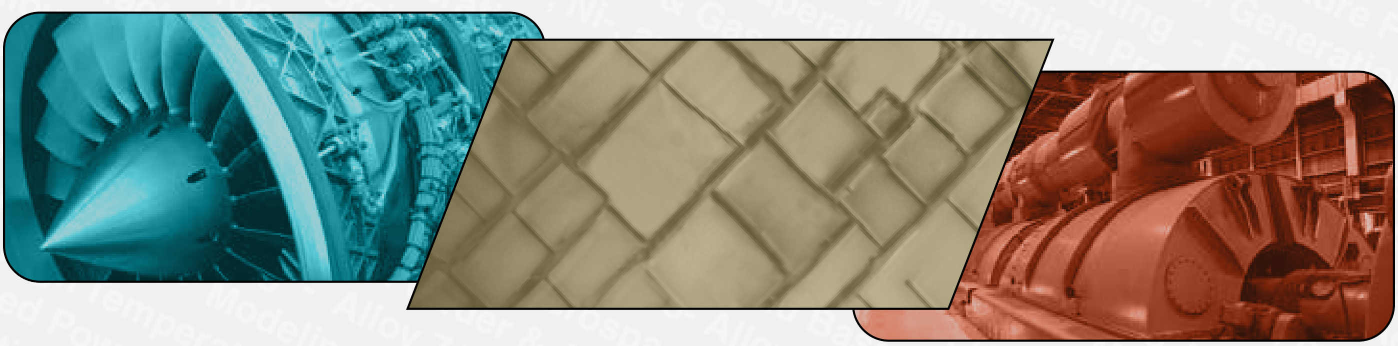
# SUPERALLOY 718 and Derivatives

**MAY 14–17, 2023**
Sheraton Pittsburgh Hotel at Station Square
Pittsburgh, Pennsylvania, USA

# CONFERENCE GUIDE AND FINAL TECHNICAL PROGRAM



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This conference is sponsored by the Structural Materials Division and the High Temperature Alloys Committee

www.tms.org/Superalloy718-2023

## SCHEDULE AT A GLANCE • *CURRENT AS OF APRIL 17, 2023 • Subject to change*

| **Sunday, May 14** | **Time** | **Location** |
|---|---|---|
| Registration | 4:30 p.m. - 9:00 p.m. | Admiral Foyer |
| Exhibition and Poster Installation | 5:00 p.m. - 8:00 p.m. | Reflections and Waterfront |
| Keynote Presentations | 7:00 p.m. - 8:00 p.m. | Admiral |
| Welcome Reception with Posters & Exhibitors | 8:00 p.m. - 9:00 p.m. | Reflections and Waterfront |
| **Monday, May 15** | **Time** | **Location** |
| Registration | 7:00 a.m. - 5:30 p.m. | Admiral Foyer |
| Continental Breakfast | 7:00 a.m. - 8:00 a.m. | Reflections and Waterfront |
| Technical Sessions | 8:00 a.m. - 11:45 a.m. | Admiral |
| *Exhibition and Break* | 9:45 a.m. - 10:15 a.m. | Reflections and Waterfront |
| Conference Luncheon | 11:45 a.m. - 1:00 p.m. | Grand Station III-V |
| Technical Sessions | 1:00 p.m. - 5:30 p.m. | Admiral |
| *Exhibition and Break* | 2:55 p.m. - 3:15 p.m. | Reflections and Waterfront |
| **Tuesday, May 16** | **Time** | **Location** |
| Registration | 7:00 a.m. - 5:30 p.m. | Admiral Foyer |
| Continental Breakfast | 7:00 a.m. - 8:00 a.m. | Reflections and Waterfront |
| Technical Sessions | 8:00 a.m. - 11:35 a.m. | Admiral |
| *Exhibition and Break* | 9:55 a.m. - 10:25 a.m. | Reflections and Waterfront |
| Conference Luncheon | 11:35 a.m. - 1:00 p.m. | Grand Station III-V |
| Technical Sessions | 1:00 p.m. - 5:30 p.m. | Admiral |
| *Exhibition and Break* | 2:35 p.m. - 2:55 p.m. | Reflections and Waterfront |
| Exhibition and Poster Dismantle | 3:00 p.m. - 5:00 p.m. | Reflections and Waterfront |
| **Wednesday, May 17** | **Time** | **Location** |
| Registration | 7:00 a.m. - 2:00 p.m. | Admiral Foyer |
| Continental Breakfast | 7:00 a.m. - 8:00 a.m. | Reflections and Waterfront |
| Technical Sessions | 8:00 a.m. - 11:25 a.m. | Admiral |
| *Break* | 9:45 a.m. - 10:15 a.m. | Reflections and Waterfront |
| Conference Luncheon | 11:25 a.m. - 12:25 p.m. | Grand Station III-V |
| Technical Sessions | 12:30 p.m. - 2:00 p.m. | Admiral |

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## WELCOME

The 10th International Symposium on Superalloy 718 & Derivatives 2023 (Superalloy 718 & Derivatives 2023) conference will explore all aspects of metallurgical processing, materials behavior, and microstructural performance for a distinct class of 718-type superalloy and derivatives. First held in 1991, Superalloy 718 & Derivatives takes place every three to four years. The topics covered include broad industrial applications for a cross-section of industries, including supply chain, energy, and aerospace. Leading names in the field are involved as presenters or engaged in stringently curating presentations to ensure the highest quality programming. Attendees gain networking opportunities across industries, forge new connections for future collaborations, and learn about the latest developments in alloys, processes, applications, and modeling.

## ORGANIZING COMMITTEE

**Committee Chair:**
**Joel Andersson**, University West

**Committee Co-Chair:**
**Chantal Sudbrack**, U.S. DOE National Energy Technology Laboratory

**Lead Editor:**
**Eric Ott**, GE Aviation

**Co-Lead Editor:**
**Zhongnan Bi**, Central Iron and Steel Research Institute

**Organizing Committee:**

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- **Paul Jablonski**, U.S. DOE National Energy Technology Laboratory
- **Michael Kirka**, Oak Ridge National Laboratory
- **Xingbo Liu**, West Virginia University
- **Daisuke Nagahama**, Honda R&D Co. Ltd.
- **Tim Smith**, NASA Glenn Research Center
- **Martin Stockinger**, Montanuniversität Leoben
- **Andrew Wessman**, The University of Arizona

## REGISTRATION

Attendees are required to register. Badges must be worn for admission to technical sessions, the exhibition, and all conference events.

Your registration badge ensures admission to each of these events:

- Technical program
- Refreshment breaks during session intermissions
- Sunday night welcome reception
- Breakfast and lunch on Monday-Wednesday

**Registration Hours**
The registration desk will be in Admiral Foyer at the following times (subject to change):

Sunday, May 14, 4:30 p.m.–9:00 p.m.
Monday, May 15, 7:00 a.m.–5:30 p.m.
Tuesday, May 16, 7:00 a.m.–5:30 p.m.
Wednesday, May 17, 7:00 a.m.–2:00 p.m.

CONFERENCE GUIDE

# CONFERENCE DETAILS

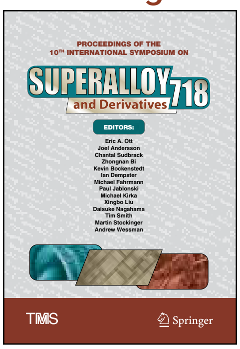
### Technical Sessions

All technical sessions and keynote presentations take place in Admiral. All poster presentations will be held in Reflections and Waterfront. Refer to the technical program for details.

### Internet Access

WiFi will be provided. Please check with the TMS registartion desk for WiFi login information.

### Proceedings




All conference attendees receive free electronic access to the *Proceedings of the 10th International Symposium on Superalloy 718 and Derivatives* publication. This publication is now available for you to download as an e-book or as individual papers. Follow these easy steps for access:

1. Go to the Superalloy 718 & Derivatives Proceedings log in page at: [www.tms.org/Superalloy718Proceedings.](www.tms.org/Superalloy718Proceedings)
2. Enter your order number and name. The order number can be found at the top of your registration confirmation. If you have misplaced your number, you can retrieve it through the log in link in step 1 above.
3. After clicking "Access Content" on the next page, you will be passed through to a page with free access to the e-book and individual papers.

Complimentary proceedings content must be downloaded by June 30, 2023, at which time standard pricing will take effect. Hard copy books and additional e-books may be purchased at [www.springer.com](www.springer.com) (TMS members receive a 40% discount, plus free shipping).

# NETWORKING & SOCIAL EVENTS

### Welcome Reception

Join us for a welcome reception with posters and exhibitors on Sunday, May 14, from 8:00 p.m. to 9:00 p.m. in Reflections and Waterfront.

# ABOUT THE VENUE

### Sheraton Pittsburgh Hotel at Station Square

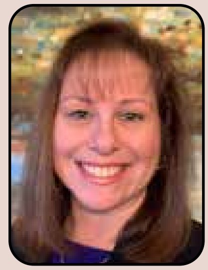
300 W Station Square Dr.
Pittsburgh, PA 15219
+1 412-261-2000

The Sheraton Pittsburgh Hotel at Station Square is ideally located in the heart of Station Square, a thriving dining and entertainment destination that began as a hub for the Pittsburgh & Lake Erie Railroad. Friendly staff and inviting interior spaces help to make guests feel at home. The hotel's amenities include high-speed internet access and a state-of-the-art fitness center. The city and its surrounding area are full of tourist attractions and interesting destinations, including the Andy Warhol Museum, Pittsburgh Zoo and Aquarium, PNC Park, PPG Paints Arena, and the Children's Museum of Pittsburgh, as well as a plethora of shopping and dining options conveniently located in Station Square.

The Sheraton's location is in the heart of Pittsburgh, just 19 miles from the Pittsburgh International Airport (PIT). Transportation options from the airport include taxi and ride-sharing services, the Port Authority Transit bus service, and car rental companies. Upon arriving in the city, visitors can enjoy convenient access to the Pittsburgh T Rail System that provides free subway rides within the downtown district.

## KEYNOTE SPEAKERS

**David Furrer**, Senior Fellow Discipline Lead, Materials and Propulsion Technology, Pratt & Whitney
**Presentation:** "Application of Computational Materials and Process Modeling to Current and Future Aero-engine Component Development and Validation"



**Melissa Martinez**, Vice President, Product & Process Technology, ATI Metals
**Presentation:** "Meeting the Challenges of the Future by Understanding Our Past"

## EXPLORE STATION SQUARE RESTAURANTS

**Kiku Japanese**
225 W Station Square Dr.
Pittsburgh, PA 15219
+1 412-765-3200
Hours: Tuesday-Thursday: 12:00 p.m.–2:00 p.m.; 5:00 p.m.–10:00 p.m.

**Terrene**
224 W Station Square Dr.
Pittsburgh, PA 15219
+1 412-709-6433
Hours: Monday-Friday: 9:00 a.m.–3:00 p.m.

**Texas de Brazil**
240 W Station Square Dr.
Pittsburgh, PA 15219
+1 412-230-4004
Hours: Tuesday-Thursday: 5:00 p.m.–9:00 p.m.
Friday: 5:00 p.m.–9:30 p.m.
Saturday: 2:00 p.m.–9:30 p.m.

**Joe's Crab Shack**
226 W Station Square Dr.
Pittsburgh, PA 15219
+1 412-690-2404
Hours: Sunday-Thursday: 11:00 a.m.–9:00 p.m.
Friday-Saturday: 11:00 a.m.–10:00 p.m.

**The Melting Pot**
242 W Station Square Dr.
Pittsburgh, PA 15219
+1 412-261-3477
Hours: Monday-Thursday: 4:00 p.m.–10:00 p.m.
Friday-Sunday: 12:00 p.m.–10:00 p.m.

**Hard Rock Cafe**
230 W Station Square Dr.
Pittsburgh, PA 15219
+1 412-481-7625
Hours: Sunday-Thursday: 12:00 p.m.–8:00 p.m.
Friday-Saturday: 12:00 p.m.–10:00 p.m.

**Homerun Harry's**
87 W Station Square Dr.
Pittsburgh, PA 15219
+1 412-594-7337
Hours: Monday-Friday: 8:00 a.m.–2:00 p.m.; 5:00 p.m.–2:00 a.m.
Saturday-Sunday: 11:00 a.m.–2:00 a.m.

**The Grand Concourse**
100 W Station Square Dr.
Pittsburgh, PA 15219
+1 412-261-1717
Hours: Monday-Thursday: 11:30 a.m.–8:30 p.m.
Friday-Saturday: 11:30 a.m.–9:00 p.m.
Sunday: 9:30 a.m.–8:00 p.m.

**Buca di Beppo**
3 E Station Square Dr.
Pittsburgh, PA 15219
+1 412-471-9463
Hours: Sunday-Wednesday: 11:00 a.m.–9:30 p.m.
Thursday-Saturday: 11:00 a.m.–10:00 p.m.

**Tupelo Honey**
111 W Station Square Dr.
Pittsburgh, PA 15219
+1 412-467-6946
Hours: Monday-Thursday: 11:00 a.m.–9:00 p.m.
Friday: 11:00 a.m.–10:00 p.m.
Saturday: 10:00 a.m.–10:00 p.m.
Sunday: 10:00 a.m.–9:00 p.m.

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# MEETING POLICIES

### Badges
All attendees must wear registration badges at all times during the conference to ensure admission to events included in the paid fee, such as technical sessions and receptions.

### Refunds
The deadline for all refunds was April 3, 2023. No refunds will be issued at the conference. Fees and tickets are nonrefundable.

### Cell Phone Use
In consideration of attendees and presenters, we kindly request that you minimize disturbances by setting all cell phones and other devices on "silent" while in meeting rooms.

### Americans with Disabilities Act
The federal Americans with Disabilities Act (ADA) prohibits discrimination against, and promotes public accessibility for, those with disabilities. In support of, and in compliance with ADA, we ask those requiring specific equipment or services to contact TMS Meeting Services at mtgserv@tms.org or by visiting the registration desk onsite.

### Anti-Harassment
In all activities, TMS is committed to providing a professional environment free of harassment, disrespectful behavior, or other unprofessional conduct.

TMS policy prohibits conduct that is disrespectful, unprofessional, or harassing as related to any number of factors including, but not limited to, religion, ethnicity, gender, national origin or ancestry, physical or mental disability, physical appearance, medical condition, partner status, age, sexual orientation, military and veteran status, or any other characteristic protected by relevant federal, state or local law or ordinance or regulation.

Failure to comply with this policy could lead to censure from the TMS Board of Directors, potential legal action, or other actions.

Anyone who witnesses prohibited conduct or who is the target of prohibited verbal or physical conduct should notify a TMS staff member as soon as possible following the incident. It is the duty of the individual reporting the prohibited conduct to make a timely and accurate complaint so that the issue can be resolved swiftly.

### Photography and Recording
TMS reserves the right to all audio and video reproduction of presentations at TMS-sponsored meetings. By registering for this meeting, all attendees acknowledge that they may be photographed by TMS personnel while at events and that those photos may be used for promotional purposes, in and on TMS publications and websites, and on social media sites.

Any recording of sessions (audio, video, still photography, etc.) intended for personal use, distribution, publication, or copyright without the express written consent of TMS and the individual authors is strictly prohibited. Attendees violating this policy may be asked to leave the session.

### Antitrust Compliance
TMS complies with the antitrust laws of the United States. Attendees are encouraged to consult with their own corporate counsel for further guidance in complying with U.S. and foreign antitrust laws and regulations.

### TMS Diversity and Inclusion Statement
TMS is committed to advancing diversity in the minerals, metals, and materials professions, and to promoting an inclusive professional culture that welcomes and engages all who seek to contribute to the field. TMS recognizes that a diverse minerals, metals, and materials workforce is critical to ensuring that all viewpoints, perspectives, and talents are brought to bear in addressing complex science and engineering challenges. To build and nurture this diverse professional community, TMS welcomes and actively engages the participation of underrepresented groups in all of its initiatives and endeavors.

# EMERGENCY PROCEDURES

The chances of an emergency situation occurring at Superalloy 718 & Derivatives 2023 are quite small. However, being prepared to react effectively in case of an incident is the most critical step in ensuring the health and safety of yourself and those around you. Please take a few moments to review the maps of the Sheraton Pittsburgh Hotel at Station Square printed on the back cover of this program. When you enter the building, familiarize yourself with the exits and the stairs leading to those exits. When you arrive at your session or event location, look for the emergency exits that are in closest proximity to you.

**IN AN EMERGENCY, DIAL 911.**

Please use the following local safety and security contact information if you or someone near you is experiencing an emergency.

**Nearest Police Department:**
830 East Warrington Avenue
Pittsburgh, PA 15210
+1 412-488-8326
pittsburghpa.gov/police/police-zone3

**Nearest Fire Department:**
Pittsburgh Bureau of Fire Station 24
1729 Mary Street
Pittsburgh, PA 15203
pittsburghpa.gov/fire/index.html

**Nearest Hospital:**
UPMC Mercy Hospital
1400 Locust Street
Pittsburgh, PA 15219
+1 412-232-8111
www.upmc.com/locations/hospitals/mercy

**Urgent Care:**
Concentra Urgent Care
1600 W Carson Street Suite 200
Pittsburgh, PA 15219
+1 412-391-1137
www.concentra.com/

# TMS UPCOMING MEETINGS

TMS offers programming that spans the technical interests of the global minerals, metals, and materials community.

**TMS FALL 2023 @ MATERIALS SCIENCE & TECHNOLOGY**
October 1–4, 2023
Columbus, Ohio, USA
www.tms.org/TMSFall2023

**3rd WORLD CONGRESS ON HIGH ENTROPY ALLOYS HEA2023**
November 12–15, 2023
Pittsburgh, Pennsylvania, USA
www.tms.org/HEA2023

**THE WORLD COMES HERE. TMS 2024 153rd Annual Meeting & Exhibition**
March 3–7, 2024
Orlando, Florida, USA
www.tms.org/TMS2024

**TMS SPECIALTY CONGRESS 2024**
June 16-20, 2024
Cleveland, Ohio, USA
www.tms.org/SpecialtyCongress/2024

**SUPERALLOYS 2024**
September 8–12, 2024
Champion, Pennsylvania, USA
www.tms.org/Superalloys2024

**TMS 2025 154th Annual Meeting & Exhibition**
March 23–27, 2025
Las Vegas, Nevada, USA
www.tms.org/TMS2025

**TMS SPECIALTY CONGRESS 2025**
June 15-19, 2025
Anaheim, California, USA
www.tms.org/SpecialtyCongress/2025

**EXTRACTION 2025**
November 16–20, 2025
Phoenix, Arizona, USA
www.extractionmeeting.org/2025

For a complete listing of upcoming meetings, scan this QR code or visit www.tms.org/UpcomingMeetings

# TMS UPCOMING COURSES

TMS offers a variety of online and in-person courses that span the technical interests of the global minerals, metals, and materials community.

TMS ONLINE COURSE

**HANDLING YOUR MATERIALS DATA FOR MAXIMUM IMPACT USING THE FAIR DATA PRINCIPLES**

July 26-27, 2023
www.tms.org/FAIRDataUse2023

TMS ONLINE COURSE

METALLURGICAL AND MATERIALS ENGINEERING

**PROFESSIONAL ENGINEER (PE) LICENSING EXAM REVIEW COURSE**

August 1, 3, and 8–10, 2023
www.tms.org/PEReview2023

TMS ALUMINUM COURSE

**ANODE TECHNOLOGY for the Aluminum Industry Course**

September 10-14, 2023
Manama, Kingdom of Bahrain
www.tms.org/Anode2023

TMS ALUMINUM COURSE

**CONTROL OF POTLINE SCRUBBER & FUGITIVE EMISSION for Aluminum Smelters Course**

September 10-14, 2023
Manama, Kingdom of Bahrain
www.tms.org/PSFE2023

For a complete listing of upcoming courses and other professional development events, scan this QR code or visit www.tms.org/UpcomingPDEvents

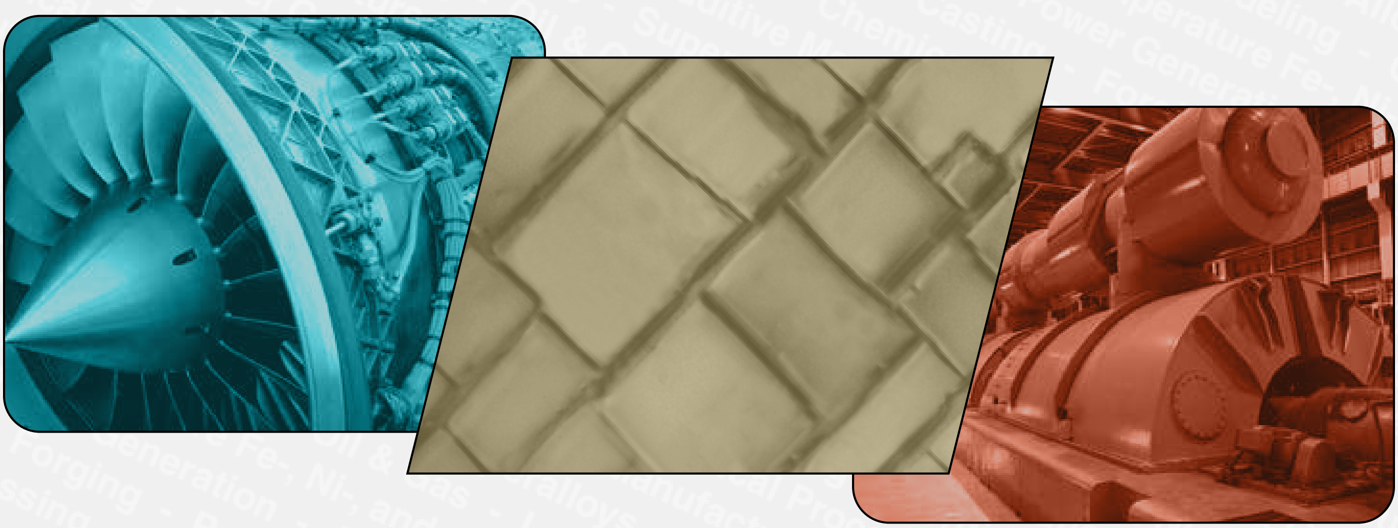
# SUPERALLOY 718 and Derivatives

MAY 14–17, 2023

Sheraton Pittsburgh Hotel at Station Square

Pittsburgh, Pennsylvania, USA

## FINAL TECHNICAL PROGRAM



www.tms.org/Superalloy718-2023

## Keynote Session

**Sunday PM**
**May 14, 2023**
**Room: Admiral**
**Location: Sheraton Pittsburgh Hotel at Station Square**

*Session Chairs:* Joel Andersson, University West; Chantal Sudbrack, National Energy Technology Laboratory

**7:00 PM Introductory Comments**

**7:05 PM Keynote**
**Meeting the Challenges of the Future by Understanding Our Past**: *Melissa Martinez*[1]; [1]ATI Metals

Spanish Philosopher George Santayana wrote in The Life of Reason, "Those who cannot remember the past are condemned to repeat it". This presentation is intended to cover portions of ATI's history related to alloy 718 and its derivatives. Company heritage and the key melting, thermomechanical processing and modeling processes will be covered. The presentation will conclude by touching on the continued advances being fueled by the growth of accessible data, characterization tools, process controls, recipe systems and the potential of machine learning.

**7:35 PM Keynote**
**Application of Computational Materials and Process Modeling to Current and Future Aero-engine Component Development and Validation**: *David Furrer*[1]; [1]Pratt & Whitney

Computational materials and process modeling capabilities have evolved over the past several decades. More recently, the Materials Genome Initiative (MGI) has provided focus on this technology and its application for rapid and lower cost materials and process development and implementation. Integrated Computational Materials Engineering (ICME) is now part of many organizations' engineering and design approaches and associated infrastructures. Nearly all current new and future materials and process technology developments do or will involve application of modeling and simulation. The evolution of materials modeling and application to mainstream and emerging supply-chain processes will be reviewed with some perspectives on what the future might hold. Special emphasis will be made to review application of ICME Alloy 718 and derivative materials and components. The use of computational modeling and simulation to material and process development is being extended to component qualification and certification. There are significant opportunities and prospects for materials and process modeling to enable further advancements in alloy design and definition, materials processing methods development, and enablement of enhanced utilization of material capabilities to new product application spaces.

## Poster Session

**Sunday PM**
**May 14, 2023**
**Room: Reflections and Waterfront**
**Location: Sheraton Pittsburgh Hotel at Station Square**

**Tensile Performance of Direct Energy Deposited IN718 and Oxide Dispersed Strengthened IN718**: *Kyle Rozman*[1]; Bruce Kang[2]; Ömer Doğan[1]; [1]National Energy Technology Laboratory; [2]West Virginia University

With needs to increase efficiencies, operational temperatures of components must increase. Oxide dispersion strengthening (ODS) has proven useful increasing the operational temperature of steels. Yttria Oxides (Y2O3) particles were mechano-chemical bonded (MCB) to IN718 powder to investigate the ability of IN718 to be strengthened by ODS particles at temperatures above 1000°C. The Y2O3 infused IN718 powder was direct energy deposited using two parameter sets for testing. Additionally, plates of standard IN718 power were built using the same deposition parameters for reference. Specimen blanks were cut from plates and tested as built, with 1080°C and 1200°C homogenization heat treatments. The initial microstructure for all four conditions was dendric with significant Mo, Nb and Ti separation. Homogenization was observed to break up the initial large Mo and Nb precipitates and form Mo, Nb and Ti rich spherical precipitates. Further the 1080°C homogenization heat treatment retained the dendritic structure while the 1200°C was observed to partially recrystallize the grain structure. Minor improvements in the tensile properties were observed at 1050°C by additions of Y2O3. This suggests with further optimization IN718 may be utilized at temperatures above 1000°C with ODS strengthening methods.

**Microstructural Studies of Heat-Treated Alloy 625 Fabricated by Laser Powder Bed Fusion**: *Karen Henry*[1]; [1]Naval Nuclear Laboratory

The ability to manufacture complex three-dimensional (3D) components on-demand by additive manufacturing (AM) methods has become increasingly attractive for use in the nuclear industry. The technology also has the potential to raise productivity by delivering parts more rapidly than conventional fabrication methods. To make the most of these benefits, it is necessary to understand process/properties/microstructure relationships. While several commercial studies have demonstrated the ability to fabricate Alloy 625 components by laser-powder bed fusion (L-PBF), these studies have also indicated as-built Alloy 625 is more susceptible to chemical segregation than conventional wrought material. Chemical homogenization of the as-built material can be achieved by heat treatment; however, deleterious phases can form when using heat treatments developed for wrought Alloy 625. This presentation will provide an overview of microstructure and mechanical properties of L-PBF Alloy 625 as a function of annealing temperature from 800 -1200°C (1472 - 2200°F). A range of characterization techniques were used including metallography, scanning electron microscopy, electron backscatter diffraction, and transmission electron microscopy to identify microstructural features associated with optimal and sub-optimal properties. Furthermore, tradeoffs in tensile behavior and Charpy absorbed energy as a result of heat treatment are discussed in relation to the microstructural evolution observed. These studies have been performed to contribute to the current understanding of process/structure/property relationships for Alloy 625 manufactured via L-PBF methods. The fundamental knowledge gained from these studies is key to using AM-fabricated metals for demanding service conditions and/or long lifetimes.

**Hot Ductility and Microstructural Evolution of Hastelloy X Produced by Laser Metal Deposition using Powder as Feedstock Material (DED-p)**: *Fabian Hanning*[1]; Daniel Benages Vila[1]; [1]University West

The microstructural evolution of Hastelloy X produced by laser metal deposition using powder as feedstock material has been investigated. A laser power of 1750W together with a scanning speed of 15mm/s and a powder feed rate of 8g/min have been used for deposition based on a DOE using single track depositions. The resulting build microstructure consists of epitaxially grown elongated grains spanning over several deposition layers. Mo-rich precipitates are present on solidification grain boundaries as continuous films. Hot ductility testing shows a narrow brittle temperature range as ductility recovery is rapid in the material, a depressed melting point is however evident as compared to equilibrium solidus of the material. The presence of hot cracks in larger build structures indicates a connection to the hot ductility signature of Hastelloy X and the presence of Mo-rich precipitates on solidification grain boundaries. Phase identification and further microstructural characterization is ongoing to identify the underlying cracking mechanism in DED-p Hastelloy X.

**(LBN - P1) Investigation of the Deformation Mechanisms for Bi-Modally Distributed γ' Precipitates in Allvac 718Plus Superalloy:** *Geeta Kumari*[1]; Carl Boehlert[1]; S Sankaran[2]; M Sundararaman[2]; [1]Michigan State University; [2]IIT Madras **(See Oral talk for more details)**

**(LBN - P2) Phase Stability and Phase Transformation Related to Nb/Ta Additions in a Ni-based Superalloy:** *Chang-Yu Hung*[1]; Stoichko Antonov[2]; Paul Jablonski[2]; Martin Detrois[2]; [1]NETL Support Contractor; [2]National Energy Technology Laboratory **(See Oral talk for more details)**

**(LBN - P3) Development of Ni Based Superalloys with Medium Entropy Alloys Concept:** *Elyorjon Jumaev*[1]; Amir Abidov[1]; Abdullo Khursanov[1]; [1]Almalyk Mining And Metallurgical Combine JSC; **(See Oral talk for more details)**

**(LBN - P4) Laser-Powder Bed Fusion Additive Manufacturing of Haynes 282 Concentrating Solar-Thermal Power (CSP) Plant Parts: Printability, Geometry, Surface, and Microstructure.:** *Junwon Seo*[1]; Nicholas Lamprinakos[1]; Anthony Rollett[1]; [1]Carnegie Mellon University **(See Oral talk for more details)**

**(LBN - P5) Phase Evolution and Tensile Deformation of IN718-René41 Graded Superalloy Fabricated by Directed Energy Deposition:** *Shenyan Huang*[1]; Ke An[2]; Chen Shen[1]; Changjie Sun[1]; Alex Kitt[3]; [1]GE Research; [2]Oak Ridge National Lab; [3]Edison Welding Institute **(See Oral talk for more details)**

**(LBN - P6) Exploring High Temperature Fretting Wear Behaviour in Wrought and Additively Manufactured DA-718 Superalloy:** *Sathisha Ch*[1]; Kesavan D[2]; Sridhar MR[1]; Arivu Y[2]; [1]GE Rerearch; [2]Indian Institute of Technology **(See Oral talk for more details)**

## Melting, Forging, and Wrought Processes

**Monday AM** **Room: Admiral**
**May 15, 2023** **Location: Sheraton Pittsburgh Hotel at Station Square**

*Session Chairs:* Andrew Wessman, The University of Arizona; Paul Jablonski, National Energy Technology Laboratory

**8:00 AM Introductory Comments**

**8:05 AM Invited**
**Segregation and Freckles in Alloy 718 and Related Alloys**: *Alec Mitchell*[1]; Stephane Hans[2]; [1]University of British Columbia; [2]Aubert Duval

The defect known as "freckle", normally identified on billet sections, has been extensively studied by modeling and experimentation. It appears to form as an upward-flowing channel due to gravitational forces acting on the segregated liquid between the growing dendrites. This liquid is less dense than the bulk liquid in many superalloys. The Nb-containing superalloys (and several other complex alloys) also form freckles, but examination shows that they are channels of liquid which has flowed in a downward direction as the segregated liquid becomes more dense than the bulk. The mechanism proposed for the "upward" freckles does not fully explain the phenomenology of the "downward" freckles in several key aspects. In this work we propose that a different series of events leads to the "downward" freckle formation; a mechanism which more fully explains the observed facts. The conclusion is that the present direction of alloy development, that of composition manipulation to reduce the segregation density changes, is likely to be only partially successful and that changes in other process parameters will also be required.

**8:35 AM Invited**
**Manufacturing Large Superalloy Pipe Bends**: *John De Barbadillo*[1]; Brian Baker[1]; [1]Special Metals

The U.S. Department of Energy, through its' office of Fossil Energy has funded programs to develop materials technology for advanced energy systems such as Advanced Ultra-supercritical (AUSC) coal-fired steam boilers and turbines. The AUSC plant would operate in the 700-800°C temperature range which requires the use of nickel-base alloys to meet design creep -rupture life requirements for welded structures. Specific components include large-diameter, heavy-wall pipes, induction bends and forged fittings. INCONEL alloy 740H is a γ'-strengthened nickel-base superalloy that was developed for this application and down-selected for the manufacturing demonstration program. Work was recently completed on the Phase 2 program under DOE contract DE-FE0025064 that had the goal of demonstrating the ability of US industrial supply chain to manufacture full-scale components. Alloy 740H contains 16-20% γ' and is sensitive to thermal stress cracking and auto-aging which affects each stage of the manufacturing operation. This paper describes the manufacture of these components at Special Metals and various subcontractors, the resulting material properties, and the mitigation of process cracking encountered in this work. The test articles are now stored at Oak Ridge National Laboratory awaiting future programs for more detailed material characterization.

**9:05 AM**

**Local Assessment of Mechanical Properties in Forged Alloy 718 Components Based on the Simulation of the Microstructure Evolution During Production**: *Christian Gruber*[1]; Peter Raninger[2]; Aleksandar Stanojevic[1]; Flora Godor[1]; Hans-Peter Gänser[2]; Stefan Marsoner[2]; Martin Stockinger[3]; [1]voestalpine Böhler Aerospace GmbH & Co KG; [2]Materials Center Leoben Forschung GmbH; [3]Montanuniversität Leoben

The characterization of local and global fracture mechanical properties is carried out with destructive testing methods and is increasingly required in the specifications of forgings. Especially in the case of alloy 718 aircraft parts, the numerical estimation of local material properties is essential for lightweight design, geometry optimization and a significant reduction of development and experimental characterization costs. This leads to a demand for numerical models to capture initial microstructural inhomogeneities, describe the forming history and reflect the local microstructure and properties of the final product.Therefore a digital twin for the complex forging process was developed in order to reproduce and evaluate the resulting local microstructure across the complete process chain. Since the microstructure determines the mechanical properties like yield stress and fracture toughness, a dedicated model was implemented to describe the local evolution of the relevant microstructural features.

**9:25 AM**

**Towards Enhancing Hot Tooling to Form High $\gamma'$- Superalloys:** *Arthi Vaasudevan*[1]; Enjuscha Fischer[2]; Thomas Witulski[2]; Catherine Rae[1]; Enrique Galindo-Nava[3]; [1]University of Cambridge; [2]Otto Fuchs; [3]University College London

Ni-superalloys are overwhelmingly relied upon in aerospace, power generation and automotive sectors, yet, are seldom considered as materials for hot tooling. The operational conditions of hot forming dies potentially exceed those experienced by aircraft turbine discs. Fortunately, new disc alloys have pronounced elevated temperature capabilities and the current study focuses on implementing two advanced alloys, VDM 780 and Haynes 282 (H282) as hot tool materials. There is, however, inadequate evidence of their life-limiting properties and mechanisms in the in-service temperature regime of 700 – 900 °C. Thus, realistic operating conditions were replicated by combining interrupted short and long-term thermal-mechanical tests. To begin, isothermal ageing in the furnace, assisted in comparing the extent of $\gamma'$ coarsening between the alloys, and subsequent in-situ ageing and compression testing reflected the accompanying loss in strength. Compression creep testing at stresses near appropriate yield point (250 – 750 MPa) revealed accelerated creep rates at high temperatures with creep behaviour directly transitioning from primary to tertiary regime, the steady-state creep region being absent. The results indicated that even as exposure duration, temperature, and applied stress all influence microstructural evolution, the exposure temperature was pivotal in determining the effective life of these $\gamma'$-strengthened alloys. Dissolution kinetics of $\gamma'$ around near-solvus temperatures was crucial and was governed by elemental additions. As a result, the research paves the way for better understanding and design of superalloys with improved thermal integrity for hot tooling.

**9:45 AM Break**

**10:15 AM Invited**

**The Effect of Microstructure on the Strength of VDM Alloy 780**: *Mark Hardy*[1]; Masood Hafez[2]; Christos Argyrakis[1]; Ross Buckingham[1]; Andrea La Monaca[1]; Bodo Gehrmann[2]; [1]Rolls-Royce Plc; [2]VDM Metals International GmbH

Nickel-base alloys have been developed, which offer higher temperature capability from ingot metallurgy than Alloy 718. However, these alloys have higher volume fractions of gamma prime precipitates, require further processing steps and consequently, have higher material processing costs, show a greater propensity for freckle and are not readily electron beam (EB) welded. There is an appetite for an alloy that shows improved forgeability, that is EB weldable and can be used at temperatures of up to 700˚C. This study examines VDM Alloy 780, first using laboratory compression tests and heat treatment experiments to determine suitable thermo-mechanical processing (TMP) conditions. Subsequently, pancakes that were 18-20 mm in height and 137-144 mm in diameter were forged from 70 mm in diameter x 76 mm high bars, which were extracted from mid-radius locations of 8-inch diameter billet. From these, test piece blanks were extracted, and heat treated for tensile tests at temperatures between 20 and 750˚C. Results from these tests were compared with microstructure and data from 30 mm thick pancake forgings that received different TMP conditions from earlier work at VDM Metals International. The combined experiences provide an insight into the effect of forging and heat treatment conditions on the microstructure and tensile test properties of VDM Alloy 780. They show that strength levels for fine grain Alloy 720Li can be achieved if specific sizes of gamma grains and gamma prime precipitates can be produced.

**10:45 AM**

**In-situ HT-EBSD Measurements and Calibration of Multi-class Model for Grain Growth and $\delta$-phase Dissolution Kinetics of Alloy 718**: *Peter Raninger*[1]; Christian Gruber[2]; Walter Costin[1]; Aleksandar Stanojevic[2]; Ernst Kozeschnik[3]; Martin Stockinger[4]; [1]Materials Center Leoben Forschung GmbH; [2]voestalpine BÖHLER Aerospace GmbH & Co KG; [3]TU Wien, Institute of Materials Science and Technology; [4]Montanuniversität Leoben

In the aerospace industry the microstructure evolution of alloy 718 during forging and heat treatment and the resulting mechanical properties are decisive in view of the high quality requirements of aircraft components. During thermomechanical processing the temperature control and adiabatic heating lead to grain growth and, if $\delta$-solvus temperature is exceeded, to the dissolution of the $\delta$-phase, which further results in accelerated grain growth. To describe the history of the microstructure in terms of grain size during and after forging or heat treatment an existing multi-class microstructure model is optimized with focus on grain growth kinetics and parameterized by experimental results. The multi-class model describes the microstructure and the coarsening during processing more precisely in terms of the grain size distribution than previously used single-class models. This is crucial in order to be able to predict mechanical properties such as tensile strength, fracture toughness and creep resistance, which are topics for other but related work. The experimental data basis for the presented work stems from in-situ high-temperature electron backscatter diffraction (HT-EBSD) investigations and supporting experiments. The experimental setup and the results are discussed in detail.

**11:05 AM**

**Abnormal Grain Growth Maps of Wrought Ni-base Superalloys**: *Michael Fahrmann*[1]; David Metzler[1]; [1]Haynes International

Abnormal grain growth (AGG) upon sub-solvus annealing of hot worked material has been reported for a number of cast & wrought and powder metallurgy superalloys, irrespective of the nature of the grain boundary pinning phase (e.g., delta phase in alloy 718 or gamma-prime phase in Rene 88DT). A common feature are large overgrown grains that exhibit the original precipitate distribution as well as a high density of annealing twins (Fig. 1). It has also been established that these phenomena occur only for certain hot working conditions. Identifying these special hot working conditions a priori has proven difficult.Taking a more industry-oriented approach, we studied the (sub-solvus) annealing response of a sizeable number of hot-worked product forms of two very different wrought Ni-base superalloys: HAYNES 244 alloy and HAYNES 233 alloy. The main grain boundary pinning phase in 244 alloy is an intermetallic Mo-rich phase with a solvus temperature of approximately 2050oF (1120oC). In contrast, the key pinning phase in 233 alloy are secondary Cr- and Mo-rich carbides that precipitate in sufficient quantities below 2100oF (1149oC).

**11:25 AM**

**Alloy Design and Development of a Novel Ni-Co Based Superalloy GH4251**: *Hongyao Yu*[1]; Hailong Qin[1]; Xizhen Chen[1]; Guangbao Sun[1]; Bin Gan[1]; Yu Gu[2]; Teng An[2]; Jinglong Qu[2]; Jinhui Du[2]; Zhongnan Bi[1]; [1]Beijing Key Laboratory of Advanced High Temperature Materials; [2]Gaona Aero Material Co. Ltd.

The need of developing new high temperature materials has increased significantly in the last decade owing to the demand of higher engine operating temperature. This demand has motivated the development of a new Ni-Co based superalloy GH4251 with service temperature up to 700°C~800°C. Based on disk used alloy U720Li, the GH4251 alloy is designed by adjusting the content of Co, Cr, Ti, Nb and other elements. On the one hand, by increasing the Co content to 25 wt.%, the stacking fault energy is effectively reduced, which makes it easy to form nano-twins and other substructures that strengthening the alloy together with precipitates. The yield strengths of the alloy can achieve 1100MPa at 750 and the creep-rupture life is more than 500h at 750 under 530MPa with fine grain size (ASTM 8), which is superior than U720Li. On the other hand, a certain Nb element is added to replace Ti element, which can reduce the solvus temperature and its precipitating dynamic, along with a changed thermal deformation behavior caused by lower stacking fault energy, leading to a significant better hot work ability and weld ability compared with U720Li. Beside being used as disk or ring forgings, this novel GH4251 alloy can also be well processed by additive manufacturing due to its low cracking tendency. Keywords: Ni-Co based superalloy, alloy design, disk forging, additive manufacturing

**11:45 AM Conference Luncheon**

## Environmental Behavior & Protection I

**Monday PM**
**May 15, 2023**
**at Station Square**

**Room: Admiral**
**Location: Sheraton Pittsburgh Hotel**

*Session Chairs:* Eric Ott, GE Additive; Ian Dempster, Wyman Gordon /PPC

**1:00 PM Introductory Comments**

**1:05 PM Invited**

**Compatibility of Wrought Superalloys with Supercritical $CO_2$**: *Bruce Pint*[1]; [1]Oak Ridge National Laboratory

Supercritical $CO_2$ ($sCO_2$) power cycles, particularly direct-fired cycles, have the possibility of revolutionizing clean fossil energy. To maximize efficiency, the peak temperatures are expected to be above 700°C and, therefore, require the use of wrought superalloys for structural components. For the highest temperature applications >750°C, precipitation strengthened alloys such as 740 and 282 have been shown to have good compatibility in $sCO_2$ without impurities (i.e. indirect cycles). At temperatures <650°C, it would be desirable to use less expensive alloys, however, steels are known to be susceptible to carburization, especially with $O_2$ and $H_2O$ impurities in 300 bar $sCO_2$. Laboratory autoclave results with and without $O_2$ and $H_2O$ impurities typical of direct-fired cycles are being collected on a range of alloys including less expensive Ni-based alloys like 825 and 120 and advanced austenitic steels like 709. Their relative performance is being compared after 1-2 kh exposures at 600°-800°C and reaction products are being characterized using a variety of characterization techniques to study the reaction products and quantify the C content. Research sponsored by the U.S. Department of Energy, Office of Fossil Energy and Carbon Management.

**1:35 PM**

**Long Term Thermal Stability and Oxidation Resistance of HAYNES 233 Alloy**: *Lee Pike*[1]; Bingtao Li[1]; [1]Haynes International Inc

HAYNES® 233™ alloy was recently developed to provide the market with a readily fabricable alloy combining the properties of high creep strength and excellent oxidation resistance to temperatures of 2000°F (1093°C) and above. This combination of properties is desirable for a number of high temperature applications, including hot gas components in aerospace and industrial gas turbines, industrial heating fixtures and sensors, and various structural components in the emerging technology market. The development and key features of 233 alloy have been detailed elsewhere [L.M. Pike et al., Journal of Materials Engineering and Performance, Vol. 28 (4), 2019, pp. 1929-1935].

## Microstructure & Properties

**Monday PM**
**May 15, 2023**
**at Station Square**

**Room: Admiral**
**Location: Sheraton Pittsburgh Hotel**

*Session Chairs:* Eric Ott, GE Additive; Ian Dempster, Wyman Gordon /PPC

**1:55 PM**

**Tailoring the $\gamma$- $\gamma'$-$\gamma''$ Dual Superlattice Microstructure of Ni-based Superalloy IN725 by High Temperature Aging and Nb/Ta Additions for Superior Creep Properties**: *Stoichko Antonov*[1]; Chang-Yu Hung[1]; Jeffrey A. Hawk[1]; Paul D. Jablonski[1]; Martin Detrois[1]; [1]National Energy Technology Laboratory

Next generation energy systems require superior resistance to creep deformation due to the considerably pro-longed exposure times at operating stress and temperature. To improve the elevated temperature properties of Inconel alloy 725 (IN725), a corrosion resistant alloy, several variants with different Ti/Al ratio and judicious amounts of Nb and Ta were made. Furthermore, a high temperature aging (HTA) heat treatment – where a higher temperature first step was used to promote precipitate phase formation - was explored. These adjustments allowed tailoring of the amount and type of precipitate strengthening which led to significant increases in time to failure. The Ti/Al ratio was used to design alloys with preferential formation of $\gamma'$ or $\gamma''$ precipitates. Compact morphology precipitates, which have superior coarsening resistance, were formed in alloys with a low Ti/Al ratio. The HTA increased the creep life of various alloy formulations up to a maximum improvement of 371% as compared to the standard aging heat treatment. The Nb and Ta additions had a similar effect on increasing creep life by promoting and stabilizing $\gamma''$ precipitation. The positive effect of the additions was even more pronounced when coupled with the HTA. Although the low Ti/Al ratio resulted in favorable microstructures, the effect on the creep life was less evident than that of the HTA. The findings of this study enable design of dual superlattice alloys through microstructural engineering that yields superior performance alloys and can be applied to a wide range of alloys in the 718 and derivative family.

**2:15 PM**
**Investigating Deformation Mechanisms in a Creep-deformed 718-variant Superalloy**: *Semanti Mukhopadhyay*[1]; Hariharan Sriram[1]; Richard DiDomizio[2]; Andrew Detor[2]; Robert Hayes[3]; Yunzhi Wang[1]; Michael Mills[1]; [1]The Ohio State University; [2]GE Global Research Center; [3]Metals Technology Inc.

Improving the efficiency of a land-based industrial gas turbine ultimately relies on novel alloy development for the turbine wheel. However, this alloy development task is challenging because it necessitates higher temperature capabilities along with phase stability during low cooling rate processing of a full-scale wheel. These challenges make 718-based variant alloys an attractive choice because of their superior thermal stability. However, to develop these novel alloys, their deformation behavior must also be accounted for. Thus, in the present work, we investigate the microstructure and creep deformation behavior of a novel 718-variant alloy. Detailed microstructural characterization reveals that the phase fraction of the $\gamma''$ phase in the variant alloy is much lower than 718. In addition, the presence of Mo causes detrimental grain boundary precipitation which leads to final failure during tensile creep deformation. The variant alloy accumulates creep strain faster than 718, ultimately fracturing at 0.6% strain. Finally, a detailed characterization of the deformed variant alloy reveals extensive microtwinning.

**2:35 PM**
**Effect of Pre-straining on the Tensile and Stress-rupture Properties of a Novel Ni-Co Based Superalloy**: *Bin Gan*[1]; Zhongnan Bi[1]; Cheng Yang[2]; Hongyao Yu[1]; Rui Hu[2]; Jinhui Du[1]; [1]Central Iron and Steel Research Institute; [2]Northwestern Polytechnical University

Ni-base superalloys are well suited for aero engine and power generation system, as they possess an extraordinary combination of excellent high temperature mechanical properties, a long-term structural integrity and microstructural stability, and robustness to surface degradation in highly corrosive and oxidizing environment. For most Ni-base superalloys, high strength is mainly derived from precipitation hardening by intermetallic compounds. While the recent development of Ni-Co based superalloys demonstrates that with the addition of Co content, the stacking fault energy could be effectively reduced that will assist the formation of microtwins or nanotwins. In the present study, a Ni-Co based superalloy with a chemistry of Ni-20.0Co-16.5Cr-5.0W-2.5Al-2.5Ti-2.5Nb-0.02C (wt.%) was produced by a vacuum induction melting and electro slag remelting. The cast ingot was homogenized and then forged into a rod with a diameter of 150 mm. The rod was solution treated at 1080 °C for 4 h followed by water quenching to room temperature. The influences of pre-straining temperature and pre-straining amount on the tensile properties of Ni-Co based superalloy at different temperatures as well as the stress-rupture properties at elevated temperatures were investigated. Dislocations are commonly formed at room temperature, while stacking faults and microtwins or nanotwins could be formed at elevated temperatures. The tensile testing results reveal that the application of pre-straining could effectively increase the yield strength of Ni-Co based superalloys while retaining a decent level of stress-rupture properties. The assimilated body of knowledge will give insight to the further alloy development for the fastener applications.

**2:55 PM Break**

**3:15 PM Invited**
**Preferential $\gamma'$ Precipitation on Coherent Annealing Twin Boundaries in Alloy 718**: Semanti Mukhopadhyay[1]; Fei Xue[2]; Hariharan Sriram[1]; Robert Hayes[3]; Emmanuelle Marquis[2]; Yunzhi Wang[1]; *Michael Mills*[1]; [1]The Ohio State University; [2]University of Michigan; [3]Metals Technology Inc.

Early strain localization parallel and adjacent to annealing twin boundaries (ATBs) have been reported in several superalloys. While strain localization is generally attributed to local shear stresses developed near ATBs due to elastic anisotropy, it is presently unclear if local microstructural features near ATBs might also play an important role. Precipitate-free zones (PFZ) parallel to ATBs in a $\gamma''$–strengthened alloy 945X have been reported and were found to influence strain localization in the alloy greatly. However, it is unclear if such PFZs near ATBs occur in other superalloys, potentially influencing strain localization. The present work investigates microstructures near ATBs in a Ni-based superalloy - 718, strengthened by both $\gamma'$ and $\gamma''$ phases. This work aims to characterize the precipitates present at the ATBs and to explore if a microstructural cause for strain localization exists in this alloy. Based on our characterization experiments, Alloy 718 shows a high density of herringbone-like γ^'-γ'' precipitates at ATBs. However, the ATBs exhibit a much higher fraction of $\gamma'$ (25.3±2.8%) than $\gamma''$ (18.4±2.4%), ultimately causing the coprecipitate fraction at ATBs to be as high as 43%. We also report a local HCP-phase at the ATBs within $\gamma'$ precipitates exhibiting Nb segregation and Al depletion. On the contrary, no appreciable change in the ATB composition was observed within $\gamma''$. Finally, our characterization experiments also reveal precipitate-free zones parallel and adjacent to the ATBs in alloy 718.

**3:45 PM**
**Effect of Short-term Isothermal Exposure on the Ductility Signature of Waspaloy in the Temperature Range of 750-950°C – A Comparison with Haynes® 282®**: *Fabian Hanning*[1]; Abdul Khan[2]; Olanrewaju Ojo[2]; Joel Andersson[1]; [1]University West; [2]University of Manitoba

The evolution of microstructure and ductility has been investigated for Waspaloy after isothermal exposure between 5 and 1800s at 750 to 950°C. Gamma prime ($\gamma'$) with 1.7 nm diameter is found in the mill-annealed condition, while precipitate-growth following a t1/3 relationship is observed for isothermal exposure. Grain boundary carbide networks are formed during isothermal exposure together with a rapid hardness increase. A drop in ductility is observed with the lowest values at 750 and 800°C. Further ductility reduction during isothermal exposure correlates with the rapid hardness increase of Waspaloy. While grain boundary strengthening can compensate for the moderate age hardening observed for Haynes® 282®, the more rapid hardness increase due to $\gamma'$ precipitation appears to be the dominating effect on ductility in Waspaloy. Carbide precipitation and growth kinetics are slower than those of Haynes® 282®, further increasing the relative effect of age hardening reactions on the ductility of Waspaloy.

**4:05 PM**

**(LBN - P1) Investigation of the Deformation Mechanisms for Bi-Modally Distributed γ' Precipitates in Allvac 718Plus Superalloy**: *Geeta Kumari*[1]; Carl Boehlert[1]; S Sankaran[2]; M Sundararaman[2]; [1]Michigan State University; [2]IIT Madras

Alloy Allvac 718Plus is a relatively new superalloy developed to improve the properties of the widely-used superalloy Inconel 718 (IN 718). The strength of IN 718 significantly decreases at temperatures greater than 650˚C due to the transformation of the metastable γ' (tetragonal, D022 structure) phase into the δ phase (orthorhombic, D0a structure). Allvac 718Plus, which was designed to address this issue, exhibits service temperature up to 704˚C (55˚C more than that for IN 718 and close to that for Waspaloy) and its formability is similar to IN 718 and better than that for Waspaloy. Allvac 718Plus contains γ' precipitates as a major strengthening phase along with some grain boundary δ phase. The volume fraction and size of the γ' and the δ phases are controlled by solution treatment followed by aging.

**4:25 PM**

**(LBN - P2) Phase Stability and Phase Transformation Related to Nb/Ta Additions in a Ni-based Superalloy**: *Chang-Yu Hung*[1]; Stoichko Antonov[2]; Paul Jablonski[2]; Martin Detrois[2]; [1]NETL Support Contractor; [2]National Energy Technology Laboratory

Alloys based on Inconel 725, and with elevated levels of Nb and Ta, have been designed for application in environments requiring high strength and corrosion resistance at elevated temperatures. The present study further examines the phase stability and subsequent phase transformation in those alloys following aging and long-term exposure of up to 10,000 hours at 700 ℃. Changes in the microstructure were characterized using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Two alloy bases with different Ti/Al ratio were considered. Following aging, the Nb/Ta additions favor the development of γ'/γ'' co-precipitates in the low Ti/Al ratio alloy, whereas the high Ti/Al ratio counterpart only contained γ'' precipitates. Upon 10,000 hours of exposure, complex geometrical closed-packed (GCP) phases formed from the γ'/γ'' co-precipitates in a layer-by-layer manner, i.e., the plate-like δ phase precipitates became decorated by blocky α-Cr and enveloped by a wavy γ' film. Increasing the concentration of Nb and/or Ta did not change the basic characteristic of this phase transformation; however, the precipitate number density increased in the grain interior. The underlying phase transformation behavior of the layer-by-layer structure is likely initiating from the γ''-δ phase transition that ejects Cr, Al, and Ti into the neighboring phases, thus resulting in local phase separation into α-Cr and γ' thin film. This phase transformation process had a significant impact on the phase morphologies with experimental results contradicting those from computational prediction.

**4:45 PM**

**(LBN - P3) Development of Ni Based Superalloys with Medium Entropy Alloys Concept**: *Elyorjon Jumaev*[1]; Amir Abidov[1]; Abdullo Khursanov[1]; [1]Almalyk Mining And Metallurgical Combine JSC

The Ni-based Ni48(CrAlFe)15Ti7 and Ni48(CrCuFe)12.5Al7.5Ti7 medium entropy alloys were designed by Thermocalc software and fabricated using arc suction casting method having Ti-guttered in an argon atmosphere. The effect of Cu element on phase evolution, microstructure, and mechanical characteristics was investigated. Detailed characterization reveals that the alloys exhibit dual microstructures consisting of BCC dendrite and FCC interdendritic in Ni48(CrAlFe)15Ti7 alloy meanwhile, rectangular shape morphology (γ + γ′ phases) in Cu addition Ni48(CrCuFe)12.5Al7.5Ti7 alloy. The result of the mechanical property test illustrates that alloys present outstanding strength at a high-temperature range compared to Inconel 713C and excellent ductility with the microstructure of γ + γ′ phases.

**5:05 PM**

**Characterization of γ′ Precipitation Behavior in Additively Manufactured IN738LC Superalloy via In-situ Small-angle Neutron Scattering**: *Hailong Qin*[1]; Ying Tao[2]; Songyi Shi[1]; Hongyao Yu[1]; Jinli Xie[1]; Zhongnan Bi[1]; [1]Central Iron and Steel Research Institute; [2]University of Science and Technology Beijing

IN738LC is a typical high-end Ni-based superalloy developed to meet the needs for harsh working environment (~980 ℃). The total amount of Al and Ti in its composition is over 6.8 wt%, which cause the intensive susceptibility to strain age cracking (SAC). Particularly, γ′ phase precipitates rapidly during the subsequent heating process, resulting in the volume shrinkage and local stress concentration. In the present study, quantitative evaluation of the size and volume fraction of γ′ particles have been studied f by Small-Angle Neutron Scattering (SANS) and FE-SEM in additively manufactured IN738LC Superalloy employing isothermal heat treatment conditions of 850 ℃. The results shows that there is no observable γ′ precipitation in the as-deposited alloy, while a large number of small cellular and striated sub-structures can be characterized with widths ranging from 0.5 to 1.5 m. During the 850℃ isothermal heat treatment, the γ′ phase rapidly precipitates in large quantities and shows a unimodal irregular sphere-like shape. The average size of the γ′ particles increase on prolonging the time: After isothermal heat treatment for 10 min, the average particle size is 72.5 nm; and it reaches 137.3 nm when ageing time is 120 min. However, the volume fraction of γ′ phase do not change with the extension of isothermal heat treatment time, which reaches about 40% after 10 minutes, which is quite different from that prepared by traditional casting process. Key words: Small-Angle Neutron Scattering, IN738LC; Precipitation behavior; Additive manufacturing.

## Modeling & Data Analytics

**Tuesday AM**
**May 16, 2023**
**at Station Square**

**Room: Admiral**
**Location: Sheraton Pittsburgh Hotel**

*Session Chairs:* Michael Fahrmann, Haynes International; Chantal Sudbrack, National Energy Technology Laboratory

**8:00 AM Introductory Comments**

**8:05 AM Invited**
**Application of CALPHAD Based Tools to Modeling of Alloy 718:** *Paul Mason*[1]; Carl-Magnus Lancelot[2]; Taiwu Yu[1]; Thomas Barkar[2]; Adam Hope[1]; [1]Thermo-Calc Software Inc; [2]Thermo-Calc Software AB

For forty years, CALPHAD based tools have been used to design alloys of industrial importance and gain insight into composition-process-structure-property relationships. This presentation will illustrate how such tools can be applied to alloy 718 and its derivatives for applications relevant to solidification, heat treatment and additive manufacturing. Examples will be given of calculations made under equilibrium and non-equilibrium conditions to predict phase stability, phase transformation temperatures and thermophysical properties, such as density, coefficients of thermal expansion and thermal conductivity which can be used in an ICME framework. The simulation of precipitation kinetics for non-isothermal heat treatments to predict volume fraction, coarsening and average size of precipitates will also be described along with how such calculations can be extended to model yield strength. Finally, examples will be given of how CALPHAD can be incorporated to improve the accuracy of finite element simulations for additive manufacturing.

**8:35 AM**
**Multi-variate Process Models for Predicting Site-specific Microstructure and Properties of Inconel 706 Forgings**: Nishan Senanayake[1]; Reese Capo[1]; Tiffany Dux[2]; *Jennifer Carter*[1]; [1]Case Western Reserve University; [2]Howmet Aerospace Forgings

The performance of Inconel 706 forgings hinges on the careful design of the thermomechanical history to promote distributions of oft-dependent microstructural features. Establishing predictive process-structure-property (PSP) models to tailor manufacturing routes requires immense cost due to the time and cost-consuming tasks of quantifying statistically significant observations of different predictor and property metrics. Power analysis indicates that for a simple multivariate linear model of one performance metric, P, dependent on six input process predictors (k = 6) (i.e., P = f(k1, k2, … k6)) with 80% predictive power would require over 120 observations; to predict n performance metrics (P1, P2, …Pn), a statistical study protocol would require 120n observations (ANOVA would require 175n). Most processing and microstructure predictors and property metrics are observed/measured destructively. This motivates the development of high-throughput measurements of both experimental approaches and physics-based simulations that enable dimensionality reduction of the predictor space (i.e., time and temperature are not independent predictors of diffusion-mediated metrics such as precipitate fraction). In this paper, we highlight how thermal profiles from finite element simulations (processing predictors) can establish time-temperature boundary conditions for CALPHAD predictions of the combined $\gamma'$, $\gamma''$ precipitate distribution in Inconel 706 (structure predictors). Experimental observations of these precipitate distributions allow for the tailoring of the CALPHAD interfacial energy. In this manner, a 25x reduction in the number of physical observations of $\gamma'$ and $\gamma''$ distribution (100 to 4) still results in site-specific PSP models of forged parts with 80% predictive power.

**8:55 AM**
**Linking Stress Rupture Properties to Processing Parameters of HAYNES® 718 Nickel Superalloy via Machine Learning**: David Farache[1]; George Nishibuchi[1]; John Gulley[1]; Sebastian Elizondo[1]; Alex Post[2]; Kyle Stubbs[2]; Keith Kruger[2]; Arun Mannodi-Kanakkithodi[1]; *Michael Titus*[1]; [1]Purdue University; [2]Haynes International

Requirements of stress rupture life and elongation of nickel alloy 718 are often prescribed by specification AMS5596 or AMS5663, which broadly state that the stress rupture life and elongation must exceed 23 h and 4% at 649 °C (1200 °F), respectively. Variability in product stress-rupture life can range from less than 2 h to more than 1000 h, which can cause significant delays for testing, shipping, and delivery of product. In this work, we predict the stress-rupture life and elongation of HAYNES® 718 sheet product utilizing machine learning models. The models utilized data from 448 lots of material and inputs including composition, room temperature mechanical property data, processing data such as finish gauge, total reduction, final reduction, rule of mixture average properties including density, electronegativity, and bulk and Young's modulus, and environmental factors such as daily maximum and minimum temperatures and humidity. Different sets of input features were chosen from the highest absolute Pearson correlation values, Gini coefficient, SHAP, and SISSO analysis, and four separate random forest models were trained using an 80%-20% split between training and testing data. The resulting mean squared errors of best performing models of stress-rupture life and elongations were 102 h and 7.2%, respectively. Input features of highest importance were observed to be room temperature tensile properties, finish gauge, and tramp elements such as Co, P, and Si. These models can be utilized to accelerate acceptance testing of 718 product by identifying product exhibiting anomalously low or high creep rupture life and elongation.

**9:15 AM**
**Competitor Ti-comprising Refractory High Entropy Alloys to Superalloy 718 for Aeroengine Applications**: *Tanjore Jayaraman*[1]; Ramachandra Canumalla[2]; [1]University of Michigan-Dearborn; [2]Weldaloy Specialty Forgings

Superalloy 718 and its derivatives are ubiquitous to aeroengine applications owing to their excellent formability, ultra-high-strength, good thermal stability, adequate weldability, and so forth. However, currently, the relatively lighter Ti-comprising high entropy alloys, having a unique combination of ambient and elevated temperature mechanical properties and corrosion resistance, are projected as potential competitors to superalloy 718 and their derivatives. We analyzed the data of several Ti-comprising high entropy alloys available in the literature by a novel combination of multiple attribute decision making (MADM) and advanced statistics—hierarchical clustering (HC) and principal component analysis (PCA)—to identify the probable competitors to superalloy 718 for aeroengine applications. The ranks assigned by six MADMs, chosen for the investigation, including ARAS (additive ratio assessment), MEW (Multiplicative exponent weighing), OCRA (operational competitiveness ratio), ROVM (range of value method), SAW (simple additive method), and WEDBA (weighted Euclidean distance-based approach), were concordant. PCA consolidated the MADM ranks of the alloys, while HC identified similar top-ranked alloys. The analyses identify the Ti-comprising high entropy alloys having properties comparable to superalloy 718 and reveal the potential of the Ti-comprising high entropy alloys to substitute critical parts in aeroengines.

**9:35 AM**
**An ICME Framework to Predict the Microstructure and Yield Strength of INCONEL 718 for Different Heat Treatments**: *Taiwu Yu*[1]; Thomas Barkar[2]; Carl-Magnus Lancelot[2]; Paul Mason[1]; [1]Thermo-Calc Software Inc; [2]Thermo-Calc Software AB

The superalloy 718 stands out for its excellent manufacturability and strength at ambient temperature. In most studies currently, people tried to improve the mechanical properties of the 718 alloy through adjusting different processing conditions such as solution annealing temperature, aging temperature and holding time, and the amount of intermediate cold work. Such study could be expensive and time consuming. In this study, we would like to build an ICME framework to investigate the microstructural stability and mechanical properties through CALPHAD method as well as TC-PRISMA tools incorporated in Thermo-Calc Software. In this study, the formation of secondary phases such as gamma prime-phase, gamma double prime-phase, and delta-phase as well as consequent mechanical properties of the microstructure with respect to the processed conditions has been studied. The evolution of precipitates can be characterized by TC-PRISMA tool with TC databases. Furthermore, Reppich's model is applied to predict the precipitate strengthening of the alloy, and grain boundary and solid solution strengthening mechanisms are also quantified to predict the yield strength with respect to different processing. The framework can be built by the Thermo-Calc software to design alloys in terms of the processing to obtain properties needed.

**9:55 AM Break**

## Environmental Behavior & Protection II

**Tuesday AM**
**May 16, 2023**
**Room: Admiral**
**Location: Sheraton Pittsburgh Hotel at Station Square**

*Session Chairs:* Michael Fahrmann, Haynes International; Chantal Sudbrack, National Energy Technology Laboratory

**10:25 AM Invited**
**Effects of High-temperature Oxidation on Fatigue Life of Additive-manufactured Alloy 625**: Grace de Leon Nope[1]; Guofeng Wang[1]; Juan Manuel Alvarado Orozco[2]; *Brian Gleeson*[1]; [1]University of Pittsburgh; [2]CIDESI (Centro de Ingenieria y Desarrollo Industrial)

The effect of thermal oxidation on fatigue performance of additive-manufactured Alloy 625 was studied. Uniaxial fatigue tests at room temperature were performed after exposures at 800°C for 24h, 300h, and 1000h in either air or argon. Exposures in air resulted in chromia-scale formation, internal attack, and subsurface precipitates. Fatigue results indicated a life reduction for the oxidized additive manufactured samples. By contrast, any of the prior high-temperature exposures were not detrimental to the performance of the wrought Alloy 625. Fractographic analysis indicated that crack initiation occurred in the subsurface, closer to the edge, for exposures to oxidation compared to those exposed to argon. The observed behavior in AM-processed samples is attributed to the exacerbation of subsurface defects during oxidation (i.e., internal attack, decohesion in the scale, and subsurface precipitates). These defects act as preferential crack-initiation sites, leading to reduce a reduction in fatigue life.

**10:55 AM**
**Subcritical Crack Growth of 718 Alloy in Marine Exposure Conditions and Microstructural Modeling**: *Attilio Arcari*[1]; Derek Horton[1]; Mohammed Zikry[2]; M. Chen[2]; [1]Naval Research Laboratory; [2]North Carolina State University

UNS N07718 is widely used in marine service applications and under a variety of conditions: alternate immersion, different levels of cathodic protection, freely corroding galvanic couples. Environmentally assisted cracking can significantly affect the performance of this alloy and constraint design as it needs to account for subcritical crack growth in service. We measured subcritical crack growth rates and thresholds in different environmental conditions for two different heat treatments of UNS 07718. The first heat treatment, following AMS 5664 is typically used in the aircraft industry, and the second, following API 6A, is used in the marine and oil and gas industry. Other materials studied are UNS R30035 and UNS S66286. The material environmentally assisted cracking was studied under alternate immersion to natural seawater, and under cathodic protection in natural seawater.Microstructural modeling of simultaneous fracture nucleation and propagation modes is presented to further understand and predict how precipitates, their volume fraction, morphology, and properties, on the evolution and accumulation of dislocation-densities within the microstructure affect the fracture process at different physical scales. Furthermore, a dislocation-density crystalline plasticity formulation is coupled to a hydrogen diffusion approach and the nonlinear fracture framework to further understand how cracks and dislocation-densities diffuse and interact.

**11:15 AM**
**Hot Corrosion Behavior of a GH4720Li Disk Superalloy at 700 ℃**: *Teng An*[1]; Fangzhen Duan[2]; Yu Gu[2]; Yuting Shi[2]; Di Wang[2]; Jinglong Qu[1]; Zhongnan Bi[1]; Jinhui Du[1]; [1]Central Iron & Steel Research Institute; [2]Beijing GAONA Materials & Technology Co., LTD

The nickel-based superalloy disk components in the turbine sections were subjected to Type II hot corrosion damage in the sulfur-containing salt contaminants at 650℃–750℃. The alloy GH4720Li with different grain sizes was corroded in a mixture of sulfates (25% NaCl + 75% Na2SO4) at 700℃ for 200 h, and the microstructure evolution was investigated. The experimental results showed that when the grain size increased from 15.9 to 127 μm, the mass loss decreased by 96%, and the corrosion layer thickness decreased by 44%. The hot corrosion resistance increased with the increasing grain size, and the corrosion failure mechanisms changed from pitting corrosion to uniform corrosion. The corrosion layer comprised NiCr2O4, Al2O3, CoO, TiO, Ni3S2, and CoS2. The oxide layer, Ni/Co-rich layer, and S-rich layer were stratified and sequentially located on the alloy GH4720Li surface. The corrosion behavior was accelerated by the triangular grain boundaries (GBs) and $\gamma'$ phase, the segregation behavior of Cr elements in the GBs, as well as the $\gamma'$ phase formation promoted the tendencies for pit nucleation in the fine-grained structure. In contrast, the Ni/Co-rich layer provided better resistance to hot corrosion and was easier to form on the surface of the coarse-grained structure. The sulfide-oxidation cycle mechanism could well describe the hot corrosion behavior of the disk superalloy.

**11:35 AM Conference Luncheon**

## High Temperature Fe-, Ni- , and Co- Alloys

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|---|---|
| **Tuesday PM** | **Room: Admiral** |
| **May 16, 2023** | **Location: Sheraton Pittsburgh Hotel at Station Square** |

*Session Chairs:* Tim Smith, NASA Glenn Research Center; Kevin Bockenstedt, ATI Specialty Materials

**1:00 PM Introductory Comments**

**1:05 PM Invited**
**Factors Influencing Propensity for Stress Relaxation Cracking in Inconel ® Alloy 740H® and Practical Guidance for Applications**: John Shingledecker[1]; John Siefert[1]; *Tapasvi Lolla*[1]; John Dupont[2]; John DeBarbadillo[3]; Ronnie Gollihue[3]; [1]Electric Power Research Institute; [2]Lehigh University; [3]Special Metals Corporation

Inconel® Alloy 740H® (UNS N07740) was the first age-hardenable nickel-based alloy approved by the ASME Boiler & Pressure Vessel Code for use in pressure-boundary applications. In recent years, advanced energy systems such as supercritical CO2 power cycles have utilized alloy 740H in large demonstration projects driven by the requirement for higher fluid temperatures and pressures. Stress relaxation cracking (SRxC) following post-weld heat-treatment (PWHT), also known as strain age cracking (SAC), has been identified in a limited number of weldments during these industrial builds resulting in focused research to further clarify factors influencing this cracking tendency. This paper will summarize some of the findings from shop and field fabrication leading to successful welds and characteristics of observed SRxC. Laboratory experiments supported by microstructural characterization will be presented to highlight the importance of variables such as strain, material starting condition, and PWHT temperatures. Finally, the results will be summarized within the context of practical guidance for industry to successfully weld the material in boiler, heat exchanger, and piping applications.

**1:35 PM**
**Mechanical and Microstructural Properties of Brazed Honeycomb Liner Material Haynes 214**: *Jonas Vogler*[1]; Jieun Song[2]; Jakob Huber[3]; Rainer Völkl[4]; Uwe Glatzel[4]; [1]University of Bayreuth; [2]Karlsruhe Institue of Technology; [3]Technical University of Munich; [4]University Bayreuth

Honeycomb sealing systems are used in aircraft turbines to minimize leakage air in the gaps between rotating parts and the turbine casing in order to improve efficiency and thus reducing carbon dioxide emission [1]. The honeycomb structure of sealings protects the fins of the rotating turbine blades from critical damage when a contact caused by thermal or mechanical expansion occurs [2]. The honeycombs itself are point welded thin metal sheets of a nickel-based superalloy brazed on to a substrate usually also made of a nickel-based superalloy. During the brazing process braze filler alloy is drawn into gaps between the metal sheets by capillary forces. In this work the mechanical performance of Haynes 214 metal sheets brazed with the nickel-chromium-silicon braze filler BNi 5 (71 wt.% Ni, 19 wt.% Cr, 10 wt.% Si) is investigated. Tensile properties of as brazed metal sheet composites are tested. Interdiffusion zones and hard particles with high chromium contents are observed along the brazed joint. Even a very thin brazing layer reduces the ductility considerably. References [1] H. L. Stocker, D.M. Cox and G.F. Holle NASA Report, 1977, No. NASA-CR-135307.[2] D. Sporer and D. Fortuna Welding Journal, 2014, Volume 93(2),44–48.

**1:55 PM**
**(LBN - P4) Laser-Powder Bed Fusion Additive Manufacturing of Haynes 282 Concentrating Solar-Thermal Power (CSP) Plant Parts: Printability, Geometry, Surface, and Microstructure.**: *Junwon Seo*[1]; Nicholas Lamprinakos[1]; Anthony Rollett[1]; [1]Carnegie Mellon University

Laser powder bed fusion (L-PBF) additive manufacturing has been successful in fabricating simple geometries using high-temperature materials such as Inconel 718 and Haynes 282 (H282). However, printing larger and more complex geometries can be challenging due to the variations in thermal profiles adjacent to the melt pool compared to printing simple geometries. We describe the fabrication of part-scale specimens, including molten salt-to-supercritical CO2 heat exchangers and supercritical CO2 solar receivers, for concentrating solar-thermal power (CSP) generation. The specimen designs were optimized to maximize performance while ensuring printability and resistance to high temperatures and pressures by printing and analyzing sub-scale units. The effects of various process parameters, including scan strategy, laser power, and scanning speed, on the density, surface roughness, and microstructure at various regions of the complex geometries were investigated. Furthermore, the effects of heat treatment on large-scale specimens were investigated to ensure mechanical integrity throughout the components.

**2:15 PM**
**Effect of Heat Treatment on the Mechanical Property and Deformation Mechanism of a Novel Cast Nickel-base Superalloy**: Pengfei Zhao[1]; *Min Wang*[1]; Xianchao Hao[1]; Weiwei Xing[1]; Meiqiong Ou[1]; Yingche Ma[1]; Kui Liu[1]; [1]Institute of Metal Research, Chinese Academy of Sciences

A novel cast nickel-base superalloy named K4800 is developed, which can be used at 800-850 ℃. The yield and ultimate tensile strengths of K4800 can reach 780 and 910Mpa at 800 ℃ with an elongation no lower than 7%, and the creep life of K4800 is generally not less than 120h under 870 ℃/255MPa. Meanwhile, this material has outstanding microstructural stability at 800 and 850 ℃ without the precipitation of $\sigma$ and $\eta$ phase during long-term aging. The microstructure of K4800 consists of $\gamma$, MC, M23C6, and the $\gamma'$ in two sizes, following the heat treatment of solution annealing plus double-stage aging. Accurate control of the content and proportion of the $\gamma'$ phases in two dimensions is the key to obtaining an optimal mechanical property of K4800. With the decrease of large-sized and the increase of small-sized $\gamma'$ in content, the material is gradually strengthened by paired dislocations shearing without an apparent ductility drop.

**2:35 PM Break**

## Additive: Powder & Processing

**Tuesday PM** **Room: Admiral**
**May 16, 2023** **Location: Sheraton Pittsburgh Hotel**
**at Station Square**

*Session Chairs:* Tim Smith, NASA Glenn Research Center; Kevin Bockenstedt, ATI Specialty Materials

**2:55 PM Invited**
**Surface Roughness of Additively Manufactured IN718 & H282 Superalloys from Multi-size and Multi-laser Machines**: Ramesh Subramanian[1]; *K Cwiok*[1]; Anand Kulkarni[1]; [1]Siemens Corporation

Laser Powder Bed Fusion (LPBF) of metallic components is unlocking new design options for high efficiency gas turbine component designs not possible by conventional manufacturing technologies. Surface roughness is a key characteristic of LPBF components that impacts heat transfer correlations and crack initiation from co-located surface defects - both are critical for gas turbine component durability and performance. However, even for a single material, there is an increasing diversity in laser machines (single vs multi-laser), layer thicknesses (~20-80 microns) and orientations to the build plate (upskin, vertical and downskin) that result in significant variability in surface roughness. Build direction effects are particularly important when considering three-dimensional gas turbine components each having unique cooling features. This study systematically compares the external and internal surface roughness of two gas turbine superalloys - Inconel 718 and Haynes 282 - from multi-laser and multi-size machines. This presented data will be discussed in detail, to show potential applicability of a 3D process signature surface across machines and substrate orientations for additively manufactured superalloys.

**3:25 PM**
**Effects of Scan Strategy Induced Microstructural Differences on Thin-wall SLM IN718 Fatigue Performance**: *Connor Varney*[1]; Imran Noor[1]; Paul Rottmann[1]; [1]University of Kentucky

The as-printed microstructure of additively manufactured parts is a function of many variables that span from scan strategy to part geometry. This is particularly relevant in precipitation strengthened alloys (e.g. IN718), as thermal history—which itself varies across a build—dictates the distribution of precipitates in the microstructure. Elucidation of the complex relationship between geometry, scan strategy, and resultant microstructure is necessary to optimize scan strategies. In this study a series of IN718 compact tension fatigue test samples were printed via selective laser melting at 1.25mm in thickness using a contour+hatching scan strategy with both rotating and static beam directions at each build layer with half having the crack oriented parallel and the others perpendicular to the build direction. To quantify the effect of sub-surface porosity on fatigue crack initiation, a selection of the samples had an internal (~0.5mm) pore placed in front of the notch. To investigate the influence of scan strategy on the low-cycle fatigue (LCF) resistance of AM IN718, these samples were LCF tested to failure using a custom micromechanical test setup equipped with piezo actuator and digital image correlation (DIC) to identify the onset of plasticity and the initiation and propagation of fatigue cracks and across sample surfaces. The driving hypothesis for this study is that the rotated scan strategy increases the fatigue resistance due to a more uniform microstructure with smaller grains. As-printed defects and microstructural features were characterized utilizing several techniques (SEM, EBSD, microCT) and compared to observations from mechanical testing.

**3:45 PM**
**Characterization of Laser Powder Bed Fusion of Nickel Based Superalloy Haynes 282**: *Kameshwaran Swaminathan*[1]; Jonas Olsson[1]; Tahira Raza[1]; Joel Andersson[1]; Peter Harlin[1]; [1]University West

Nickel based superalloy Haynes 282 cubes were manufactured using Laser powder bed fusion process with powder layer thickness of 60 and 90 microns to study the effect of Laser Power, Laser Scan Speed and Hatch distance on the melt pool dimensions and porosity. The melt pool dimensions, and porosity were measured at the center of the cubes parallel to the build direction. Variation of melt pool depth and overlap exist within the same cube signifying the scatter present in the process. Laser scan speed was found to be the most significant parameter for porosity and Hatch distance was found to be the most significant parameter affecting the average melt pool overlap depth in the cubes built with 60 microns layer thickness. Interaction of speed and hatch distance was found to be the most significant parameter for porosity and Laser scan speed was the most significant parameter for average melt pool overlap depth in cubes built with 90 microns layer thickness. Comparison of measured responses with individual parameters provide partial trends of melt pool dimensions and porosity. A better trend of the melt pool dimensions and a marginal trend of porosity is obtained on comparison with line and area energy densities. Ratio of maximum length to minimum length of a defect is measured to determine the shape of the defects and averaged to provide insight into the dominant shape of defect for a given set of parameters.

**4:05 PM**
**Investigating the Influence of Build Parameters and Porosity on Fatigue of AM IN718**: *Alexander Caputo*[1]; Rick Neu[1]; Xiayun Zhao[2]; Chaitanya Vallabh[2]; Haolin Zhang[2]; [1]Georgia Institute of Technology; [2]University of Pittsburgh

Using laser powder bed fusion additive manufacturing a series of 10 walls along with two turbine blades were made, sectioned into fatigue specimens, and tested using high cycle fatigue testing with a stress ratio of 0.1 at 538 °C. Each wall was built with different parameters to explore the effects of different laser-material interaction modes (conduction, transition, keyhole) on the effect of the internal porosity and microstructure of AM IN718 as well as the subsequent fatigue properties. The internal porosity in the full gage regions of all fatigue specimens was characterized prior to testing using X-ray computed tomography. Following fatigue testing, SEM fractography was used to identify the location of the fatigue critical flaw that led to failure. Using the XCT porosity data and fatigue test results, and critical flaw locations, a machine learning model was trained to predict fatigue performance of IN718 at high temperature given information on build parameters and non-destructively collected XCT porosity data.

**4:25 PM**
**(LBN - P5) Phase Evolution and Tensile Deformation of IN718-René41 Graded Superalloy Fabricated by Directed Energy Deposition**: *Shenyan Huang*[1]; Ke An[2]; Chen Shen[1]; Changjie Sun[1]; Alex Kitt[3]; [1]GE Research; [2]Oak Ridge National Lab; [3]Edison Welding Institute

A compositionally graded material comprised IN718 and René41 (a medium gamma prime superalloy) was fabricated using laser blown-powder directed energy deposition (DED/LB-M). Hot gas path components that require high and low temperature capabilities at different locations may benefit from such graded superalloy, potentially eliminating the use of welded or mechanically joined components. In-situ neutron diffraction experiment coupled with heating/cooling was performed to understand phase evolution up to 1150°C in as-built specimen. A decreasing lattice spacing from IN718 to René41 was observed over the temperature range. Linear expansion and average coefficient of thermal expansion calculated from neutron data upon cooling showed consistency with model prediction. Fraction and solvus temperature of gamma prime increased with compositions approaching René41. In addition, in-situ tensile loading experiment at 650°C was performed to investigate elastic, plastic deformation behavior within the graded composition at grain and phase levels. Diffraction elastic constants and Poisson's ratios showed small difference between as-built and heat-treated specimens and between gamma and gamma prime phases. The applied heat treatment significantly improved grain-level yield stress for IN718 rich compositions, while small improvement was observed in R41 rich compositions. These results provide insights into optimization of graded superalloy and crucial data for modeling material behavior.

**4:45 PM**
**(LBN - P6) Exploring High Temperature Fretting Wear Behaviour in Wrought and Additively Manufactured DA-718 Superalloy**: *Sathisha Ch*[1]; Kesavan D[2]; Sridhar MR[1]; Arivu Y[2]; [1]GE Rerearch; [2]Indian Institute of Technology

The occurrence of fretting wear is due to the small oscillatory motion of two contacting surfaces under gross-contact pressure. Further, wear mechanisms are dependent on the material's response to these contact conditions. Elevated temperature plays a significant role in determining material performance and changes the wear regime. This research explores the fretting wear behaviour of DA-718 nickel-based superalloys made through both wrought and Laser Powder Bed Fusion (LPBF) additive manufacturing methods. Gross-slip fretting wear tests were conducted at constant high contact pressure and elevated temperature, and the wear behaviour of the two alloys was compared using a custom-built fretting test setup to simulate fretting wear. The results indicate that the additively manufactured DA-718 had similar wear behaviour to the wrought DA-718, but with a higher degree of variation attributed to microstructure-dependent wear phenomena. The microstructure of the alloys was also analyzed to understand the mechanisms governing wear behaviour. These findings have significant implications for the use of additively manufactured DA-718 in high-contact pressure and high-temperature applications, such as gas turbine engines.

**5:05 PM**
**Influence of Morphology and Size Distribution of Haynes 230 Particles on the Powder Spreading Behavior and Performance on Selective Laser Melting**: *Peng Zhang*[1]; Rui Wang[1]; Shaoming Zhang[1]; Zhongnan Bi[1]; Xizhen Chen[1]; Hailong Qin[1]; Guangbao Sun[1]; [1]Central Iron And Steel Research Institute

There is increasing interest in the use of additive manufacturing (AM) for superalloys due to their broad applications in the aerospace industry. As the raw materials, high-quality metal powder is very important for successful selective laser melting in AM. In this work, Haynes 230 powders manufactured by VIGA and PREP were characterized and compared. Results demonstrated P-230 powder is superior to V-230 powders. P-230 powder exhibits the lower Hausner ratio and better flowability. Meanwhile, attributed to superior sphericity and fewer satellite particles, lower dynamic angle of repose and cohesive index were achieved by P-230 powder, which means better dynamic flow and spreading of the powder during the recoating process of selective laser melting (SLM). In terms of their performance on SLM, the powder bed density of the P-230 powder is higher, and samples prepared with P-230 powder exhibited higher relative density. Although both V-230 and P-230 samples were all HIPed at 1200 for 4h, P-230 samples revealed much higher yield strength at room temperature.

## Additive: Microsturcture & Properties

**Wednesday AM**
**May 17, 2023**
**Room: Admiral**
**Location: Sheraton Pittsburgh Hotel at Station Square**

*Session Chair:* Joel Andersson, University West; Daisuke Nagahama, Honda R&D Co Ltd

**8:00 AM Introductory Comments**

**8:05 AM**
**Correlating Alloy 718 and Haynes 282 Solidification Microstructures to Local Thermal History using Laser Powder Bed Fusion Process Monitoring**: *Andrew Wessman*[1]; Timothy Smith[2]; Yi Zhang[1]; Fan Zhang[3]; Thomas Spears[4]; John Middendorf[4]; Mohammed Shafae[1]; Nazmul Hasan[1]; [1]University of Arizona; [2]NASA Glenn Research Center; [3]Computherm LLC; [4]Open Additive, LLC

Additive manufacturing processes such as laser powder bed fusion produce material by localized melting of a powder feedstock layer by layer. The small meltpools and high energy density generate very different microstructures in nickel superalloys when compared to more traditional cast or wrought processing, including features such as cellular structures and epitaxial grain growth. The features of these microstructures vary depending on local thermal history, alloy chemistry and processing parameters. In this work in-situ monitoring of a laser powder bed fusion process is used to characterize the local thermal conditions throughout an AM build for alloys IN718 and Haynes 282, and this information is correlated to observations on the microstructural features of these alloys in the as-built condition. In IN718, segregation of niobium and molybdenum are found in interdendritic regions of the 200nm wide cellular precipitate structures, while in Haynes 282 segregation of gamma prime forming elements such as titanium and aluminum segregate to the interdendtritic cell walls. In-process monitoring using thermal tomography is utilized to observe the local thermal conditions during the solidification of the AM material and correlate those conditions to the microstructures formed through computational modeling of the segregation and dendrite formation. Results for both IN718 and Haynes are compared.

**8:25 AM**
**Understanding Annealing Behavior during Post-build Heat Treatment of Ni-based Alloys Across Additive Manufacturing Processes**: Juan Gonzalez[1]; Yi Zhang[2]; Andrew Wessman[2]; *Jonah Klemm-Toole*[1]; [1]Colorado School of Mines; [2]University of Arizona

Ni-based alloys are used for high temperature structural components that span from small, highly complex, with fine feature resolution to large, simple shapes with low dimensional tolerances. Accordingly, a range of additive manufacturing (AM) processes from high precision laser powder bed fusion (LPBF) to high deposition rate wire arc additive manufacturing (WAAM) can be used to produce components. However, the microstructure evolution during post processing varies considerably between LPBF and WAAM. In this presentation, we show how the annealing responses during post build heat treatment systematically vary in LPBF and WAAM IN625 and Haynes 282. Despite suggestions in literature, primary carbides do not control the recrystallization behavior in these alloys. Differences in stored energy in the as built condition, which is heavily influence by AM process, has the greatest effect on recrystallization behavior. The implications of these results on microstructure control in AM Ni-based alloys is discussed.

**8:45 AM**
**High-temperature Properties of Alloy 718 Made by Laser Powder-bed Fusion**: *David Witkin*[1]; Tait McLouth[1]; Glenn Bean[1]; Julian Lohser[1]; Robert Hayes[2]; [1]The Aerospace Corporation; [2]Metals Technology, Inc.

The properties of alloy 718 made by laser powder-bed fusion have been widely reported, and while their room-temperature static properties are often similar to wrought material, elevated temperature properties have proven inferior, especially at slow strain rates. Stress rupture tests performed on LBPF 718 material after Hot isostatic Pressing (HIP) and heat treating in conformance with AMS 5663 have persistently led to brittle notch failures with limited elongation. Creep testing at 650 °C and 690 MPa shows a similar tendency, with samples showing capability of sustaining a load but with limited elongation and abrupt, transgranular failure. Alternative heat treatments performed to enhance high-temperature ductility have shown success in adjusting delta phase population but without benefit for stress rupture. Alternative HIP schedules have also been performed that led to changes in room-temperature and elevated temperature static strength but no benefit in stress rupture behavior. The root cause of this behavior is attributed to the dispersion of NbC that is a consequence of the LPBF process that results in fine-scale segregation of Nb and C during rapid solidification. Deliberately lowering the carbon content of the powder feedstock led to a greater number of smaller Y" particles and smaller size NbC particles resulting in an increase in static strength at room and elevated temperatures but no improvement in stress rupture. The presence of a large number of NbC particles leads to environmental sensitivity of LPBF 718 that is most apparent at elevated temperatures and slow strain rates.

**9:05 AM**
**Microstructure and Mechanical Properties of Selective Laser Melting Processed TiC/GTD222 Nickel-based Composite**: *Rui Wang*[1]; Zhe Zhang[1]; Peng Zhang[1]; Hailong Qin[1]; Zhongnan Bi[1]; [1]Central Iron & Steel Research Institute

In this study, the microstructure and deforming mechanisms of selective laser melted GTD222 and TiC/GTD222 composite were studied. The results show that the TiC/GTD222 composite has finer grains and more precipitation phases. Meanwhile, TiC/GTD222 composite has higher yield strength both at room and high temperatures, which can be mainly attributed to the synergistic effect of the TiC strengthening and $\gamma'$ strengthening. The deformation mechanisms of TiC/GTD222 composite at 800 °C were identified as isolated stacking faults shearing the $\gamma'$ phase, continuous stacking faults shearing the $\gamma$ and $\gamma'$phases, dislocations cutting $\gamma'$ phase, and dislocation slip within the $\gamma$ matrix. This study provides insights for understanding the influence of TiC particles on the deformation mechanisms of additive manufactured nickel-based alloys.

**9:25 AM**
**Fabrication and Weldability Aspects of Ni- and Ni-Fe Based Superalloys – A Review**: *Joel Andersson*[1]; [1]University West

Superalloys are commonly used in structural components of aero engines. Superalloys in general, Ni- and Ni-Fe-based superalloys, belong to an important group of materials used in aerospace applications. Fabrication and associated weldability aspects of structural components for the hot section of aero-engine gas turbines continue to be of high importance to the manufacturing industry within this discipline. Cracking and specifically hot cracking as well as strain age cracking is a serious concern during the welding and additive manufacturing (AM) of these structural components. The cracking phenomena can occur during welding, AM or subsequent heat treatment of precipitation-hardening superalloys. The cracking behaviour can be influenced by several factors i.e., chemical composition in terms of hardening elements and impurities, the microstructure of base material, and weld zone, together with corresponding welding, AM and post-treatment process parameters. This paper offers a review of Ni- and Ni-Fe-based superalloys concerning fabrication and weldability aspects within the context of structural components of aeroengines.

**9:45 AM Break**

## Welding, Manufacturing & Repair

**Wednesday AM**
**May 17, 2023**
**Room: Admiral**
**Location: Sheraton Pittsburgh Hotel at Station Square**

*Session Chair:* Joel Andersson, University West; Daisuke Nagahama, Honda R&D Co Ltd

**10:15 AM Invited**
**Tensile Properties of Inconel 718 Produced by LMD-Wire**: *Jonathan Cormier*[1]; Sandra Cabeza[2]; Guillaume Burlot[1]; Romain Bordas[1]; Mélanie Bordas-Czaplicki[1]; Fabio Machado Alves da Fonseca[1]; Stefan Polenz[3]; Franz Marquardt[3]; Elena Lopez[3]; Patrick Villechaise[1]; [1]ENSMA - Institut Pprime - UPR CNRS 3346; [2]Institut Laüe Langevin (ILL); [3]Fraunhofer IWS

The anisotropy in tensile properties of Wire Laser Metal Deposited Inconel 718 has been investigated from room temperature up to 850°C at a strain rate of 5.0 10-4 s-1. These properties have been investigated along, at 45 degrees and perpendicular to the building direction. Moreover, different heat treatments have been used: as-built, solution treated to dissolve Laves phases, solution treated + aged to trigger $\gamma'/\gamma''$ precipitation and direct-aged. According to this extensive characterization of tensile properties, complemented by SEM, EDS and EBSD characterizations, it is shown that, whatever the temperature, Yield stress and tensile resistance have a very weak anisotropy and that tensile properties are mostly dependent to the prior heat treatment state. The anisotropy is only observed on elastic properties, due to a pronounced crystallographic texture inherited from the directional thermal gradient during the building process. Moreover, Laves phases do not seem to have a strong impact on tensile properties for this coarse grain material. The relative contributions of $\gamma'/\gamma''$ precipitation, grain size, stored "processing" dislocations to tensile properties will be analyzed on the light of comparisons with C&W processed Inconel 718.

**10:45 AM**
**Microstructural and Tensile Properties Evolutions of Direct-aged Waspaloy Produced by Wire Arc Additive Manufacturing**: *Marjolaine Sazerat*[1]; Azdine Nait-Ali[1]; Lucie Barot[2]; Alice Cervellon[2]; Inmaculada Lopez-Galilea[3]; Dominique Eyidi[1]; Anne Joulain[1]; Patrick Villechaise[1]; Jonathan Cormier[1]; Sebastian Weber[3]; Roland Fortunier[4]; [1]Institut Pprime; [2]Safran Aircraft Engines; [3]Ruhr University Bochum; [4]LTDS

The microstructure and tensile properties of direct aged Waspaloy manufactured using wire arc-based Cold Metal Transfer (CMT) have been investigated. Samples were exposed to temperatures ranging from 700°C to 900°C, for up to 96 hours. In the as-deposited condition, pronounced chemical segregation is inherited from the process, leading to heterogeneous γ′ precipitation between dendrite cores and interdendritic spacings. Precipitate size and distribution were measured in both areas for each heat treatment, and a diffusion-controlled coarsening behavior following the LSW theory was observed for temperatures above 760 °C. Activation energies were calculated. Tensile tests at room temperature were carried out on the additive alloy pre- and post-aging, but also on wrought sub-solvus and super-solvus treated material for reference. Results showed that heat treatment significantly increased the yield strength and ultimate tensile strength of the CMT samples, of up to +340 MPa compared to the as-built conditions. Elongation, however, decreased from 40-45% to 16-28%. Direct aged CMT Waspaloy exhibited a similar behavior to that of wrought super-solvus Waspaloy, due to their large grains (~200-250 µm). Anisotropy in tensile properties was estimated by calculating the ratio of properties for horizontal and vertical specimens. Finally, the formation of secondary phases was assessed. Thermodynamic calculations predicted the formation of M23C6, η and σ in interdendritic spacings at thermodynamic equilibrium. By using Electron diffraction patterns and Energy-Dispersive X-ray Spectroscopy in TEM, intergranular (Cr,Mo)23C6 secondary carbides decorating grain boundaries and near (Ti,Mo)C primary carbides in the interdendritic spacings were observed to nucleate and grow.

**11:05 AM**
**IN718 Cold Gas Repair Spray of Large Cavities – Microstructure and Residual Stresses**: *Florian Lang*[1]; Johannes-Christian Schmitt[2]; Sandra Cabeza[3]; Thilo Pirling[3]; Jochen Fiebig[2]; Robert Vaßen[2]; Jens Gibmeier[1]; [1]Karlsruhe Institute of Technology; [2]Forschungszentrum Jülich GmbH; [3]Institut Laue-Langevin

Cold spraying is an established process for coating substrates with similar or dissimilar materials. By use of a high-pressure process gas stream, solid particles are accelerated onto a substrate at high velocities. The method is particularly suited for repair applications, since neither structural changes nor oxidation occur during the process. Furthermore, cold spray coating usually induces compressive residual stresses in the coating system that positively influence the fatigue behaviour.To investigate the suitability of the cold spray process for repairing large cavities in Inconel 718 components, sample geometries were manufactured, containing tapered cavities with a depth of 4 mm. The cavities were filled with Inconel 718 particle by cold gas spraying. Non-destructive high-resolution neutron diffraction experiments were performed using the SALSA instrument at the Institut Laue-Langevin (ILL) to evaluate the local residual stress state in the as-sprayed condition. 2D maps of the residual stress distribution over the cross- sectional area of the samples were determined. Additionally, complementary laboratory X-ray diffraction (XRD) and incremental drilling analyses were carried out. The results indicate compressive residual stresses within the filled process zone, which are considered positive for the fatigue and wear resistance of the repaired components. Furthermore, metallographic examinations show a good bonding between the repair filling and the substrate as well as strongly deformed particles within the repaired region. The latter indicates significant plastic deformation during cold spraying, which is in agreement with the broader diffraction lines from the neutron and X-ray diffraction analyses in the filler compared to the substrate.

**11:25 AM Conference Luncheon**

**12:25 PM Introductory Comments**

**12:30 PM**
**Design of Graded Transition Interlayer for Joining Inconel 740H Superalloy with P91 Steel using Wire-arc Additive Manufacturing**: *Soumya Sridar*[1]; Xin Wang[1]; Mitra Shabani[1]; Michael Klecka[2]; Wei Xiong[1]; [1]University of Pittsburgh; [2]Raytheon Technologies Research Center

Design of an efficient interlayer is imperative for joining dissimilar materials using additive manufacturing to achieve smooth variation in properties. In this work, two graded transition interlayers were designed using a CALPHAD-based ICME framework (CALPHAD: Calculation of Phase Diagrams; ICME: Integrated Computational Materials Engineering) for joining Inconel 740H superalloy with P91 steel. Successful builds with the designed interlayers (60 and 85 wt.% P91) sandwiched between the constituent materials were fabricated using wire-arc additive manufacturing. The 60 wt.% P91 interlayer was found to exhibit an FCC matrix while the 85 wt.% P91 interlayer had a martensitic matrix. A two-step post-heat treatment consisting of homogenization and aging was designed. The key temperatures for each step were determined supported by CALPHAD-prediction of phase stability diagrams. The 60 wt.% P91 graded interlayer showed no improvement in hardness after aging. This agrees with the CALPHAD model predictions, which showed a lack of γ′ precipitates after aging for this composition. The hardness of 85 wt.% P91 improved considerably after aging with an optimum aging time of 8 hours. In addition, mechanical tests were performed to determine the location of failure as well as tensile properties. The 60% P91 graded interlayer builds failed at the interlayer while the 85% P91 build failed in the pure P91 region. This proves that the post-heat treated 85% P91 is much stronger than the pure P91 and hence, the strategy used in this work is successful for design of interlayers for dissimilar joining.

**12:50 PM**
**Microstructure Evolution During Post-heat Treatment of Haynes 282 Alloy Processed by Wire-arc Additive Manufacturing**: *Luis Ladinos Pizano*[1]; Soumya Sridar[1]; Chantal Sudbrack[2]; Wei Xiong[1]; [1]University of Pittsburgh; [2]National Energy Technology Laboratory

In order to perform microstructure engineering for improved mechanical properties, post-heat treatment optimization is imperative for additive manufacturing of advanced superalloys. In this work, the effect of solution heat treatment on the microstructural heterogeneity and γ′ precipitation for Haynes 282 fabricated using wire-arc additive manufacturing (WAAM) has been investigated. The results suggest that the standard solution heat treatment carried out at 1150°C for 2 hours is insufficient to remove the heterogeneities in the grain structure formed during WAAM. However, solution heat treatment at 1250°C for 2 hours promoted the dissolution of secondary precipitates and recrystallized the grain structure without causing excessive coarsening. In addition, solution heat treatment temperature affects the growth kinetics of γ′ precipitates. By increasing the solution treatment temperature, γ′ grows faster, achieving the peak hardness in a shorter aging time. Moreover, increasing the solution treatment temperature favors the development of a bimodal distribution of γ′ precipitates during aging. Tensile tests are performed for samples extracted from build (XZ) and transverse (YZ) planes to evaluate the effectiveness of the solution treatment in removing the microstructural heterogeneity. This work demonstrates the need for an effective post-heat treatment to eliminate the heterogeneities that form during the WAAM process and alter the γ′ precipitation and improve the mechanical properties of Haynes 282.

**1:10 PM**
**Characterization of the Anisotropic Behaviour of Inconel 718 Parts Manufactured by Wire Arc Additve Manufacturing**: *Karin Hartl*[1]; Christopher Wallis[2]; Martin Bielik[2]; Pier Curti[2]; Martin Stockinger[1]; [1]Montanuniversität Leoben; [2]RHP Technology GmbH

The usage of additive manufacturing as a process for component production is becoming increasingly important, as it offers enormous potential for material savings and therefore cost reduction. In particular, wire arc Directed Energy Deposition (wire arc DED) processes are arousing a great deal of interest in several industries by its high deposition rates at low equipment acquisition costs and the low buy-to-fly ratio. This process is being specifically investigated for aerospace and space applications, as it allows the production of large structural complex near-net-shape components in small batches. However, a major drawback of this technology is the high anisotropic behaviour of the manufactured structures in the as-welded state. Since the nickel-base alloy Inconel 718 is an anisotropic material, in which introduced textures strongly influence the mechanical properties, the impact of the wire arc DED processing route on the mechanical properties as well as the underlying microstructure is specifically focused on in this study. Using a plasma arc as heat source and Inconel 718 wire as feedstock material, test walls are produced in order to characterize the created material. In addition to the identification of factors influencing the process, temperature cycles are measured at different positions during the build-up. The resulting microstructure is subsequently evaluated macroscopically as well as microscopically and examined regarding pores and precipitates. SEM/EDX analysis is carried out to investigate the underlying microstructure of the additively manufactured parts. Furthermore, mechanical properties are evaluated in the build-up direction as well as transversal to this direction in order to characterize the anisotropy of the material.

**1:30 PM**
**Keyhole TIG Welding of New Co-lean Nickel-based Superalloy G27**: *Achmad Ariaseta*[1]; Dario Pick[1]; Joel Andersson[1]; Olanrewaju Ojo[2]; [1]University West; [2]University of Manitoba

The hot sections of aircraft engines have been preferably fabricated by joining small pieces of superalloys by the welding process instead of casting a single large component due to several benefits, such as reducing the total weight of the components and enhancing the design flexibility. The welding process and the associated control themselves, to some extent, have enhanced remarkably in the last decades. One of the recent welding techniques is Keyhole TIG (K-TIG) welding which has the capability to use lower heat input and higher energy density to achieve deeper penetration during the welding compared to the traditional one, being essential when joining superalloys in the hot sections of an aircraft engine in the aerospace industry. Alloy G27, a new Co-lean nickel-based superalloy with service temperature capability up to about 760 °C, is a promising material candidate to be utilized in the fabrication of aero-engine hot sections. From the industrial perspective, it is of paramount importance to produce a superalloy weld that meets the tight quality criteria in aerospace applications in terms of weld geometry and weld defects. Moreover, understanding the microstructures in the heat-affected zone (HAZ) and fusion zone (FZ) is essential since they influence the properties and integrity of the weldment and will become the basis for developing suitable post-weld heat treatment. Thus, this article aims to study the effect of K-TIG welding parameters on weld geometry and weld defects of G27 and to characterize the microstructures in HAZ and FZ of the welded alloy.

**1:50 PM Concluding Comments**

## P



## Q



## R



## S



## T



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## X



## Y



## Z

NOTES

NOTES

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