Modeling Long-term Creep Performance for Welded Ni-base Superalloy Structures for Power Generation Systems

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Imagination at work.

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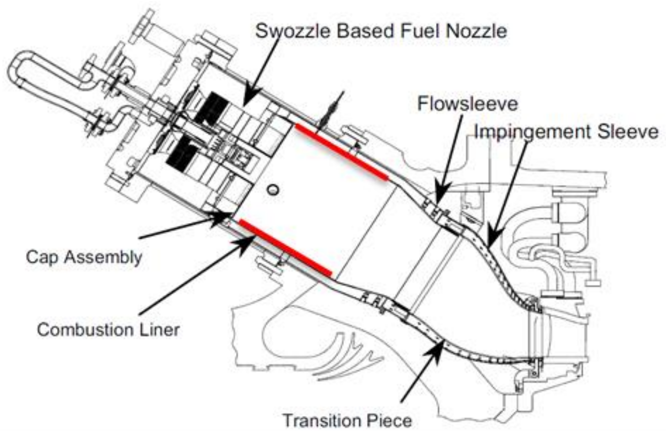
- GE Power

Project objectives

Overall goal:

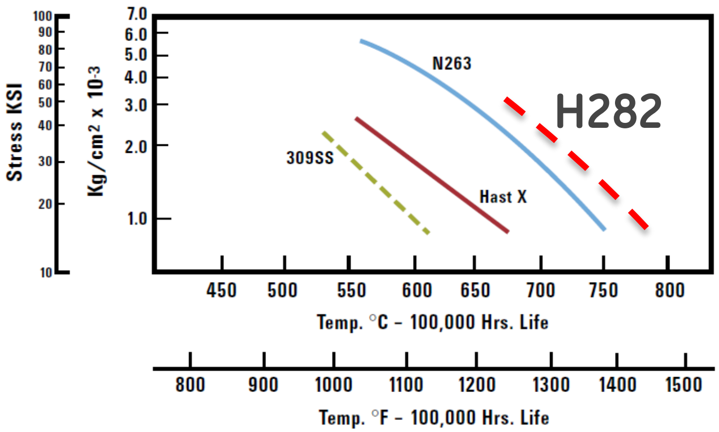
- Model long-term creep performance for Ni-base superalloy weldments
- Demonstrate on gas turbine combustion liner welded HA282



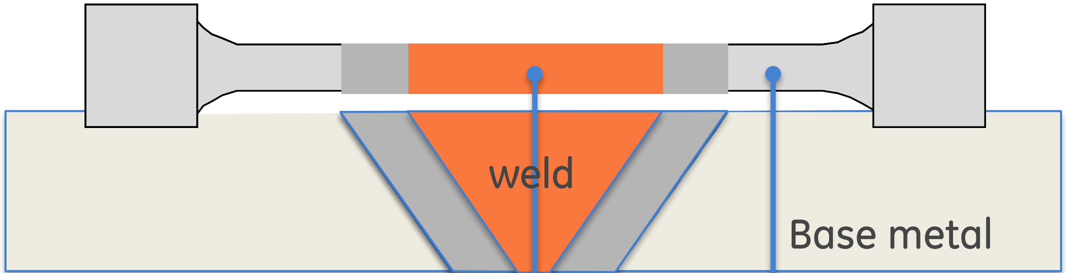
(RK Matta et al, 2000)

Objectives

- Physics-based constitutive creep modeling for welded HA282
- Microstructure modeling for welded HA282
- Mesoscale deformation model to bridge creep to heterogeneous microstructure
- Local deformation measurement in conjunction with conventional mechanical testing



Overall approach



Constitutive creep modeling → FE Analysis

Experiment →

- Microstructure & creep damage characterization
- Heat treatment
- Tensile, creep
- Local strain measure

Mesoscale deformation (CP) modeling

Microstructure (γ')

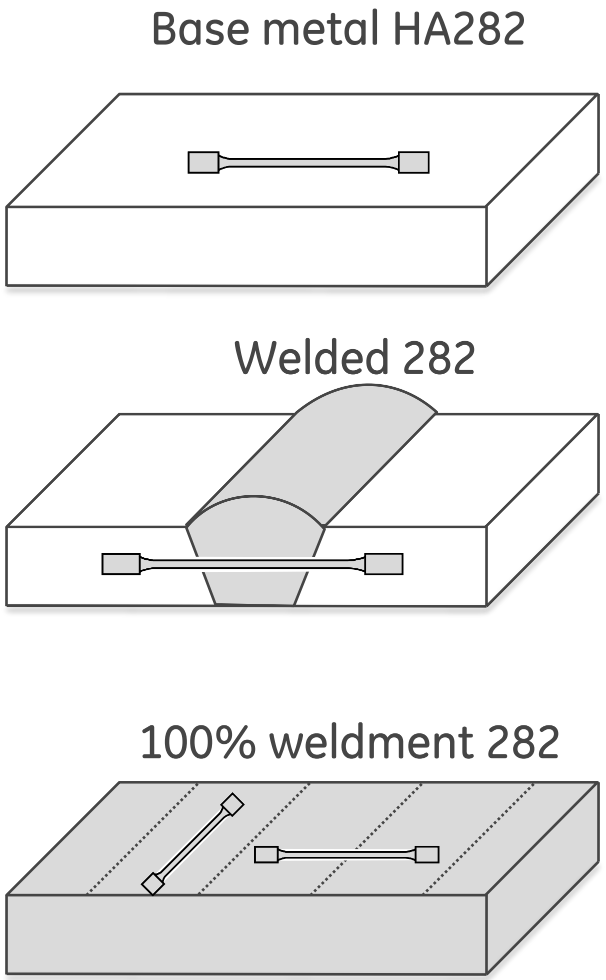
Microsegregation

Focus on HA282 weldment behaviors with a given welding process

Experimental observations

	Tensile	Creep	DIC/PD (Creep)
Base metal	X		
Welded 282	(As-weld) (PWHT2)	(PWHT2) (PWHT3a)	(PWHT2) (PWHT3a)
100% weldment	(PWHT2)	(PWHT2)	

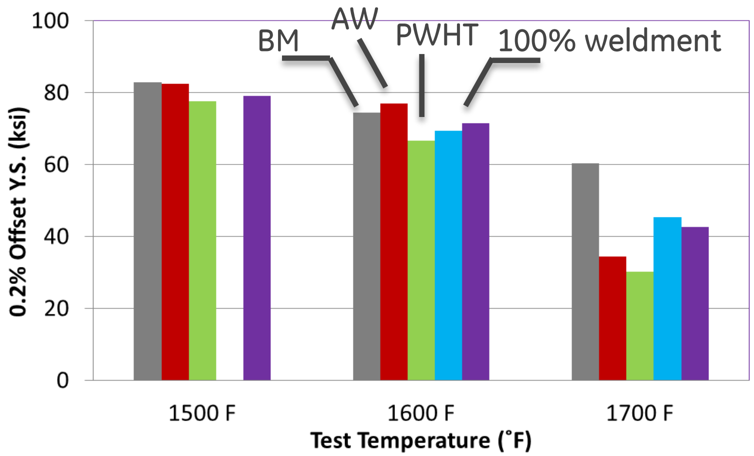
(Testing at 1500, 1600, 1700F)

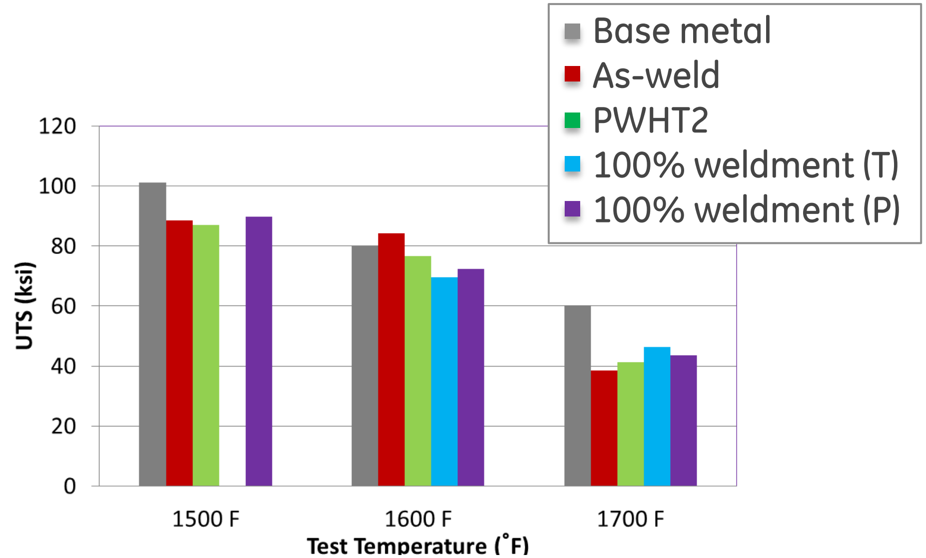


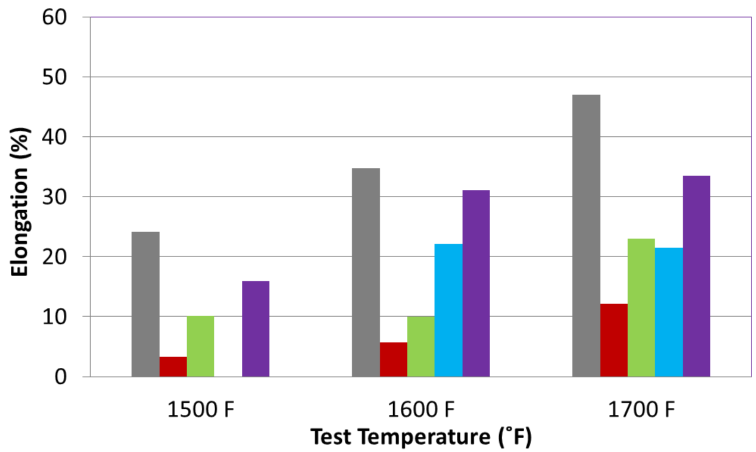
Manual Gas Tungsten Arc Welding

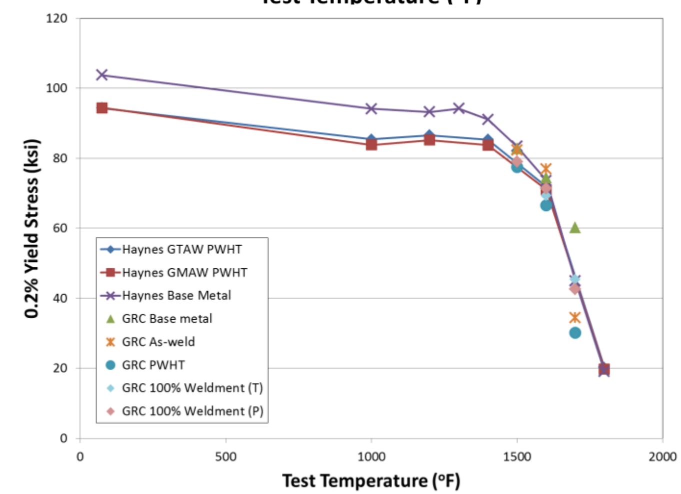
PWHT2: 2075F/0.5h + 1850F/2h + 1450F/8h
PWHT3a: 1850F/1h + 1450F/8h

Tensile properties comparison



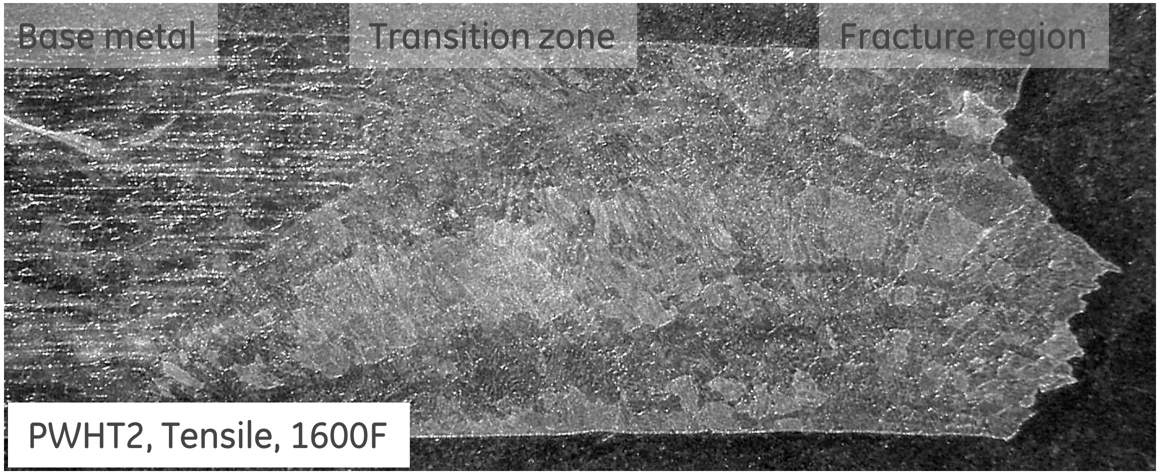


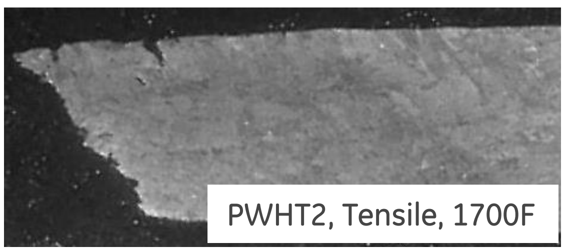


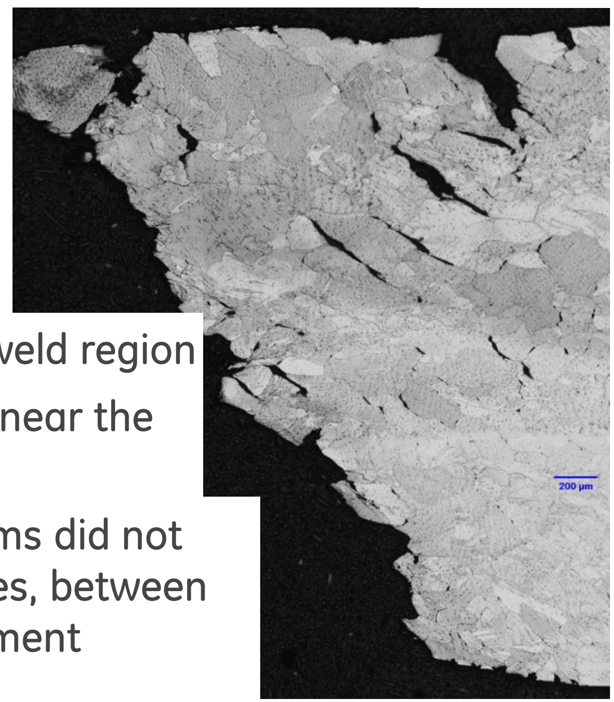


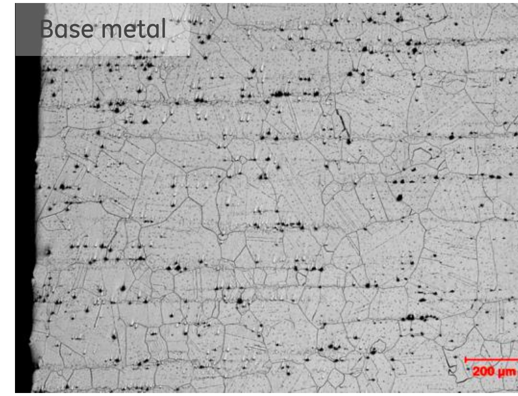
- No significant debit in UTS and YS in **Welded** and **100% weldment** at 1500F, 1600F; but a large drop at 1700F
- No difference in UTS, YS between transverse vs parallel direction in 100% weldment
- Ductility decreased: base metal > 100% weldment > Welded (PWHT) > As-weld

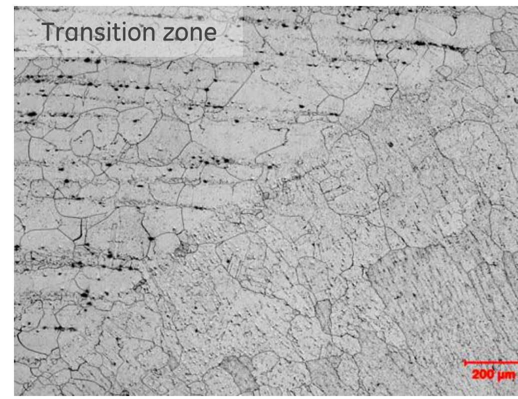
Tensile specimens: Welded HA282 & 100% Weldment

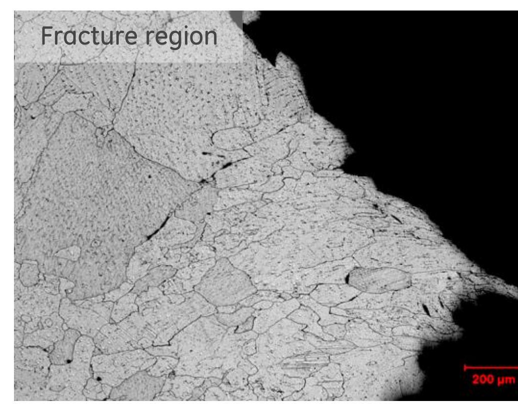






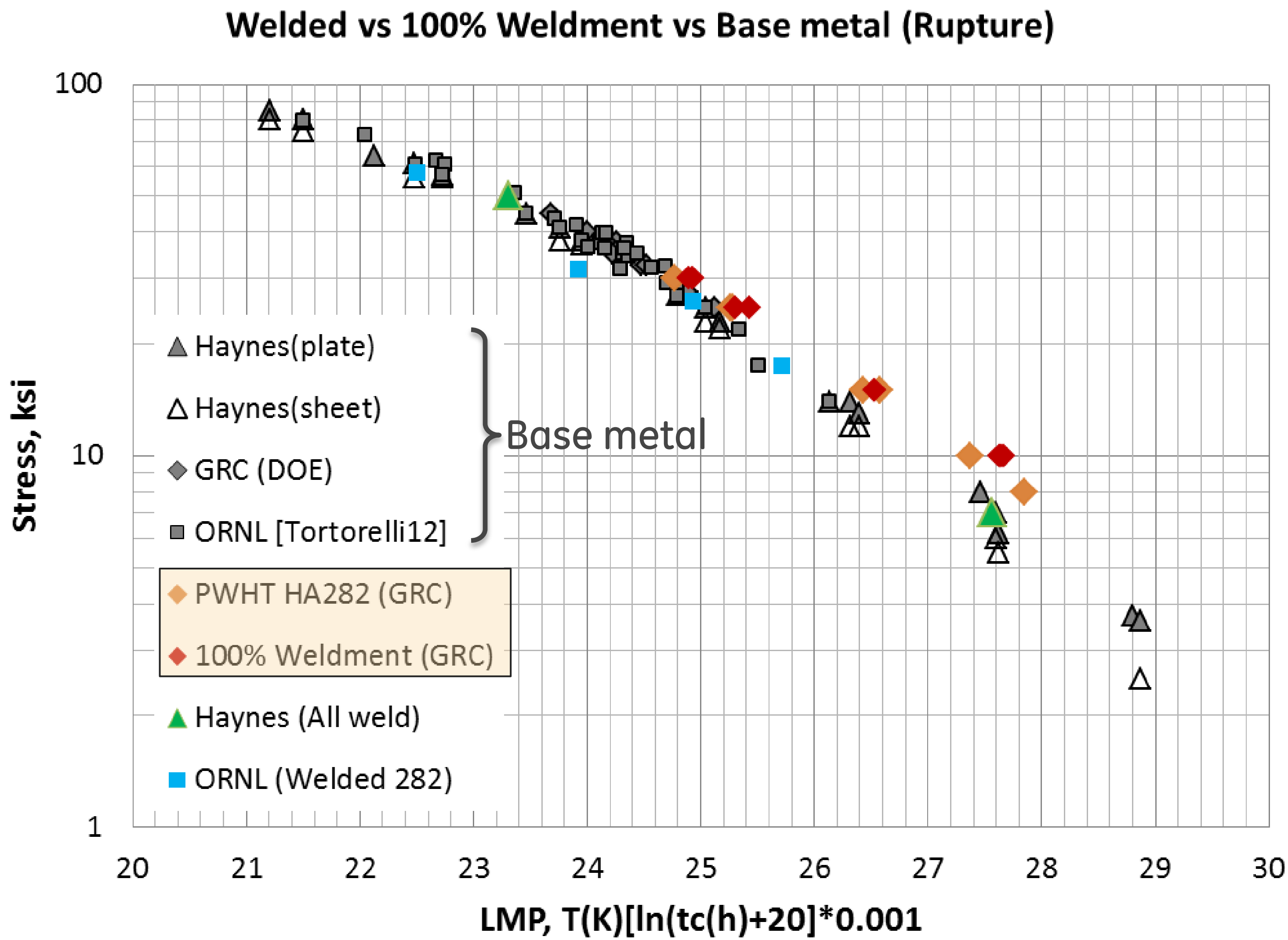






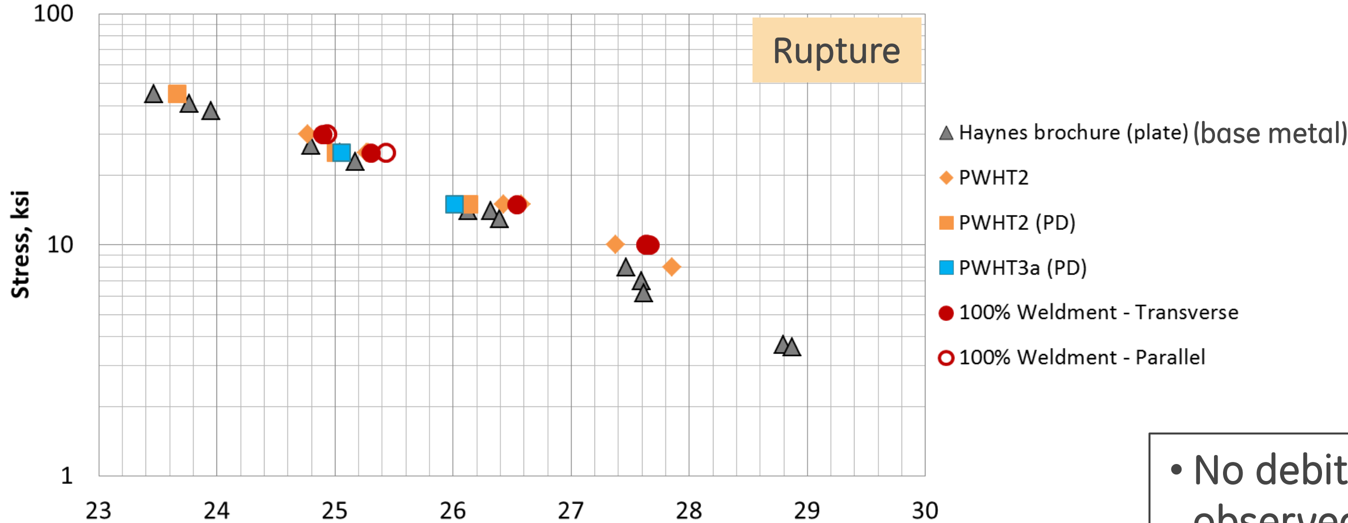
- All specimens failed within the weld region
- Inter-granular cracks observed near the fracture surface
- Failure locations and mechanisms did not change at different temperatures, between PWHT2 welded and 100% weldment

Creep properties comparison

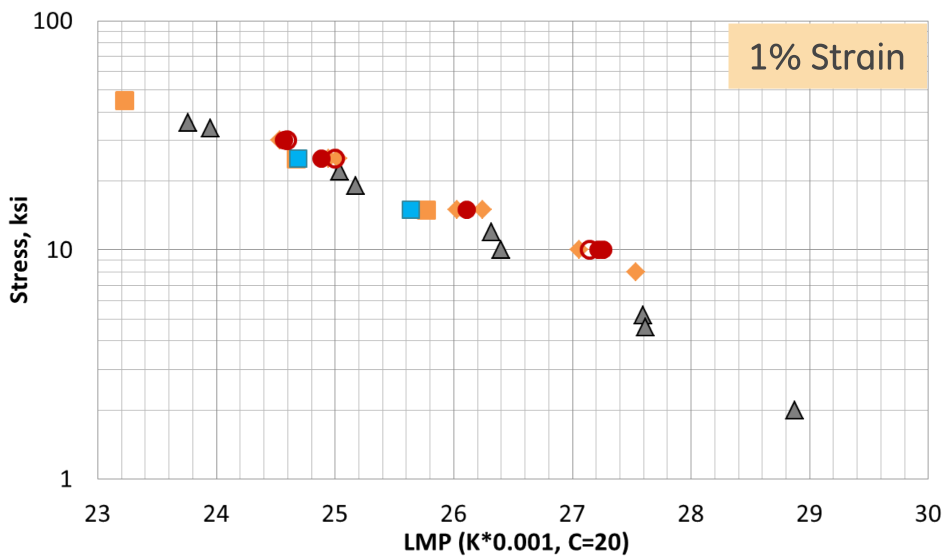


Creep properties comparison

HA282 (Base Metal vs. Welded vs. 100% Weldment) - Rupture



HA282 (Base Metal vs. Welded vs. 100% Weldment) - 1% Creep Strain

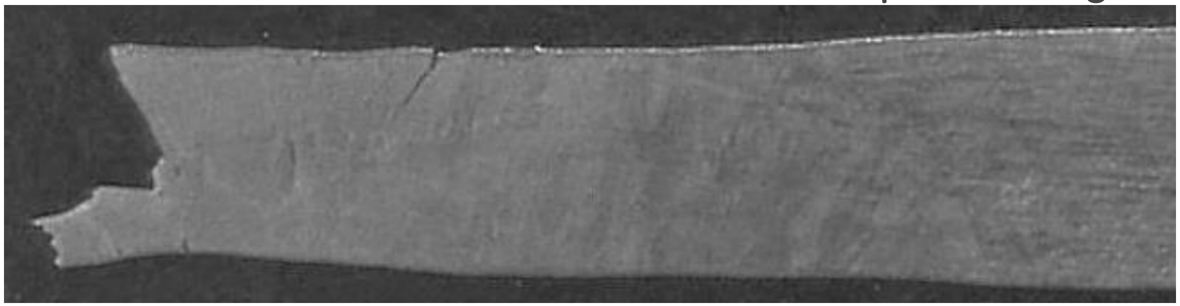


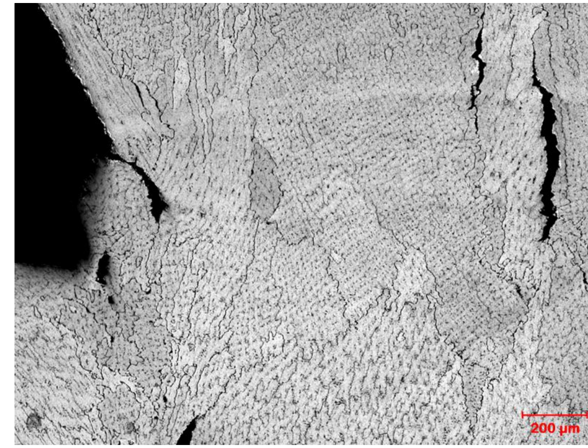
- No debit in creep was observed in welded HA282 & 100% weldment
- PWHT3a didn't show significant difference from PWHT2
- Welded 282 showed reduced rupture elongation (similar to earlier ORNL finding by Maziasz et al. *)

Maziasz et al, NETL 2015 Crosscutting
..aterials Review, April 27-30, 2015

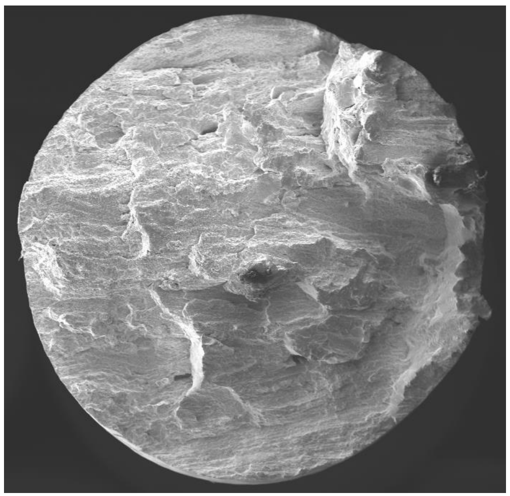
Creep specimen: PWHT2 welded HA282

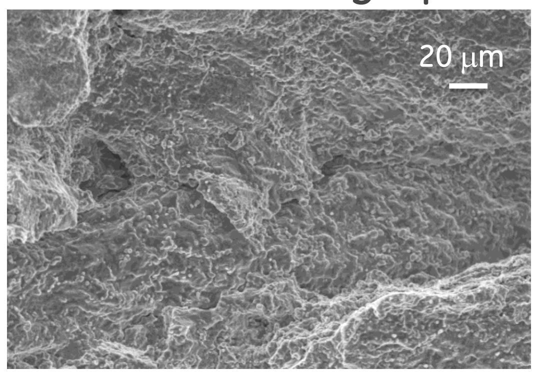
Optical Images

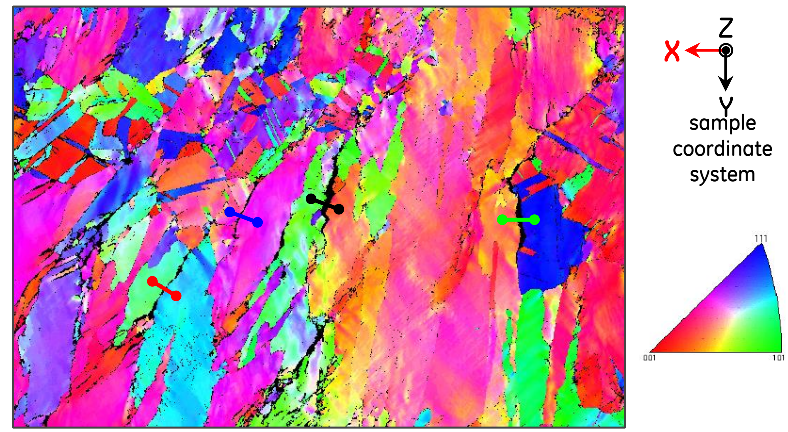




SEM Fractographs



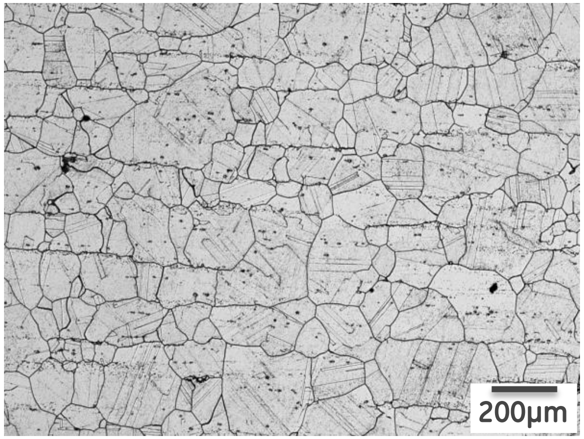




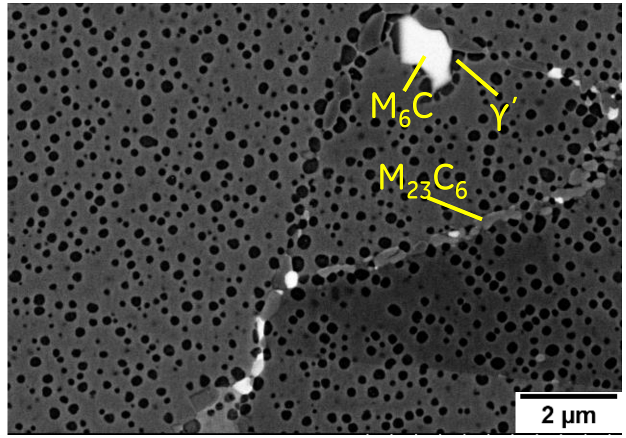
- All specimens failed within the gauge section
- Inter-granular cracks near fracture surface, along high-angle GBs (by EBSD/IPF)
- SEM fractography suggested inter-granular failure
- Failure locations and mechanisms did not appear to change at different temperatures, between welded 282 and 100% weldment (T & P orientation)

Grain boundary phases

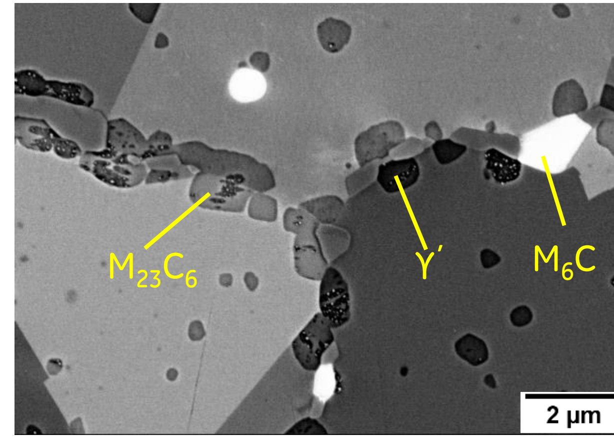
Base Metal



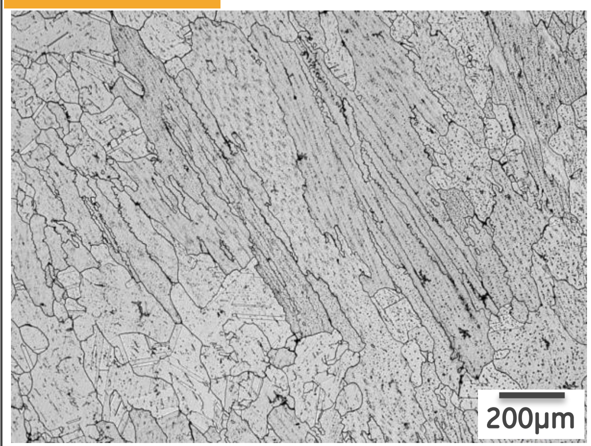
1500F 1000hrs



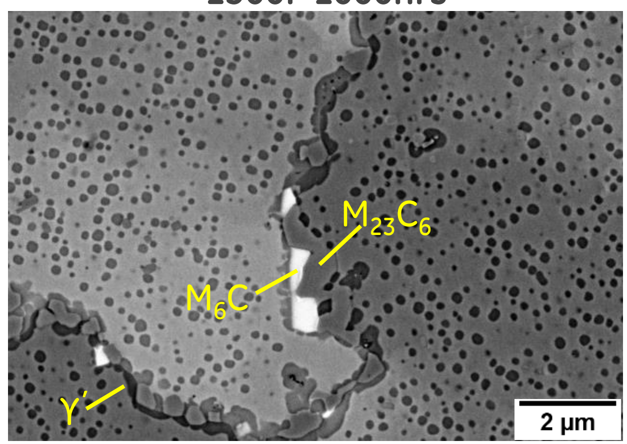
1700F 1000hrs



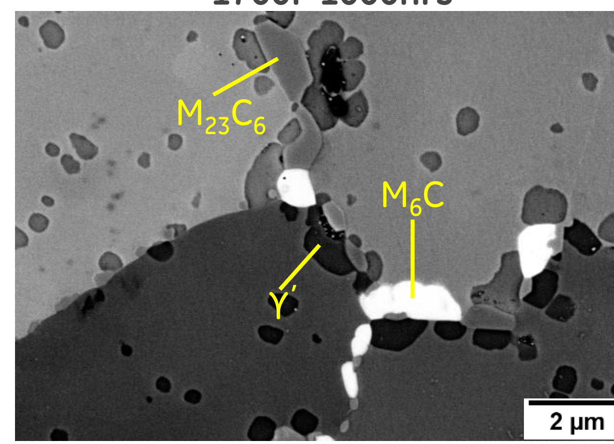
Weld zone



1500F 1000hrs

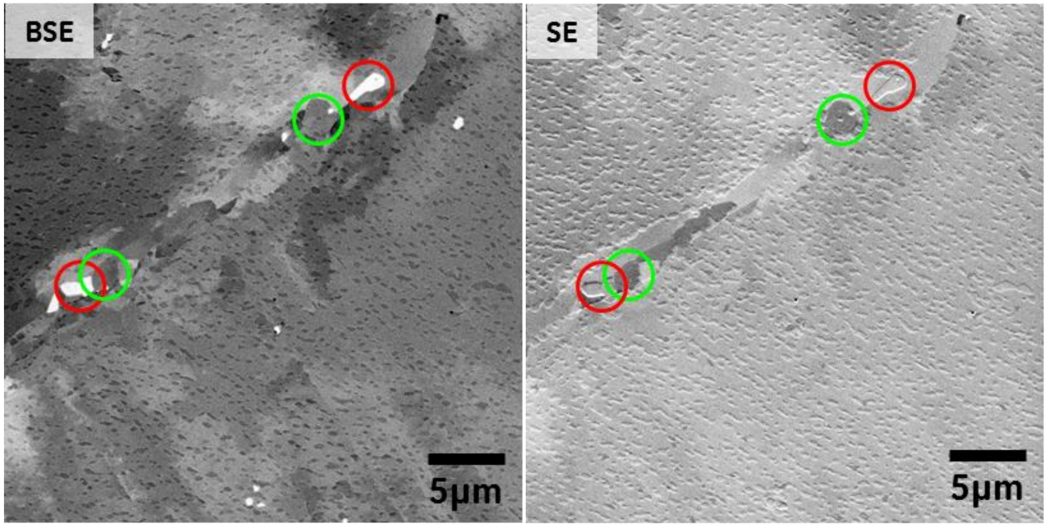


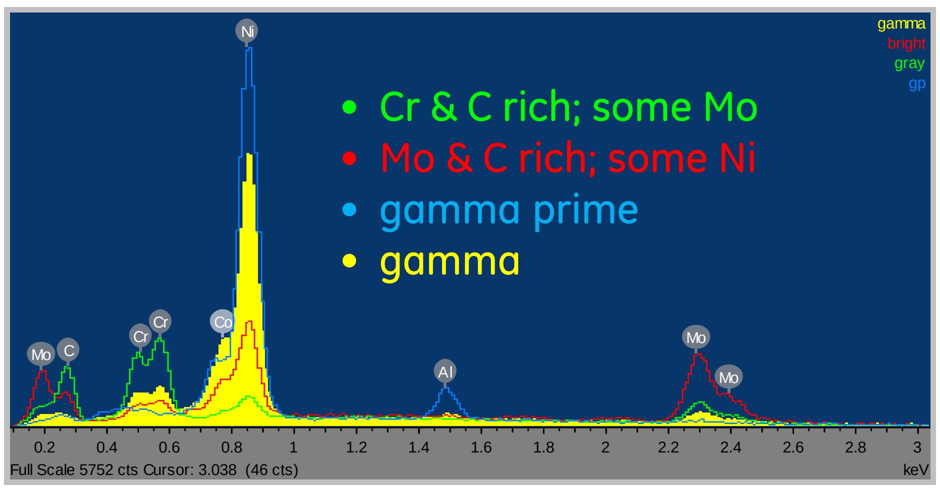
1700F 1000hrs

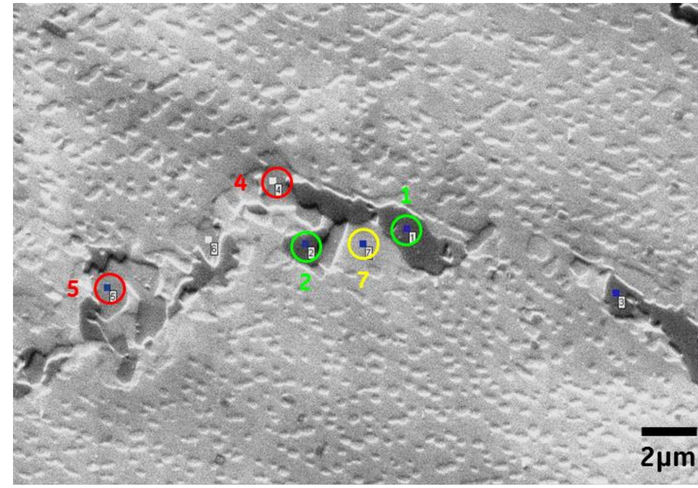


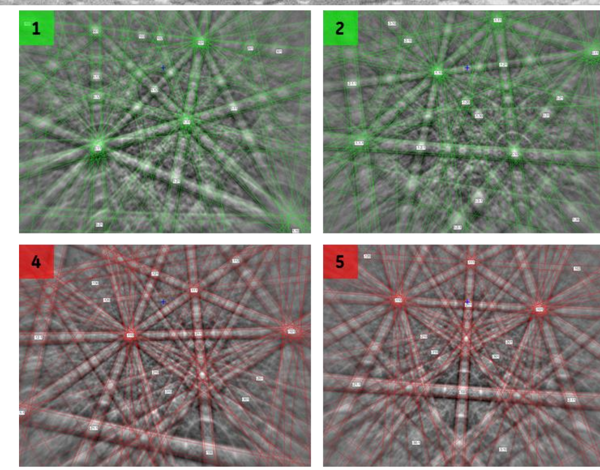
- Similar grain boundary phases were observed in **base metal** and **weld zone**, including $M_{23}C_6$, M_6C, and γ′ precipitates
- Features of these phases do not differ with annealing temperature or time

Grain boundary phase identification



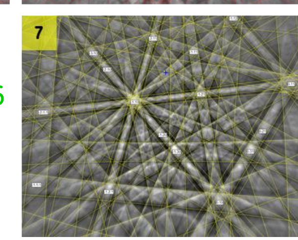






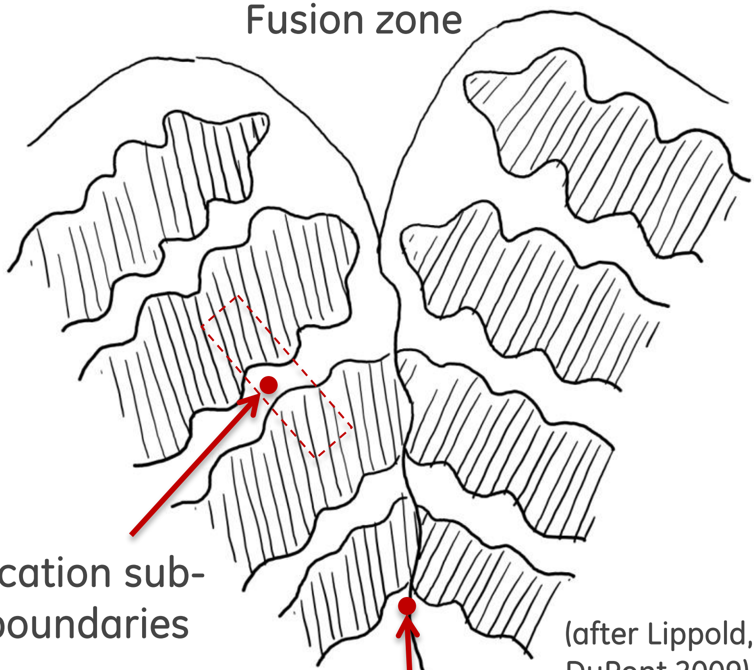
EDS and EBSD identified Cr rich $M_{23}C_6$ (dark contrast in BSE) and Mo rich M_6C (bright contrast in BSE) on grain boundaries

Spots 1&2: $M_{23}C_6$
Spots 4&5: M_6C
Spot 7: gamma



Modeling considerations

Fusion zone



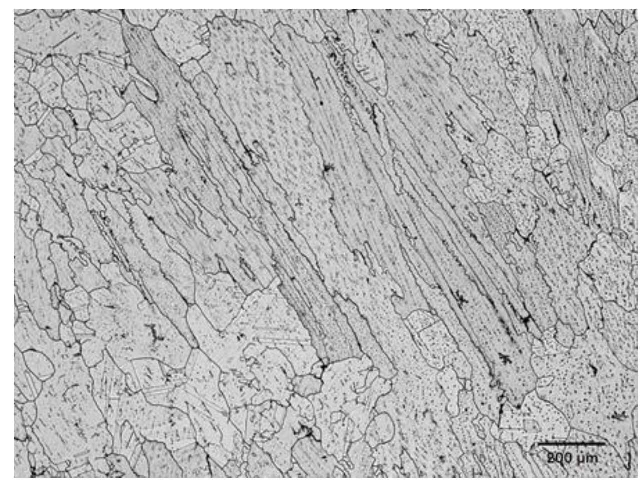
(after Lippold, 1992; DuPont 2009)

Solidification sub-grain boundaries (SSGB):
- **Microsegregation**
- **γ' variation**
- **Interdendritic phases**

Solidification grain boundaries (SGB):
- **Grain size/shape**
- **GB phases**

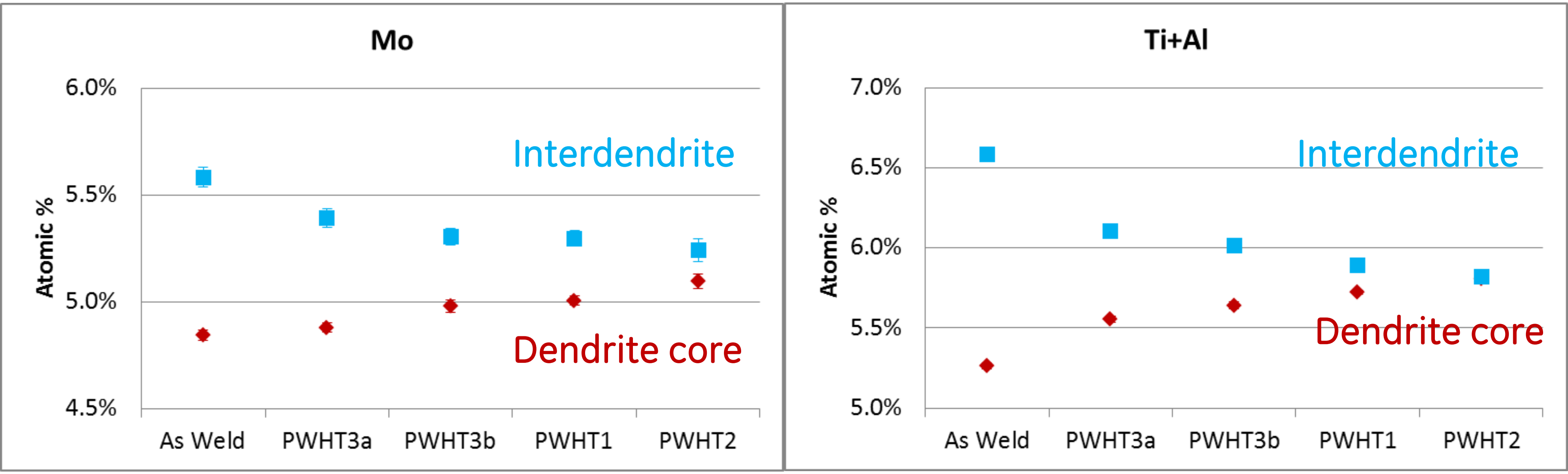
Assumptions:

1. γ' is still the main effect for creep strength
2. Changes to grain size in weldment may shift creep behaviors
3. Changes at GBs may alter damage accumulation and offsets ductility and rupture time



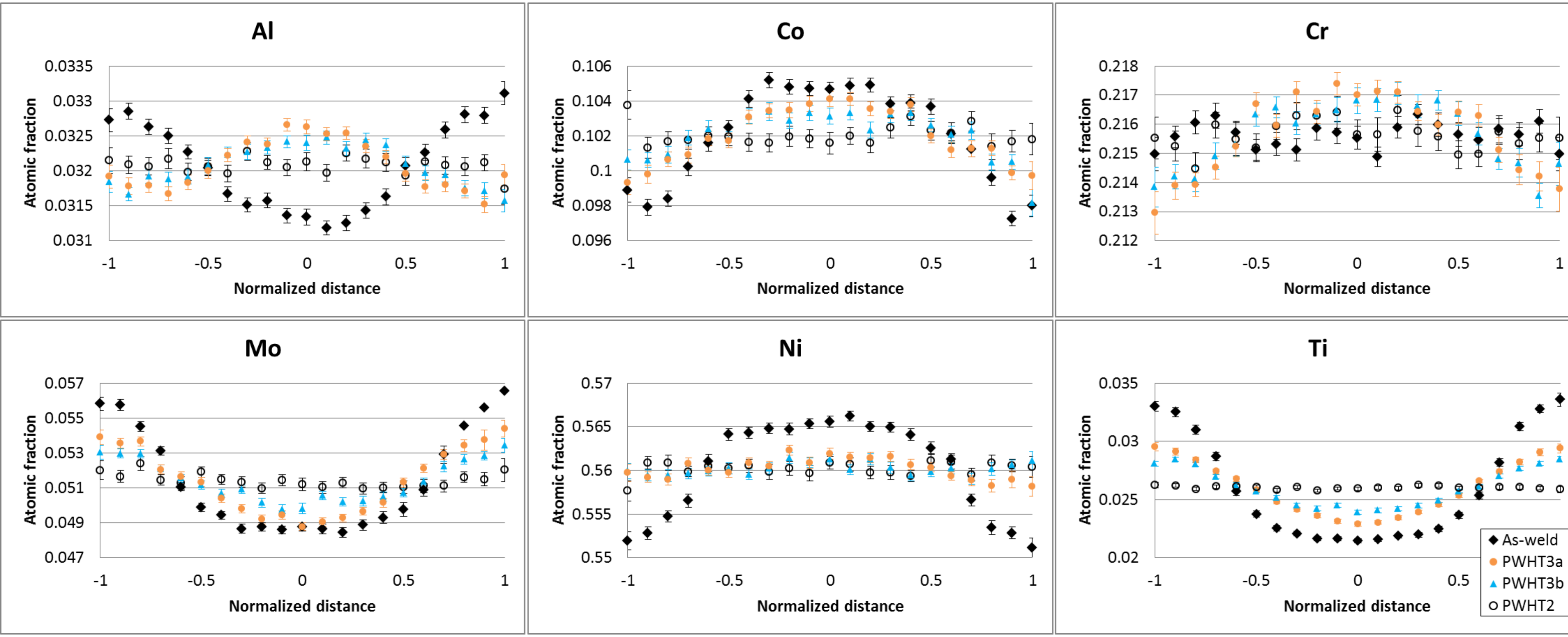
Post-weld heat treatment and residual microsegregation in HA282

EPMA



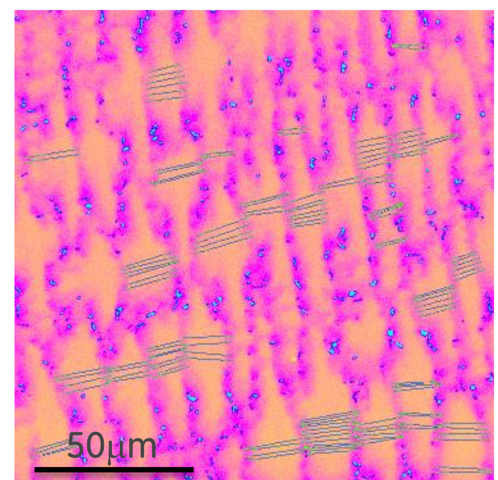
PWHT3a,b	**1850F/1h, 2h**	**+ 1450F/8h**
PWHT1	1895F/0.5h+1850F/2h	+ 1450F/8h
PWHT2	**2075F/0.5h+1850F/2h**	**+ 1450F/8h**

EPMA composition analysis

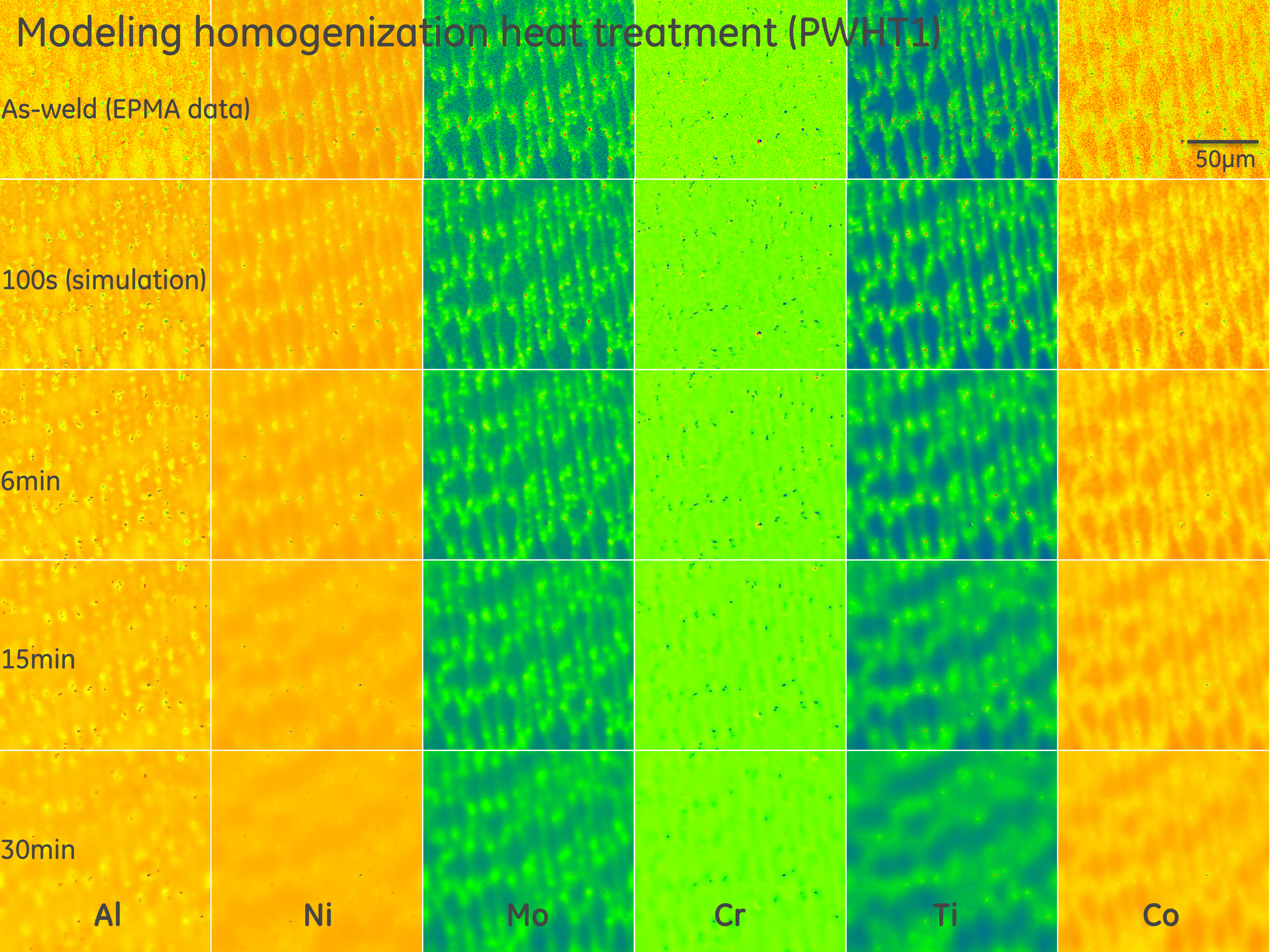


- As-weld
- PWHT3a
- PWHT3b
- PWHT2

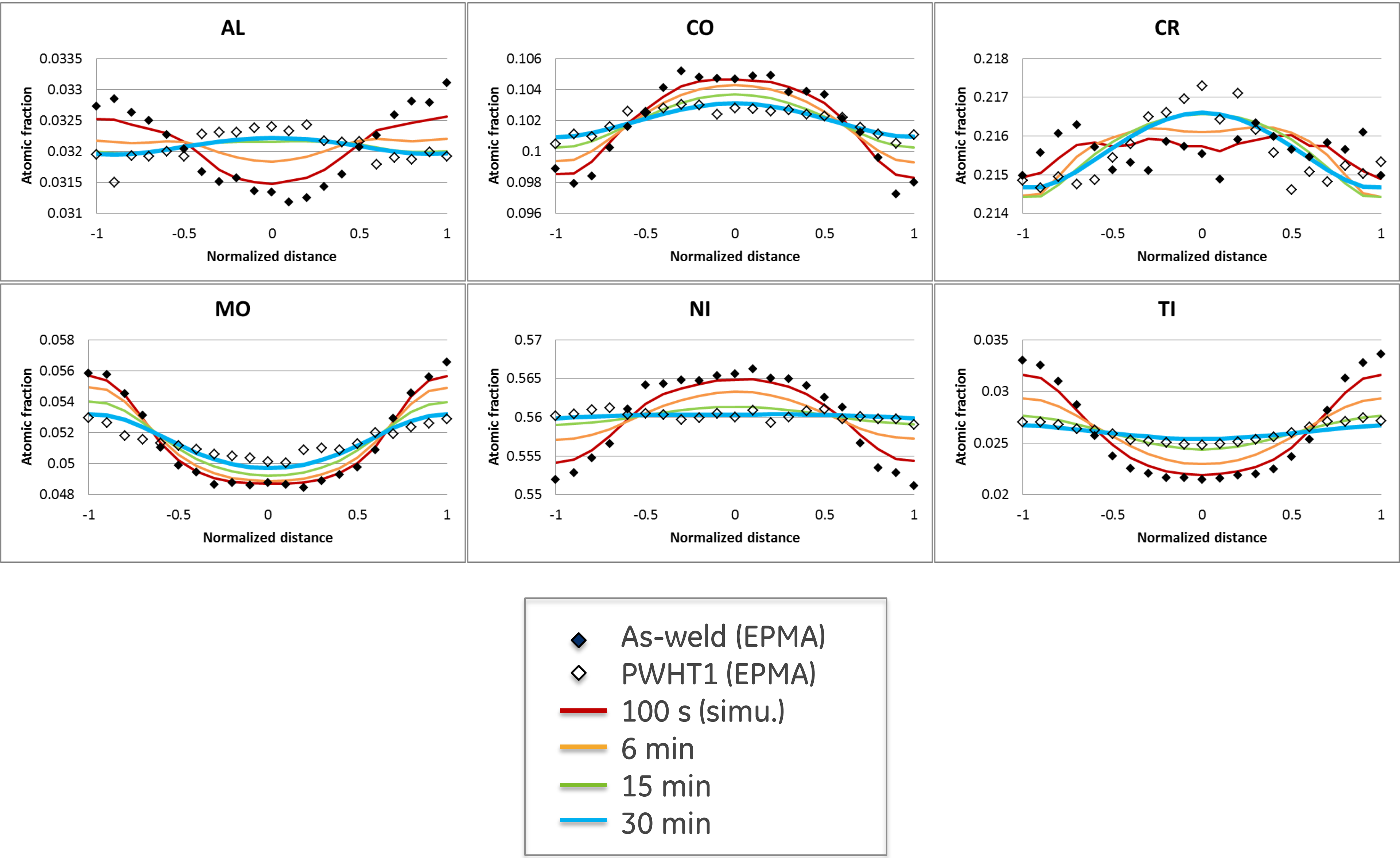
- Very homogeneous after PWHT2
- Some residual microsegregation in PWHT3a,b



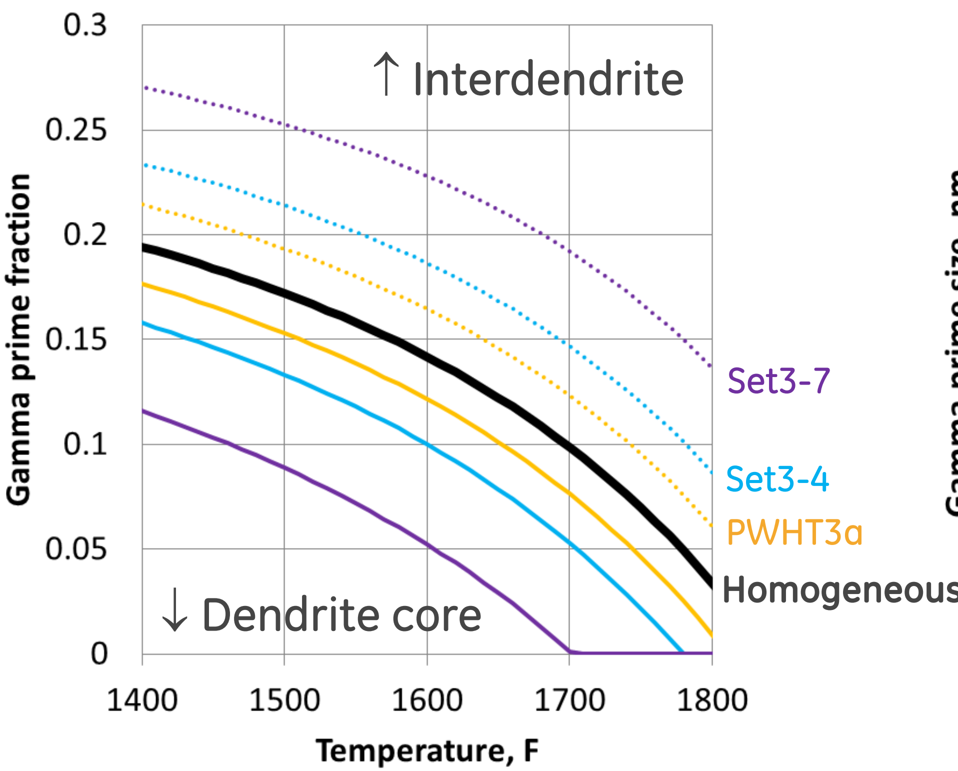
Modeling homogenization heat treatment (PWHT1)

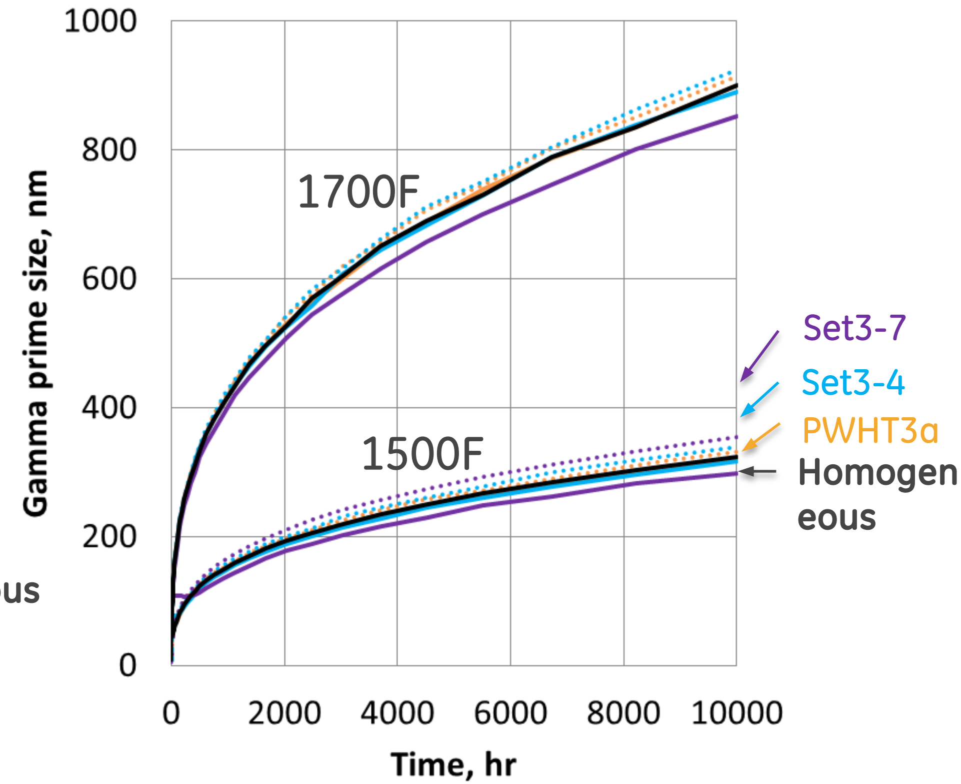


Simulated residual micro-segregations compared with EPMA data



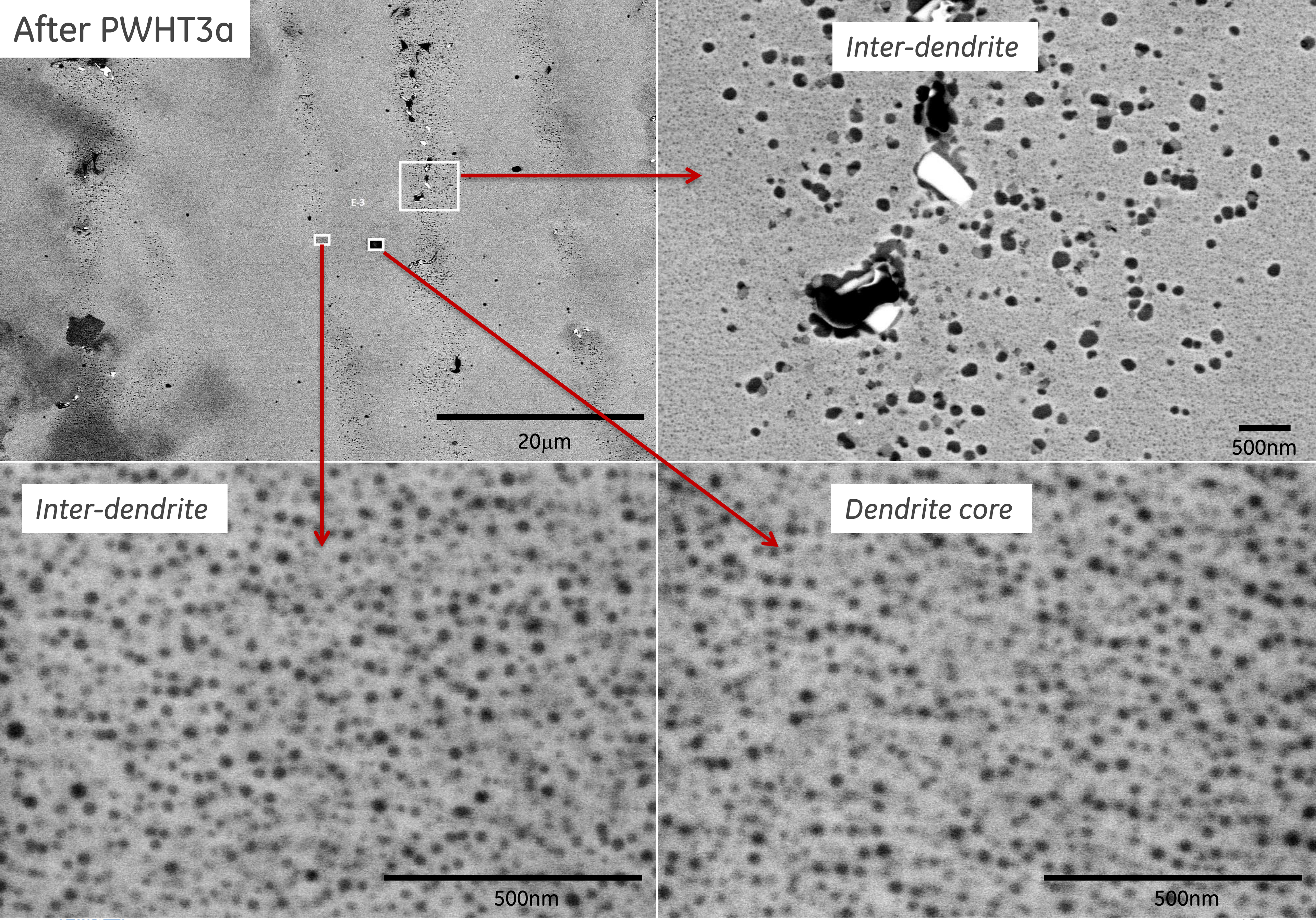
Simulate microsegregation effect on γ' precipitation



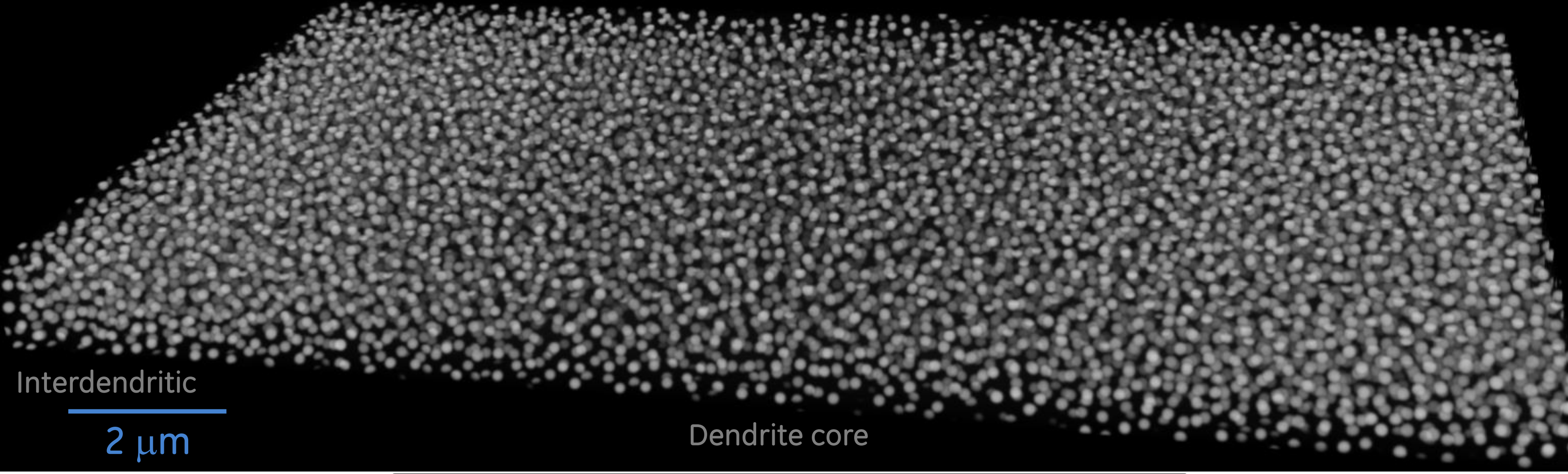


Calc γ' solvus (F)	Core	Inter-dendr.
Homogeneous	1839	
PWHT3a	1811	1868
Set3-4	1780	1894
Set3-7	1702	1938

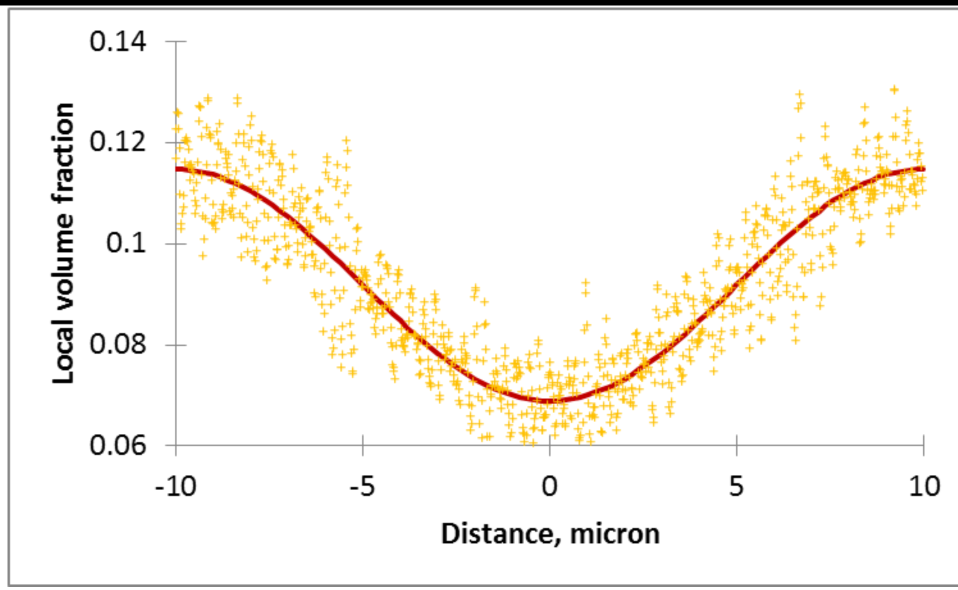
γ' variation across dendrites mainly shown in volume fraction, solvus, but much less in size



SEM shows similar γ′ size between dendrite core and interdendritic region



Interdendritic



(PWHT3a, 1700F aging)

Generate non-uniform γ' microstructures for crystal plasticity modeling

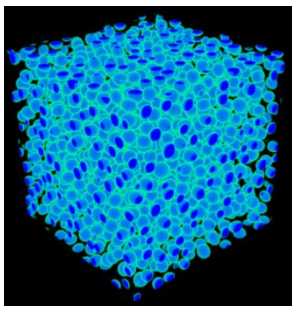
FFT elasto-viscoplastic (FFT-EVP) formulation

$$\boldsymbol{\sigma}^{t+\Delta t}(\mathbf{x}) = \mathbf{C}(\mathbf{x}) : \boldsymbol{\varepsilon}^{e,t+\Delta t}(\mathbf{x}) = \mathbf{C}(\mathbf{x}) : \left[\boldsymbol{\varepsilon}^{t+\Delta t}(\mathbf{x}) - \boldsymbol{\varepsilon}^{p,t}(\mathbf{x}) - \dot{\boldsymbol{\varepsilon}}^{p,t+\Delta t}\left(\mathbf{x}, \boldsymbol{\sigma}^{t+\Delta t}\right)\Delta t\right]$$

$$\dot{\boldsymbol{\varepsilon}}^{p}(\mathbf{x}) = \sum_{\alpha=1}^{\mathcal{N}} \mathbf{m}^{\alpha}(\mathbf{x})\, \dot{\gamma}^{\alpha}(\mathbf{x})$$

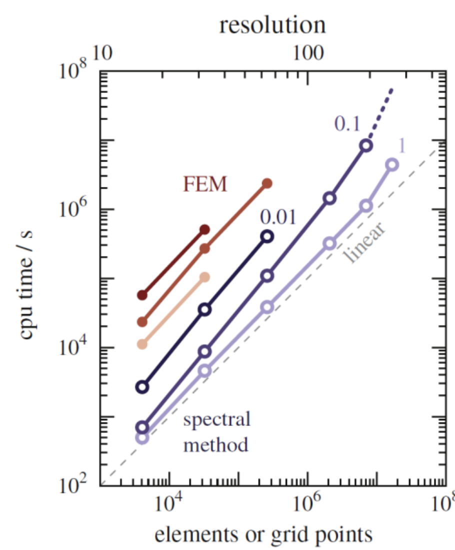
- ❑ Small-strain framework is adopted.
- ❑ Implicit Euler treatment requires numerical iteration.
- ❑ Periodic boundary condition (PBC) must be satisfied.

Phase-field or experimentally obtained γ/γ' microstructure



Direct sampling on the microstructure image → **FFT-EVP simulations**

"image-based" approaches



Spectral (FFT) method

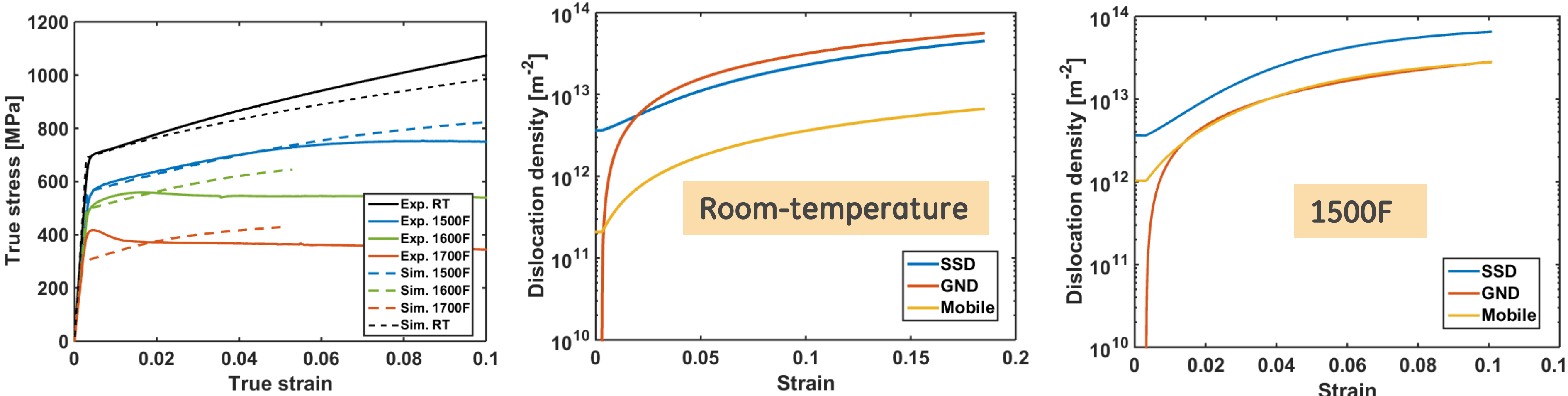
- Fields are approximated by a Fourier series
- Strong stress equilibrium is required at every discretization point

Finite element method

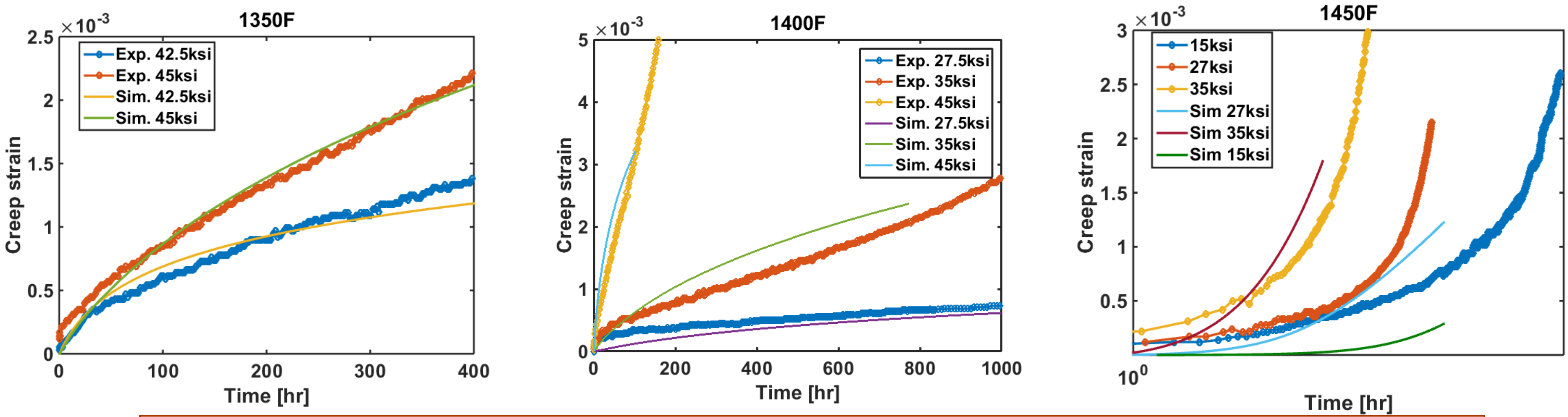
- Fields are approximated by low-order piecewise shape-functions
- Weak stress equilibrium is required in a volume-average

Lebensohn, R. A., et al. (2012). *Int. J. Plast.*, *32*, 59-69.
Eisenlohr, P., et al. (2013). *Int. J. Plast.*, 46, 37-53.

Application of crystal plasticity model to HA282 (base metal)

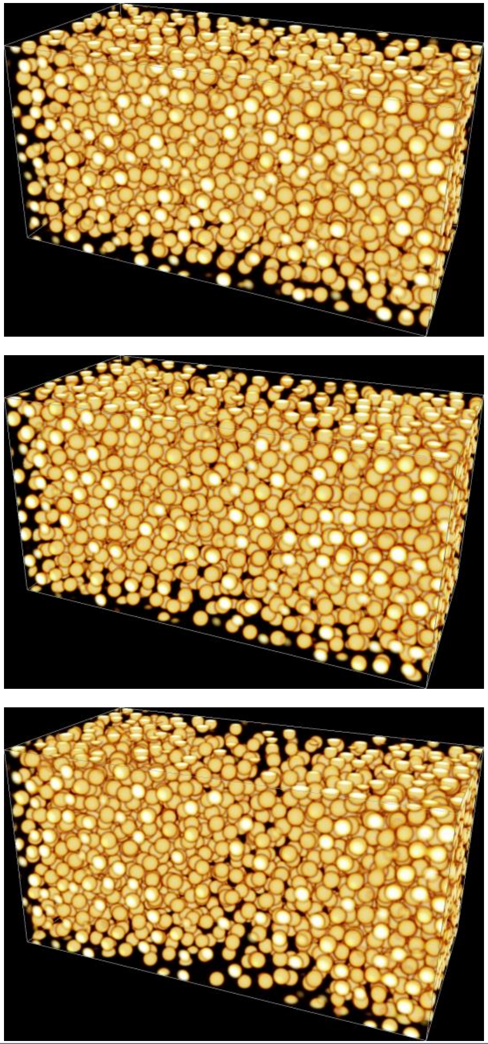


Comparison between simulated and experimental **tensile** tests, and simulation predicted dislocation density evolution during the test.

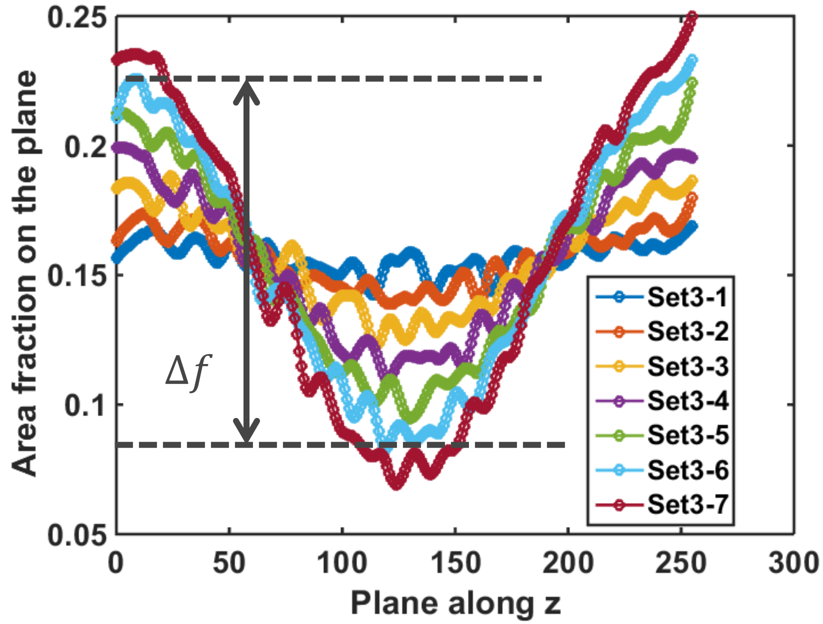


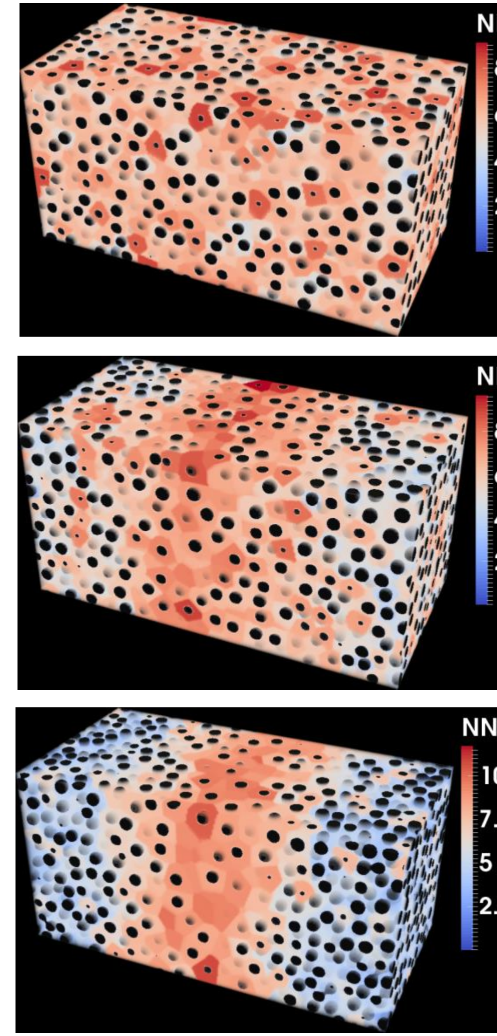
Comparison between simulated and experimental **creep** tests. The simulation can currently capture the initial and the transition up to early stages of secondary creep.

Construction of non-uniform γ' for HA282 weldment



Phase-field generated HA282 with different sinusoidal γ' variation





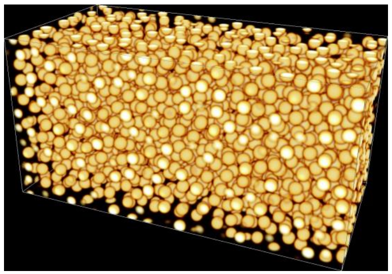
Nearest-neighbor distance maps

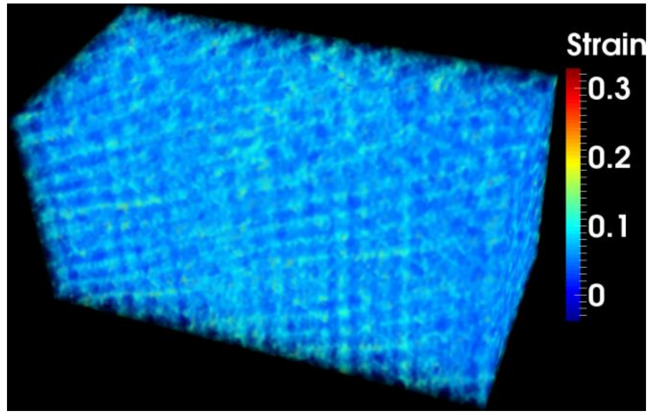
- To account for microsegregation effect
- Average volume fraction is fixed
- Variation of volume fraction with an increased amplitude from Set3-1 to 3-7

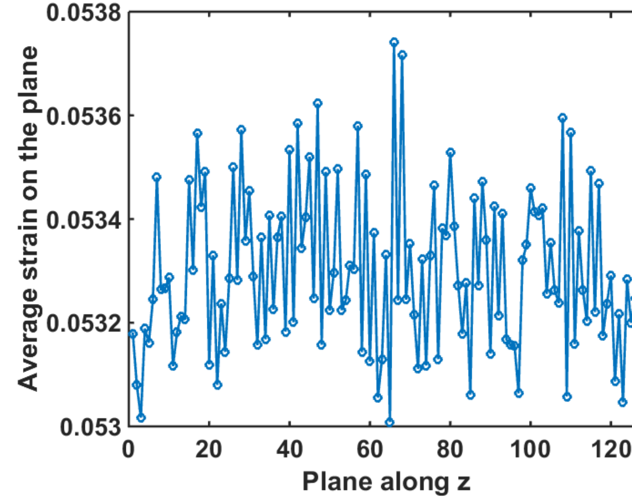
Heterogeneous deformation due to γ' spatial variation

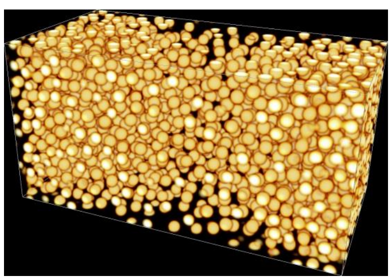
Distribution of ε_{yy} (the uniaxial tension along y–axis)

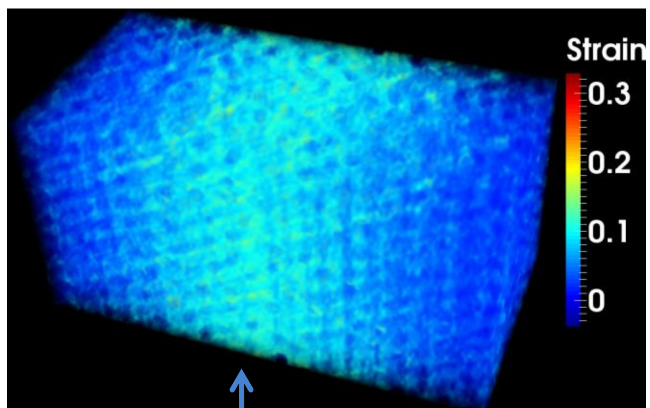
Increased γ' variation

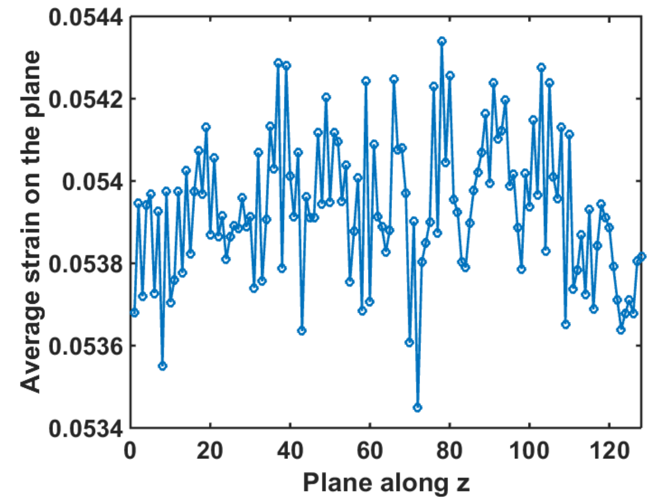






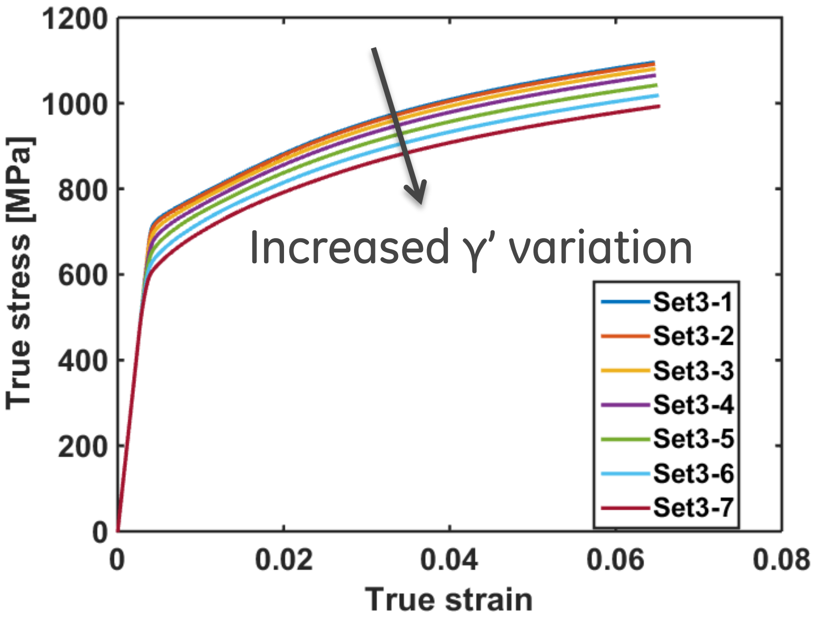


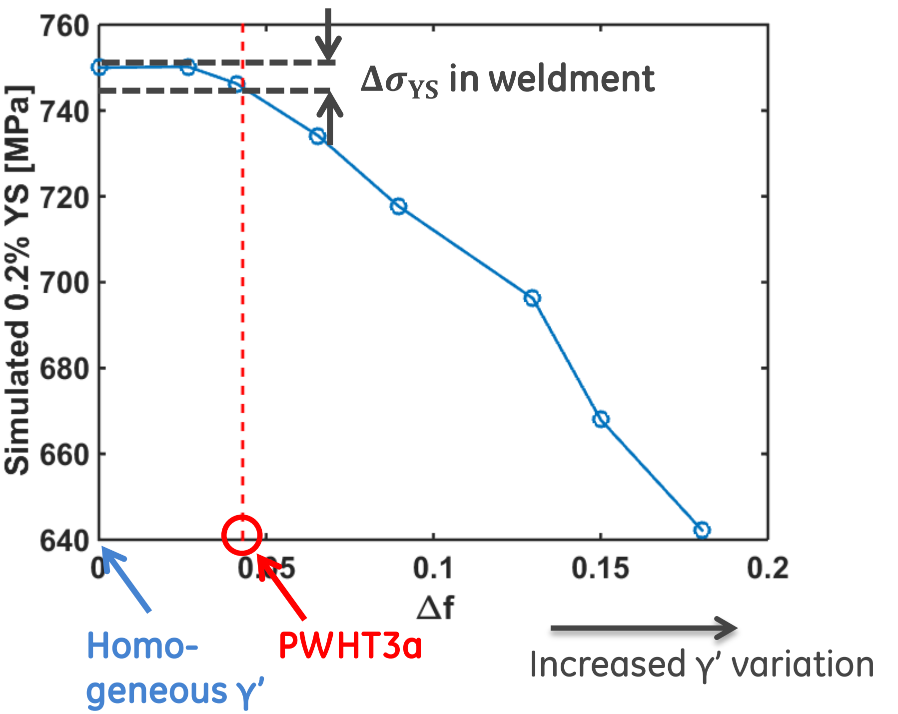




Dendrite core region

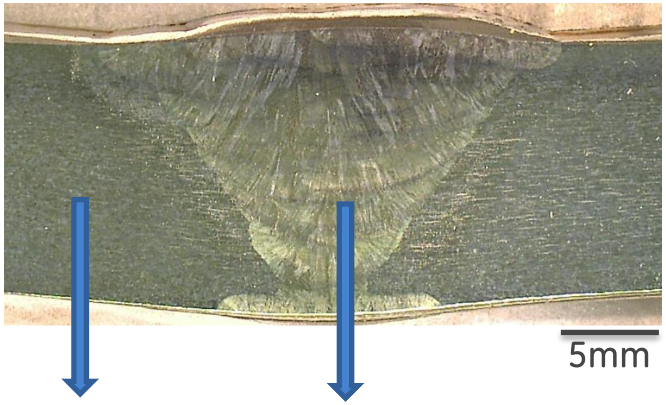
Simulated effects of γ’ spatial variation on tensile property





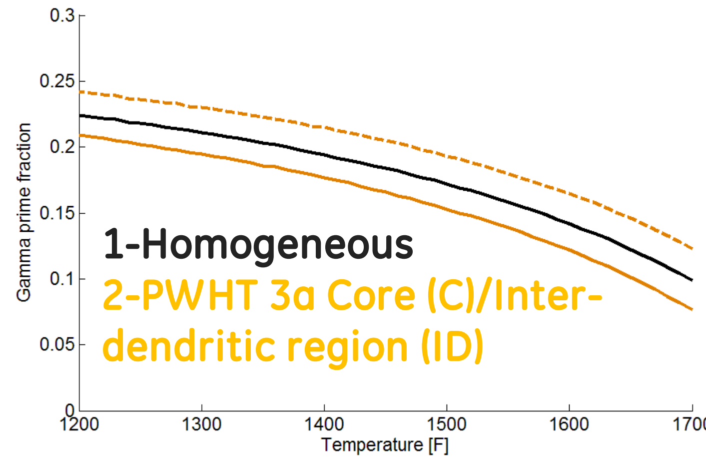
- YS decreases with increase of γ’ variation in weldment due to microsegregation
- The reduction appears small for PWHT3a

Constitutive creep model to address microstructural difference in weldment



Grain size
d~150μm
Volume fraction 1

Grain size
d~200-1000μm
Volume fraction 2



$$\dot{\varepsilon}^{boundary\_diff} = 12\pi F \frac{D_B \delta_B \Omega}{k_B T} \frac{1}{d^3} \sigma_{applied} (1 + \varepsilon^{creep})$$

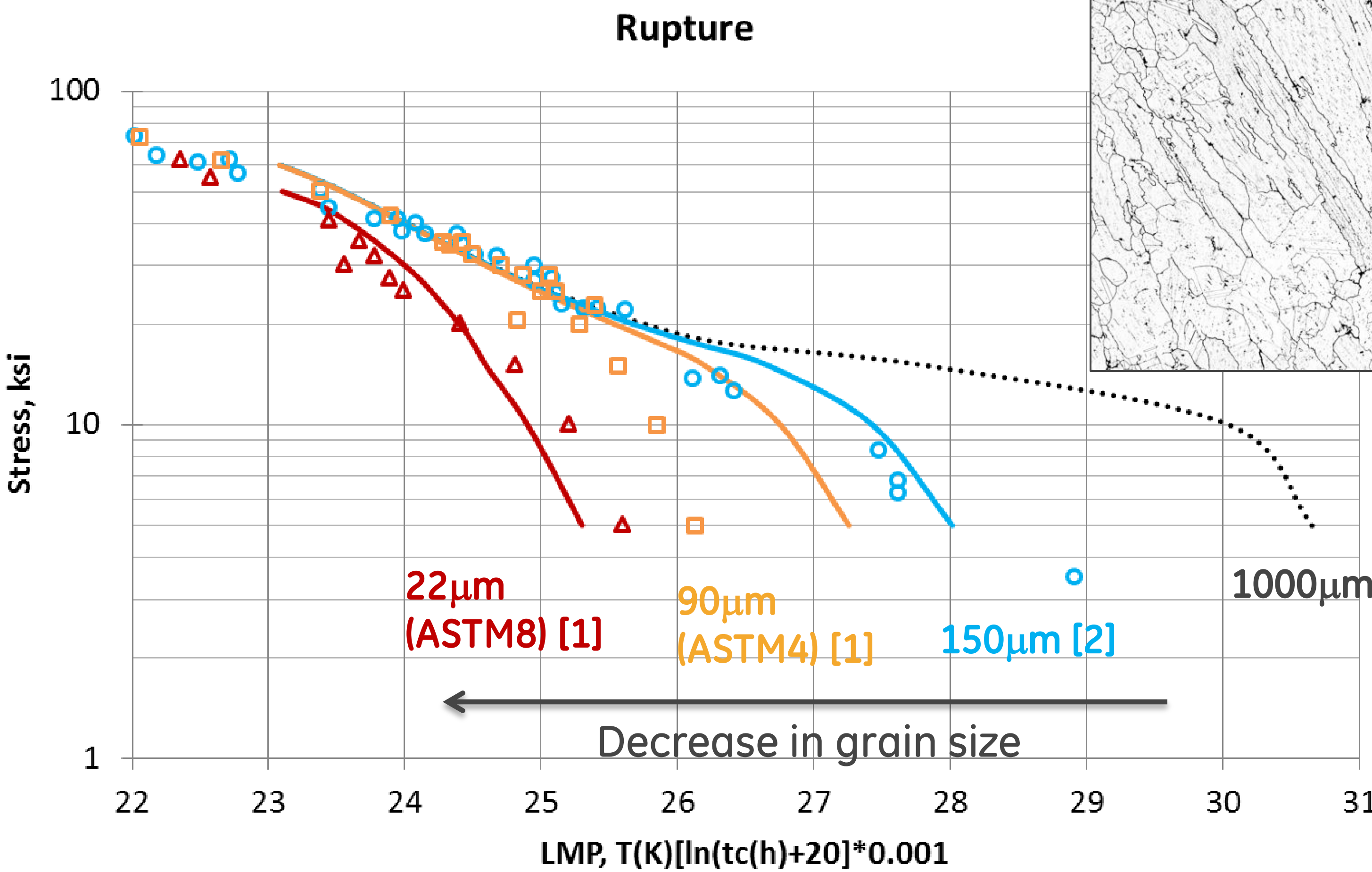
$$\dot{\varepsilon}^{lattice\_diff} = 4F \frac{D_V \Omega}{k_B T} \frac{1}{d^2} \sigma_{applied} (1 + \varepsilon^{creep})$$

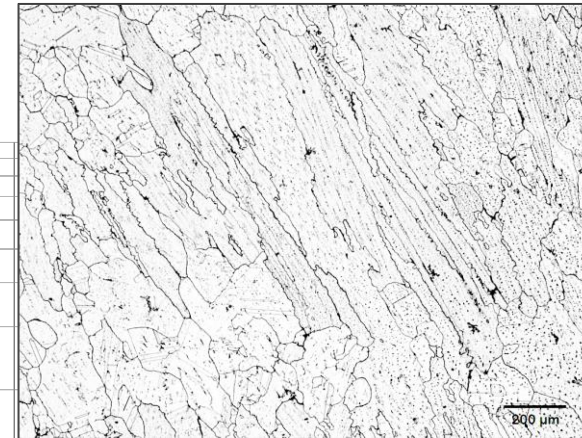
Change in the grain size affects the diffusion creep

$$\dot{\varepsilon}^{disloc} = A\rho f (1 - f) \left(\sqrt{\frac{\pi}{4f}} - 1 \right) \sinh \left(\frac{\sigma_{eff} - \sigma_{climb}(f, T) - \sigma_0(T)}{MkT} \lambda(f, T) b^2 \right)$$

Change in precipitate volume fraction affects the dislocation creep

Grain size affect - Constitutive creep model study

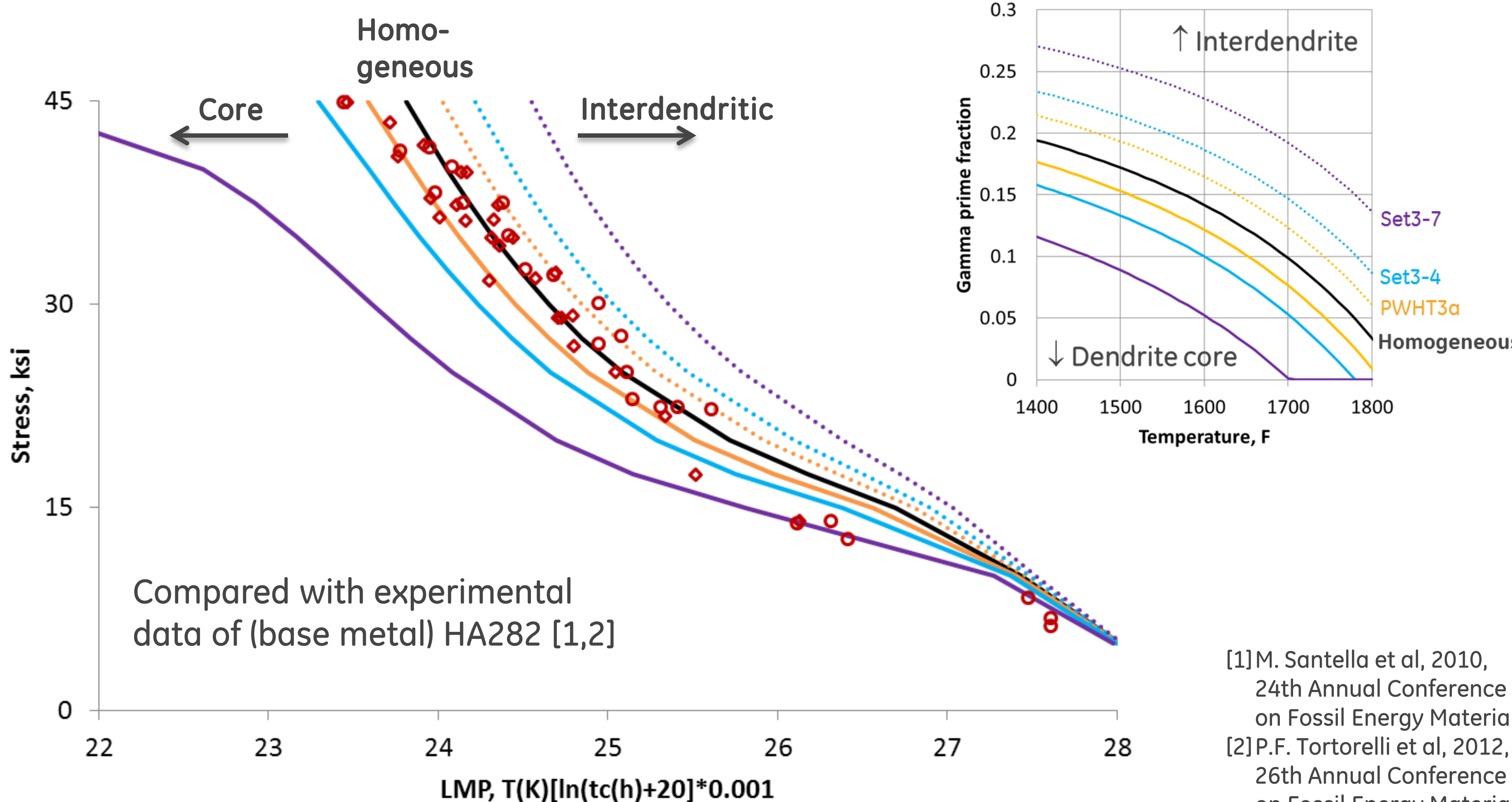




[1] D. Saha, 2015. DE-FE0000234 Topical Report, http://www.osti.gov/scitech/servlets/purl/1223685
[2] M. Santella et al, 2010, 24th Annual Conference on Fossil Energy Materials

- To a first approximation, grain size variation (anisotropy) in the weldment showed a small effect to creep strength except for low stresses

Effect of γ' spatial variation - Constitutive creep model study



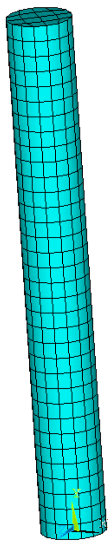
[1] M. Santella et al, 2010, 24th Annual Conference on Fossil Energy Materials

[2] P.F. Tortorelli et al, 2012, 26th Annual Conference on Fossil Energy Materials

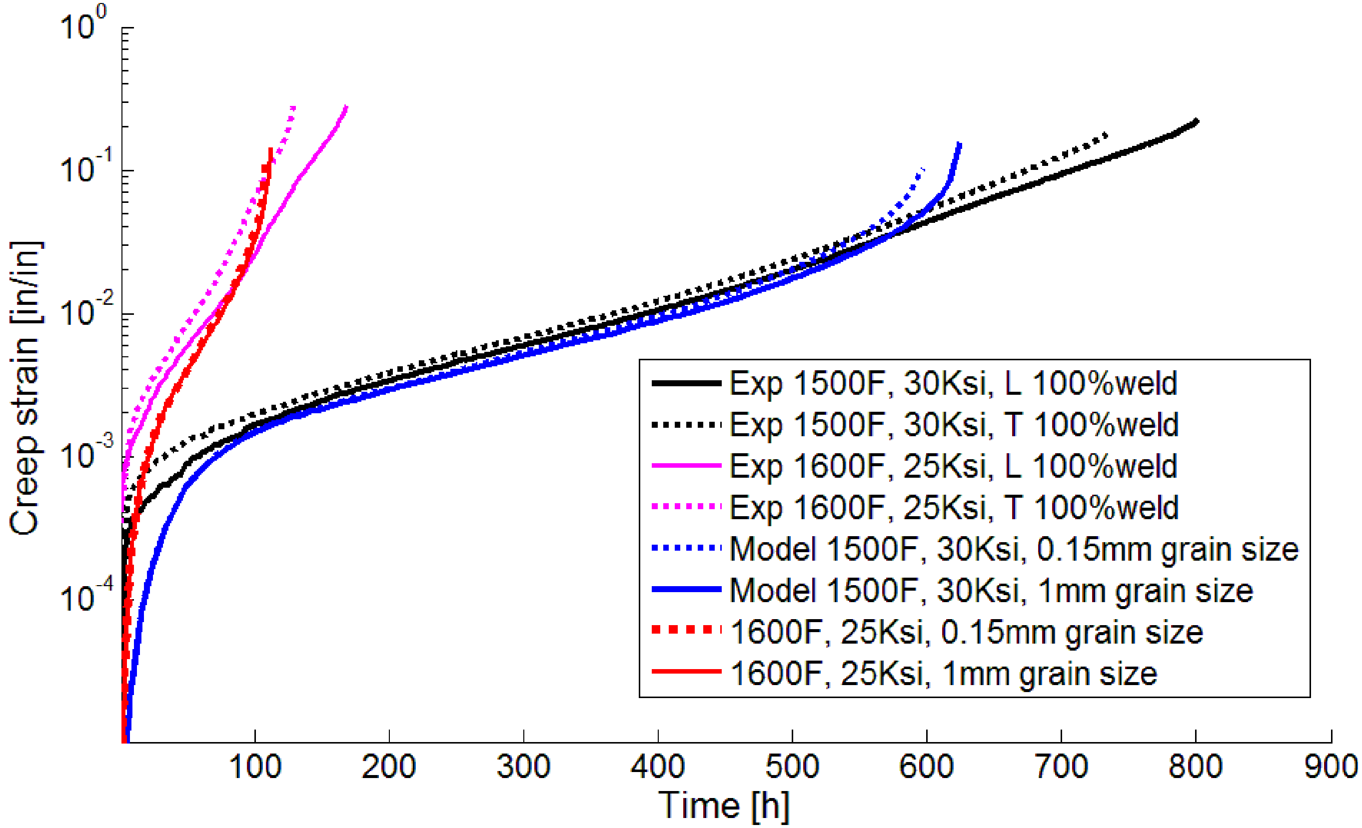
Only small effects from γ' variation in dendrites, even after PWHT3a (with no solution anneal)

FEM implementation in progress

HA282 base metal model was implemented in a finite element code via a user defined subroutine.
The creep model was applied on creep sample geometry (3D) and the results agree with material point predictions



Material HA282 at 1500 and 1600F



Summary

- Welded HA282 showed overall a small debit to creep and tensile
  - Creep rupture: no debit at 1500-1700˚F
  - YS, UTS: small debit at 1500-1600˚F , a larger drop at 1700˚F; no difference between parallel (P) and transverse (T) to welding direction
  - Ductility (elongation): reduced under both tensile and creep: As-weld < PWHT < BM
- Failure locations all in weld zone, subsurface cracks/cavities found along high angle GBs
- M_6C and $M_{23}C_6$ on GBs were identified compositionally and structurally
- PWHT2 (with solution anneal) and PWHT3a showed little difference in rupture life
- Composition very uniform after PWHT2, and some residual microsegregation in PWHT3a
- γ' size variation is very small even with PWHT3a, more noticeable in volume fraction
- Crystal plasticity modeling showed higher plastic strain in dendrite core where γ' is lean, reduction in YS however is small even for PWHT3a
- Continuum creep modeling showed effects of grain size and γ' at different regimes of temperature and stress