Materials for Advanced Ultra Supercritical Steam Turbines

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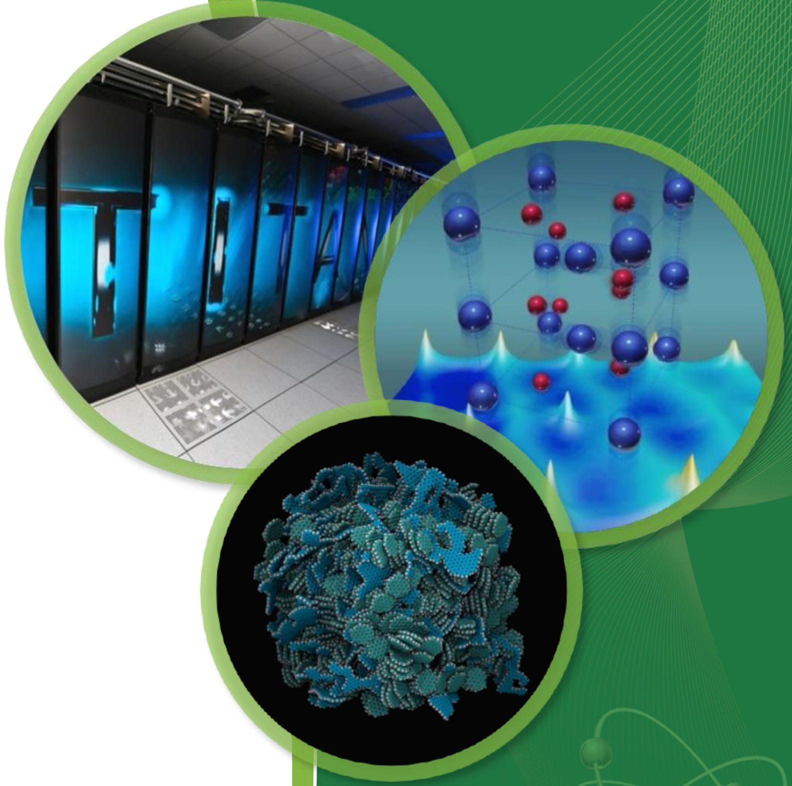

2017 CrossCutting Materials Review, March 20-23, Pittsburgh, PA

Properties of Advanced Ni-Based Alloys for A-USC Steam Turbines

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- 2017 CrossCutting Research Project Review
- March 23, 2017
- FEAA125
- 2016-2018

Collaboration Acknowledgements

- **ORNL** – Jeremy Moser, Chris Stevens, Kinga Unocic, Amit Shyam, Ying Yang, Frank Chen
- **General Electric** – Mani Thangirala, Deepak Saha
- **MetalTek** – James Myers
- **Special Metals Corp.** – Stephen Coryell, John deBarbadillo

Project Goals and Objectives, and Milestones

- The project goals are to qualify the alloys that will be used for A-USC Comtest Steam Turbine. The objectives are measure high temperature properties of forged Haynes 282 alloy for the turbine rotor and of cast Haynes 282 for the valve body and turbine casing, in close collaboration with GE.

- Begin CO_2 effects on HCF testing of Haynes 282 alloy at 750^{o}C (April, 2017)
- Complete initial HCF testing on large GE forging of Haynes 282 alloy and evaluate the effect of steam and hold times on fatigue life (April, 2017, complete)
- Complete microstructural characterization of large GE forging of Haynes 282 alloy and submit report (June, 2017)
- Begin creep testing of 740/263 piping cross weld specimens (July, 2017)
- Complete initial creep-rupture of interrupted creep tests on GE specimens from large casting of Haynes 282 alloy (August, 2017)

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Presentation Outline

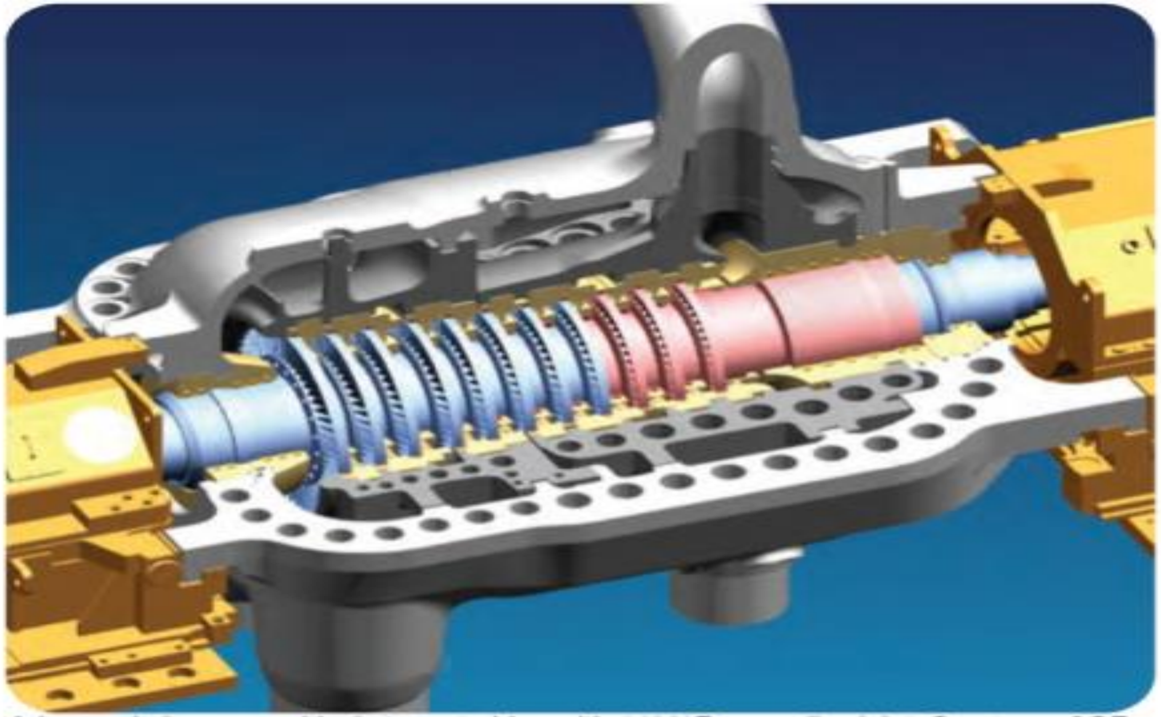
- Background and information on large forging of Haynes 282 for steam rotor application
- Background and information on large casting of Haynes 282 for the valve body and turbine casing applications
- Future work

Expansion of Outline Topics

- **Large rotor forging** – summarize GE alloy selection process for Haynes 282 alloy, summarize processing by Special Metals and properties data from GE on large forging, and summarize ORNL work on steam effects during HCF testing and microstructural analysis of the large forging
- **Large valve casting** – summarize ORNL/NETL alloy selection from small castings for Haynes 282, and summarize GE properties data on the large casting and ORNL tensile and creep data and microstructural analysis of native structure and failure analysis after tensile testing
- **Future work** – Complete interrupted creep-rupture testing on large GE casting, complete tensile testing, begin LCF testing including hold times, and complete microstructural analysis of as-cast and creep-tested specimens, and do welding of cast structure.

Background – Advanced Ultrasupercritical (A-USC) Steam Power Plants

From Schwant et al., AM&P 2013.



Advanced ultrasupercritical steam turbine with 1400°F superalloy inlet. Courtesy of GE Power & Water.

- **Advanced Ultrasupercritical (A-USC) steam power plant technology requires operation at maximum temperature of 760°C (1400°F) and 35 MPa (5000 psi) pressure.**
- **Materials technology is being developed to meet demands**

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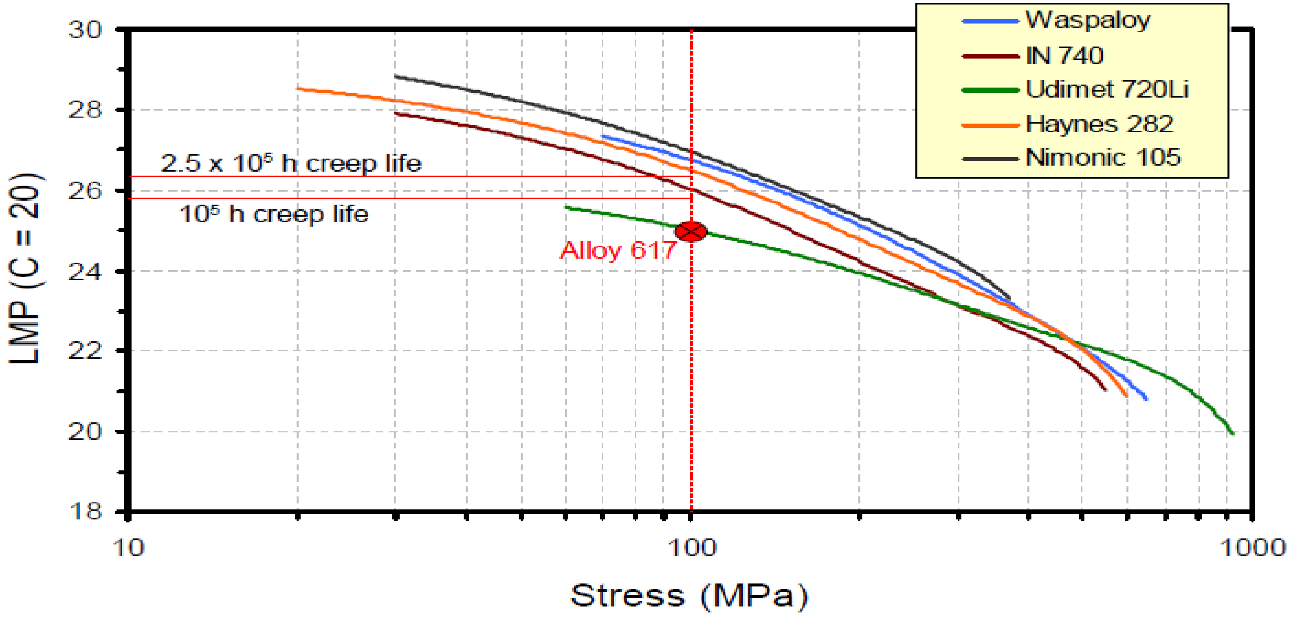
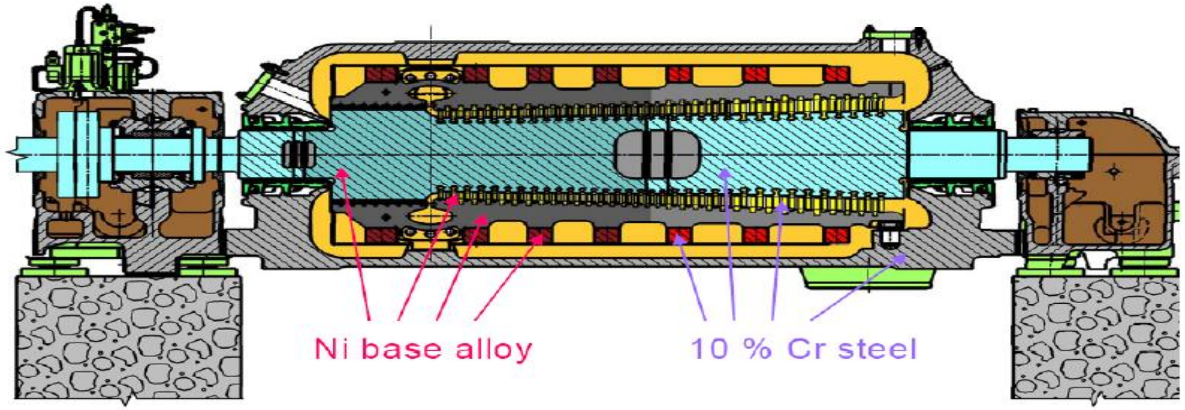
A-USC Turbine Designs Need Ni-based Superalloys (rotors, blading, casing)

Wrought Ni-based superalloys (NI 105 and HR 282) have creep-strength needed for rotors and blading to last 250,000h



Alstom HP Turbine Concept



Consortium Phase 1 Result

Cast Ni-based superalloys were needed for turbine casing

Primary & Secondary Melting

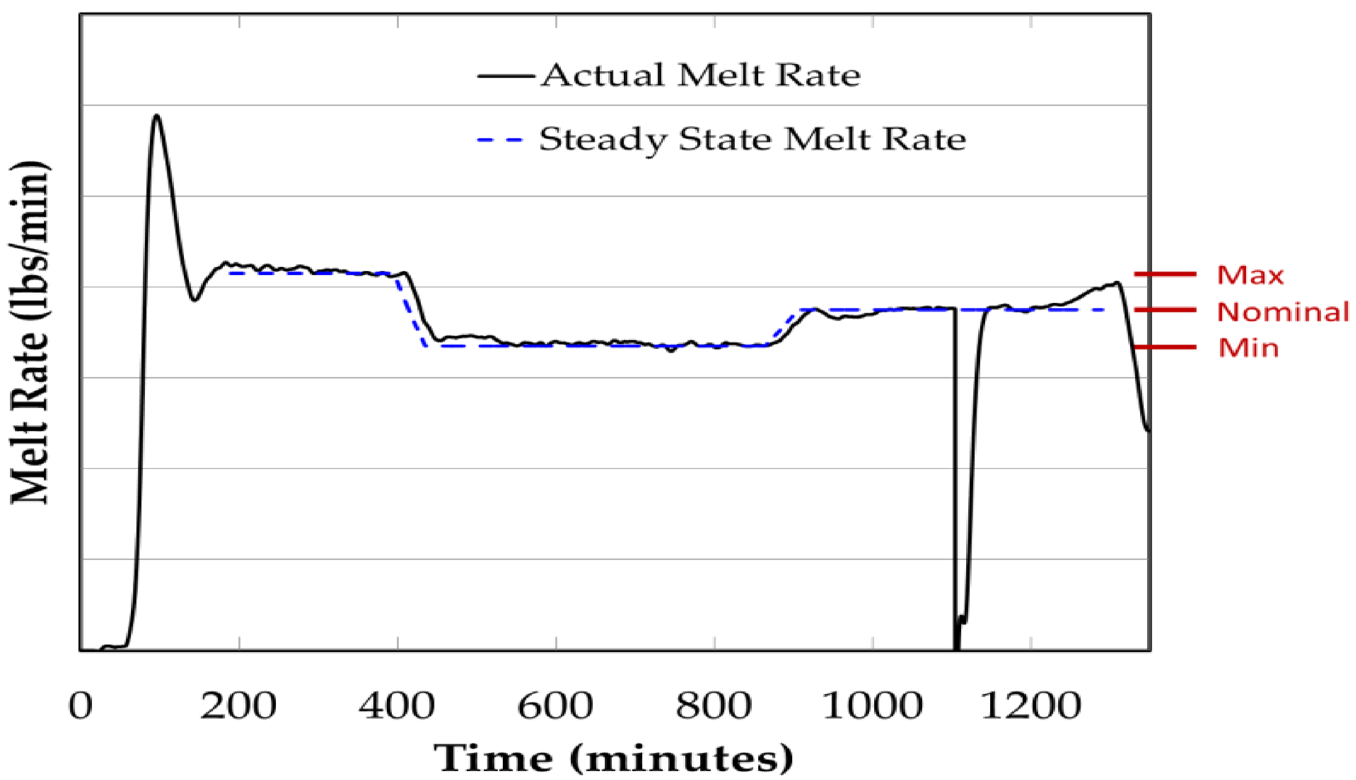
VIM Electrodes

- Two 457mm (18”) DIA electrodes were melted and cast by vacuum induction
- Electrodes were annealed before remelt to minimize stresses

ESR Ingode

- Electrodes were electro-slag remelted to 559mm (22”) DIA ingodes
- No events observed in ESR
- Slow cooled in insulated can and annealed to minimize residual stresses

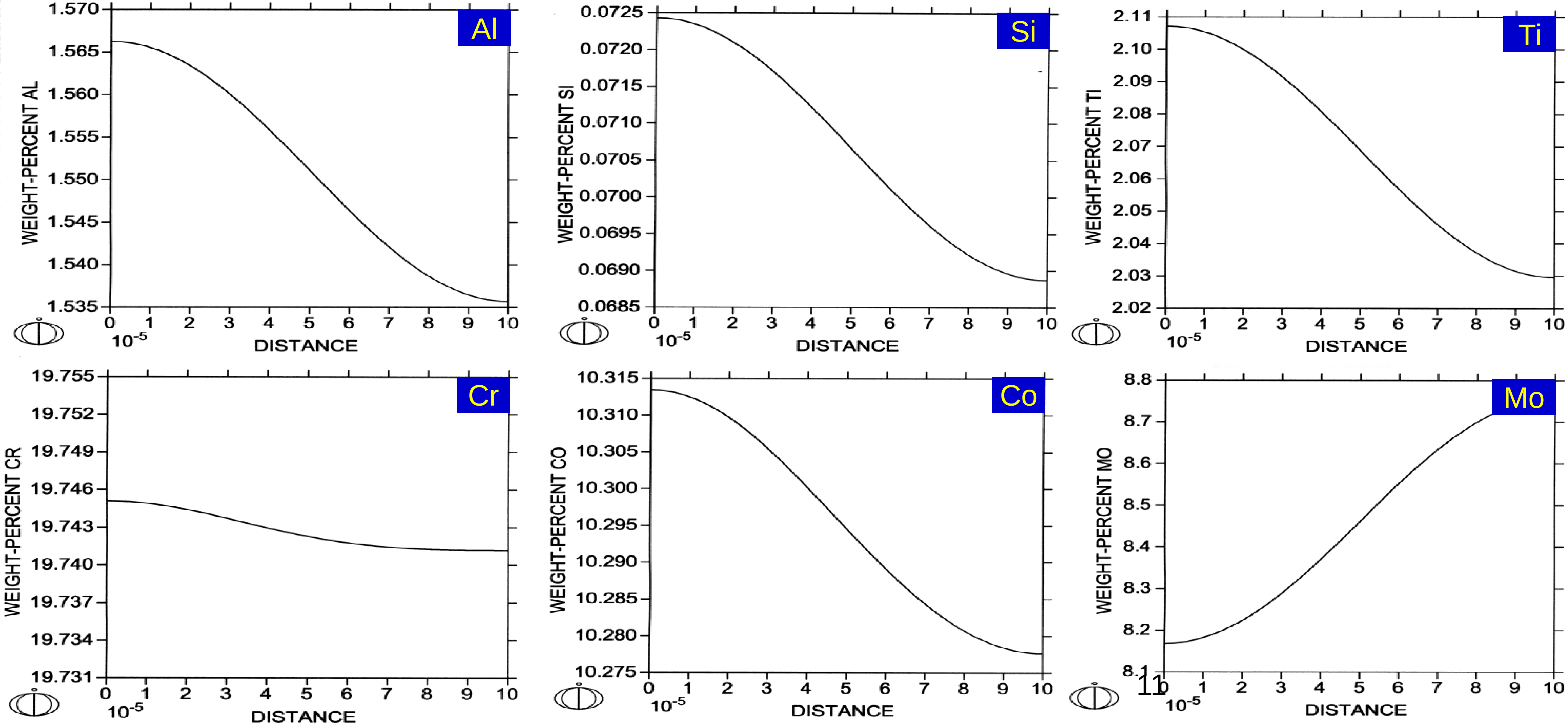
Varying Melt-Rate VAR Trial



- First VIM-ESR ingot remelted by vacuum arc remelt to 610mm (24”) DIA ingot
- Custom profile used with three melt rates and an intentional 60-second power interruption to determine the effect of segregation
  - If determined to be segregation-free, VAR fixed practice is established with allowed limits being the Min/Max melt rates evaluated

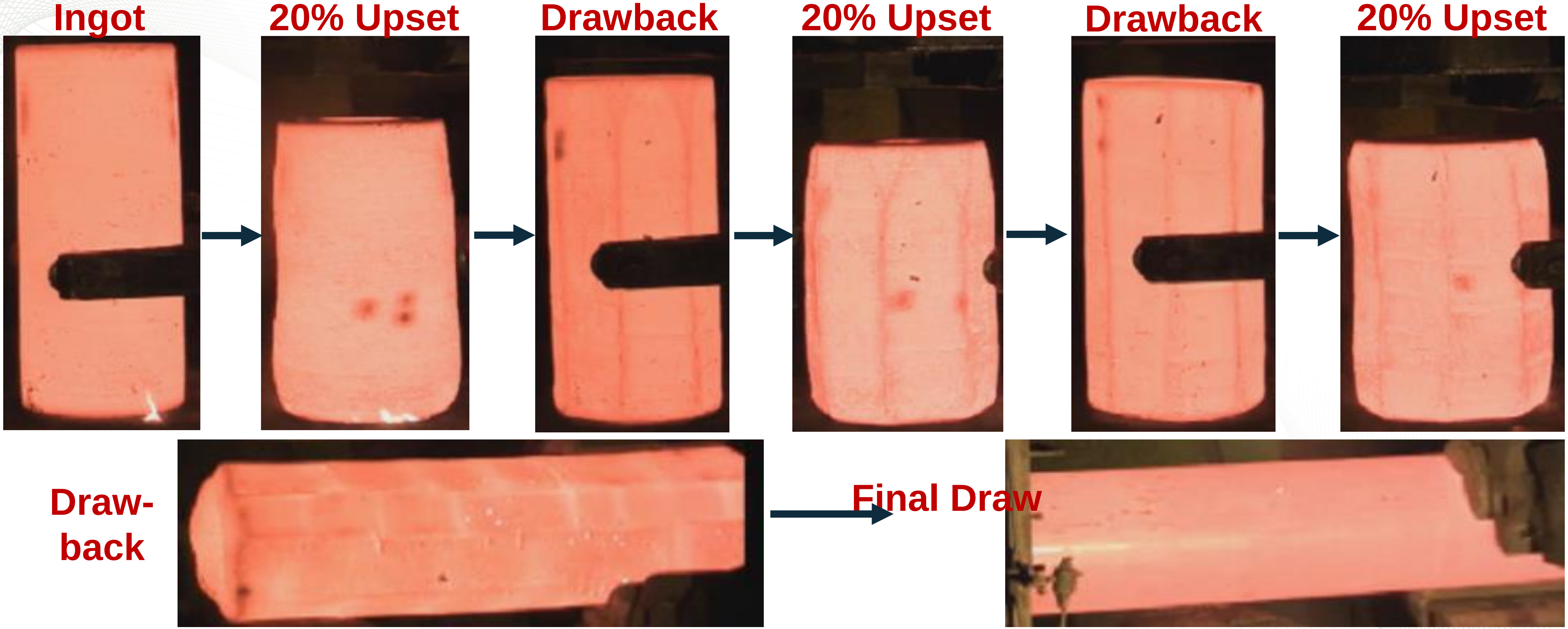
Homogenization Design

- Three-step homogenization practice developed by NETL using ThermoCalc + DICTRA to minimize micro-segregation and risk of incipient melting. (Assumes 200μm SDAS)



Ingot Billetizing

- Ingot was successfully billetized with 4:1 reduction ratio to break up cast structure.
- Minor surface cracking due to cooling – may be minimized in future process optimization



Rotor Forging

- Goal #1 – 45” diameter x 8-10” thick
- Goal #2 – Grain size ASTM 6 or finer (uniform structure)
- Alloy 282® billet from SMC was forged into a pancake using three upsets
- Forging was then aged using two-step heat treat: 1010°C/2hr/AC + 788°C/8hr/AC

Start Bingot → **1st Upset** → **2nd Upset** → **3rd Upset**

Final Dimensions:

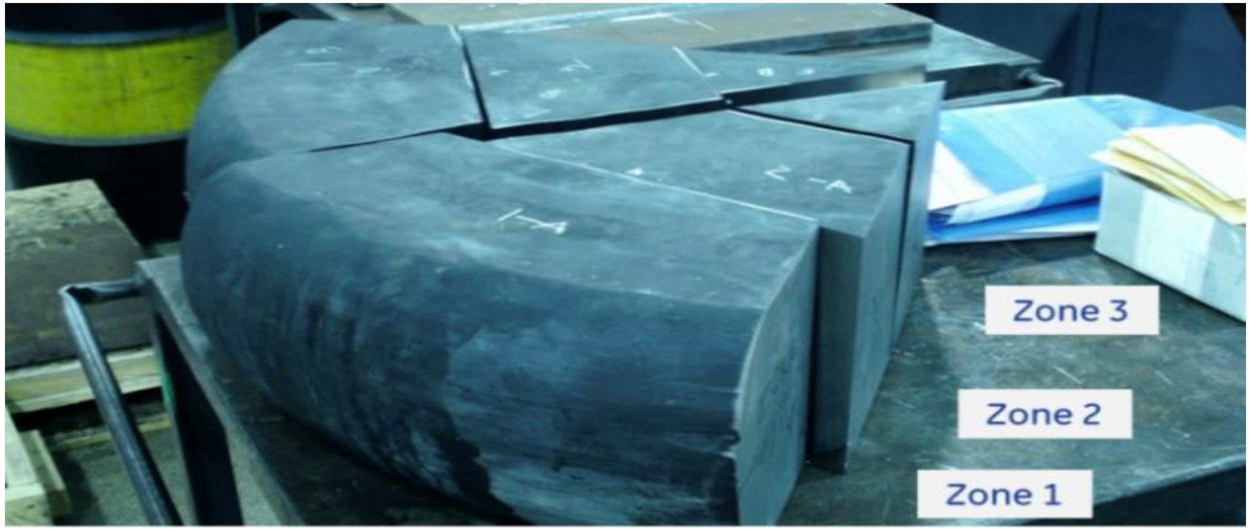
Diameter (Top): 44”

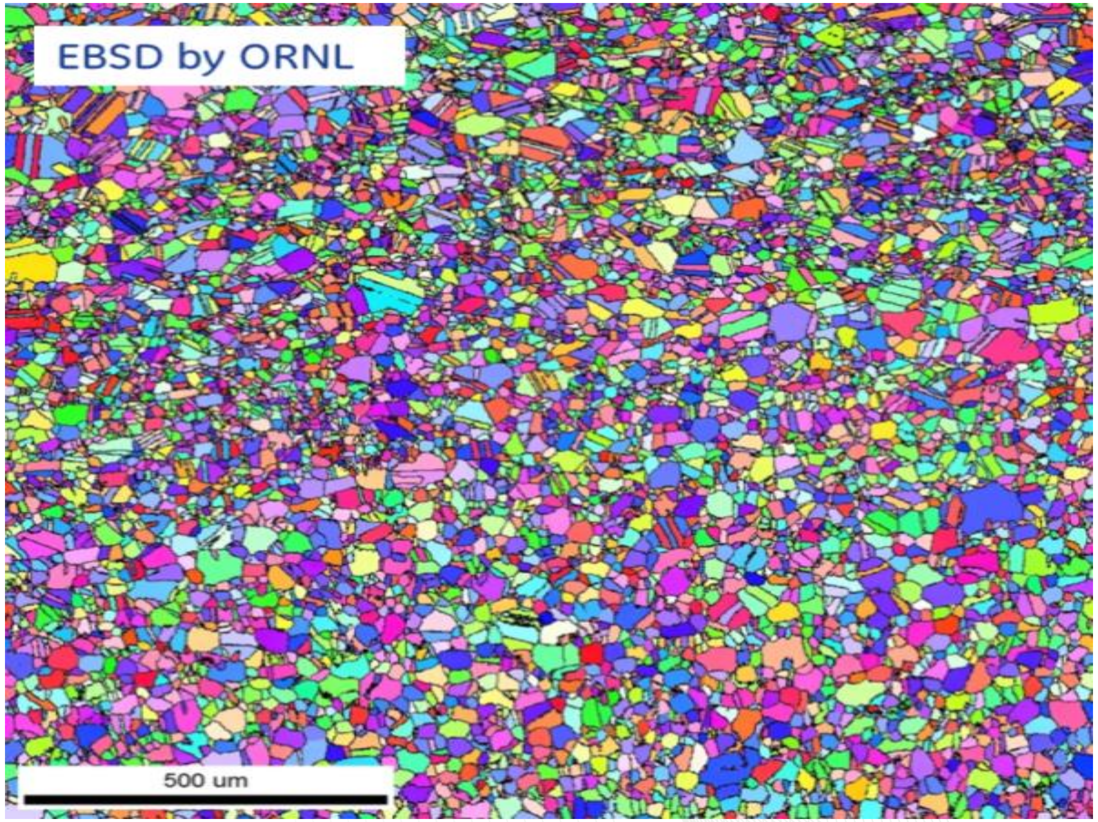
Diameter (Bulge): 49.5”

Thickness: 9.5”

Testing & Evaluation

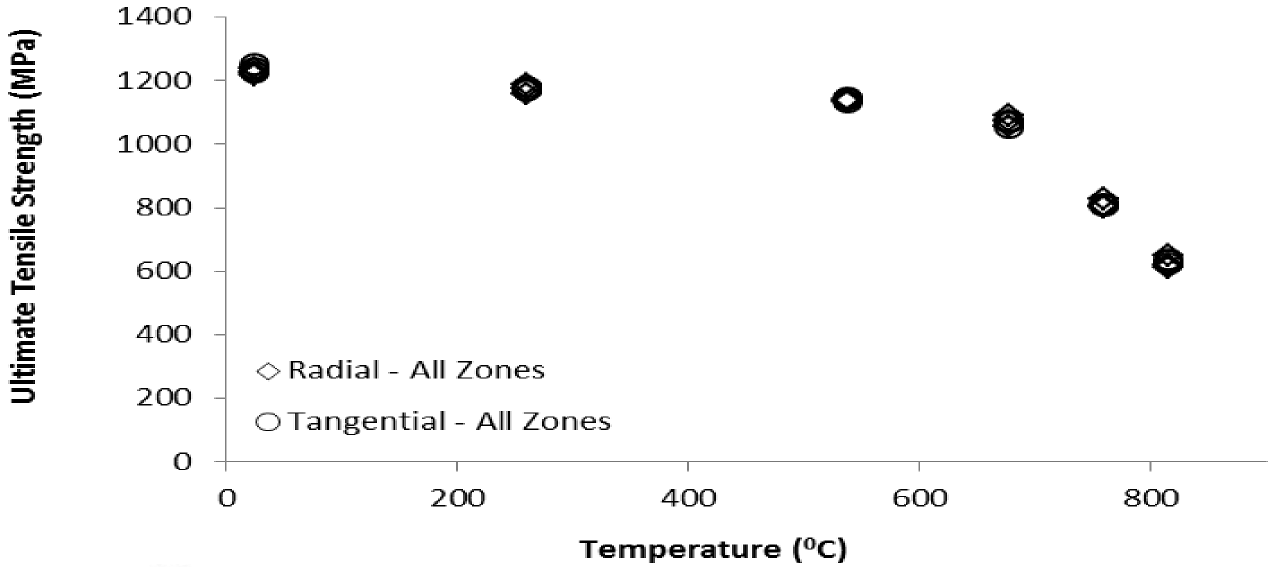
- The forging was sectioned into zones for property evaluation
- Microstructure was determined to be fine and uniform with:
  - Typical Grain Size: ASTM 8-9
  - Grain Size ALA: ASTM 4
- No texture observed

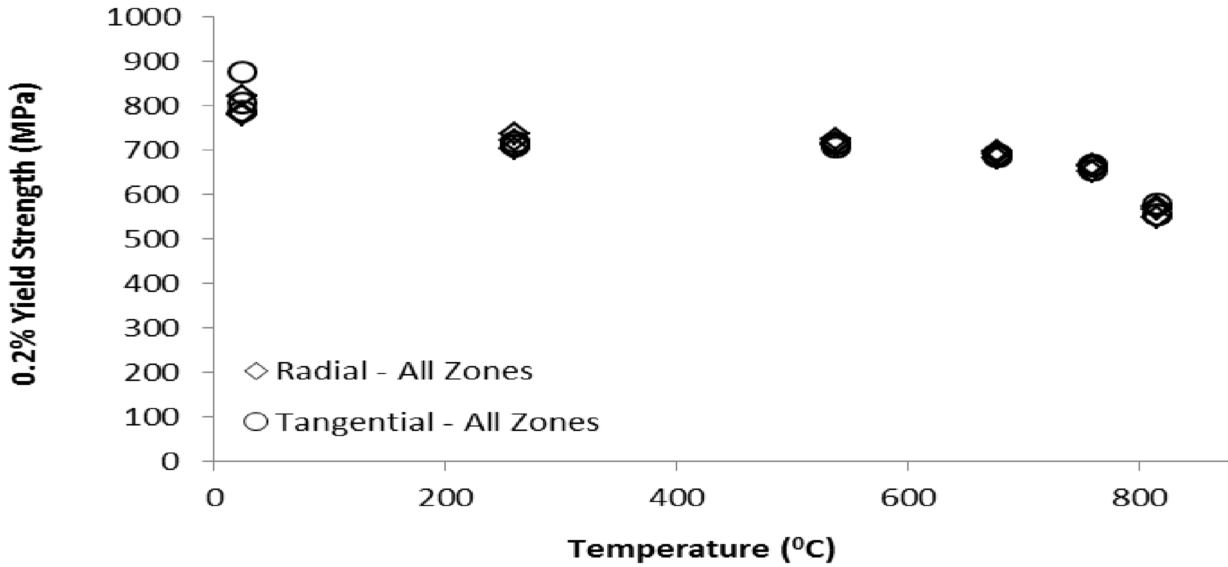


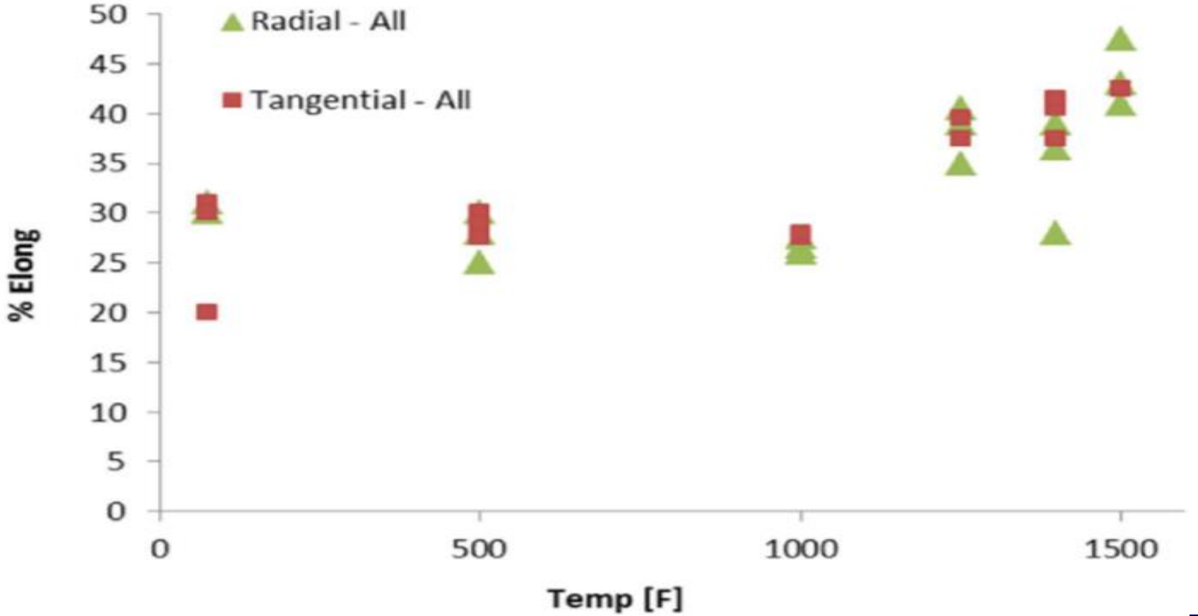


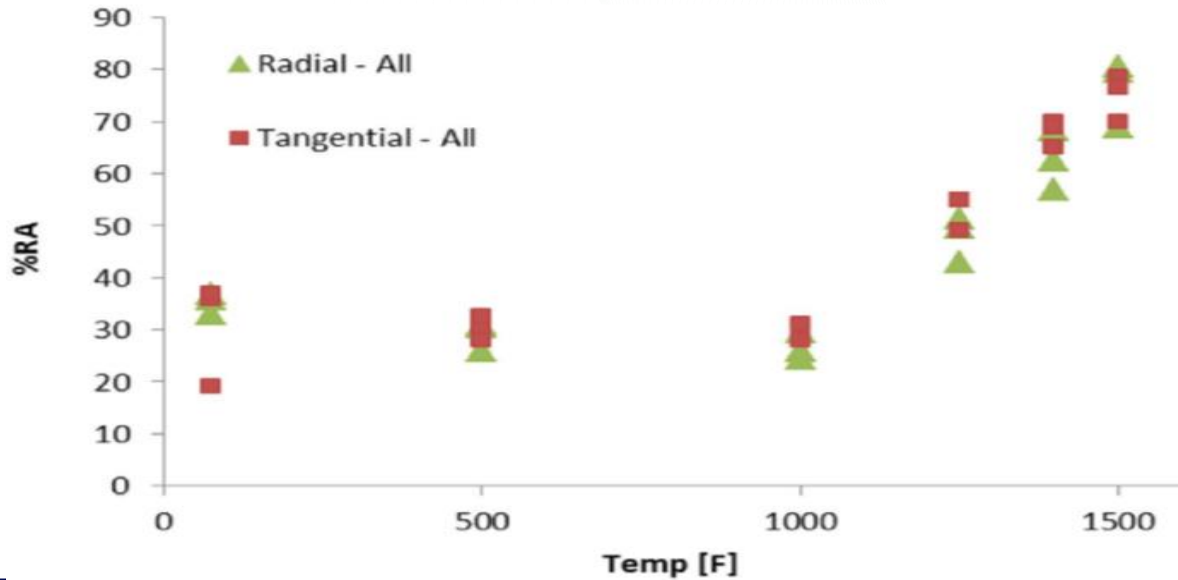
GE Testing & Evaluation

- The disk forging exhibited uniform and isotropic tensile behavior in all zones





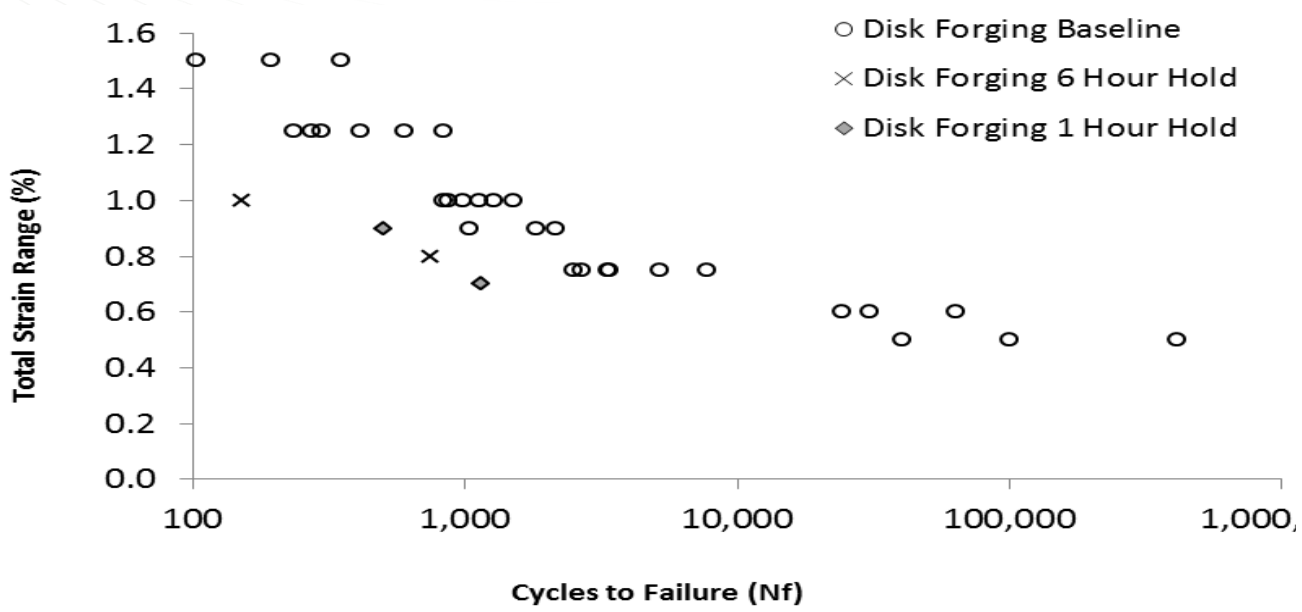




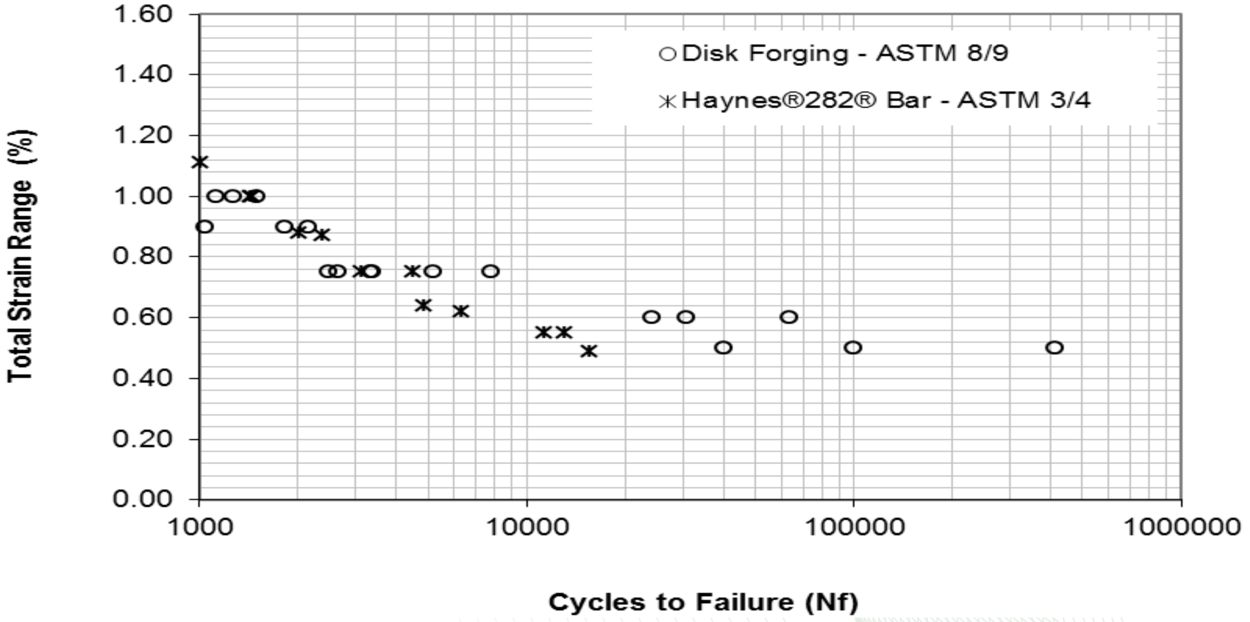
GE Testing & Evaluation

- Low cycle fatigue tests at 760°C were performed in all orientations at 20cpm
- The Alloy 282® forging exhibited superior fatigue properties when compared to rolled bar
- Debits in the hold time fatigue life of the forging were less pronounced when compared to similar studies on larger grain VIM-ESR bar product

LCF life using trapezoid waveform (Hold at peak stain for 1 & 6 Hours) of the disk forging at ***760 °C***



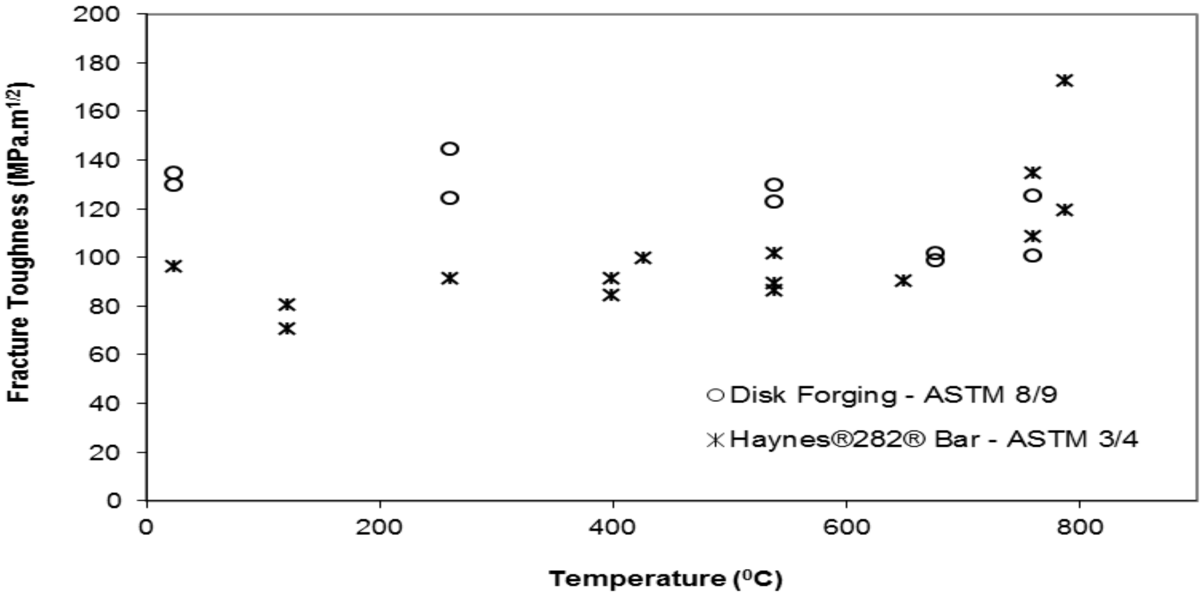
LCF at ***760 °C****, comparing the fine grain triple melted disk forging to VIM-ESR rolled bar (A_{strain} =1, 20 cpm)*

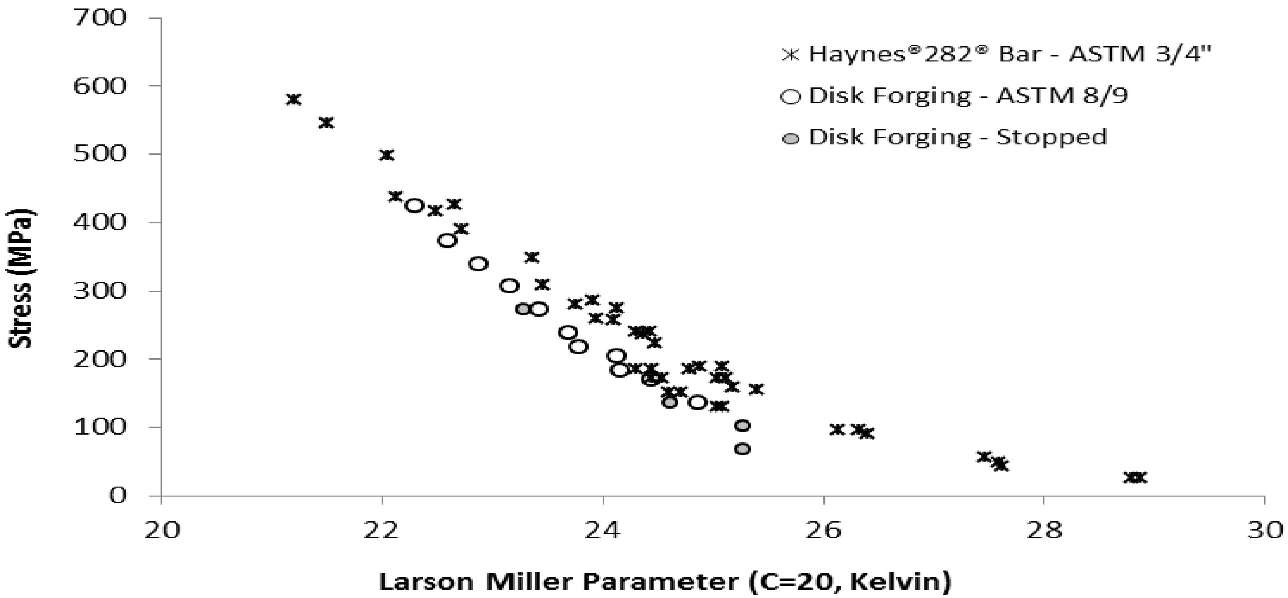


Chen Shen, Department of Energy [DOI: 10.2172/1134364], 2014.

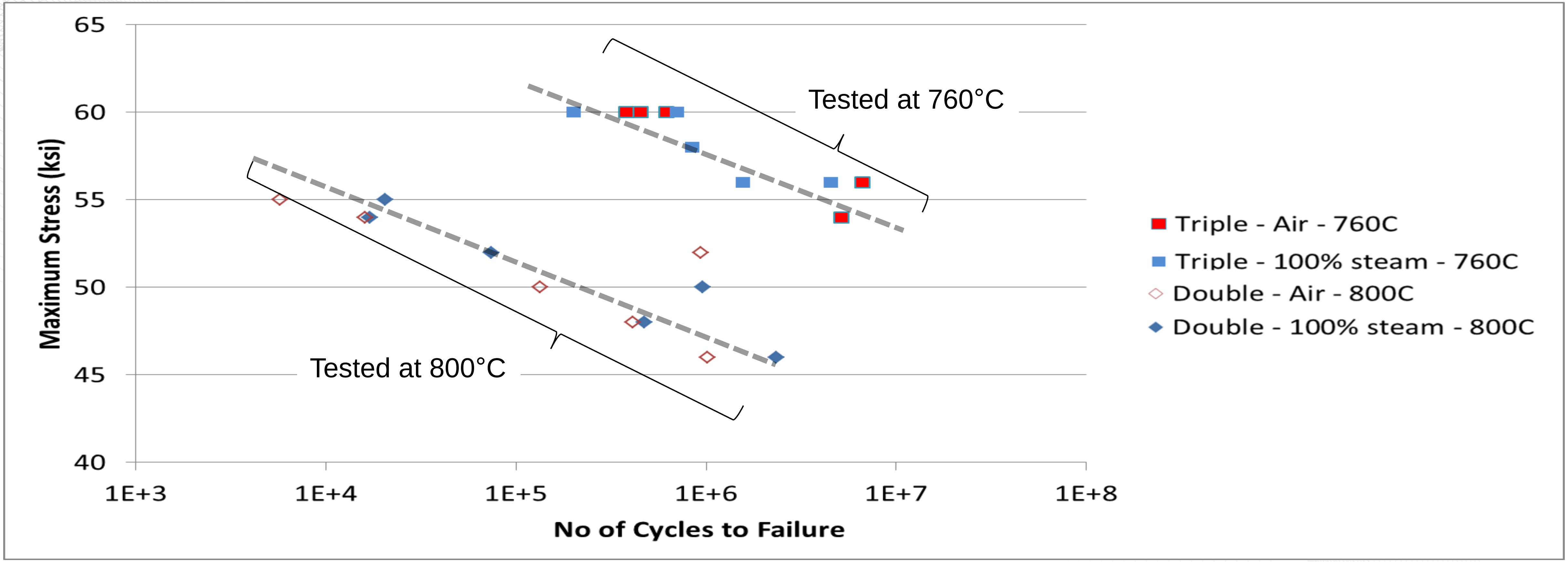
GE Testing & Evaluation

- The forged disk demonstrated superior fracture toughness compared to rolled bar due to the finer grain size and microstructure cleanliness from triple melting.
- The disk forging had a slightly lower rupture strength due to the finer grain size.
- The reduced rupture strength is considered a trade-off for higher fatigue behavior that needs to be balanced during design of the final A-USC component.



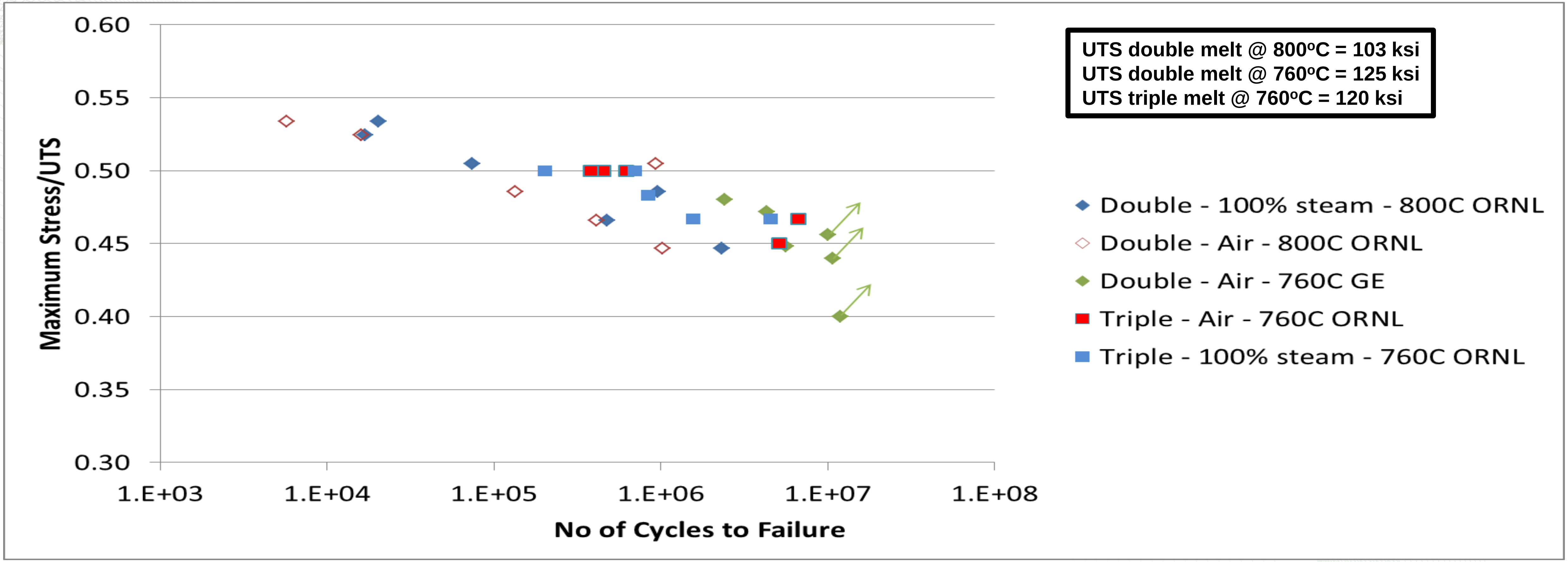


All R = -1 HCF fatigue testing performed at ORNL (on double/triple melt materials)



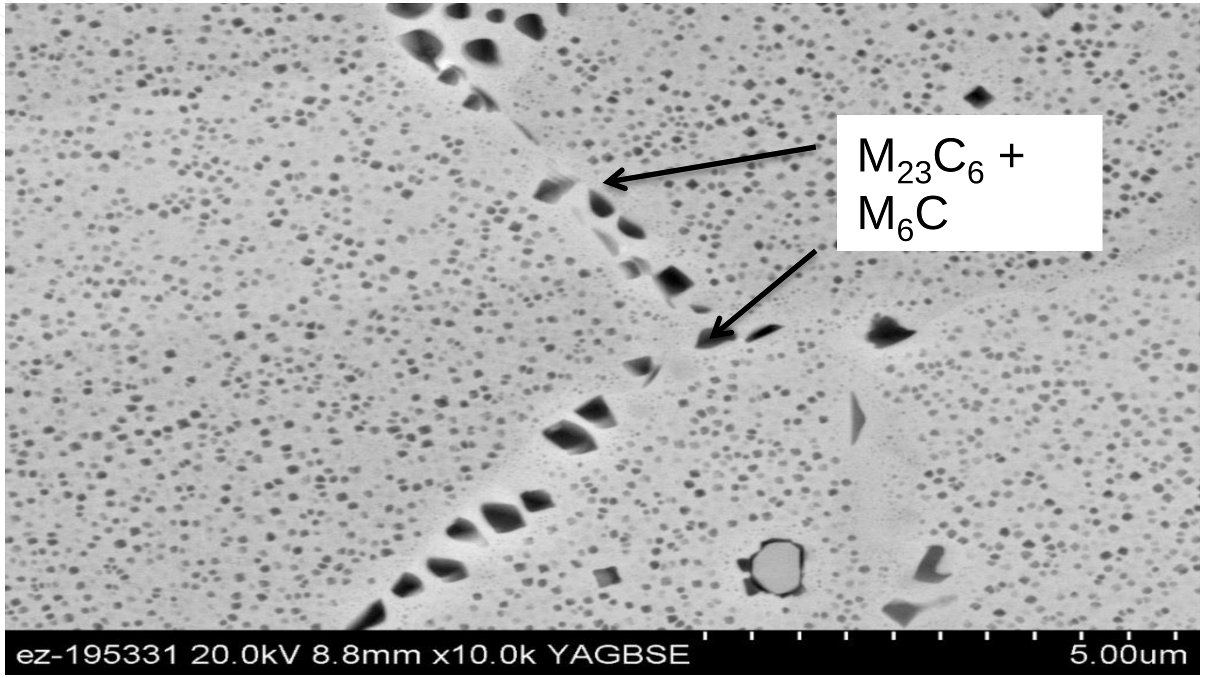
- Improvement in fatigue behavior for the finer triple melt microstructure (at 760 ^{o}C)
- No discernible effect of steam for either microstructure

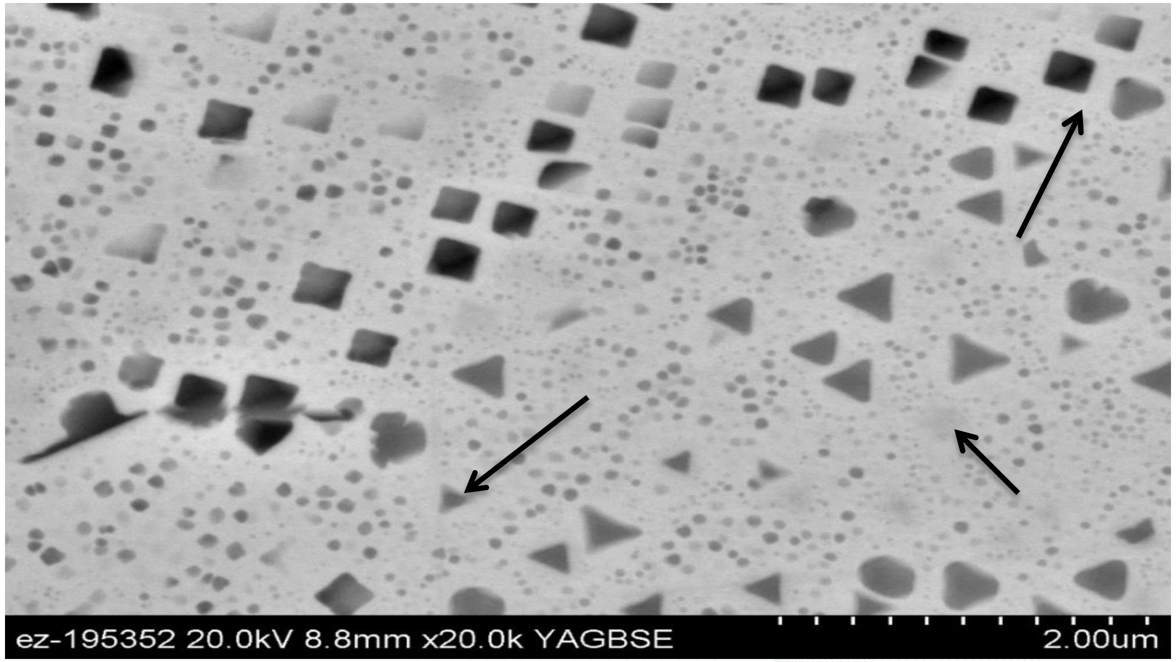
There is ***no significant effect*** of microstructure and environment after this normalization



- Compare double and triple melted material fatigue data (normalized)

As-forged and heat-treated microstructure of Haynes 282 alloy (ORNL data)





BS-SEM

Lower magnification

Small grains lack gamma prime

Higher magnification

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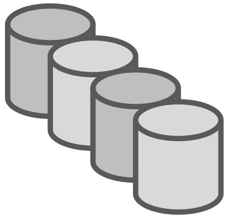
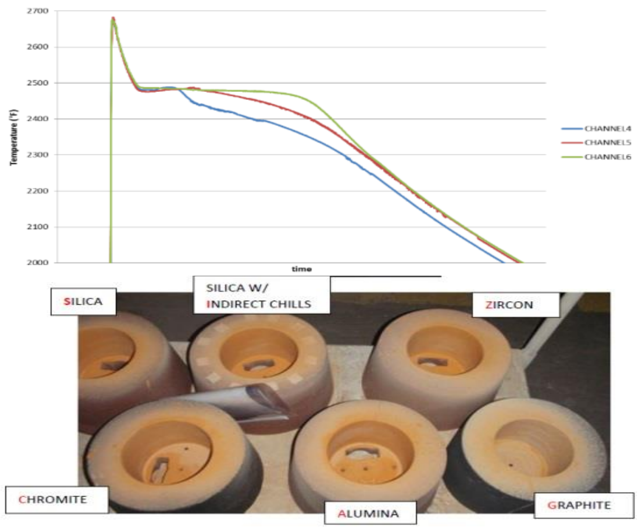
DEVELOPMENT PROGRESSION OF AIR MELT H282 CASTING PROCESS

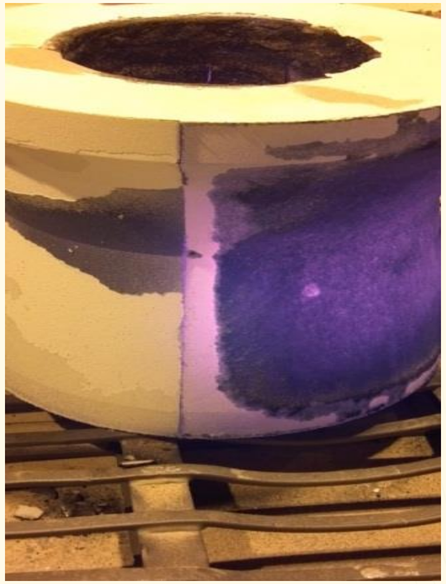


Lab Scale
NETL
<10kg

Step Block
Casting
Carondelet
~150kg



Mold Material Trial
Carondelet



Split Mold
Centrifugal
WC
~650kg

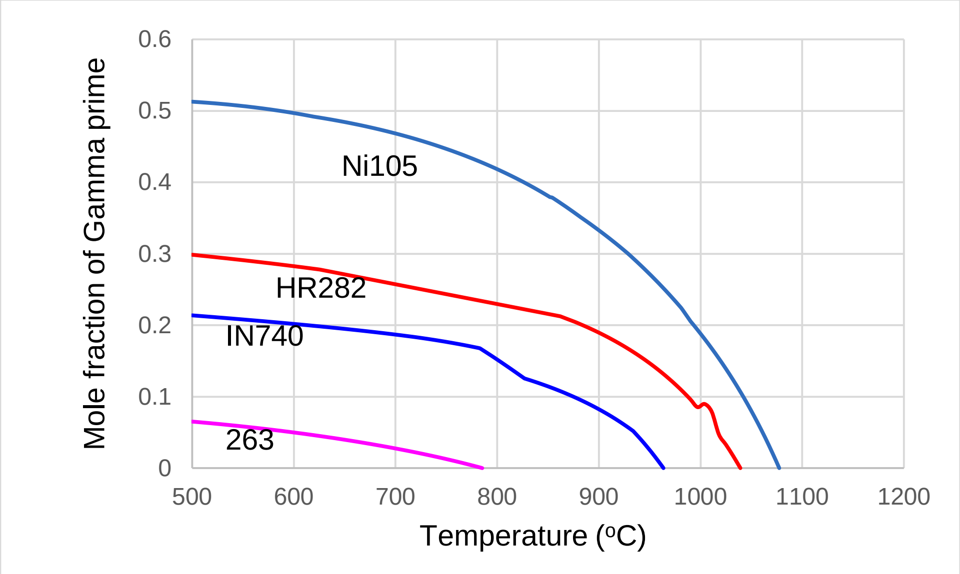
Partial Valve Body
Carondelet / WC
~7500kg

Compositions of Ni-based superalloys that were considered for A-USC steam turbine cast casing

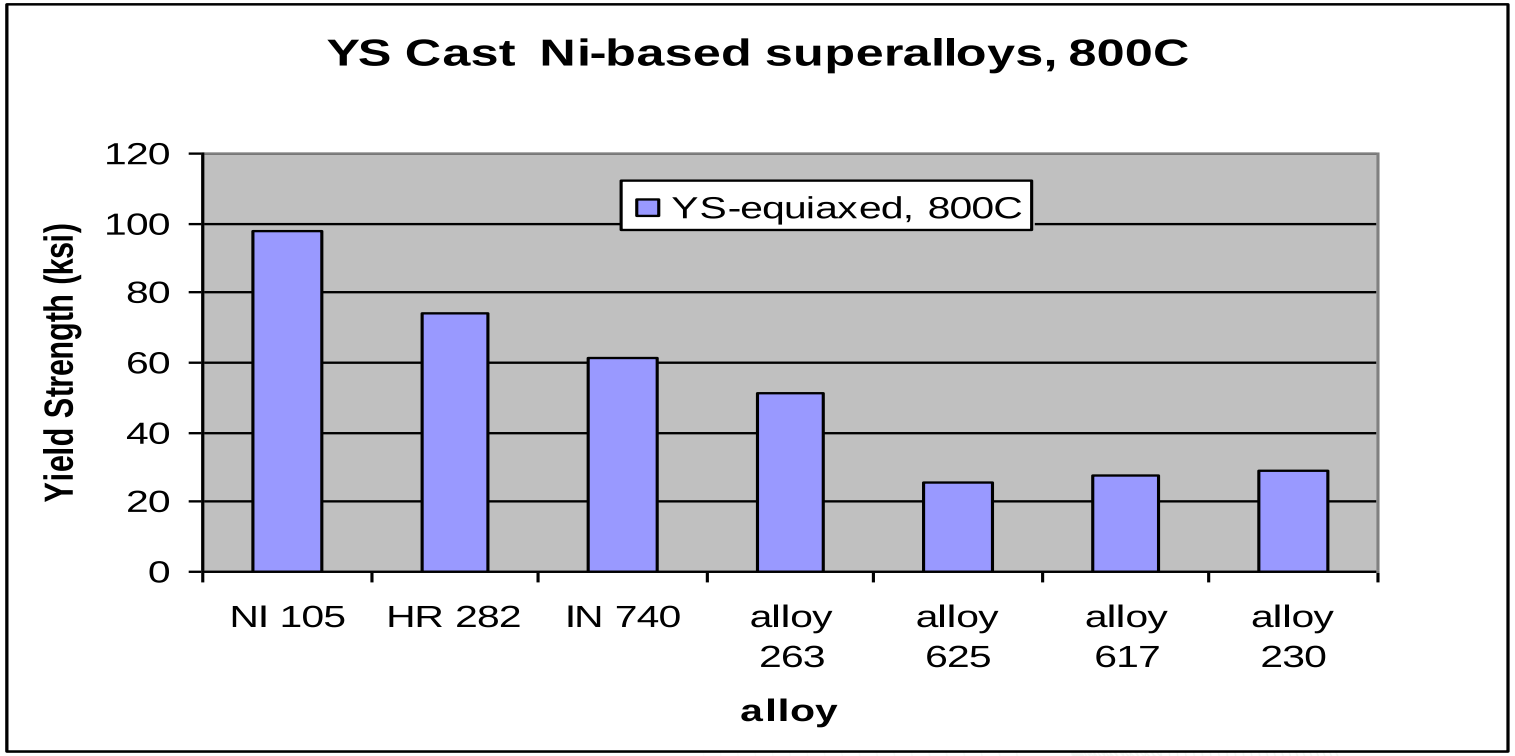
Alloy	Ni	Cr	Co	Mo	Nb	Ti	Al	Mn	Si	C
NI 105	bal	14.85	20.0	5.0	-	1.1	4.7	0.5	0.5	0.15
HR 282	bal	19.5	10.0	8.5	-	2.1	1.5	0.15	0.15	0.07
IN 740	bal	25.0	20.0	0.5	1.5	1.5	1.3	0.3	0.3	0.03
Alloy 263	bal	20.0	20.0	5.8	-	2.1	0.35	0.5	0.35	0.07

High-Temperature Strength of Cast Ni-based Superalloys Depends on gamma-prime

Alloy	(Ti+Al) Wt%
N105	5.8
282	3.6
740	3
263	2.45



Pandat



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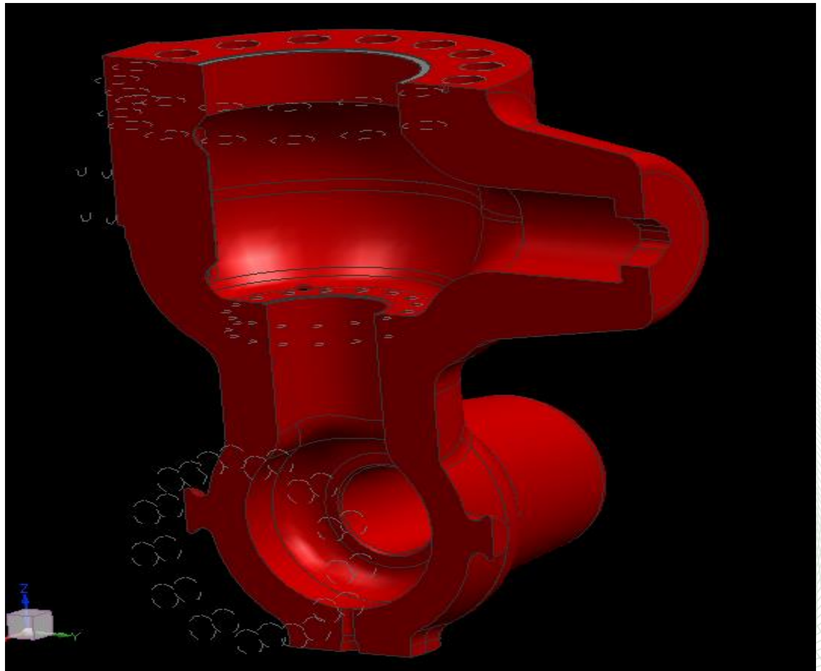
Development of Large Sand Casting Process

- Confirm manufacturing feasibility of full scale components
- Develop material property dataset applicable to large section thickness castings
- Due to material availability, “partial” valve body component selected



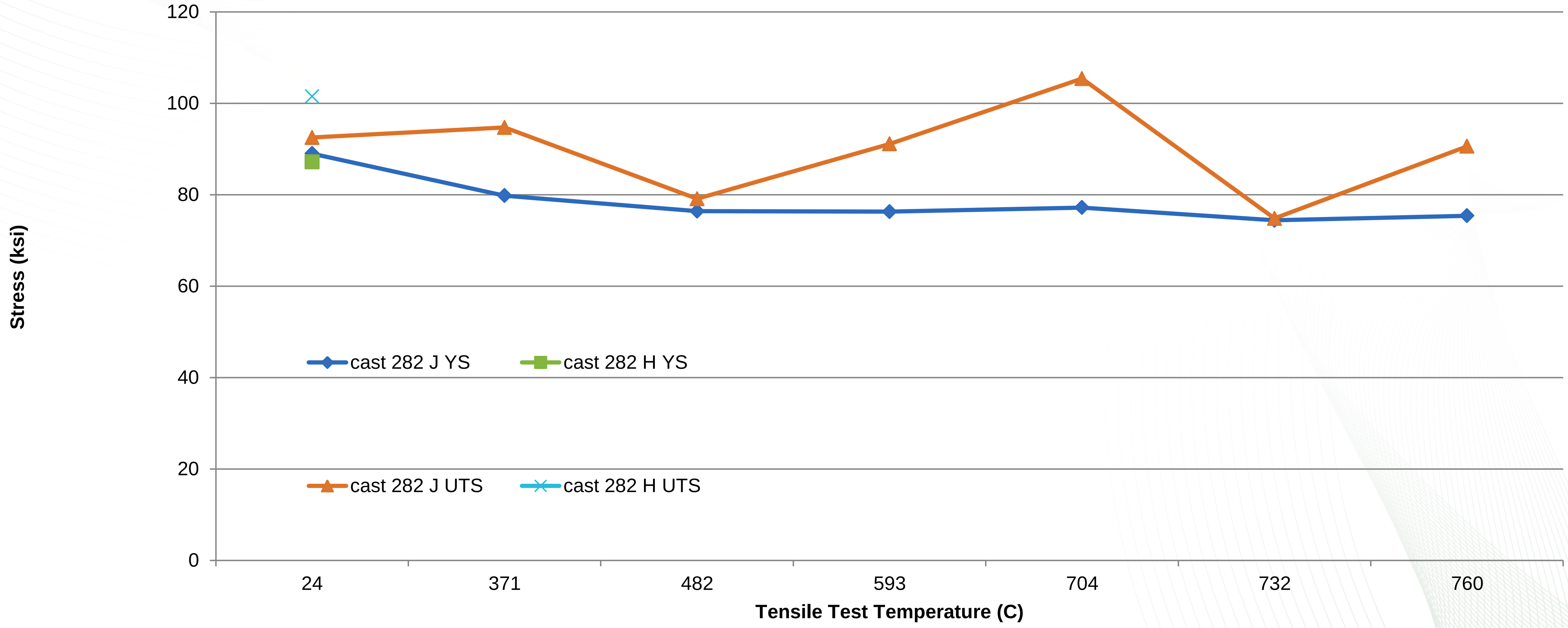
DEVELOPMENT OF SAND CASTING PROCESS

- H282 ingot used as melt stock
- Same melt practice developed for centrifuga casting used
- Reactive element and timing concerns
- Mold purging
- Simulation

DEVELOPMENT OF SAND CASTING PROCESS

- Cast on coupons removed
- SDAS analysis for solution heat treatment
- Solution and Age heat treatment of casting

The Large GE/MetalTek casting of Haynes 282 shows good YS and UTS at various temperatures (ORNL data)



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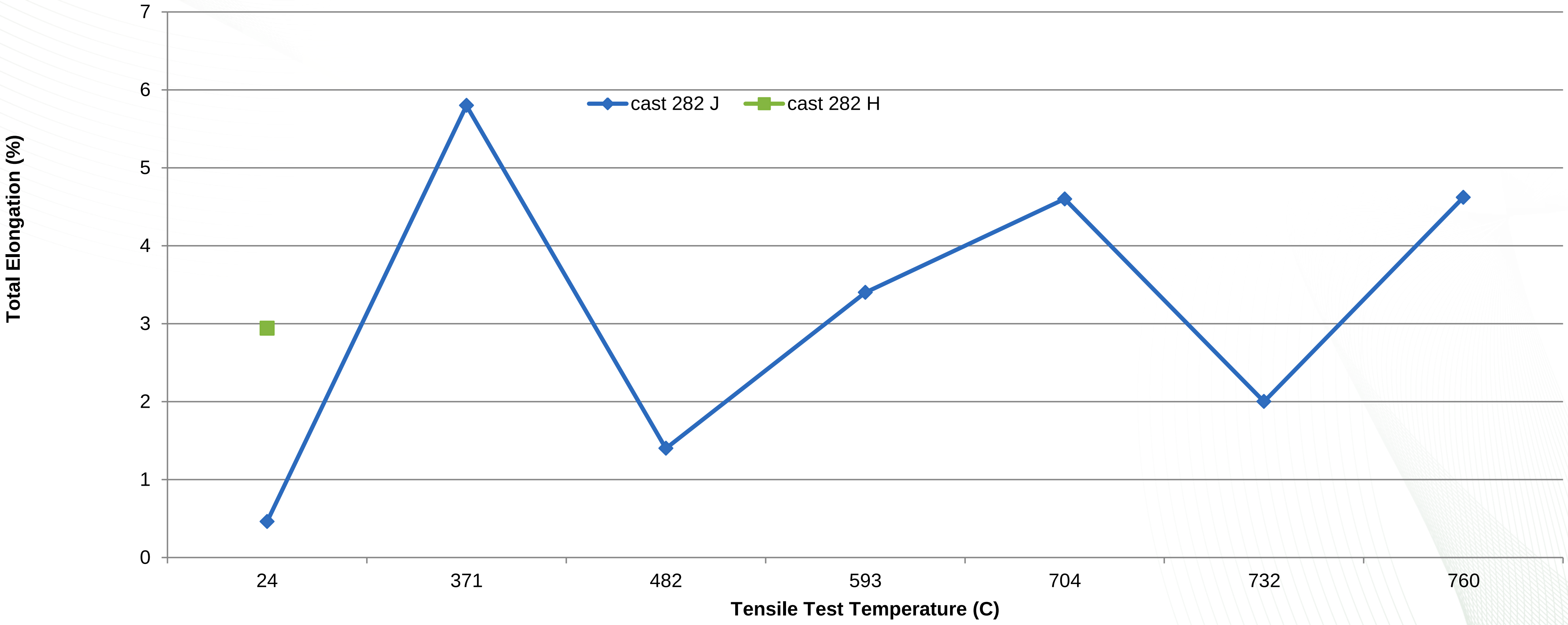
In the large Haynes 282 casting total elongation varies from about 2-6% (ORNL data)



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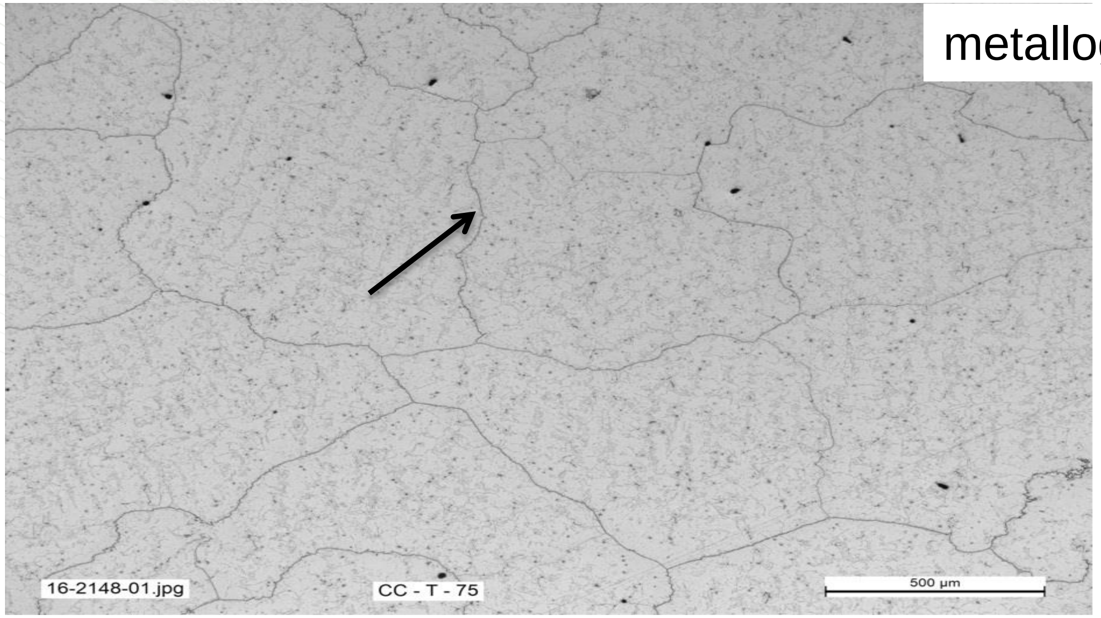
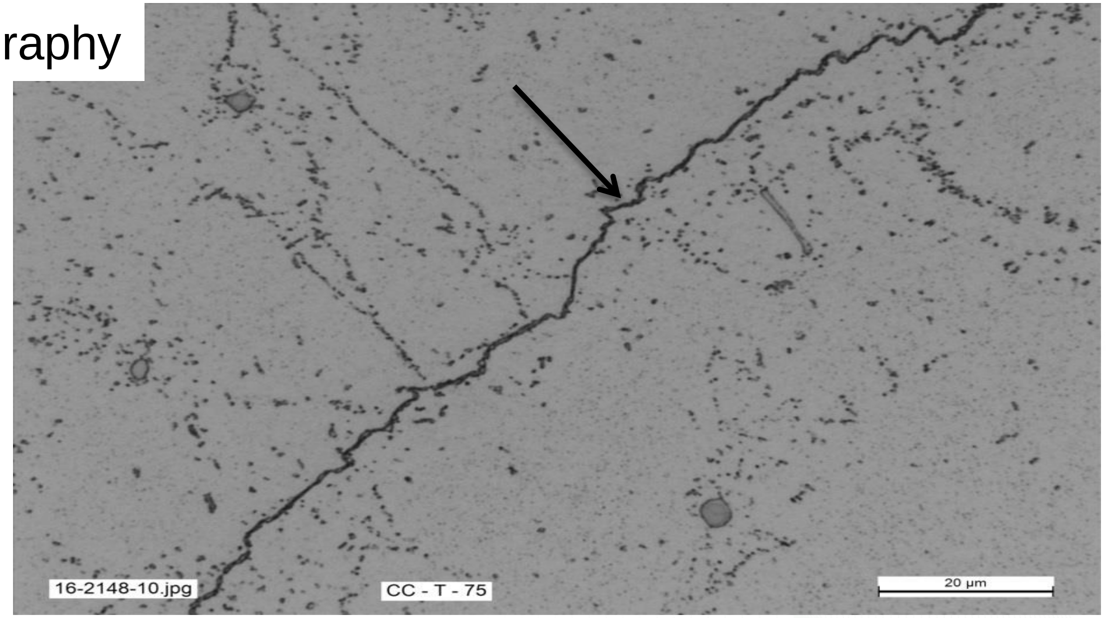
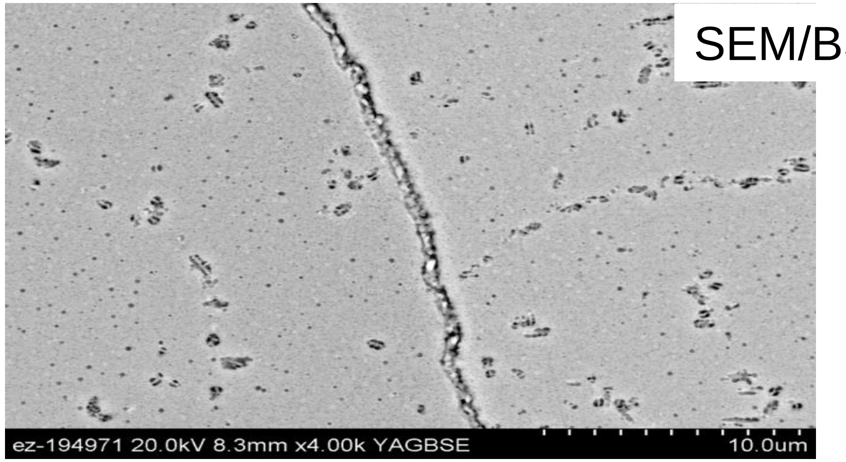
Cast Haynes 282 (fully heat-treated) show heavy precipitation along dendritic colony boundaries (ORNL data)

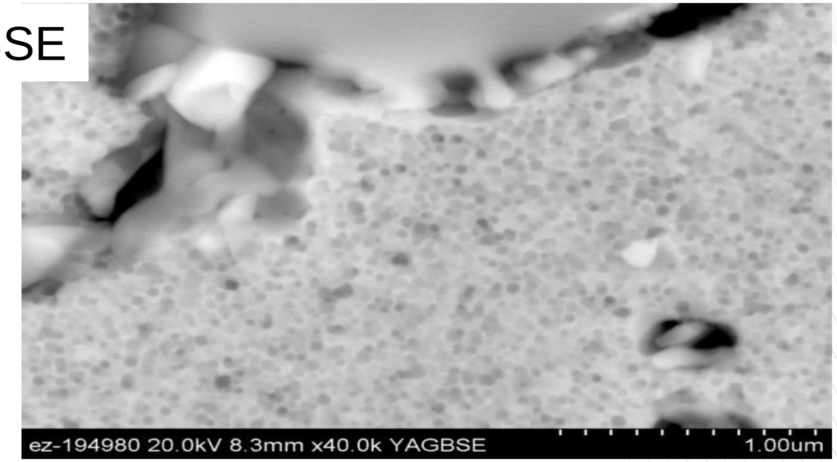
metallography



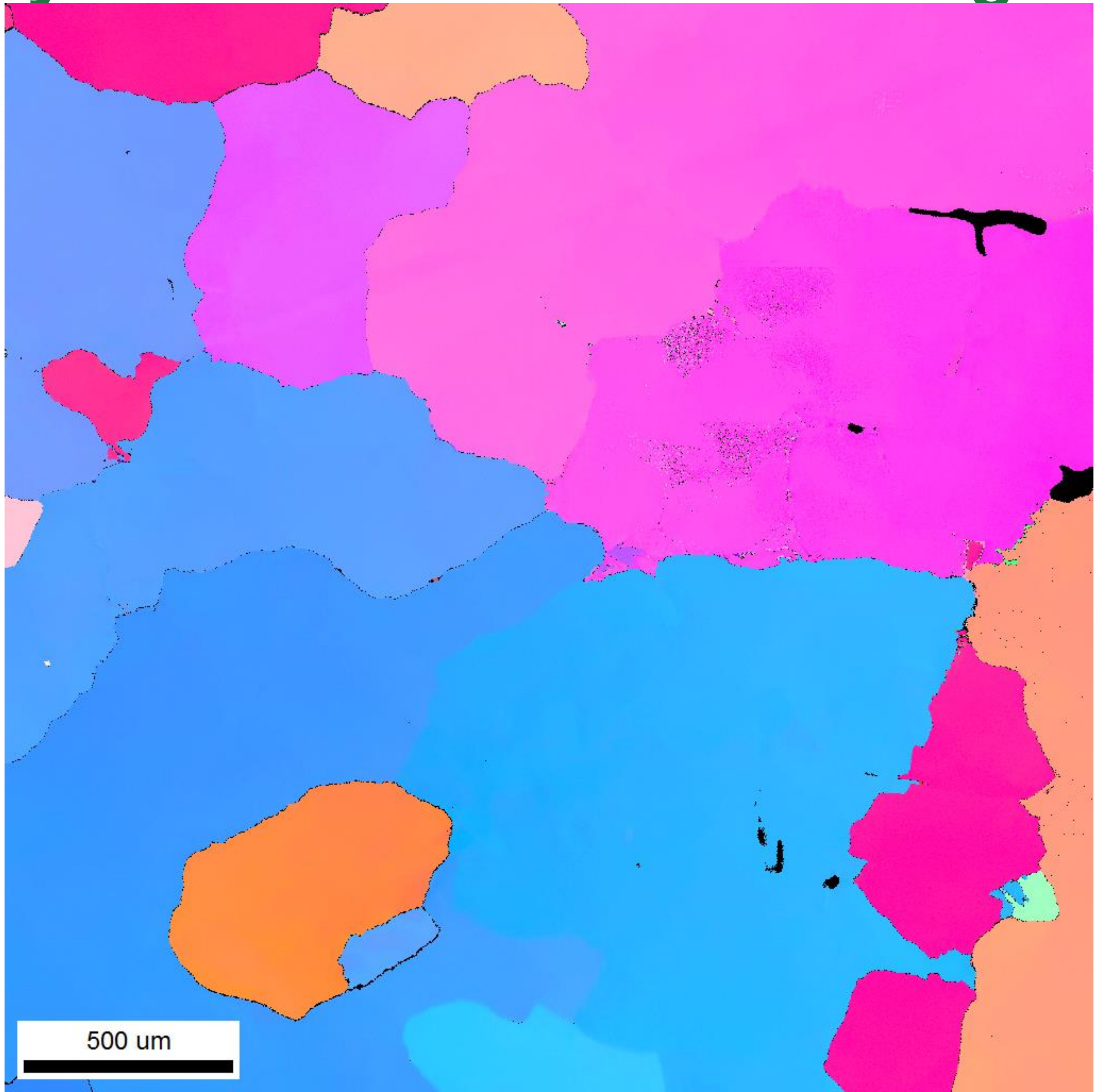


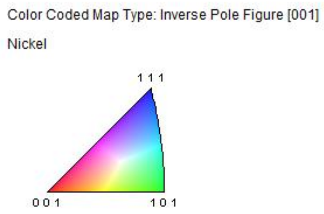
SEM/BSE





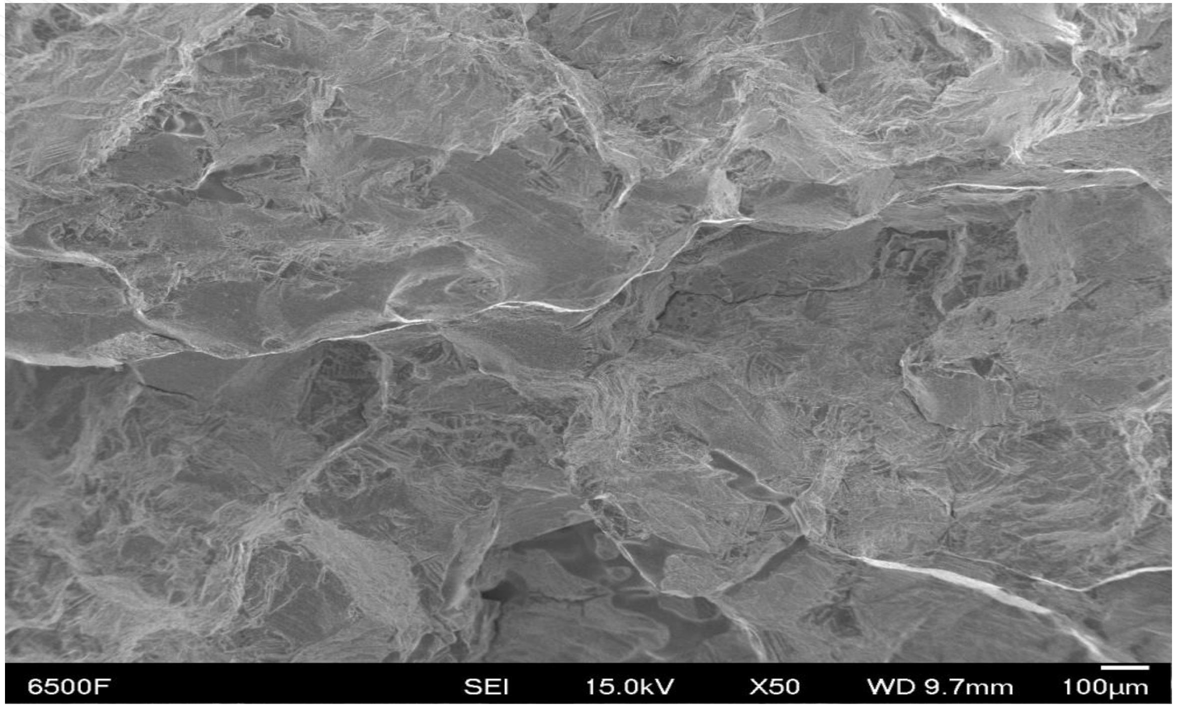
EBSD Map showing the dendrite colony size and intercolony boundaries that are the grain structure of H1

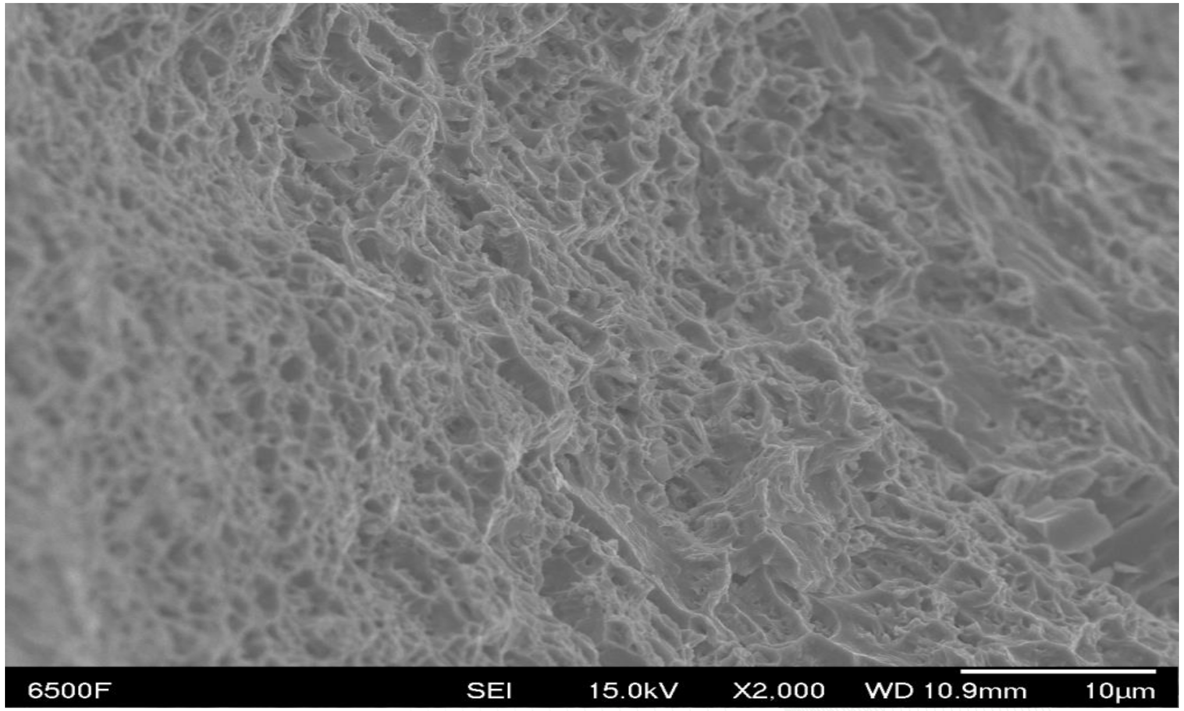




Haynes 282 alloy large casting (ORNL data)

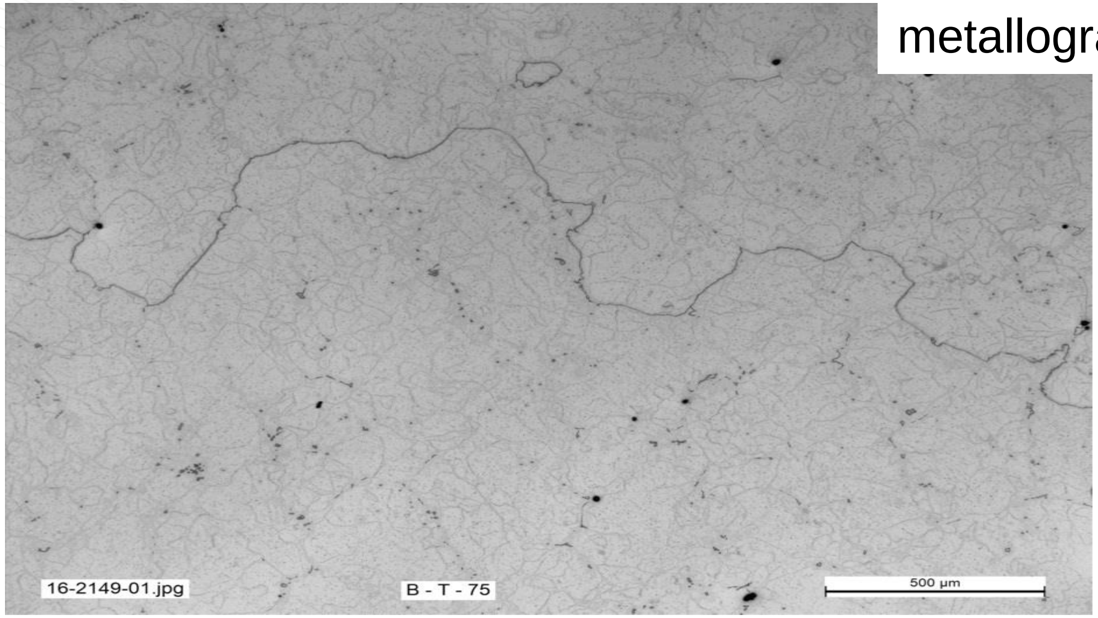
Cast Haynes 282 fractures mainly along heavily precipitated dendrite colony boundaries (ORNL SEM data)



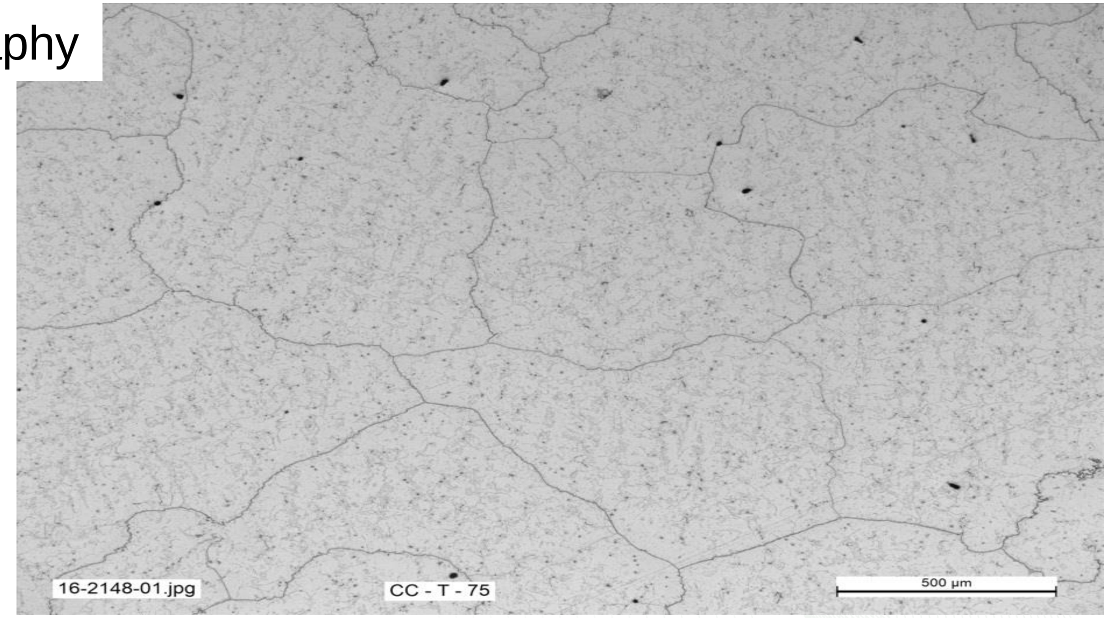


Cast Haynes 282 (fully heat-treated) show heavy precipitation along dendritic colony boundaries (ORNL data)

metallography



Faster cooling rate



Slower cooling rate

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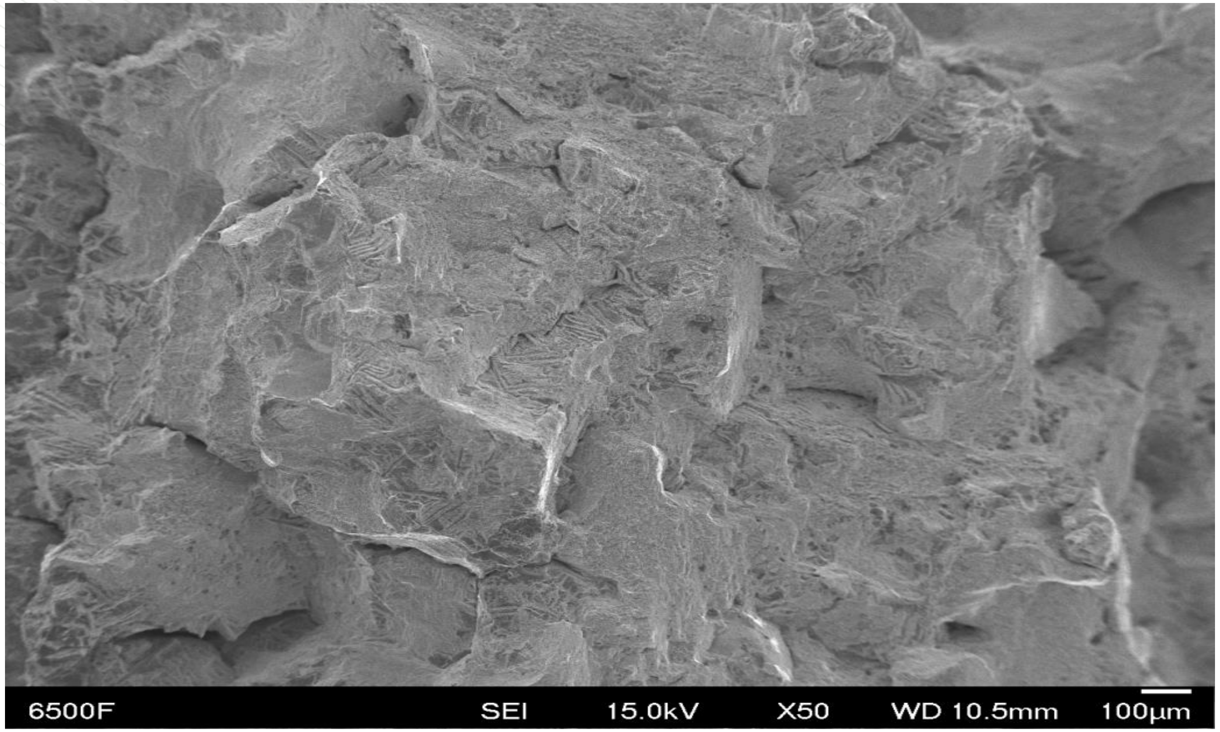
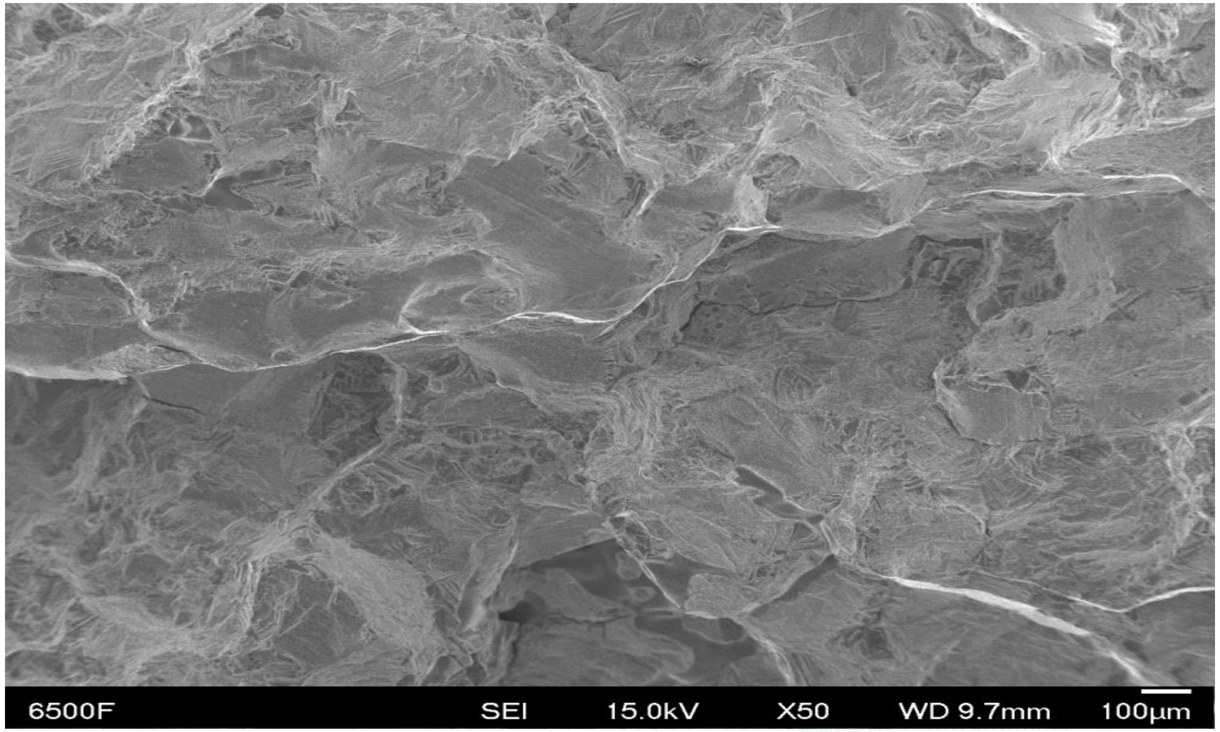
Higher total elongation means more transdendritic fracture and a ductile fracture mode



H1, 3% TE



J1, 0.5% TE

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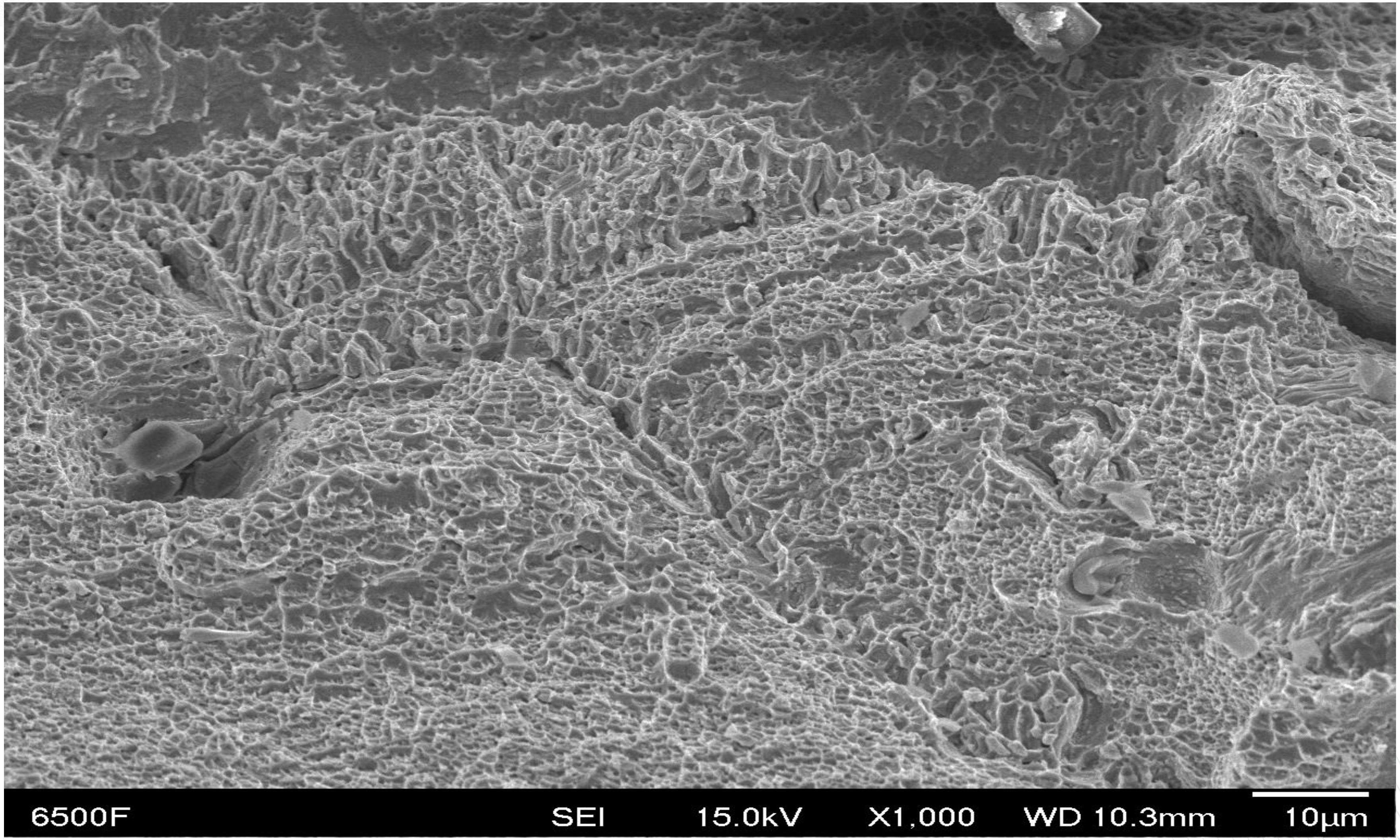
H1 with 3% TE has a predominantly ductile fracture mode



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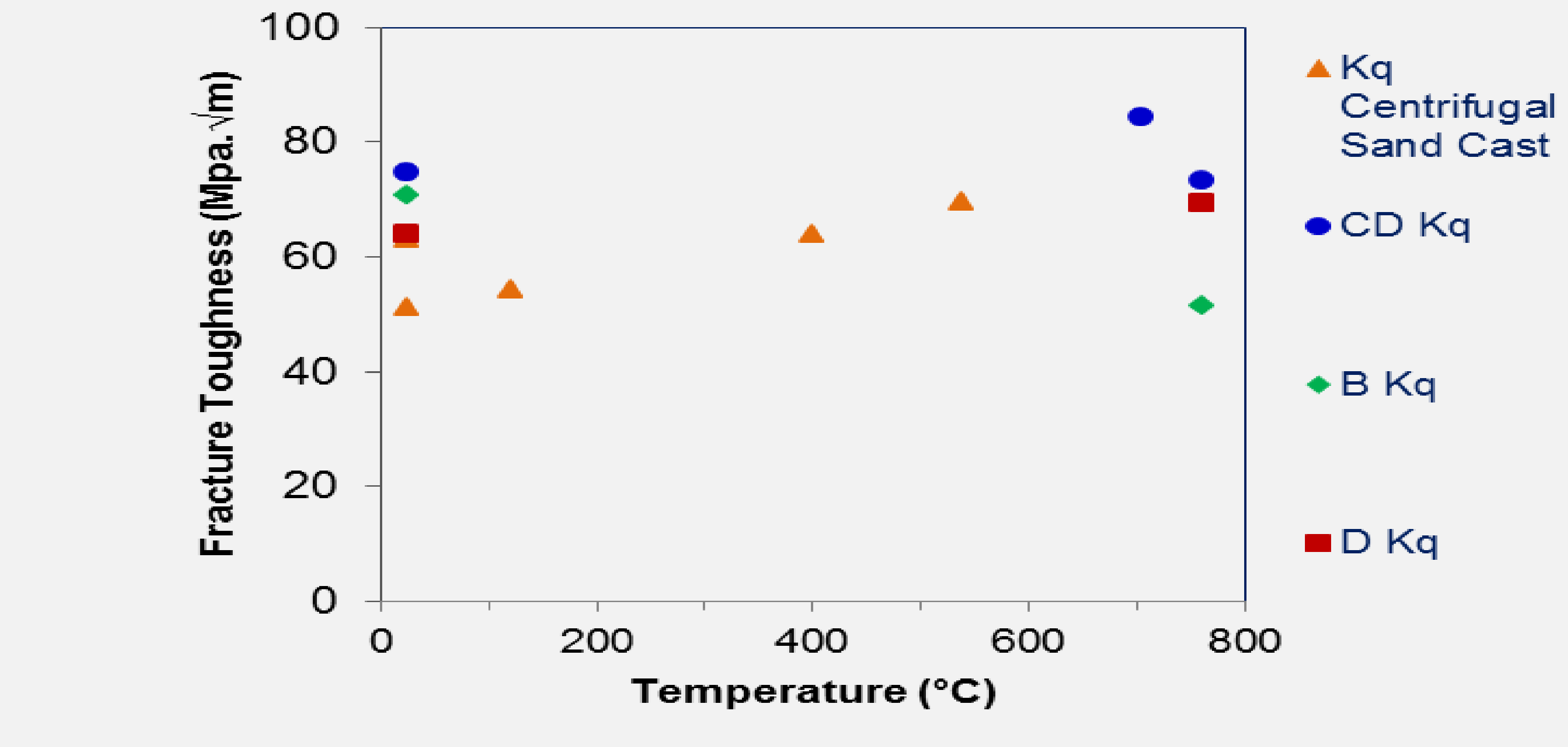
GE data - SAND CAST Fracture Toughness PROPERTY EVALUATION

Conditional Fracture toughness Kq of cast section trepans (B and D) compared with centrifugal casting and cast-on coupons (CD).



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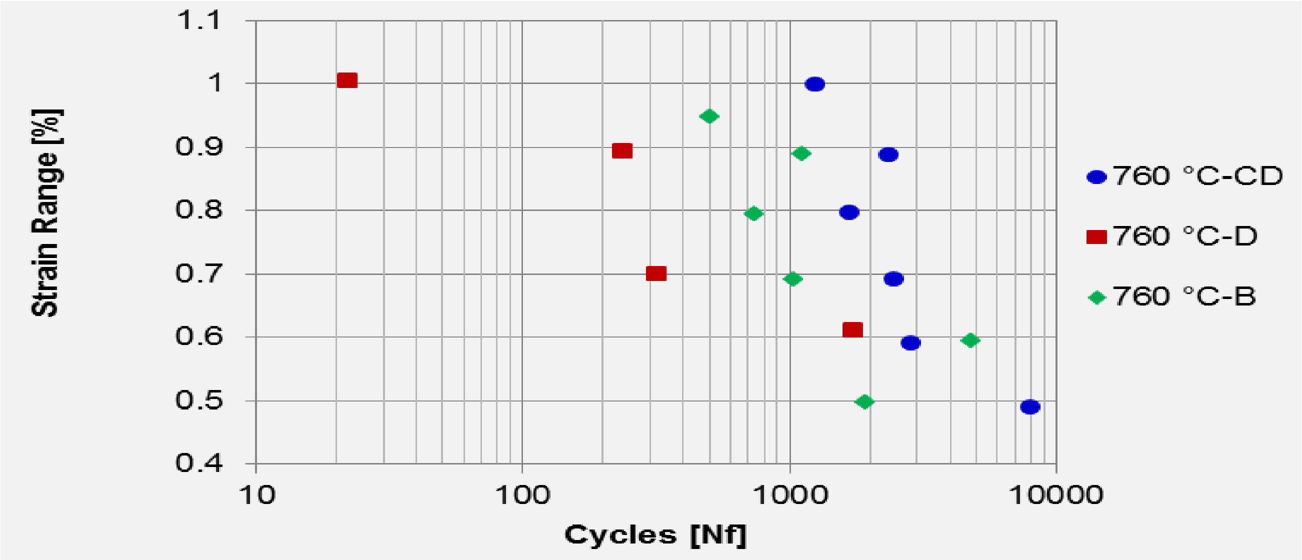
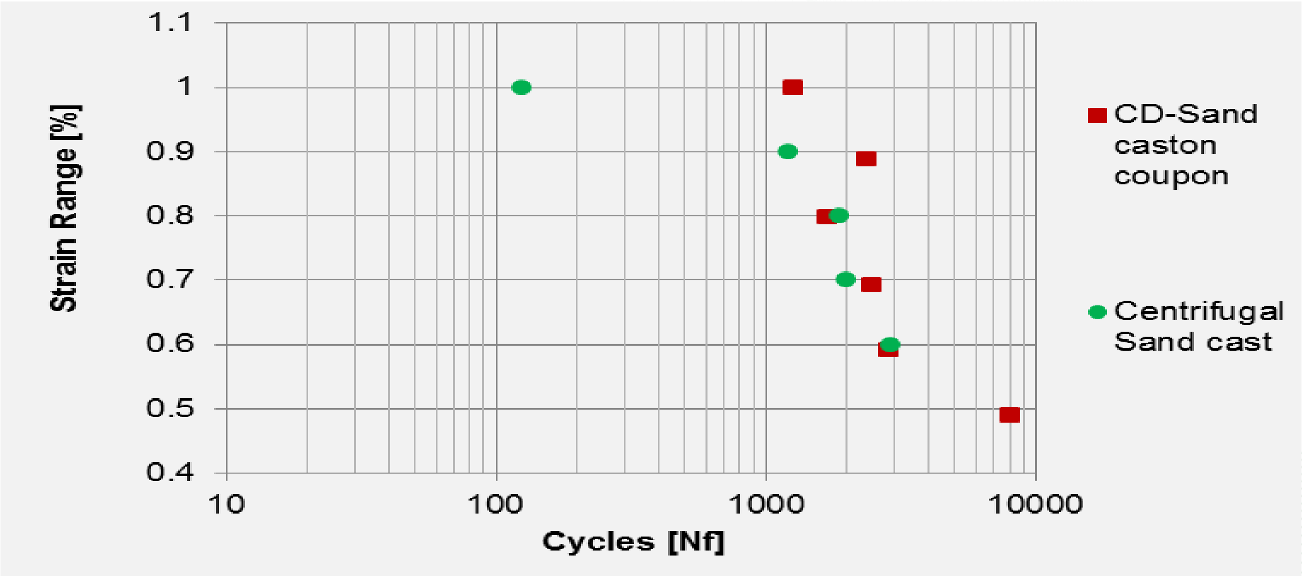
GE data - SAND CAST LCF PROPERTY EVALUATION

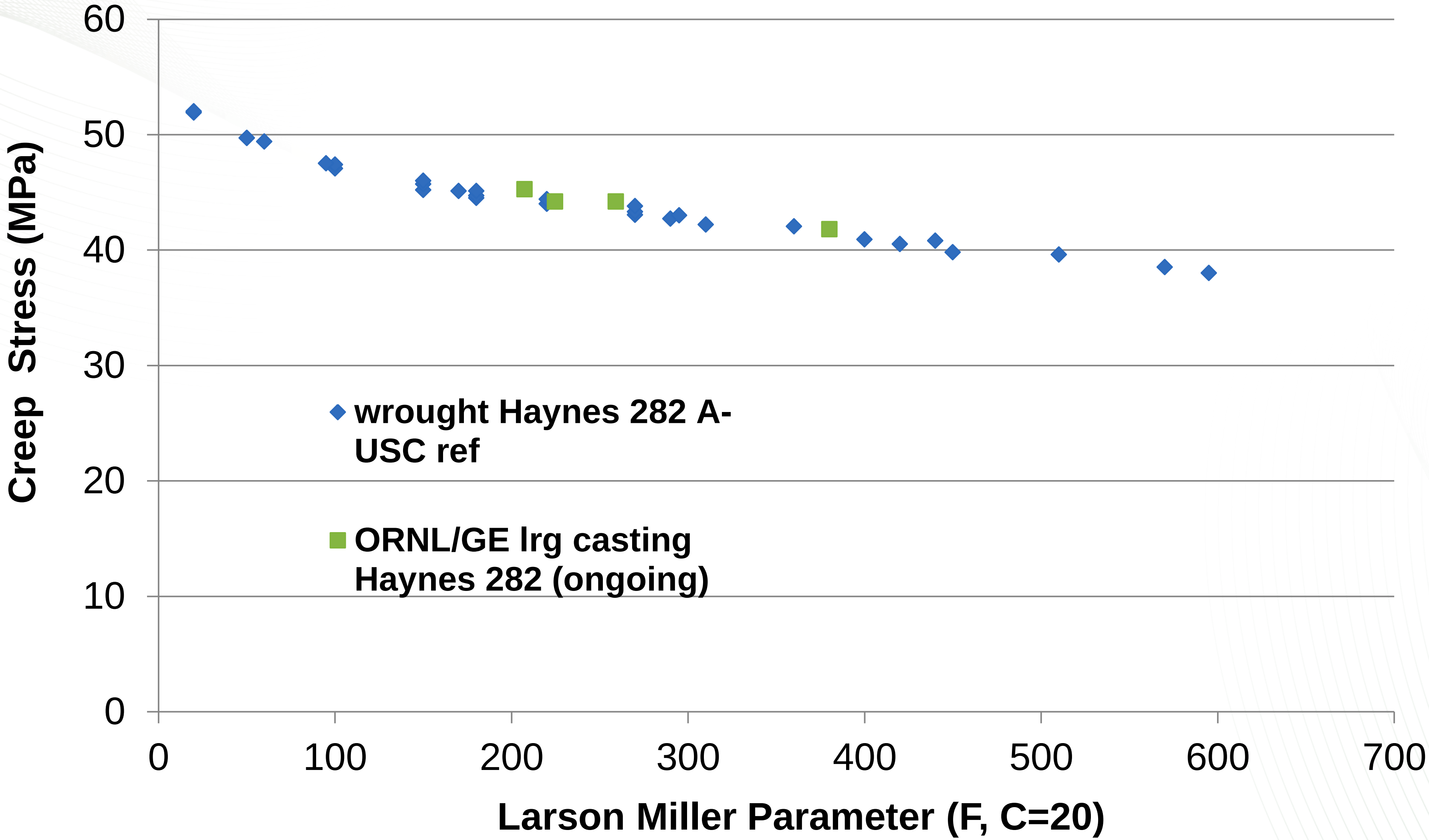
LCF behavior at 760°C (1400 °F) comparing the cast-on coupons (CD), trepan (B) and chilled section (D)



Static sand cast and centrifugal cast with sand mold show similar LCF behavior at 760°C (1400°F). At higher strains > 0.8% TSR, sand cast shows better performance.



ORNL/GE Creep-Rupture of Large Sand Casting of Haynes 282 alloy (tests have not ruptured yet)



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