracks initiated within inclusions in the high carbon content material despite a much higher density of NMIs. The inclusions and grain size distributions, the particles alignment orientations as well as the environment strongly contribute to the crack initiation mechanisms.

High Temperature Dwell Fatigue Crack Growth in Cold-worked and Direct-aged 718Plus™: *Andrew Merrison*[1]; Hangyue Li[1]; Wei Li[2]; Paul Bowen[1]; [1]University of Birmingham; [2]Rolls-Royce
The high temperature dwell fatigue crack growth behaviors of 30% cold-drawn and direct aged ATI 718PlusTM were studied. This was compared to an annealed and direct aged variant of the same material. This was in order to rationalize the effects of cold work. Tests were conducted at 650°C using different dwell times, in air and in relative vacuum, at R=0.1. It was found that the cold worked and direct aged condition produced slower dwell fatigue crack growth rates in all tests. This has been linked to the larger elongated grain morphology and the dislocation structure retained after cold working. Increased crack tortuosity and roughness-induced crack closure is considered to enhance the cycle-dependent crack growth properties. Superior resistance to environmentally-assisted intergranular failure is related to greater crack tip stress relaxation and more homogeneous grain boundary deformation.

Contribution of Primary γ' Precipitates in the Deformation Creep Mechanisms in the Ni-based Polycrystalline AD730™ Superalloy: *Florence Pettinari-Sturmel*[1]; Muriel Hantcherli[1]; Winnie Vultos[1]; Cécile Marcelot[1]; Bénédicte Warot-Fonrose[1]; Maud Tisseyre[1]; Joël Douin[1]; Patrick Villechaise[1]; Jonathan Cormier[1]; [1]CEMES - Université de Toulouse

TEM characterization of the deformation micromechanisms in the case of AD730TM disk superalloy have been performed in order to identify the relevant parameters controlling its creep behavior at 700 °C under 600 MPa or 850 MPa. The creep behavior has been investigated for different microstructures resulting from different heat treatments: a coarse grain (CG) and a fine grain microstructures (FG). The specific influence of the primary g' precipitates, which are only present in the fine grain microstructure, is of main focus. TEM observations indicate that, in the first stage of the creep deformation, primary g' precipitates may act as dislocation sources. The stability of this phase was confirmed using samples aged at 850 °C for several hundreds of hours. TEM spectroscopy has been used to characterize the local chemical composition after aging. A clear evolution of these primary g' precipitates has been evidenced and a dissolution of the secondary g' precipitates during aging. The presence of these primary g' precipitates induces a strong localization of the deformation. Its detrimental effect on the creep properties in the case of polycrystalline Ni-based superalloy at high temperature may be concluded.

Impact of Coarse γ' Phase on Recrystallization Modeling in new Ni-based Superalloy M647: Nishimoto Takashi[1]; *Takuma Okajima*[1]; Kenta Yamashita[1]; Qiaofu Zhang[2]; Jiadong Gong[2]; Greg Olson[2]; [1]Daido Steel.Co; [2]QuseTek Innovations

M647, a Ni-based superalloy with excellent mechanical properties and good hot deformability, was recently developed for application in airplane engine disks. In airplane engines, fine-grained superalloys are required to improve high-temperature fatigue properties. Methods to control fine grains have been extensively studied, including a refined method of applying the pinning effect of a coarse ã' phase. However, previous reports focused on the mechanism of nucleation and abnormal grain growth, and reports on modeling to predict grain size are rare, making it difficult to optimize the forging process. The present study proposes a modeling method of M647 recrystallization with a coarse ã' phase and compares modeling and experimental results. Recrystallization was experimentally observed in M647 with a coarse ã' phase originating from the grain boundaries of the prior ã phase. Moreover, recrystallization is promoted by heating at a high temperature, applying a high strain, and maintaining the heat for a long duration. Grain growth is restricted by the pinning effect of the coarse ã' phase. The area fraction of the coarse ã' phase changed with the heating temperature, and the ã' grain size increased with heating. Electron backscatter diffraction analysis shows that the kernel average misorientation increased with increasing forging temperature. These trends indicate that the pinning and driving forces of recrystallization fluctuate continuously during forging and reheating. The microstructure is predicted by applying Avrami-type equations, but the accuracy is insufficient because the fluctuation effects are not considered.

Development of a Prediction Model and Process-microstructure-property Database on Forging and Heat Treatment of Superalloy 720Li: *Nobufumi Ueshima*[1]; Chuya Aoki[2]; Toshio Osada[3]; Satoko Horikoshi[4]; Akira Yanagida[4]; Hideyuki Murakami[3]; Toshiki Ishida[2]; Yoko Yamabe-Mitarai[3]; Katsunari Oikawa[1]; Nobuki Yukawa[5]; Jun Yanagimoto[6]; [1]Tohoku University; [2]Hitachi Metals, LTD.; [3]National Institute for Materials Science (NIMS); [4]Tokyo Denki University; [5]Nagoya University; [6]The University of Tokyo

A process-microstructure-property database on forging and heat treatment of superalloy 720Li was established by high precision large-scale 1,500 ton forging simulator and laboratory-scale forging simulator. The database was utilized to determine the parameters of flow stress, microstructure and strength prediction models. The models were integrated to CAE software to predict process-microstructure-property relationships. In the integrated model, the stress, strain and temperature distributions and their temporal development are calculated by using flow stress model and thermophysical properties. The calculated stress, strain and temperature data are inputted into the microstructure model. The microstructure model considers grain growth, recrystallization and precipitation of ã' and calculates the temporal evolution of microstructural features. The strength model considers solution, grain boundary and precipitation strengthening and calculates high-temperature 0.2% tensile proof stress, which is related to creep and low cycle fatigue properties, from the calculated microstructural features. The integrated model successfully predicted the load, microstructure and strength distribution of a prototype forging experiment conducted by the Hitachi Metals 6,000 ton forging machine. The integrated model is a promising tool to design the forging and heat-treatment process of the alloy.

Phase-field Modeling of γ' and γ'' Precipitate Size Evolution during Heat Treatment of Ni-base Superalloys: *Felix Schleifer*[1]; Michael Fleck[1]; Markus Holzinger[1]; Yueh-Yu Lin[1]; Uwe Glatzel[1]; [1]University of Bayreuth

The goal of an aging heat treatment in Ni-base superalloys is to control the volume fraction and size of the strengthening precipitates. We predict the precipitate size evolution of primary L12 and D022 precipitates in the industrially relevant alloys CMSX 4, René80 and IN718 using a one-dimensional phase-field model with an artificial Gibbs-Thomson driving force considering the shape of non-spherical precipitates. In comparison to the classical theory of precipitate ripening, the presented phase-field model considers all alloying elements, non-isothermal cooling and heating stages and off-equilibrium volume fraction. We implicitly consider elastic effects between precipitate and fcc solid solution matrix by adjusting the mobility parameters and considering size dependent non-spherical D022 precipitate shapes. Literature data reveals the strong predictive potential of this multi-scale method for integrated computational materials engineering. We identify individual aging stages during which precipitate growth is dominated by either ripening, or precipitation from the supersaturated matrix phase.

Role of Non-metallic Inclusions and Twins on the Variability in Fatigue Life in Alloy 718 Nickel Base Superalloy: *Damien Texier*[1]; Jean-Charles Stinville[2]; Marie-Agathe Charpagne[2]; Zhe Chen[2]; Valéry Valle[3]; Patrick Villechaise[3]; Tresa Pollock[2]; Jonathan Cormier[3]; [1]Institut Clément Ader - UMR CNRS 5312; [2]University of California, Santa Barbara; [3]Institut Pprime - UPR CNRS 3346

Non-metallic inclusions (NMIs) and slip bands parallel to and slightly offset from twin boundaries are observed to be preferential sites for fatigue crack nucleation in wrought superalloys. Potential interactions between NMI cracking and slip activity within neighboring grains or at twin boundaries were investigated under monotonic tensile loading (up to 1.3 % total strain) at room temperature. High resolution- and Heaviside-digital image correlation measurements were performed during interrupted tensile loading to identify strain localization, associated slip systems, and damage initiation. Different mechanisms and scenarios were identified: (1) Microplasticity generally starts at twin boundaries even at stresses as low as 70 % of the macroscopic yield strength, (2) Transgranular slip activity intensively develops above the macroscopic yield stress, (3) Intense slip activity develops near and parallel to 21 % of the twin boundaries intercepting NMIs, (4) 7 % of the twin boundaries intercepting NMIs lead to slip-assisted NMI cracking, (5) No transgranular slip activity participates in NMI cracking, (6) The fraction of cracked NMIs progressively increases with the load, and (7) Within the NMIs that initiated cracks, 67 % cracked below 90 % of the macroscopic yield strength without the presence of slip activity in the neighboring grains. While slip assisted-NMI cracking was evidenced in the present study, most NMI cracking is due to strain incompatibility between NMIs and neighboring grains at the high end of the elastic regime without slip interaction.

Effect of Nb Alloying Addition on Local Phase Transformation at Microtwin Boundaries in Nickel Based Superalloys: *Ashton Egan*[1]; You Rao[1]; Babu Viswanathan[1]; Timothy Smith[2]; Maryam Ghazisaeidi[1]; Sammy Tin[3]; Michael Mills[1]; [1]Ohio State University; [2]NASA Glenn Research Center; [3]Illinois Institute of Technology

This work investigates two nominally similar polycrystalline alloys, with a subtle difference in Nb content, intended to elucidate its effect on local phase transformation strengthening during high temperature creep. Tests were conducted at 750 ˚C and 600 MPa to target the creep regime dominated by superlattice intrinsic and extrinsic stacking faults, as well as microtwinning. Alloy A, with higher Nb and lower Al, was found to be superior in creep strength to Alloy B, with lower Nb and higher Al, as well as previously investigated ME3 and LSHR. Atomic resolution scanning transmission electron microscopy and energy dispersive spectroscopy found that this increased creep strength was due to a novel local phase transformation occurring along microtwin boundary interfaces as a result of the Nb increase. Complementary density functional theory calculations helped to confirm that this was ÷ phase formation. It is hypothesized that this transformation was the cause of the increased creep strength exhibited by Alloy A.

Atomic Structure and Chemical Composition of Planar Fault Structures in Co-base Superalloys: Malte Lenz[1]; Mingjian Wu[1]; Junyang He[2]; Surendra Makineni[2]; Baptiste Gault[2]; Dierk Raabe[2]; Steffen Neumeier[3]; *Erdmann Spiecker*[1]; [1]Institute of Micro- and Nanostructure Research; [2]Max-Planck-Institut für Eisenforschung GmbH; [3]Institute for General Materials Properties

We report atomic structures and chemical compositions of defects associated to planar faults in a creep deformed Co-base superalloy and discuss their formation and contribution to plastic deformation. The multinary single crystalline Co-base superalloy was creep deformed under tension along -direction at 850 ˚C and 400 MPa. The creep microstructure comprises a high density of planar defects. Solute segregation to superlattice intrinsic stacking faults (SISF) is characterized via EDXS analysis of a statistically relevant number of faults and compared at different creep stages. The amount of solute segregation shows negligible difference at different creep stages indicating that segregation directly occurs during planar fault formation and does not significantly evolve afterwards. Based on the observation and analysis of Frank partial dislocations with Burgers vectors terminating SISF, we discuss a new route to SISF formation via dislocation climb. Additionally, two more complex fault structures are analyzed and potential formation mechanisms are discussed. The first of these structures is a terminating end of an SISF where an partial dislocation splits up into two closely spaced partials separated by an SESF. The second structure consists of two parallel SISFs connected by an anti-phase boundary (APB). All deformation mechanisms described in this study show an involvement of solute segregation directly affecting formation and propagation of creep defects by changing planar fault energies and chemical environments of dislocations. Solute segregation is therefore expected to be key to future alloy design by enabling control of creep deformation mechanisms in specific temperature and stress regimes.

Characteristic Flow Behavior of $\gamma+\gamma'$ Duplex and Its Significant Applications in Hot Working Process of Superalloys: *Beijiang Zhang*[1]; [1]China Iron & Steel Research Inst Group

The characteristic flow behavior of the ã+ã′ duplex structure during the thermomechanical processing (TMP) of highly alloyed disc alloys was comprehensively investigated. Based on the TMP of the ã+ã' duplex, a series of promising techniques for the billet conversion and microstructure customization can be developed. The superplasticity of ã+ã′ duplex was confirmed by tensile tests, and the optimum combination of temperature and strain rate was determined. For a certain alloy, the maximum elongation up to more than 1000% can be achieved at the temperature of equilibrium ' solvus minus 100 ˚C. Near-net-shape forgings can be produced within this temperature region. During conversion of the VAR ingots, a proper TMP can trigger a discontinuous precipitation instead of the dynamic strain aging effect which usually leads to a drastic degradation of plasticity. Therefore, the processing window of ingot conversion can be greatly broadened. Producing the dual microstructure disc forging using TMP from a ã+ã' duplex billet exhibits the inherent advantages over standard heat treatment techniques. The grain size of coarse-grained region can be continuously modulated by controlling the local plastic strain, and the location of the interface between the coarse-grained region and fine-grained region can be precisely determined by controlling the strain distribution. The multi-cycle TMP techniques can play a constructive role in the conversion of the as-HIP billets of P/M material. By producing the ã+ã' microduplex, prior particle boundaries (PPBs) and inclusions can be efficiently broken up during TMP. As a result, the hot working ductility and the quality of the ultrasonic-inspections can be greatly improved.

Abnormal Grain Growth in the Presence of Grain Boundary Pinning Precipitates: *Michael Fahrmann*[1]; David Metzler[2]; [1]Haynes International, Inc.; [2]Haynes International

The occurrence of abnormally large overgrown grains upon sub-solvus annealing of certain hot-worked structures has been reported for several cast & wrought and powder metallurgy superalloys. These overgrown grains typically feature a high density of annealing twins and a precipitate distribution similar to the one in the adjacent fine-grained areas. While these special hot working conditions can be established experimentally for a given alloy, it is desirable to provide some general guidance for the avoidance of these features. Following a recently published framework by Bozzolo's group in France, i.e., Zener pinning pressure versus stored energy driving force, abnormal grain growth (AGG) maps were generated for two commercial HAYNES alloys. Thermo-mechanical processing paths resulting in AGG in these alloys are studied in detail. The generality and limitations of aforementioned framework are discussed.

Deformation Mechanisms of γ' and γ" Co-precipitates in IN718: *Longsheng Feng*[1]; Donald McAllister[1]; Christopher Zenk[1]; Michael Mills[1]; Yunzhi Wang[1]; [1]The Ohio State University

Alloy 718 is widely used in gas turbine engines. Even though recent studies have been focusing on the unique deformation mechanisms of the tetragonal ã phase as compared to those of the cubic ã' phase, ã' and ã'' often co-precipitate and form composite particles. The deformation mechanisms of these composite particles have not been investigated in detail. In this work, we use a combination of ab initio and microscopic phase field methods to study shearing of a dual-lobed type ã′′/ã′/ã′′ composite particle by various dislocations. Complicated fault structures within both ã' and ã'' phases are predicted and some of them have been observed in the experiment. The difficulty associated with experimental characterization of the fault structures in the co-precipitates is also discussed.

Tuesday Part IV - Environmental Behavior

Begins Tuesday at 4:10 PM EDT
September 14, 2021

Session Chairs: B. Pint, Oak Ridge National Laboratory; V. Seetharaman, Pratt & Whitney

4:10 PM
Investigation into the Effects of Salt Chemistry and SO_2 on the Crack Initiation of CMSX-4 in Static-loading Conditions: *Fabian Duarte Martinez*[1]; Grant Gibson[2]; Jonathan Leggett[2]; Julian Mason-Flucke[2]; Nicolau Morar[1]; Gustavo Castelluccio[1]; John Nicholls[1]; Simon Gray[1]; [1]Cranfield University; [2]Rolls-Royce Plc.
Although evidence exists of the potential impact of stress, co-incident with corrosive environments at high temperature, for single crystal turbine blades, the mechanism responsible is not fully understood. This work explores the effect of CaSO4, Na2SO4 and sea salt on the scale formation and crack initiation of CMSX-4 at 550°C in 50 ppm of SO2 and synthetic air under a static stress of 800 MPa. The fracture surface analysis showed that the CaSO4 and the Na2SO4 salted specimens did not undergo a significant degree of corrosion degradation and no cracks were detected after 400 hours of exposure. However, sea salt caused significant degradation to the scale and cracks were detected by X-ray CT scanning after 400 hours of exposure. The findings from this study suggests that the sulfation of chlorine containing species in sea salt led to the formation, vaporisation and re-oxidation of metal chlorides and this mechanism was found to play a key role in the formation of a non-protective scale. An active oxidation mechanism has been proposed to interpret the results. In conclusion, it is hypothesized that due to the synergistic effect of stress and the formation of a non-protective scale, fast diffusion paths for sulfur, oxygen and chlorine ingress were formed. Further work is currently being undertaken to understand the effect of these species on the local embrittlement of CMSX-4 that ultimately led to the initiation of cracks in the specimen.

4:35 PM
Characterization of the Benefit of APS Flash Coatings in Improving TBC Lifetime: *Bruce Pint*[1]; Michael Lance[1]; Ercan Cakmak[1]; Kenneth Kane[1]; James Haynes[1]; Edward Gildersleeve[2]; Sanjay Sampath[2]; [1]Oak Ridge National Laboratory; [2]Stony Brook University
The addition of an air plasma sprayed (APS) "flash" layer on top of a high velocity oxygen fuel (HVOF) bond coating has been shown to extend the lifetime of thermal barrier coatings. A series of furnace cycle tests (FCTs) has been conducted at 1100 °C in air + 10 % H2O to study the benefit of flash coatings on rod and disk alloy 247 specimens and provide a better mechanistic understanding of their benefit. Flash coatings of NiCoCrAlY and NiCoCrAlYHfSi both improved the FCT lifetime of rod specimens tested in 100-hr cycles and disk specimens tested in 1-hr cycles. In 1-hr cycles, the NiCoCrAlY flash coating significantly outperformed an HVOF-only NiCoCrAlYHfSi bond coating and a NiCoCrAlYHfSi flash coating. Both flash coatings increased the bond coating roughness compared to HVOF. During exposure, the flash layer formed an intermixed alumina-metal layer that appeared to inhibit crack formation. Using a time series of observations, the lower Y+Hf content in the Y-only flash coating appeared to reduce Al consumption. The HVOF layer acted as a source of Al for the adjacent mixed zone. A second series of specimens included a fully APS bond coating where oxide had penetrated through the entire coating to the substrate after only 100, 1-hr cycles and lifetime was similar to an HVOF-only bond coating. The inner HVOF layer with the outer APS flash coating prevented this complete penetration from occurring.

5:00 PM
Using Rapid Thermal Annealing for Studying Early Stages of High Temperature Oxidation of Superalloys: *Dorota Kubacka*[1]; Yolita Eggeler[1]; Nicklas Volz[1]; Steffen Neumeier[1]; Erdmann Spiecker[1]; [1]FAU Erlangen-Nuremberg
The great potential of Rapid Thermal Annealing (RTA), a widespread technique in semiconductor technology, for studying high-temperature properties of superalloys is demonstrated. As an application example, early stages of high-temperature oxidation of Co/Ni-base superalloys are investigated. Model alloys with different Co/Ni ratio are oxidized in synthetic dry air at 900 °C to understand the differences between the oxidation behavior of Ni- and Co-base alloys. Upon short exposure times (below 64 s), the two-phase ã/ã' microstructure has a pronounced influence on both the morphology and growth kinetics of Al2O3 precipitates. Depending on the base element, Al2O3 nucleates in either the ã' phase in the form of needles (Ni-base superalloy) or in the ã matrix as lath- and plate-like precipitates (Co-base superalloy) with the latter showing much slower formation kinetics. Observed differences in oxidation behavior can be directly correlated to changes in the partitioning of W, which acts as a ã former in Ni- and a ã' former in Co-base superalloys. We propose that a significant amount of W in ã' has an inhibitory effect on the diffusion of Al, suppressing the formation of Al2O3 in the ã' phase of Co-base superalloys. Our approach proved to be very successful for oxidation studies and opens up new opportunities for superalloys research.

5:25 PM Question and Answer Period

Wednesday Part I - Blade Alloy Behavior

Begins Wednesday at 8:30 AM EDT
September 15, 2021

Session Chairs: J. Cormier, ENSMA - Institut Pprime - UPR CNRS 3346; J. Zhang, Institute of Metal Research

8:30 AM
Evidence of Short Range Order (SRO) by Dislocation Analysis in Single Crystal Ni-base Matrix Alloys with Varying Re Content after Creep: *Florence Pettinari-Sturmel*[1]; Joël Douin[1]; Fabian Krieg[2]; Ernst Fleischmann[2]; Uwe Glatzel[2]; [1]CEMES - Université de Toulouse; [2]Universität Bayreuth
TEM characterization of the deformation micromechanisms after interrupted creep test at 980 °C is proposed in the case of two single crystal Ni-based matrix alloys without rhenium (Re) and with 9 wt.% Re. This paper is aimed to propose an identification of the physical parameter at the origin of the strengthening effect of Re. The TEM observations carried out in the alloy with 9 wt.% Re indicate that the deformation proceeds through the propagation of long dislocation pile-ups. A leading pair is observed within these pile-ups. As this dislocation configuration is a signature of short-range-order (SRO), a quantitative approach is used to evaluate the SRO degree and thus the resistance due to SRO. The experimental positions of the dislocations are used to evaluate the total elastic force experienced by the dislocations. The strength associated with the SRO is evaluated to: 0 ≈ 50-60 mJ/m2. The observation of the matrix alloy without Re indicates the presence of both individual dislocations and some short dislocation pile-ups. It is also associated with a lower SRO degree. It can be concluded that the Re effect leads to an increase of the SRO degree. SRO is still present at high temperature (930°C) whereas it has been shown to disappear in similar matrix alloy with a lower amount of Re. Rhenium appears then to promote SRO. It can be at the origin of its well-known strengthening effect.

FINAL PROGRAM

8:55 AM

Fretting Fatigue Life Extension for Single Crystal Ni-based Superalloy by Applying Optimized Surface Texturing: *Masakazu Okazaki*[1]; Rengaraj Balavenkatesh[1]; Satoshi Yamagishi[2]; Motoki Sakaguchi[3]; [1]Nagaoka University of Technology; [2]Niigata Institute of Technology; [3]Tokyo Institute of Technology

Fretting fatigue (FF) lives of the CMSX-4 single crystal alloy have been measured, via some different counterpart materials in similar and dissimilar material combinations at room and elevated temperatures. The CMSX-4 specimens were machined so that the [001] crystallographic orientation was within 5˚along the longitudinal axis of the SC specimen. In this work the work special attention was paid to find some useful methods to extend the FF lives by controlling the surface texture of contacting pad, as well as to get the metallurgical and mechanical aspects in the FF damage. The experimental works demonstrated that the texturing was effective to improve the FF lives. The stress field equations along the contacting interface have also been derived employing contact mechanics theories, so that the FF lives and the failure characteristics can be rationally estimated, on the basis of mechanical backgrounds. A new method proposed successfully provided reasonable predictions in agreement with the experimental results.

9:20 AM

Initiation of Fatigue Cracks in a Single Crystal Nickel Based Superalloy at Intermediate Temperature: *Jian Zhang*[1]; [1]Institute of Metal Research

Fatigue tests under a series of stress amplitudes at 760 ˚C of a single crystal nickel based superalloy were conducted to investigate the relationships between loading conditions and initiation sites of fatigue cracks. It was found that initiation sites of the dominant fatigue crack gradually transferred from pores to MC carbides with an increase of the stress amplitude. At low stress amplitude, the fatigue crack that causes the final fracture initiated at pores and the fatigue life depended on size and shape of pores. Although the carbides on surface cracked as a result of oxidation and cyclic loading, the cracks did not penetrate the carbide/matrix interface. However, at high stress amplitude, the cracks in the carbide can penetrate the carbide/matrix interface rapidly under applied stress, and following crack propagation resulted in decisive fatigue fracture. Compared to blocky carbides on the surface, script carbides at subsurface were more likely to induce fatigue crack initiation.

9:45 AM Question and Answer Period

Wednesday Interactive Session on Blade Alloy Behavior

Begins Wednesday at 10:10 AM
September 15, 2021

Measurement and Evaluation of Co-existing Crack Propagation in Single Crystal Superalloys in Hot Corrosion Fatigue Environments: *Laurie Brooking*[1]; Julian Mason-Flucke[2]; Grant Gibson[2]; Jonathan Leggett[2]; Iain Palmer[1]; John Nicholls[3]; Simon Gray[3]; [1]Frazer-Nash Consultancy Ltd; [2]Rolls-Royce plc; [3]Cranfield University

Gas turbines blades are required to operate at high temperatures whilst being subjected to stress and corrosive environments. These demanding conditions have led to the need to better understand the interactions between corrosion and loading in order to improve lifing algorithms used for service interval predictions. A new crack growth measurement technique involving direct current potential difference (PD) has been developed for use in these harsh conditions. A good correlation between PD signal and crack area has been achieved. Estimations of the crack depth have been made based on fracture surface imaging, these experimentally measured crack depth propagation rates have been compared with Paris law predictions. A stress intensity factor (SIF) interaction between multiple cracks was found, where the SIF is enhanced when cracks become close. It was found that both the fatigue cycle rate and the crack shape appear to influence the SIF magnitude and the crack depth at which specimens fail, or initiate into crack propagation which is consistent with fatigue.

Understanding the Effects of Alloy Chemistry and Microstructure on the Stress Relaxation Behavior of Ni-base Superalloys: *Linhan Li*[1]; Joshua McCarley[1]; Eugene Sun[2]; Sammy Tin[3]; [1]Illinois Institute of Technology; [2]Formerly of Rolls-Royce Corporation; [3]University of Arizona

The stress relaxation behavior of two experimental and one commercial powder processed Ni-base were assessed using a servo-hydraulic frame under strain control at 700 ˚C. In addition to quantifying the effect of composition on the stress relaxation behavior, the effect of microstructure and initial strain were also evaluated. The magnitude and rate of stress reduction for the various samples was measured during testing and an apparent activation model was used to normalize the magnitude of the stress drop with the initial stress. Stress relaxation tests with an initial strain of 0.6 % exhibited characteristic behaviors that could be correlated to alloy chemistry and microstructure. The extent of stress relaxation in highly alloyed RRHT5P samples possessing high volume fractions and a high number density of intragranular ã' precipitates was limited. Although P additions were not observed to exert any significant effect, processing of these alloys with lower cooling rates from solution to coarsen the ' precipitates was shown to effectively increase the degree of stress relaxation. Reducing the degree of alloying and maintaining a lower overall fraction of ' precipitates effectively confers a higher degree of stress relaxation at 700 ˚C. Stress relaxation testing and the application of an apparent activation volume model may be effectively used for characterizing the notch sensitivity and crack growth behavior of high temperature structural materials.

HIP +ITF of SS-PREP® Superalloy Powder: *Qu Zonghong*[1]; [1]Sino-Euro Materials Technologies of Xi'an Co., Ltd

The HIP (Hot Isostatic Pressing) + ITF (IsoThermal Forging) process was carried out for SS-PREP® (Super Speed Plasma Rotating Electrode Process) powder of nickel-based superalloy FGH4097. Powder made via SS-PREP® shows fine and uniform particle size, high sphericity and purity. The HIPed compact has good hot workability during isothermal forging to obtain refined grains. The heat treatment tests were performed at different solution temperatures, and mechanical properties were measured. Compared with the established as-HIP process, SS-PREP®+HIP+ITF with 1180 ˚C solution heat treatment resulted in higher strength, ductility and LCF (Low Cycle Fatigue) life, with acceptable increase in accumulated creep strain.

Laboratory-scale Replication of Deposit-induced Degradation of High-temperature Turbine Components: *Matthew Kovalchuk*[1]; Brian Gleeson[1]; [1]University of Pittsburgh

This study investigated the linkages between deposit chemistry and degradation morphology of field-exposed aero-turbine parts and the associated development of effective lab-scale replication testing procedures. Inductively coupled plasma-optimal emission spectroscopy (ICP-OES) analysis indicated that the water-soluble deposit constituents were mainly Na-rich, Ca-rich or a mix of these, with the relative amounts having a dependence on geographic region in which a given part was mainly exposed. Degradation of the field-exposed parts was characterized using scanning electron microscopy (SEM) and revealed unconventional hot corrosion attack. Microstructures included duplex oxide scales, Ca-containing oxide, internal oxidation, sulfidation, and nitridation. Degradation mechanisms elucidated by replication testing were deposit-induced selective depletions at high-temperature and low-temperature oxidation. Field degradation was replicated when considering the thermal dependences of both stages. Replication of a chromide-coated field part required calcium chromate liquid formation during high-temperature testing. Electron probe microanalysis (EPMA) of the coating subsurface revealed extensive Cr depletion after exposure to CaO above the calcium chromate eutectic temperature. Oxidation temperature also contributed to replicating field degradation microstructures. Specifically, matching degradation was observed after the depleted superalloy or chromide coating was oxidized in air at an intermediate temperature.

Strengthening Mechanisms of Ni-Co-Cr Alloys via Nanotwins and Nanophases: *Bin Gan*[1]; Ji Gu[2]; Miguel Monclus[3]; Xue Dong[4]; Yunsong Zhao[5]; Hongyao Yu[1]; Jinhui Du[1]; Min Song[2]; Zhongnan Bi[1]; [1]Central Iron and Steel Research Institute; [2]Central South University; [3]IMDEA Materials Institute; [4]University of Science and Technology Beijing; [5]Beijing Institute of Aeronautical Materials

The ultra-high strength of multiphase (MP) alloys for fastener applications is endowed by cold deformation, which induces deformation twinning or phase transformation in the materials. In the present work, MP159 alloy as well as NiCoCr medium entropy alloy are investigated to assess the effectiveness of a torsional pre-straining as well as surface mechanical grinding treatments to further improve their strength. For the pre-torsion route, microstructural analysis shows that with the activation of different twinning systems and stacking faults, the sequential torsion and tension tests lead to the observed hierarchical microstructure, which gives rise to the significant increase in the yield strength in the investigated alloys while retaining a good ductility. Further studies reveal that aging treatment of the pre-torsion bars provides additional strengthening to MP159 alloys, with the synergistic strengthening of nanotwins and nano-precipitates. After the surface mechanical grinding treatment of NiCoCr alloys, a nanocrystalline structure is formed in a region extending about 150 mm from the edge. Considering the high applied strains, a high density of deformation twins is expected in the nanocrystalline region. Micropillar compression of single crystal and nanocrystalline NiCoCr alloy shows that with the refinement of grain size from 200 mm to 40 nm, the yield strength could increase from 900 MPa to 2500 MPa. This reveals that the refinement of grain sizes can significantly increase the yield strength of NiCoCr alloys with a low stacking fault energy.

A New Approach to Strength Prediction of Ni-Base Disc Superalloys with Dual Phase γ/γ': *Liberty Wu*[1]; Toshio Osada[1]; Ikumu Watanabe[1]; Tadaharu Yokokawa[1]; Toshiharu Kobayashi[1]; Kyoko Kawagishi[1]; [1]National Institute for Materials Science

Previously reported strength prediction models for polycrystalline Ni-base superalloys tend to underestimate the overall strength. This is primarily due to neglecting the rule of mixtures for hardening by g/g' and inaccurate estimation of other strengthening factors such as solid solution hardening of g matrix and grain boundary strengthening, etc. To address these issues, a series of single-crystal tie-line modeling alloys with g' size suitable for validating the strong pair-coupling and Orowan looping mechanisms were prepared, in an attempt to develop more reliable g' hardening models. Critical resolved shear stress values were measured on these modeling alloys at 650 °C using compression tests, which allowed the distinction between strength contribution from rule of mixture and interfacial strength. Compared with the experimentally obtained interfacial strengths, the predicted results by classical models could not reflect the strength increment expected at higher g' volume fraction. Hence, a modified version of the classical equations has been proposed here for improved predictability.

On Optimising Ring-rolling Manufacturability of C&W Nickel Superalloys for Aero-engine Turbine Disk: *Fauzan Adziman*[1]; Ryosuke Takai[2]; Yuanbo Tang[1]; Shigehiro Ishikawa[2]; Daniel Barba Cancho[1]; Enrique Alabort Martinez[1]; Andre Nemeth[1]; Naoya Kanno[2]; Roger Reed[1]; [1]University of Oxford; [2]IHI Corporation

Ring-rolling has proven notoriously difficult to model, control and optimise accurately. We have studied a multi-objective optimisation involving (1) process parameters, (2) geometrical design, and (3) alloy design for manufacturability of a newly developed M647 gamma-prime strengthened C&W nickel superalloy suitable for aero-engine turbine disk. Accurate computational models based on accurate experimentation which allow for knowledge-based choice of the manufacturing variables, built to mitigate the occurrence of excessive adiabatic heating and crack nucleation sites, represent an important step towards the sought-after optimised ring-rolling manufacturability. The results indicate a major improvement of ring-rolling manufacturability by cutting more than 80 percent of processing time whilst maintaining crack-free condition.

Crystal Plasticity Model for Nickel-based Superalloy René 88DT at Elevated Temperature: *Monica Soare*[1]; Shenyan Huang[1]; Mallikarjun Karadge[1]; [1]GE Global Research

A micro-structurally informed crystal plasticity model was developed for polycrystalline alloy René 88DT (R88DT) at a high temperature (650 oC). R88DT is a precipitation strengthened Ni-based superalloy used in gas turbine engine disks due to high tensile strength, superior creep resistance, and high resistance to fatigue crack growth. It was experimentally observed [1] that crack initiation in polycrystalline superalloys is highly dependent on the grain size, orientation and microstructure, as well as on the inelastic sub-grain properties. Thus, understanding the fundamental deformation mechanisms at the sub-grain level is a necessary step for development of fatigue life models. For this purpose, single crystals with microstructures representative of R88DT were first created by the investment casting process. Specific crystallographic orientations were mechanically tested in tension and compression to investigate dominant deformation mechanisms as activation of various slip systems, stacking faults/micro twin formation and precipitate shearing. These mechanisms were incorporated into a physics - based viscoplastic constitutive model. The model was calibrated using data from tests on single crystals and it was then applied for each grain in polycrystalline R88DT to predict the macroscopic stress-strain response as well as heterogeneous local stress and strain fields.

Recent Progress in Local Characterization of Damage Evolution in Thermal Barrier Coating under Thermal Cycling: *Vincent Maurel*[1]; Vincent Guipont[1]; Lara Mahfouz[1]; Basile Marchand[1]; Alain Köster[1]; Anne Dennstedt[2]; Marion Bartsch[2]; Fabrice Gaslain[1]; Florent Coudon[3]; [1]Mines Paris - PSL University; [2]DLR Koln; [3]SAFRAN

Thermal barrier coating (TBC) systems are currently often tested by thermal cycling with or without temperature gradient on cylinder coupons. As a major drawback, edge effect associated with this geometry induces large scatter in TBC life at spallation. Thus, we promote the use of a laser shock to induce an artificial defect located at the top-coat/oxide interface. This method enables firstly to monitor damage evolution by means of non-destructive methods from this defect during thermal cycling at homogeneous temperature and for burner rig testing with superposed thermal gradient across the TBC. Secondly, by the knowledge of artificial defect location, an accurate 3D reconstruction of the crack tip was performed based on serial sectioning by focus ion beam and viewing by scanning electron microscopy. Founded on these observations, a sensitivity analysis of the measurement uncertainties with respect to the energy release rate of propagating cracks and to the process zone where damage elaborates is proposed.

Assessment of Mechanical and Metallurgical Features of Inconel 680 Weld Metal: Rafaella Silva[1]; Emerson Miná[1]; Ricardo Marinho[1]; Giovani Dalpiaz[1]; Marcelo Piza Paes[1]; Marcelo Motta[1]; *Cleiton Silva*[1]; Hélio Miranda[1]; [1]Universidade Federal do Ceará

The present study assessed the mechanical properties and metallurgical features of a new solid-solution Ni-based alloy called Inconel 680, which has been developed for high strength applications, including dissimilar welding for high strength steels. Steel plates were buttered with Inconel 680, to prevent any dilution with the steel. In sequence, the buttered steel plates were joined. Samples from the test plates were extracted for chemical composition analysis, metallography preparation, uniaxial tensile testing, and hardness and microhardness evaluations. Microstructural characterization was performed using scanning electron microscopy and energy-dispersive X-ray spectroscopy. The results of the mechanical properties showed that the Inconel 680 alloy filler metal provides an excellent mechanical strength, including a high yield strength, with an average value superior to 600 MPa, and good ductility, reaching an elongation of at least 40%. In addition, this study provides valuable insight into the microstructure of the Inconel 680 alloy. The overall evaluation indicated that this filler metal is an excellent option for many dissimilar welding applications, such as API 5L X65 pipes internally cladded with Inconel 625.

High-throughput Approaches to Establish Quantitative Process-structure-property Correlations in Ni-base Superalloy: *Nishan Senanayake*[1]; Semanti Mukhopadhyay[2]; Jennifer Carter[1]; [1]Case Western Reserve University; [2]The Ohio State University

A high-throughput approach for collecting microstructure and mechanical properties was developed to model the process-structure-property (PSP) correlations in polycrystalline Ni-based superalloy ME3. The semi-automated image processing algorithm captured the area fraction and size distribution of secondary and tertiary ã' particles from scanning electron microscopy (SEM) images of polished samples. The yield strength and elastic modulus were calculated with an automated algorithm using load-time-displacement data generated by microindentation. Thirty heat treatments were conducted to create various ã' distributions which are the primary strengthening mechanism of Ni-based superalloys. The PSP correlations among the predictor and response variables were evaluated with regression models and validated with adj-R2 and residual standard error statistics. The PSP statistical models built by using high-throughput protocols align with the previous statistical and theoretical models.

The Influence of Hot Corrosion Damage on the Low Cycle Fatigue Fracture Modes of a Disk Superalloy: *Jeremy Hart*[1]; Michael Task[1]; Mario Bochiechio[1]; [1]Pratt & Whitney

Fatigue cracking of nickel disk superalloy fatigue specimens subjected to hot corrosion exposures prior to and during fatigue testing at 704 °C has been investigated. Pre-corroded notched fatigue specimens were exposed to a mixture of sulfates at 677 °C prior to fatigue testing, while in situ treated specimens were only exposed to the sulfate mixture during the elevated temperature fatigue test. Both the pre-corroded and in situ corrosion treatments resulted in a significant reduction in fatigue life compared to uncorroded specimens tested at the same temperature and stress conditions. Investigation of fracture surfaces by scanning electron microscopy and electron microprobe equipped with an energy dispersive spectrometer allowed for determination of fatigue crack initiation sites, as well as morphological and chemical evaluation of the alloy microstructure damaged by hot corrosion. Fatigue crack initiations originated from pit features and microstructural degradation caused by hot corrosion. For pre-corroded specimens, cracks initiated along grain boundaries near the pit depth and propagated intergranularly into the alloy. For in situ treated specimens, cracks formed near the surface oxide above growing pits and propagated into the pit as it grew, eventually propagating in a transgranular nature further into the alloy. Sulfur-rich precipitates were detected along grain boundaries below the hot corrosion pits of both pre-corroded and in situ treated specimens. Sulfur was also detected along crack surfaces and grain boundaries that were 50-100 ìm below crack initiation sites in the in situ treated specimens.

Wednesday Part II - Alternative Materials

Begins Wednesday at 11:10 AM EDT
September 15, 2021

Session Chairs: Q. Feng, University of Science and Technology Beijing; M. Goken, Friedrich-Alexander-University Erlangen-Nürnberg

11:10 AM
Microstructure and Tensile Properties of a CoNi-based Superalloy Fabricated by Selective Electron Beam Melting: Sean Murray[1]; Kira Pusch[1]; Andrew Polonsky[1]; Chris Torbet[1]; Gareth Seward[1]; Peeyush Nandwana[2]; Michael Kirka[2]; Ryan Dehoff[2]; Ning Zhou[3]; Stéphane Forsik[3]; William Slye[3]; *Tresa Pollock*[1]; [1]University of California, Santa Barbara; [2]Oak Ridge National Laboratory; [3]Carpenter Technology Corporation

Successful application of selective electron beam melting to a novel CoNi-based superalloy named SB-CoNi-10 is demonstrated. Crack-free as-printed microstructures exhibit excellent ductilities above 30% and ultimate tensile strengths above 1.1 GPa at room temperature in tension. Conventional post-processing consisting of a super-solvus hot isostatic pressing (HIP), a solution heat treatment (SHT), and a low-temperature aging has been applied to remove microstructural inhomogeneities present in the as-printed microstructure. The microstructures of the as-printed and HIP+SHT+Aged alloys have been investigated to determine the effect of post-processing heat treatments on the nanoscale γγ/γ'γ' microstructure and the mesoscale grain structure. Tensile tests have been conducted at room temperature and elevated temperatures above 850 ° C to investigate mechanical properties in both the as-printed and HIP+SHT+Aged conditions. The high-temperature ductility and strength are strongly affected by the microstructure, with a mostly columnar-grained microstructure in the as-printed condition exhibiting superior ductility to the fully recrystallized microstructure in the HIP+SHT+Aged condition.

11:35 AM

Recent Developments in the Design of Next Generation γ'-strengthened Cobalt-nickel Superalloys: *Stephane Forsik*[1]; Ning Zhou[1]; Tao Wang[1]; Alberto Polar Rosas[1]; Gian Colombo[1]; Andrea Ricci[1]; Austin Dicus[1]; Mario Epler[1]; [1]Carpenter Technology Corporation

A new ã'-strengthened Co-Ni-base superalloy was developed using a combination of computational thermodynamics and lab-scale experimental heats. Multiple 18 kg and 180 kg ingots were melted under vacuum and forged to study the composition-process-property relationship. Several heat treatments were developed to evaluate the balance between strength and creep resistance. In the fine-grain condition, the superalloy exhibits a yield strength of almost 1300 MPa at room temperature, 1071 MPa at 704 ˚C and 766 MPa at 816 ˚C. In the coarse-grain condition, the creep resistance is superior to that of Waspaloy and comparable to that of alloy 720. Sulfidation and cyclic oxidation tests show better resistance to environmental damage than Waspaloy and alloy 720 due to the formation of a protective alumina layer. We also show that this superalloy can be atomized and processed via powder metallurgy. Potential applications include discs and casings in land-based and jet engine turbines, fasteners, bolts and studs in automotive exhaust systems, and exhaust valves in internal combustion engines.

12:00 PM

The Effect of Alloying on the Thermophysical and Mechanical Properties of Co–Ti–Cr-Based Superalloys: Christopher Zenk[1]; *Nicklas Volz*[1]; Andreas Bezold[1]; Laura-Kristin Huber[1]; Yolita Eggeler[1]; Erdmann Spiecker[1]; Mathias Göken[1]; Steffen Neumeier[1]; [1]FAU Erlangen-Nürnberg

The system Co–Ti–Cr was recently identified as a very promising base for low mass-density Co-based superalloys. This study presents the influence of quaternary alloying additions on the thermo-physical and mechanical properties of a Co–11Ti–15Cr model superalloy. Al, Ta, Re and W were selected as a starting point for alloy development as they represent important alloying elements in both Ni-based and Co–Al–W-based superalloys. Microstructure analysis reveals that the addition of only 1 at.% of either of these elements causes the formation of different undesired intermetallic phases in addition to ã and ã' phases, which is in agreement with thermodynamic calculations. However, a diffusion-couple between the Co–Ti–Cr and a Co–Al–W–Ta alloy suggests that the tolerance for alloying elements without destabilizing the ã/ã' two-phase microstructure is higher when they are present in a certain ratio. Energy-dispersive X-ray spectroscopy shows that Cr and Re are enriched in the ã phase whereas Ti and W preferentially partition to ã'. All alloying elements increase the yield strength at room temperature, but are disadvantageous at 1000 ˚C. Re and W retain their strengthening effect up to 900 ˚C.

12:25 PM Question and Answer Period

Wednesday Part III - Additive

Begins Wednesday at 1:30 PM EDT
September 15, 2021

Session Chairs: A. Wessman, University of Arizona; P. Kantzos, Honeywell Aerospace

1:30 PM

Novel Approach for Suppressing of Hot Cracking via Magneto-fluid Dynamic Modification of the Laser-induced Marangoni Convection: André Seidel[1]; Luise Degener[1]; Jakob Schneider[1]; *Frank Brueckner*[1]; Eckhard Beyer[1]; Christoph Leyens[1]; [1]Technical Univ Dresden & Fraunhofer IWS

The occurrence of hot cracking is a significant problem during welding processing of highly heat resistant nickel-base superalloys. Hot cracking is most often associated with liquid films that are present along grain boundaries in the fusion zone and the partially melted zone and can only be suppressed to a very limited extent. The latter is the case despite remarkable studies and analyses of the phenomenon. In this work, a new approach is presented which intends the suppression of hot cracking by using a non-contact method to influence the solidification process. It is based on the idea of a modification of the laser-induced melt pool convection (Marangoni convection) using customized magnetic fields. As a consequence, special system technology is derived on the basis of theoretical considerations while the effectiveness to be expected is estimated on the basis of the information available in the literature. The implemented system technology is described in detail. The focus of this description is on the magnetic flux density distribution or the temporal change, respectively, with respect to the laser-induced melt pool. The presented experimental results provide a comparative view of samples welded with and without the influence of a magnetic field while a significant difference is evident. The outlook of this work describes key data of a test stand specially developed for examining the identified topic in in-depth investigations.

1:55 PM

3D Characterization of the Columnar-to-Equiaxed Transition in Additively Manufactured Inconel 718: *Andrew Polonsky*[1]; Narendran Raghavan[2]; McLean Echlin[1]; Michael Kirka[2]; Ryan Dehoff[2]; Tresa Pollock[1]; [1]University of California, Santa Barbara; [2]Oak Ridge National Laboratory

Additive manufacturing (AM) provides enormous processing flexibility, enabling novel part geometries and optimized designs. Access to a local heat source further permits the potential for local microstructure control on the scale of individual melt pools, which can enable local control of part properties. In order to design tailored processing strategies for target microstructures, models predicting the columnar-to-equiaxed transition must be extended to the high solidification velocities and complex thermal histories present in AM. Here, we combine 3D characterization with advanced modeling techniques to develop a more complete understanding of the solidification process and evolution of microstructure during electron beam melting (EBM) of Inconel 718. Full calibration of existing microstructure prediction models demonstrates the differences between AM processes and more conventional welding techniques, underlying the need for accurate determination of key parameters that can only be measured directly in 3D. The ability to combine multisensor data in a consistent 3D framework via data fusion algorithms is essential to fully leverage these advanced characterization approaches. Thermal modeling provides insight on microstructure development within isolated solidification events and demonstrates the role of Marangoni effects on controlling solidification behavior.

2:20 PM
Microstructure and Mechanical Properties of Additively Manufactured Rene 65: *Andrew Wessman*[1]; Laura Dial[2]; Jonathan Cormier[3]; Kelsey Rainey[4]; Sammy Tin[5]; Dhruv Tiparti[5]; Florence Hamon[3]; [1]University of Arizona; [2]GE Global Research; [3]Institut Pprime; [4]GE Additive; [5]Illinois Institute of Technology
Additive manufacturing has enabled the production of highly complex designs that are not producible using traditional manufacturing techniques. While superalloys such as IN718 have been used in these processes for the manufacture of turbine engine structural components, applications requiring higher service temperatures necessitate the development of alloys with increased capability. Rene 65 was developed as a cast-and-wrought alloy with increased capability relative to wrought IN718, and characteristics of that alloy, including temperature stability and thermal crack-resistance, made Rene 65 an appealing candidate to withstand the extreme temperature gradients that are characteristic of direct metal laser melting (DMLM) additive manufacturing. The as-built DMLM microstructure is very different from as-forged microstructure, and this work will examine the effect of heat treatments both below (sub-) and above (super-) the gamma prime (ã') solvus on the grain and precipitate structure of AM Rene 65 material. Tensile, fatigue and creep behavior of the alloy in these different heat treatment conditions is reported. Relative to AM IN718, AM Rene 65 shows the desired improvement in temperature capability analogous to that in the cast and wrought versions of the alloys. Differences in the balance of properties are noted between AM Rene 65 and cast and wrought Rene 65, which are attributable to the differences in grain size and precipitate distribution and which may provide benefits for certain applications.

2:45 PM Question and Answer Period

Wednesday Interactive Session on Alternative Materials and Additive

Begins Wednesday at 3:10 PM EDT
September 15, 2021

Anisotropic Deformation and Fracture Mechanisms of an Additively Manufactured Ni-based Superalloy: *Cheng-Han Yu*[1]; Ru Lin Peng[1]; Mattias Calmunger[1]; Vladimir Luzin[2]; Håkan Brodin[3]; Johan Moverare[1]; [1]Linköping University; [2]ANSTO/ NSTLI Neutron Scattering; [3]Siemens Industrial Turbomachinery AB
This study investigates the anisotropic mechanical and microstructural behavior of the laser powder bed fusion (LPBF) manufactured Ni-based superalloy Hastelloy X (HX) by using slow strain-rate (10-5s-1 and 10-6s-1) tensile testing (SSRT) at 700°C. LPBF HX typically exhibits an elongated grain structure along the building direction (BD) and the texture analysis from the combination of neutron diffraction and EBSD discloses a major texture component <011> and a minor texture component <001> along BD, and a texture component <001> in the other two sample directions perpendicular to BD. Two types of tests have been performed, the horizontal tests where the loading direction (LD) is applied perpendicular to BD, and the vertical tests where LD is applied parallel to BD. The vertical tests exhibit lower strength but better ductility, which is explained by the texture effect and the elongated grain structure. A comparison of the mechanical behavior to the wrought HX shows that LPBF HX has better yield strength due to the high dislocation density as proved by TEM images. Creep voids are observed at grain boundaries in SSRT for both directions and are responsible for the poor ductility of the horizontal tests. The vertical ductility in SSRT maintains the same level as the reference tensile test at the strain rate of 10-3s-1, due to the extra deformation capacity contributed by the discovered deformation twinning and lattice rotation. The deformation twinning, which is only observed in the vertical tests and has not been found in the conventionally manufactured HX, is beneficial to maintain the ductility but does not strengthen the material.

Microstructural Control and Optimisation of Haynes 282 Manufactured through Laser Powder Bed Fusion: *Katerina Christofidou*[1]; Hon Tong Pang[1]; Wei Li[2]; Yogiraj Pardhi[2]; Colin Jones[2]; Nick Jones[1]; Howard Stone[1]; [1]University of Cambridge; [2]Rolls-Royce plc
The microstructure and properties of alloy Haynes 282 produced through laser powder bed fusion were investigated as a function of the post-deposition heat-treatment. Scanning electron microscopy and X-ray diffraction were utilised to characterize the microstructure, whilst electro-thermal mechanical testing was used to evaluate the tensile and creep properties at 900°C. In the as-deposited state, the initial microstructure consisted of the ã and ã' phases along with M6C and M23C6 carbides. These carbides were observed to govern the recrystallization behavior of the material and resulted in a minimum recrystallization temperature of 1240°C. Following post-deposition heat-treatments the microstructures consisted of a monomodal distribution of ã' with M6C and M23C6 carbides along the grain boundaries. Tertiary ã' particles were found to form in the vicinity of carbides in samples that employed a ã' super-solvus step prior to ageing at 788°C. The tensile properties were found to be similar in all heat-treated states, consistent with the minimal differences observed in the microstructures. In contrast, significant differences in the creep behavior of the alloy was observed following the different heat-treatments, although no correlation with the microstructures was observed.

Additive Manufacturability of Nickel-based Superalloys: Composition-process Induced Vapourisation: *Chinnapat Panwisawas*[1]; Yuanbo Tang[1]; Joseph Ghoussoub[1]; Roger Reed[1]; [1]University of Oxford
Mass loss due to vaporization induced by the high energy heat source during powder bed fusion additive manufacturing (AM) is one of central issues which concerns the compositional variations across the AM build. Potentially, defects can be initiated where local chemistry in the AM build is not homogeneous. In this work, the evaporation effect of powder bed fusion AM has been first developed in a binary alloy Nitinol (NiTi) and then applied to nickel-based superalloys via physics-based integrated modelling framework and experimental investigation. Volatile species which depart from the nominal composition result in significant mass lost up to 2 atomic percent of Ni in the binary alloy system Nitinol, consistent with energy-dispersive X-ray analysis. As for the multicomponent alloy system of nickel-based superalloys, inductively coupled plasma optical emission spectroscopy (ICP-OES) results reveal further that Al, Co, and Cr are preferable to vaporise first with the loss up to 1.2 atomic percent; this affects the thermal fluid behaviour given that the thermophysical property is altered by composition variations. Hierarchical microstructures have been characterised to rationalise the process-structure-property relationship. The mathematical tool validated with targeted experimentation can be further developed for AM materials design, particularly for taking care of vapourisation.

Castability and Recrystallization Behavior of γ'-strengthened Co-base Superalloys: *Nicklas Volz*[1]; Christopher Zenk[1]; Timur Halvaci[1]; Katarzyna Matuszewska[1]; Steffen Neumeier[1]; Mathias Göken[1]; [1]FAU Erlangen-Nuremberg

Casting of single-crystalline superalloys is known to be difficult due to a variety of challenges. Co-base superalloys, however, promise to show quite good castability compared to Ni-base superalloys, as documented in this manuscript. Therefore, an alloy series, which is designed by changing only the Co- to Ni-ratio is used to address this topic. In addition to the casting behavior, segregation and recrystallization behavior were also investigated, since these are closely related to casting challenges. It was found that in the as-cast state all alloying elements distribute more homogeneously in the Co-rich alloys which is beneficial for casting. Casting of directionally solidified tubes revealed that the Co-rich alloys show a lower susceptibility to hot tearing and predominantly develop cold cracks. Since cold cracking can be addressed by component design, Co-base superalloys are suggested to show a better castability compared to Ni-base superalloys. Recrystallization, however, is more pronounced for the Co-rich alloys. This might become a problem during casting of single crystalline Co-base components, if high deformation is introduced in the solidified component.

Strain Monitoring during Laser Metal Deposition of Inconel 718 by Neutron Diffraction: *Sandra Cabeza Sanchez*[1]; Ozcan Burak[1]; Jonathan Cormier[2]; Thilo Pirling[1]; Stefan Polenz[3]; Franz Marquardt[3]; Thomas Hansen[1]; Elena Lopez[3]; Arantxa Vilalta-Clemente[2]; Christoph Leyens[3]; [1]ILL; [2]Institut Pprime, UPR CNRS 3346, ISAE-ENSMA; [3]Fraunhofer IWS

In this study, we provide novel in-situ monitoring of strain during laser metal deposition of Inconel 718 by neutron diffraction. Thermal, phase and stress-related contributions to the lattice parameter evolution are addressed for the representative regions during processing: melt pool, near melt pool and far-field. The evolution showed a strong dependency on the build height and distance to the melt pool, i.e time and temperature gradient, as expected. The different regions of interest reached at different moments the processing stable regime, which is contrasted with microstructural characterization. A homogeneous microstructure of coarse epitaxial dendrites and Laves phase was found from the third printed layer on, with fine globular delta phase precipitation at the grain boundaries. In comparison, neutron diffraction strain monitoring highlighted an offset of process stabilization after 29 layers for the melt pool region, after 12 for near-melt pool region, and after 13 layers for the far-field region.

Development of a New Alumina-forming Crack-resistant High-' Fraction Ni-base Superalloy for Additive Manufacturing: *Ning Zhou*[1]; Austin Dicus[1]; Stéphane Forsik[1]; Tao Wang[1]; Gian Colombo[1]; Mario Epler[1]; [1]Cartech

A new high-ã' volume fraction Ni-base superalloy for additive manufacturing was developed using a CALPHAD-based approach. Selective laser melting followed by hot isostatic pressing produces a microstructure that is free of microcracks and fusion defects. Post-processing includes a solution-and-age heat treatment to precipitate about 55 vol.% of ã'. Two chemistries with different levels of grain boundary strengthening elements were tested to evaluate the balance between printability and high-temperature properties. After heat treatment, the alloy exhibits 980 MPa yield strength and 1400 MPa ultimate tensile strength at room temperature and maintains that level of yield strength up to 800 °C. Cyclic oxidation tests show good resistance to environmental damage due to the formation of a protective alumina layer.

The Effect of Heat Treatment on Tensile Yielding Response of THE New Superalloy ABD-900AM for Additive Manufacturing: *Yuanbo Tang*[1]; Joseph Ghoussoub[1]; Chinnapat Panwisawas[1]; David Collins[2]; Sajjad Amirkhanlou[3]; John Clark[3]; Andre Nemeth[3]; David McCartney[1]; Roger Reed[1]; [1]University of Oxford; [2]University of Birmingham; [3]OxMet Technologies

The heat treatment response of the new superalloy ABD-900AM, designed specifically for additive manufacturing (AM), is studied. The as-fabricated microstructure is characterised at multiple length-scales including by X-ray synchrotron diffractometry. The very high cooling rates arising during the process suppress g' precipitation; thus the details of heat treatment are shown to be important in establishing properties. The yield stress and tensile strength developed are marginally improved by super-solvus rather than sub-solvus heat treatment, but the ductility is then compromised. The tensile behaviour is superior to the heritage alloy IN939 which has a comparable fraction of g'; this is due to the larger refractory content of ABD-900AM and its finer scale precipitation. The internal strains developed during processing are sufficient to promote recrystallization during super-solvus heat treatment which breaks down microstructural anisotropy and promotes grain growth; however, this effect is absent for the sub-solvus case.

Effects of Ti and Cr Additions in a Co-Ni-Al-Mo-Nb Based Superalloy: Nithin Baler[1]; Prafull Pandey[1]; Mahander Singh[1]; *Surendra Kumar Makineni*[1]; Kamanio Chattopadhyay[1]; [1]Indian Institute of Science, Bangalore

In the present work, we show the feasibility of microstructural control by additions of Ti and Cr to a /' Co-30Ni-10Al-5Mo-2Nb superalloy. Solutioning at 1300 °C followed by aging at 900 °C leads to homogenous distribution of L12 ordered cuboidal ' precipitates in face-centered-cubic (fcc) matrix. Compositional measurements show Al, Mo and Nb partition to ' that indicates the ' can be described as (Co,Ni)3(Al,Mo,Nb). An addition of 2 at.% Ti leads to increases in the ' volume fraction from 56 % to 70 % and solvus temperature from 990 °C to 1030 °C. Ti strongly partitions to ' with respect to ã matrix. Similarly, an addition of 10 at.% Cr to the base alloy leads to a morphological transition of ' precipitates from cuboidal to near spherical shape, indicating a direct influence on the /' lattice misfit. Unlike Ti, Cr partitions to matrix and additionally, Cr influences Mo to partition into matrix. A combined addition of Ti and Cr leads to high ' volume fraction ~ 76 % and an increase in solvus temperature to 1045C, while maintaining the spherical ' morphology. These superalloys show 0.2 % proof strength comparable to those of Co-Al-W based superalloys. At 870 C, 10 at.% Cr and 2 at.% Ti added alloys show higher specific 0.2 % proof stress than Co-Al-W based superalloys. The obtained results show the microstructural sensitivity of these Co-based superalloys towards their designing for better performance.

Machine Learning-assisted Design Approach for Developing γ'-Strengthened Co-Ni-base Superalloys: *Min Zou*[1]; Wendao Li[1]; Longfei Li[1]; Ji-Cheng Zhao[2]; Qiang Feng[1]; [1]University of Science and Technology Beijing; [2]University of Maryland

As a new class of promising high-temperature materials, Co-Al-W-base alloys have been developed by alloying additions to improve the microstructure stability and other properties. However, the optimization of Co-Al-W-base alloys becomes more complicated with increasing variety and content of alloying elements. In this study, an accelerated approach to design '-strengthened Co-Ni-base superalloys with well-balanced properties was developed, by integrating the diffusion-multiple approach and machine-learning tools. A large amount of experimental data was obtained using the diffusion-multiple approach and fed into machine learning tools to establish the relationship between alloy compositions and important thermodynamic and microstructural parameters such as the phase constituent, the ã' phase fraction (Fã') and the ã' solvus temperature (Tã'). The established machine-learning models were then employed to predict the characteristic parameters of multicomponent Co-Ni-base superalloys containing up to nine elements (Co, Ni, Al, W, Ta, Ti, Cr, Mo, Nb), even though most of the collected compositions from experiments were quinary to septenary alloys. Using the predicted results from the models and the computational thermodynamics tools, a multicomponent Co-Ni-base superalloy aimed at the application as single crystal blades was designed and characterized to test the reliability and robustness of the novel design approach.

FINAL PROGRAM

Computational Design of Additively Printable Nickel Superalloys: *Adarsh Shukla*[1]; Sanket Sarkar[1]; Durga Ananthanarayanan[2]; Raghav Adharapurapu[1]; Laura Dial[3]; Sanjay Sondhi[1]; [1]GE Research, Bangalore, India; [2]KTH Royal Institute of Technology; [3]GE Research, Niskayuna, USA

The recent advances in additive manufacturing (AM) have led to printing of complex structural components. The highly non-equilibrium processing conditions encountered during Direct Metal Laser Melting (DMLM) frequently lead to micro-cracking in high-temperature capable Ni-superalloys, irrespective of processing conditions, limiting their current applicability. This paper aims to develop a general criterion to assess printability of a Ni-superalloy solely based on its composition. Thirty-four Ni-superalloys spanning a wide range of alloying elements were printed, each with twenty-four process conditions, and their crack densities were measured in order to have a consistent set of experimental data for building a model. The models available in literature for predicting cracking susceptibility were evaluated against the experimental data. Finally, a hybrid model, based on physics based quantities, was built with the most significant input features (x's). This model correlates well with the experimental data and is applicable across a wide range of Ni-superalloy compositions.

Mechanical Performance of a Non-weldable Ni-base Superalloy: Inconel 738 Fabricated by Electron Beam Melting: *Michael Kirka*[1]; Peeyush Nandwana[1]; Sean Yoder[1]; Patxi Fernandez-Zelai[1]; Obed Acevedo[1]; Daniel Ryan[2]; Mark Lipschutz[2]; [1]Oak Ridge National Laboratory; [2]Solar Turbines Incorporated

Additive manufacturing processes are becoming increasingly utilized throughout industry. These technologies enable novel design and manufacture of complex components, reduce material waste streams, and potentially reduce development cycles via rapid prototyping. The high-'' Ni-base superalloys are of particular interest to the gas turbine engine industry due their high-temperature resistance. However, as a result of the high '' volume fraction, these alloys are traditionally termed non-weldable due to a propensity to crack during welding from a host of mechanisms including hot-tearing and strain-age cracking. These mechanisms are subsequently found in fusion-based additive manufacturing processes. Furthermore, there is a long history of employing traditionally processed components in gas turbine engines, and hence, the performance of materials produced by additive manufacturing needs to be closely investigated. In this work is presented the tensile, high-temperature fatigue, and creep deformation behavior for Inconel 738 fabricated through electron beam melting (EBM) additive manufacturing. Under tensile and fatigue conditions, the material was observed to perform in an isotropic manner when tested parallel and transverse to the build direction. Although under creep conditions, the material exhibited an anisotropy between material tested parallel and transverse to the build direction. With the difference attributed to the fine columnar grain structure observed in the additively manufactured Inconel 738. Ultimately, the EBM material was observed to perform comparably to the conventional cast Inconel 738.

Wednesday Part IV - Alloy Development and Component Manufacture & Repair

Begins Wednesday at 4:10 PM EDT
September 15, 2021

Session Chairs: S. Tin, University of Arizona; M. Hardy, Rolls-Royce Plc

4:10 PM
On the Influence of Alloy Chemistry and Processing Conditions on Additive Manufacturability of Ni-based Superalloys: *Joseph Ghoussoub*[1]; Yuanbo Tang[1]; Chinnapat Panwisawas[1]; Andre Nemeth[2]; Roger Reed[1]; [1]University of Oxford; [2]OxMet Technologies Ltd.

Additive manufacturing trials are carried out on two new nickel-based superalloys designed specifically for this processing method. Their performance—with emphasis on their capability to resist cracking—is assessed by comparing with the two legacy alloys IN939 and CM247LC. The two new alloys are found to have demonstrably superior printability. Thermophysical testing and quantitative characterization, particularly via stereology, are used to help rationalize the physical basis of the improved manufacturability displayed.

4:35 PM
Microstructure and Material Properties of Alloy 718/713LC Joints Using Orbital Friction Welding: *Bjoern Hinze*[1]; [1]Rolls-Royce Deutschland Ltd & Co KG

This work demonstrates on flat test specimens that orbital friction welding is a suitable process to join a typical disk alloy 718 and a typical blade alloy 713LC. The capability to join nickel-based blades on disks enables the manufacture of blisks instead of the typically used bladed disks. Blisks have the potential to save weight within an aero engine. Orbital friction welding is an alternative process to linear friction welding to enable blade and disk joints. The advantage of orbital friction welding is that the movement is homogenous and the amplitude (or eccentricity) is smaller compared to linear friction welding. This allows joints in areas which are geometrically challenging and impossible to join for linear friction welding. Due to the solid state joining process, there is basically no material mixing within the weld, but within both alloys recrystallization can be seen near the weld line. The result is a fine grained microstructure within both alloys adjacent to the bond line. While this means only a small microstructural change for alloy 718, it is a major microstructural change for the cast coarse grain alloy 713LC. Consequently, the mechanical properties are changed compared to the base material due to the friction welding process. The microstructural changes of orbital friction welding and their influence on the material properties are presented within this work.

5:00 PM

Enhancing the Efficiency and Surface Integrity of Chemical Cleaning during Repair of Ni-base Superalloy Rotating Disks: *Eric Huron*[1]; Nicole Tibbetts[1]; Zeynep Bolukoglu[1]; Thomas Webster[1]; [1]GE Aircraft Engines

The rotating turbine disks, spools, and seals in the hot section of gas turbine engines are typically made of Nickel-base superalloys. These components operate at high temperatures resulting in dirt accumulation, oxidation, and hot corrosion, and must be cleaned during overhaul to enable inspection and repair. It was found that the typical cleaning solutions used may dissolve the fine carbides present in some superalloys with potential impact on Low Cycle Fatigue (LCF), but that prior shot peening can mitigate this effect. It was also found that, for the highest operating temperatures, grain boundary oxidation may occur in some superalloys and the resultant very fine grain boundary oxides near the surface may be removed by the cleaning process with potential impact on LCF, but that post-cleaning shot peening can address this effect. Studies also showed that more aggressive cleaning solutions may be possible but their impacts on surface condition must be carefully assessed. Finally, it was shown that ultrasonic energy can improve the productivity of the cleaning solutions but must be introduced with proper care to prevent unintended resonance vibration risk to the part.

5:25 PM Question and Answer Period

5:50 PM Concluding Comments

Additional On-Demand Pre-Recorded Talks

Available starting Monday, September 13, 2021

Stress-induced Variant Selection of " Phase in Inconel 718 during Service: Mechanism and Effects on Mechanical Behavior: *Hailong Qin*[1]; Zhongnan Bi[1]; Ruiyao Zhang[2]; Tung-Lik Lee[3]; Hongyao Yu[1]; Hongbiao Dong[2]; Jinhui Du[1]; Ji Zhang[1]; [1]Central Iron and Steel Research Institute; [2]University of Leicester; [3]ISIS Neutron Source

The stress-induced variant selection (SIVS) of " phase caused by thermo-mechanical coupling condition is studied systematically. The SIVS index f is devised and utilized to quantify the degree of SIVS via SEM image post-processing within <001> oriented grains. Applied stress condition does not affect the volume fraction, average size and crystallographic orientation of the ", but changes the proportion of the three variants. The SIVS behavior of " phase is dependent upon the applied stress direction and grain orientation. By considering the variation of the SIVS index with thermal aging and creep parameters, a causal relationship between degree of SIVS with temperature, stress, and time is elucidated. The yield strength and tensile strength at 650˚C decreases with the increase of SIVS degree. Contour map for the degree of SIVS is presented to evaluate the service temperature and stress of an Inconel 718 component. The formation mechanism of SIVS of ã" is proposed: the orienting effect of stress conditon is appreciable only during Ostwald ripening, due to the change of the ã"/ã lattice mismatch.

Hot Corrosion and Creep Properties of Ni-base Single Crystal Superalloys: *Yutaka Koizumi*[1]; Kyoko Kawagishi[1]; Tadaharu Yokokawa[2]; Michinari Yuyama[1]; Yuji Takata[1]; Hiroshi Harada[1]; [1]National Institute for Materials Science; [2]National Institute for Materials Sciencei

Hot corrosion behavior at 700 ˚C (Type II) and 900 ˚C (Type I) and creep property from 800 ˚C to 1100 ˚C were investigated for representative alloys from the 1st generation to the 6th generation of Ni base single crystal superalloys. From the metal loss in the corrosion test and creep rupture life, it is found that corrosion resistance and creep strength are improved with generation advances. Regression analysis was performed to the results of the corrosion test at both 700 ˚C and 900 ˚C. Equations for predicting corrosion characteristics were constructed, and alloying elements contributing to corrosion resistance were estimated.

Effect of Re on Long-term Creep Behavior of Nickel-based Single Crystal Superalloys for Industrial Gas Turbine Applications: *Fan Lu*[1]; Longfei Li[1]; Stoichko Antonov[1]; Yufeng Zheng[2]; Hamish Fraser[2]; Dong Wang[3]; Jian Zhang[3]; Qiang Feng[1]; [1]University of Science and Technology Beijing; [2]The Ohio State University; [3]Institute of Metal Research, Chinese Academy of Sciences

Understanding the long-term creep behavior (creep lives longer than 5000 h) of nickel-based single crystal (SX) superalloys is of great interest for the service safety of industrial gas turbine (IGT) blades. However, understanding the influence of various factors on long-term creep behavior of nickel-based SX superalloys has always been a challenge. In this study, the creep behavior of nickel-based SX superalloys with or without 2 wt.% Re addition were investigated at 900 °C and 200 MPa. Microstructural characterization was systematically conducted to elucidate the microstructural evolution of the experimental alloys after creep rupture tests. The results indicated that the creep lifetime was increased significantly by 2 wt.% Re addition, which dramatically reduced the creep strain rate and caused the lattice misfit of ã/ã' phases to inverse from positive to negative, leading to N-type rafting exhibiting a stronger barrier to dislocations during creep. The evolution of lattice misfit of the ã/ã' phases was closely associated with the elemental partitioning behavior between the ã/ã' phases, which was determined as a consequence of "time accumulation effect" and corresponding elemental diffusion special for prolonged time. This study provides a new insight in the effect of Re on the long-term creep life and microstructure evolution of nickel-based SX superalloys. Such knowledge will be helpful to provide the guideline of superalloys design for large-scale IGT blades.

Effects of Al, Cr and Ti on the Oxidation Behaviors of Multi-component γγ/γ′ CoNi-based Superalloys: Xiaoli Zhuang[1]; *Longfei Li*[1]; Qiang Feng[1]; [1]University of Science & Technology Beijing (USTB)

The effects of Al, Cr and Ti on the oxidation behaviors of multi-component ã/ã' CoNi-based superalloys, Co-30Ni-(6-8)Al-3W-1Ta-(3-6)Ti-(12-14)Cr, were investigated at 800 °C, 900 °C and 1000 °C for 100 h. The results show that Al has a superior effect for improving the oxidation resistance of the alloys in comparison with Cr, particularly at 900 °C and 1000 °C, while Ti was detrimental to the oxidation performance of the alloys. Oxidation resistance of alloys containing 6 at.% Al were primarily provided by Cr2O3 layer, which was not sufficiently protective at 900 °C and 1000 °C. Continuous Al2O3 layers could form in alloys containing 8 at.% Al at 800 °C and 1000 °C, but failed at 900 °C. Higher content of Cr can assist the formation of continuous Al2O3 layer. For the target service temperature of 800 °C or below, alloys with lower Al and higher Ti content may be suitable since higher solvus temperature and volume fraction of the ã' phase could be achieved with sufficient oxidation resistance provided by dense Cr2O3 layer. While for a higher target service temperature above 900 °C, higher content of Al (= 8 at.%) is required to form continuous Al2O3 layer. The current study is helpful to understand the oxidation behavior of multi-component CoNi-based superalloys and provide guidance for alloy composition design and optimization.

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