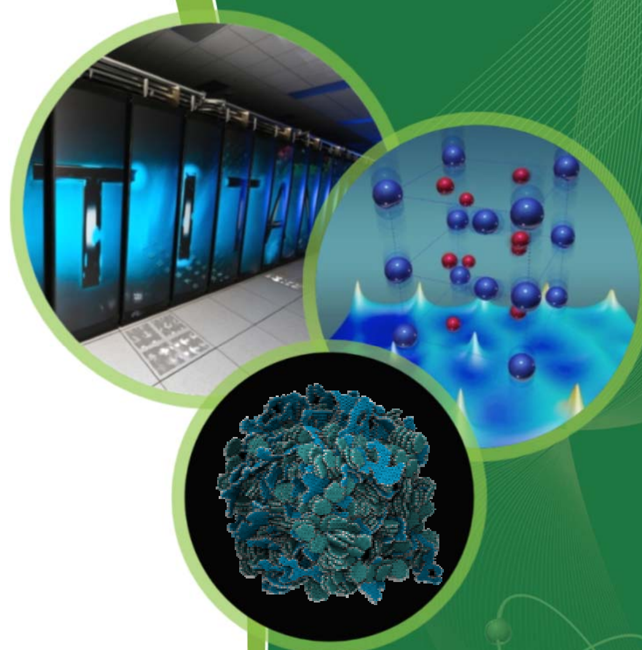
Weldability of Creep-Resistant Alloys for Advanced Fossil Power Plants



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Project Goal and Technical Scope

- Develop an Integrated Computational Welding Engineering modeling (ICWE) tool to predict creep deformation and failure in welded structures of Creep Strength Enhanced Ferritic (CSEF) Steels
  - Integrate multi-physics and multi-scale weld modeling framework for welding process and structural creep performance simulations
  - The model will be microstructure-based and consider key microstructure feature at different length scale.
  - Use advanced experimental testing techniques to validate and refine the model
- Two levels of modeling frameworks have been considered
  - An engineering approach to quickly assess weld creep performance based on experimental data (Level 1 model)
  - Microstructure-based ICWE model for CSEF steels weld creep performance prediction (Level 2 model)

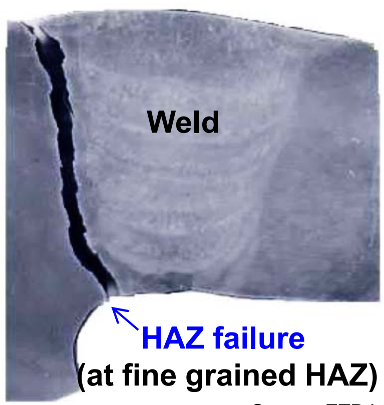
Outline

- Background
- Summary of Level 1 model
- Introduction of Level 2 model
  - Microstructure model
  - Structural performance model
    - Creep damage model
    - Micromechanics model for precipitate-matrix interaction
- Conclusion

Background: Weld can be the weakest link

- Weldability issues in heat-resistant alloy due to microstructure inhomogeneity in the Creep Strength Enhanced Ferritic Steels weldments

HAZ cracking in 9-12Cr steels



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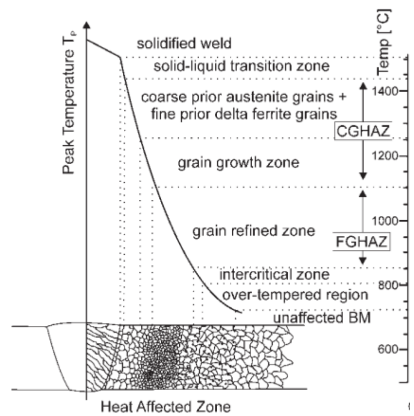

Cerjak and Mayr: Woodhead, 2008

- Weld and HAZ microstructure could be totally different from original well-designed base materials
- Failure mechanism of the weldments could also be very different from base materials
- Weld creep performance model need to include a wide range of microstructure variations and different creep deformation/failure mechanisms

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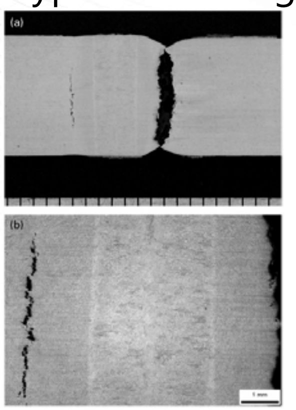
Background: Weld can be the weakest link

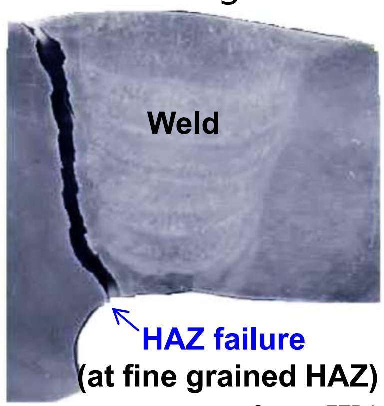
- Weldability issues in heat-resistant alloy due to microstructure inhomogeneity in the Creep Strength Enhanced Ferritic Steels weldments

Type IV cracking



Abson 2013

HAZ cracking in 9-12Cr ste



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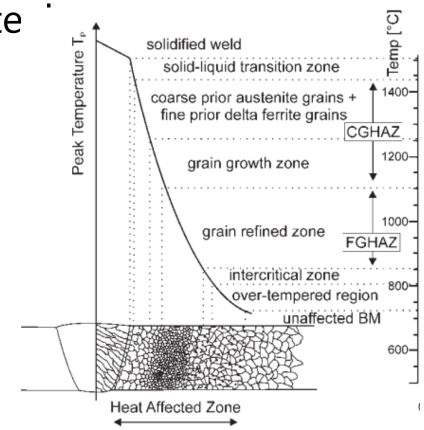
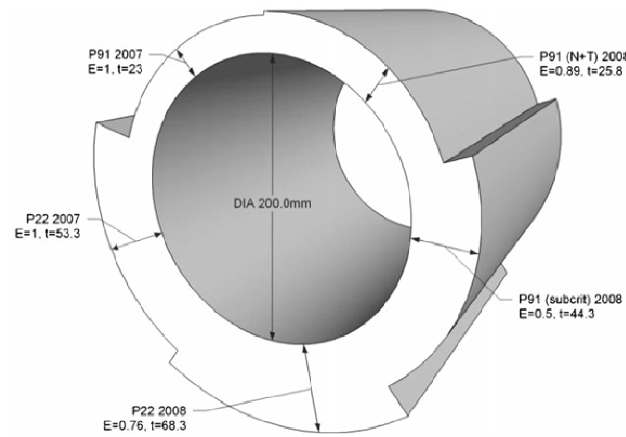


Cerjak and Mayr: Woodhead, 2008



- Major reduction in creep strength in the weld region can be as high as 50% of base metal. Effectively negate the benefit of higher creep resistance steels such as P91, P92 etc.
- Lack of reliable predictive modeling tool makes it difficult to effectively incorporate welding technology innovations for creep resistance improvement in design and service

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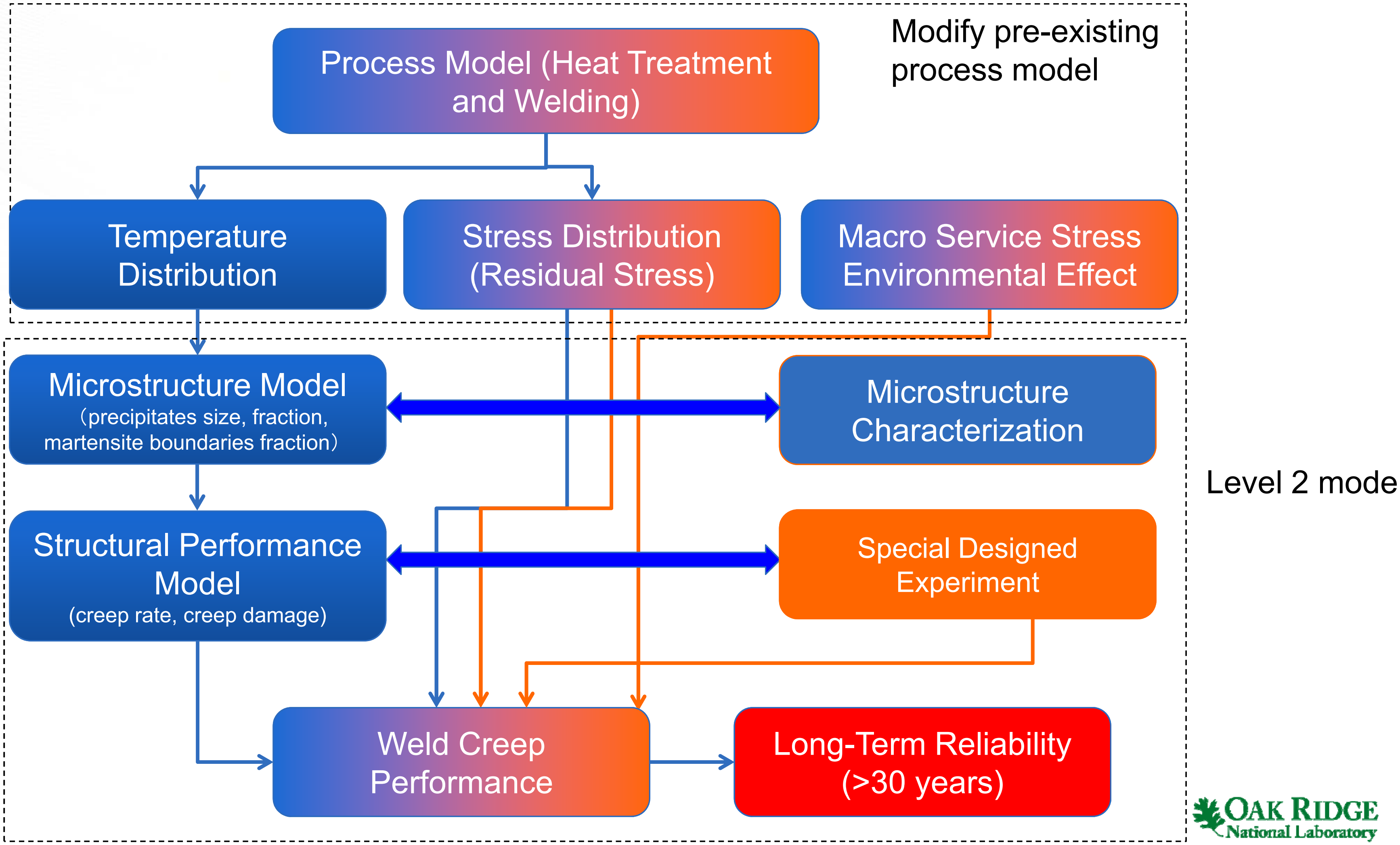
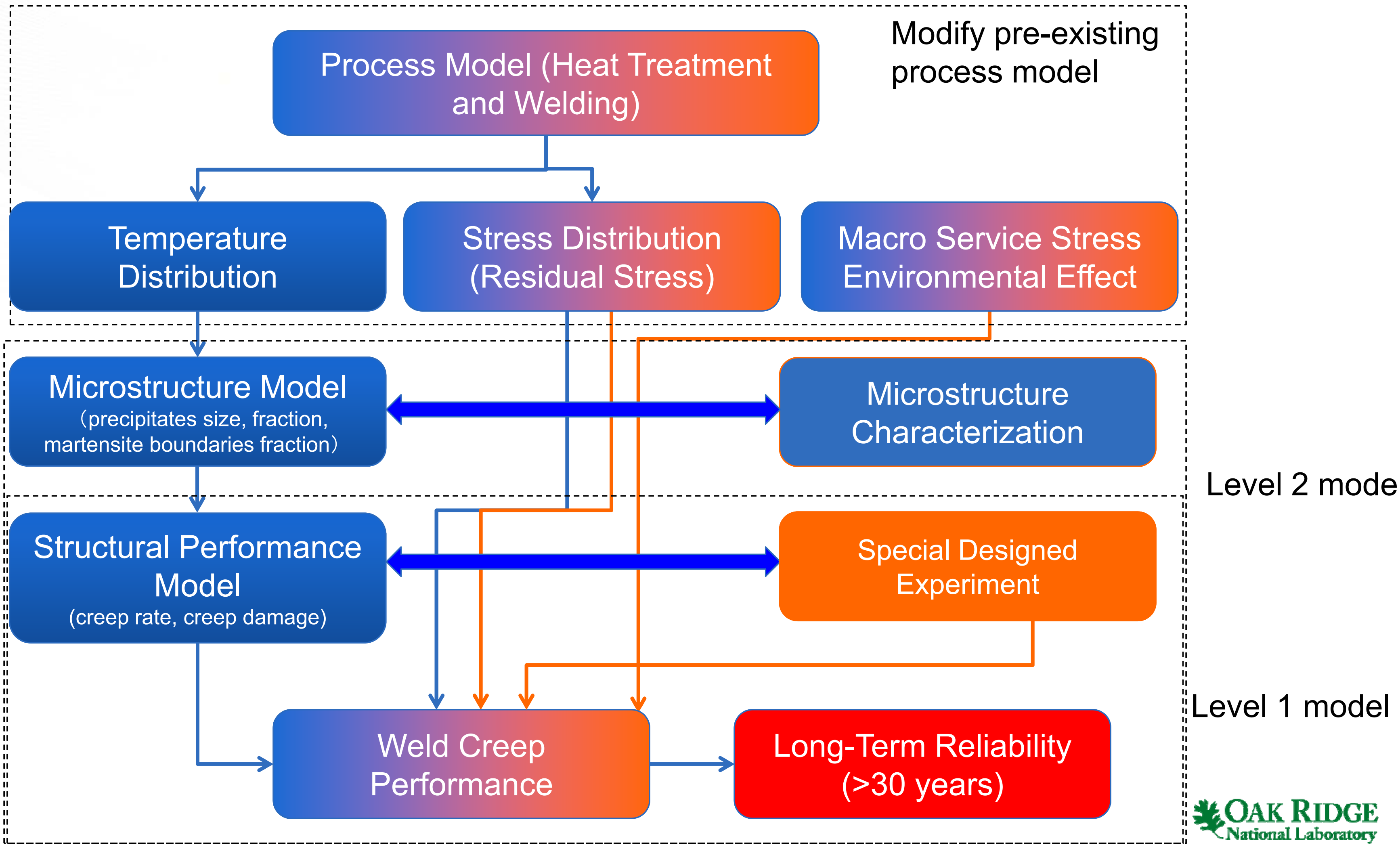
Integrated Modeling Approach for Weld Creep Performance



Integrated Modeling Approach for Weld Creep Performance



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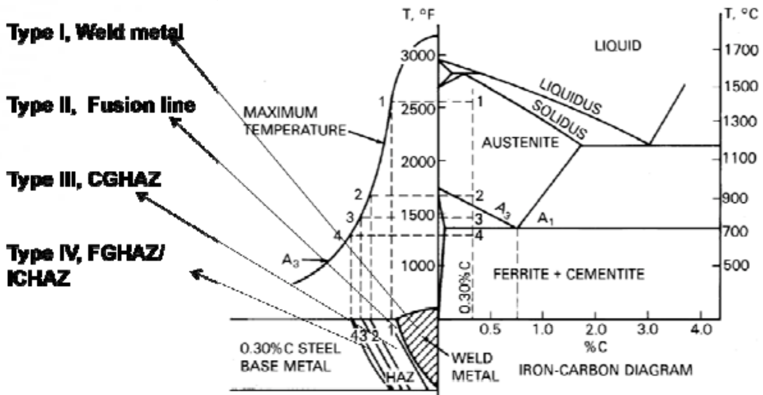
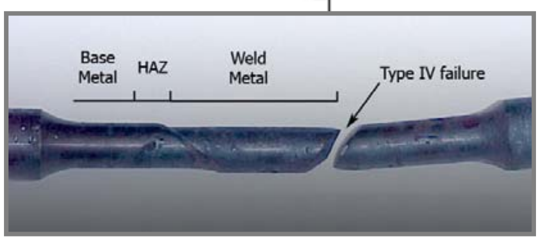
Level 1 Model Overview

Specially Designed Experiment (DIC) → Structural Performance Model (Creep rate, Creep damage) → Weld Creep Performance





Weld Joint Strength Reduction Factors (WSRF = $\sigma_{weld}/\sigma_{base\ metal}$) for CSFE steels can be as low as 0.5 at ~600ºC.

- Digital Image Correlation (DIC) based mechanical properties measurement
  - Necessary due to microstructure and property gradient in the weld region
- High temperature stress-strain, Young's modulus
- High temperature Creep strain evolution
- Measured properties can be incorporated in constitutive equations or used as direct input in finite element models.

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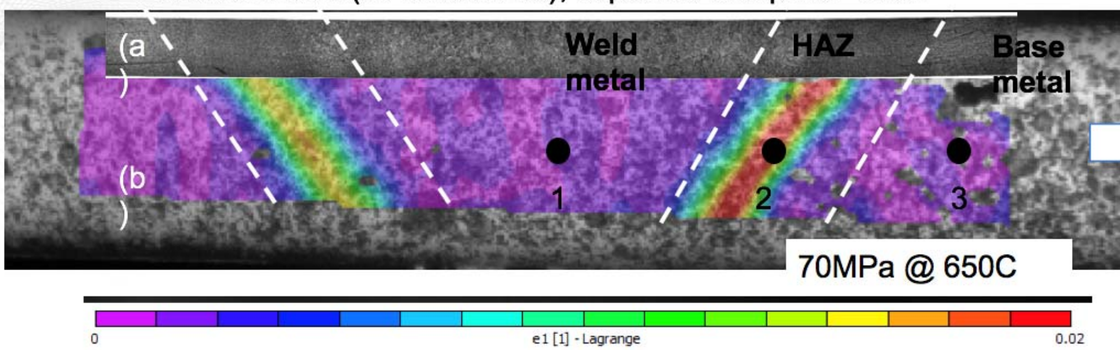
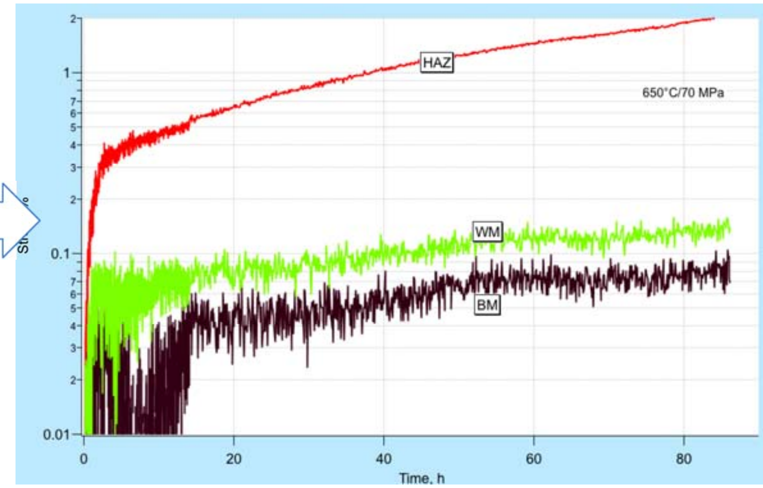
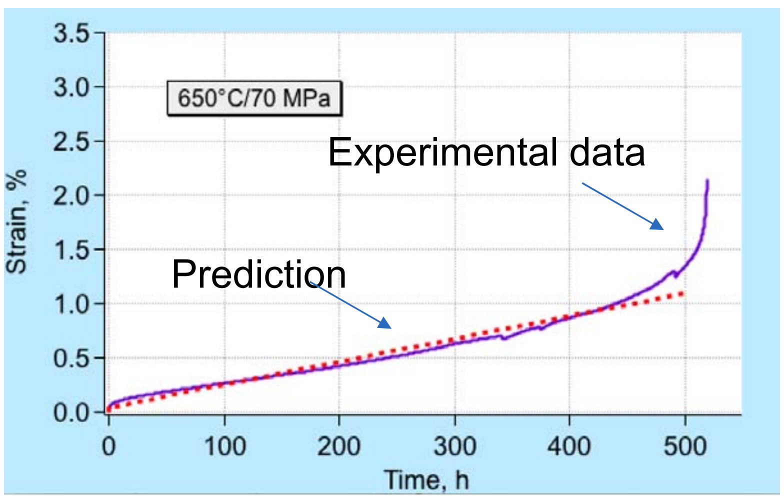
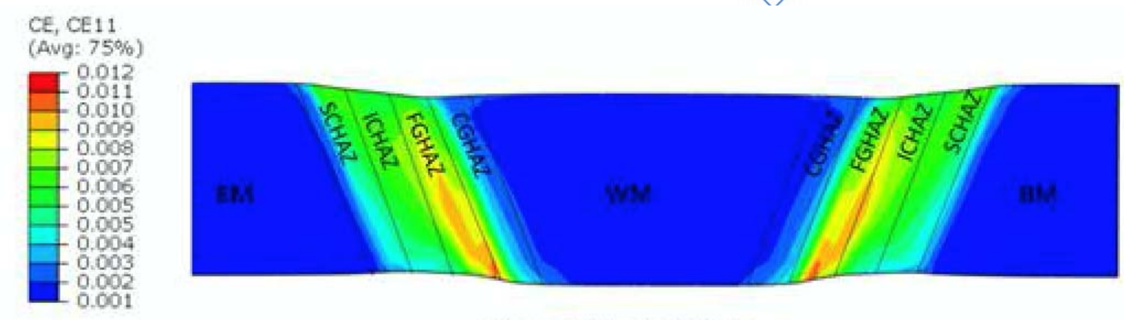
From 80 hours 500 hours

Heat treatment (1040/760/760), expected creep life:~500h





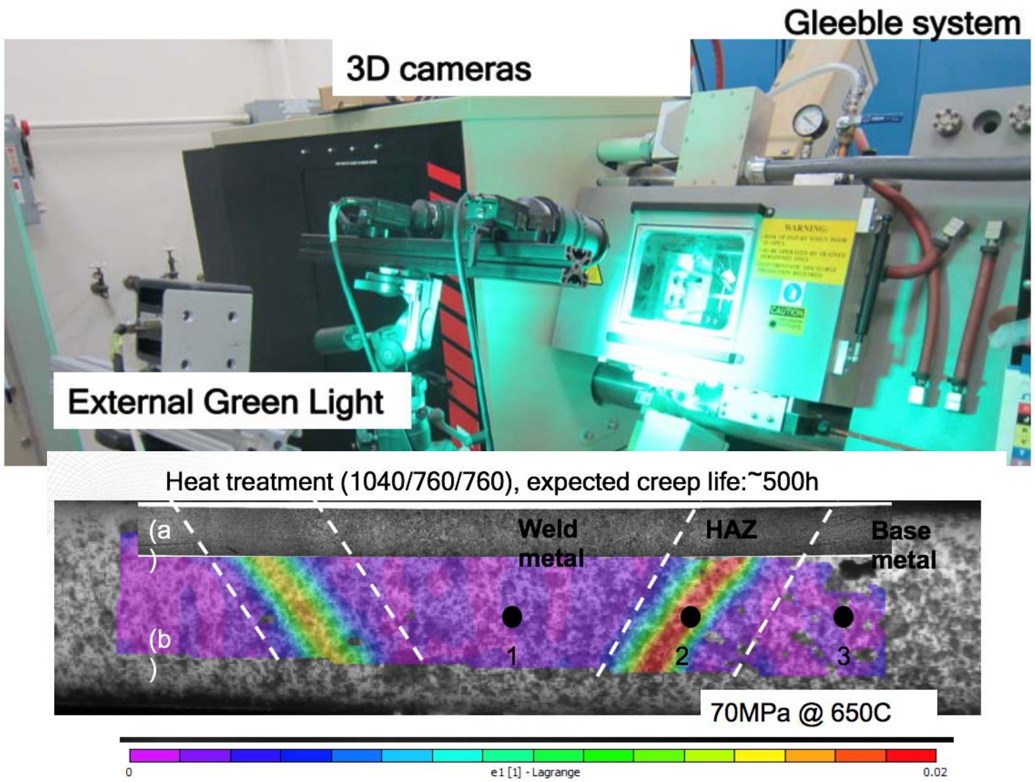




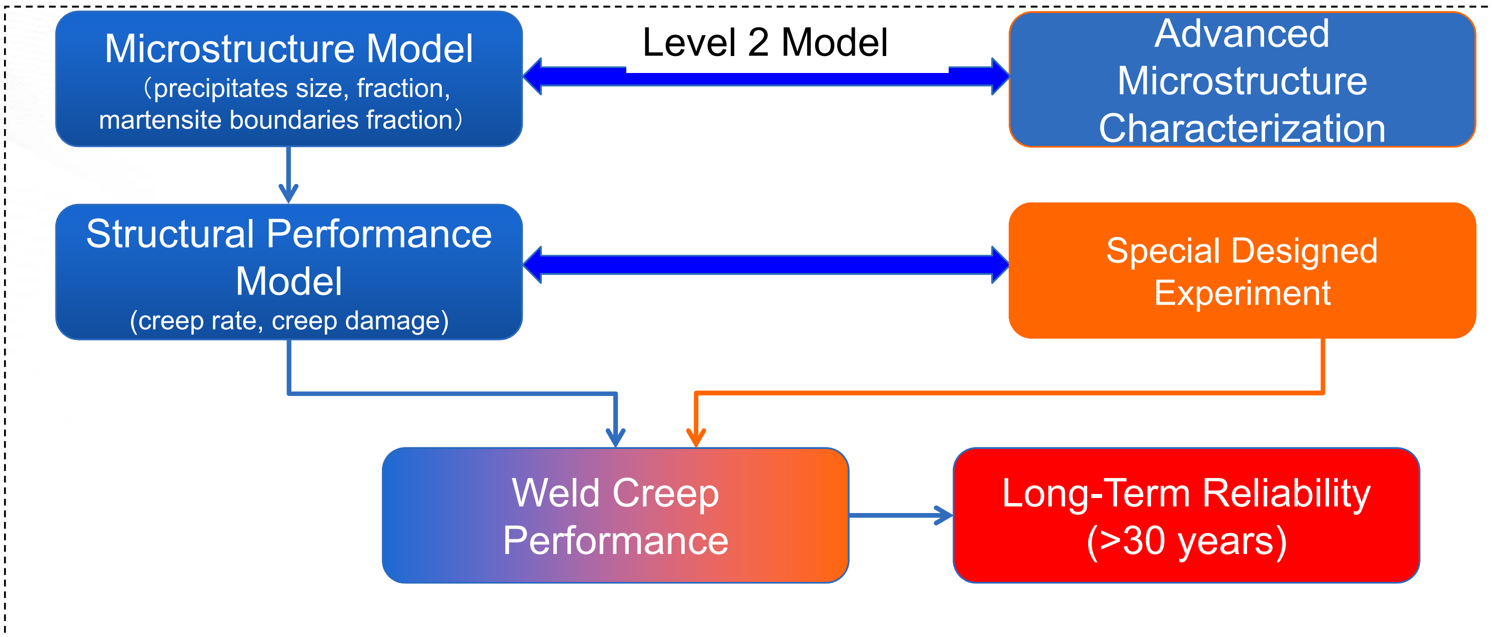
Creep strain at 80h

Long-term Prediction and Validation

Short term creep testing using Gleeble



Level 2 Model Overviews

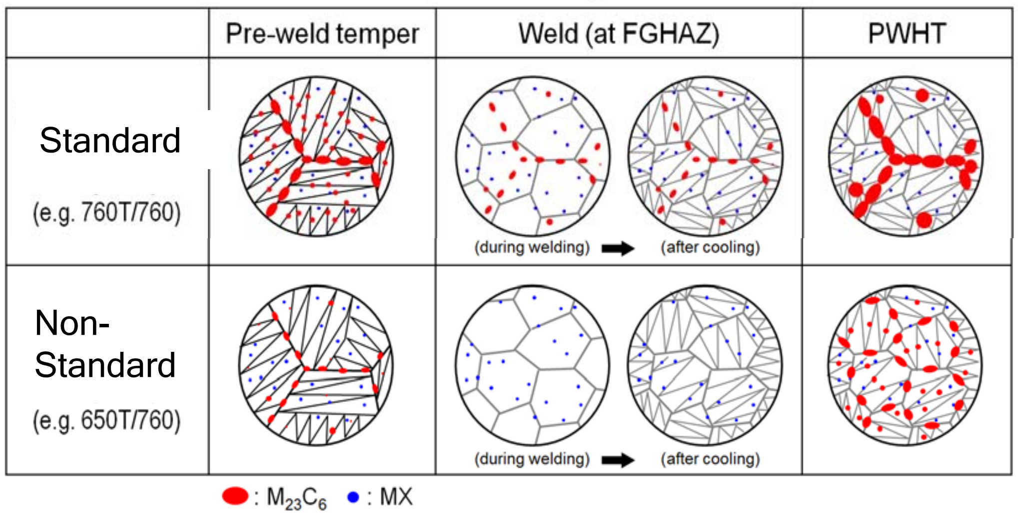


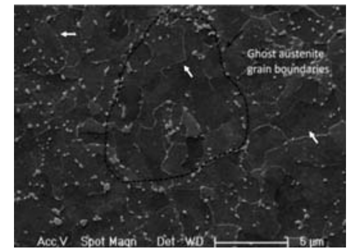
What are the key microstructure features for creep deformation?

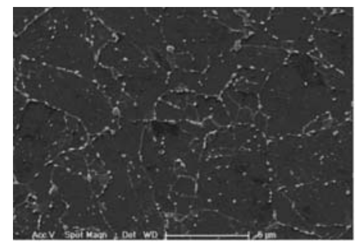
How does these key features affect creep properties?

Previous Study on Grade 91 Show Dispersion of Fine Carbides is the Key

Table: Microstructure evolution at fine grain heat affected zone







X. Yu et al., *Acta Materialia*, vol. 61 (2013) p. 2194-2206.

Carbide size, distribution, coarsening kinetics are very important microstructure features.

Microstructure gradient (carbides, martensite substructure size) is also important for weldments

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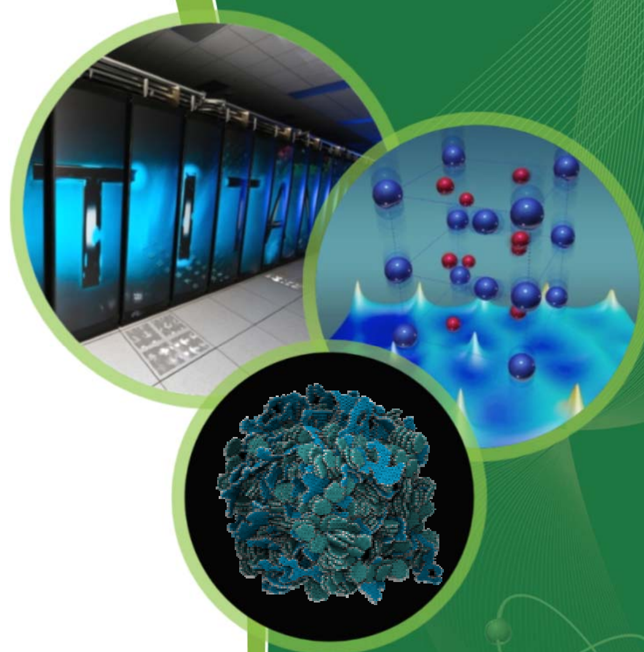
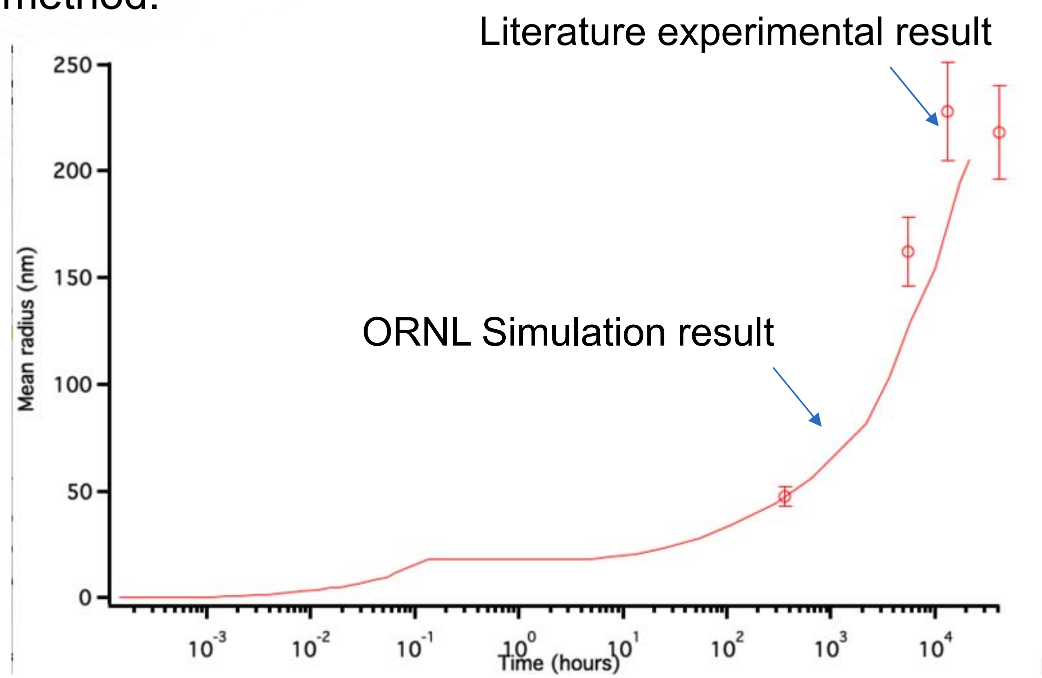
Microstructure Model



Microstructure Simulation

- TC-PRISMA is a general computational tool for simulating kinetics of diffusion controlled multi-particle precipitation process in multi-component and multi-phase alloy systems.
- TC-PRISMA is based on Langer-Schwartz theory and Kampmann-Wagner numerical method.



Hald, John, and Leona Korcakova. "Precipitate Stability in Creep Resistant Ferritic Steels-Experimental Investigations and Modelling." ISIJ international43, no. 3 (2003): 420-427

- Only Considered M23C6
- Normalized at 1050C and tempered at 760C.
- The predicted precipitate size shows very good agreement for 364 hours.
- For time longer than 1000 hours, the predicted radius is slightly smaller than the experimental result.

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Microstructure Model Validation Using Synchrotron Time Resolved X-Ray Diffraction

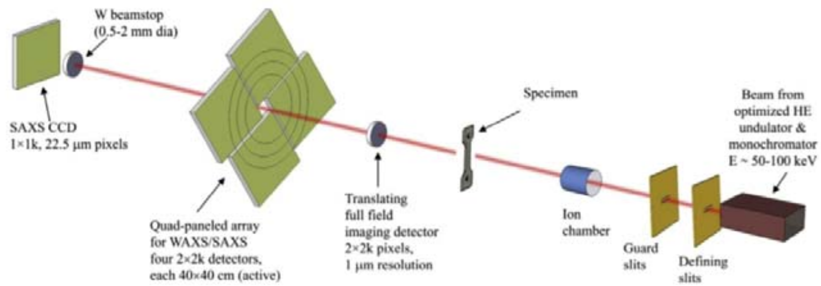
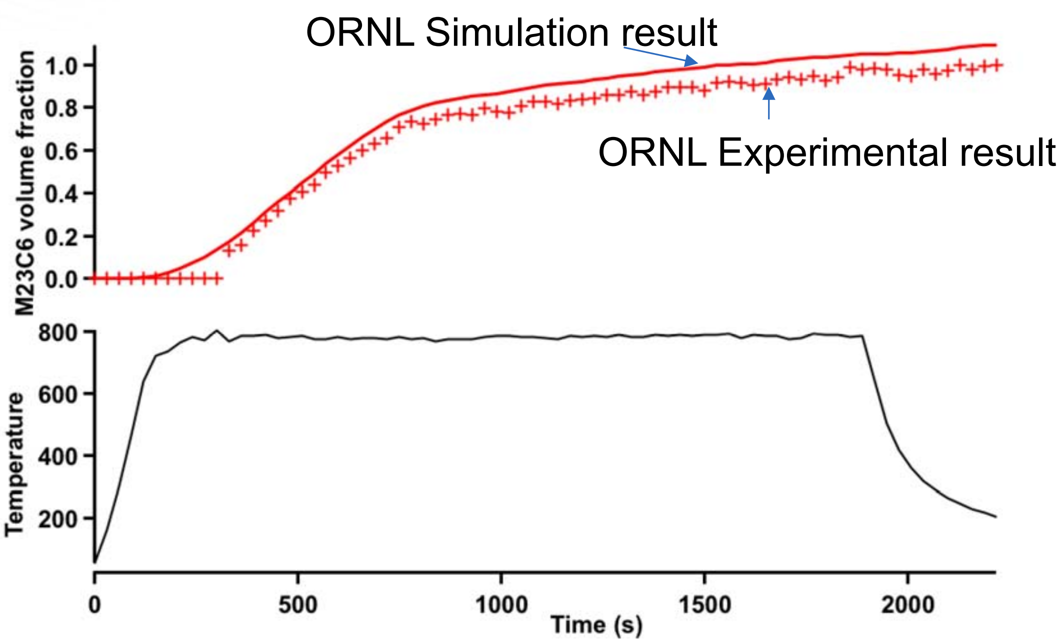


Fig. 1. Schematic layout of Beamline 1-ID at the Advanced Photon Source.

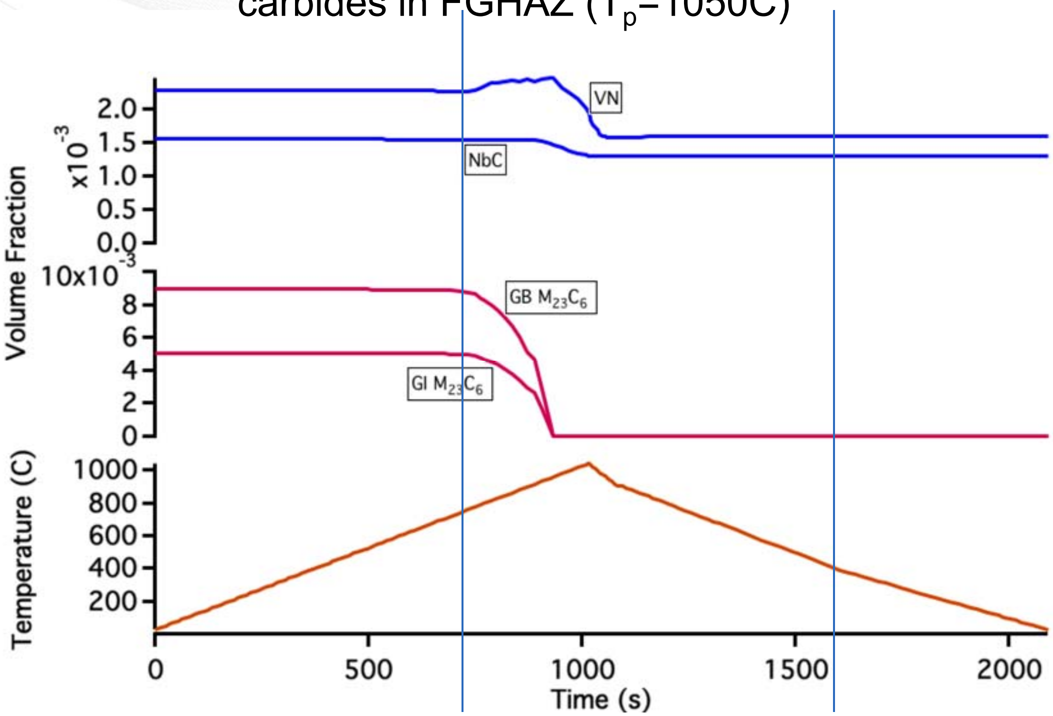


Grade 91 steel was normalized at 1040ºC
Precipitation kinetics was studied using in-situ synchrotron X-ray diffraction at 780ºC to accelerate carbide growth

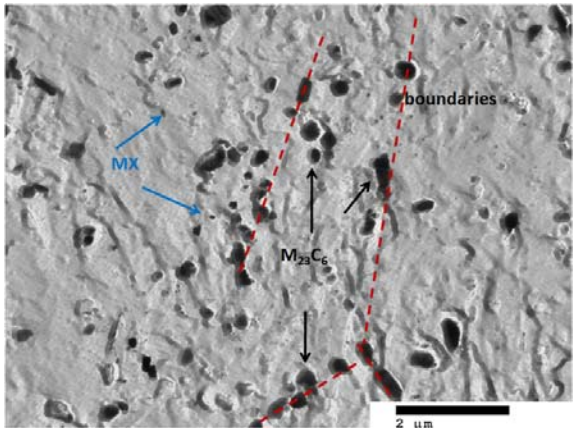
The predicted $M_{23}C_6$ volume fraction shows very good agreement with X-ray diffraction results.

Fine-Grained HAZ Microstructure Simulation

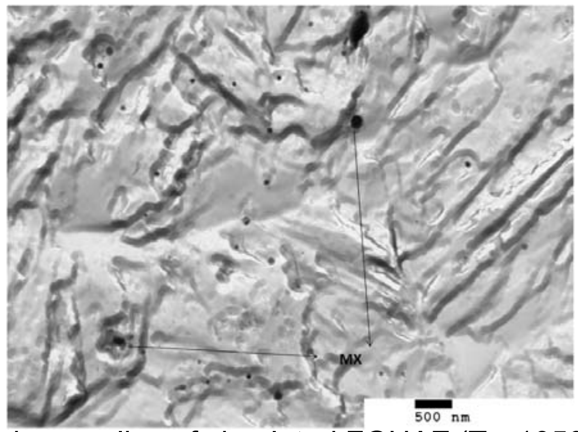
Simulation shows partial dissolution of MX precipitates and full dissolution of $M_{23}C_6$ carbides in FGHAZ (T_p=1050C)



Tempered Martensite Austenite Fresh Martensite



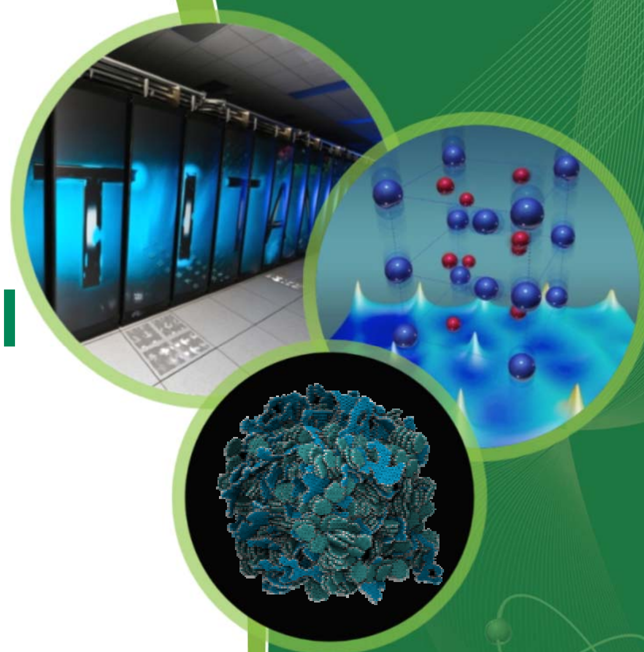
Before welding shows both M23C6 and MX carbide



Carbon replica of simulated FGHAZ (T_p=1050C) showing presence of MX

X. Yu et al., *Acta Materialia*, vol. 61 (2013) p. 2194-2206.

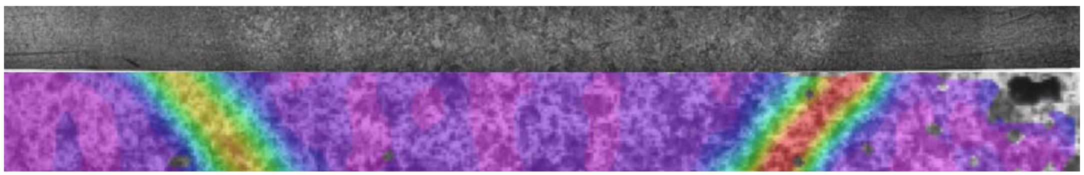
Structural Performance Model

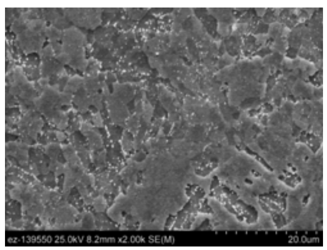


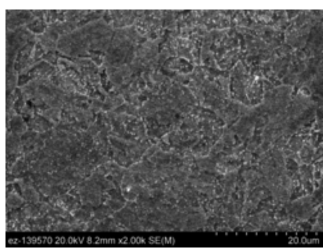
Structural Performance Model Needs to Consider Power-Law Creep, Coble Creep and Grain Boundary Sliding

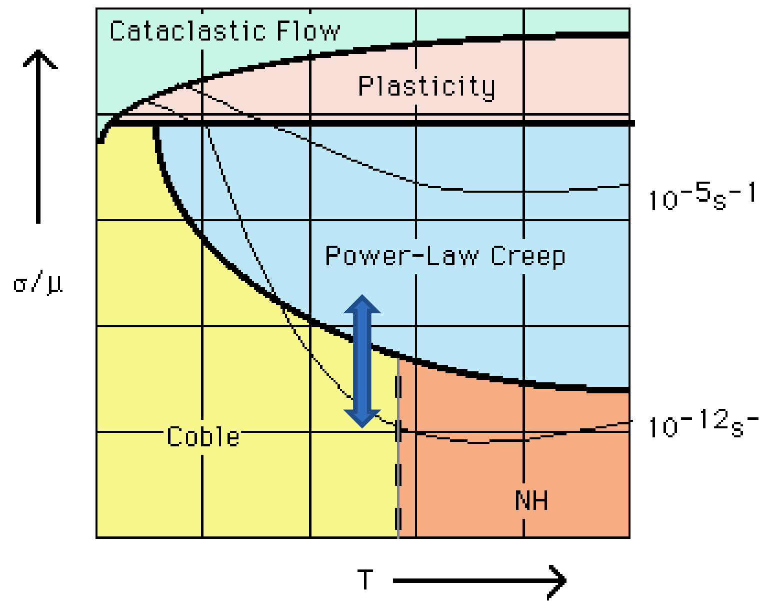
Microstructure Model
(precipitates size, fraction, martensite boundaries fraction)

Structural Performance Model
(creep rate, creep damage)









0.1mm deformation mechanism map

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Creep Mechanism for Grade 91 Weldments

- **Grain interior deformation**
  - Summation of rate equations for *Coble creep* and *Power-law creep.*
- **Grain boundary sliding (GBS) and its effect on Type IV region requires an explicit modeling of GBS**
  - General effect of grain boundary sliding:
    Control the strain rate sensitivity in the *intermediate stresses region* and small grained materials.
  - The failure of type IV cracking is governed by creep cavitation. Creep cavities and crack formation are found to be significantly affected by grain boundary sliding (e.g., Kimmins and Smith, 1998, Basirat et al., 2012).
  - The cavitation in the type IV region is very sensitive to grain boundary sliding, leading to relaxation of constraint and multiaxial rupture (e.g., Abson and Rothwell, 2013).

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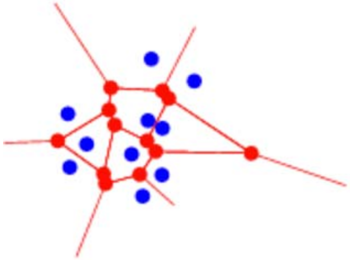
Representative Volume Element Model

- Voronoi tessellation: (Neper)
  (Quey, R., et al., 2011. Comput. Methods in Appl. Mech. and Eng., 200, 1729.)

$$R_i = \{\boldsymbol{x} \in D : \|\boldsymbol{Q}_i - \boldsymbol{x}\| < \|\boldsymbol{Q}_j - \boldsymbol{x}\| \;\; \forall j \neq i, j = 1,2,\ldots,n\}.$$

A partition of a domain *D* into *n* regions R_i corresponding to *n* distributed seed Q_i.



- RVE model for weldments

Condition: 650ºC 70 Mpa load & hold

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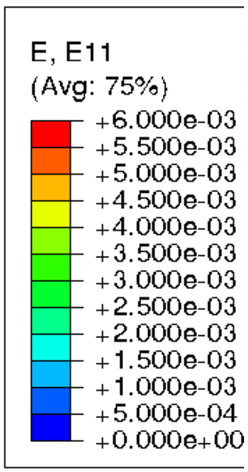
Creep Deformation Simulation

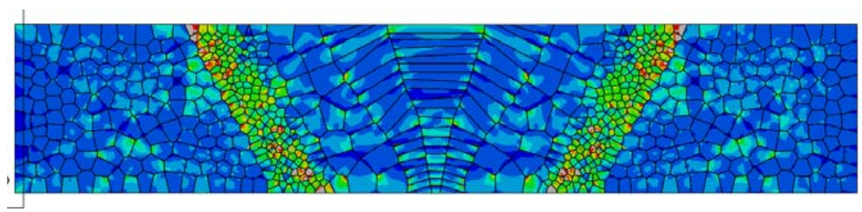
Grade 91 steel weldment at 70MPa and 650ºC

❖ *Case I*: Only **Coble creep**

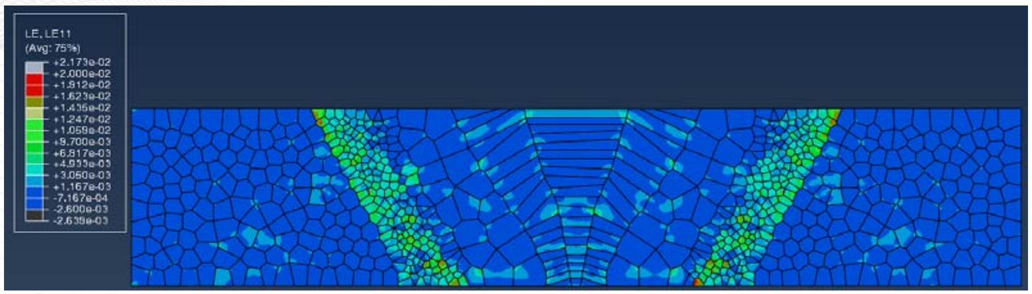


❖ *Case II*: **Coble creep + Power-law creep**

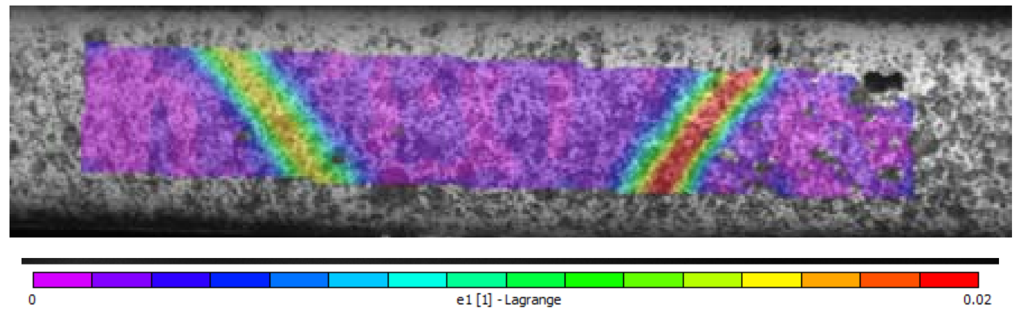
❖ *Case III*: **Coble creep + Power-law creep + Grain Boundary Sliding**



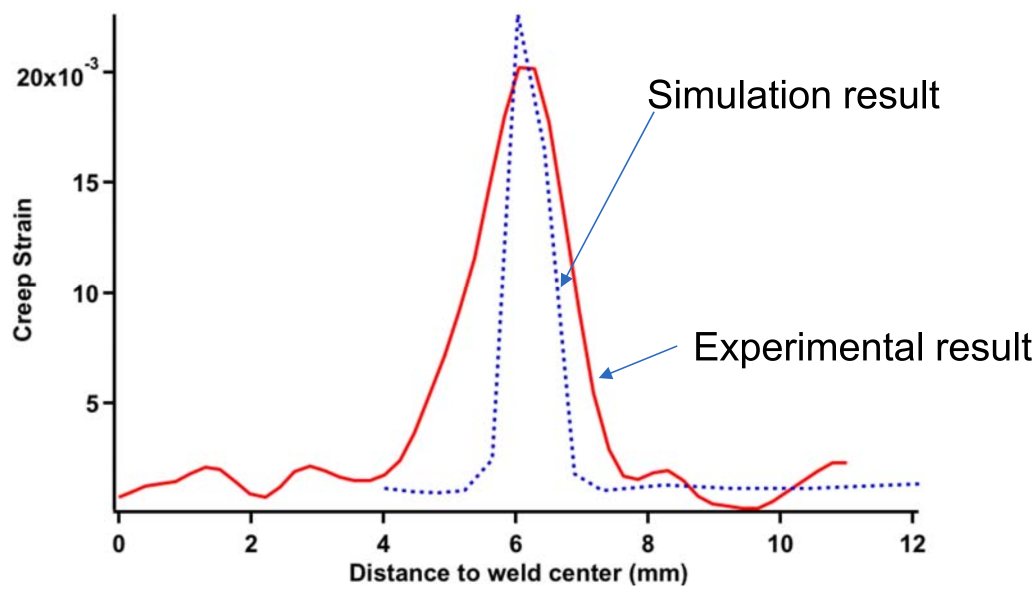
Simulation Result Shows Agreement With Experiments



Modeling result



Experimental result



Constitutive equations – Cavitation Nucleation and Growth

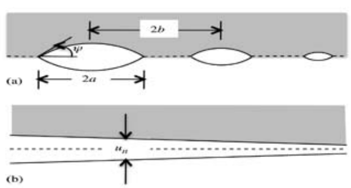
Cavity representation

Cavity volume $$V = \frac{4}{3}\pi a^3 h(\psi)$$

Shape parameter $$h(\psi) = \frac{\left[(1+\cos\psi)^{-1} - \frac{1}{2}\cos\psi\right]}{sin\psi}$$

Smeared–out separation $$\dot{u}_n = \frac{\dot{V}}{\pi b^2} - \frac{2V\dot{b}}{\pi b^3}$$

Rate of void spacing $$\frac{\dot{b}}{b} = \frac{1}{2}(\dot{\varepsilon}_{\mathrm{I}} + \dot{\varepsilon}_{\mathrm{II}}) - \frac{1}{2}\frac{\dot{N}}{N}$$



Damage evolution:

***a*/*b*~0.7**

• Cavity nucleation

Cavitation nucleation rate:

$$\dot{N} = F_n\left(\frac{\sigma_n}{\Sigma_0}\right)^2 \dot{\varepsilon}_e^c \quad \text{for } \sigma_n > 0$$

Nucleation parameter:

$$S = \left(\frac{\sigma_n}{\Sigma_0}\right)^2 \varepsilon_e^c \quad \text{for } \sigma_n > 0$$

Cavity nucleation to be triggered:

$S > S_{thr}$, ***N*<*N*$_{max}$** $$S_{thr} = \frac{N_i}{F_n}$$

• Cavity growth

Cavity growth – atom diffusion and creep:

$$\dot{V} = \dot{V}_1 + \dot{V}_2$$

Contribution of atom diffusion:

$$\dot{V}_1 = 4\pi D \frac{\sigma_n - (1-f)\sigma_s}{\ln\left(\frac{1}{f}\right) - \frac{1}{2}(3-f)(1-f)}$$

Contribution of creep deformation:

$$\dot{V}_2 = \begin{cases} \pm 2\pi\dot{\varepsilon}_e^c a^3 h(\psi)\left[\alpha_n\left|\frac{\sigma_m}{\sigma_e}\right| + \beta_n\right]^n, & \text{for } \pm\frac{\sigma_m}{\sigma_e} > 1 \\ 2\pi\dot{\varepsilon}_e^c a^3 h(\psi)[\alpha_n + \beta_n]^n \frac{\sigma_m}{\sigma_e}, & \text{for } \left|\frac{\sigma_m}{\sigma_e}\right| < 1 \end{cases}$$

where $L = [\mathscr{D}\sigma_e/\dot{\varepsilon}_e^C]^{1/3}$, represents competition between creep and diffusion

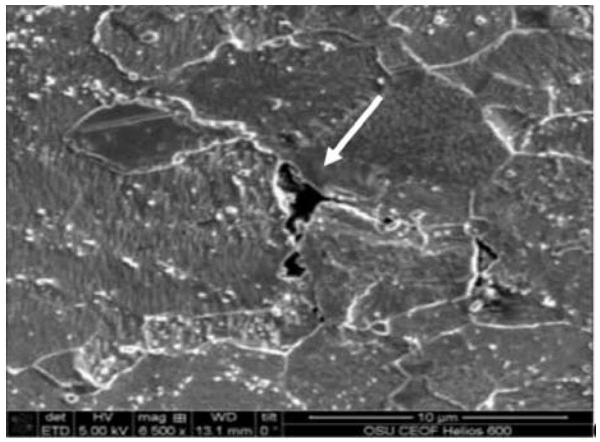
Needleman and rice, 1980. & Onck and van der Giessen, 1998,1999. & Yu C.H. et al., 2012, 2014.

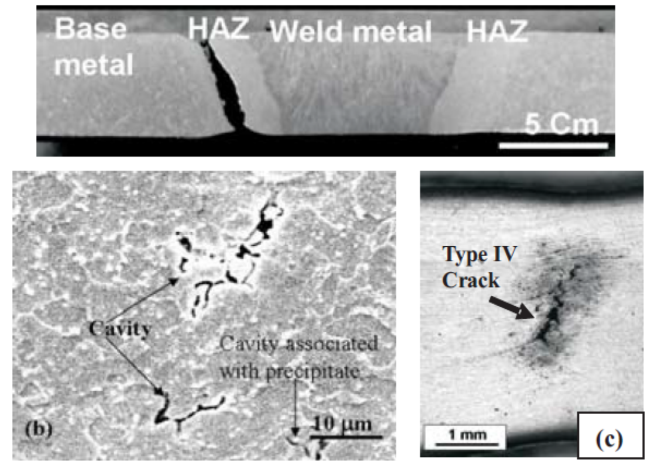
HAZ Creep Damage and Failures

- Fracture location: FG/ICHAZ.
- Failure mechanism:

  Intergranular creep fracture
- Creep voids nucleation sites:

  particle/matrix interface



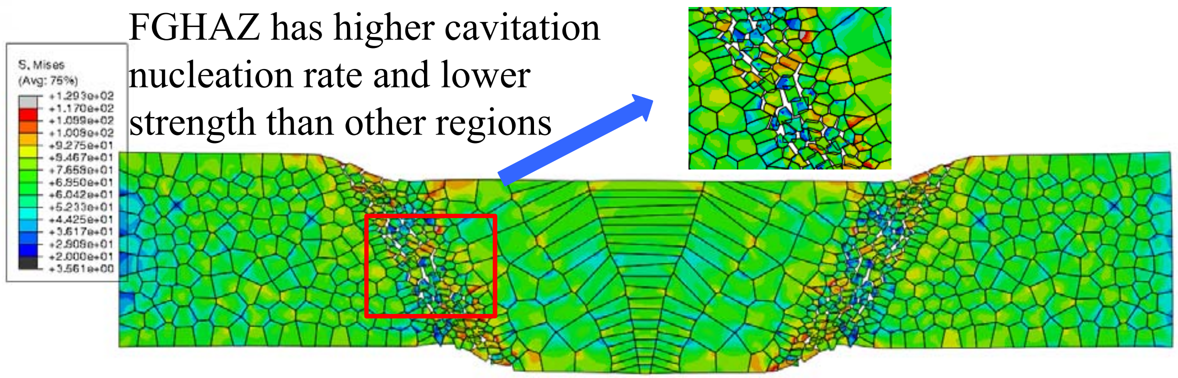


(Laha, K., et al. 2007, Met. Mater. Trans.)

- Precipitation: large particles, such as $M_{23}C_6$, are favored instead of fine precipitation on grain boundaries, in order to decrease the interfacial energy of the microstructure, and they coarsen rapidly than those in the base metal or weld metal — preferred nucleation sites for creep voids. (Abe F., Kern T. and Viswanathan R., 2008)

Results of Creep Damage Simulation

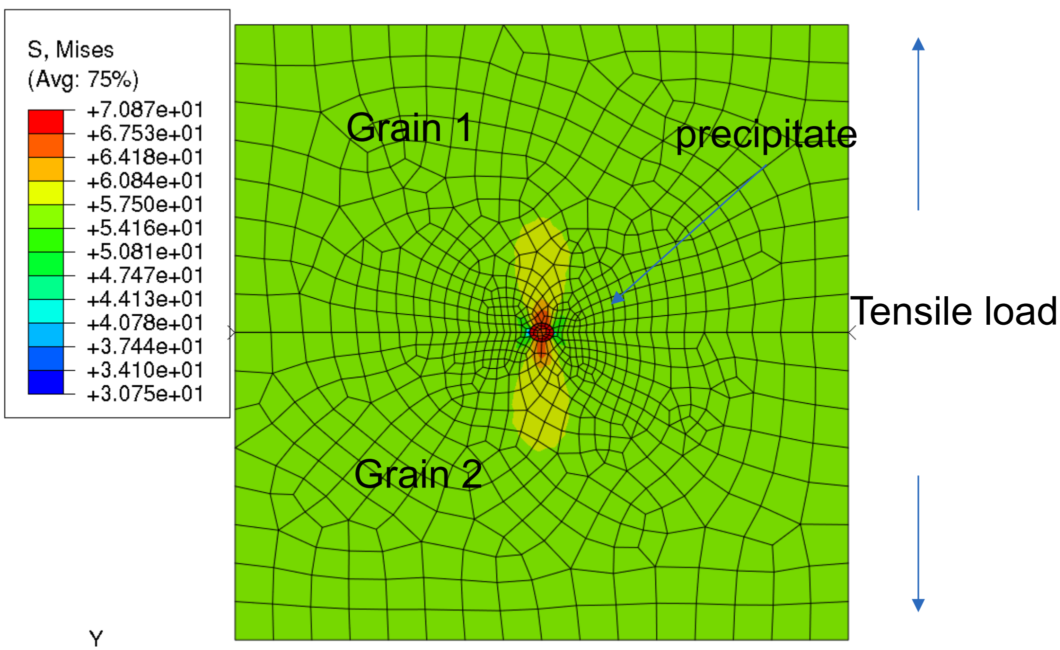
- HAZ failure is successfully simulated by using the micromechanics model.

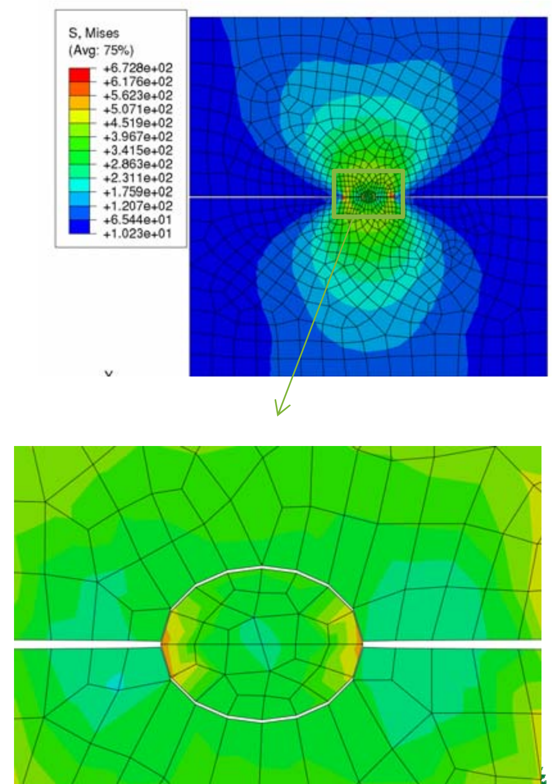


- Micromechanics model:
  Grain boundary cavity nucleation, growth as well as grain boundary sliding.
- FEA includes:
  i: UMAT=power-law creep, ii: UEL = grain boundary activities
  iii: material heterogeneity, iv: grain size and morphology

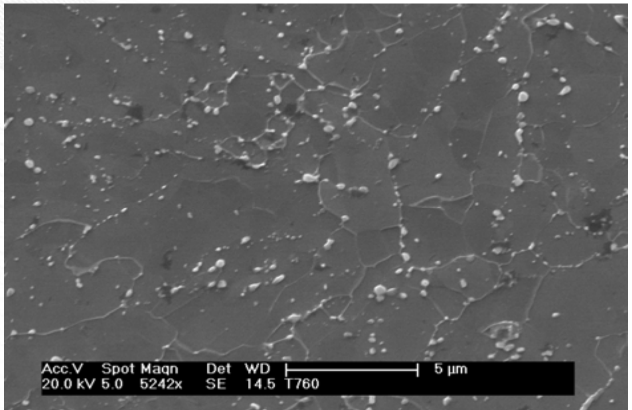
On-going Micromechanics Model of Precipitate on Grain Boundary

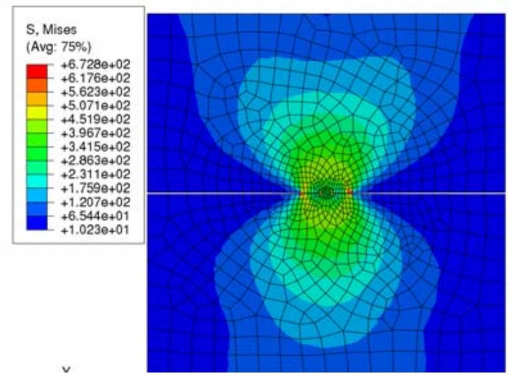
Case I: One precipitate on GB, with same parameters on all interfaces





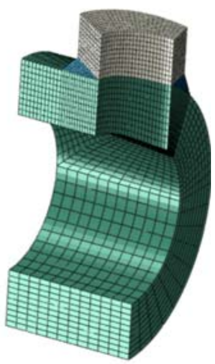
Micromechanics model to obtain improved microscopic level unified creep constitutive relation (explicitly containing key microstructure features)



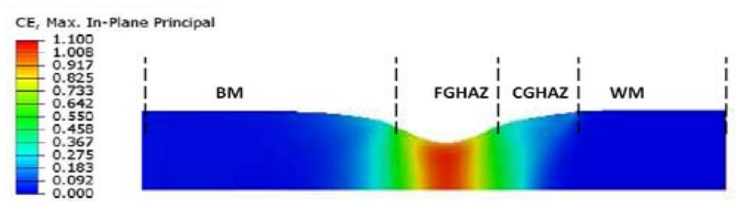


Constitutive creep relation from model

$$\dot{\varepsilon}_{creep} = f(carbides, \dot{g}rain\ boundary\ sliding, grain\ interior\ deformation, T, \sigma, etc)$$



Coupon level



Structural Component

Conclusions

- Established ICWE modeling framework Grade 91 Steel Weld Creep Performance
- Precipitation simulation at tempering condition showed good agreement with literature results.
- A deformation mechanism map (DMM) based model is utilized to analyze creep deformation of grain interiors, and a cohesive zone model (CZM) is used to model grain boundary sliding.
- A micromechanics model, accounting for grain boundary sliding, nucleation and growth of grain boundary cavities was employed to investigate the deformation and damage mechanisms in Grade 91 steels weldments

Milestones

- FY17 Milestones
  - Complete a creep deformation model using additive rule considering both grain boundary controlled creep and grain matrix controlled creep (Completed)
  - Complete an representative volume element (RVE) model with consideration of microstructure features for creep deformation prediction. (On track)
  - Complete integration of microstructure model with RVE model. (On track)

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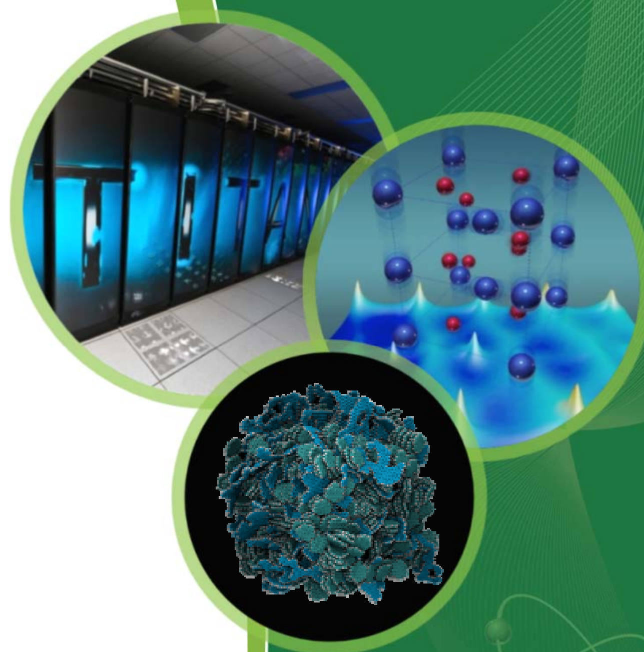
Future Work

- Continue to develop micromechanics model to obtain improved microscopic level unified creep constitutive relation.
- Integrate microstructure model with structural performance model
- Model Validation on lab coupon sample and real world structural component
- Apply high performance computing based ICWE simulation tool to simulate a weldments with thousand of grains

HPC4 MANUFACTURING

Testing Cases	A	B	C	D
Welding processes	Laser	Laser	Arc	Arc
# of elements	~126,000	~126,000	~95,000	~95,000
Baseline CPU time, sec	49,329	51,831	58,217	61,048
Speed-up factor	115.9x	28.7x	44.8x	30.1x



Thank you!

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