Evaluating Ni-Based Alloys for A-USC Component Manufacturing and Use (FWP-FEAA152)

Xiang (Frank) Chen, *Timothy Lach, Jiahao Cheng, Peter Tortorelli, Michael Santella, Edgar Lara-Curzio*

Oak Ridge National Laboratory

Jack deBarbadillo

Special Metals Corporation

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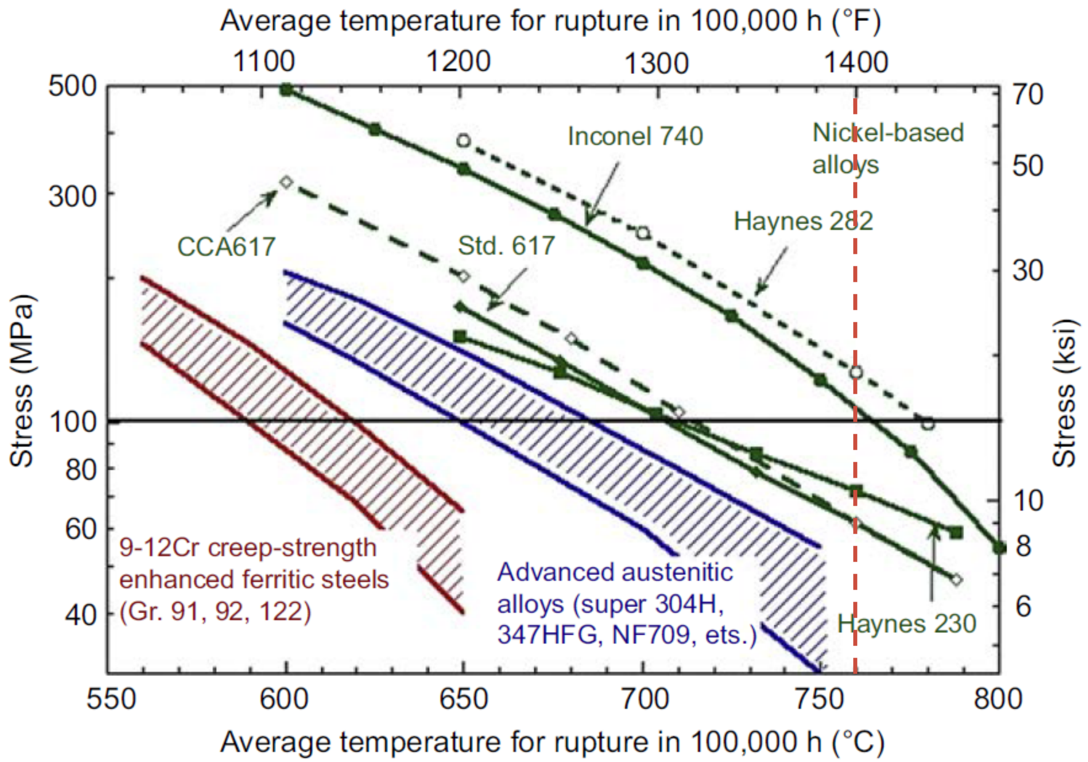
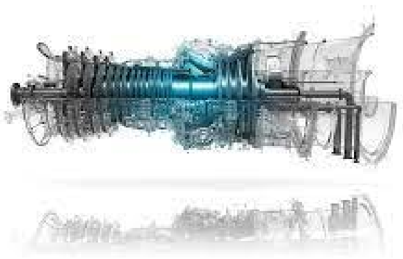
Background

- Advanced Ultra-Supercritical (A-USC) power plants promise higher efficiency and lower emissions achieved by steam conditions up to 760°C/35 MPa
- Two precipitation-strengthening Ni-based alloys, **Haynes® 282 ® and Inconel® 740H®,** are considered as leading candidate materials for A-USC applications
- Due to their high temperature strength and corrosion resistance, both materials may also find applications in **hydrogen turbine, sCO_2 plants, concentrated solar, and advanced HRSGs**

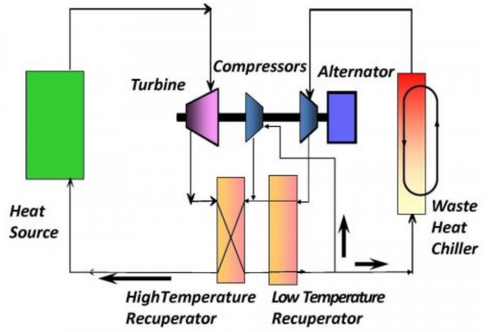


100 kh creep rupture strength as a function of temperature

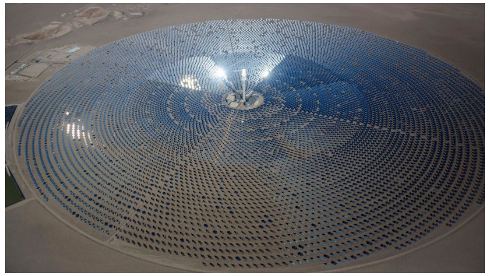
Shingledecker et al 2013



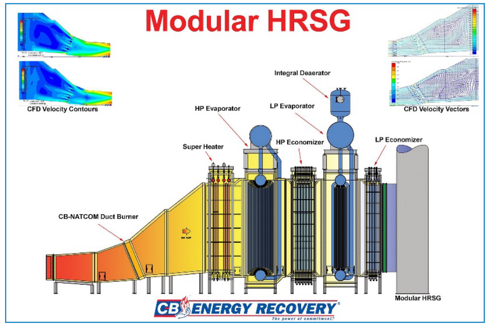
Hydrogen turbine



sCO2 plants



Concentrated solar

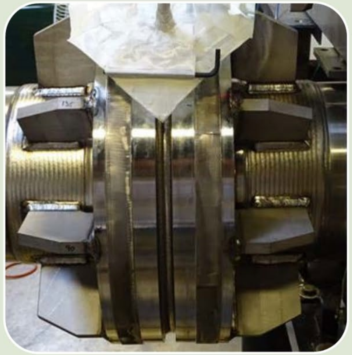


Advanced HRSGs

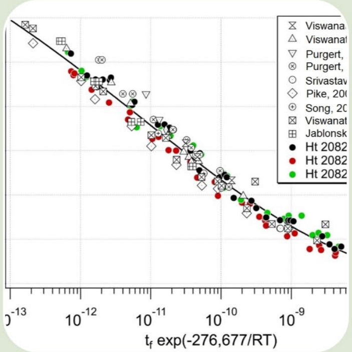
Objective: This research provides a critical evaluation of advanced Ni-based alloys supporting the manufacturing and use of components under A-USC and other extreme environment conditions

Haynes 282 sand casting

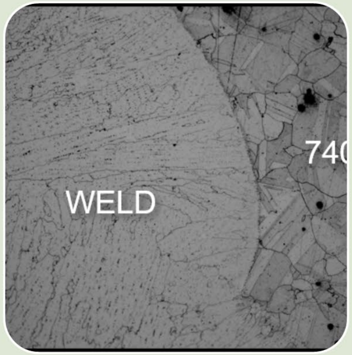
Haynes 282 forged disk



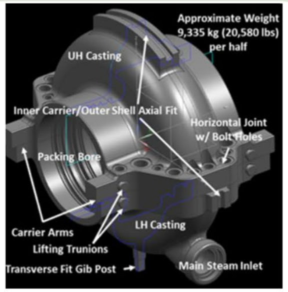
Cast Haynes 282 GTAW



Creep modeling



Inconel 740H SMAW



Planned 10-ton Haynes 282 nozzle carrier casting

ComTest Phase 2 materials

Publications under this project

1. Santella et al., Materials Science and Engineering: A vol. 838, 2022
2. Santella et al., Welding in the World vol. 65, 2021
3. Wang et al., Materialia vol. 15, 2021
4. Render et al., Met Trans. A. vol 52, 2021
5. Wang et al., Materials Science and Engineering: A, vol. 828, 2021
6. Unocic et al., JOM vol 72, 2020
7. Chen et al., Joint EPRI-123HiMAT International Conference on Advances in High Temperature Materials, 2019

Crystal Plasticity Finite Element (CPFE) modeling for Triple-melt Forged Haynes 282 and Double-melt Inconel 740H Plate

Crystal Plasticity Finite Element (CPFE) Modeling for Haynes 282 (H282) and Inconel 740H (IN740H)

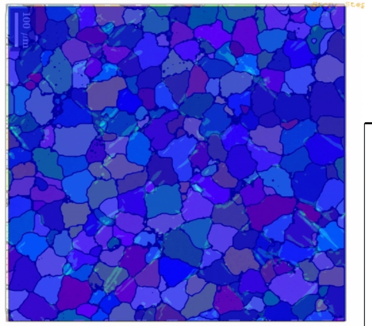
- CPFE is a versatile material modeling tool for investing the material’s microstructure-properties relationship and predicting material’s deformation and failure behavior, e.g., during service or forming process.

- **The target of work is to establish model for H282 and IN740H that predicts the deformation, ductility, and fatigue behavior under relevant service conditions, considering the influence from the microstructure**

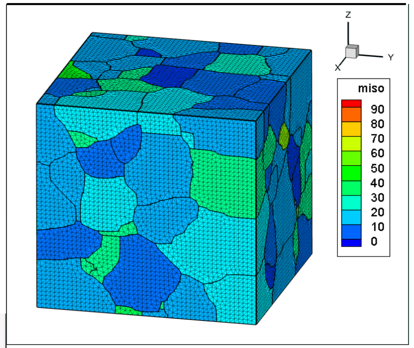
Step 1	Step 2	Step 3
Microstructural CPFE model construction	Model parameter calibration (yield, hardening, cyclic, rate sensitivity, damage)	Fatigue model. simulation and fatigue life prediction
Done	**Done**	**Ongoing**

Examples of our CPFE models

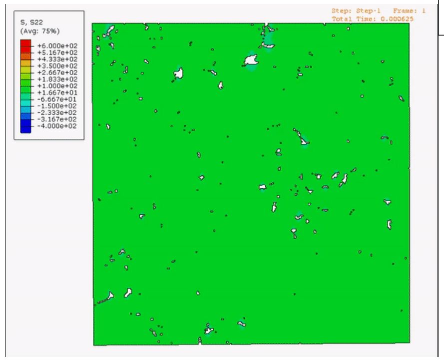
Dislocation evolution



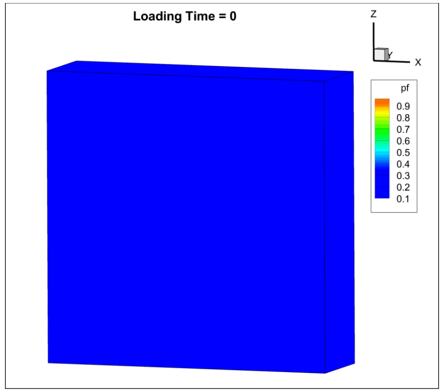
Deformation twinning



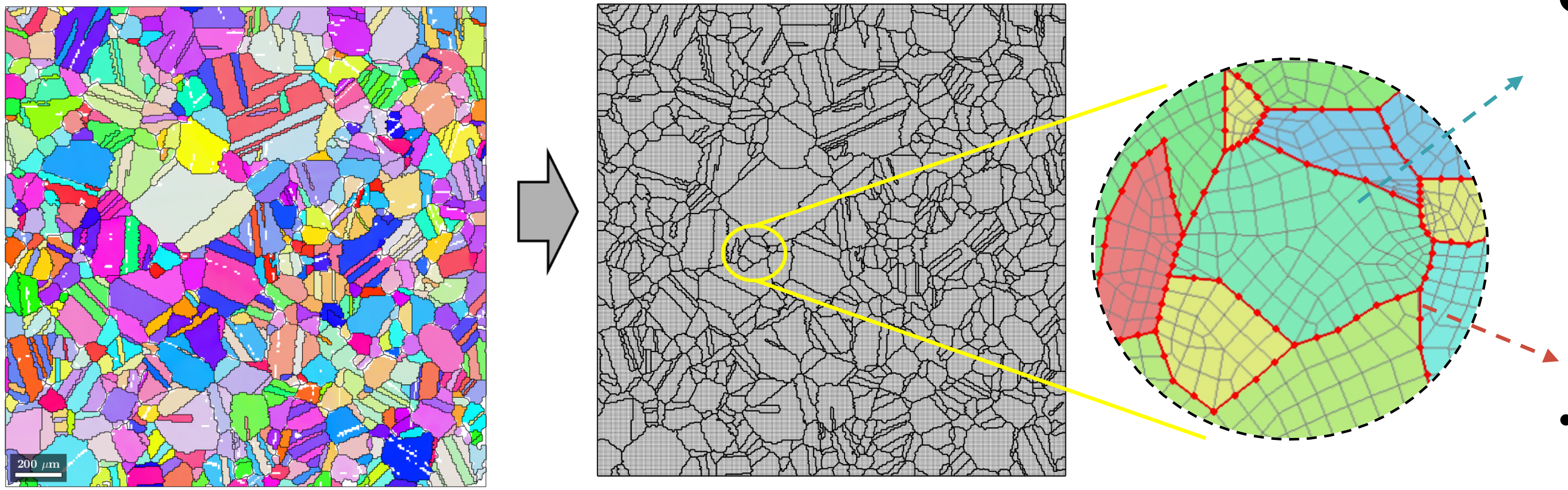
Fatigue failure



Micro-crack formation



Step 1, Conversion of EBSD into CPFE model



(EBSD) of IN740H

High resolution FE mesh

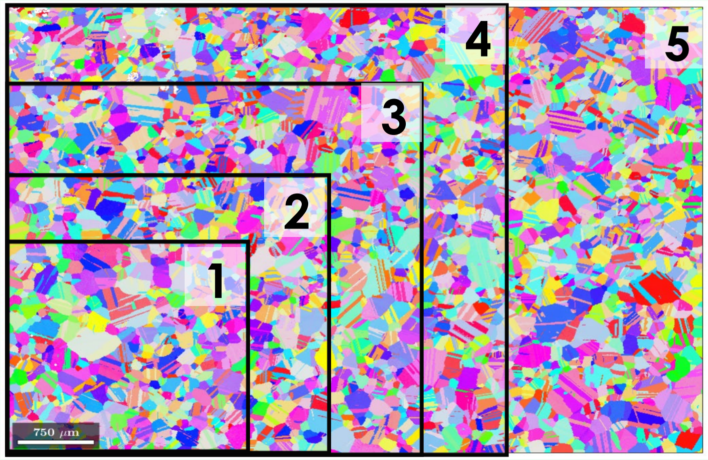
Continuum grain elements

- Slip-induced plastic flow
- Dislocation creep
- Strain hardening
- Damage and Intragranular fracture

Grain boundary interface elements

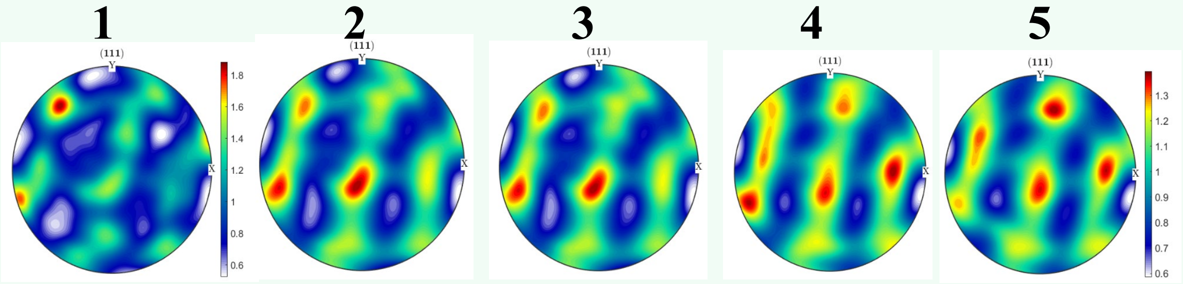
- Grain boundary diffusion (Coble creep)
- Grain boundary damage

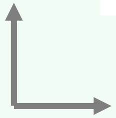
Convergence study for CPFE model



IN740H

(111) Pole figures:

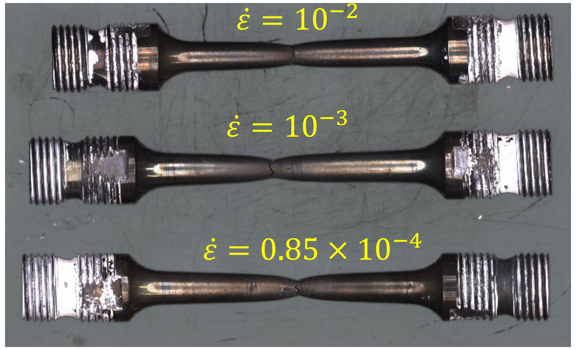




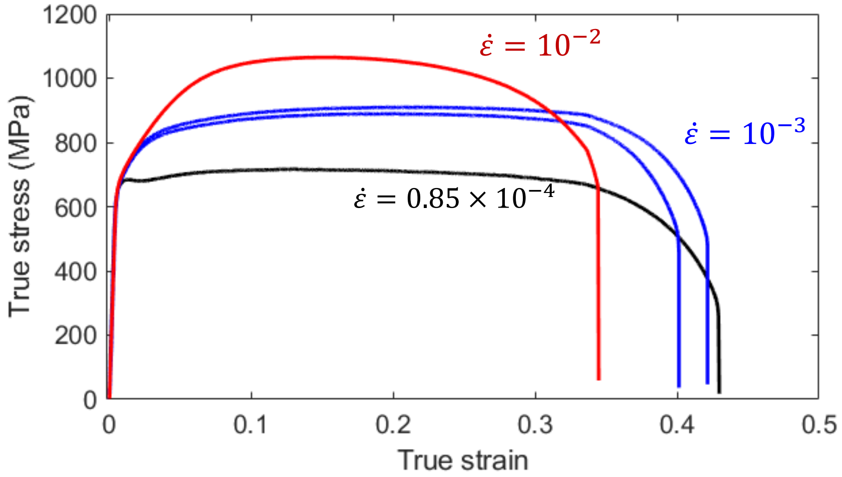
Minimum area for model

Step 2, Model parameter calibration for tensile testing of H282 at 760°C

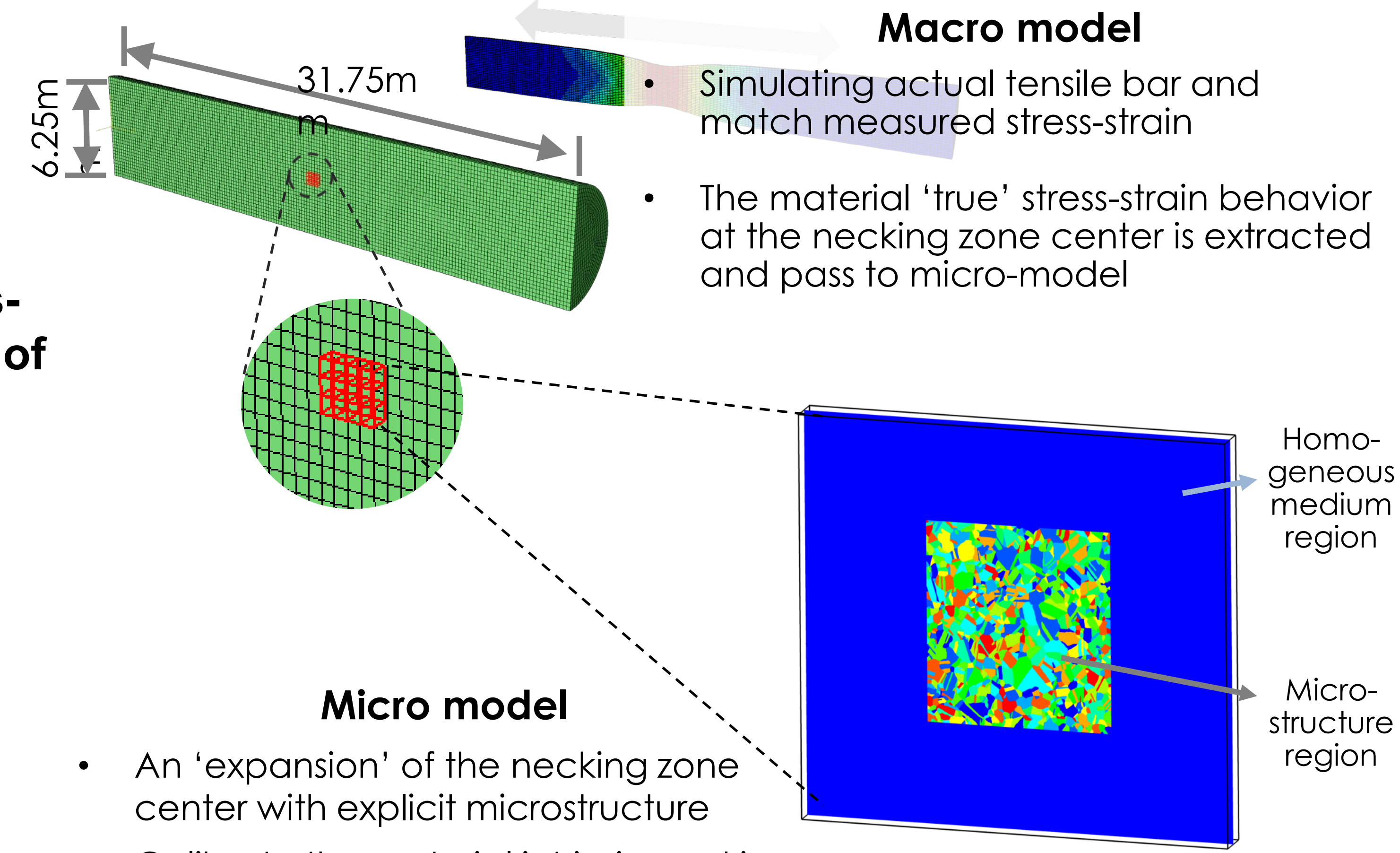
Most parameters can be calibrated from tensile tests



However, with occurrence of necking before final fracture, the measured stress-strain does not reflect the 'true' behavior of the microstructure, due to the very heterogeneous deformation



A novel macro-micro approach is developed in this work to find grains' intrinsic plasticity and failure properties.



Macro model

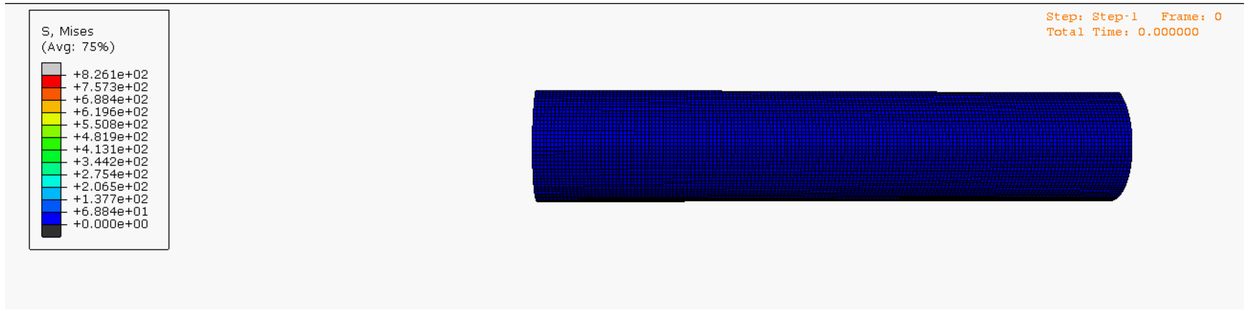
- Simulating actual tensile bar and match measured stress-strain
- The material 'true' stress-strain behavior at the necking zone center is extracted and pass to micro-model

Micro model

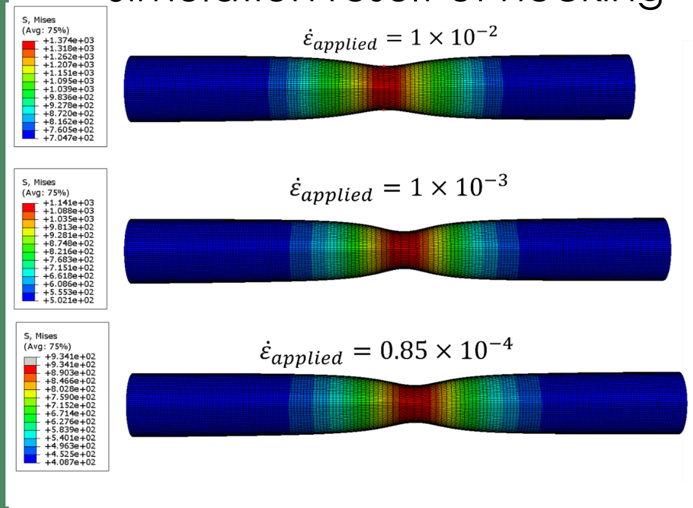
- An 'expansion' of the necking zone center with explicit microstructure
- Calibrate the material intrinsic necking and ductility properties at micro-level

Macro model simulations adequately captured the stress-strain, necking strain and reduction of area with experiments

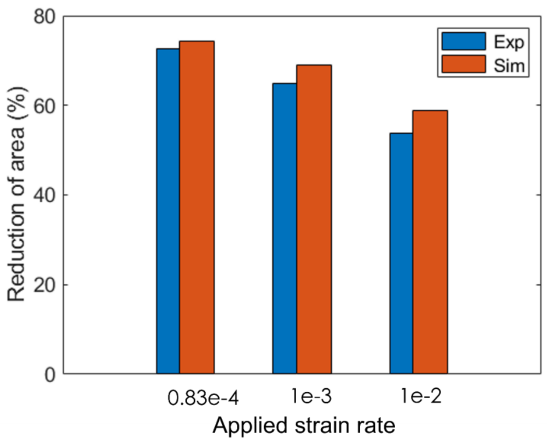
tensile rod simulation animation



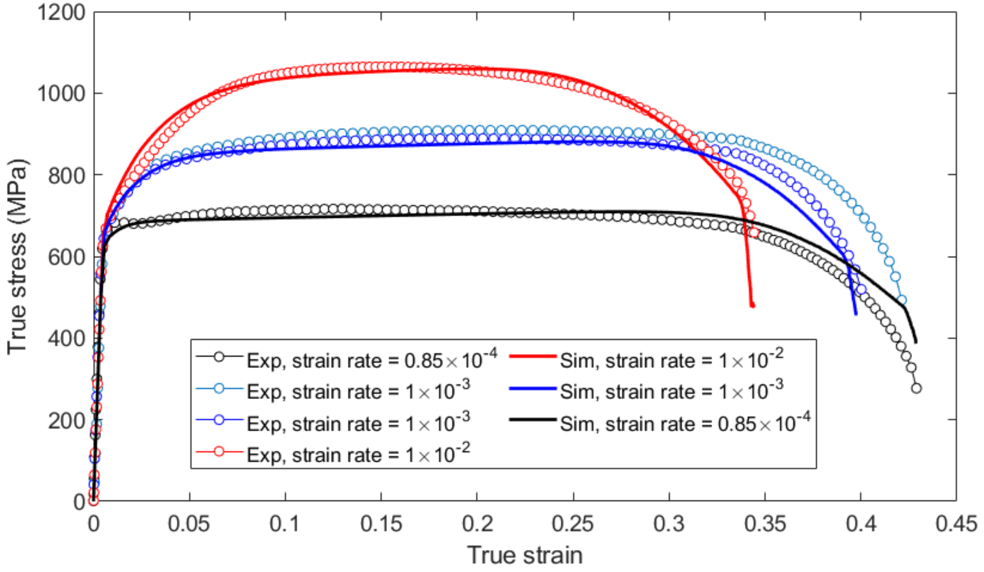
Simulation result of necking



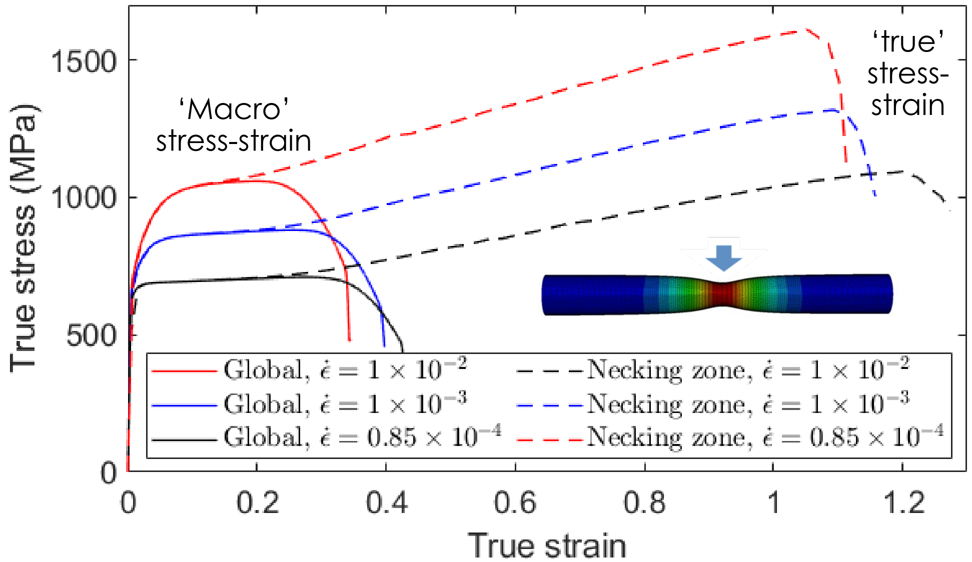
Reduction of area



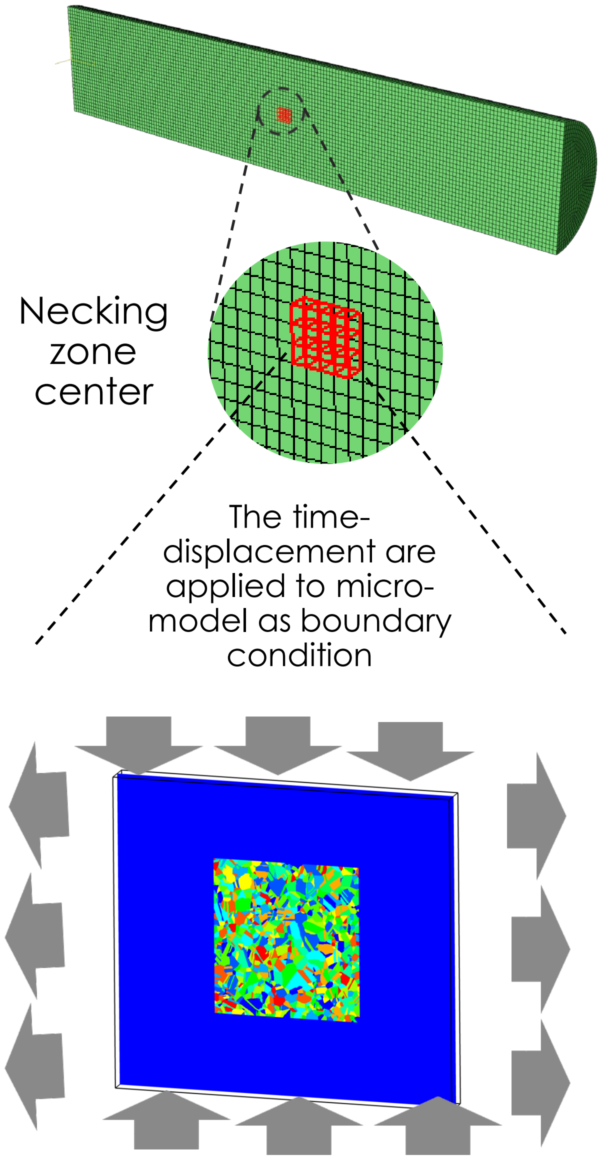
Simulation vs experiment stress-strain



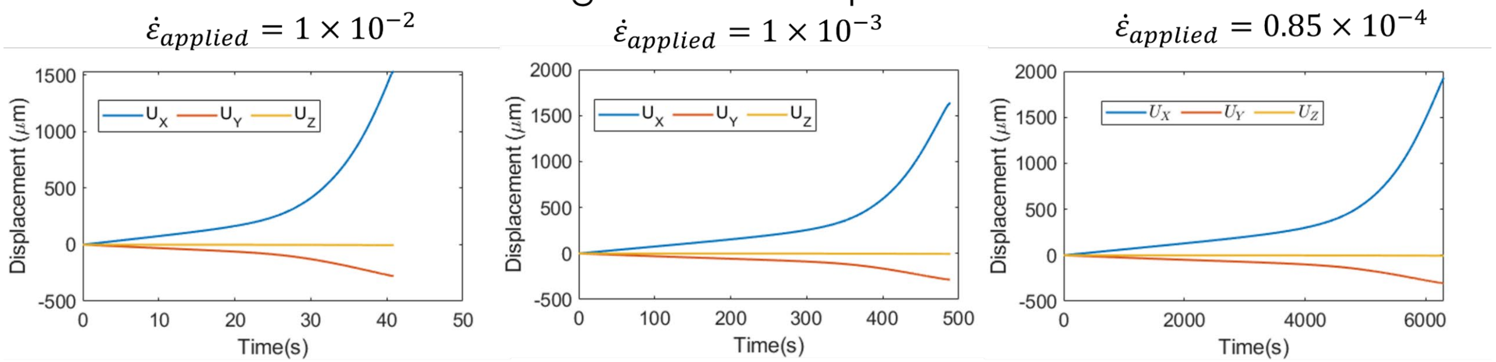
The true 'stress-strain' behavior of necking zone center is then obtained from macro-model simulation



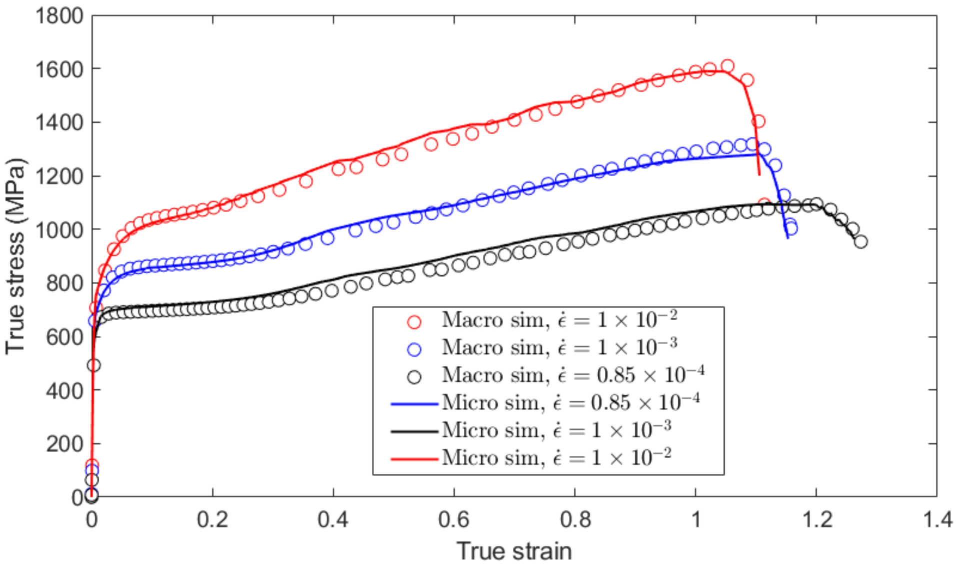
By using the local true 'stress-strain' of necking zone center to calibrate the microstructure-model, the material intrinsic parameters (such as rate-sensitivity parameter and material true ductility) are uncovered.



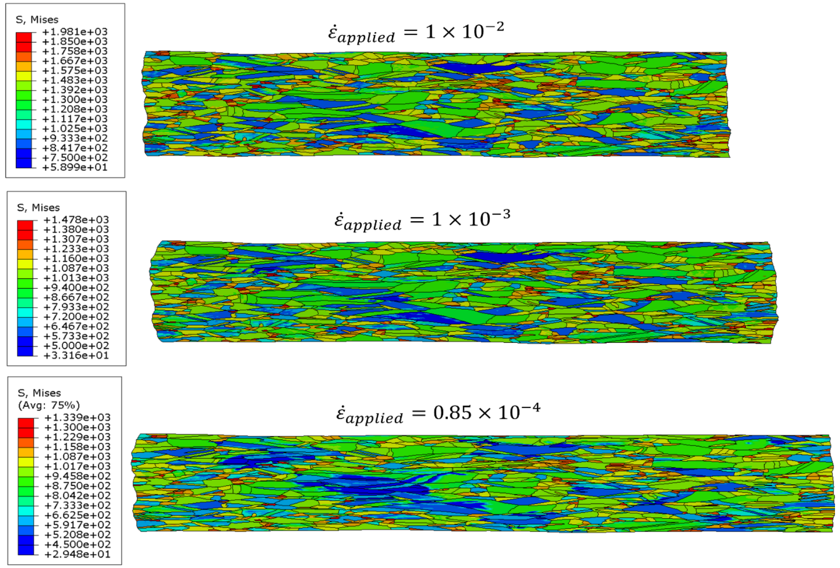
Necking zone time-displacement



Micro-model necking center region simulation results



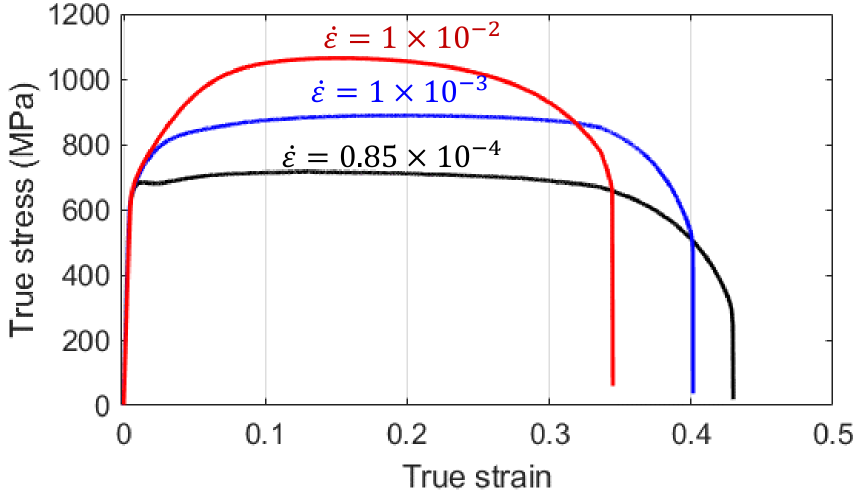
Deformed shape of micro-model microstructure region

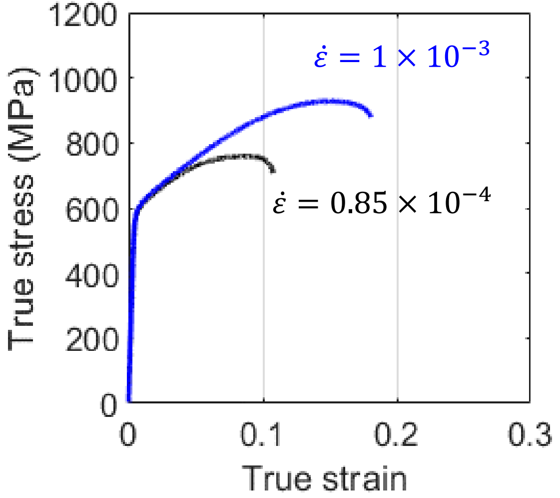


* A manuscript "A Macro-Micro Approach for Identifying Crystal Plasticity Parameters for Necking and Failure in Nickel-Based Superalloy" is under review for International Journal of Plasticity.

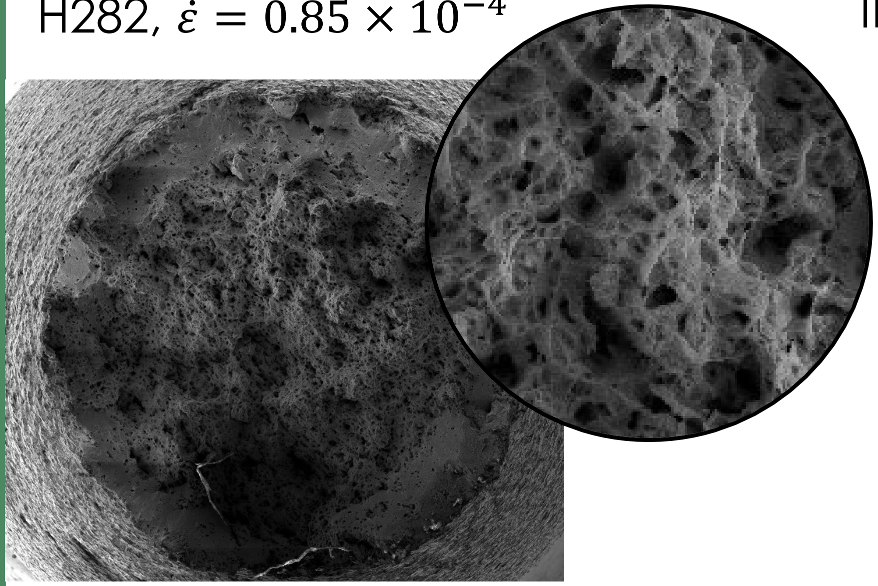
Step 2, Model parameter calibration for tensile testing of IN740H at 760°C

- Unlike H282, IN740H showed limited ductility and does not exhibit necking
- In addition, the tensile tests of IN740H showed increased ductility with tensile strain rate, which is opposite to classic metallic materials
- The fractography of IN740H revealed an interesting brittle-to-ductile transition of fracture behavior when strain rate is increased, which is not observed in H282

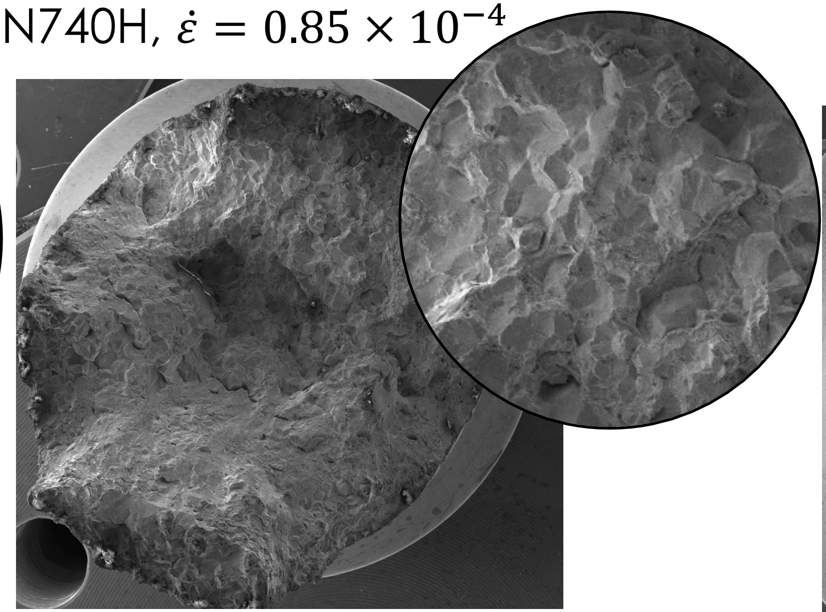




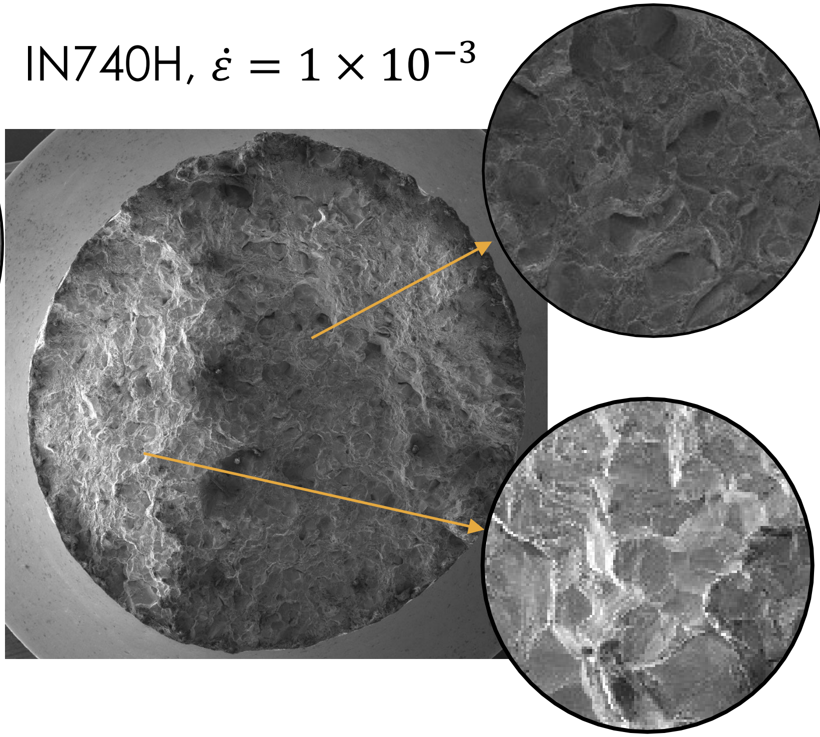
H282, $\dot{\varepsilon} = 0.85 \times 10^{-4}$



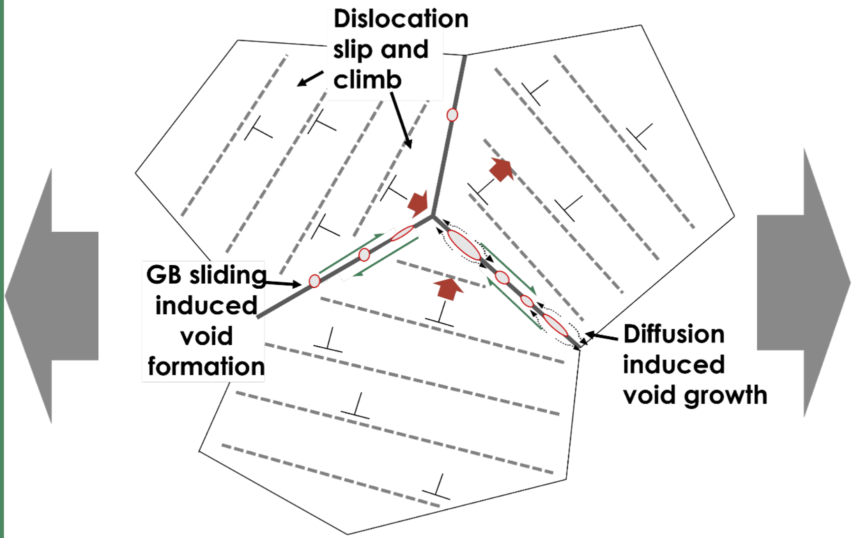
IN740H, $\dot{\varepsilon} = 0.85 \times 10^{-4}$

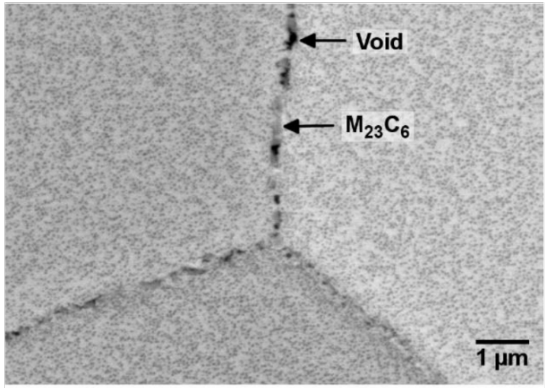


IN740H, $\dot{\varepsilon} = 1 \times 10^{-3}$

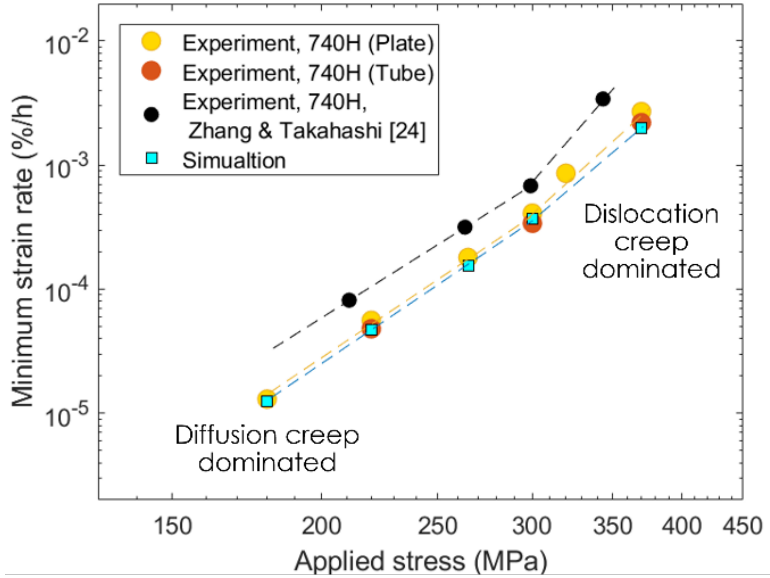


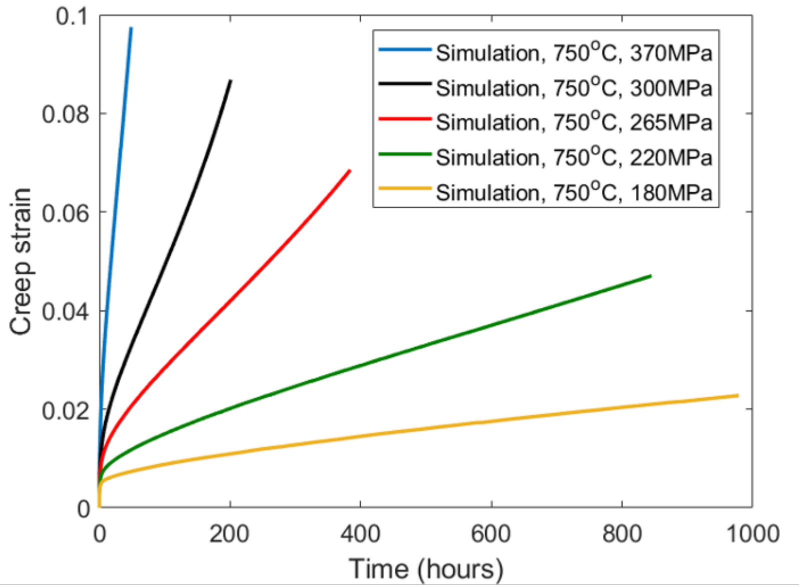
- **The fractography suggest grain boundary (GB) sliding is responsible for failure at lower strain-rate**
- **The GB sliding and damage is explicitly modeled in CPFE using grain boundary interface elements.**
- **The additional creep tests data are used to calibrate the GB model parameters.**





INCONEL 740H Creep test and simulation at 750C

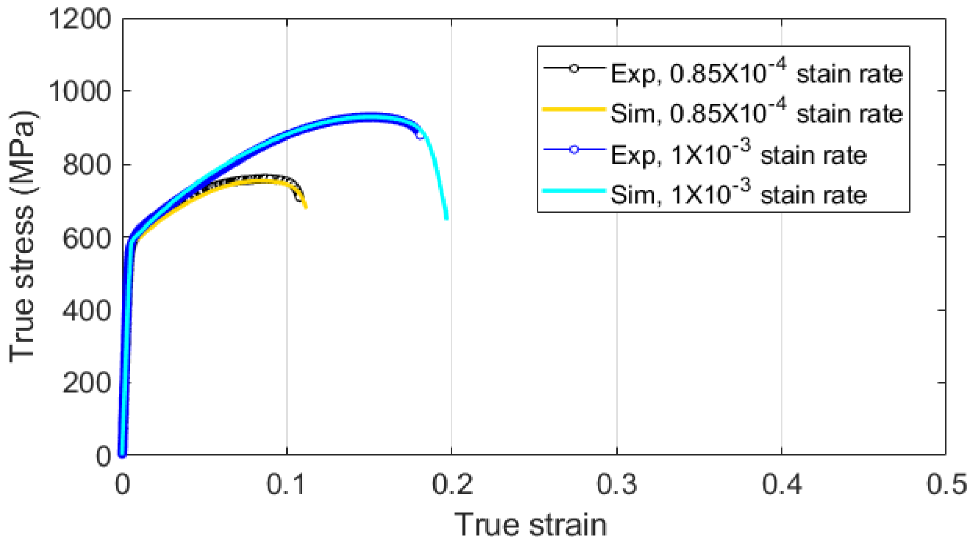




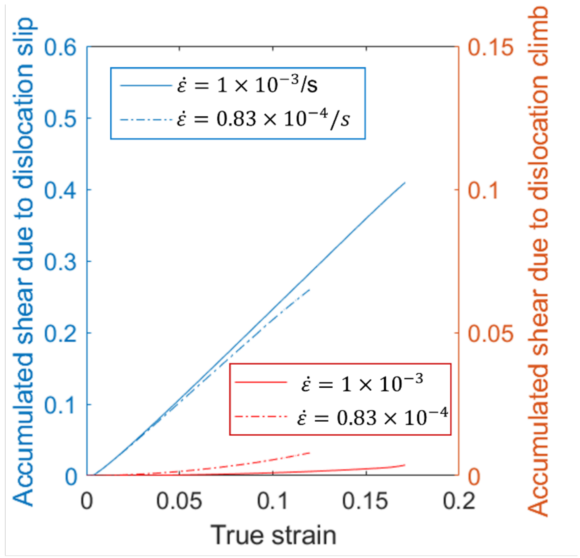
The simulation well captures the transition in creep mechanism

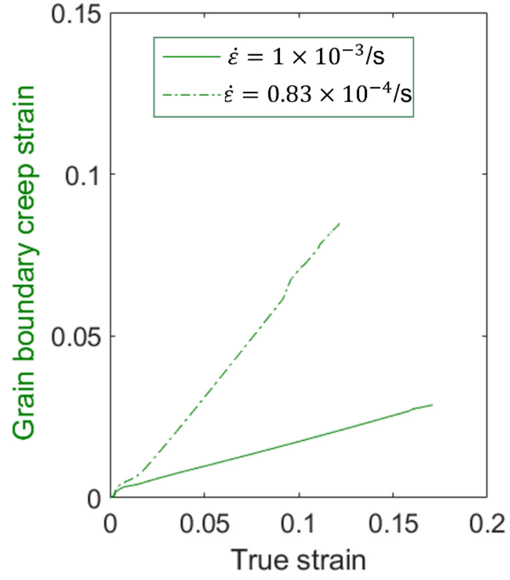
Creep simulation results, where steady-state creep strain rate is obtained

The intergranular to intragranular fracture transition is well-captured with CPFE model

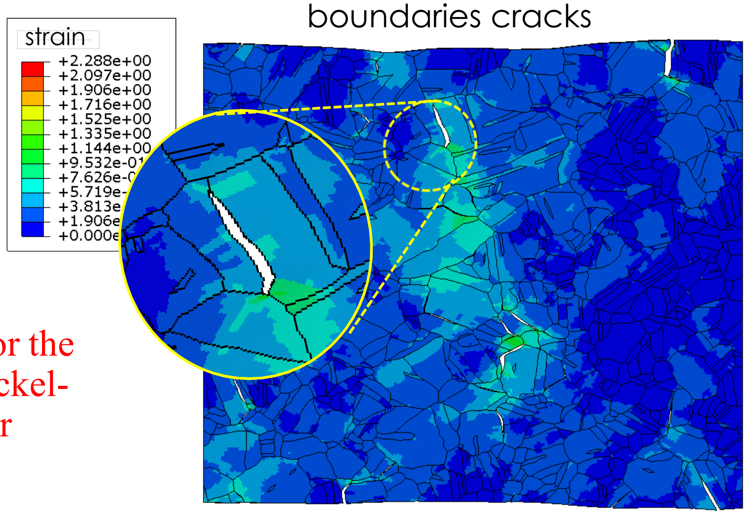


At low strain rate, the GB creep is more active and creep-induced GB void growth causes intergranular failure. As strain rate increases, the deformation is more dominated by dislocation slip, and failure is by shear band

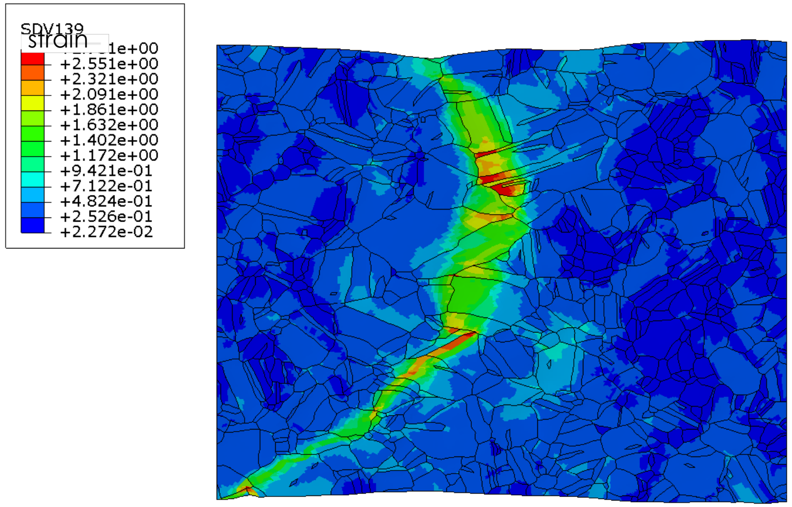




0.85×10^{-4} strain rate, grain boundaries cracks



1×10^{-3} strain rate, formation of shear bands



* A manuscript "Crystal Plasticity Modeling and Analysis for the Transition from Intergranular to Transgranular Failure in Nickel-based Alloy Inconel 740H at Elevated Temperature" is under review for MSEA

FEAA152 Milestone Status

Haynes 282 nozzle carrier casting loaded for heat treatment

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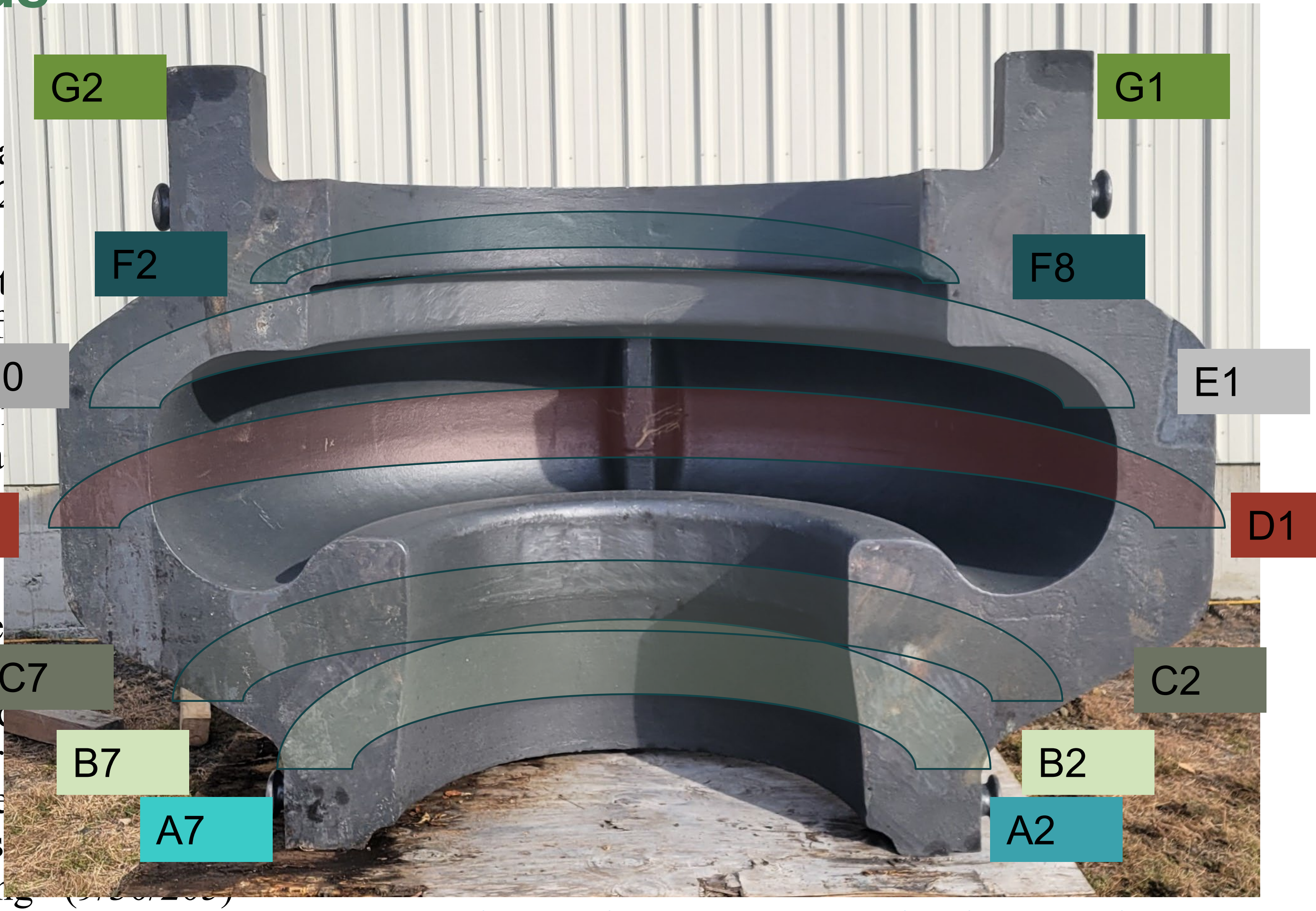
...s 282...
...truct...
...ld af...
...Hay...

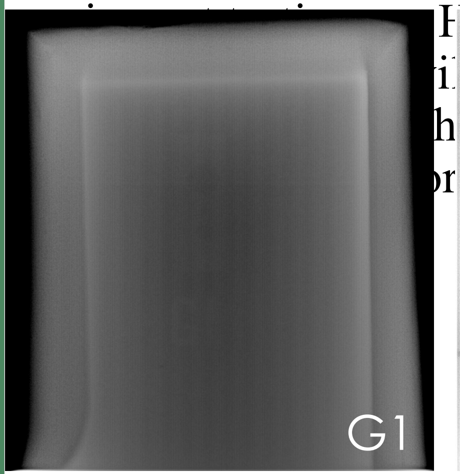
- Complete the as-received microstructure cha... gamma prime vol.%) (9/30/2024)

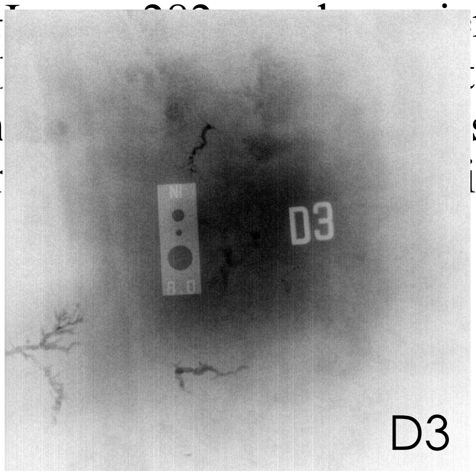
FY 2025

- Complete X-ray tomography-aided tensile te... that will dramatically affect tensile properti...
- Complete a variety of mechanical testing, inc...



Haynes 282 nozzle carrier casting RT-NDE examination locations





Sample NDE results

*Led by Special Metals

Testing of Large Wye Block Forging

John deBarbadillo

Special Metals

Huntington WV

Background

- Inconel alloy 740H
  - Age hardened Ni-base alloy developed for boiler tube
  - Characterized under US DOE AUSC program
  - Creep and hot corrosion resistance, Weldability, Microstructure stability
  - Can be made in large size components
  - Used as tube, pipe and fittings for SunShot, STEP, Net Power and Gen 3 CSP demos

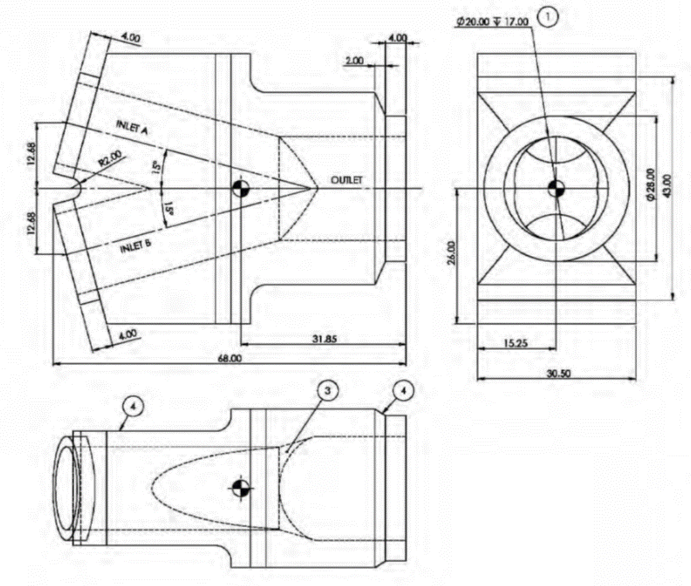
- DOE/FE AUSC ComTest
  - Wye block deliverable
  - Ingot produced by Special Metals
  - Wye design by EPRI
  - Forging, heat treatment and machining by Scot Forge

Mockup for AUSC Boiler (GE Power)

Manufacturing the Wye Block

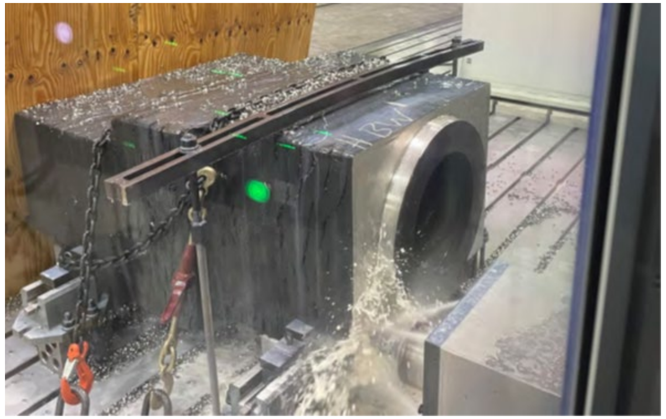
- **Ingot**
  - VIM-ESR-VAR
  - 30,250 lb, Cropped and Ground
- **Forging**
  - Upset and Draw, ~4:1 Reduction
  - Detail not Disclosed
  - Furnace cool to 1200°F, Air cool
- **Heat Treatment**
  - Solution anneal 8 hr at 2010°F, Cooling not reported
  - Age 8 hr, 1450°F, Water Quench
- **Machining**
  - Partial for cost estimate

Conditioned Ingot



Wye Drawing -EPRI

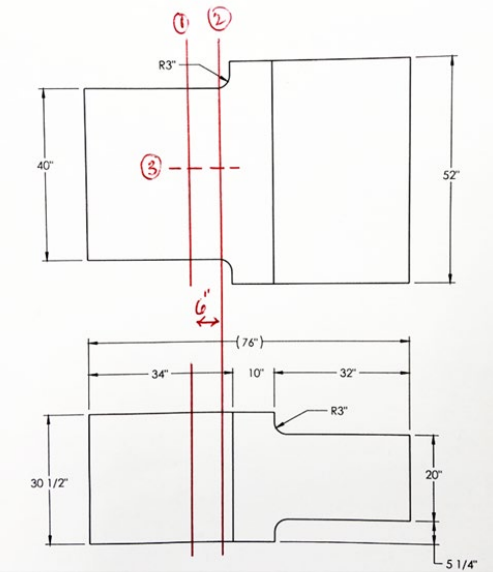
Forged Preform



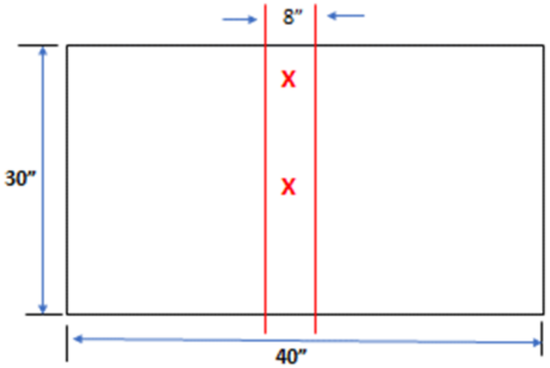
Feature Machining

Cutting and Testing Plan

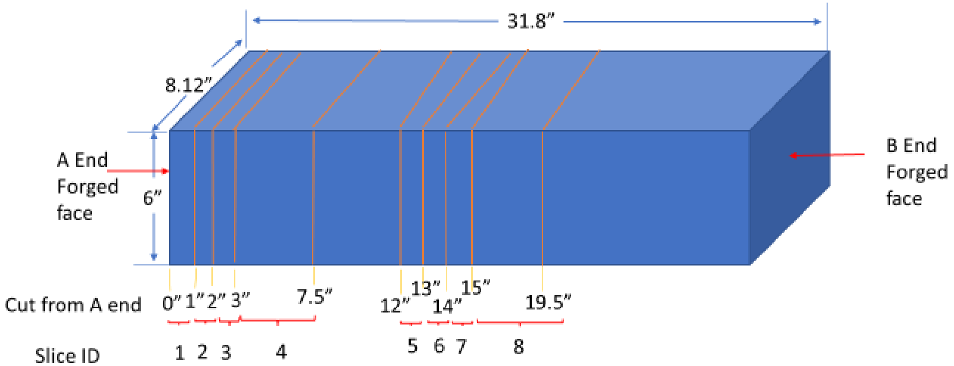
- **Cutting by ATI and SMC**



Block Cutting



Slice Cutting



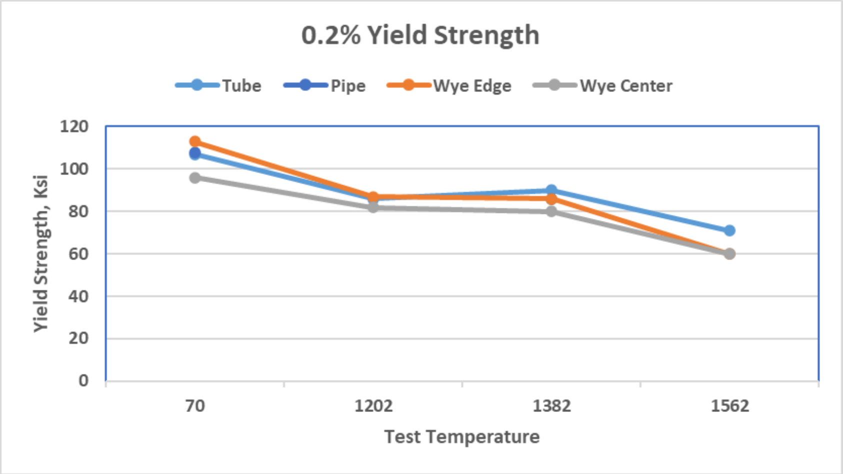
Test Blank Cutting

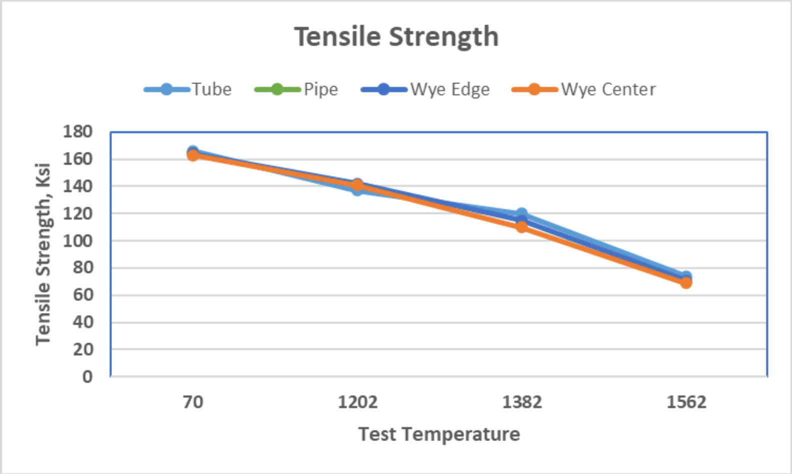
Testing by Westmoreland and SMC

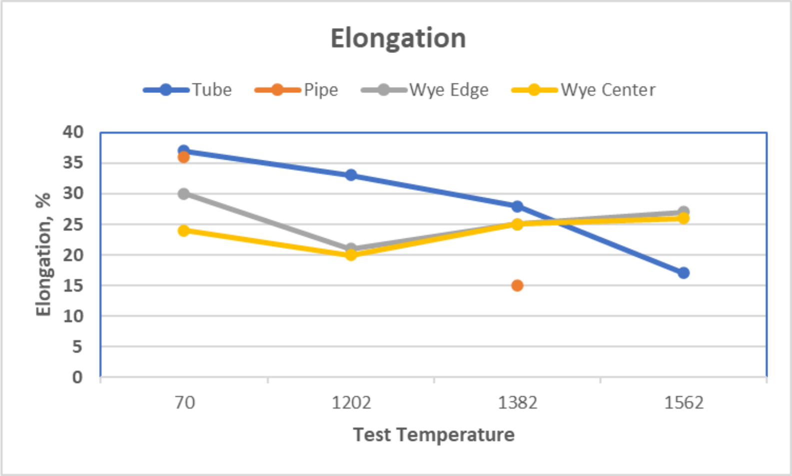
- **RTT – E&C 3 directions**
- **HTT – E&C 650,750,850°C**
- **RT CVN – E&C 3 directions**
- **Creep – C only, 650,700,750,800,850°C**
- **Hardness**
- **Grain size**
- **Microstructure – optical and SEM**

Preliminary Results

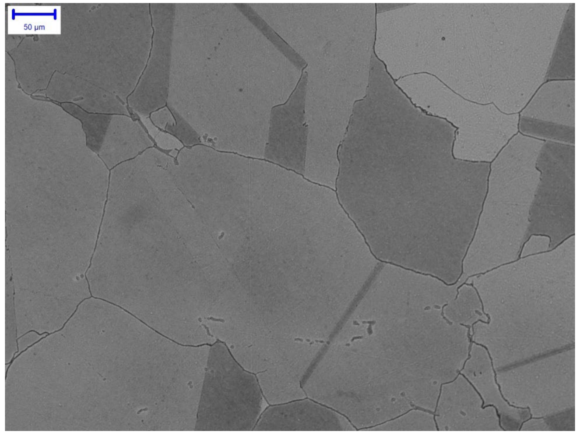
Tensile data from near edge and center of Wye Block



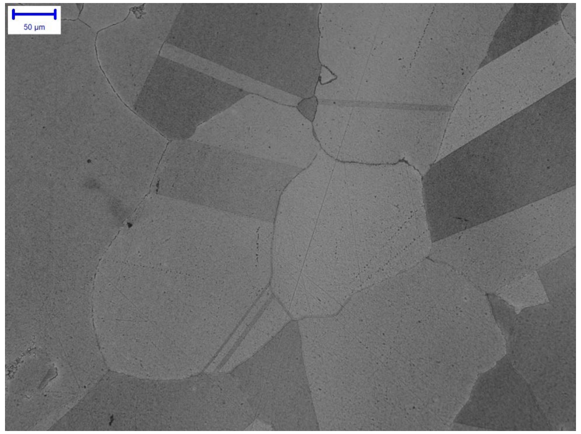




Grain Size – ASTM 1-2



Near edge



Center

Future Work

- **Creep Testing**
- **Metallography**
- **More detailed assessment of forge and stress cracking**
- **Incorporate into EPRI Conf paper on effect of cooling rate after solution anneal and section size on properties of 740H**
- **Develop generic protocol for forging, heat treating and machining large 740H parts**
- **Material available for other DOE programs**

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