DoE Award No. DE-FE31819

Additively Manufactured Graded Composite Transition Joints (AM-GCTJ) for Dissimilar Metal Weldments in Advanced Ultra-Supercritical Power Plant

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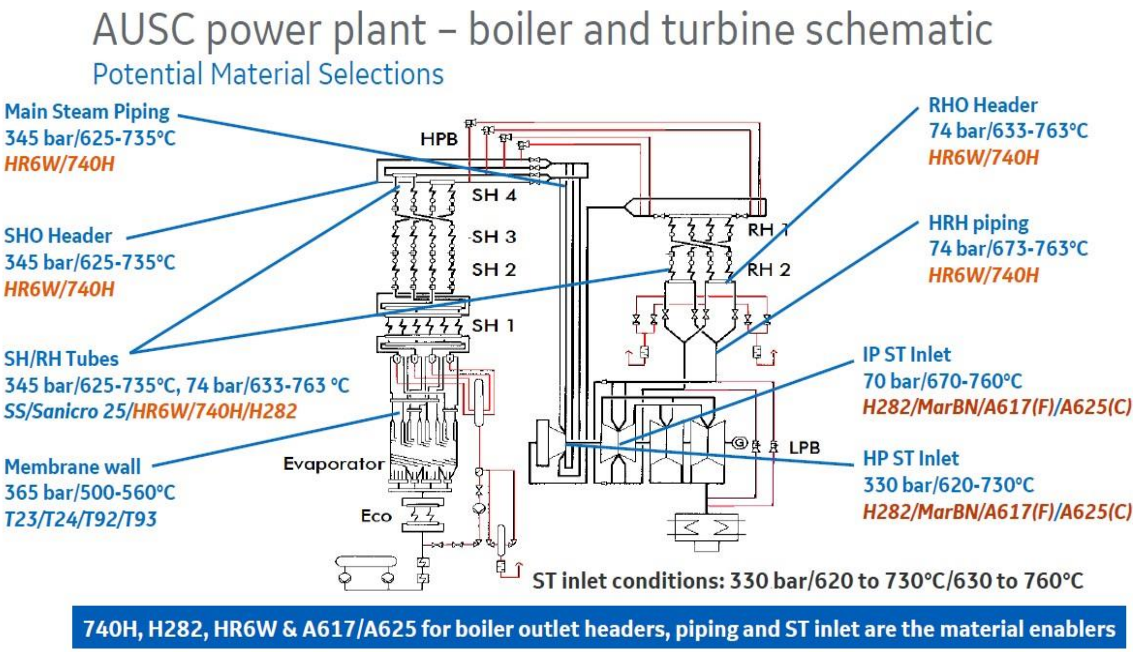
April 19, 2023

DMWs in A-USC, HRSG, others



GE Steam: A-USC Mock Header

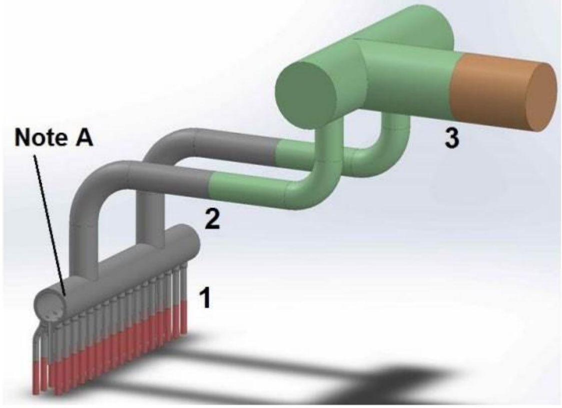


Figure 3-1
HRSG configuration highlighting potential DMW locations (1: tubing internal to the HRSG setting; 2: link piping; 3: outlet piping.)

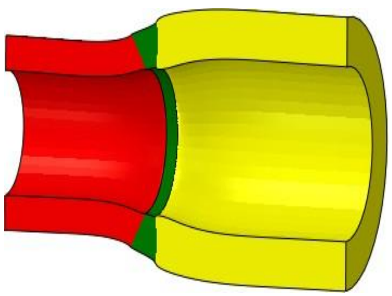
Program on Technology Innovation: Guidelines and Specifications for High-Reliability Fossil Power Plants—Best Practice Guideline for Manufacturing and Construction of Grade 91 Steel to Austenitic Stainless Steel Dissimilar Metal Welds 3002007221 Final Report, December 2017

DMW:

1. Grade 91 – Austenitic Stainless Steel
2. Ni based alloy – Austenitic Stainless Steel

Oak Ridge National Laboratory

Mismatch of coefficient of thermal expansion and thermal cycling:



DMW with sharp material transition

Higher cycling requirements in the power industry:

- Steam Boilers: A sample required a number of cycles for a new unit

	Total # of cycles of 25 years
Cold Start	455
Warm Start	910
Hot Start	4550

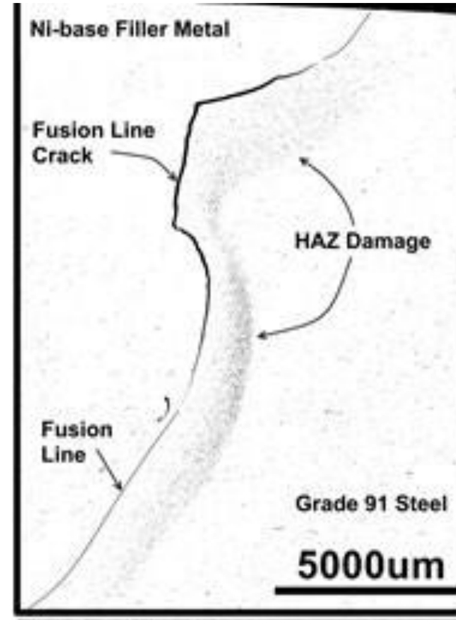
- Mismatch of the coefficient of thermal expansion between different materials leads to a high strain range along the interface during thermal transients.
- Increasing demand in the industry for flexible operation of steam boilers and more cycling capability of HRSGs.

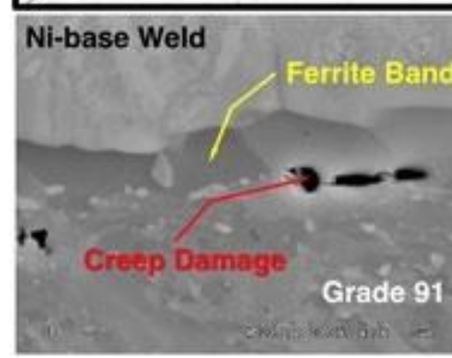
- HRSGs: Typical required number of cycles for a cyclic operating CCPP

	Total # of cycles of 25 years
Cold Start	250
Warm Start	1250
Hot Start	4250

Current Dissimilar Metal Welds (DMWs)

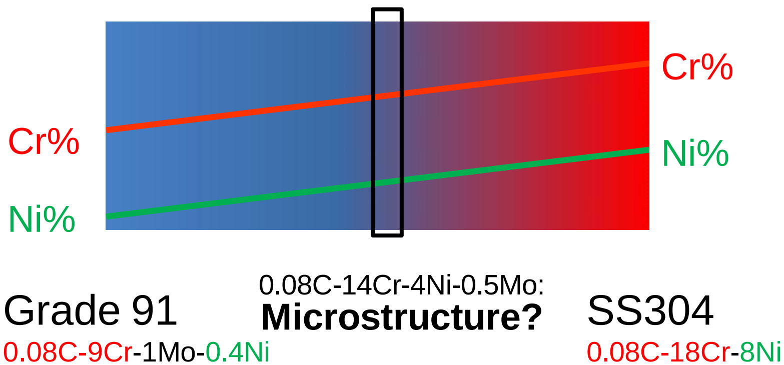
- Failures in DMWs at the fusion boundary between Grade 91 and nickel-based filler metal, often accompanied by considerable damages in the HAZ of Grade 91.
- HT exposure during PWHT or service causes carbon diffusion from the ferritic matrix toward the austenitic matrix. This leads to the formation of a carbon-depleted soft zone on the ferritic side and nucleation/growth of carbides on the ASS side that have very high hardness.
- Under imposed residual, external, and thermal stresses caused by the CTE mismatch between different alloys of the DMW, creep and/or creep-fatigue cracks can occur along the fusion boundary and HAZ.

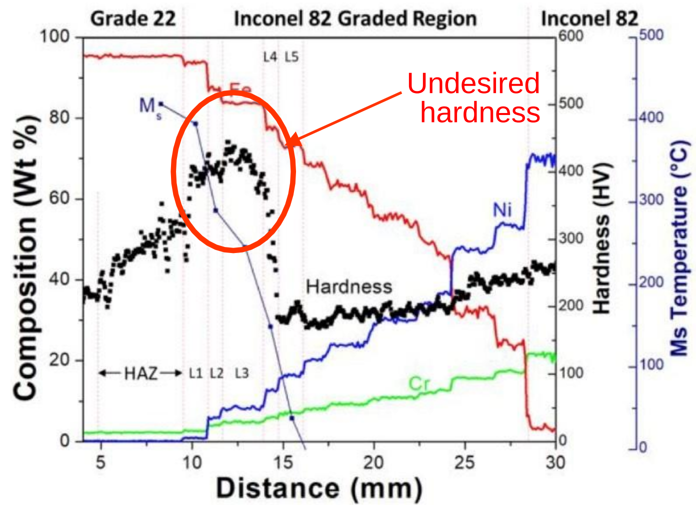




AM-Graded Transition Joints (GTJs)

- “Conventional” melting-based AM





From: DuPont, Babu, Feng, 2018

- “Conventional” AM (wire or powder) approach melts alloys A&B completely together

  - A critical issue is the continuous transition in composition creates complex and often undesired microstructure.

Advantages of AM-GCTJ

- Solid-state Process, composites material" transition with constituents of known chemistry (such as P91, SS304, A282) mixed in controlled proportion
  - •Solved the critical drawbacks of undesired/unpredictable phases/microstructure in the conventional AM approach to fabricate the transition joint
- 100% smooth transitions
- Welding happens at A-A, and B-B, no DMWs
- Minimize scale-up issues expected to manufacture large quantities of joints

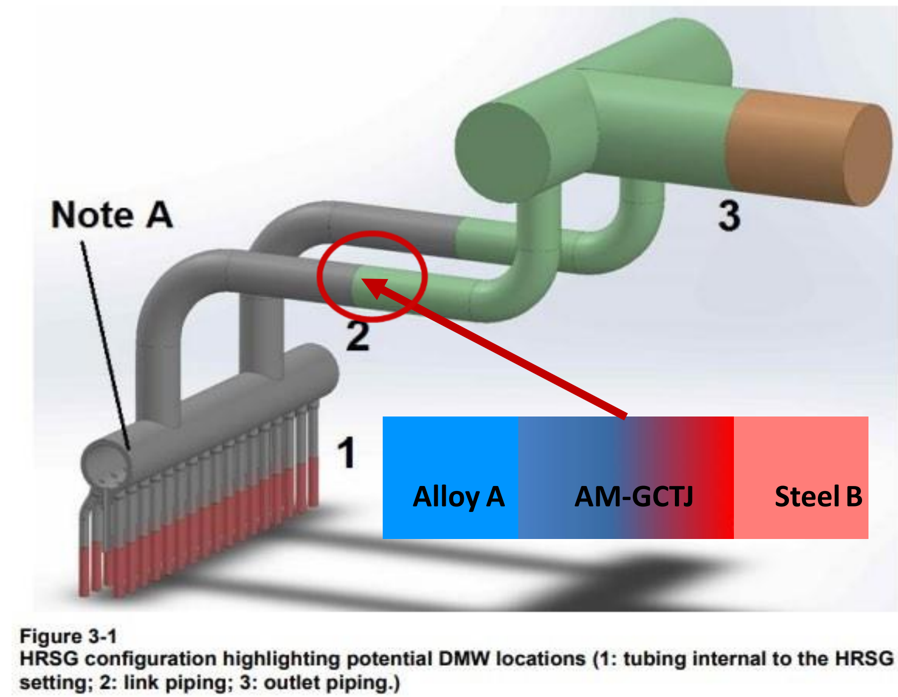


Illustration of DM weld in power plants

* U.S. Patent Appl. No. 62/704,965 – Method to Produce an Additively Manufactured-Graded Composite Transition Joint

PROJECT OBJECTIVES – PHASE II

(1) To develop and demonstrate at the lab-scale the additively manufactured graded composite transition joints (AM-GCTJ) for dissimilar metal weldments (DMW) in next generation advanced ultra-supercritical (A-USC) coal-fired power plants, that can significantly improve the microstructural stability, creep and thermal-mechanical fatigue resistance, as compared with their conventional counterparts;

(2) To manufacture and test the components with AM-GCTJ, to advance the technology readiness level to TRL-7, and manufacturing readiness level to MRL 6-7, for targeted commercial applications identified by GE Steam Power, the primary industry partner of the project team

ASME Code Case (CC) on TJ - Plan

- **ASME Transition Joint Code Case (CC) development effort**
  - Conformance with Standards and Codes is required for legal compliance.
  - ASME CC is effective immediately upon ASME approval and does not expire, i.e., it is not limited by Code book publication cycles.
  - This effort has been initiated.

- **ASME CC mechanical testing plan and test data generation**
  - CC testing support data package will be generated using coupons.
    - ❑ Three independent “heats” of transition joints (TJ)
    - ❑ Baseline conventional DMW for comparison
  - High temperature time-dependent and time-independent properties are required for developing the Code case.
    - Creep testing matrix for the TJ and comparison with DMW with selected conditions
    - Tensile tests at room temperature and elevated temperatures

ASME Code Case on TJ - Plan

Plan for ASME Code Case

- **Level 1:** Treat the TJ as a new fabrication process, not for new material, to obtain a CC within a reasonable time (targeting 12-24 months after CC submission).
- **Level 2:** Addition of optimized AM-TJ with CC revisions.

ICWE Model Guided Design of AM-TJ in support of the development of ASME Code Case

- Apple ORNL's ICWE modeling tool to optimize TJ geometry design details for joint mechanical performance.
  - Optimize for creep, creep-fatigue, and thermal fatigue behaviors
  - Flat plates, pipes, and other component geometries

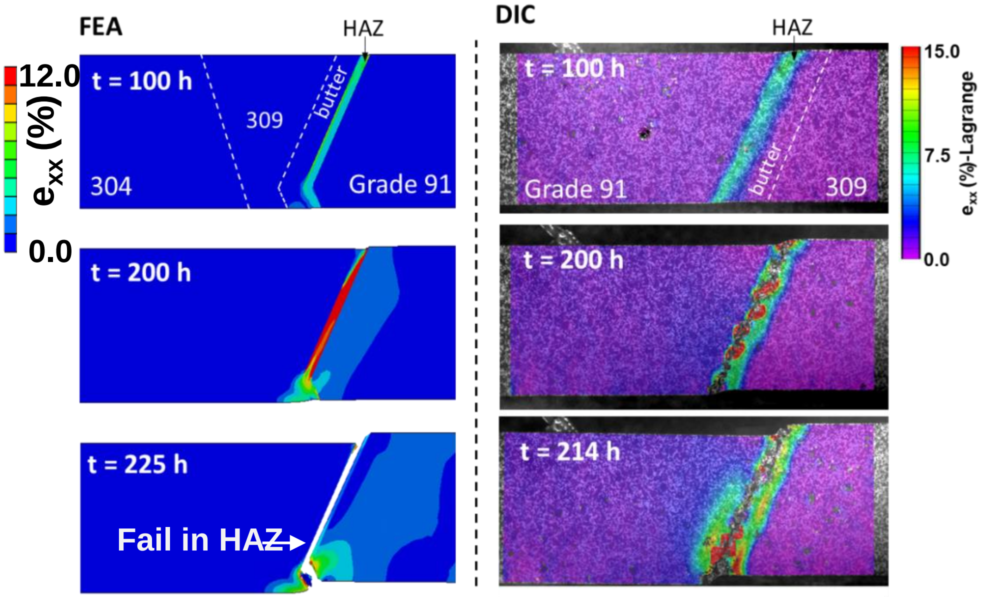
Component-level testing and demonstration

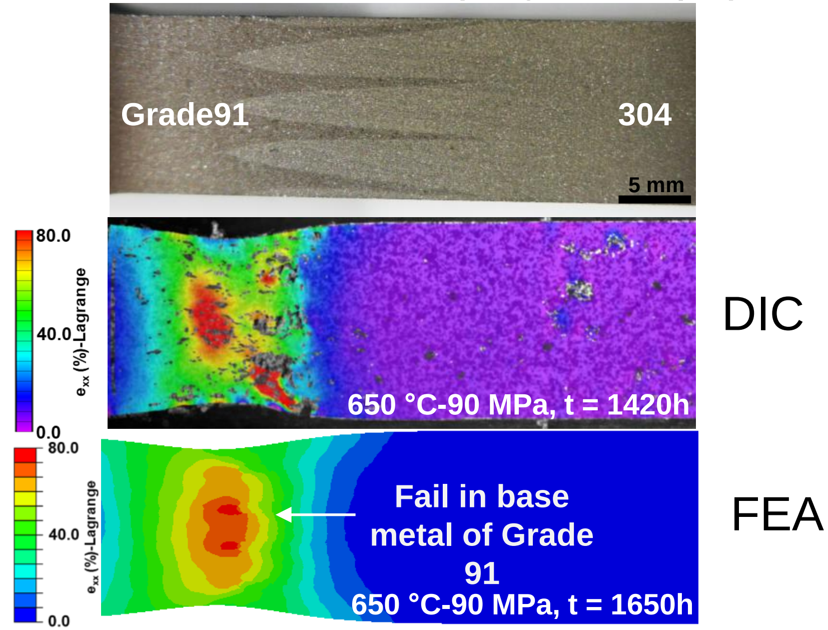
- Pipe components fabricated with AM-TJ will be tested in a testing loop with temperature and pressure transients designed to represent operational conditions.
- Information collected from the component testing will demonstrate the viability of this new technology.

ICWE Model Guided Design – Creep Characterization

- **Transition joints exhibited significantly improved creep life compared to traditional DMW at 650 ℃ and 90 MPa**

  - Conventional DMW
  - Transition Joint (finger shape)



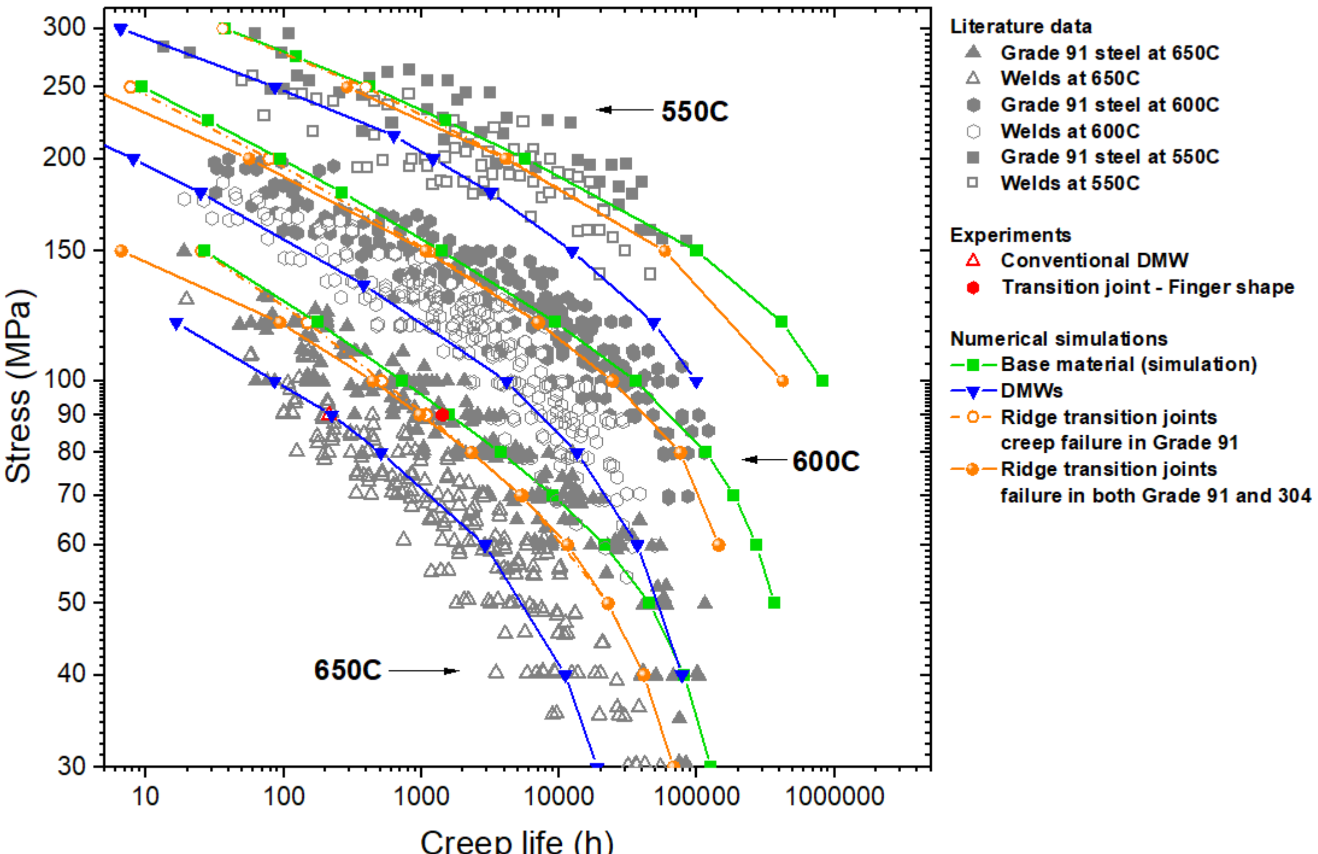


Numerical results: lifetime 225 h | Experiment: lifetime **214 h** | Numerical results: lifetime 1650 h | Experiment: lifetime **1420 h**

- **Transition design leads to > 5 times life enhancement** by reducing the stresses in the transition region; as a consequence, the **failure location** was **shifted to** the **base material** of Grade 91 steel

ICWE Model Guided Design – Creep Testing for Supporting ASME Code Case

- **Creep performance of Grade 91 – 304 transition joints simulated for a selected testing matrix for short-term to long-term creep properties**



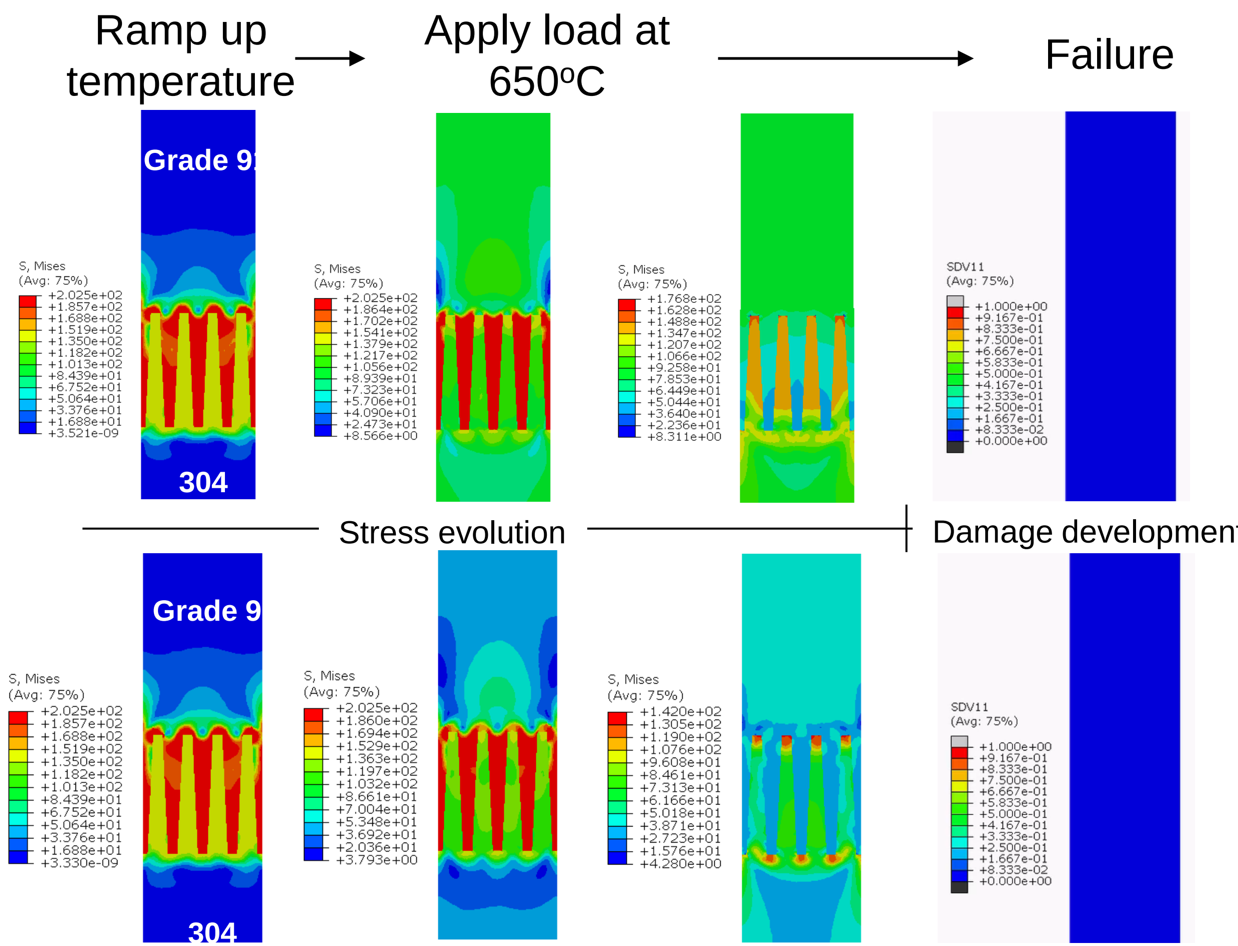
❑ Simulations

- A transition joint (dt = 2.0 mm, d0 = 1/4 ”, h =1 ”) vs DMW
- Failure criteria: creep fracture in Grade 91 steel and stress failure in 304
- **Transition design** results in **significant creep life improvement compared to the conventional DMWs** under all testing conditions
- Creep life of the transition joint approached the life of the less creep-resistant base material
- Creep life enhancement shows a strong dependence on the testing temperature and stress levels

ICWE Model Guided Design – Short-term vs Long-term Creep Performance

Creep test at 650°C, 90 MPa, **relatively short-term creep** dominated by **power law creep**

Creep test at 650°C, 40 MPa, **long-creep creep** governed by **diffusion flow creep**



❑ Deformation of TJs:

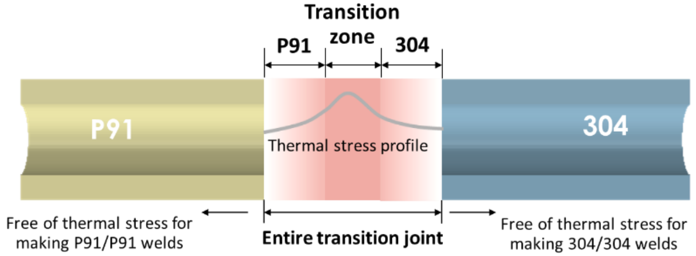
- Ramp up temperature: thermal expansion mismatch results in high thermal stresses in transition region; higher stresses in Grade 91
- Apply and hold the load at 650 ℃: higher stress in Grade 91 because of its high strength while applying load; stress relaxed during holding period; load gradually transfers to 304 due to its high creep resistance; creep deformation and damage build-up

❑ **Short-term and long-term creep: deformation mechanism changes from power-law creep to diffusion flow creep**

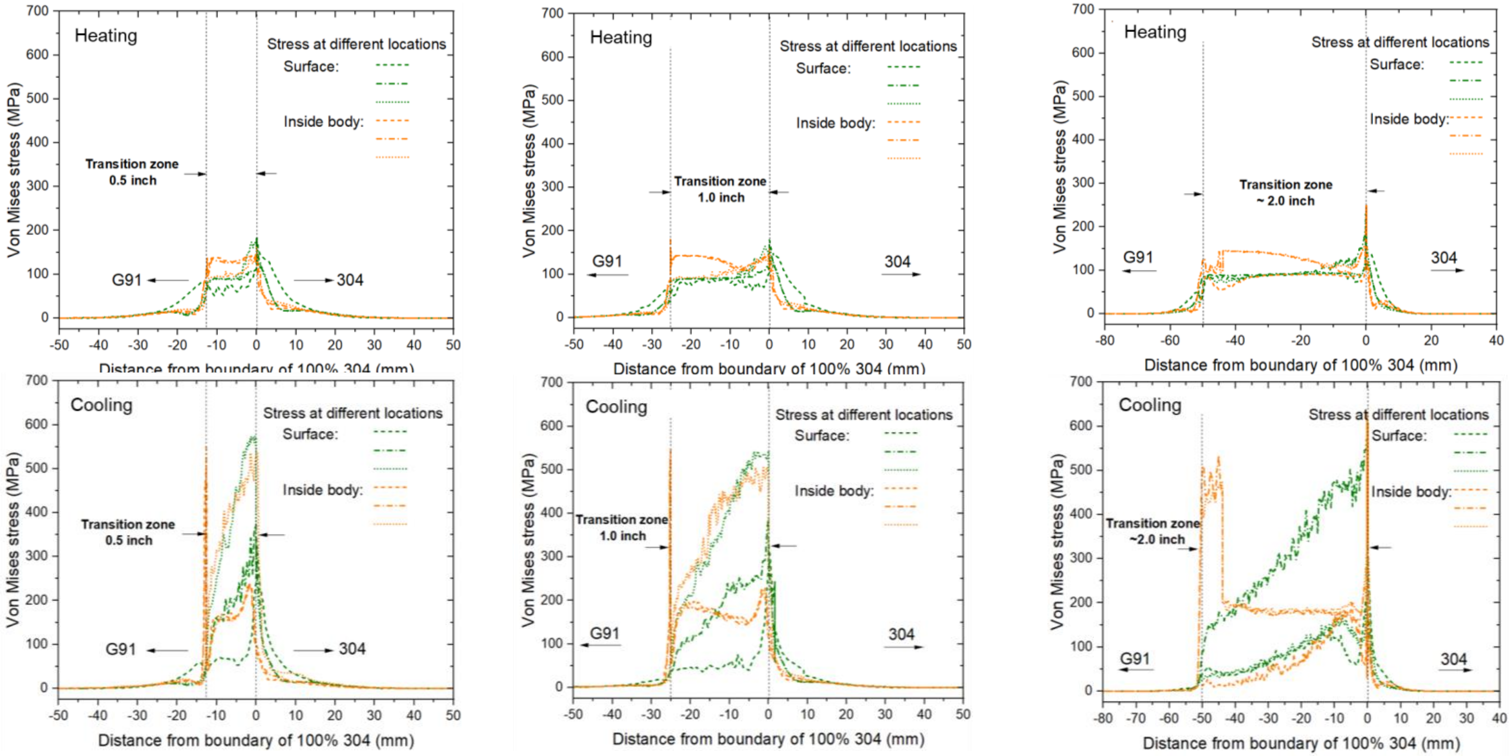
- **Short-term creep: creep damages accumulated in base material of Grade 91**
- **Long-term creep: creep damages accumulated in both transition zone and base material of Grade 91**

ICWE Model Guided Design – Geometric optimization of GCTJ

- Thermal expansion mismatch-induced stress in the TJ may extend beyond the TJ zone into the adjacent metal.
- Determine the length requirement to achieve thermal stress-free at the transition joint piece ends



- 0.5” transition zone
- 1” transition zone
- 2” transition zone



- Different length transition joints exhibited a similar profile of thermal stresses, which are high in the material transition zone and gradually decrease towards the base materials of P91 and 304
- Thermal stress-free zone can be achieved at a distance of ~40 mm from the transition zone of both P91 and 304 sides for all three joints

ICWE Model Guided Design - Summary

- Through ICWE-guided design, AM-GCTJs would have significant creep life improvement than that of the conventional DMWs
  - Creep lifetime improvement shows dependence on testing temperature and stress levels; the underlying deformation mechanism changes from dislocation creep deformation (short-term creep) to diffusion-controlled creep (long-term creep)
  - The robustness of AM-GCTJ: it can achieve significant improvement over the conventional DMW under fairly broad geometric details of the TJ zone, approaching the life of base metal
  - Fabrication length of the AM-TJ to minimize the thermally influenced zone on both ends of based materials
- ICWE-guided design analysis in support of ASME code case (CC) development

Preparation of Lab-Scale GCTJ

❑ Laser powder bed fusion (LPBF) system at UNL

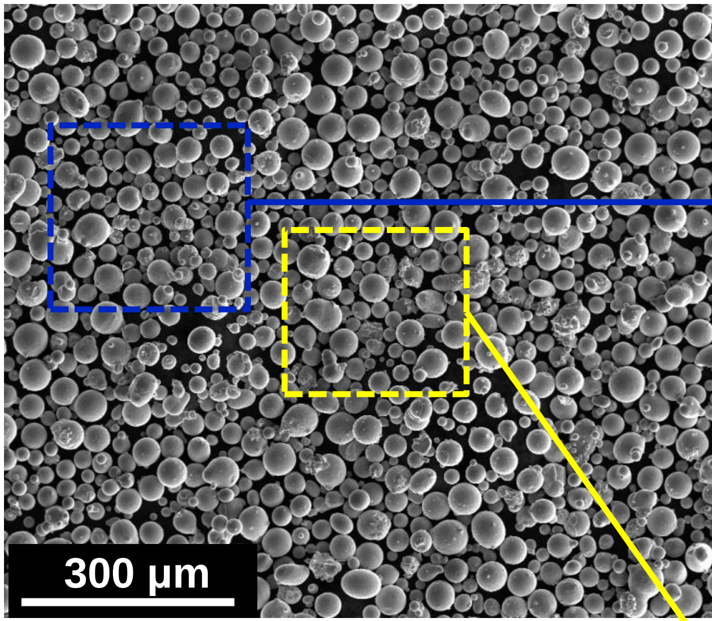
- Laser specification
  - 40-400-Watt Yb fiber Laser
  - Beam mode quality (M2) < 1.1
  - Wavelength: 1070 nm
  - Galvano scanner system
- Machine specification
  - Spindle speed range: 450 to 45,000 RPM
  - Spindle bearing inner diameter: 25 mm
  - 1/10 taper special BT20 tool shank
  - Max spindle torque: 0.7 N-m
  - Linear feed rate: 1-30,000 mm/min
- Capabilities
  - Hybrid additive/subtractive manufacturing
  - Nitrogen or argon atmosphere
  - Position accuracy: ± 2.5 μm
  - Layer thickness: 50 μm to 80 μm

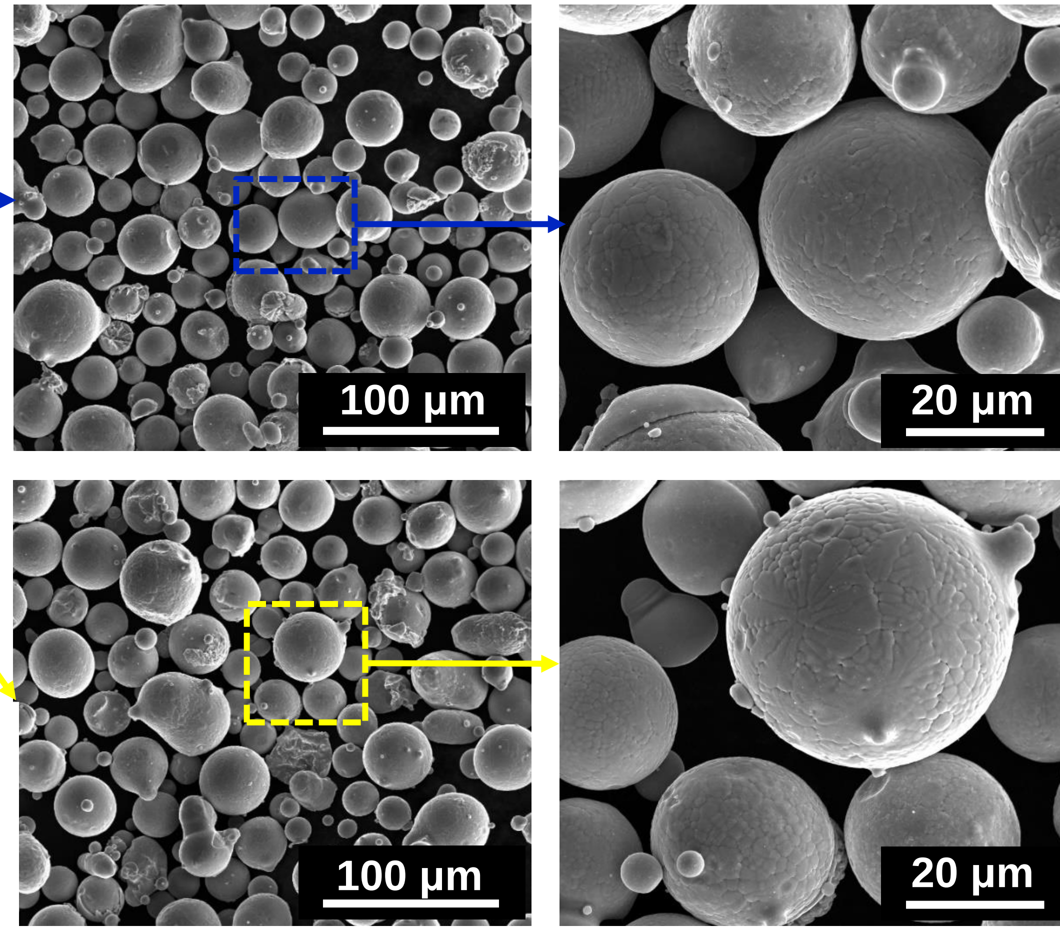
[Lumex Avance-25 Metal 3D Printer]

Preparation of Lab-Scale GCTJ - Powder

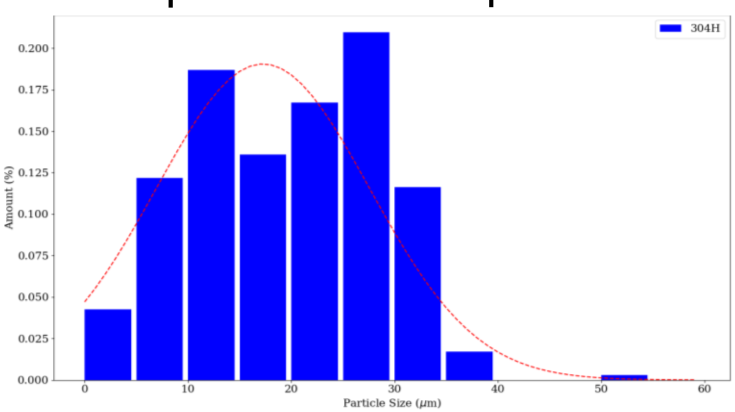
- **SEM of 304H powders**

Vendor: Atlantic Equipment Engineers





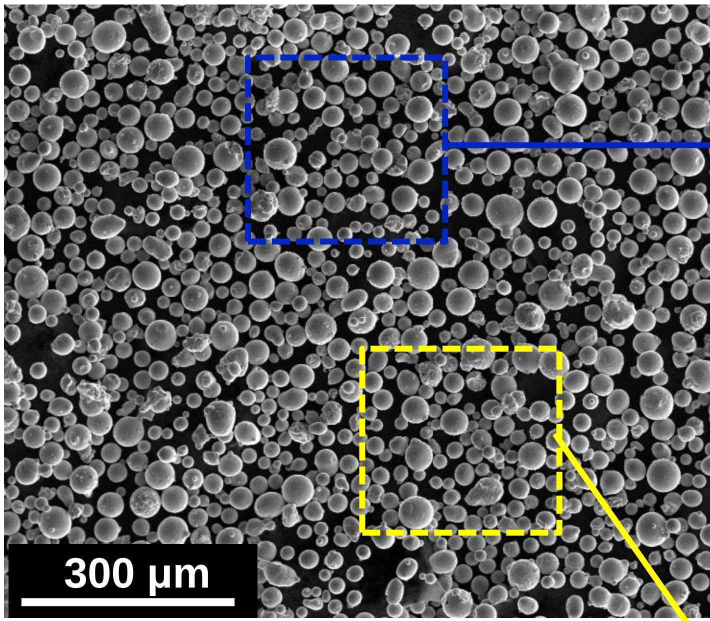
304H powder: 10-45 μm

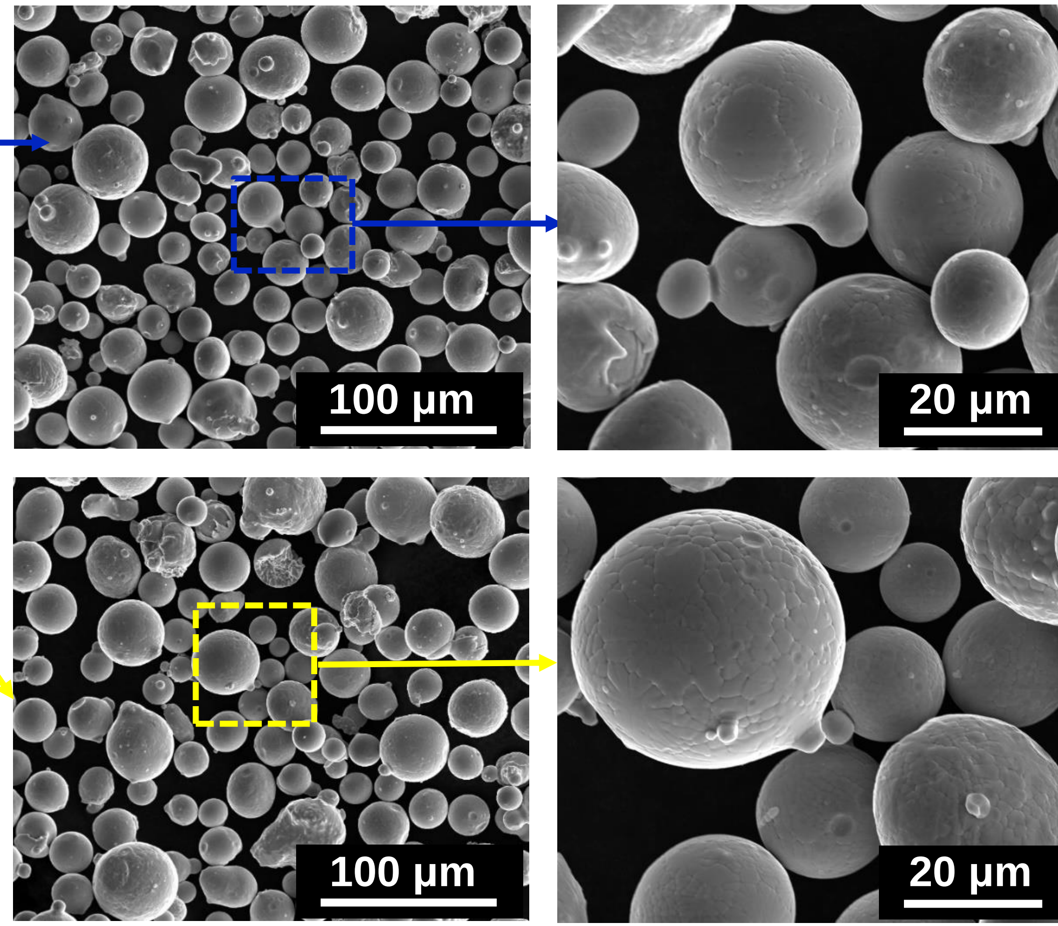


Preparation of Lab-Scale GCTJ - Powder

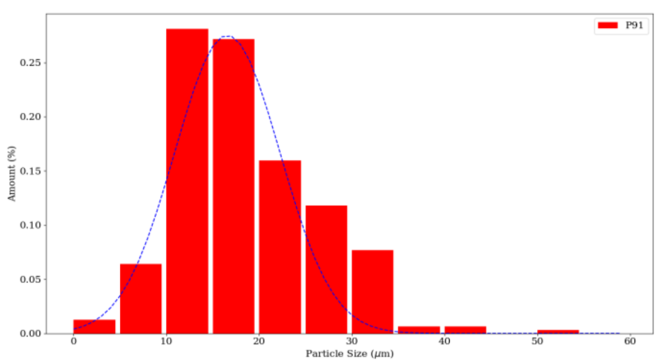
- **SEM of P91 powders**

Vendor: Atlantic Equipment Engineers





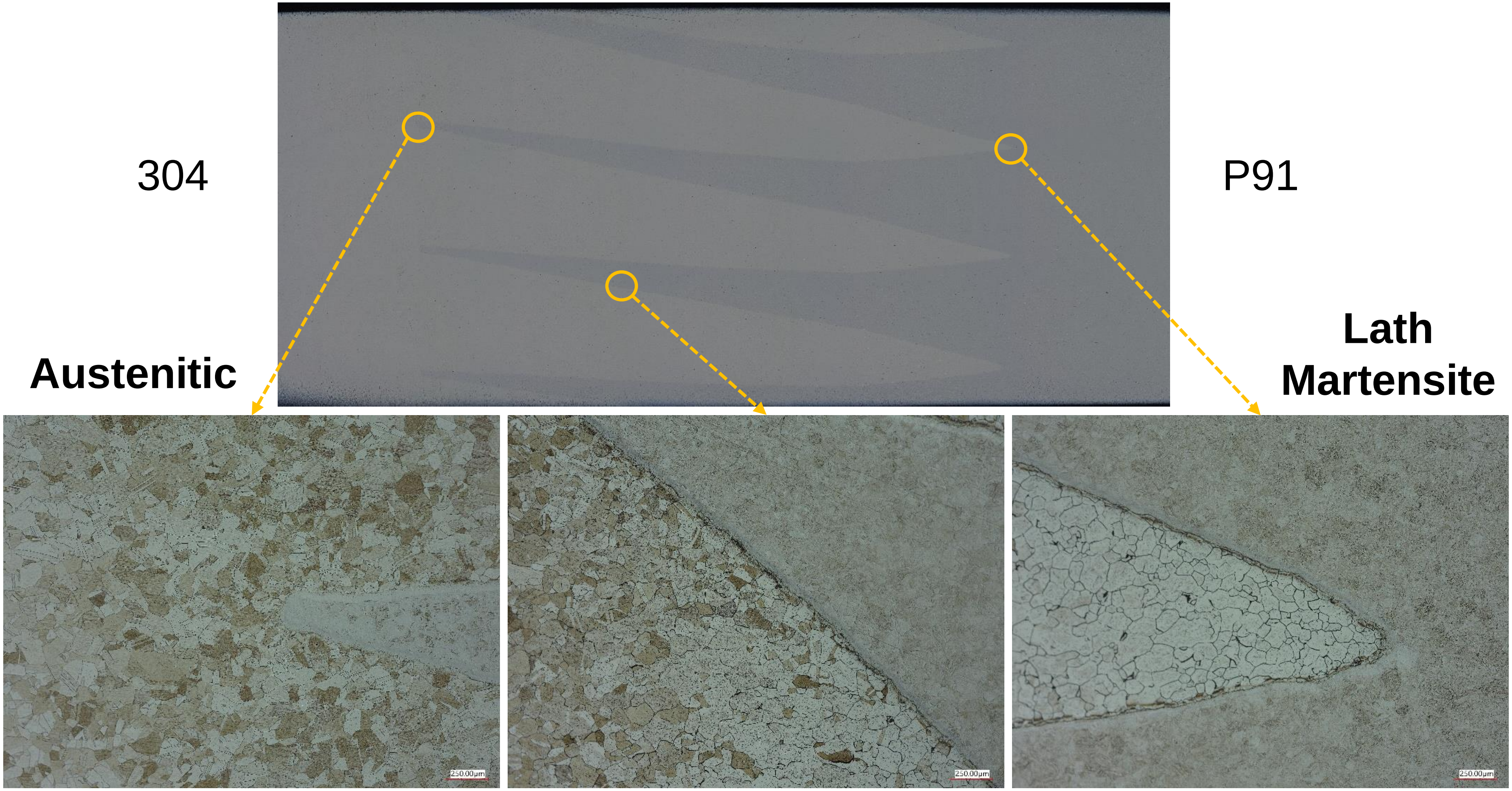
P91 powder: 10-45 µm (vendor)



Microstructure Analysis - AM-GCTJ

❑ **Microstructure of 304 & P91 AM-GCTJ (as received)**

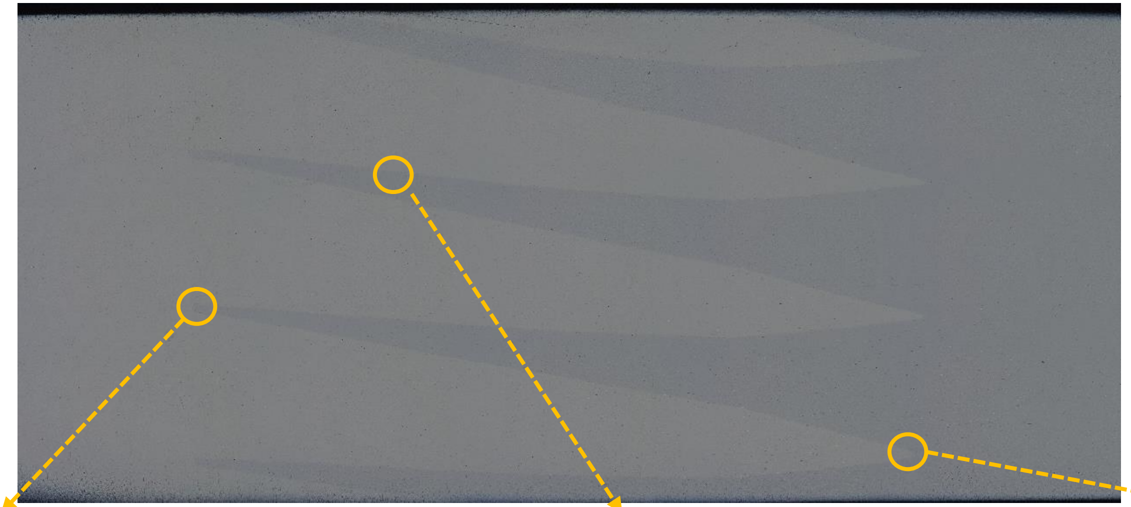
➢ Both 304 and P91 are **with no obvious pores**, and the **adhesion** between 304 and P91 is **good without any visible gaps**



Microstructure Analysis - AM-GCTJ

- **Microstructure of 304 & P91 AM-GCTJ (After Heat Treatment)**
  - **1040°C 1h (AC), 760°C 2h (AC)** was adopted as the heat treatment.
  - **Narrow interface (~40 μm)** between 304 & P91 was observed in the TJ.

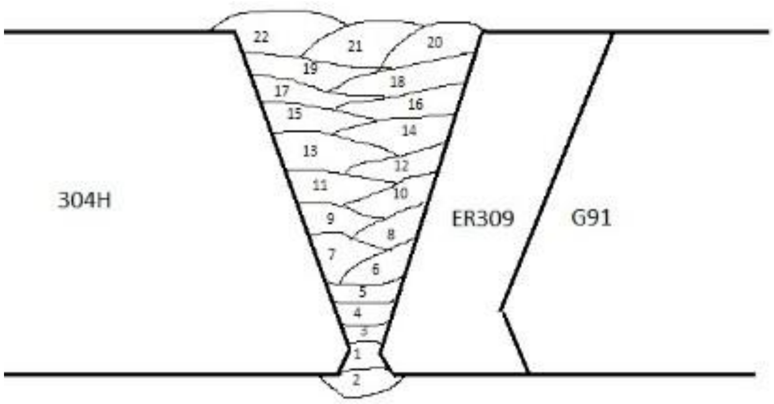
304

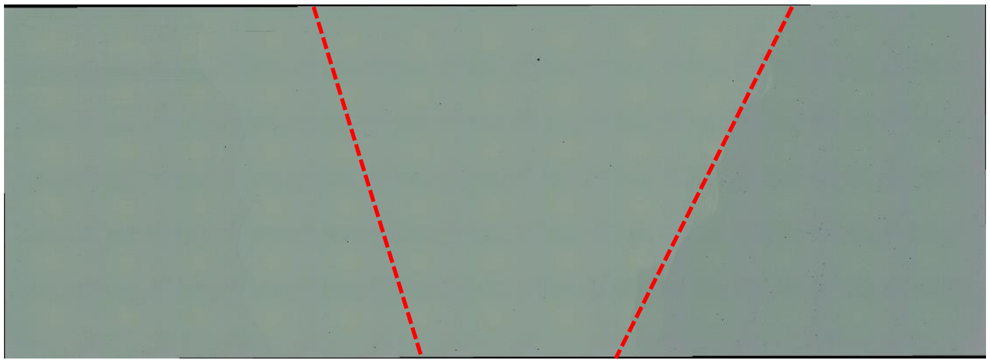


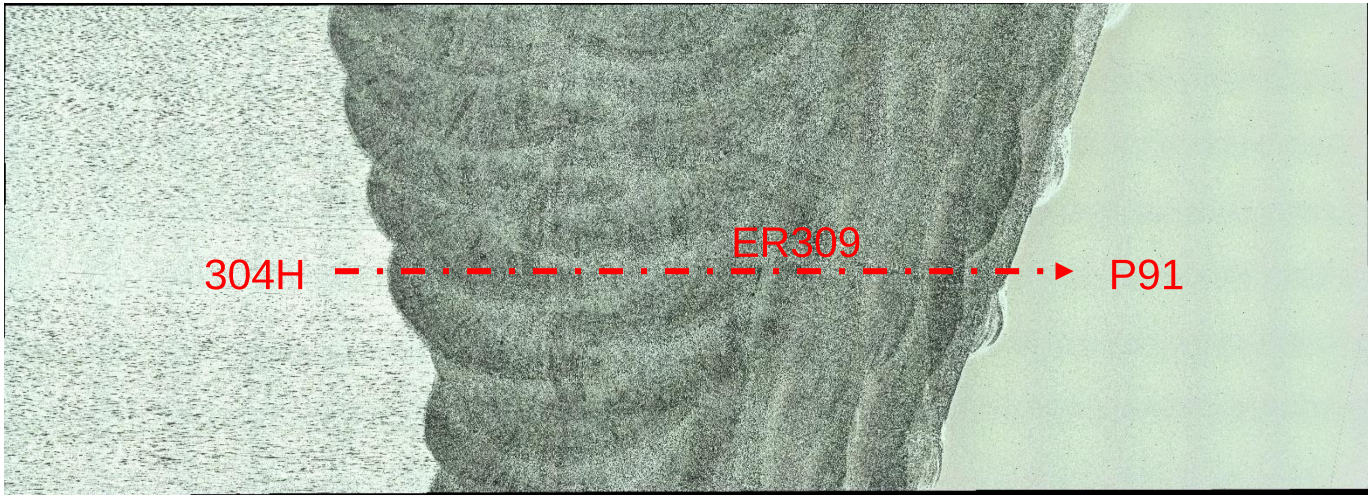
P91

Microstructure Analysis - DMW

- **Microstructure of 304H & P91 DMW**
  - **Abrupt microstructure change** in DMW.

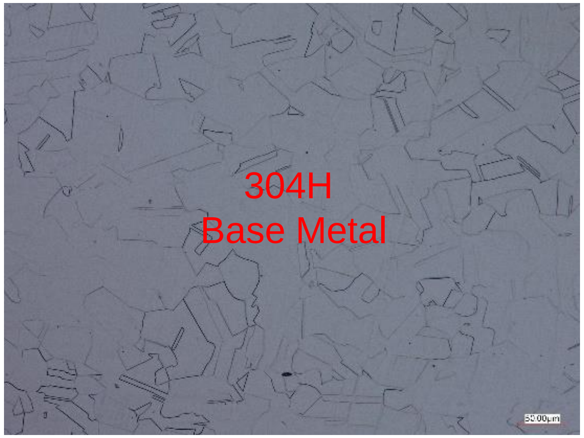


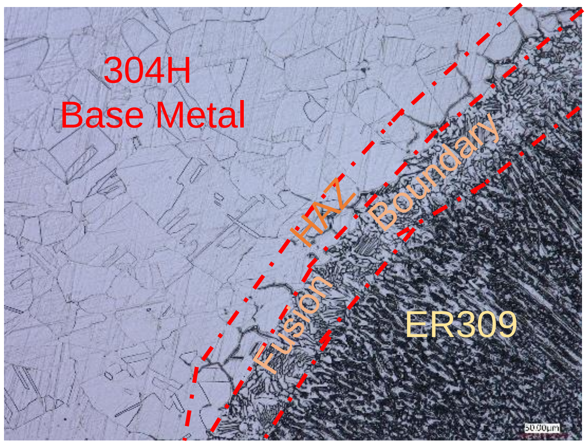


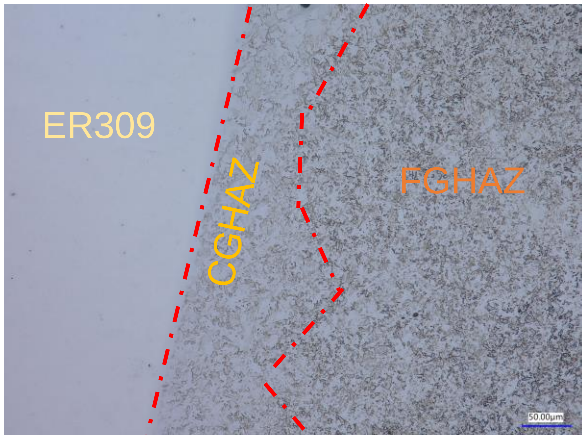


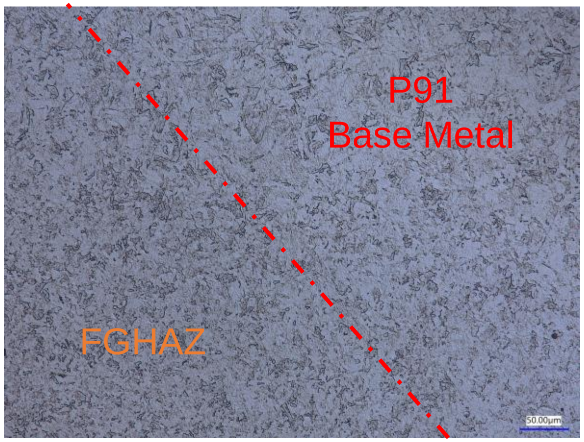
Microstructure Analysis - DMW

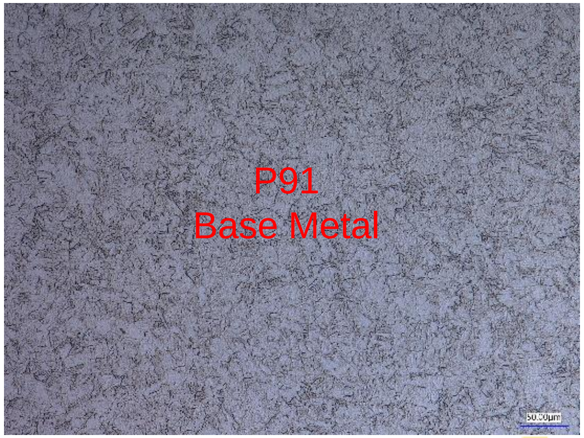
- **Microstructure of 304H & P91 DMW**
  - **Wide Heat Affected Zone (~300 μm)** of P91 was observed in DMW.





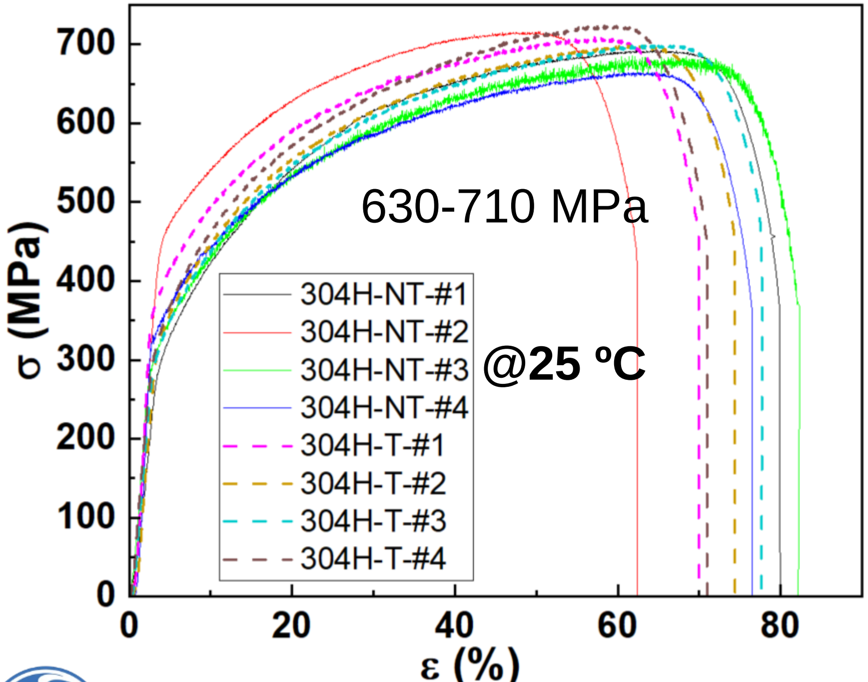


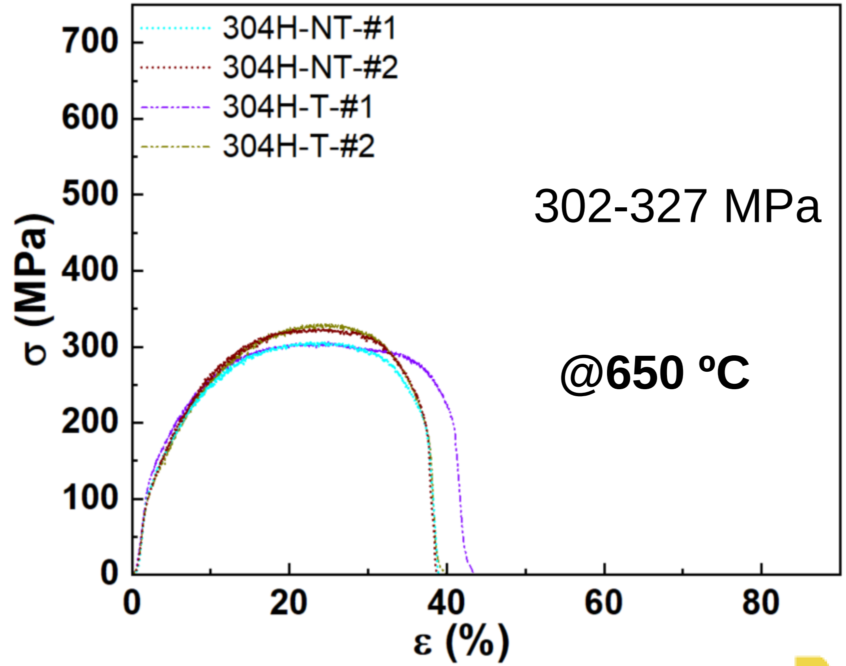




Heat Treatment Assessment – Tensile Strength

- **Tensile strength of 304H sample at room temperature (RT) and 650ºC**
  - Ultimate tensile strength (UTS) of heat treated (T) and non-treated (NT) 304H is **630-710 MPa at RT**, close to the value provided by the vendor (611 MPa).
  - **UTS of 304H are almost same** before and after heat treatment, in the range of **302-327 MPa at 650ºC**.

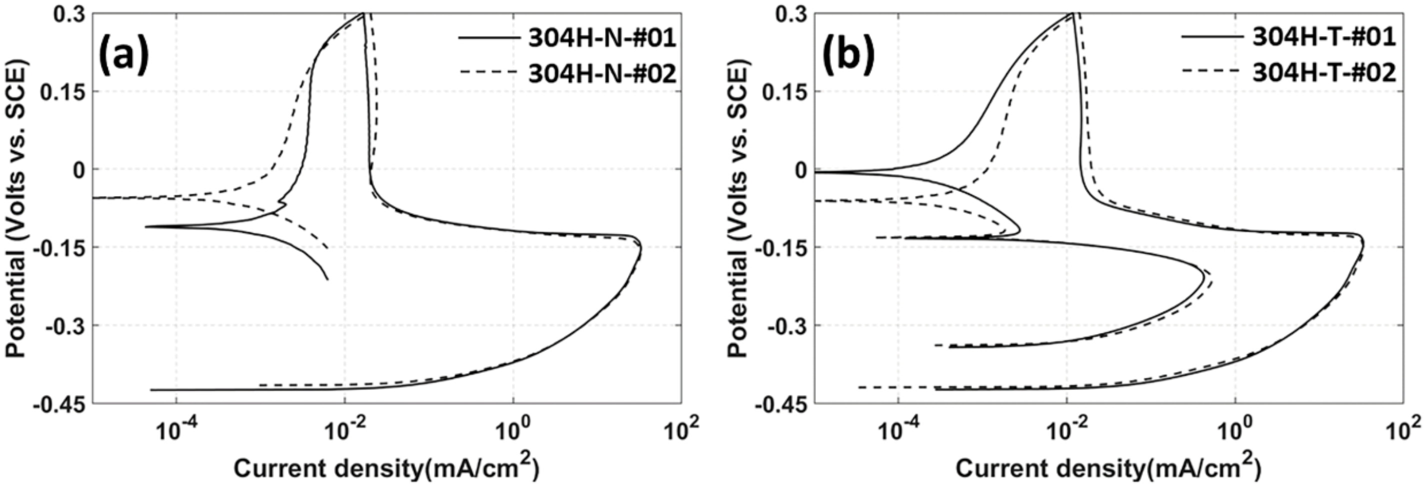




Heat Treatment Assessment – Sensitization

❑ Sensitization and intergranular corrosion resistance

- Degree of sensitization (DOS) is determined using the double-loop electrochemical potentiodynamic reactivation (EPR) tests (ASTM standard G108-94).
- DOS of 304H is increased a little after heat treatment.



Potential vs current density of a) 304H-NT, b) 304H-T.

T: Heat treated

N: Non-treated

<u>Degree of sensitization</u>

- 304H-NT#01: 0.02%
- 304H-NT#02: 0.02%
- 304H-T#01: 1.28%
- 304H-T#02: 1.59%

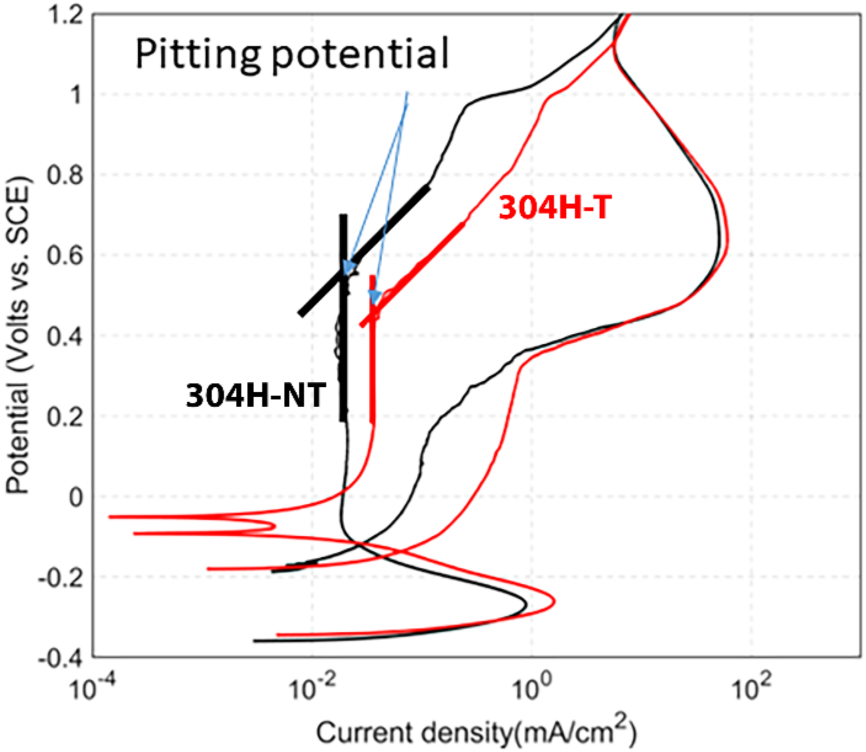
<u>Testing condition</u>

- Solution: 0.5 M H_2SO_4 + 0.01 M KSCN
- Scan rate: 1.67 mV/s

Heat Treatment Assessment – Sensitization

❑ Pitting corrosion resistance

- Pitting resistance is evaluated by potentiodynamic anodic polarization tests (ASTM standard G5-14).
- Pitting resistance is decreased after heat treatment.



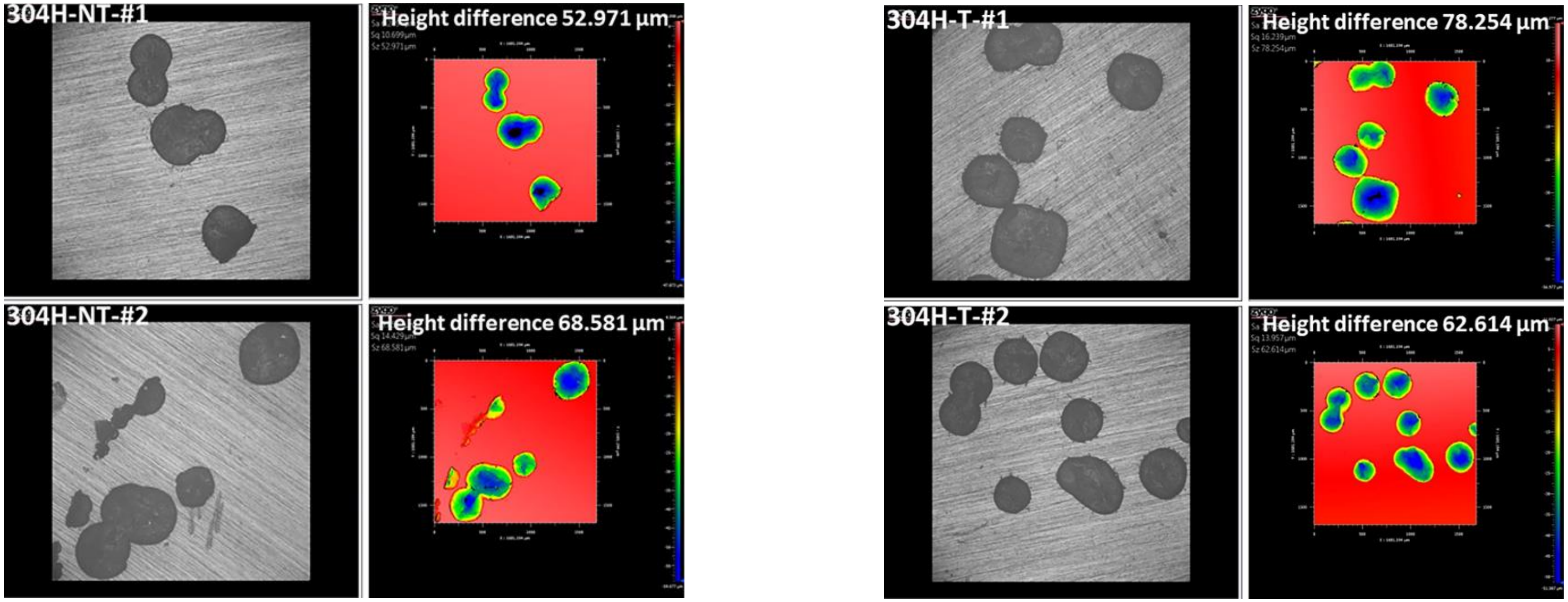
<u>Testing condition</u>

- Solution: 0.5M H_2SO_4 + 0.5M NaCl
- Scan rate: 1.67 mV/s
- Scan range: corrosion potential to 1.2 V

	304H-NT	304H-T
Pitting potential (V)	0.569	0.494
Passivation current (mA)	0.02072	0.0353

Heat Treatment Assessment – Sensitization

- **Pitting corrosion resistance**
  - Pit morphology is characterized using 3D optical profilometry.
  - Pit area percent and depth is increased after heat treatment.



Optical images of pits: (left) 304H-NT, (right) 304H-T

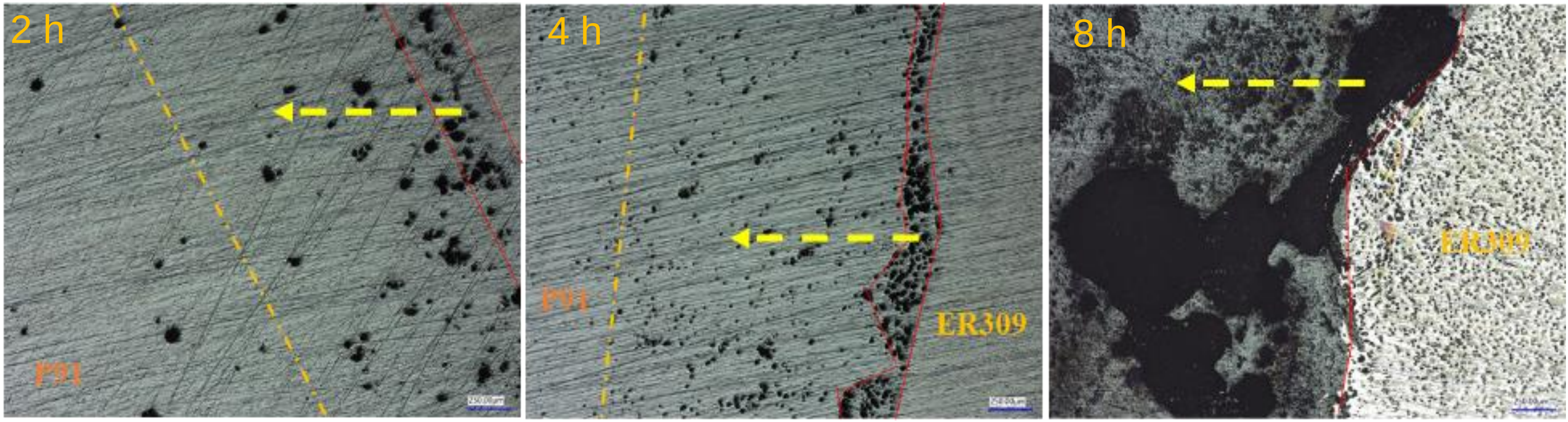
- Pit area percent: 304H-NT (13-20%), 304H-T (23-26%)
- Pit depth: 304H-NT (53-69 µm), 304H-T (63-78 µm)

Microstructure & Heat Treatment - Summary

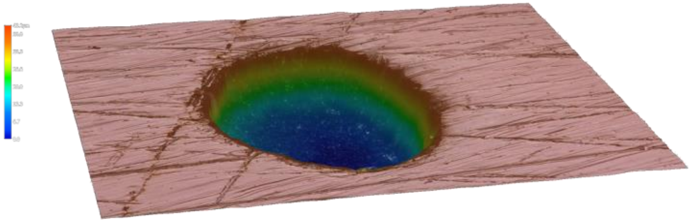
- The bonding interface of AM-GCTJs is much narrower than that of DMWs
  - Good connecting between 304H and p91.
  - Eliminate the heat-affected zone (HAZ) which is vulnerable to creep cracks.
- Heat treatment for 304H & P91 AM-GCTJs does little hurt to their strength and intergranular corrosion resistance of 304H
  - Ultimate tensile strength (UTS) of heat-treated (T) and non-treated (NT) 304H tested at room temperature is close to the value provided by the vendor and the UTS of 304H-T and 304H at 650^{o}C is close to each other.
  - The Degree of Sensitization increased a little after heat treatment.
  - Heat treatment affects the pitting resistance of 304H due to sensitization.

Localized Hot Corrosion Resistance Comparison - DMW

- **Pitting Corrosion**
  - ~1 mg/cm^2 Na_2SO_4+ $MgSO_4$ (55 at%:45 at%) as deposited salts were applied on the surface of DMW.
  - Localized hot corrosion initially happened in the form of pits along the HAZ of P91 in DMW.

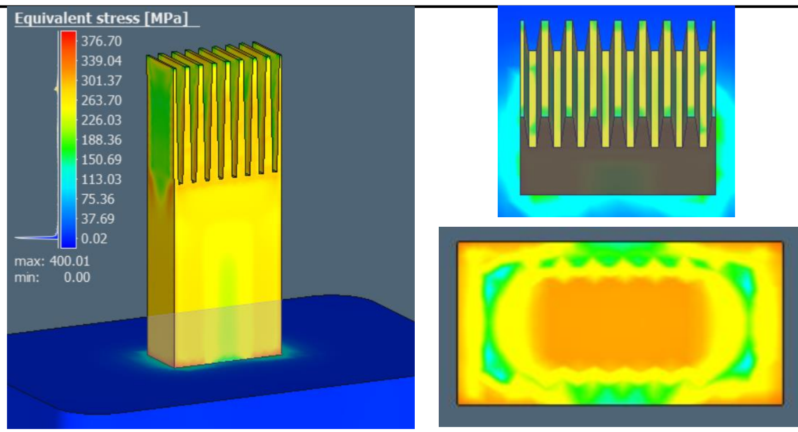
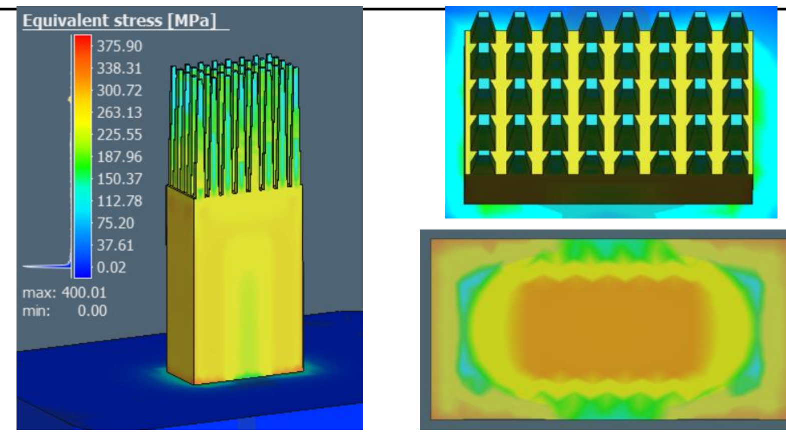
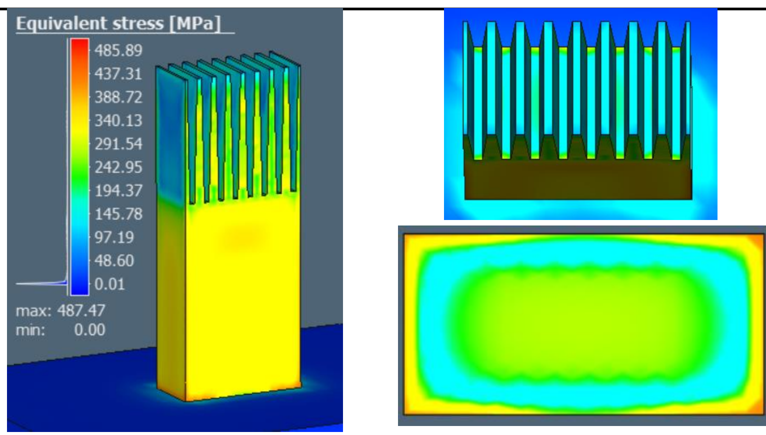
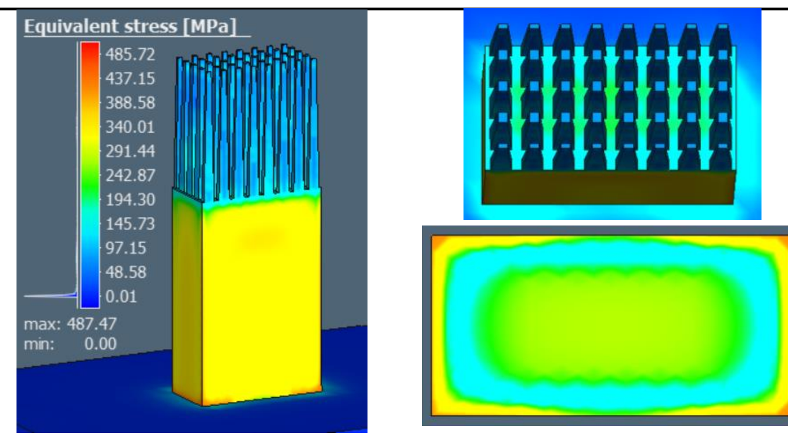


After 4 h
Depth of pits: 43 μm



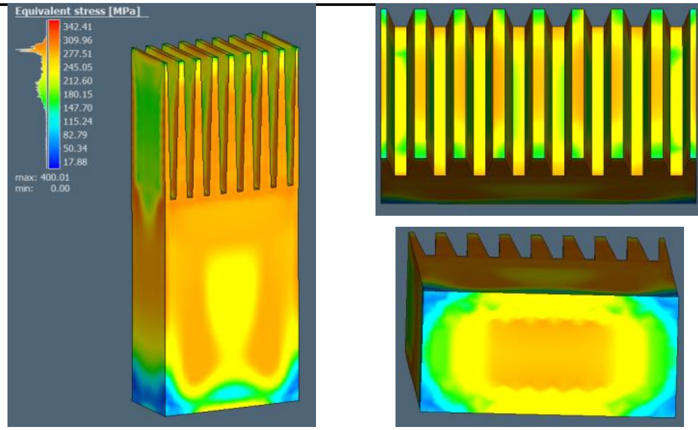
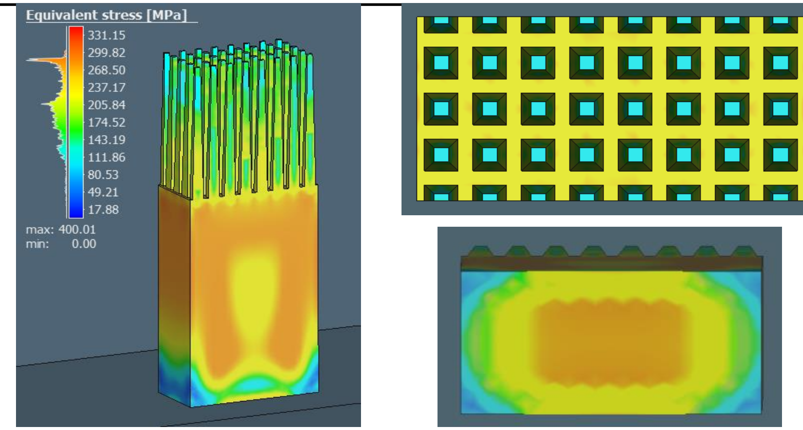
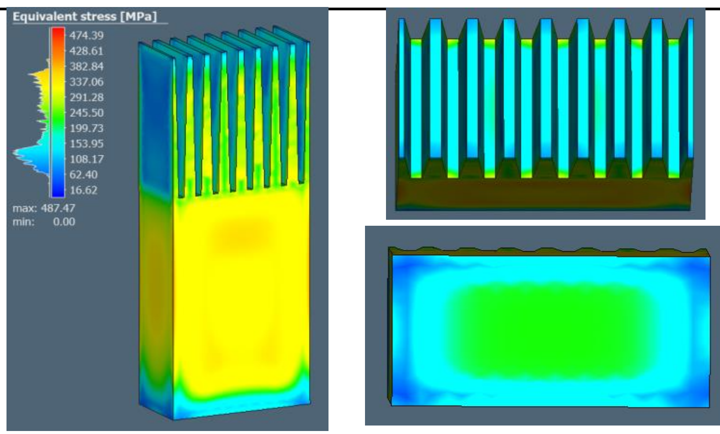
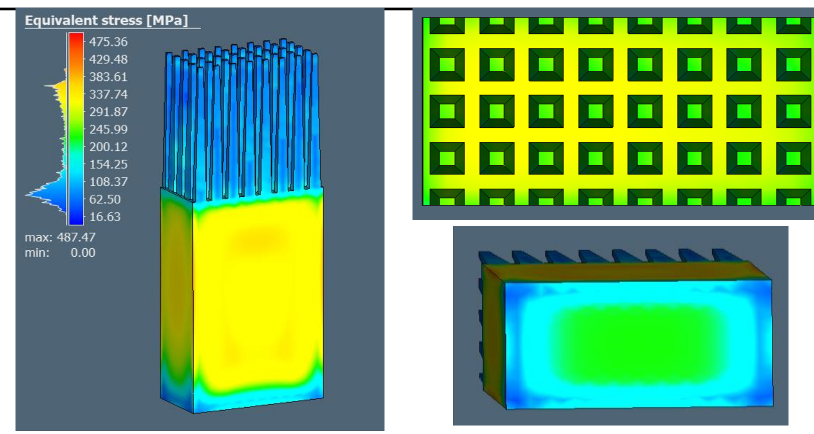
Prototype GCTJ Development - Process Simulation

- Stress before being removed from the build plate

	Ridges	Pyramids
SS304 H		
IN617		

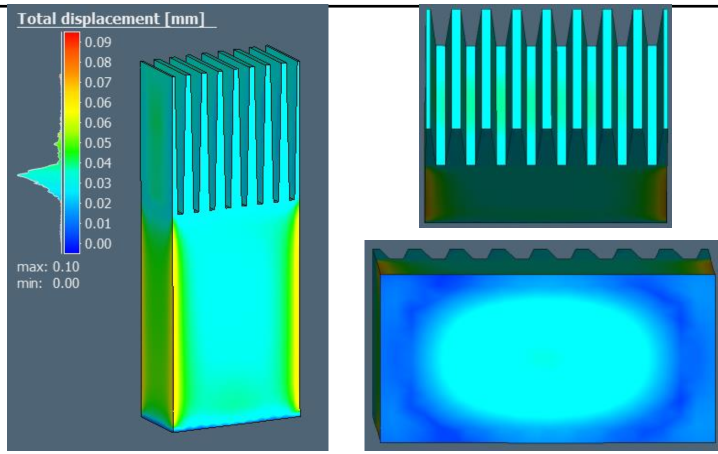
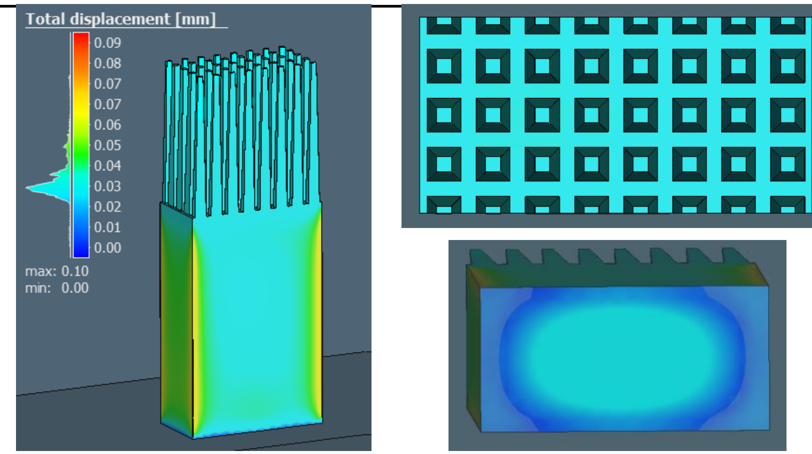
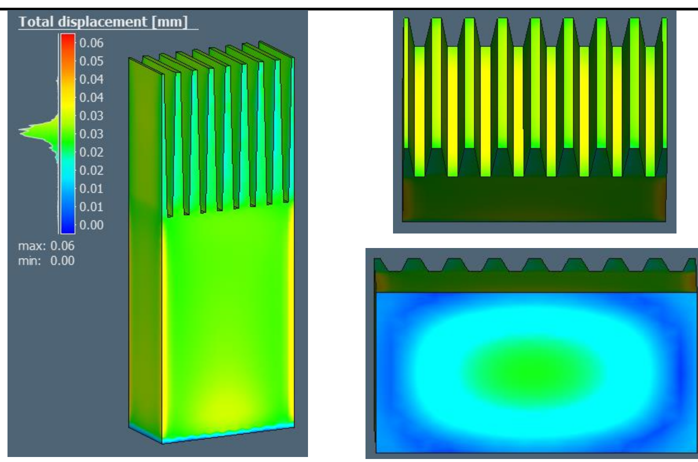
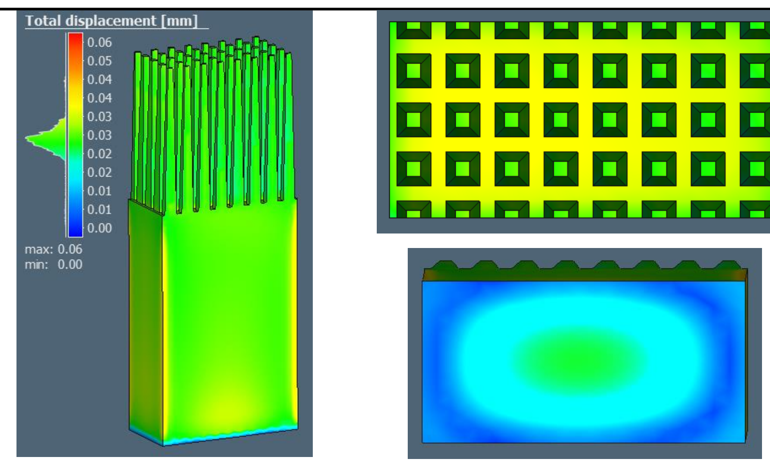
Prototype GCTJ Development - Process Simulation

- Stress after being removed from the build plate

<table>
<tr><th></th><th>Ridges</th><th>Pyramids</th></tr>
<tr><td>SS304 H</td><td></td><td></td></tr>
<tr><td>IN617</td><td></td><td></td></tr>
</table>

Prototype GCTJ Development - Process Simulation

❑ Strain after being removed from the build plate

	Ridges	Pyramids
SS304H		
IN617		

Process Simulation - Summary

- Future Inputs that could improve analysis:
  - Machine specific print rotation angle
  - Machine specific print layer height
  - Physical cantilever testing to improve inherent strain values
- Points of interest are:
  - Vertical edges for all specimens
  - Base of pyramid specimens
- B vs A geometries:
  - Very similar equivalent stress magnitudes
  - Similar stress and displacement distribution
- SS304H vs Inconel 617
  - Higher peak stress in Inconel 617
  - Larger deflection in SS304H
  - Similar average stress between materials

Summary

- We designed and fabricated a new class of AM- GCTJ
  - Optimize the geometry of GCTJ by the ICWE model
  - Avoid the wide heat-affected zone compared with DMWs
  - Improve the microstructure by reasonable heat treatment
  - Significantly enhance creep resistance, as compared with conventional DMW
- AM-GCTJ has broad applications in various energy systems, AUSC, Gas, CSP, NE, etc.

Future Plan

- Investigate the interfacial diffusion between P91 and 304, 282 and 304
- Optimize the heat treatment process of AM-GCTJ for 304&282
- Continue the characterization of thermal-fatigue and creep test of the AM-GCTJ and optimize the design of AM-GCTJ
- To manufacture and test the components with AM-GCTJ, to advance the technology readiness level to TRL-7, and manufacturing readiness level to MRL 6-7
- Work on detailed TEA and start code case

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- All Collaborators and Team Members

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