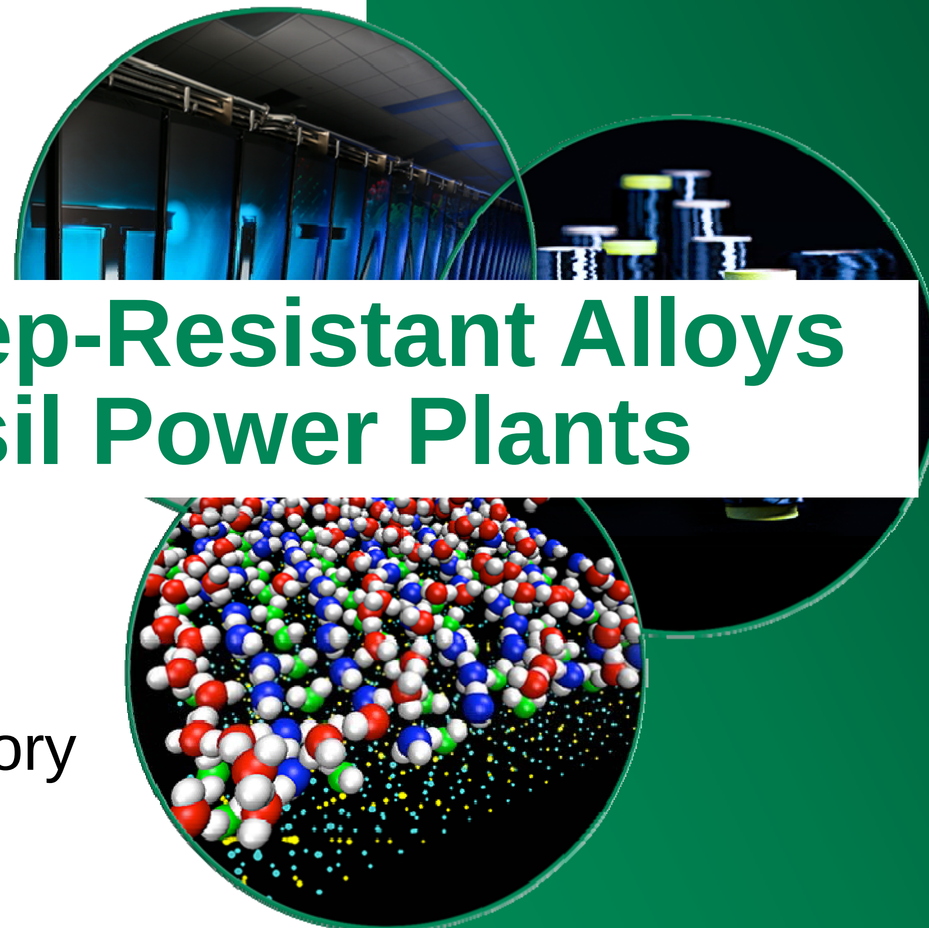
Weldability of Creep-Resistant Alloys for Advanced Fossil Power Plants



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OAK RIDGE NATIONAL LABORATORY
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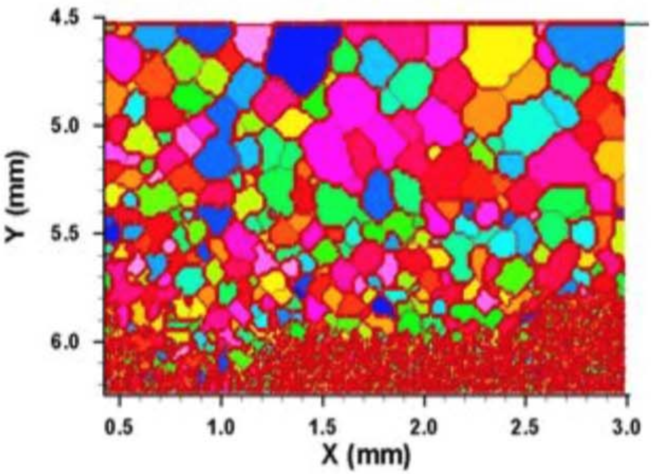
Project Goal and Technical Scope

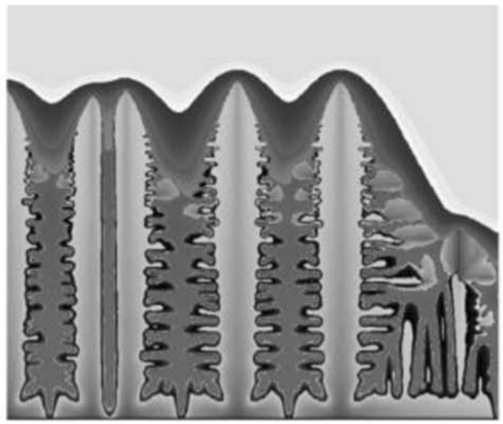
- Develop the capability of Integrated Computational Welding Engineering model to predict creep deformation and failure in welded structures of Creep Strength Enhanced Ferritic (CSEF) Steels
  - Develop an engineering approach to quickly assess weld creep performance based on experimental data (Level 1 model)
  - Develop microstructure-based ICWE model for CSEF steels weld creep performance prediction (Level 2 model)
  - Use advanced experimental testing techniques to validate and refine the model

Modeling of Microstructure & Properties

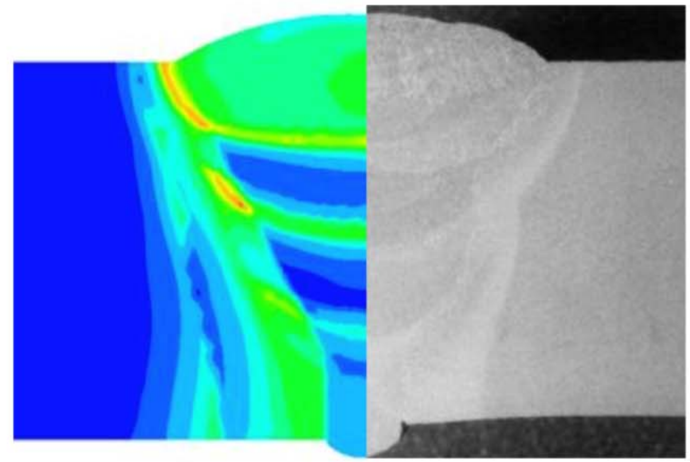
High-fidelity microstructure modeling provides insight into microstructure evolution and property heterogeneity of welds



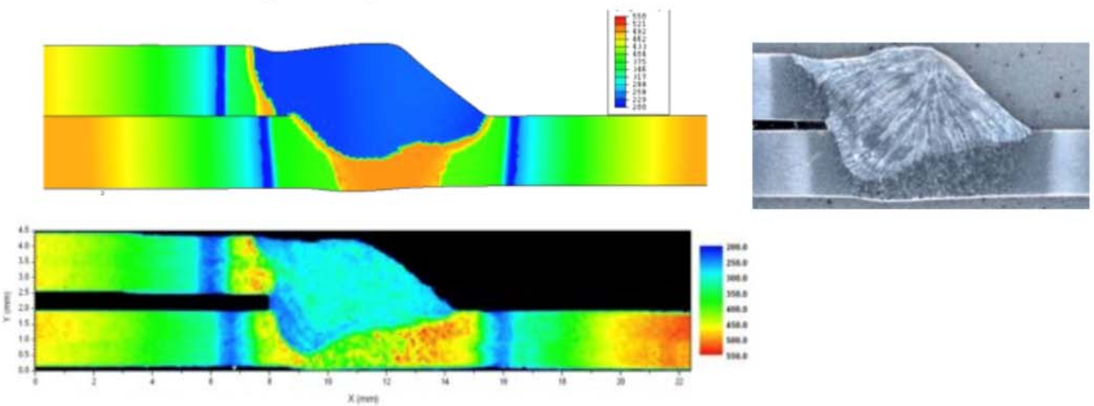
Monte Carlo simulation of grain growth



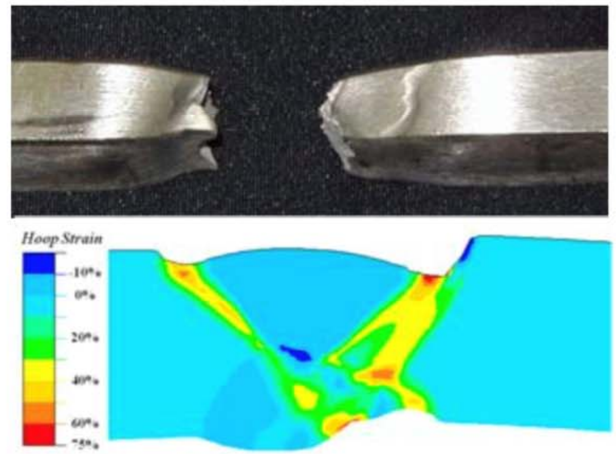
Phase field simulation of solidification



Yield strength gradient simulation in a multi-pass steel weld

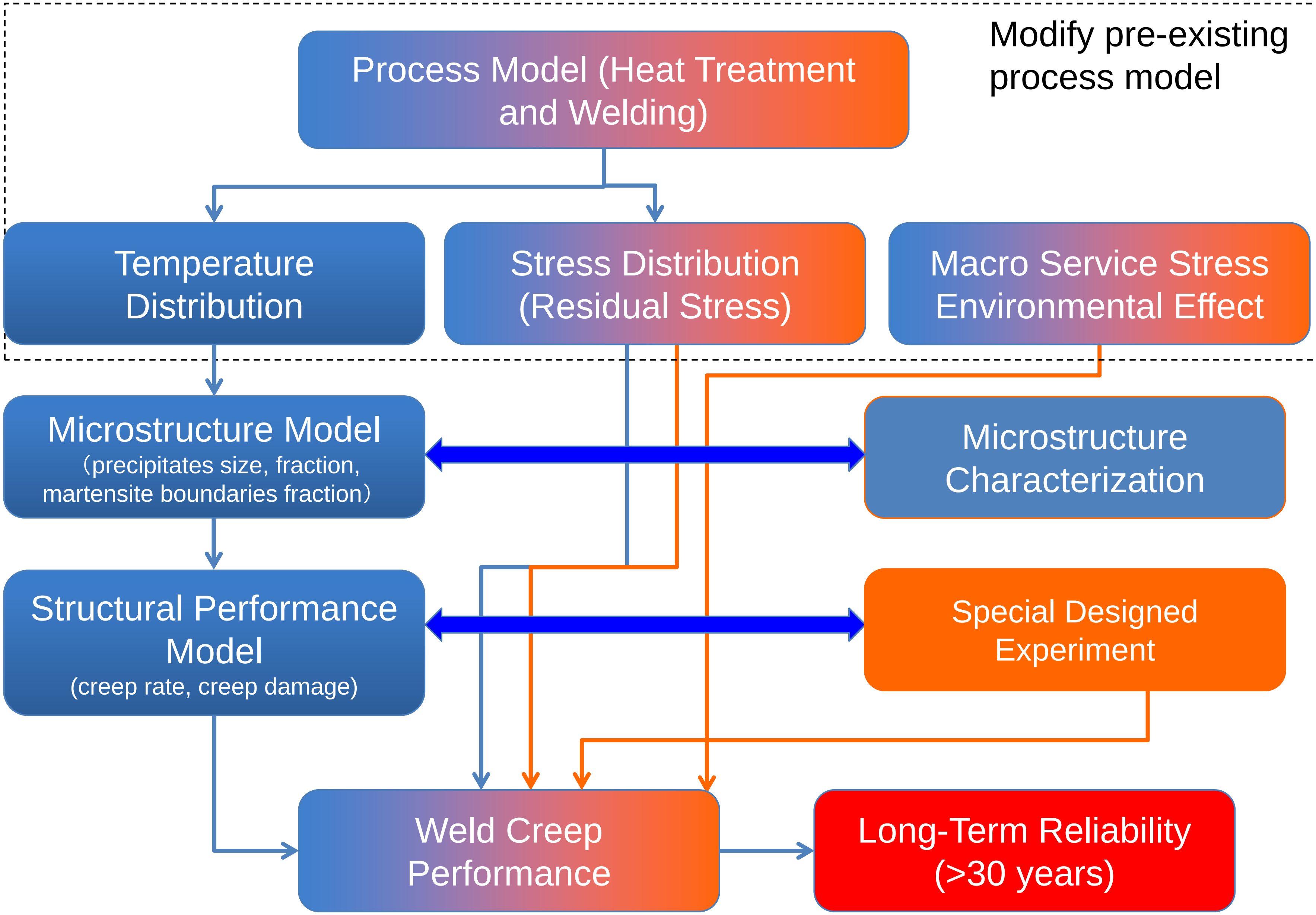


Simulation of HAZ softening of a boron steel top: simulation; bottom: measurement



Performance simulation of a high strength steel weld

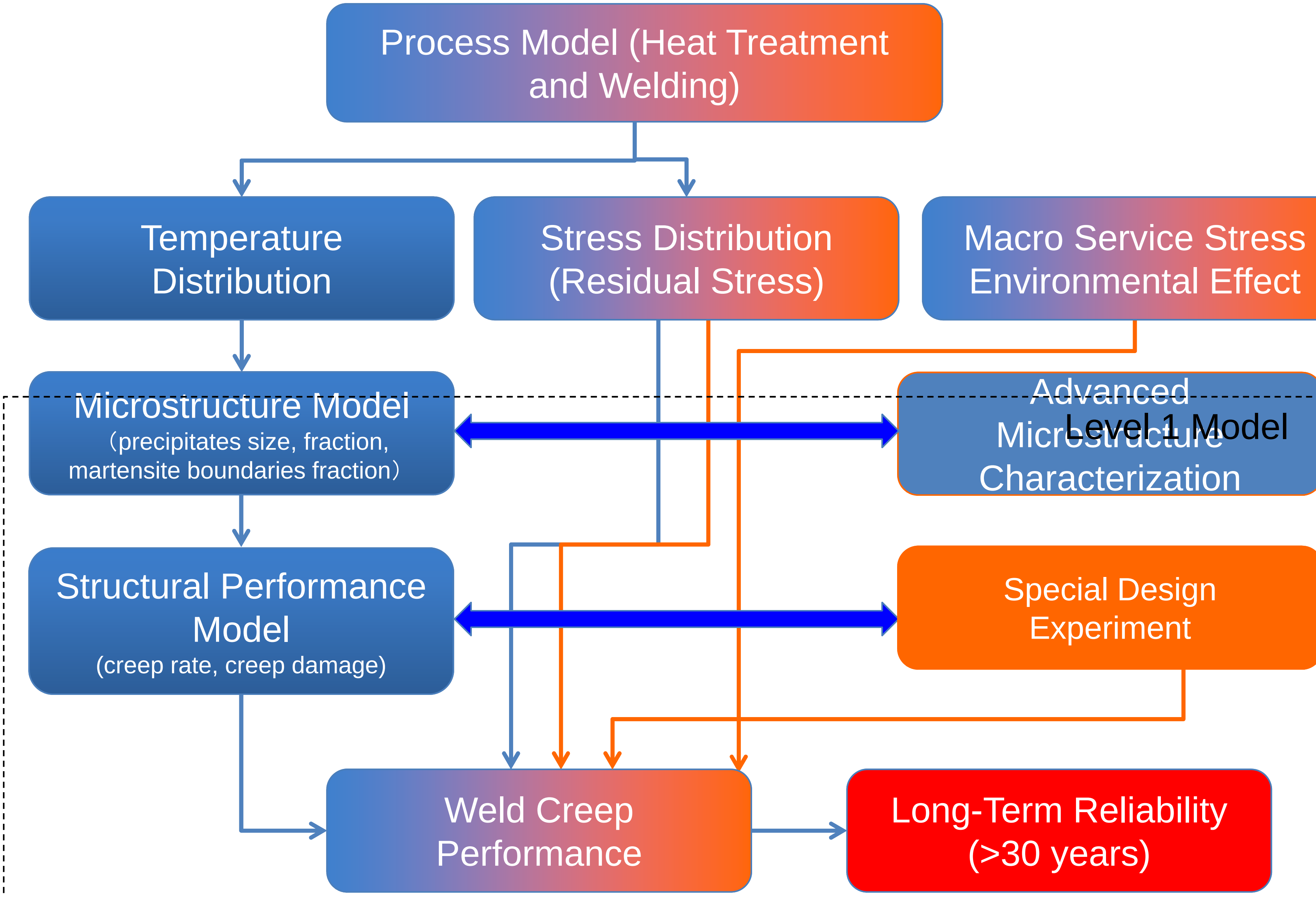
Integrated Modeling Approach for Weld Creep Performance



Model Needs Integrated Multi-scale Modeling Techniques

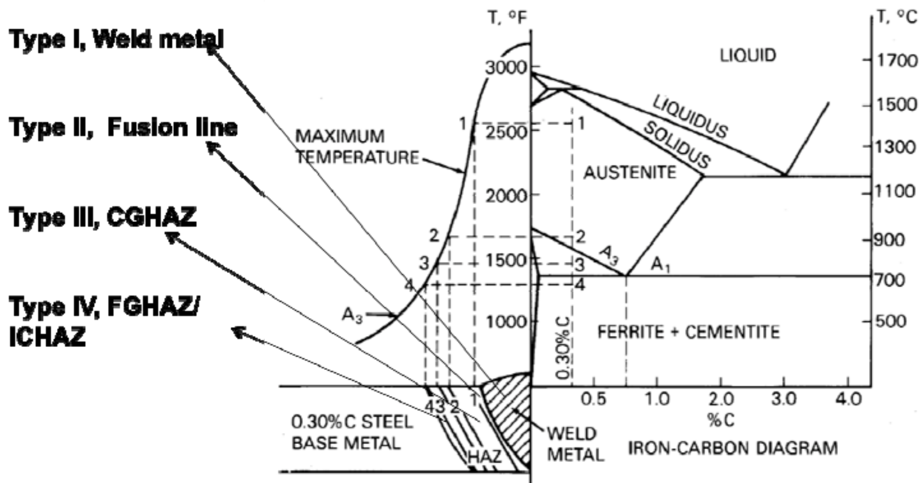
- Need to Integrate multi-physics and multi-scale weld modeling framework for welding process and structural performance simulations
- Some mechanisms and theories are still not clear and under development
- Materials properties need to be measured as model input or for model validation. It involves significant amount of experimental works.
- Is there a quick way to access weld performance?

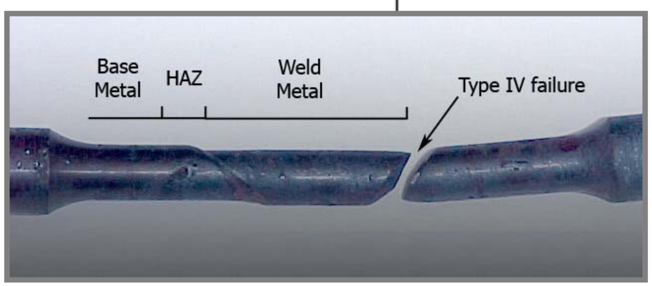
Integrated Modeling Approach



Level 1 Model Overview

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



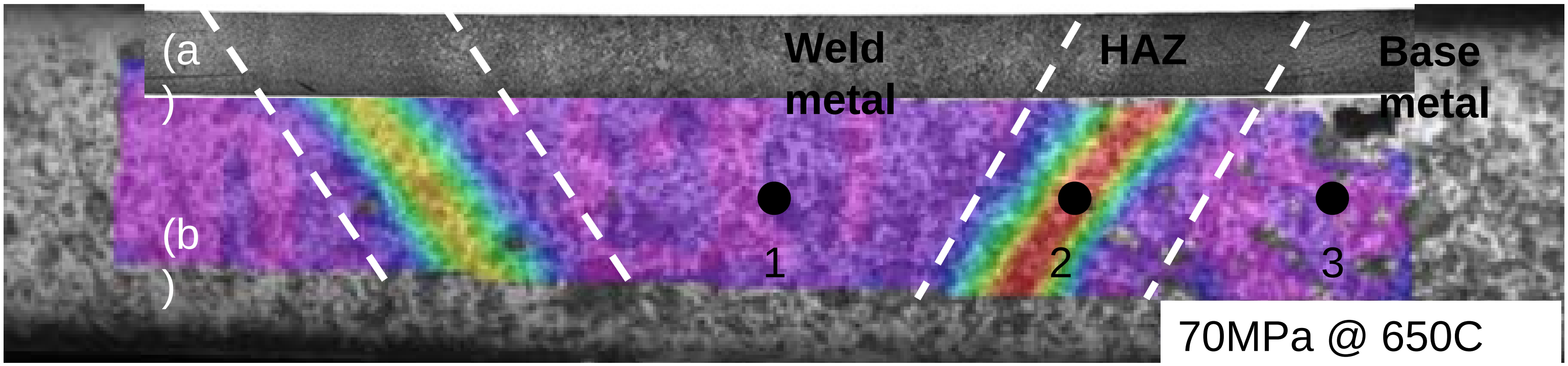


Weld Joint Strength Reduction Factors (WSRF = σ_{weld} / $\sigma_{base\ metal}$) for CSFE steels can be as low as 0.5 at ~600ºC.

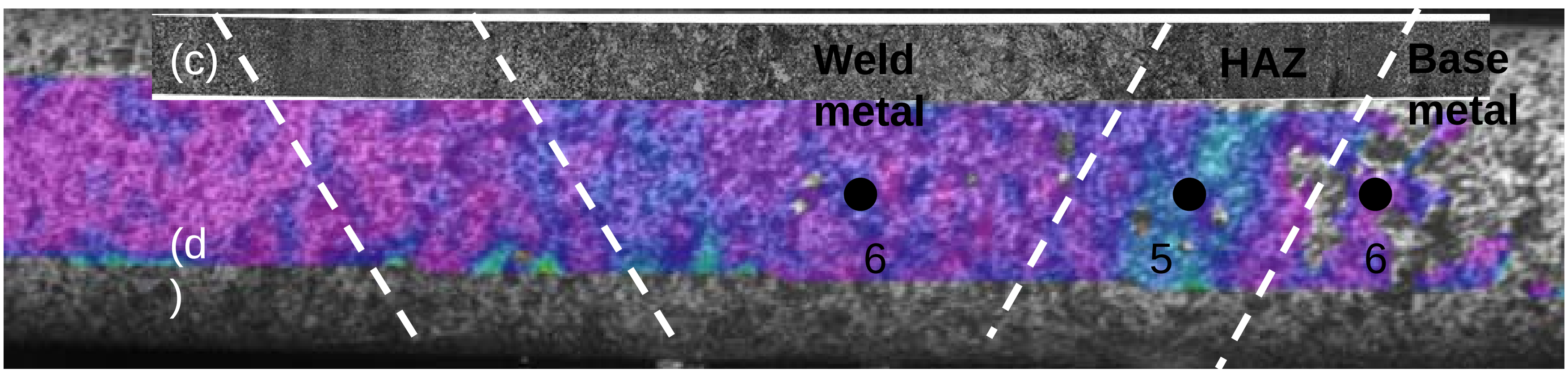
- Digital Image Correlation (DIC) based mechanical properties measurement
- High temperature stress-strain, Young's modulus
- High temperature Creep strain evolution
- Measured properties or behavior can be fitted to constitutive equations or used as direct input in finite element models.

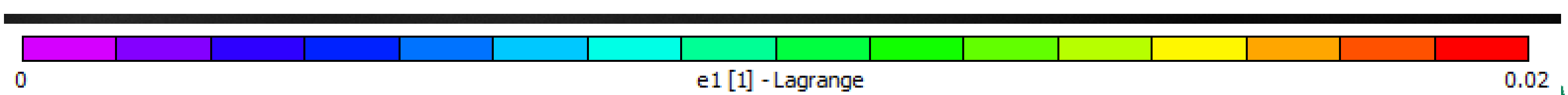
Creep Strain Distribution after 90 Hours

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

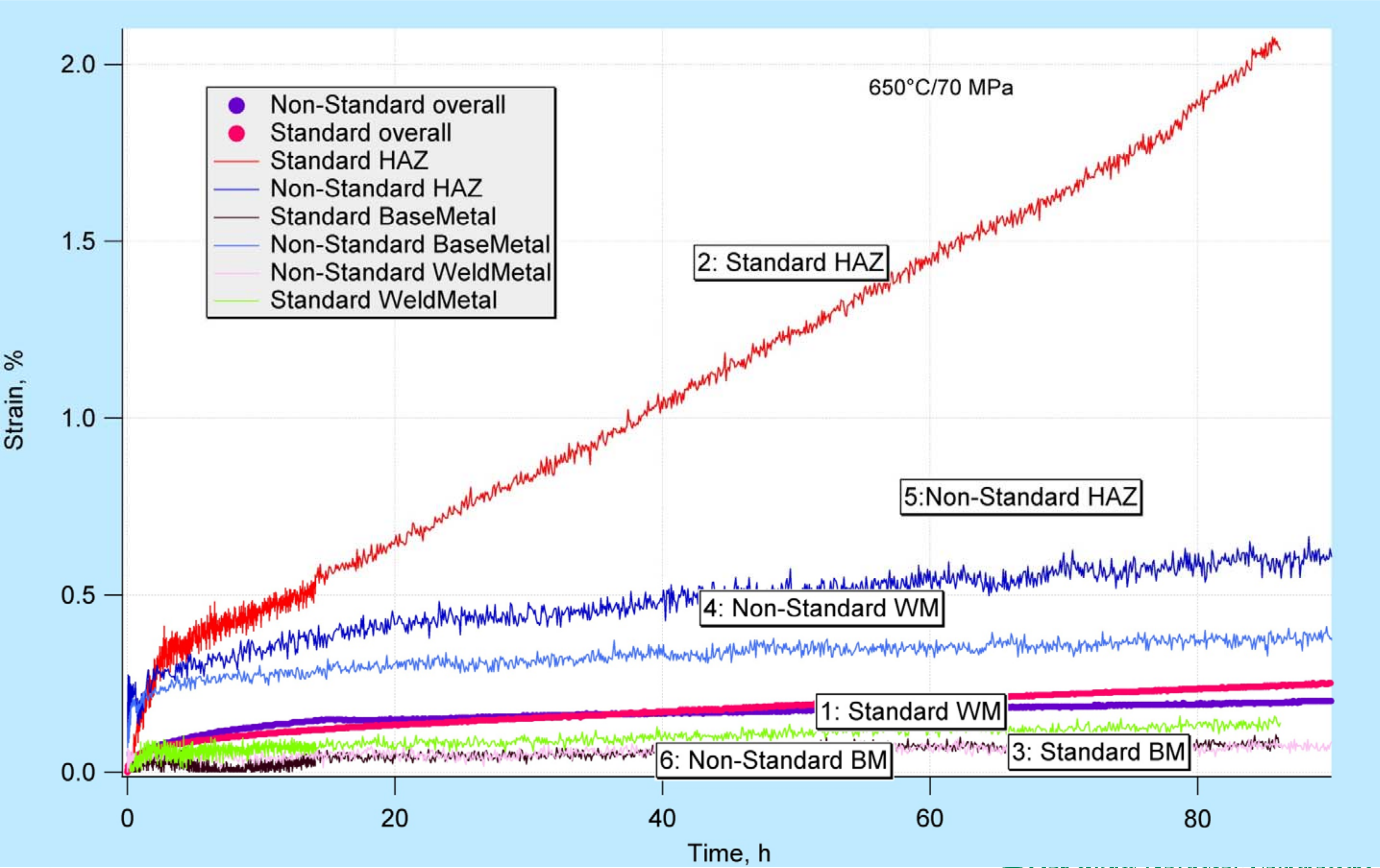


Modified heat treatment (1040/650/760), expected creep life:~2500h

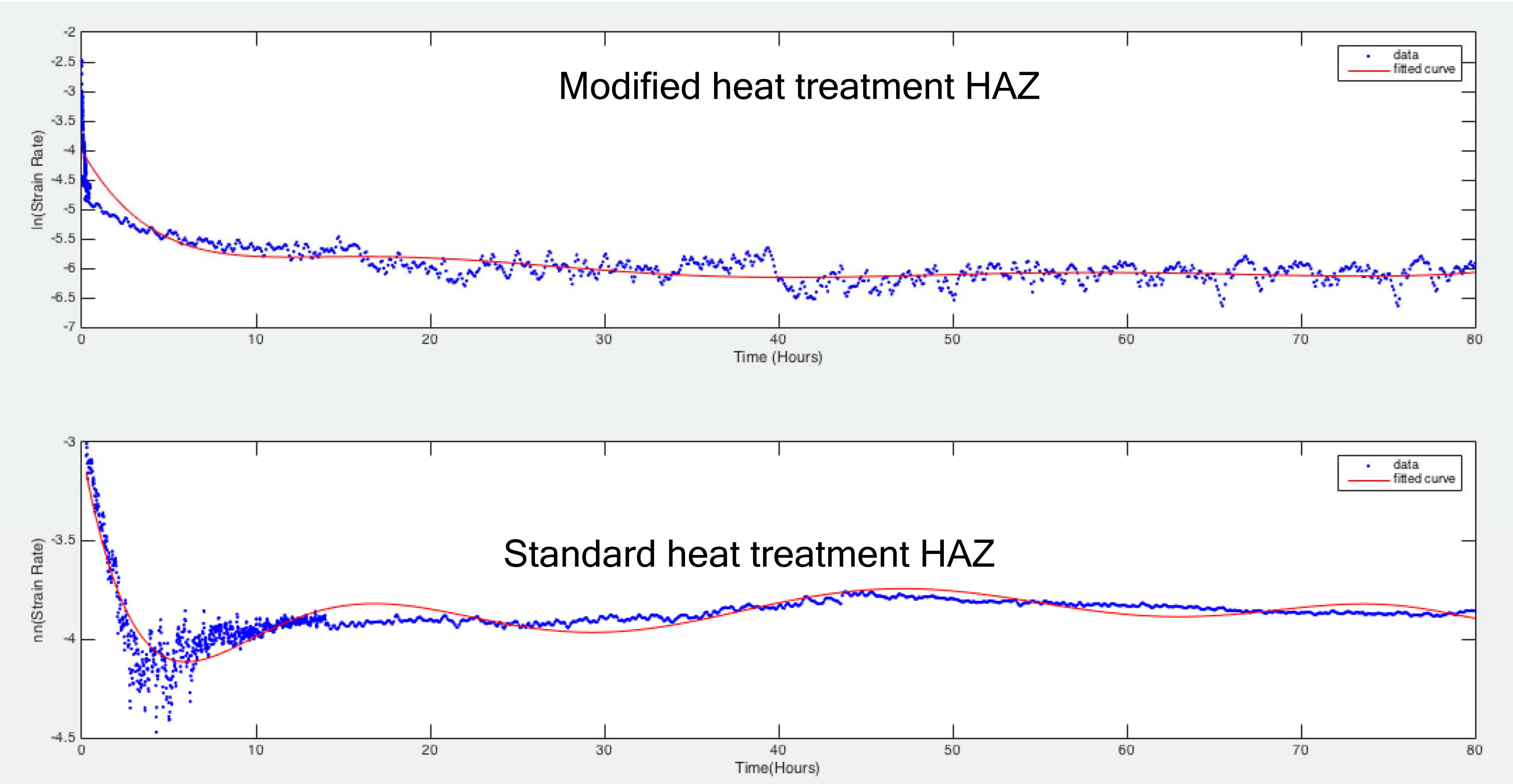




Creep Strain Evolution in Different Regions



Polynomial curve fitting



Will evaluate other continuum creep models, including MPC Omega, Theta, and Sin-Hyperbolic Models

FEA model

- Initial feasibly demonstration of ICWE model to capture local creep deformation and failure in a representative cross weld tensile specimen

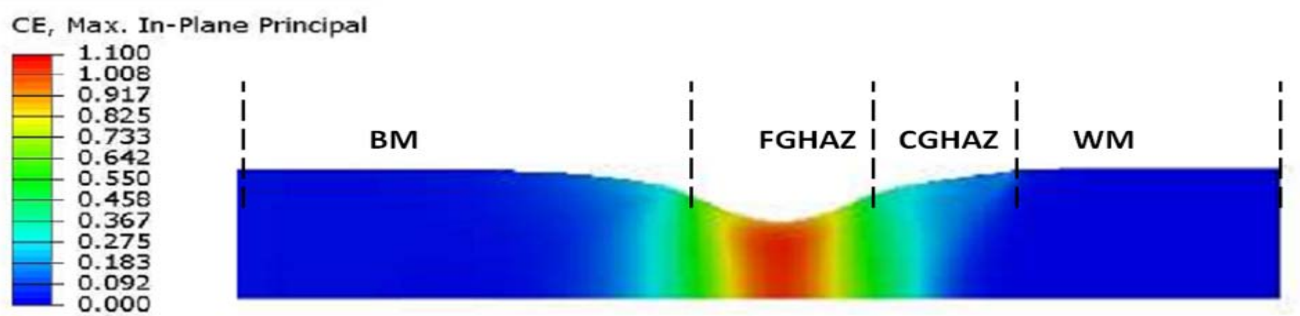
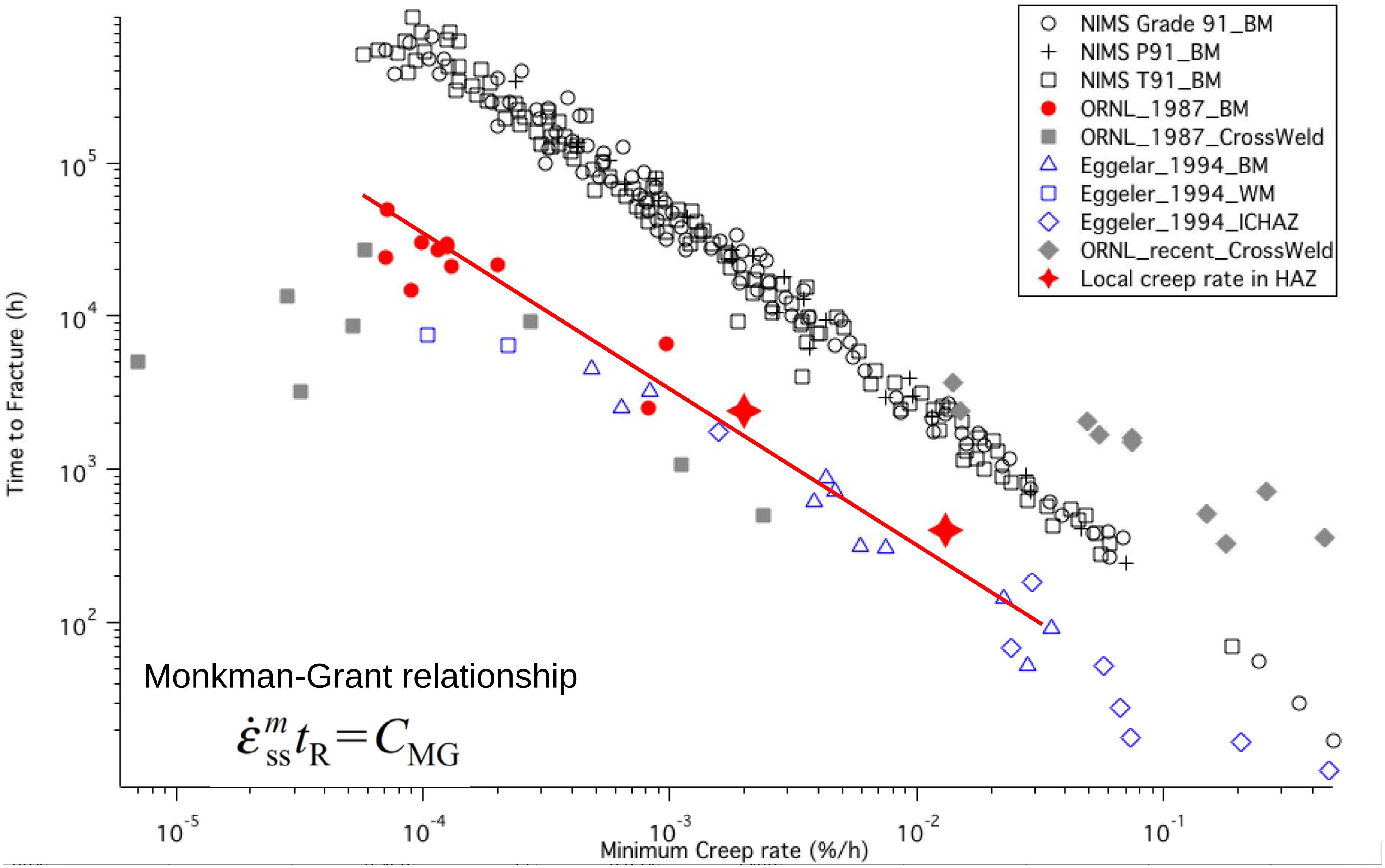


Figure 1. Maximum in-plane creep strain in a cross-weld specimen after 13000 hours creep. (CE is in-plane principal creep strain)

- Further develop and refine the creep testing technique. Design new sample geometry for creep-microstructure correlation.

Minimum Creep Rate in Cross-Weld Creep Testing

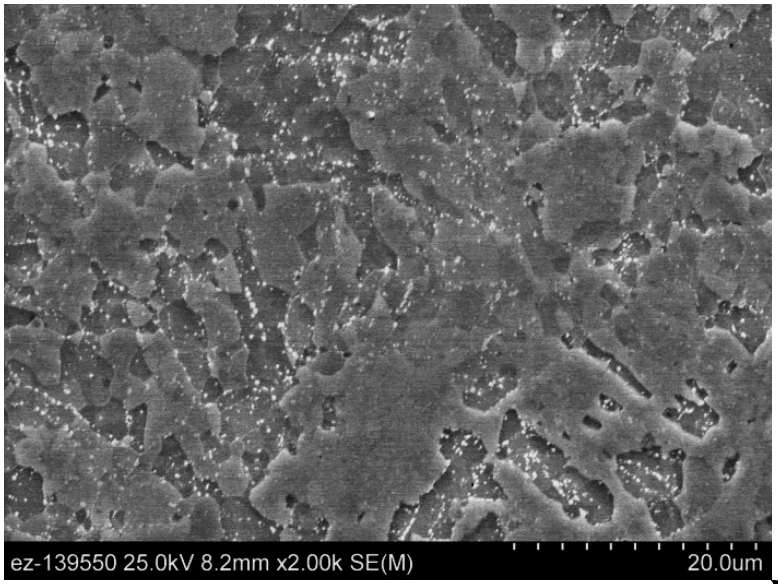


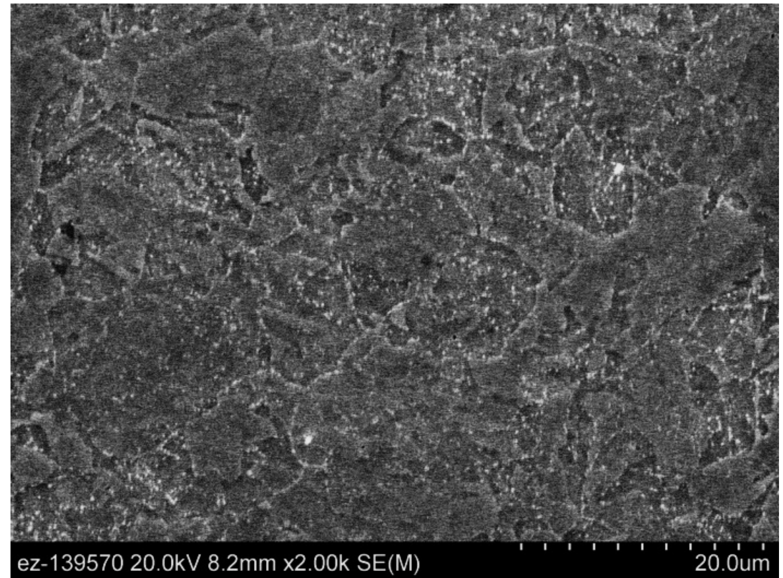
$$\dot{\varepsilon}_{ss}^{m} t_R = C_{MG}$$

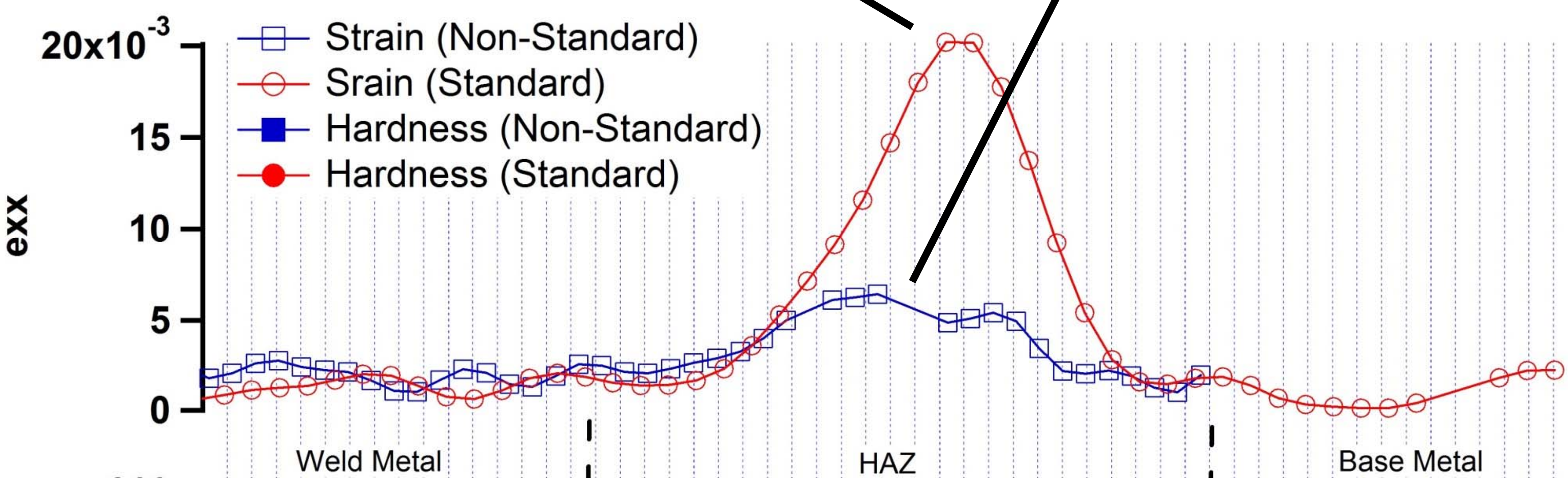
Level 1 Model Summary

- Level 1 model is based on experimental data and for weld performance assessment. It is more engineering approach than scientific approach.
- Measured local minimum creep rate can be used to predict creep life.
- A Long-term weld creep model should consider the fundamentals of creep deformation, damage and failure and should be microstructure-based.
- Level 2 model will be developed considering microstructure evolution and creep deformation mechanism.

Strain-Microstructure Correlation

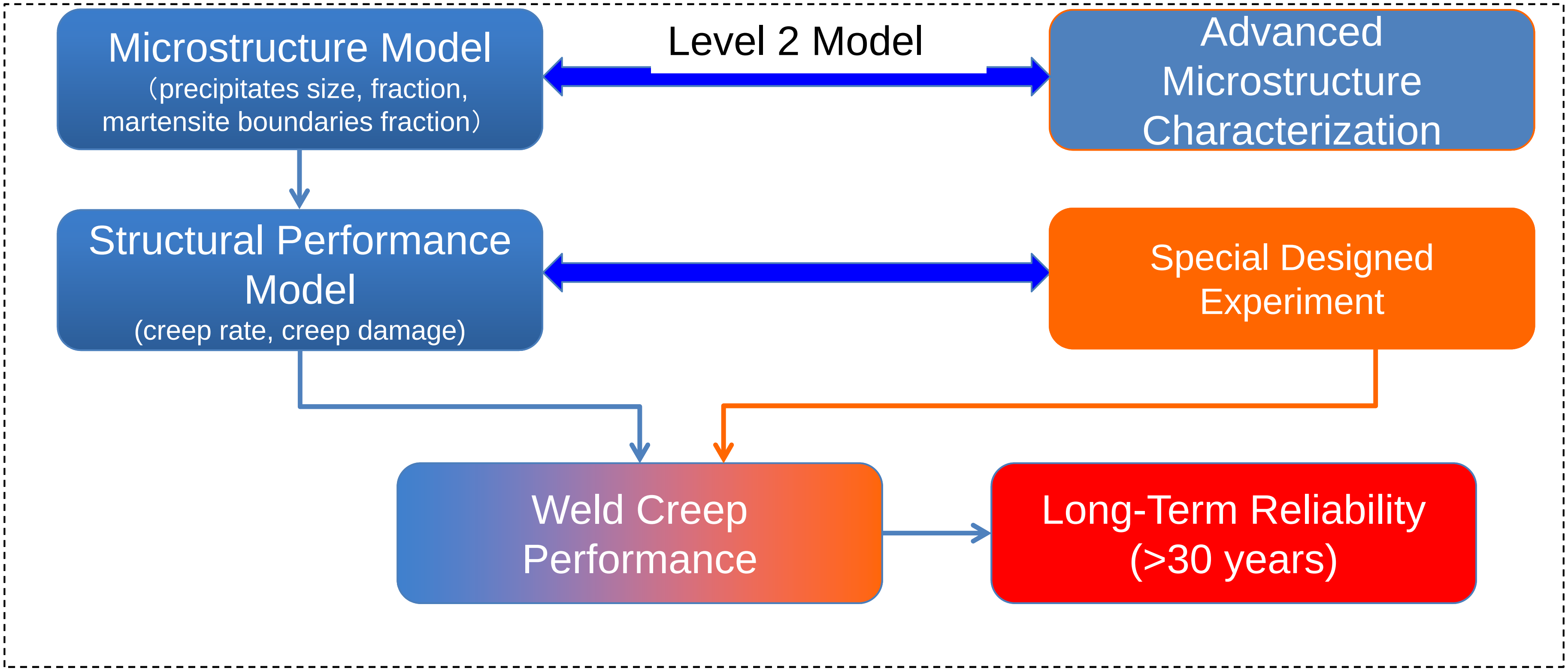






Coarse carbides in “standard” weld and fine carbides in “modified” weld

Level 2 Model Overviews

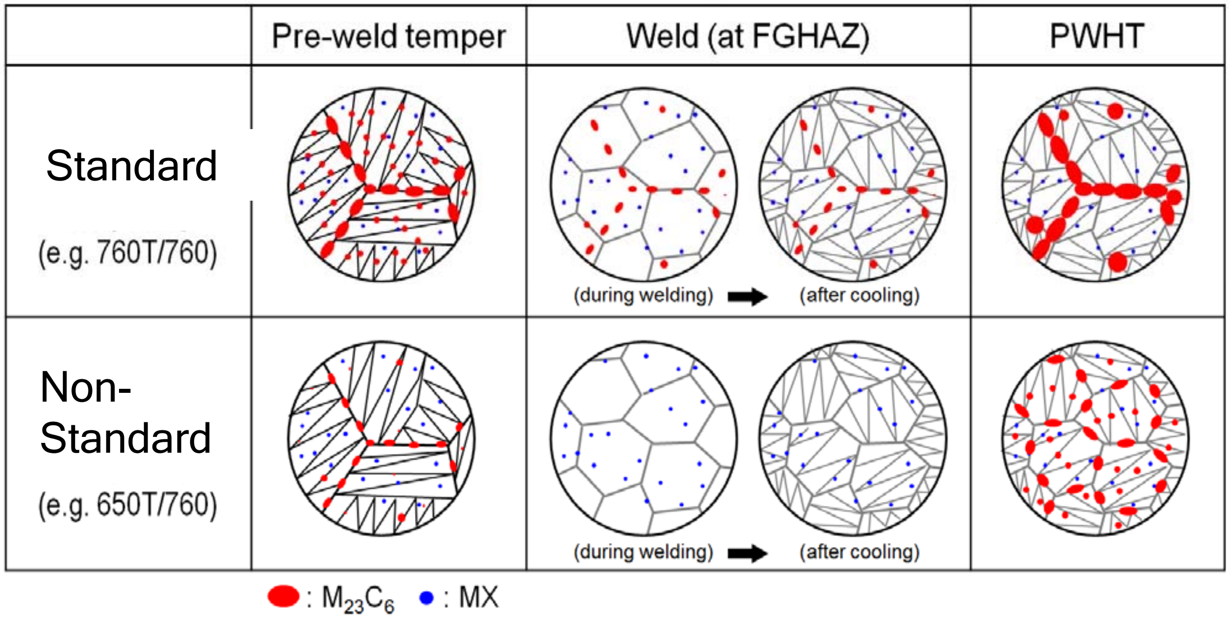


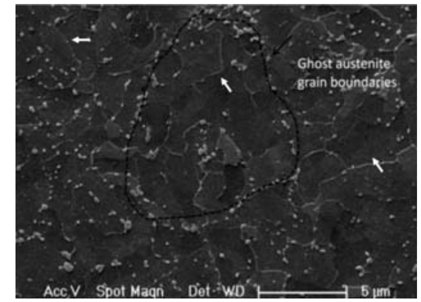
What are the key microstructure features for creep deformation?

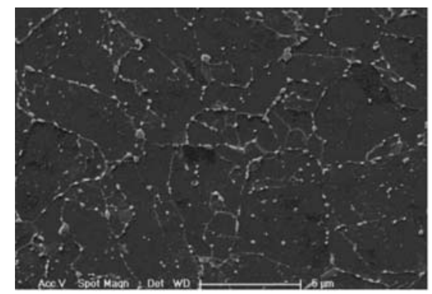
How does these key features affect creep properties?

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.

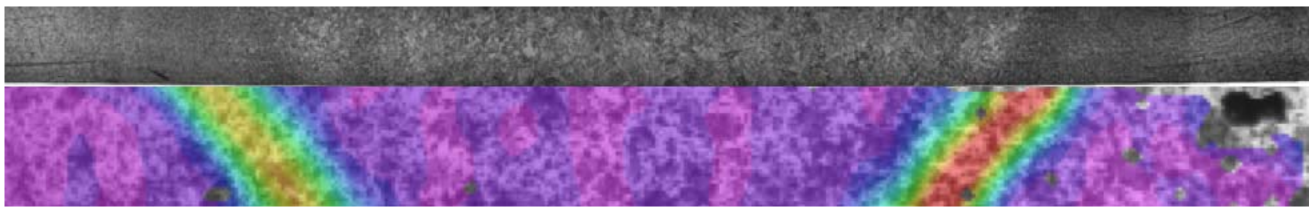
Carbide size, distribution, coarsening kinetics are very important microstructure features.

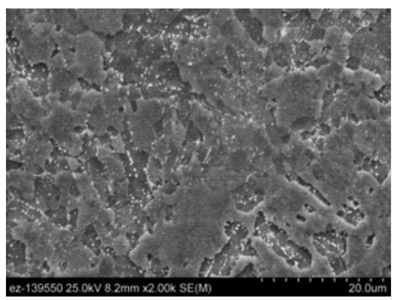
Microstructure gradient (carbides, martensite substructure size) is also important for weldments

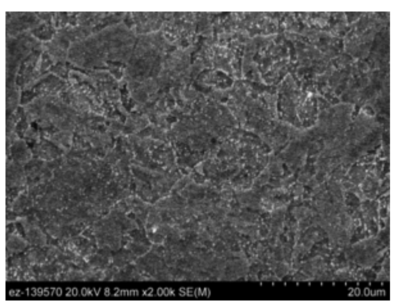
Structural Performance Model Needs to Consider Both Power-Law Creep and Coble Creep

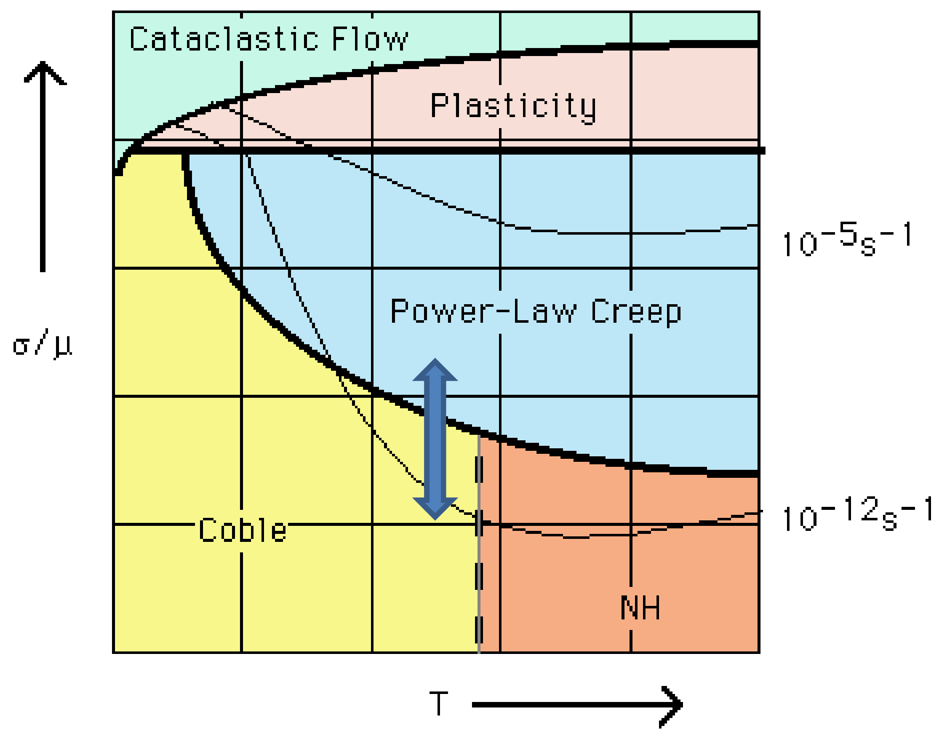
Microstructure Model
（precipitates size, fraction, martensite boundaries fraction）

Structural Performance Model
(creep rate, creep damage)



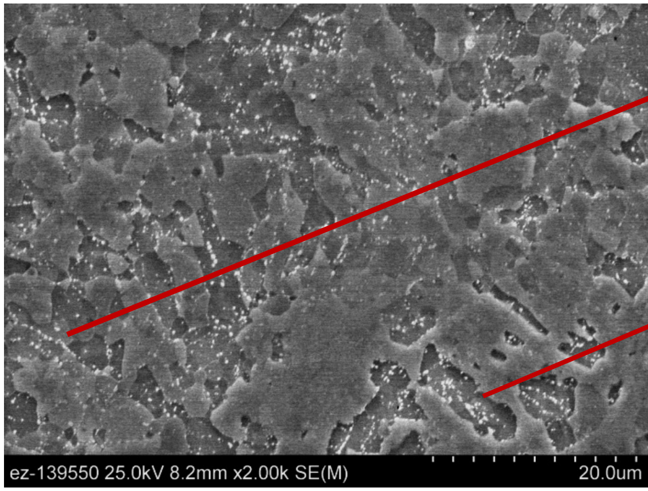






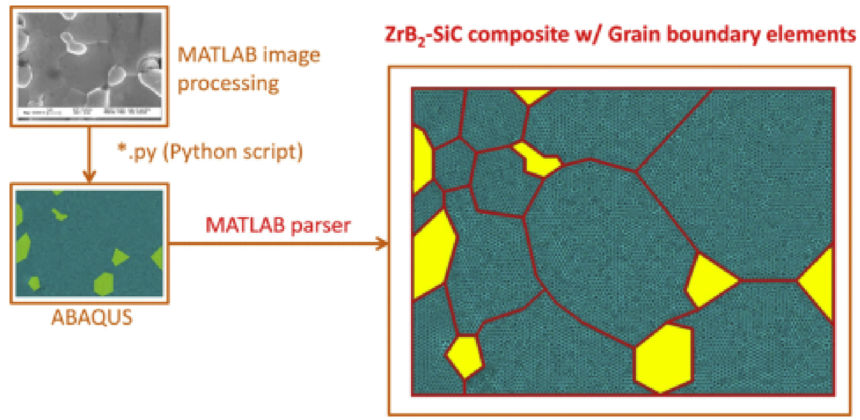
0.1mm deformation mechanism map

Representative Volume Element Model



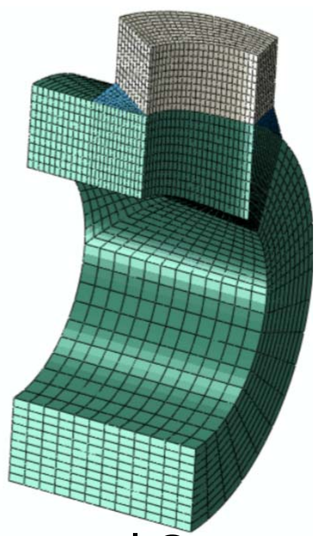
Coble Creep applied at grain boundaries

Power law creep applied at grain interior (including precipitate strengthening)

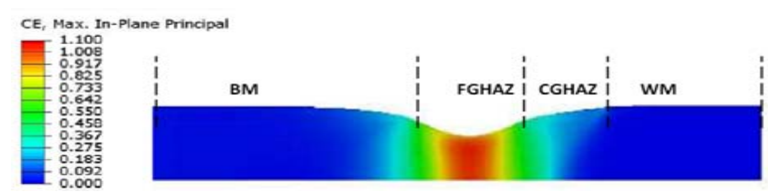


Constitutive creep law obtained from RVE model

Coupon level

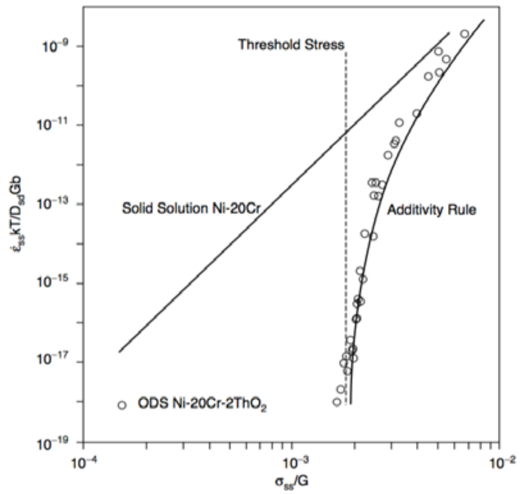


Structural Component

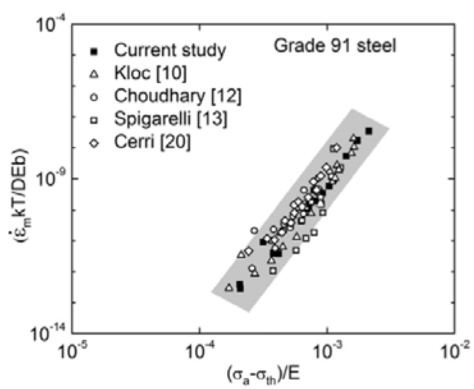


Power Law Creep and Coble Creep

Power Law Creep of Alloy with Secondary Phase



$$\frac{\dot{\varepsilon}_{\mathrm{m}} kT}{DE_{\mathrm{b}}} = A_{D_{\mathrm{is}}} \left(\frac{\sigma_{\mathrm{a}} - \sigma_{\mathrm{th}}}{E} \right)^{n},$$



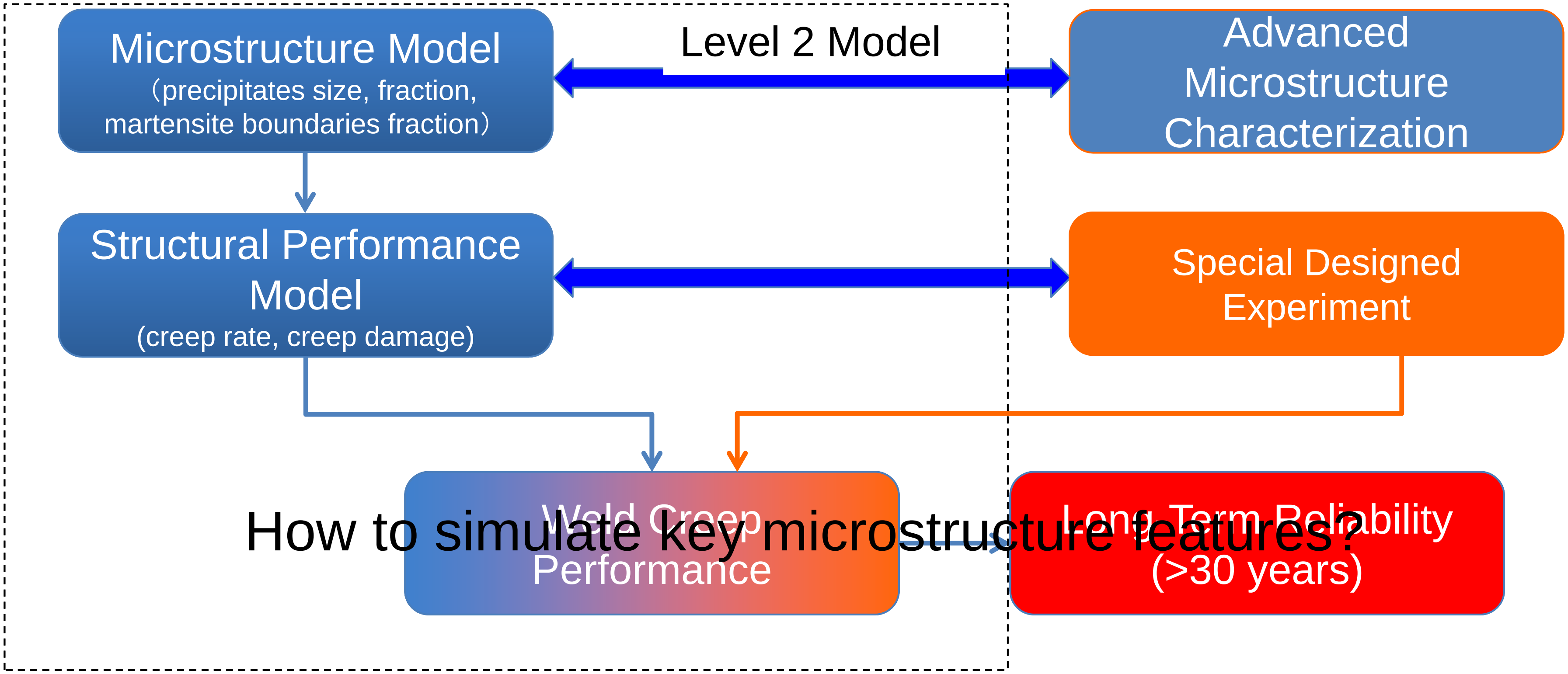
Coble creep

$$\dot{\varepsilon}_{Coble} = \frac{\alpha \delta D_{gb} \sigma \Omega}{kTd^{3}}$$

Easier to be activated and grain size dependent

Both mechanism contribute to creep deformation of Grade 91 steels

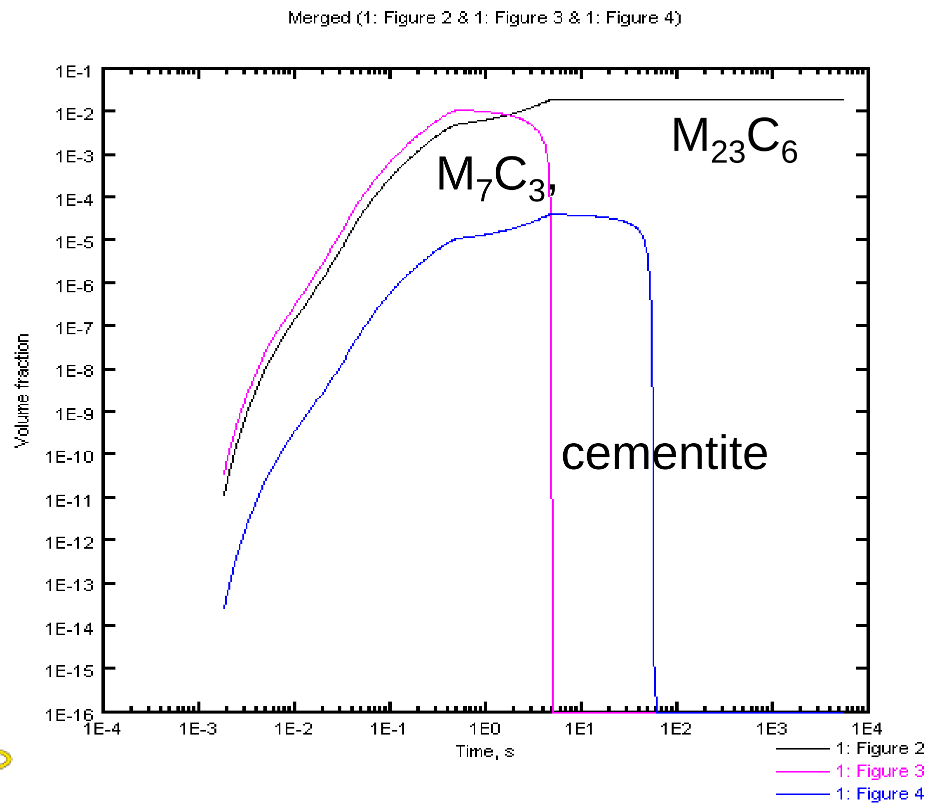
Level 2 Model Overviews



How to simulate key microstructure features?

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

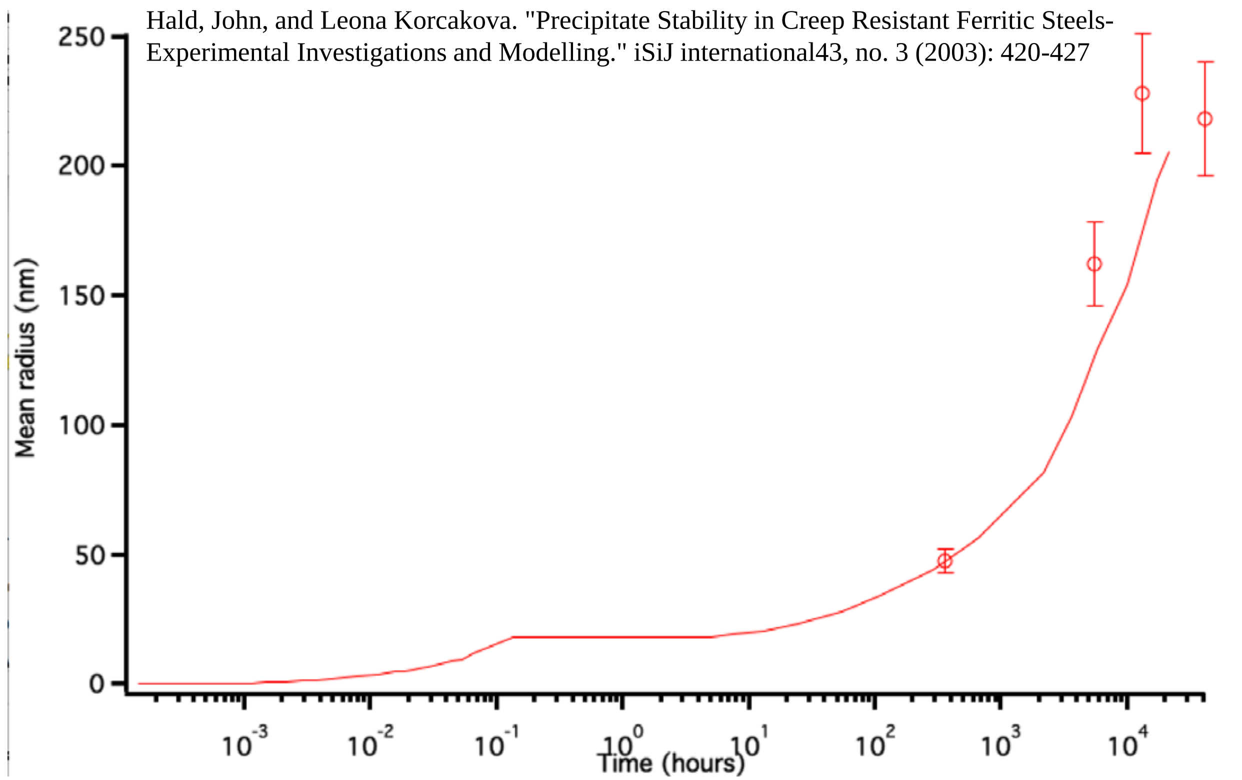


- Initial simulation of P91 tempering.
- 9Cr-1Mo-0.1C BCC matrix and 3 secondary phases, M_7C_3, $M_{23}C_6$ and cementite were considered.
- Temper at 760C for 1.5 hours after 1 hour normalizing at 1050C.
- The precipitation sequence shows agreement with the simulation from A. Schneider and G. Inden.

Schneider, A., and G. Inden. "Simulation of the kinetics of precipitation reactions in ferritic steels." Acta materialia 53, no. 2 (2005): 519-531.

Simulation of Carbide Coarsening Process Shows Good Agreement with Experimental

- 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.



Plan to use the same modeling approach to predict carbide in weldments.

Microstructure Model Validation Using Synchrotron X-Ray

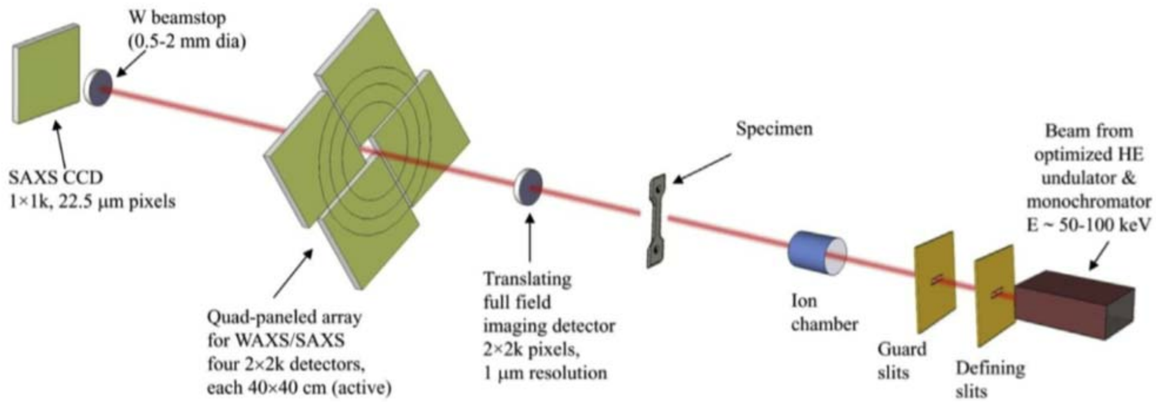
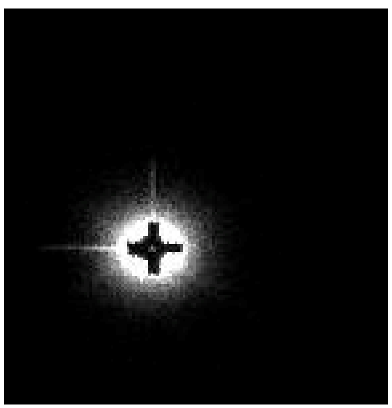
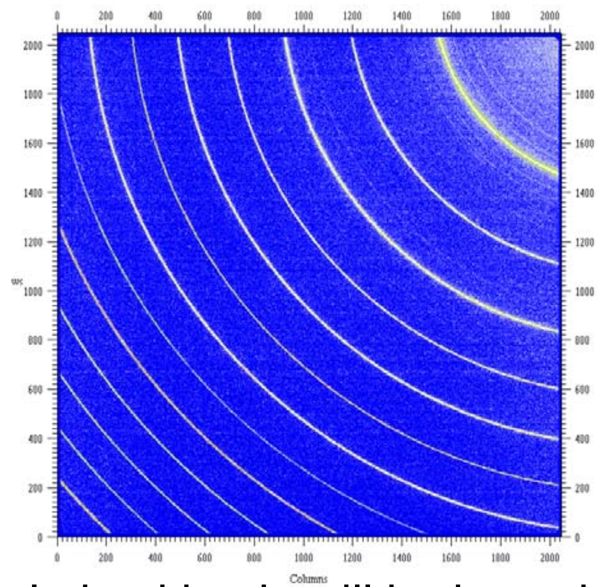


Fig. 1. Schematic layout of Beamline 1-ID at the Advanced Photon Source.

SAXS





$M_{23}C_6$ 420

Ferrite 011

Precipitate growth, coarsening and dissolution kinetic will be investigated.

Conclusions

Level 1 model:

- Special designed creep experiment could capture local creep deformation in a representative cross weld tensile.
- Local creep strain rate can be used in creep deformation model.
- Level 2 model:
- Established ICWE modeling framework Grade 91 Steel Weld Creep Performance
- Making progress on structural performance model.
- Precipitation simulation showed good agreement with literature results.

Q & A