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

Xiang (Frank) Chen[1], *Timothy Lach[1], Ling Wang[1*], Peter Tortorelli[2], Michael Santella[2], Kinga Unocic[3], Edgar Lara-Curzio[1]*

[1]Materials Science and Technology Division
[2]ORNL Retiree Subcontractor
[3]Center for Nanophase Materials Science
*currently affiliated with SLAC, work performed at ORNL

Oak Ridge National Laboratory

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Crosscutting (High Performance Materials) Virtual Session
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Acknowledgement

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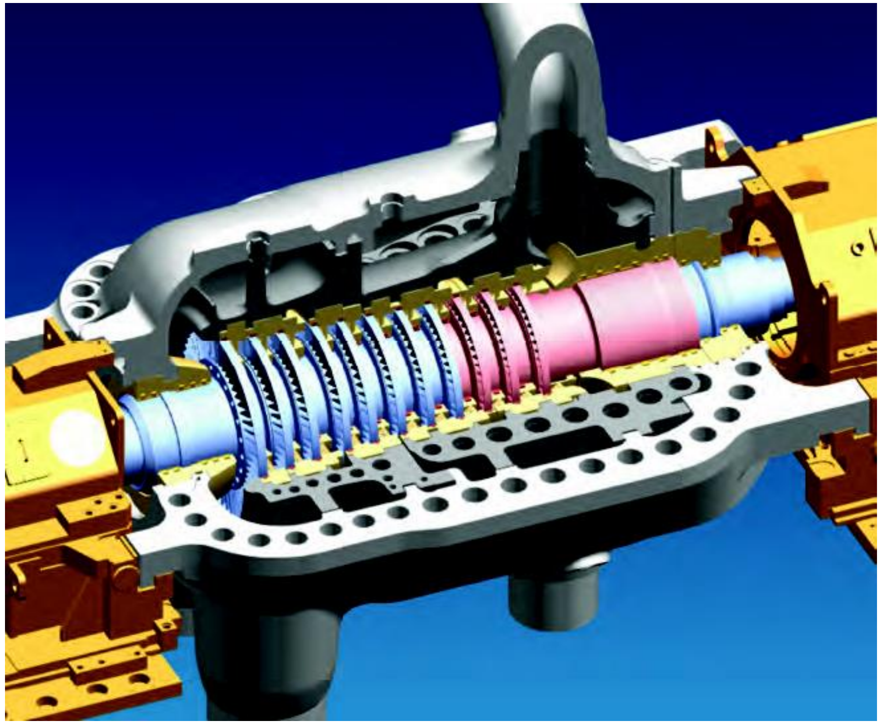
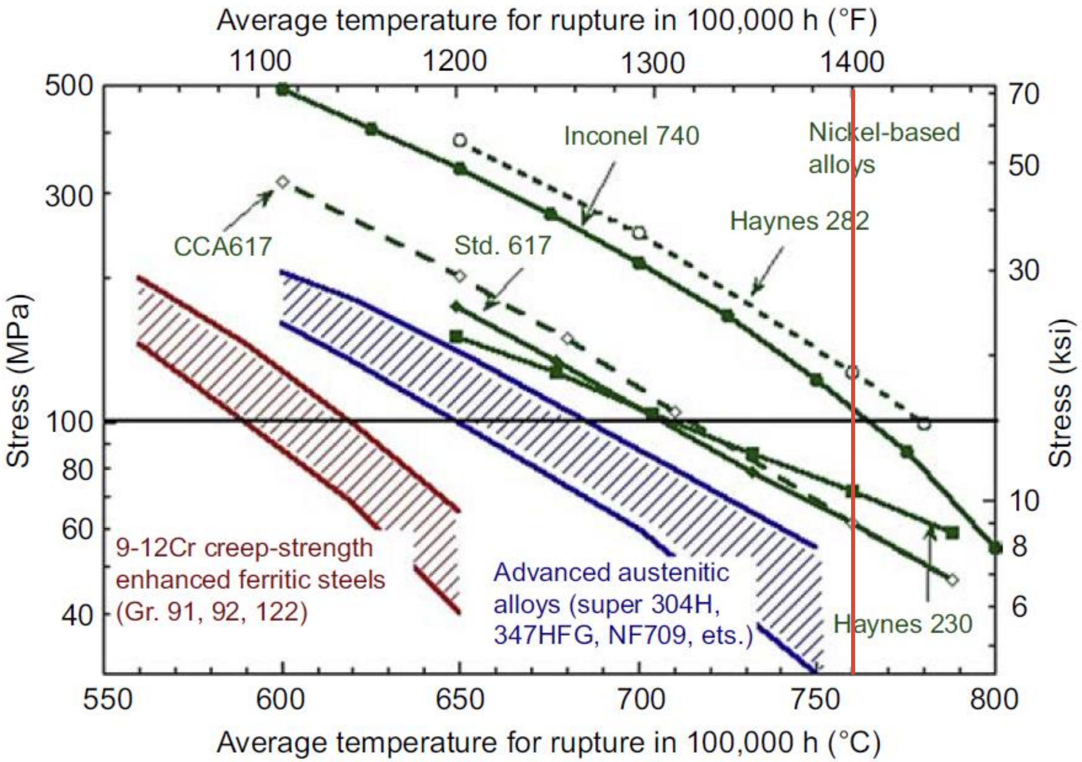
Background (1/3)



Advanced ultrasupercritical steam turbine
Schwant et al 2013



100 kh creep rupture strength as a function of temperature Shingledecker et al 2013

- Advanced Ultra-Supercritical (A-USC) power plants promise higher efficiency and lower emissions achieved by steam conditions up to 760°C (1400°F)/35 MPa (5 ksi), which mandates the use of Ni-based alloys
- Two precipitation-strengthening Ni-based alloys, i.e., Haynes® 282 ® and Inconel® 740H®, are considered as leading candidate materials for A-USC applications

Background (2/3)

- Ni-based alloys account for an important portfolio of the Fossil Energy and Carbon Management materials program

2001-2015

Boiler materials for ultra supercritical coal power plants

2009-2015

Materials for advanced ultrasupercritical steam turbines

2015-2018

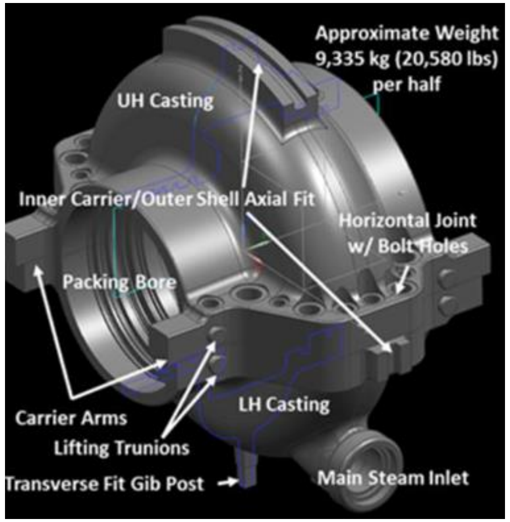
ComTest Phase 1

2019-

ComTest Phase 2

IN740H pipe
15" OD, 8" ID, 34.5 feet long
Viswanathan et al 2009

Haynes 282 triple-melt forged disk
Purgert et al 2015

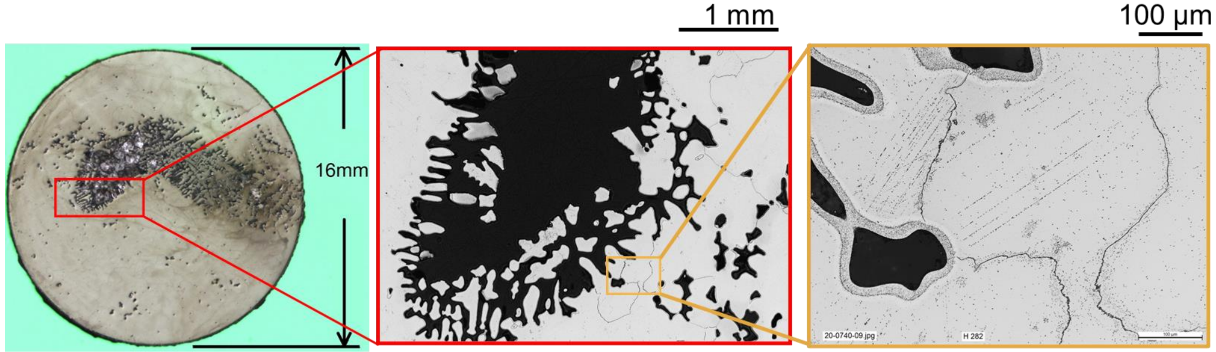


10-ton Haynes 282 nozzle carrier casting
Purgert and Hack 2019

Background (3/3)

- Characterization of Ni-based alloys provides
  - **Data needed for materials qualification**
  - **Insights into potential manufacturability issues**

Sand casting 7.7-ton Haynes 282, Purgert et al 2015



Cast Haynes 282 shrinkage defect, Wang et al., Materialia 15, 2021

Case 2702-6
Ni-25Cr-20Co Material
Section I

Inquiry: May precipitation-hardenable Ni-25Cr-20Co alloy (UNS N07740) ASTM B983-16 seamless alloy pipe and tube, ASTM B1007-17 welded tube, and ASTM B637-18 bars, forgings, and forging stock; wrought plate, sheet, strip, and fittings material conforming to the chemical requirements shown in Table 1, the mechanical properties listed in Table 2, and otherwise conforming to the applicable requirements in the specifications listed in Table 3 and in this Case be used in welded and nonwelded construction under Section I rules?

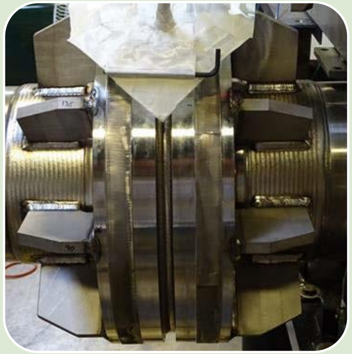
ASME code case for Inconel 740H

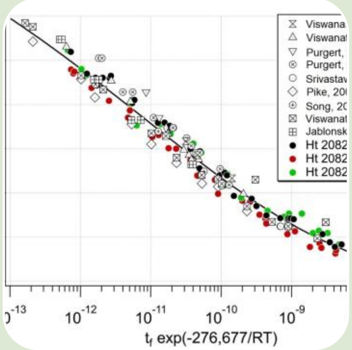
Case 3024
Ni-Cr-Co-Mo-Ti Precipitation Hardened Alloy UNS N07208
Section I; Section VIII, Division 1

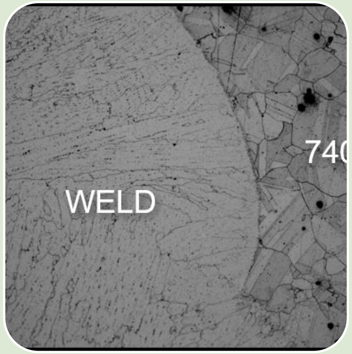
Inquiry: Under what conditions may Ni-Cr-Co-Mo-Ti Precipitation Hardened Alloy (UNS N07208) wrought bar, fittings, forgings, forgings stock, plate, sheet, strip, seamless pipe and tube, and welded pipe and tube be used in welded and nonwelded construction under the rules of Section I and Section VIII, Division 1?

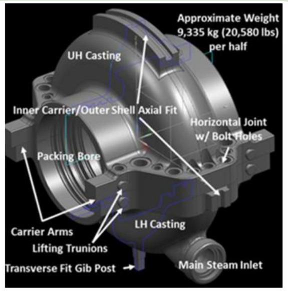
ASME code case for Haynes 282

Objective: This research provides a critical evaluation of advanced Ni-based alloys supporting the manufacturing and use of components under advanced ultra-supercritical (A-USC) steam conditions





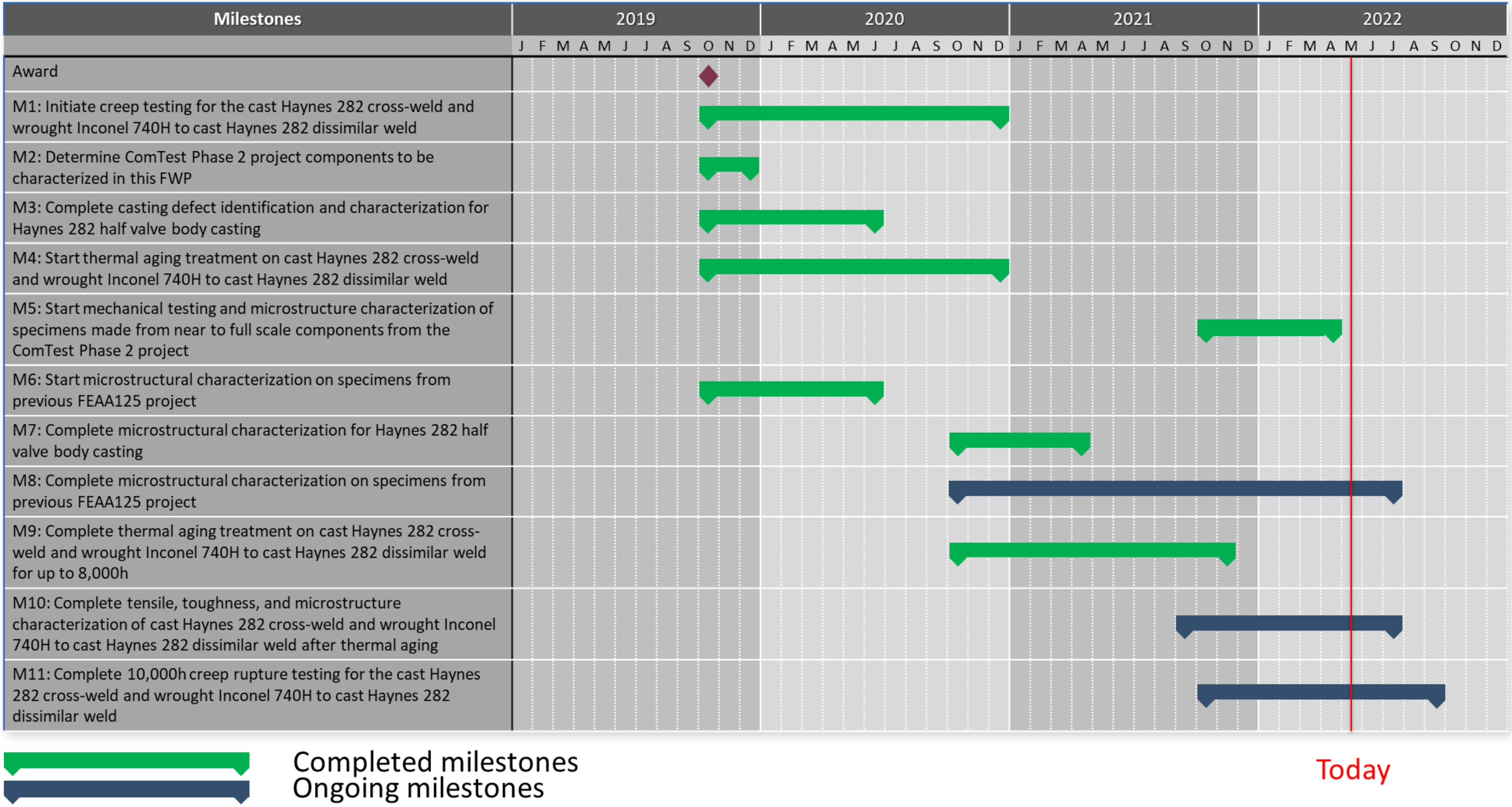




Planned 10-ton Haynes 282 nozzle carrier casting

- Haynes 282 sand casting
- Haynes 282 forged disk
- Cast Haynes 282 GTAW
- Creep modeling
- Inconel 740H SMAW
- ComTest Phase 2 materials

Milestone Status



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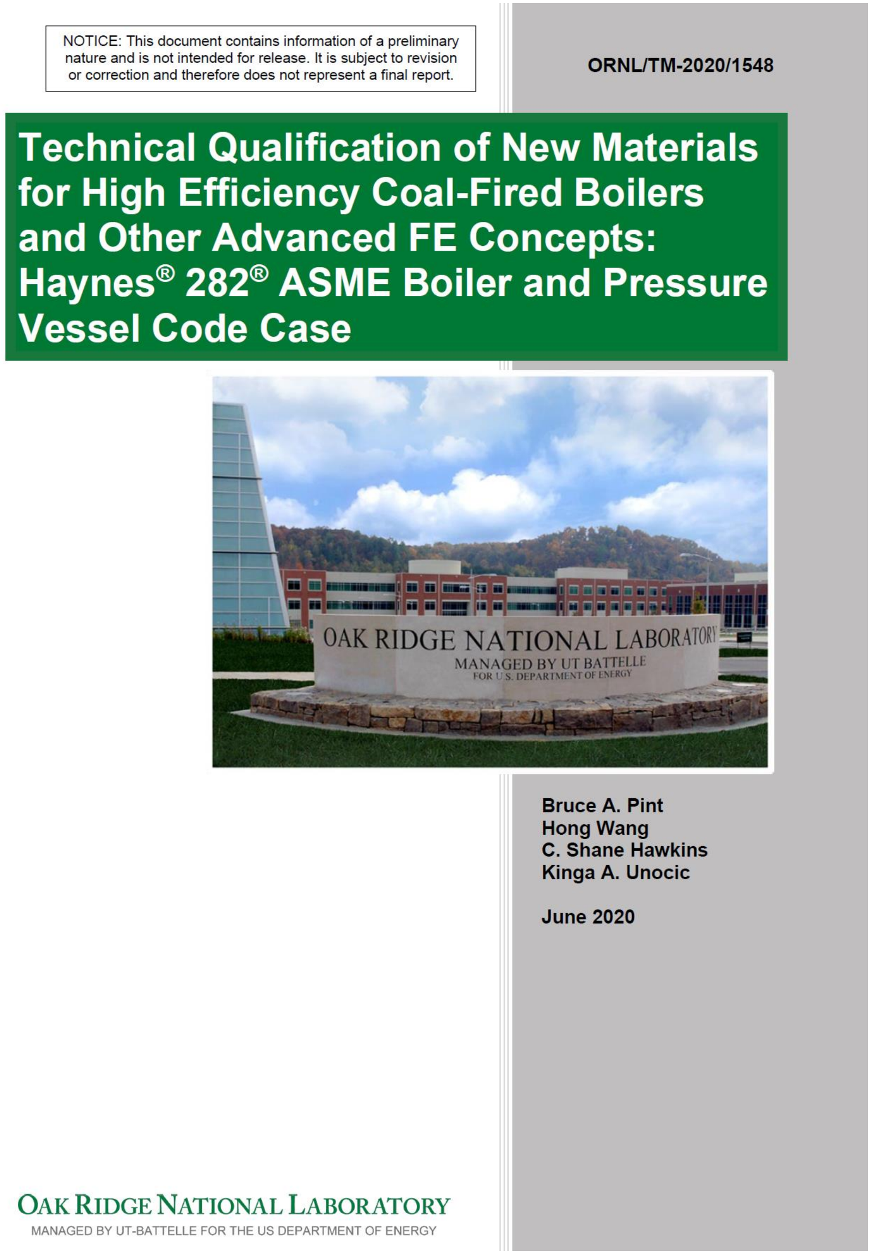
Creep Rupture Lifetime Prediction for Wrought Haynes 282 Alloy

Michael L. Santella, Peter F. Tortorelli, Mark Render, Bruce Pint, Hong Wang, Vito Cedro III, and Xiang Frank Chen. "Effects of applied stress and grain size on creep-rupture lifetime prediction for Haynes 282 alloy." Materials Science and Engineering A 838(2022), 142785

Background

- DOE-FECM FEAA117 funded ORNL in generating the experimental basis for the development of ASME Boiler and Pressure Vessel (BPVC) code cases for wrought Haynes 282 in collaboration with Haynes International
- Code case #3024 led by Haynes International was approved and published in 2021 ASME BPVC Code Cases Supplement 2
- The study explores the efficacy of creep lifetime prediction for Haynes 282 based on either the Wilshire model or the Larson-Miller Parameter (LMP) using standard creep-rupture data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ORNL/TM-2020/1548

Technical Qualification of New Materials for High Efficiency Coal-Fired Boilers and Other Advanced FE Concepts: Haynes® 282® ASME Boiler and Pressure Vessel Code Case

Bruce A. Pint
Hong Wang
C. Shane Hawkins
Kinga A. Unocic

June 2020

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

Materials and Methods

Courtesy from Hayr

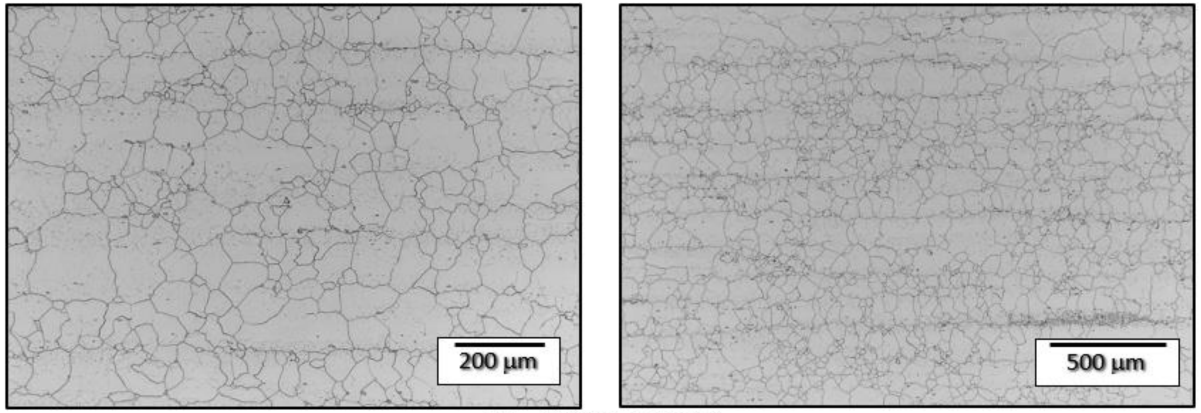
Heat No.	Cr	Co	Mo	Al	Ti	W
2082-2-8389	19.4	10.2	8.5	1.55	2.20	0.05
2082-2-8391	19.5	10.3	8.8	1.39	2.12	<0.01
2082-3-8354	19.5	10.4	8.6	1.46	2.22	<0.01

All three heats: Nb: <0.1, Ta: <0.01, Cu: <0.01, S

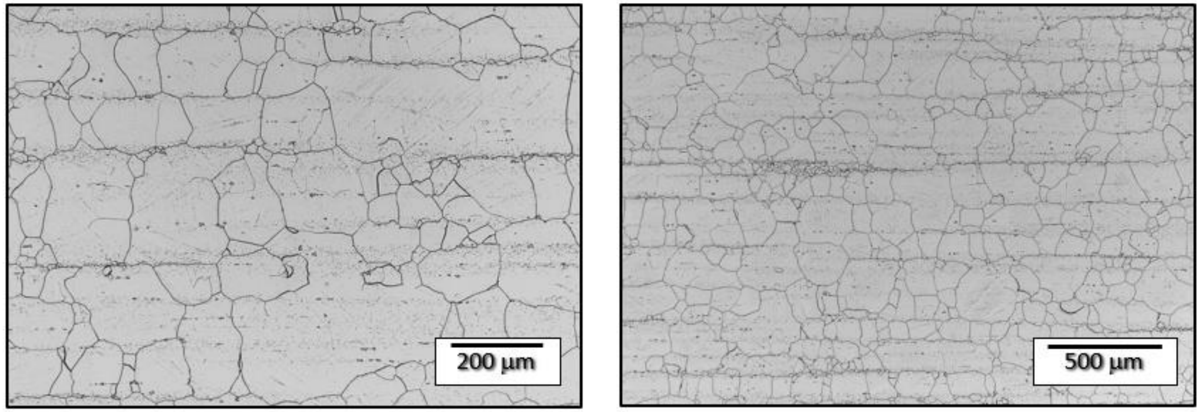
- 3 heats of wrought Haynes 282 after 1 ste smaller average grain size than the other
- Two creep models were evaluated:

– Wilshire model: $\sigma_a/\sigma_{TS} = exp\left\{-k\left[t_f exp\left(^{-Q_c^*}/_{RT}\right)\right]^u\right\}$

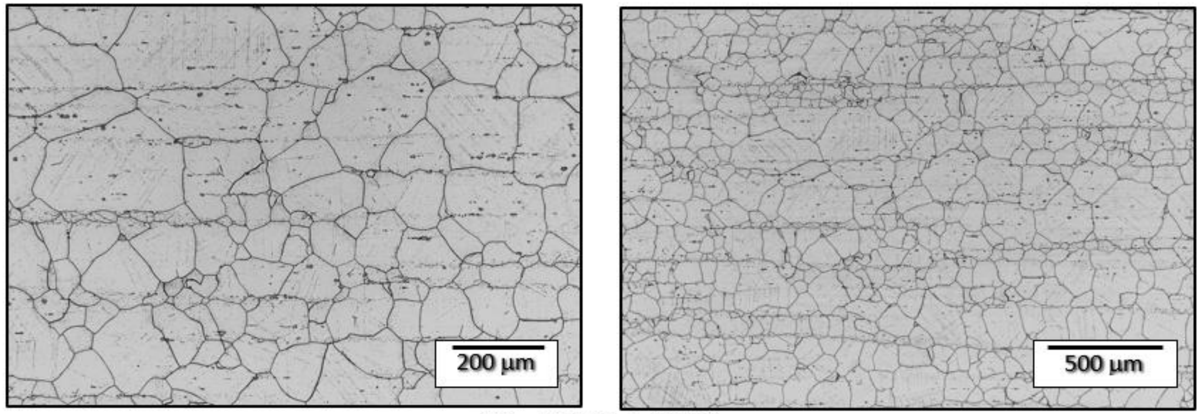
– Larson Miller parameter: $LMP = B_0 + \Sigma B_n \log(\sigma_a)^n =$



Heat 2082-2-8389

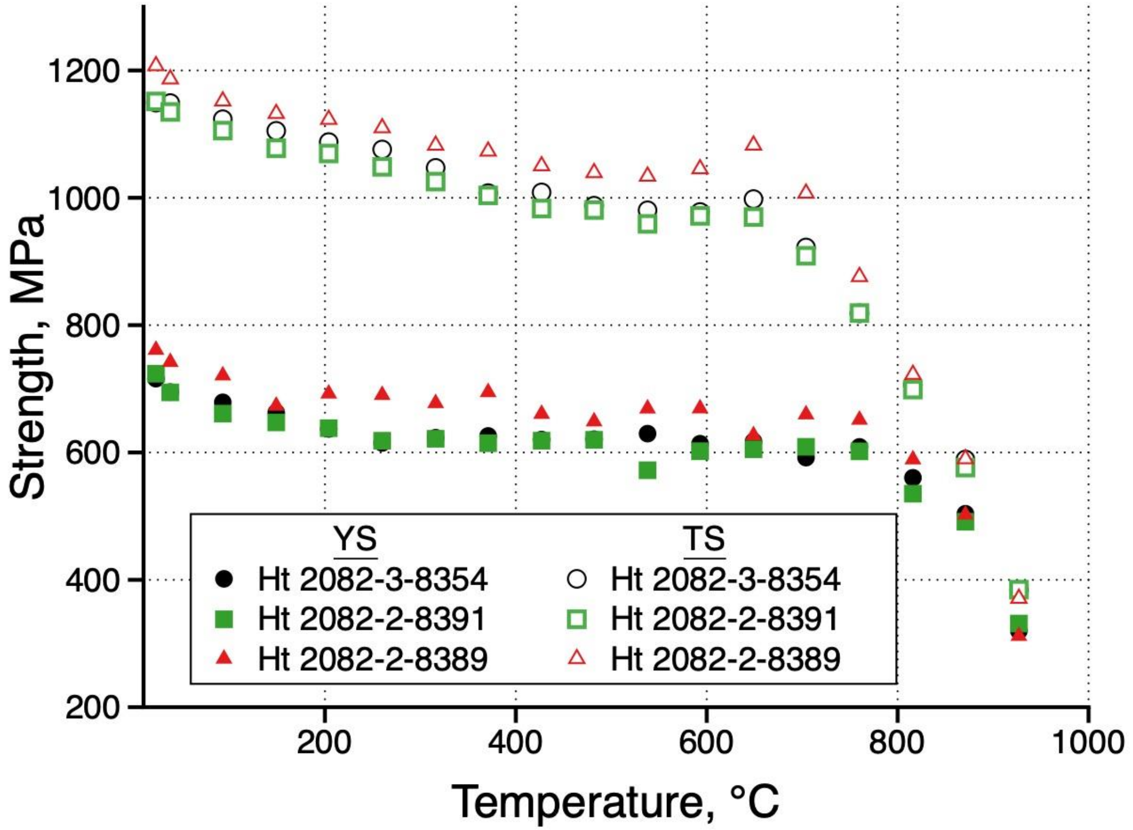


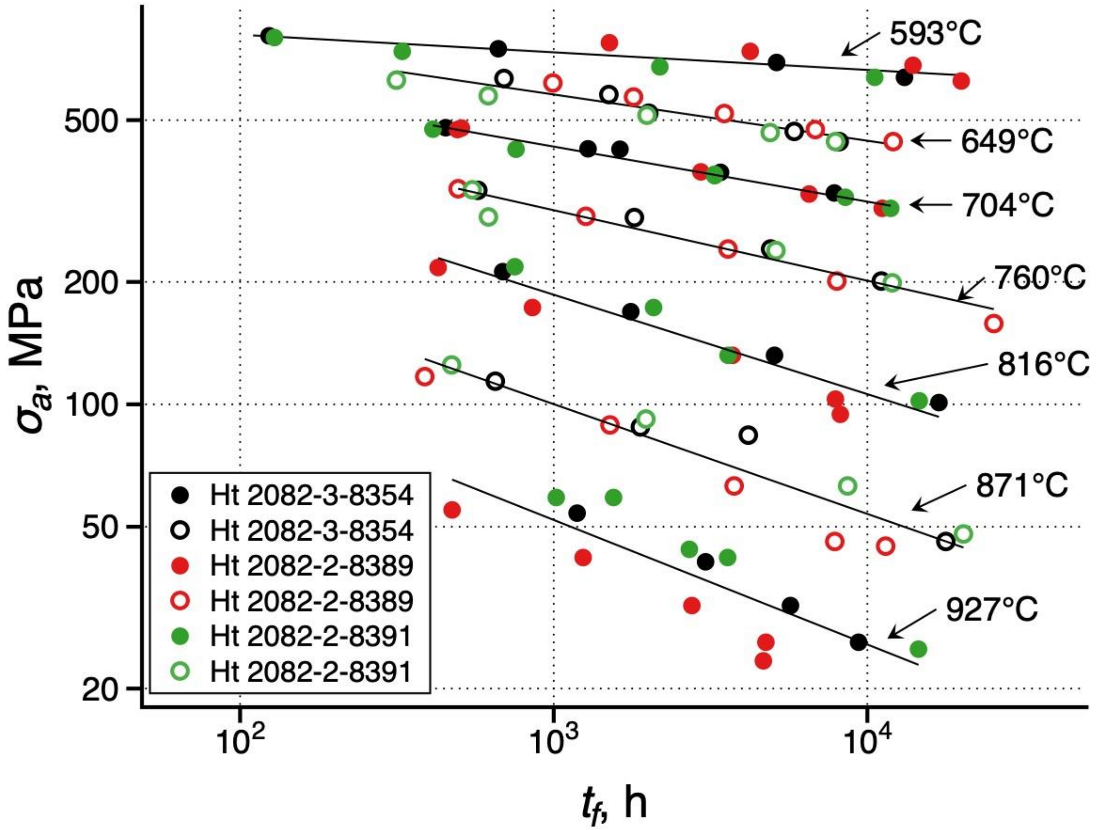
Heat 2082-2-8391



Heat 2082-3-8354

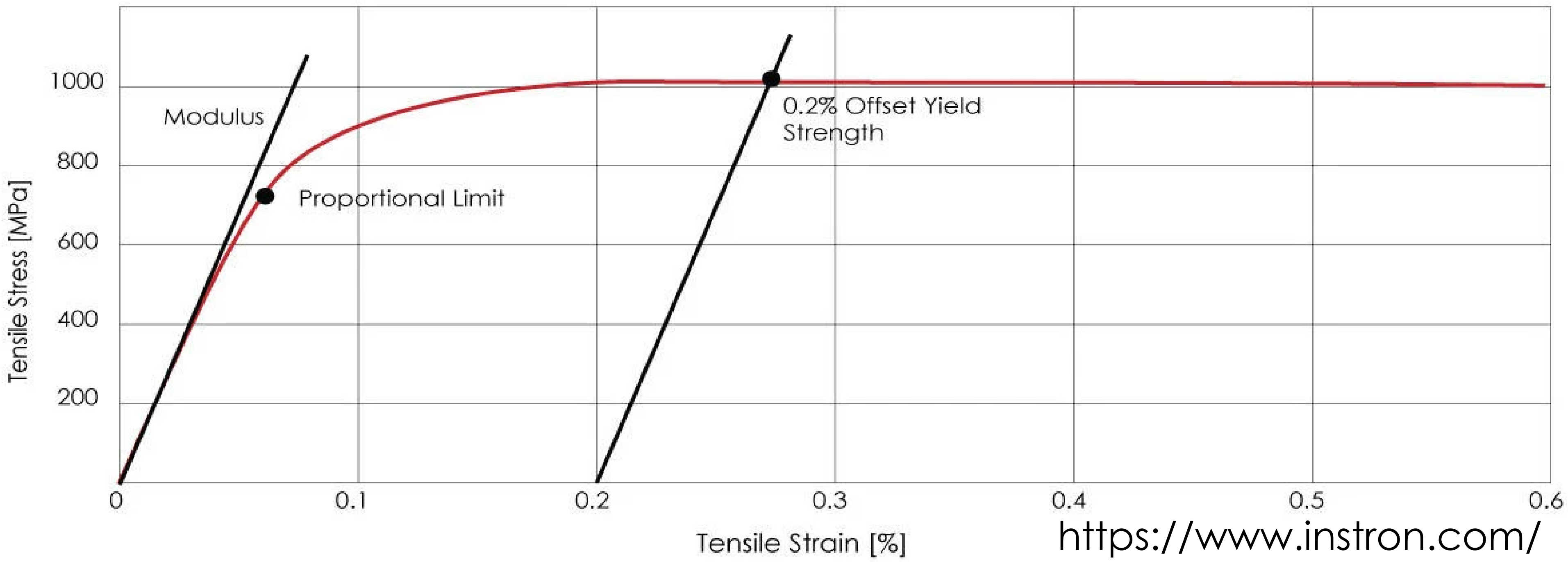
Three Heats Wrought Haynes 282 Tensile and Creep Properties





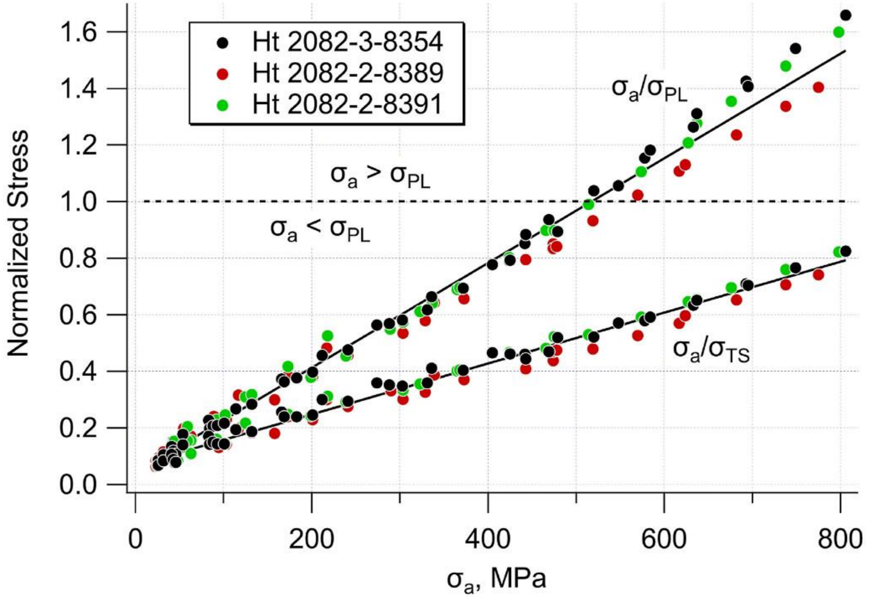
- Below 800°C, heat 8389 with a smaller grain size showed higher yield strength (YS) and tensile strength (TS) than the two other heats (8354 and 8391) while above 800°C, all three heats showed similar tensile strength
- Below 760°C, all three heats showed similar creep life while above 760°C, heat 8389 showed shorter creep life compared with the two other heats (8354 and 8391)

The Need for Split Region Analysis

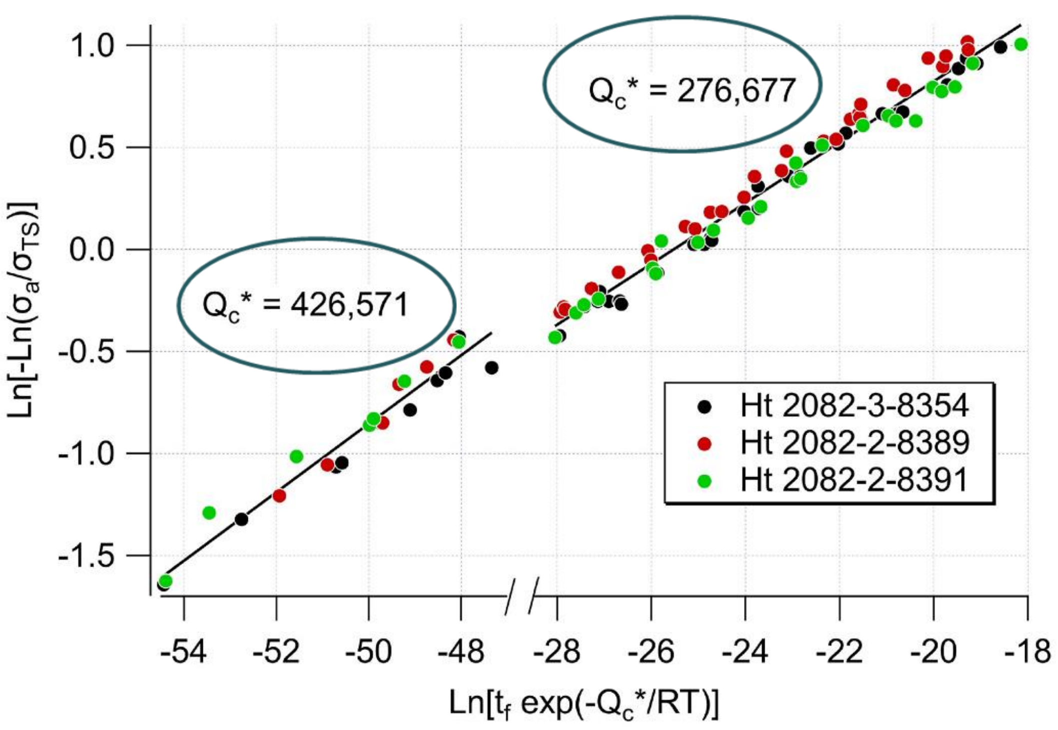


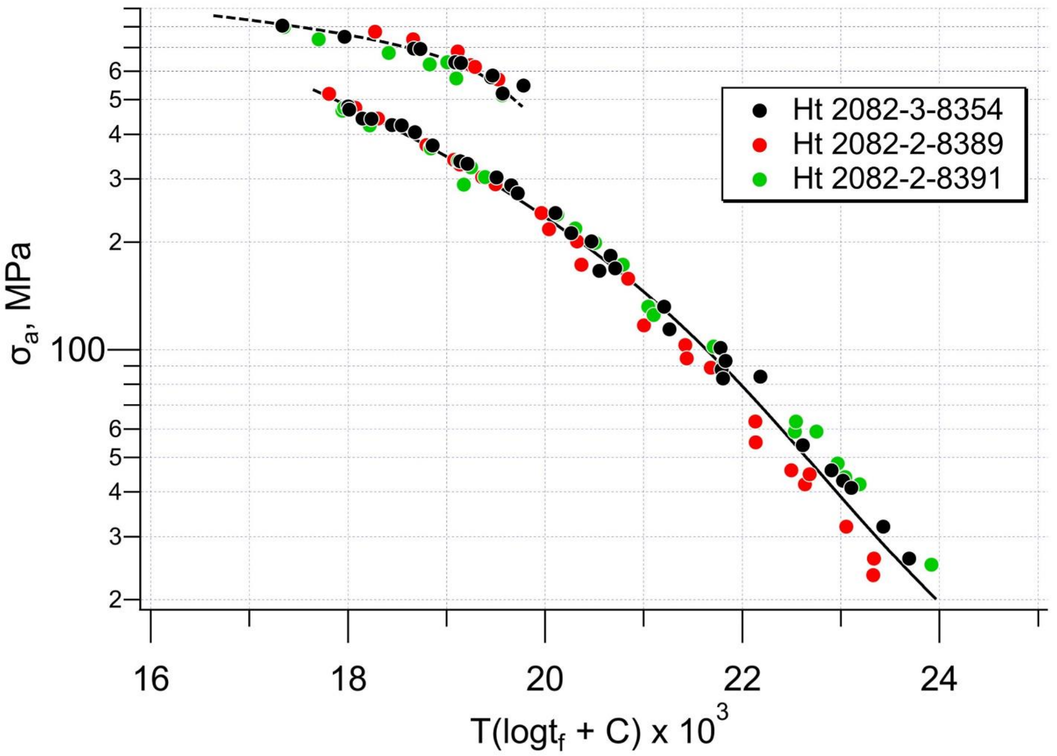
https://www.instron.com/

- Both Wilshire and LMP models yielded poor prediction on creep lives when applied stresses were high
- In those tests, the applied stress σ_a was higher than the materials proportional limit σ_{PL} at the test temperature
- We proposed two different creep mechanisms for $\sigma_a < \sigma_{PL}$ and $\sigma_a \geq \sigma_{PL}$ and there is a need to perform split region analysis



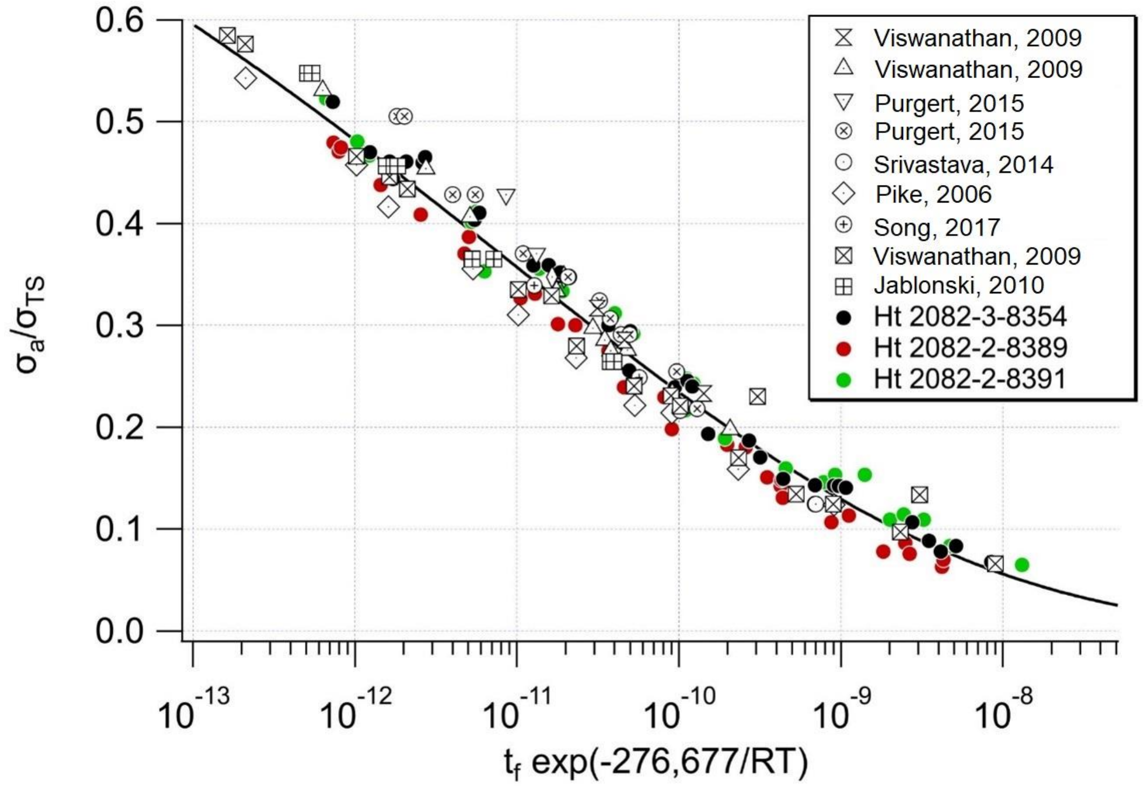
Split Region Analysis

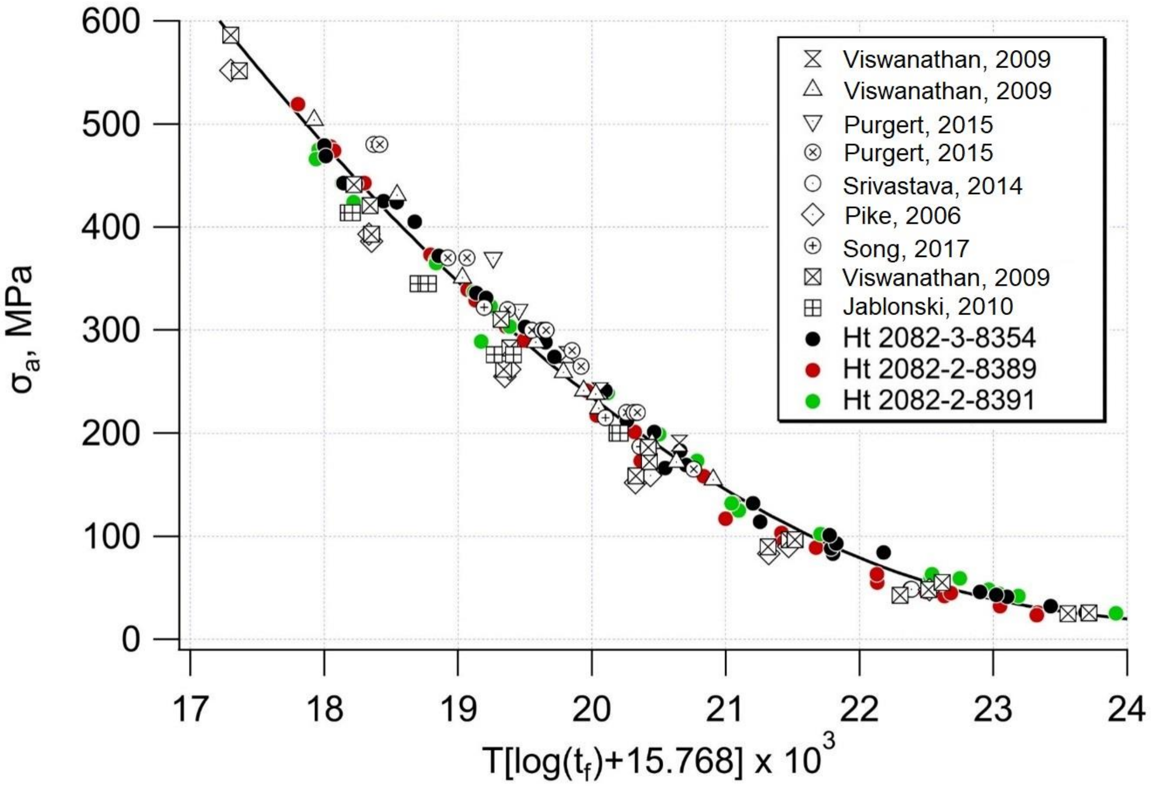




- Split region analysis based on σ_{PL} improved the creep life prediction accuracy for both **Wilshire** (left) and **LMP** (right) models for the entire creep stress region
- The fitted activation energy in the Wilshire model indicated plasticity-driven ($\sigma_a \geq \sigma_{PL}$) vs. diffusion-driven ($\sigma_a < \sigma_{PL}$) creep mechanisms

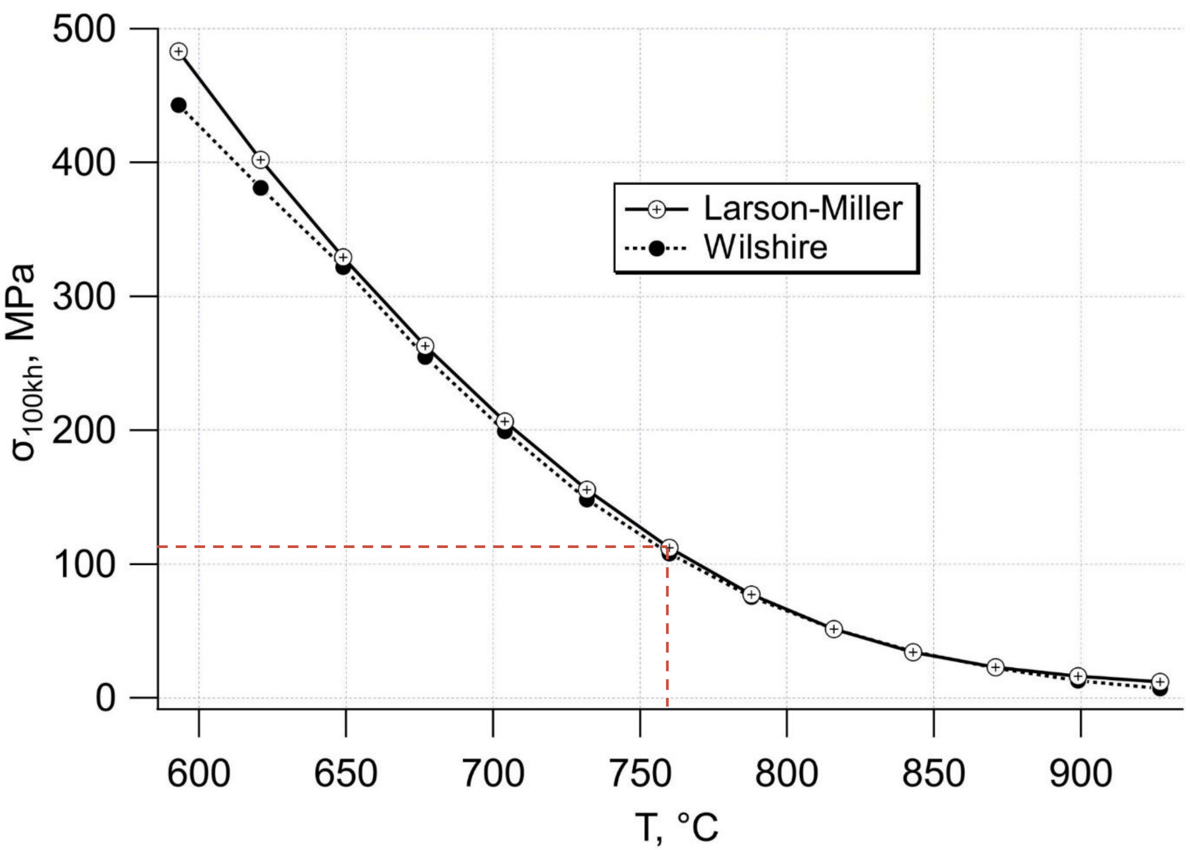
Model Prediction on Literature Data





- Both **Wilshire** (left) and **LMP** (right) models developed with ORNL 1-step aging creep data yield reasonable prediction of literature creep life data for wrought Haynes 282 despite wide varieties in material heats/compositions, processing, and aging heat treatment conditions

Prediction of Creep Strength for 100kh Creep Life



- Slightly more conservative prediction of Wilshire model than LMP
- Both models indicate that at 760°C, Haynes 282 can meet the requirement of 100 MPa creep strength for 100kh creep life

Evaluation of Tensile and Creep Properties for Haynes 282 sand casting

Wang, L., Mao, K., Tortorelli, P. F., Maziasz, P. J., Thangirala, M., Unocic, K. A., & Chen, X. F. (2021). Effect of heterogeneous microstructure on the tensile and creep performances of cast Haynes 282 alloy. Materials Science and Engineering: A, 828, 142099.

Background

Haynes 282 sand casting. Letters indicating sampling locations

[Purgert et al., MATERIALS FOR ADVANCED ULTRASUPERCRITICAL STEAM TURBINES, Final Technical Report, 2015]

- Haynes 282 sand casting was manufactured in the A-USC steam turbine project with poured weight of 7.7 tons (17,000 lbs).
- After casting, the material was homogenized and age-hardening heat treated (Haynes 282 2-step aging: 1010°C/2 hours + 788°C/8 hours)

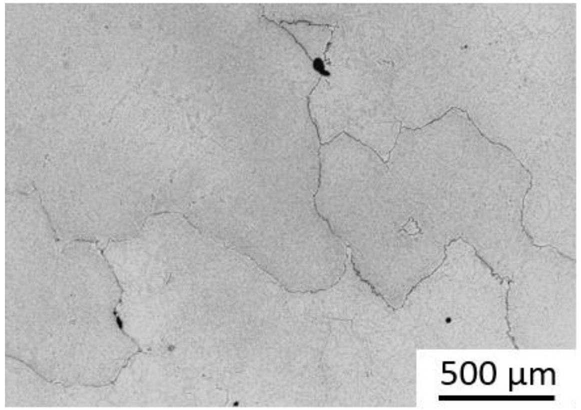
Haynes 282 Sand Casting: initial microstructures

- Heterogeneous microstructures (cast defects, grain size, γ’ size) were observed in the Haynes 282 sand casting

Shrinkage porosity indicated by red color after dye penetration

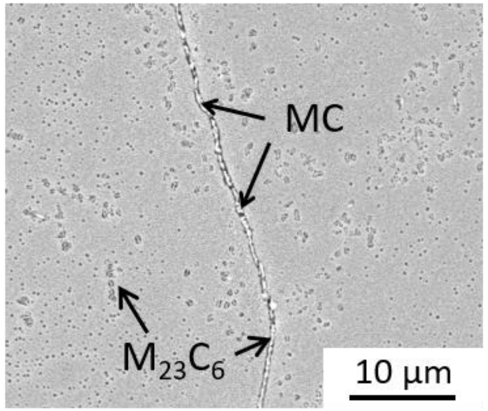
Shrinkage porosity

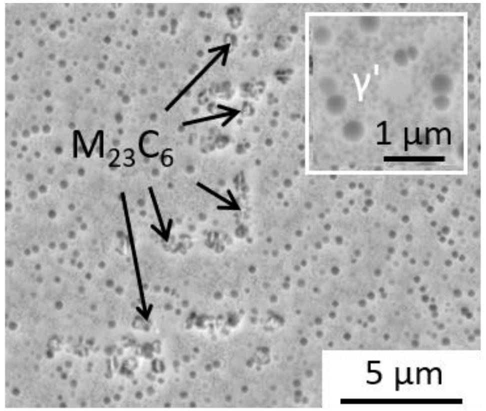
Heterogeneous grain size



Optical image

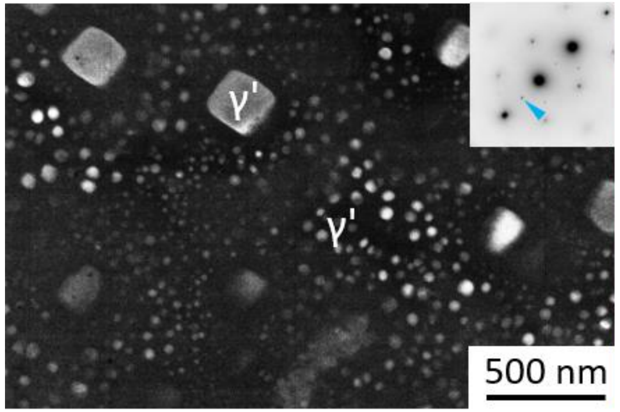
Grain boundary and matrix carbides



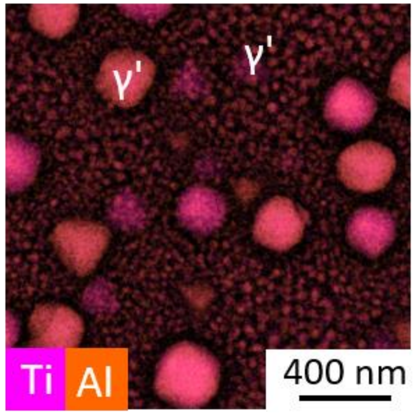


SEM-SE mode

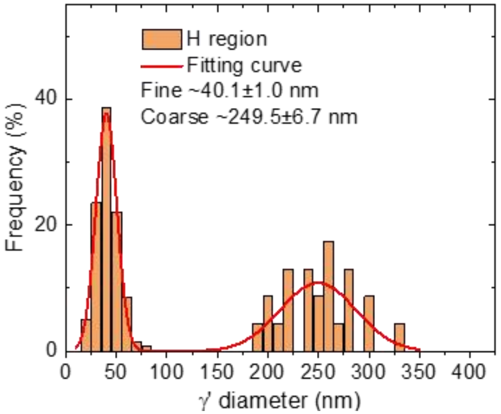
Matrix γ’ precipitates



TEM-CDF



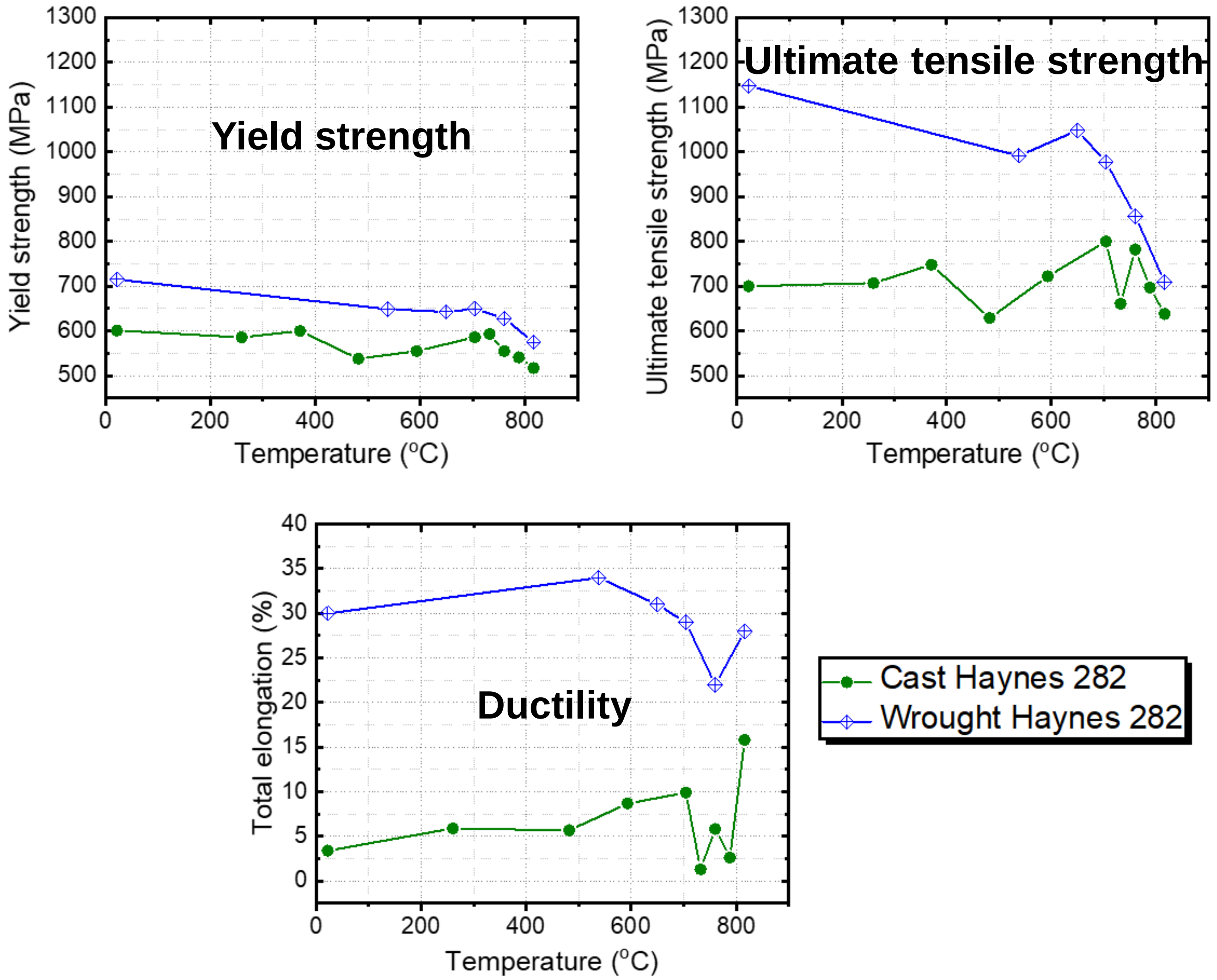
STEM-EDS



γ’ bimodal distribution

Haynes 282 Sand Casting: tensile properties

- The cast material showed lower tensile strength and ductility in comparison with the wrought materials.



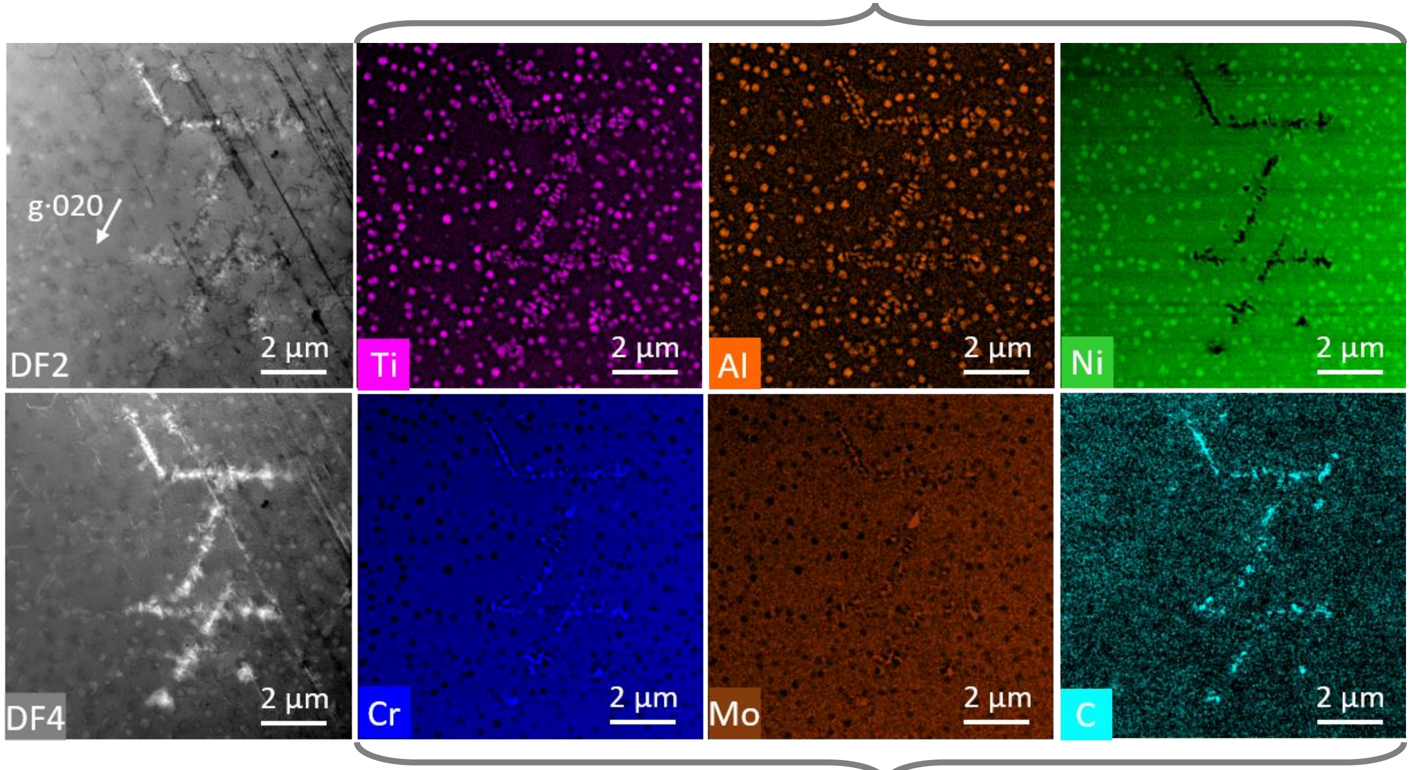
[1] X. Chen et al. Characterization of Ni-based alloys for advanced Ultra-Supercritical power plants, 2019

[2] Haynes 282 brochure

Haynes 282 Sand Casting Post Tensile Test Microstructure: room temperature

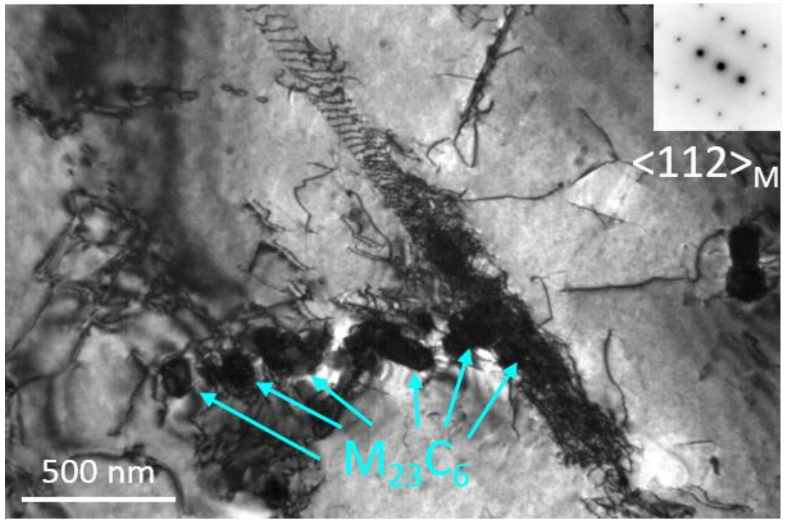
- Slip bands were dominant deformation features at room temperature.
- Clustered carbides behave as obstacles to the dislocation movement.
- Fine-scale γ' precipitates were sheared by the slip bands.

$Ni_3(Al,Ti)$ γ' precipitates

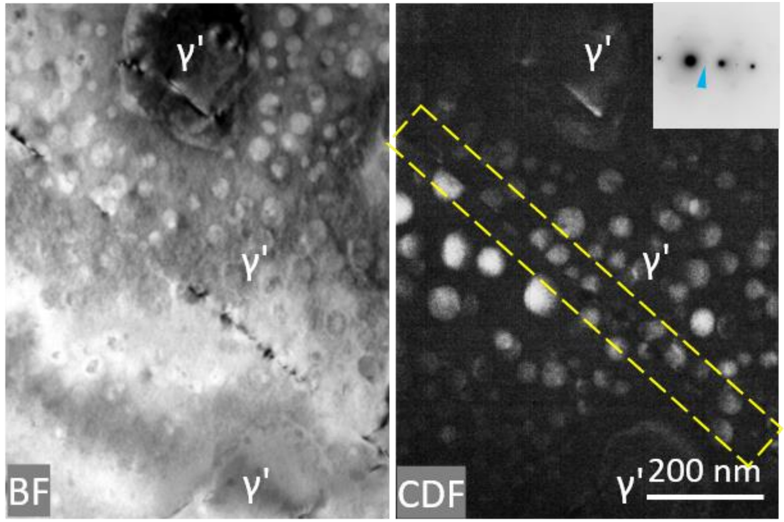


$(Cr,Mo)_{23}C_6$

dislocation tangles at $M_{23}C_6$

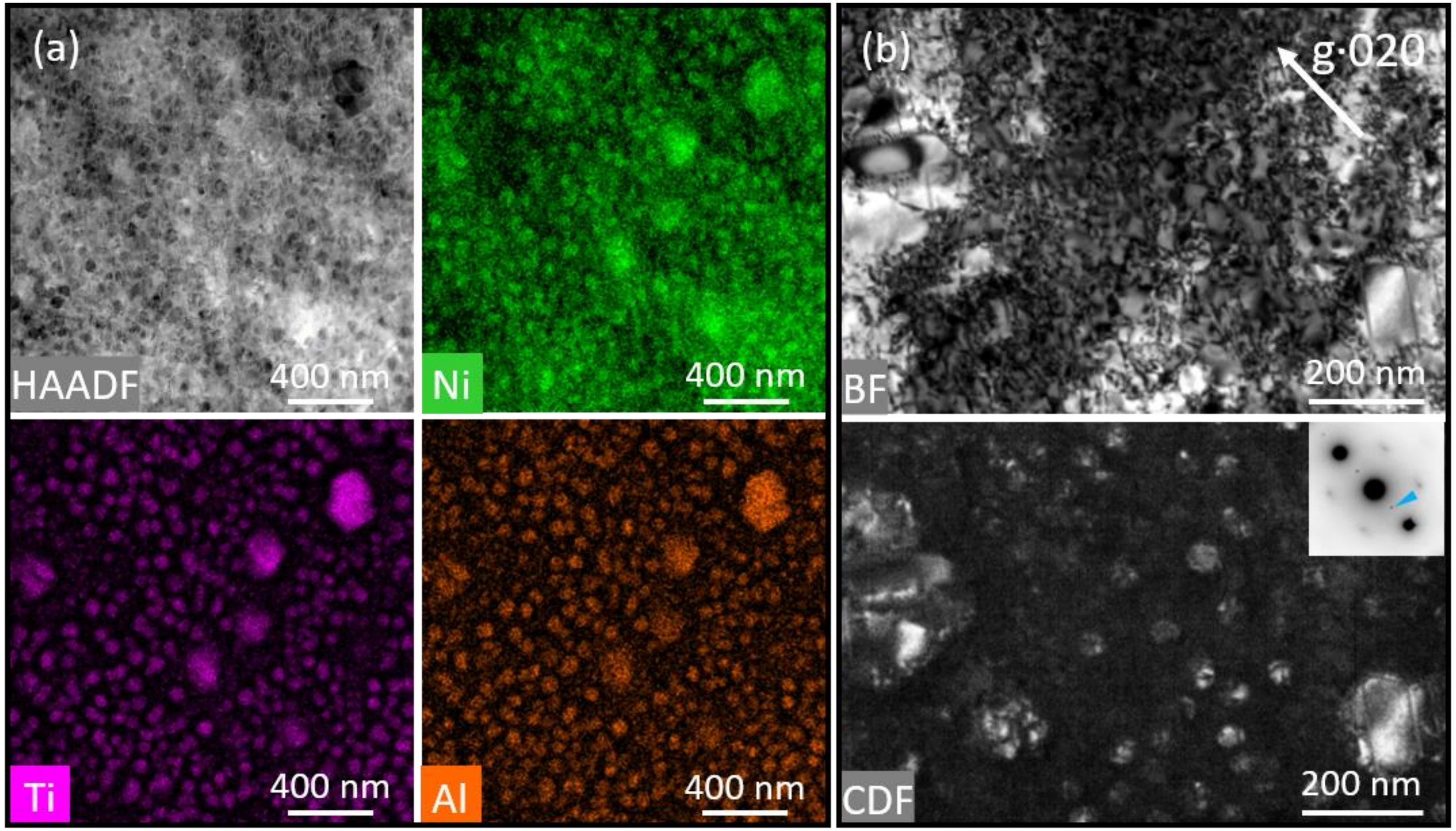


γ' precipitates sheared by slip bands



Haynes 282 Sand Casting Post Tensile Test Microstructure: elevated temperature

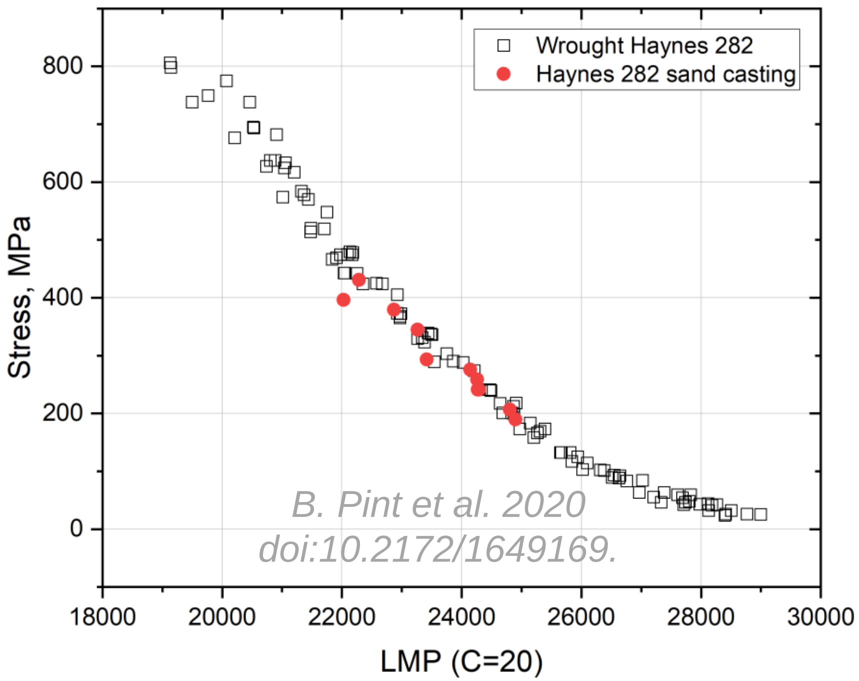
- Similar microstructures were observed after tensile testing at 704-816°C
- Dislocation network was dominant at elevated temperatures, indicating deformation was quite uniform
- γ' precipitates, including both fine-scale and coarse-scale, served as obstacles to the dislocation migration and show internal stacking faults after interaction with dislocations



Microstructure of a sand cast Haynes 282 specimen after tensile test at 760°C

Haynes 282 Sand Casting: creep properties and mechanisms

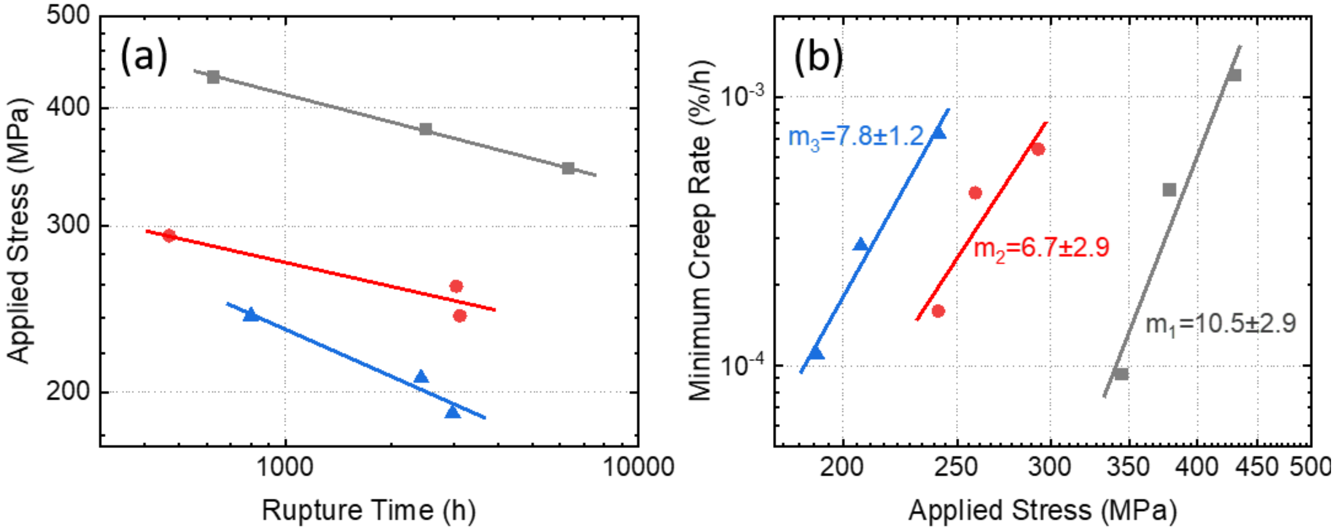
- The cast material showed similar Larson-Miller Parameter behavior in comparison with the wrought materials
- The dominant creep mechanisms over the temperatures of 704-788°C were found to be diffusional creep.



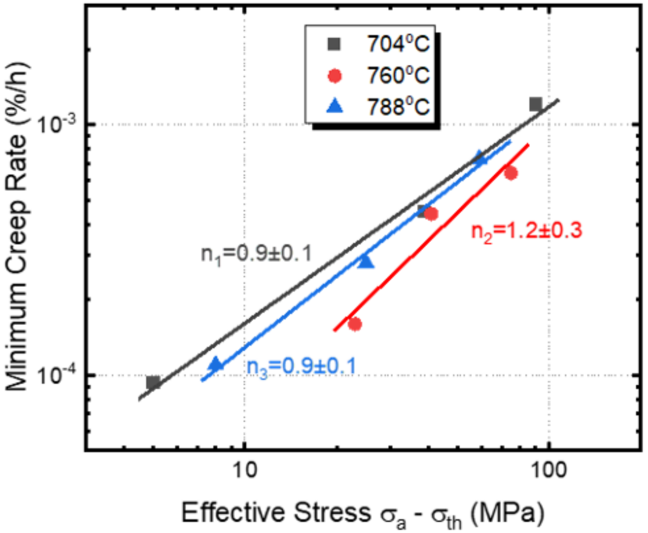
T = creep testing temperature in kelvin

C = material constant usually expressed as 20

t_r = creep rupture life in hours



Selected creep results from 704 to 788°C. (a) stress vs. rupture, (b) minimum creep rate vs. applied stress



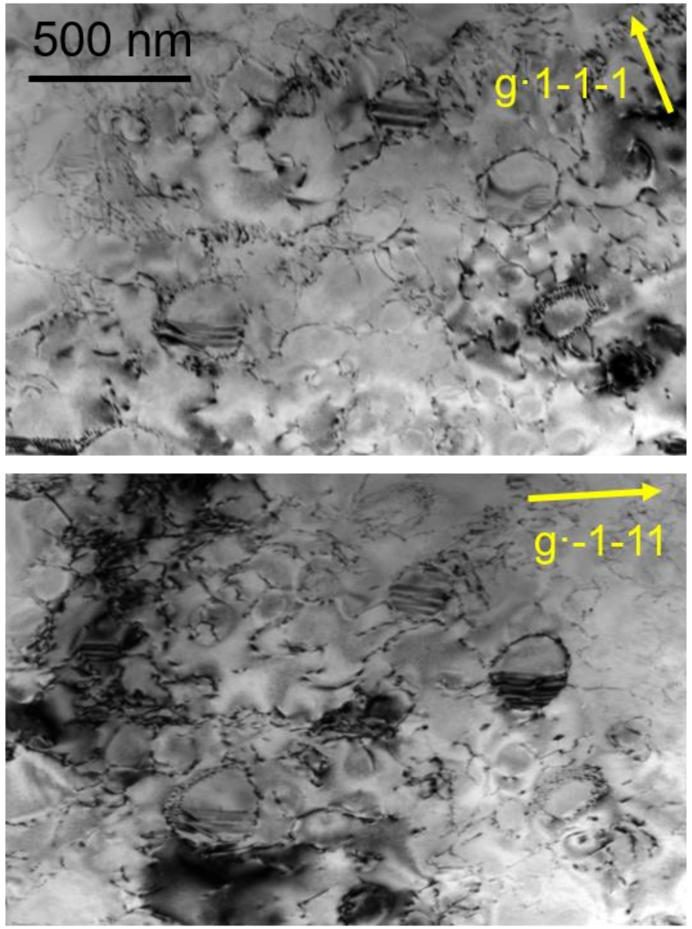
$$\dot{\varepsilon}_m = A(\sigma_a - \sigma_{th})^n exp\left(\frac{-Q_c}{RT}\right)$$

- Effective stress: $\sigma_a - \sigma_{th}$
- Threshold stress σ_{th} = 340 MPa (704°C)
  218 MPa (760°C)
  182 MPa (788°C)

- n= ~1 (diffusional creep)

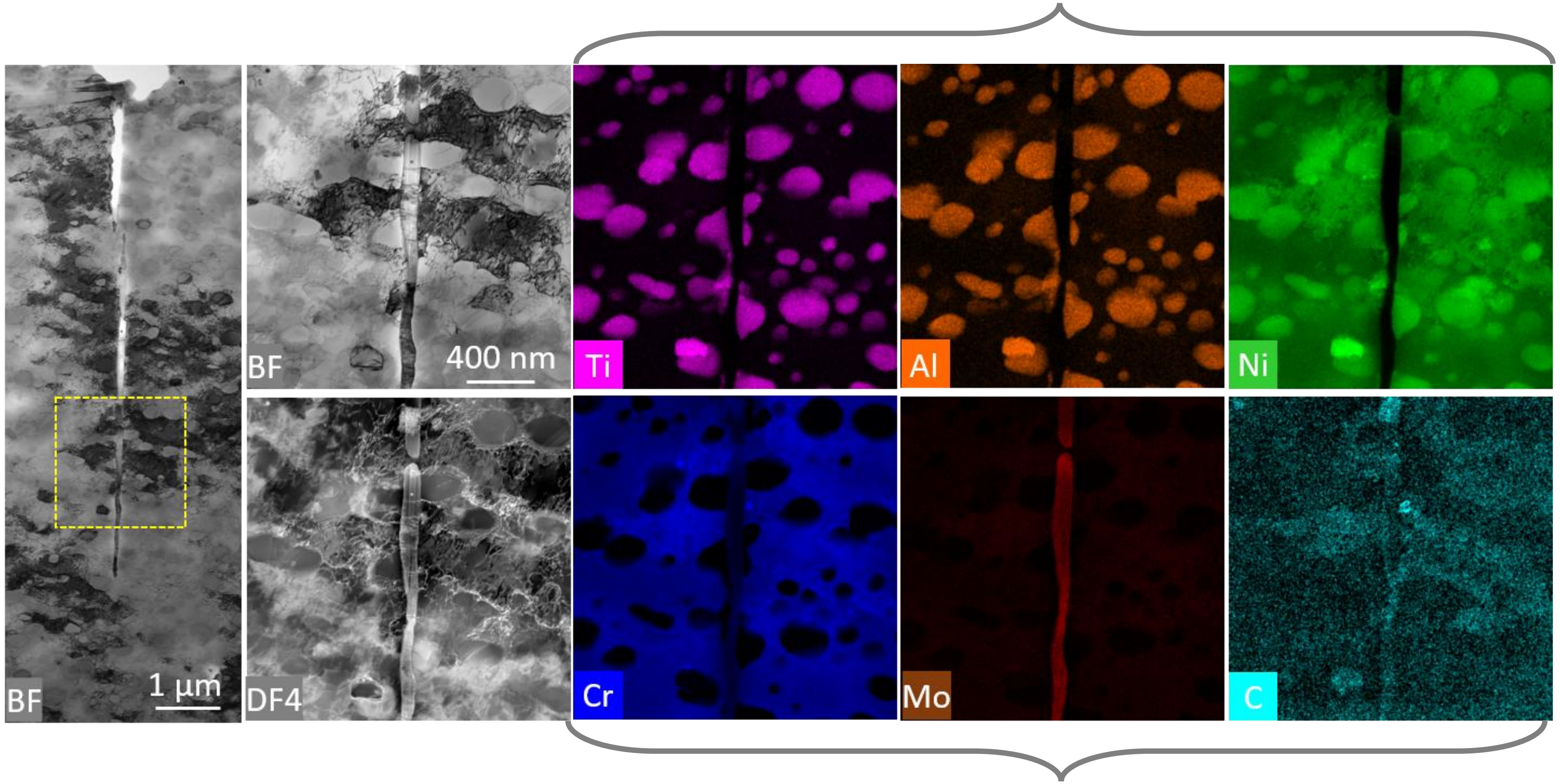
Haynes 282 Sand Casting: creep deformation microstructures

- Dislocation network was dominant at elevated temperatures, indicating deformation was quite uniform.
- $M_{23}C_6$ and γ' precipitates are comparably stable in size after creep tests over the temperature range of 704-788°C.



TEM-kinematic BF

Ni$_3$(Al,Ti) γ' precipitates



STEM-BF,-DF4,-EDS

(Cr,Mo)$_{23}$C$_6$

Creep condition: 760°C/241 MPa for 3,125 hrs

ComTest Phase 2 Haynes 282 Nozzle Carrier Casting Heat Treatment study (ongoing)

Background (1/2)

GE steam header assembly

Haynes 282 nozzle carrier casting

Haynes 282 rotor forging

Inconel 740 pipes

- ComTest Phase 2 Project manufactured a variety of large-scale components from Inconel 740H or Haynes 282
- Several components were shipped to ORNL which included a Haynes 282 nozzle carrier casting with a weight of 9.2 tons (20,260 lbs)

Background (2/2)

As-received (homogenized+2 step aging)

Solution anneal: 1149°C/1h/air cool

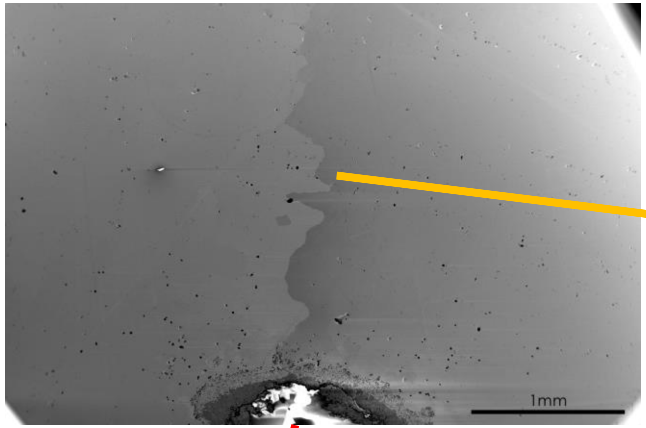
Solution anneal: 1149°C/1h/water quench

- 1 step aging (800°C/4 h/air cool, reserve materials for longer aging time)
- 2 step aging (1010°C/2 h/air cool + 788°C/8 h/air cool)
- 1 step aging (800°C/4 h/air cool, reserve materials for longer aging time)
- 2 step aging (1010°C/2 h/air cool + 788°C/8 h/air cool)

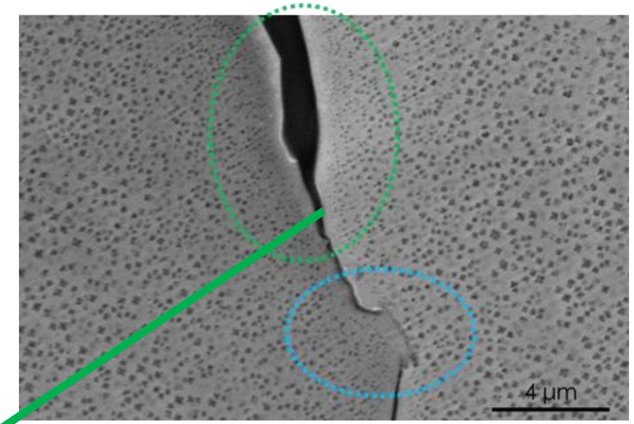
- The standard double aging treatment for Haynes 282 is time-consuming and costly
- ASME code case for wrought Haynes 282 only requires one-step aging and if a similar aging treatment can be applied to the cast material to produce similar structures and properties, it would be highly beneficial
- This study is set to determine the effect of heat treatment on microstructure (specifically precipitate structure) and mechanical properties
- Compare these treatments with that of one-step aging treatment of wrought Haynes 282 previously studied (Unocic et al., https://doi.org/10.1016/j.scriptamat.2018.11.045)

Haynes 282 Nozzle Carrier Casting: as-received microstructures

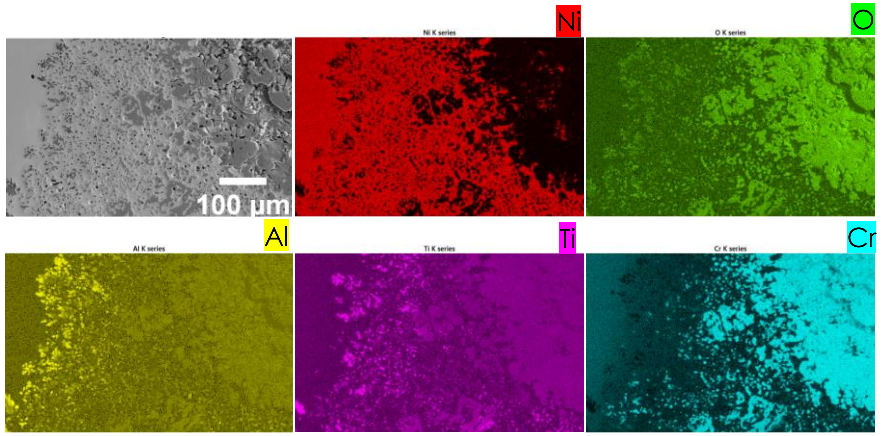
➢ Large mm+ size grain structure combined with intragranular and grain boundary carbides, occasional large grain boundary oxide inclusions, and $Ni_3(Al,Ti)$ γ’ precipitates



Grain boundary carbides and gradient of γ’ precipitates near carbides but less so at clean boundary

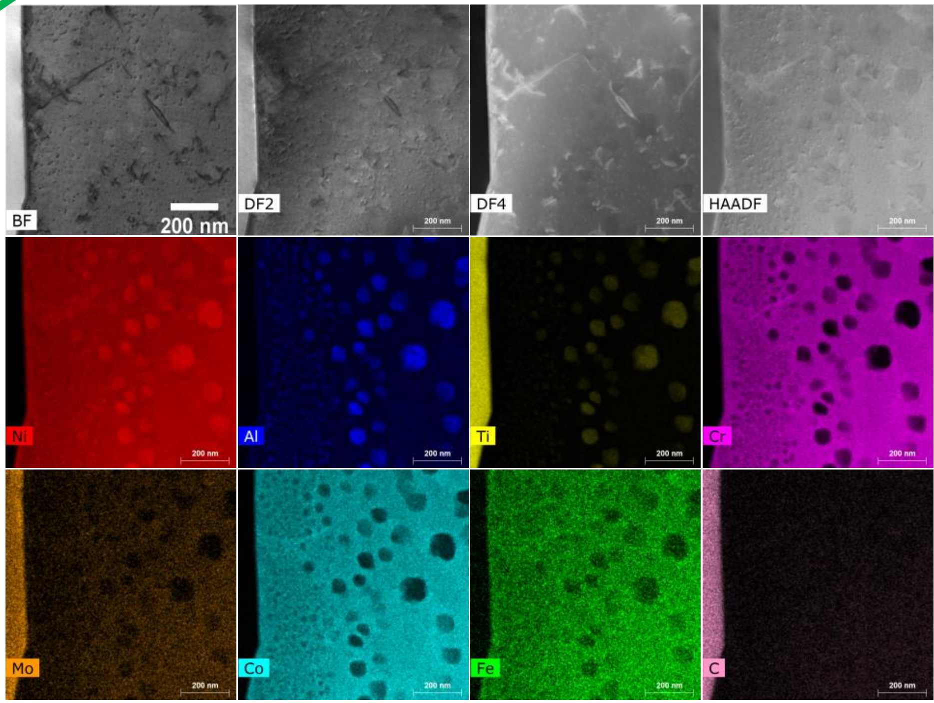


- **Large heterogeneous oxide inclusions**
- **Al-oxide nearest periphery and Cr-oxide at center**
- **No γ’ precipitates in vicinity of oxide**



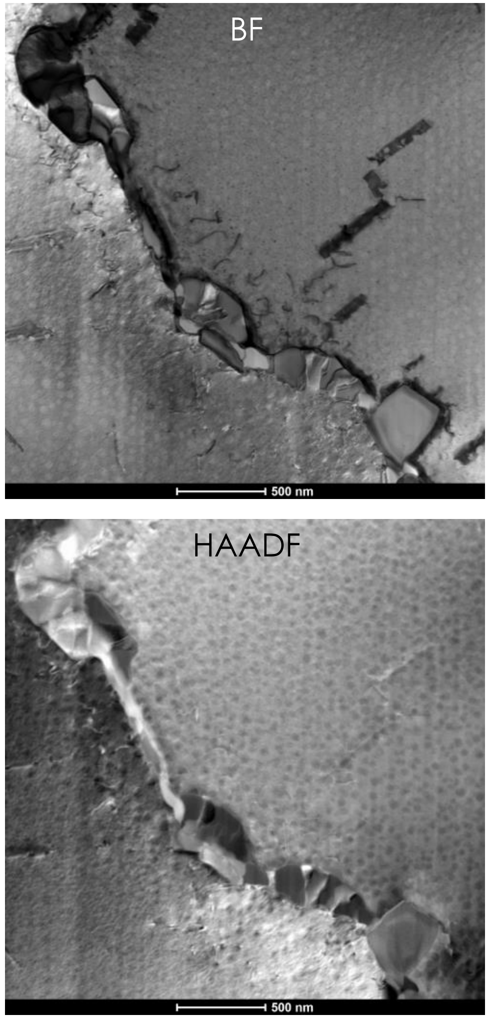
γ’ precipitate gradient near (Ti,Mo)C carbides with these smaller particles appearing to have slightly reduced Ti compared to the larger ones

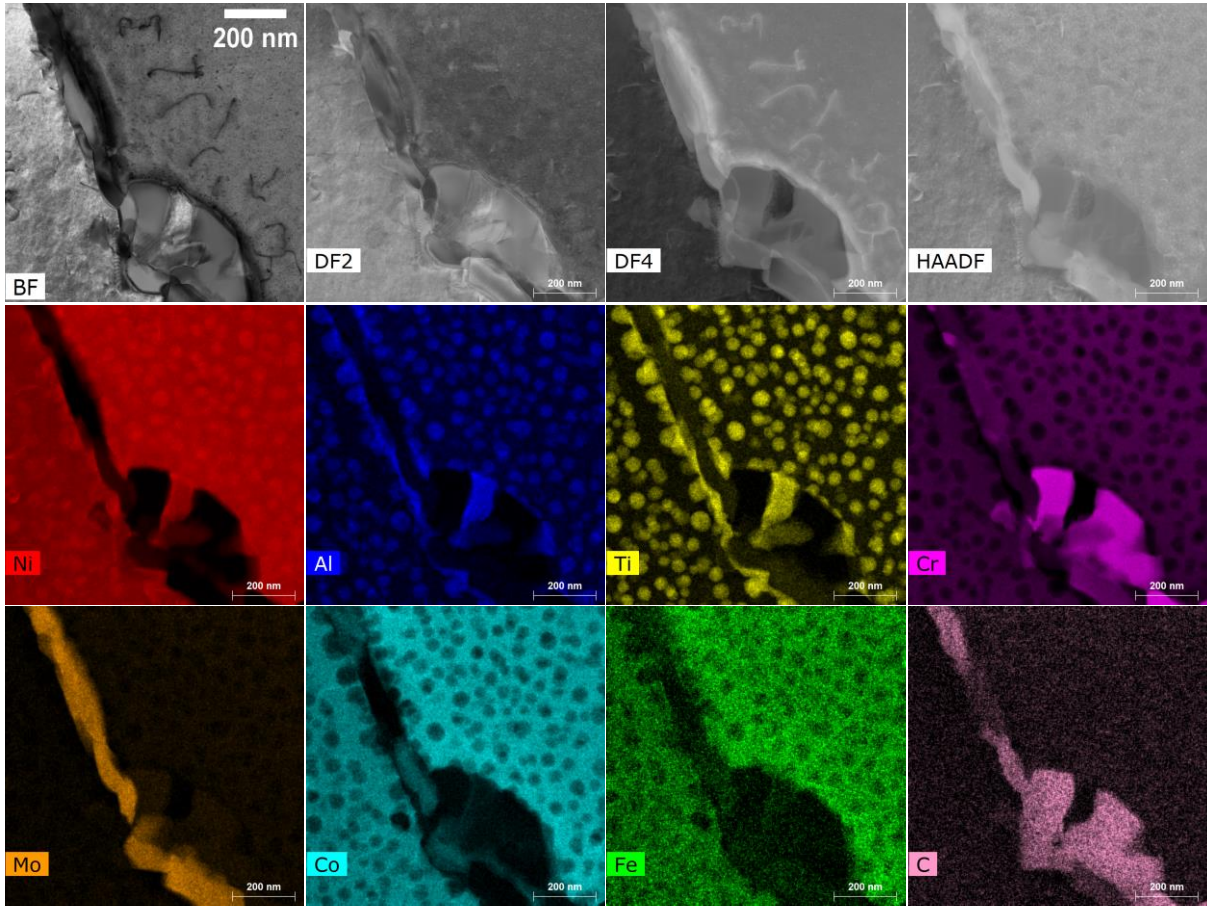
- **~50nm from carbide denuded zone with no precipitates**
- **~200-300nm from carbide with precipitates <~30nm**
- **~0.5-1µm from carbide with precipitates smaller than intragranular precipitates (~100-130nm)**

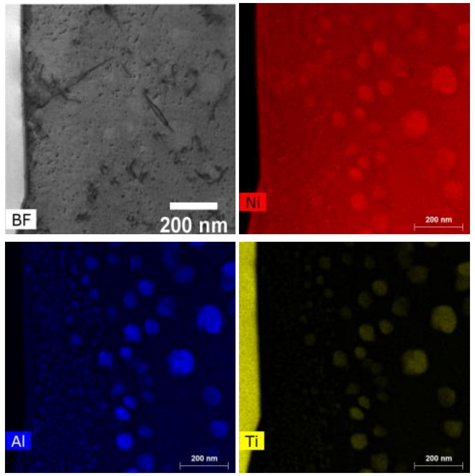


Haynes 282 Nozzle Carrier Casting: solution anneal + one-step aging

- Large size grain structure combined with intragranular and grain boundary carbides, and γ’ precipitates







γ’ near GB precipitate in the as-received Haynes 282 casting

- **Grain boundaries carbides enriched with Cr and Mo***

***no Ti-rich carbides observed does not prove they aren’t there**

- **No gradient in size of γ’ near boundary**
- **Smaller γ’precipitates (~20-60nm) compared with the as-received casting**

This research provides a critical evaluation of advanced Ni-based alloys supporting the manufacturing and use of components under advanced ultra-supercritical (A-USC) steam conditions

Ni alloys for A-USC

Haynes 282 large sand casting
- Tensile
- Creep
- Low cycle fatigue and Creep-fatigue

IN 740H shielded metal arc welding with Thermanit 263 filler metal
- Creep
- Microstructure characterization

Haynes 282 casting cross-weld with 282 filler metal
- Creep
- Thermal aging

Haynes 282 casting to IN 740H plate dissimilar weld
- Metallography & microhardness
- Tensile
- Creep
- Thermal aging

Wrought Haynes 282 and Haynes 282 triple-melt forged disk
- Creep
- Environmental high cycle fatigue

ComTest Phase 2 components
- Nozzle carrier casting

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