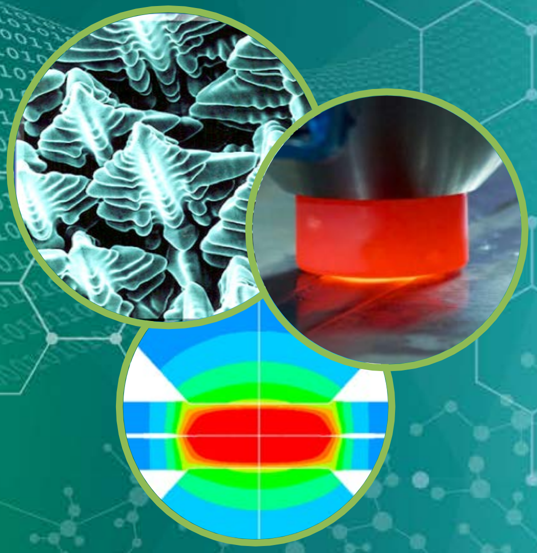
Microstructure and mechanism based lifetime predictions in SRC of SS347 weldment under complex thermomechanical conditions



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Dr. Vito Cedro, DOE Cross-Cutting Materials R&D Program
Dr. Jorge Penso, Shell (via Ma2JIC, an NSF I/UCRC program)

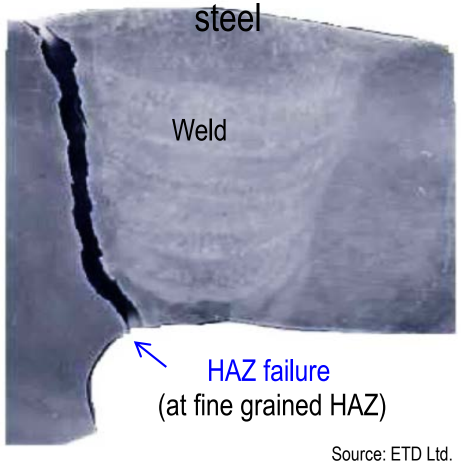
Oak Ridge National Laboratory

The University of Tennessee Knoxville

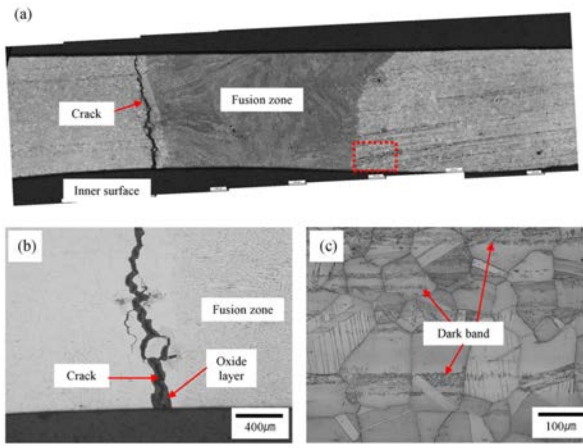
ICWE Based Weld Life Prediction Modeling Tool at ORNL/UTK

- Address the critical **performance reduction in weldment** of creep-resistant steels and alloys .
  - Develop, validate, and apply an Integrated Computational Welding Engineering (ICWE) prediction tool for weld deformation and failure prediction in creep resistance alloy welds
    - Target practical engineering modeling tool for weld creep performance (**Level 1 Model**)
    - More fundamental microstructure informed macro-meso scale model (**Level 2 Model**)
  - Develop new testing system and experimental approach necessary to quantify the highly nonuniform deformation and failure in a weldment to validate and refine the models
  - First successfully applied to Type IV cracking of CSEF steels (Grade 91 etc). Now extending to SRxC/SAC/reheat cracking
- Apply the ICWE modeling tool for
  - Welding technology innovations for creep resistance improvement in design and service.
  - Life assessment of existing power plants and scheduling maintenance and repair
- Research sponsored by DOE FE office, EPRI (NE and FE programs) and Shell Oil

Type IV HAZ cracking in a 9-12Cr steel



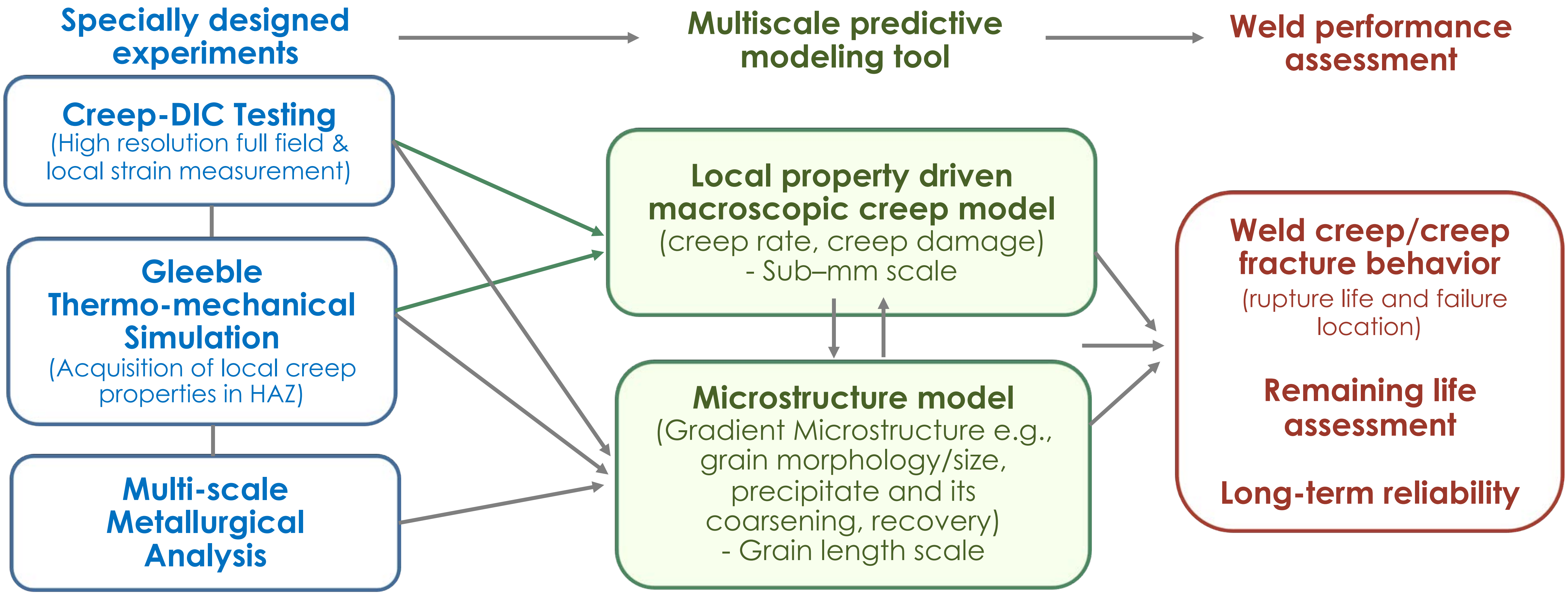
Source: ETD Ltd.



Cracking of 347H weld
(Lee et al, 2015)

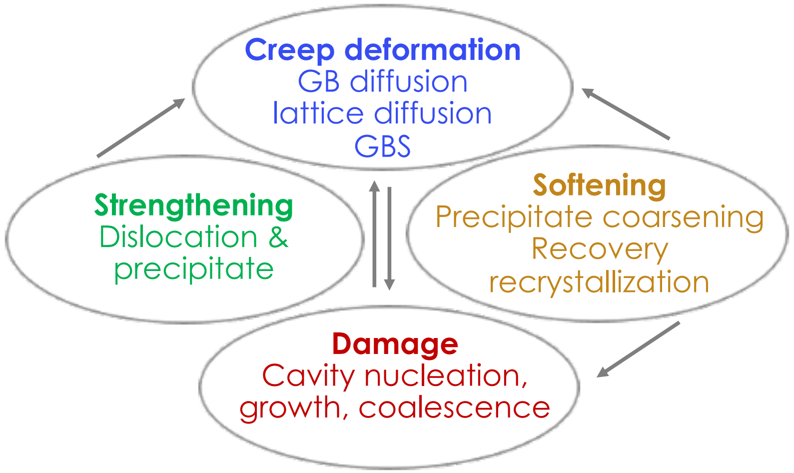
Integrated Approach for Weld Life/Performance Prediction

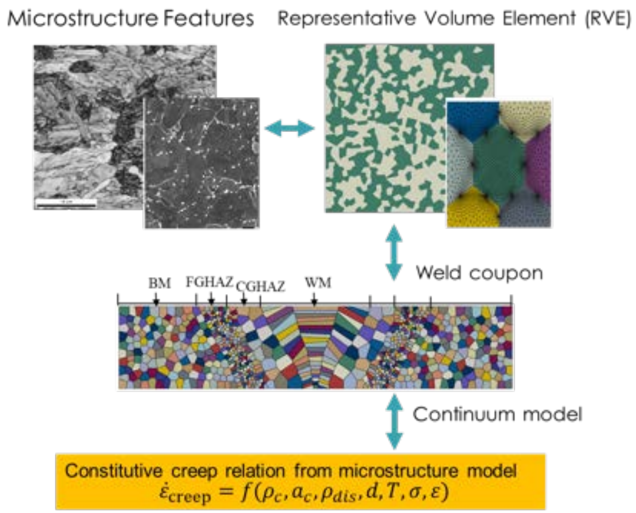
- Developed an integrated experimental and computational welding engineering modeling approach for creep deformation and failure in weldments of Creep Strength Enhanced Ferritic (CSEF) Steels

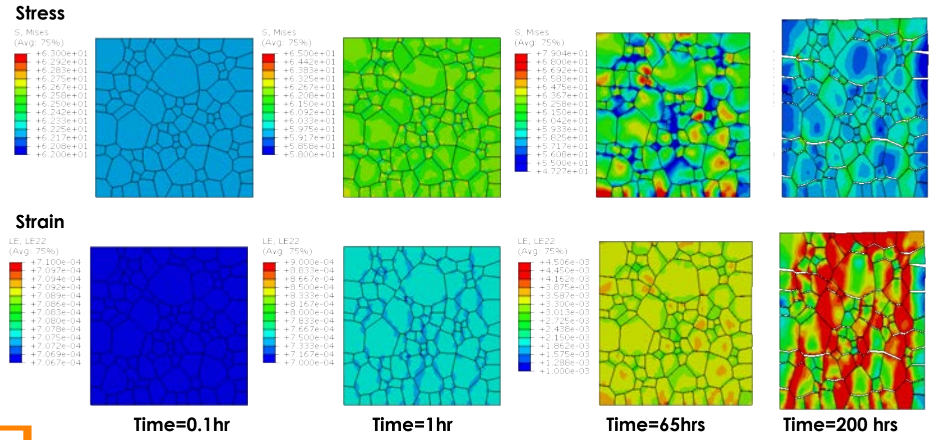


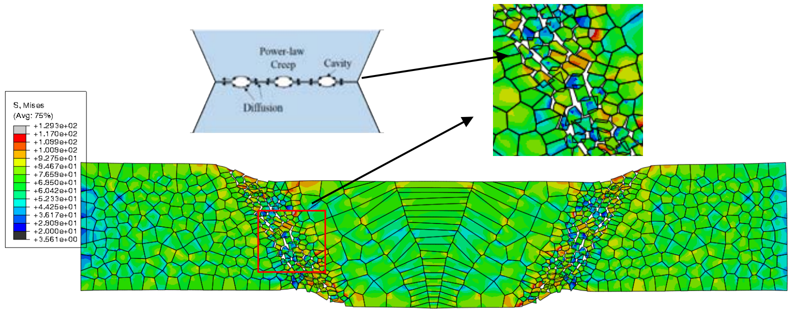
Microstructure informed Level II Model provided the foundation for Level 1 practical engineering modeling tool for creep modeling of large welded structures

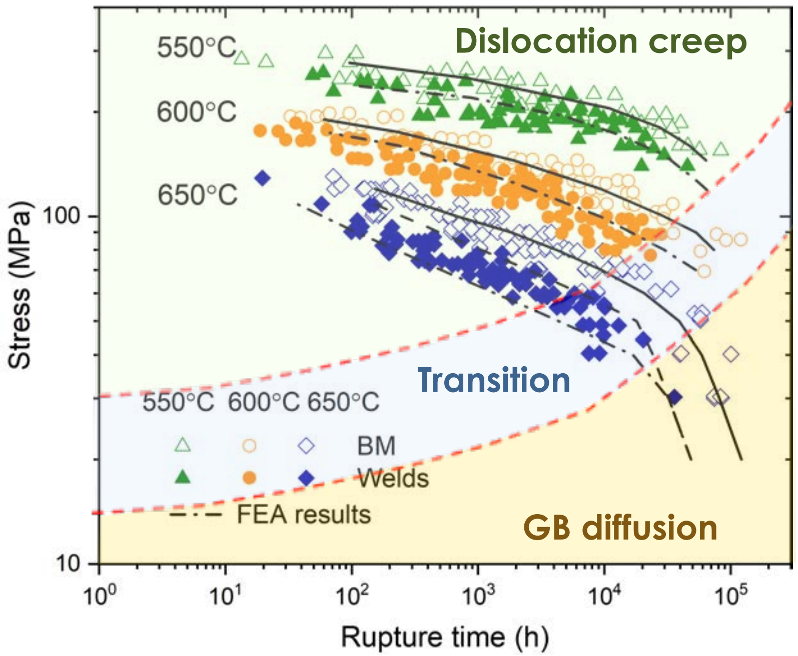
- Leve II Model: A mechanistic constitutive model was developed to account for the effects of microstructure, stress and temperature on the creep deformation and damage mechanisms of high temperature alloy weldments.











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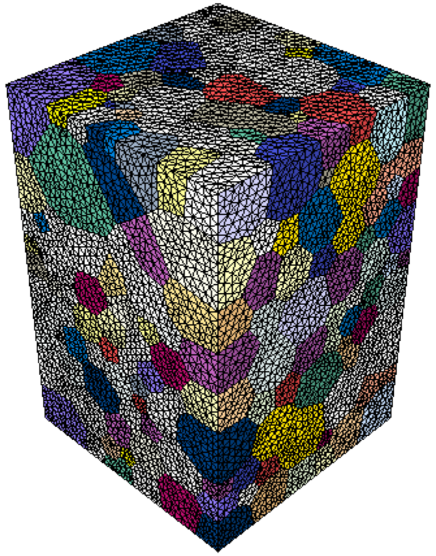
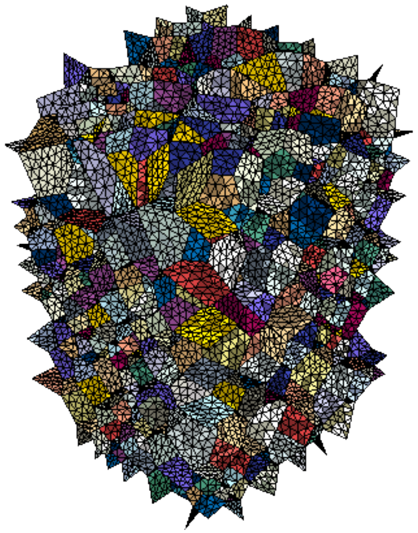
Level II Three Dimensional Model based on crystal plasticity with explicit grain boundary damage

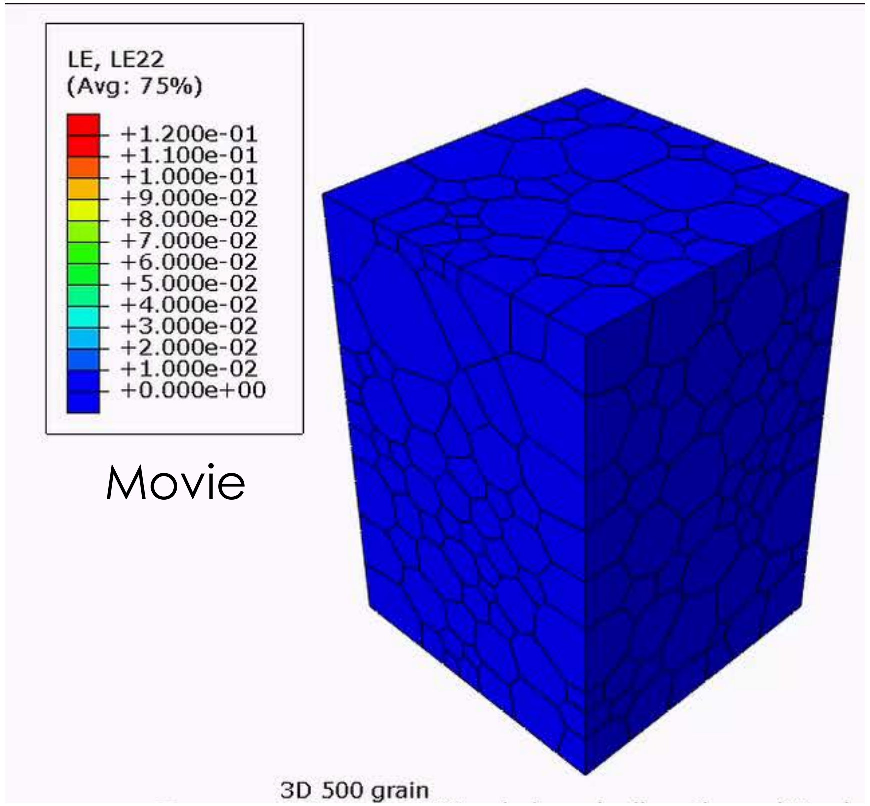
- To obtain more realistic localized and macroscopic deformation of the critical subregions in the weldment.



Model: 500 grains
~ 600,000 elements



Grain boundary
Cohesive element

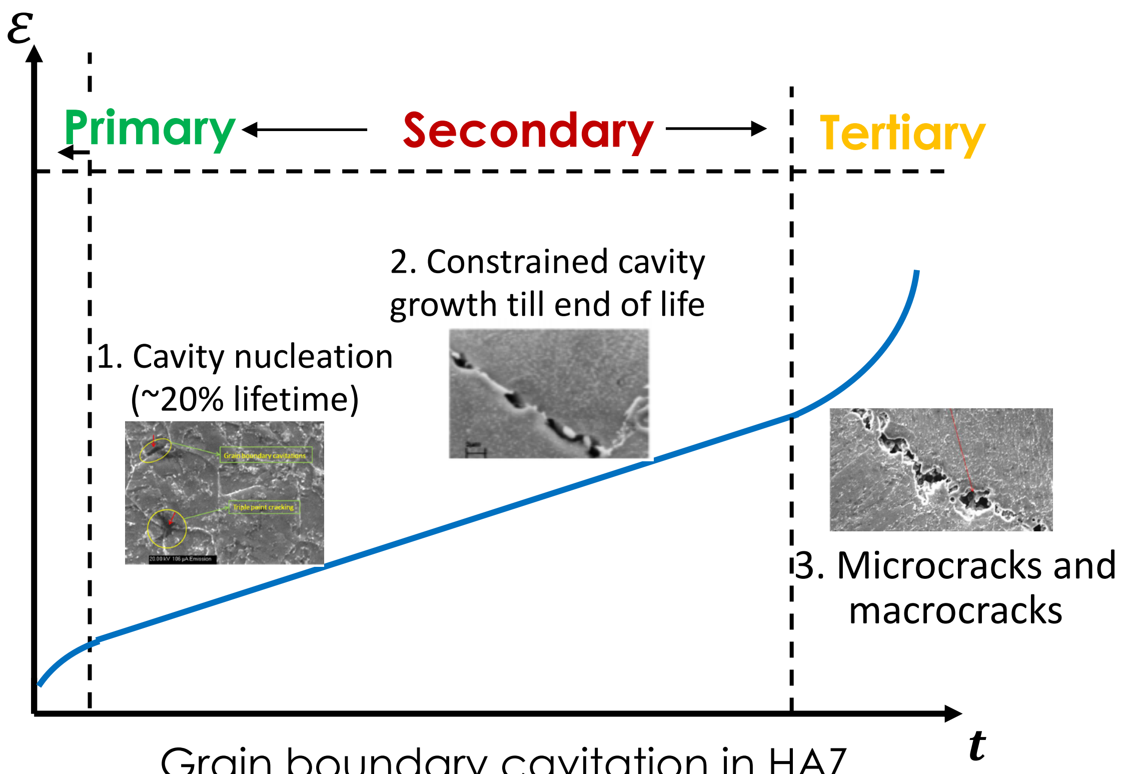


Strain evolution

Level 1 Engineering Predictive Tool: Cavity-evolution based constitutive model

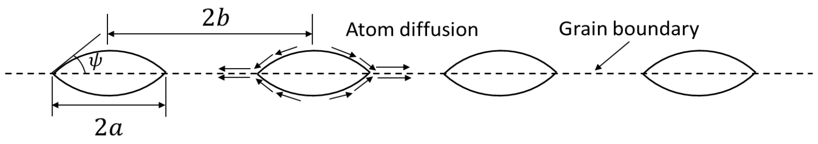
- **Three stages of damage evolution determines the lifetime:**

$$t_f = t_n + t_g + t_p$$



Grain boundary cavitation in HAZ

- **Cavity evolution-based creep model**



- **Cavity nucleation**

Cavitation nucleation rate: $\dot{N} = F_{\mathrm{n}} \left(\frac{\boldsymbol{\sigma}_{\mathrm{I}}}{\Sigma_0}\right)^2 \dot{\varepsilon}_{\mathrm{e}}^{\mathrm{c}} \quad \text{for } \sigma_{\mathrm{I}} > 0$

- **Cavity growth**

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

1. Contribution of GB diffusion:

$$\dot{V}_1 = 4\pi D_{\mathrm{GB}} \frac{\sigma_{\mathrm{I}}}{\ln(1/f) - \frac{1}{2}(3-f)(1-f)}$$

2. Contribution of creep deformation:

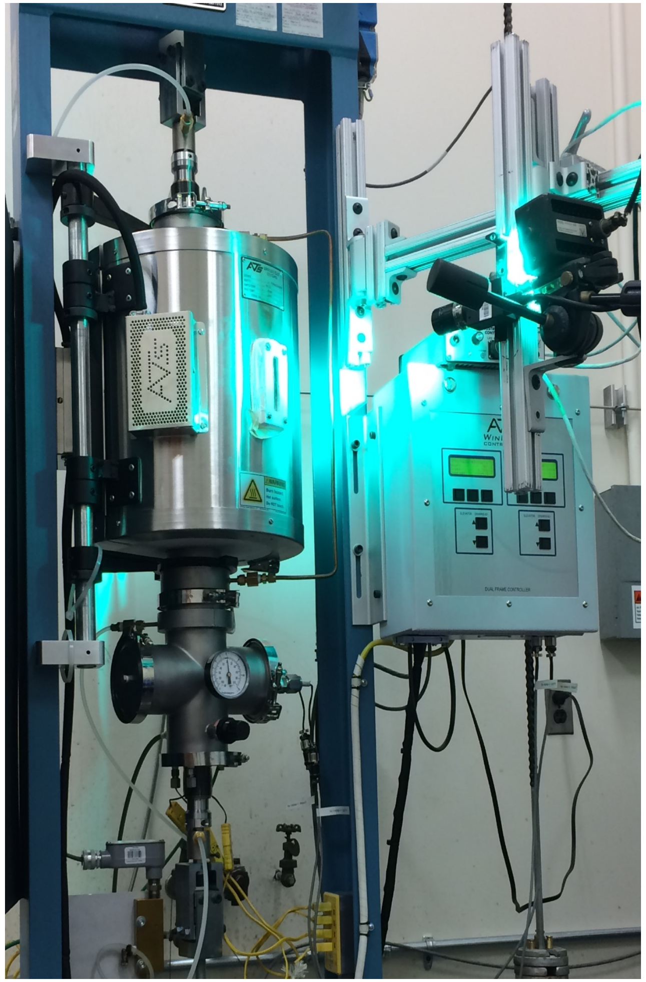
$$\dot{V}_2 = \begin{cases} \pm 2\pi \dot{\varepsilon}_{\mathrm{e}}^{\mathrm{c}} a^3 h(\psi) \left[\alpha_{\mathrm{n}} \left|\frac{\boldsymbol{\sigma}_{\mathbf{m}}}{\boldsymbol{\sigma}_{\mathbf{e}}}\right| + \beta_{\mathrm{n}}\right]^n, & \text{for } \pm \frac{\sigma_{\mathrm{m}}}{\sigma_{\mathrm{e}}} > 1 \\ 2\pi \dot{\varepsilon}_{\mathrm{e}}^{\mathrm{c}} a^3 h(\psi) [\alpha_{\mathrm{n}} + \beta_{\mathrm{n}}]^n \frac{\boldsymbol{\sigma}_{\mathbf{m}}}{\boldsymbol{\sigma}_{\mathbf{e}}}, & \text{for } \left|\frac{\sigma_{\mathrm{m}}}{\sigma_{\mathrm{e}}}\right| < 1 \end{cases}$$

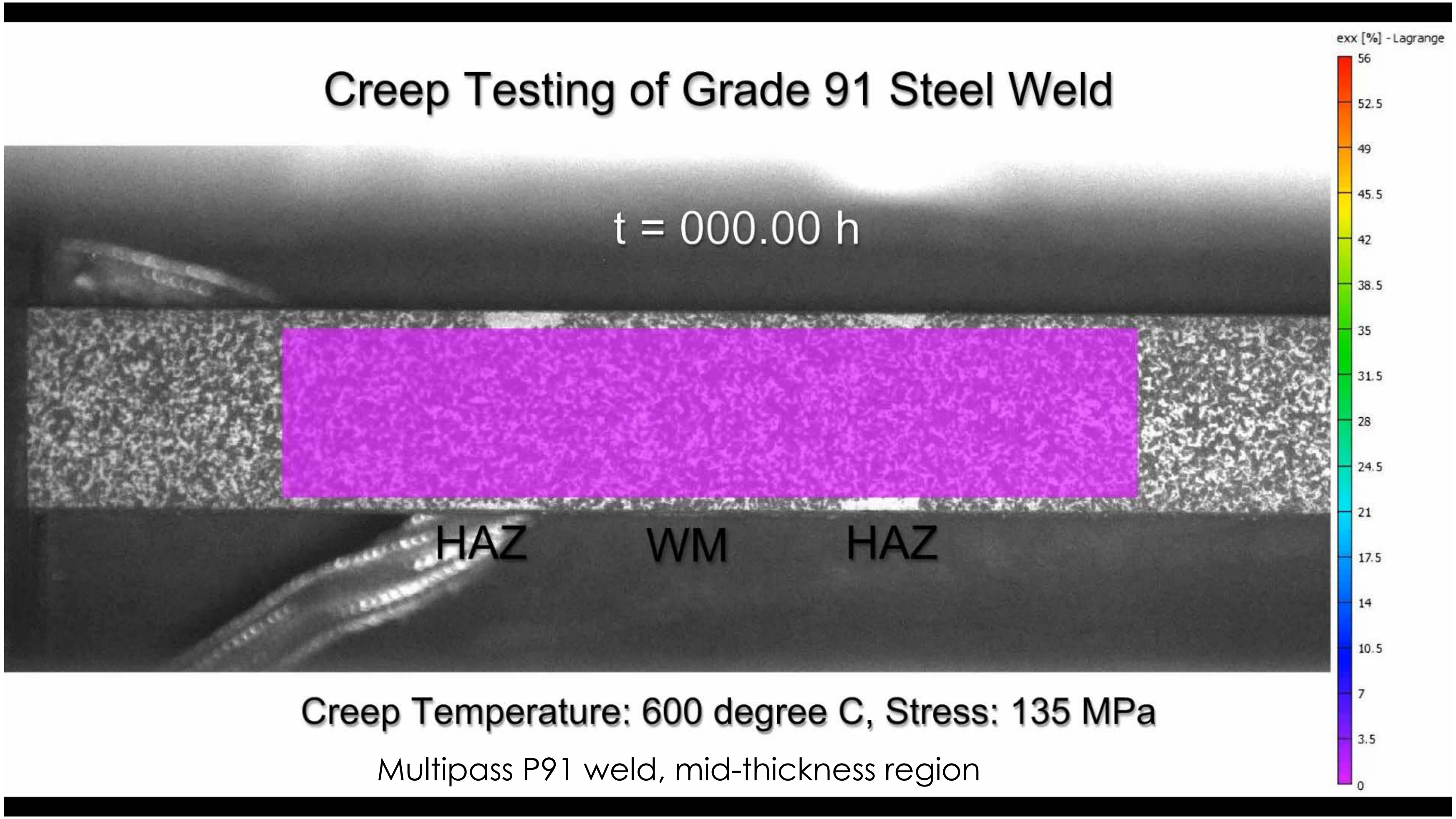
- **Creep rate accelerated by the cavitated area fraction**

$$\dot{\varepsilon}^c = A_{\mathrm{dis}} \frac{E b D_1}{k_{\mathrm{B}} T} \left(\frac{\sigma_e}{\sigma_0 (1 - \omega(t))}\right)^n, \quad \omega(t) = (a(t)/b(t))^2$$

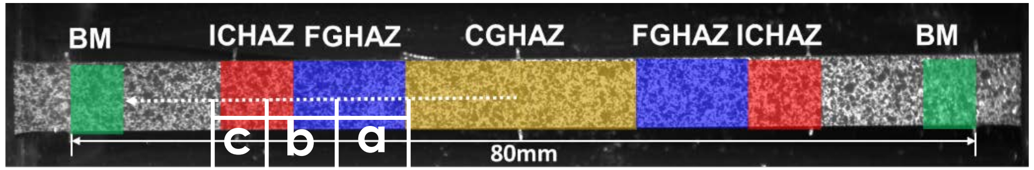
Microcracking $a/b \to 0.75$

Designed and built a special in-situ full-field creep strain measurement system with high temperature DIC to determine the heterogenous creep deformation in Grade 91 steel weld

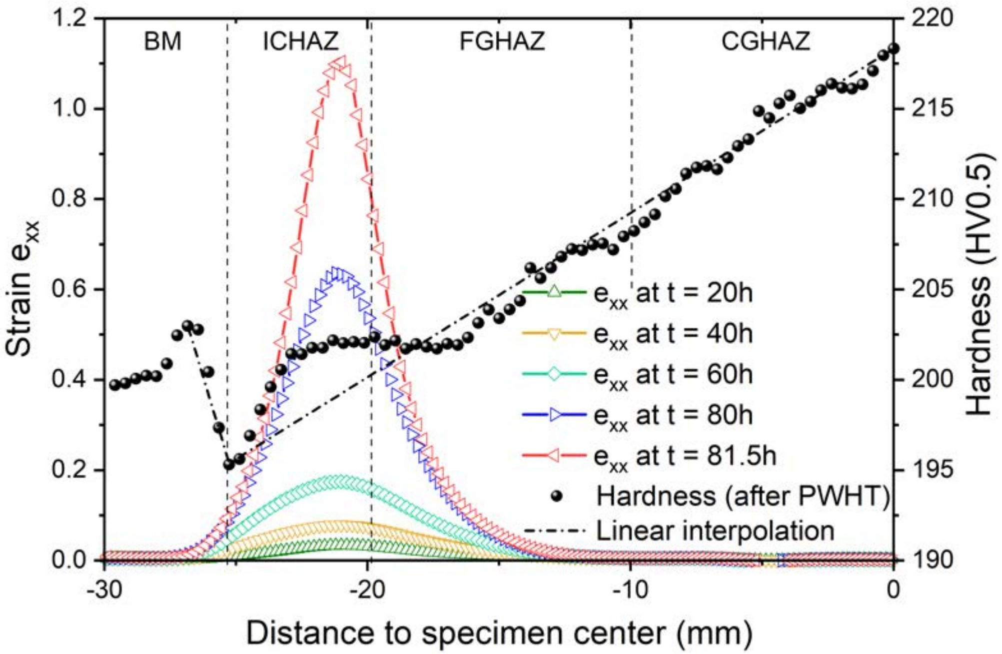


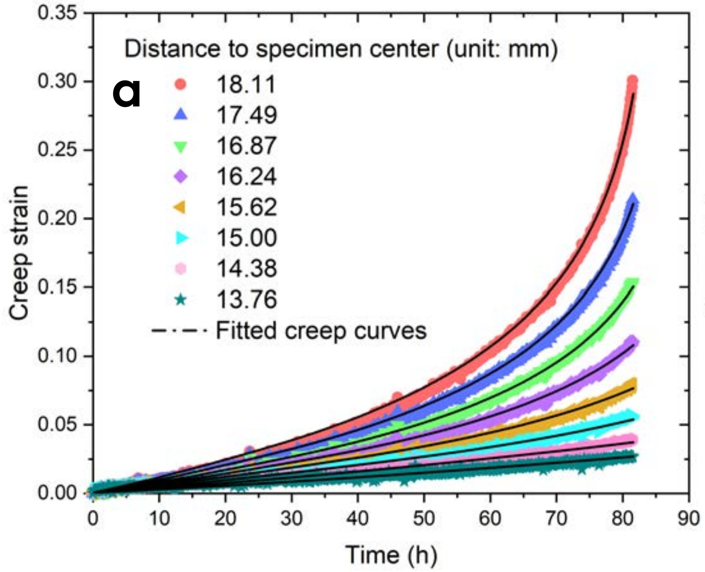


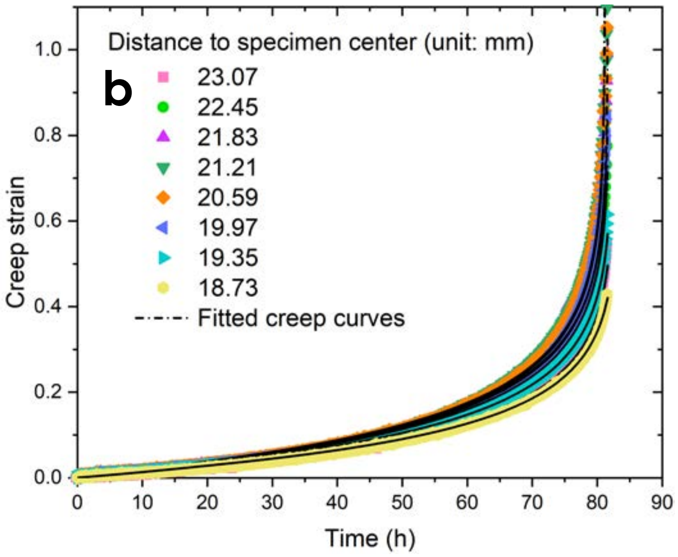
ORNL's special testing system make it possible to extract material property parameters in different subregions of HAZ with sufficient spatial resolution that are necessary for use in ICWE creep model



Measured creep strain,
equivalent spatial resolution in typical weld HAZ: **0.04mm**



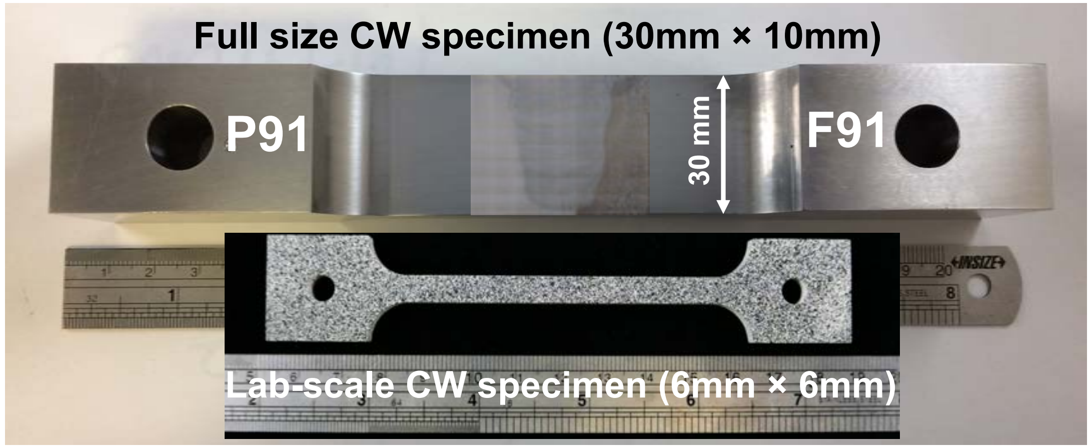


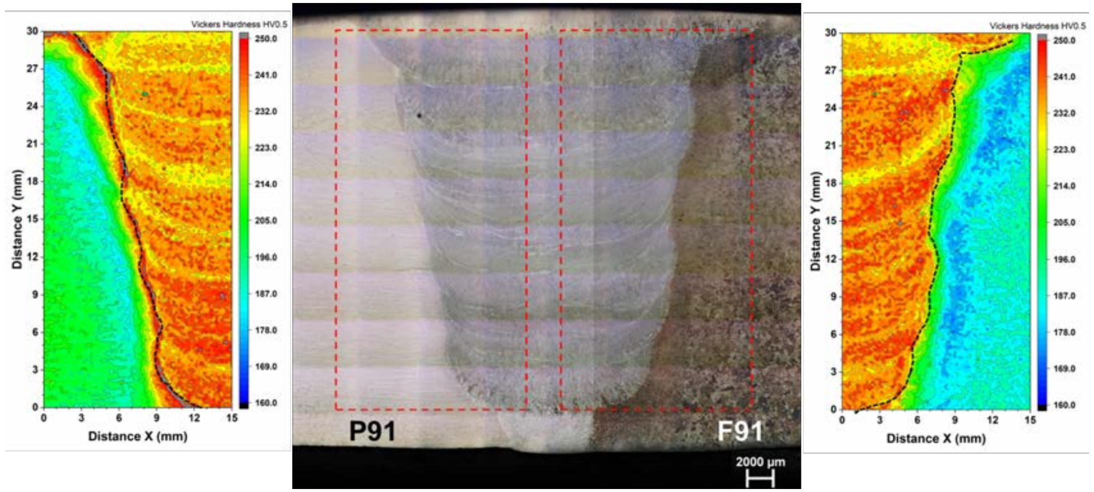


ORNL Invention Disclosure, 2020

EPRI EEM project: Ex-service Grade 91 forging (F91)-Grade 91 piping (P91) header

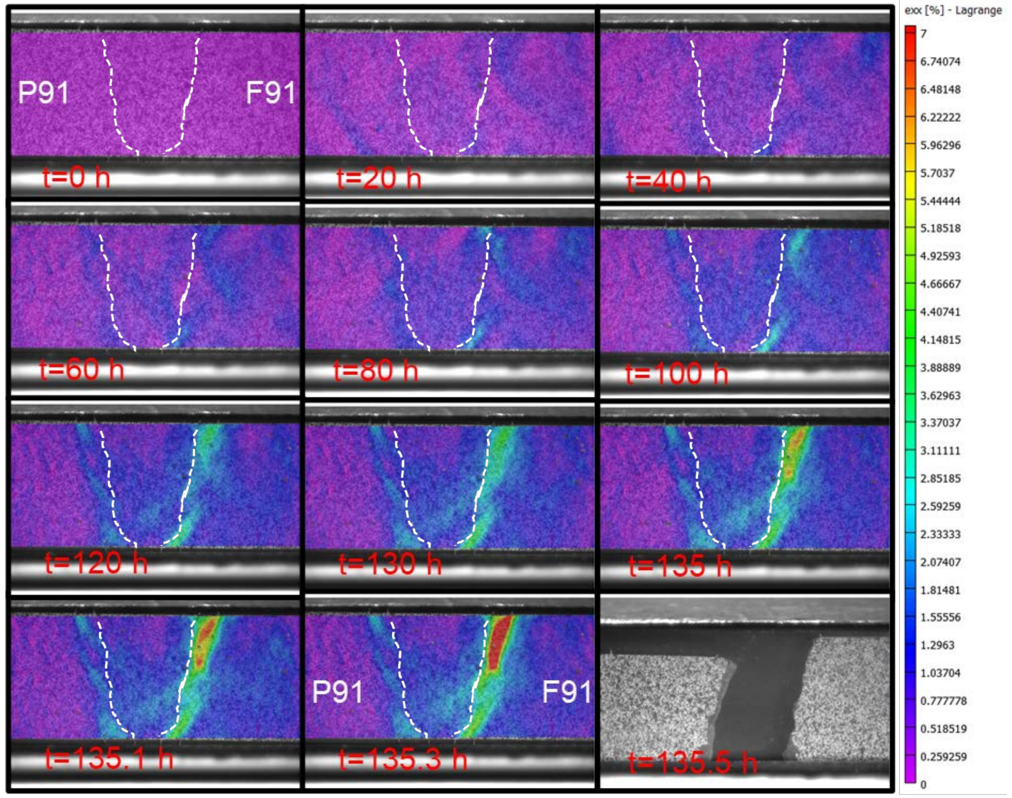
(G1848, 141,000 hrs, 1067°F/575°C, 2590 psi/17.9MPa)



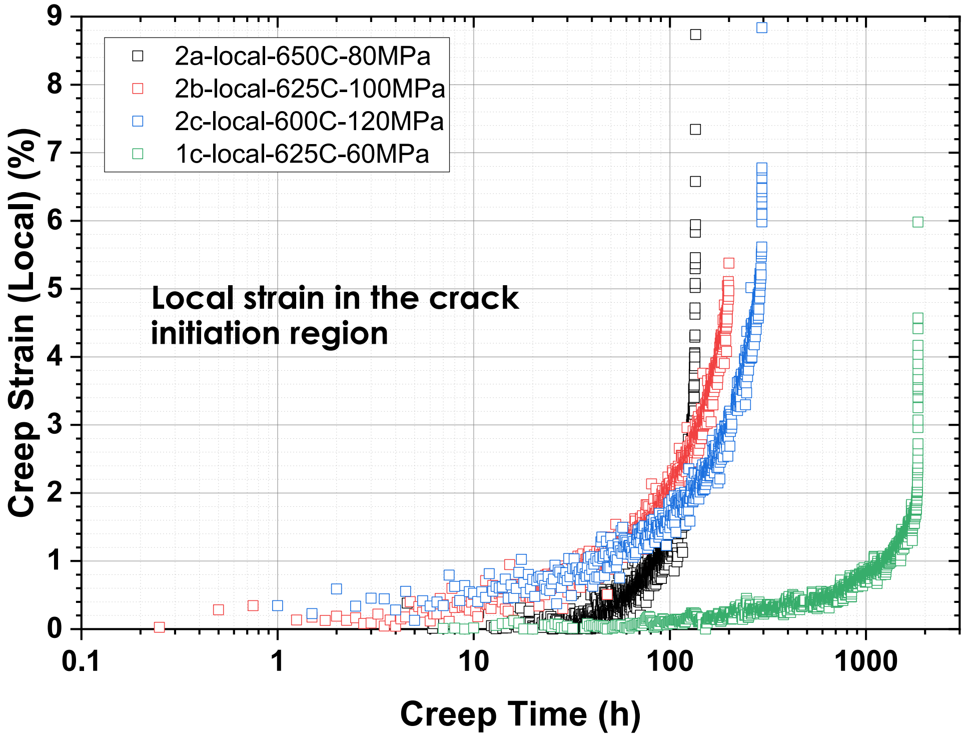


- Need for full size cross-weld test necessitated upgrade of testing system
  - ✓ Constraint effect plays a significant role in creep deformation mechanism
  - ✓ Nonuniform weld configuration and microstructure along the wall thickness direction

Nonuniform creep strain distribution in multi-pass F91-P91 weld



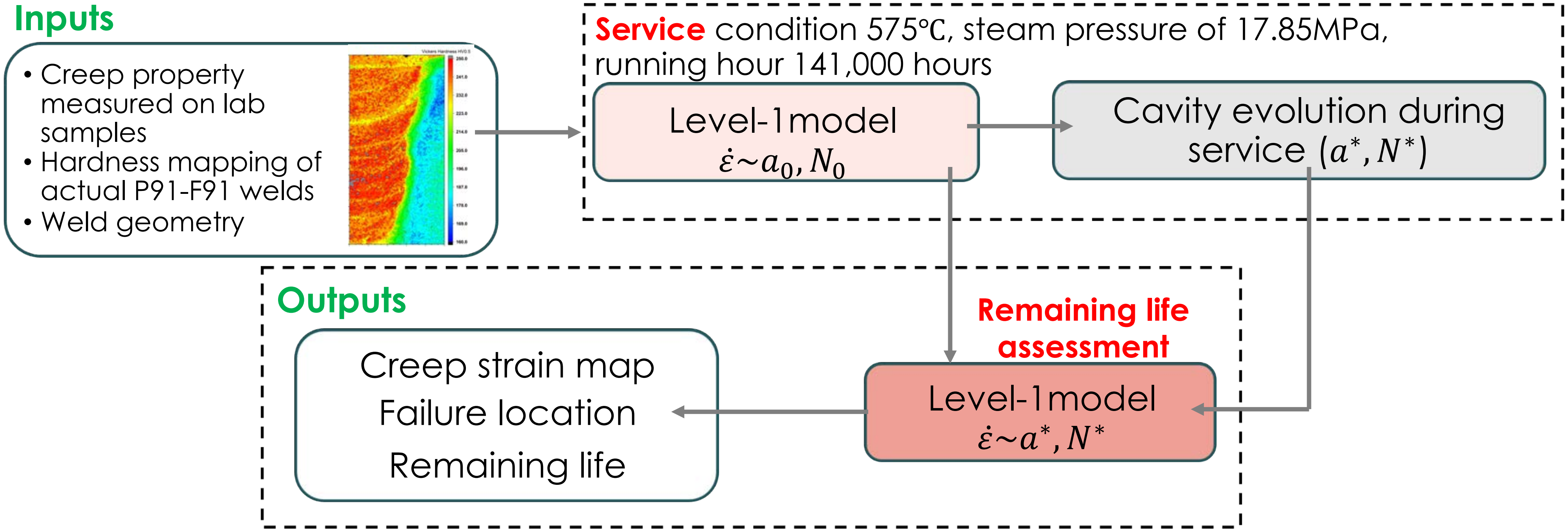
t_f=135.1 h Test ID: 2a, 650 °C-80MPa



- A non-typical three-stage creep curve, short tertiary creep (Type IV cracking)
- Creep strain preferentially accumulated from the root and cap region of the weld
- **Creep resistance across the weld : P91 BM > F91 BM > WM > P91 HAZ > F91 HAZ**

Creep Life Prediction of EPRI EEM ex-service weld

- Step 1: physically-based model for prediction of **creep cavity evolution** for P91-F91 cross welds **during 144,000hrs of service**
- Step 2: predict the creep response and **remaining rupture life** during creep test using the Level-1 model with the initial creep voids



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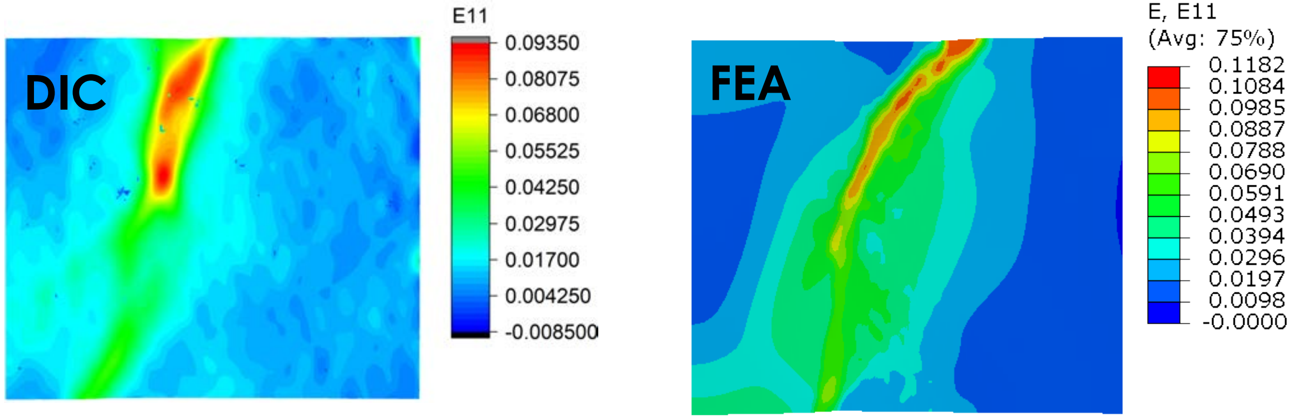
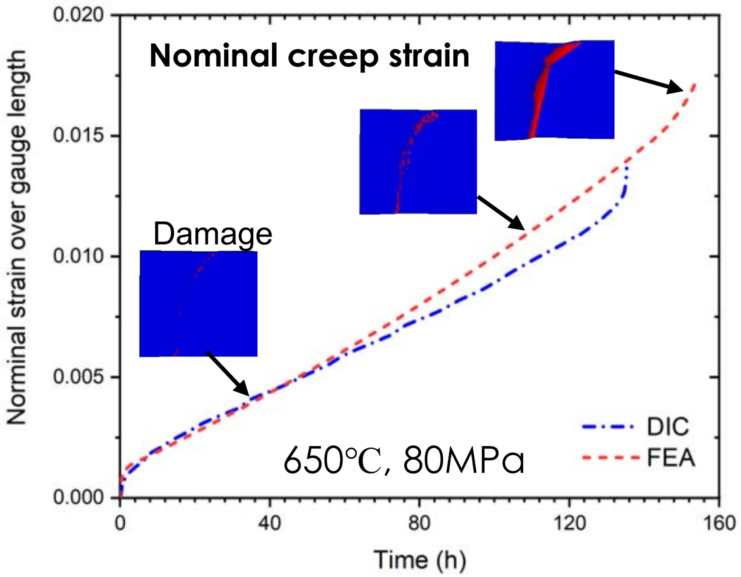
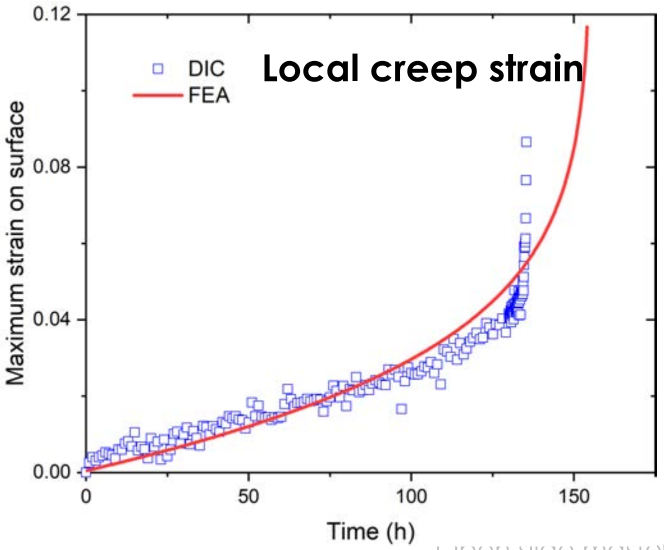
Level 1 Model is capable to predict the deformation and remaining life of the P91-F91 cross weld after service conditions





Test ID	Temperature (℃)	Stress (MPa)	Failure life, hrs experiment	Predicted Life, hrs
2a	650	80	135.5	154.1
2b	625	100	200.0	296.8
2c	600	120	294.5	419.3
1c	625	60	1843.0	2702.3

- ORNL's ICWE model provides a practical and reasonable approach for remaining life assessment of creep-resistant steel weldments by including the pre-damage effects
- The predicted creep rupture strain and failure location are comparable with DIC measurement

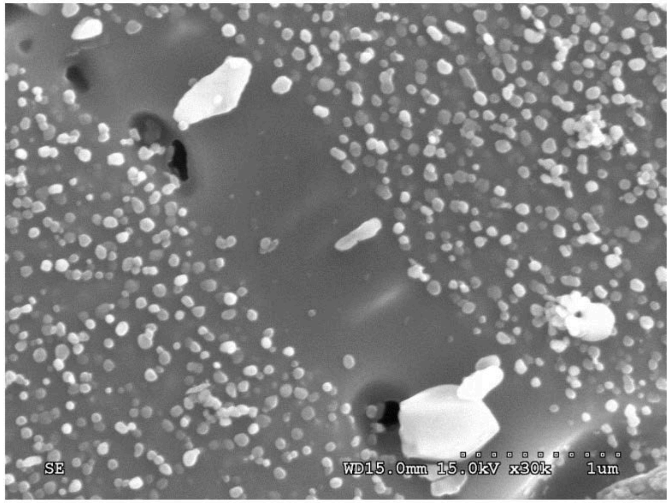


Stress relief cracking (SRC)

- Intergranular cavitation and fracture – same failure process as in Type IV cracking
- But much more complicated, due to dynamic interactions of weld residual stress change and microstructure evolution over time

The precipitation during heating tends to occur in the same temperature range where significant stress relaxation occurs, and this can lead to locally high strains at the grain boundaries. If these strains are sufficiently high, grain boundary failure will occur and a strain age crack will form. Thus, SRxC/SAC takes its name from the simultaneous presence of both strain and a strong aging reaction.

Siefert, Shingledecker, DuPont, David, 2016.



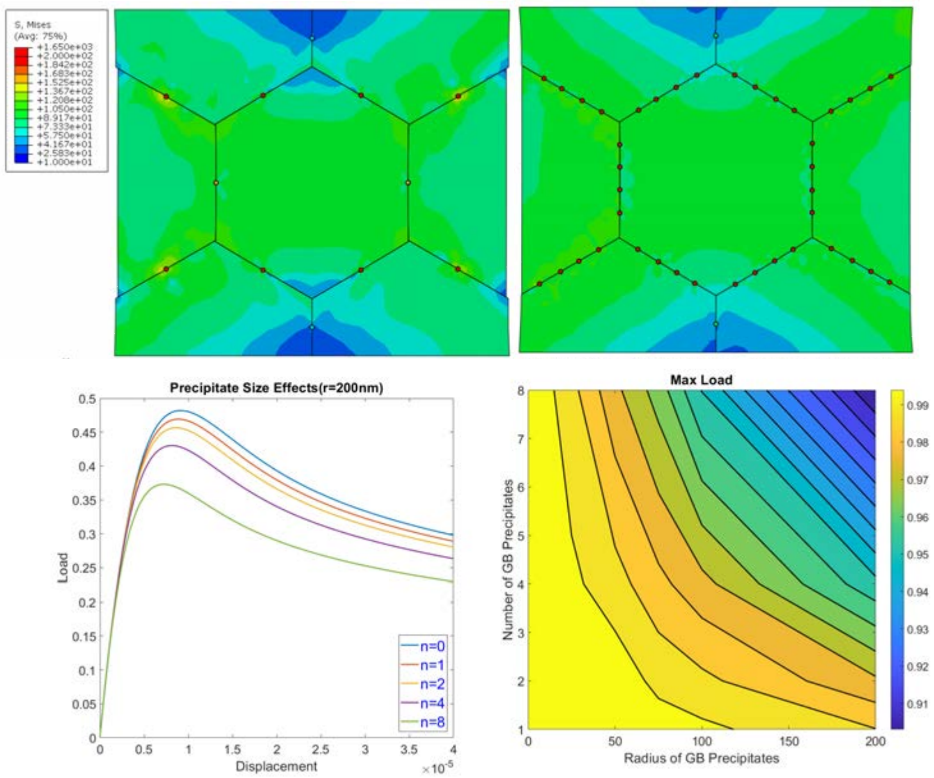
Bechetti and DoPunt, 2013

Stress relaxation cracking (SRxC): short term during PWHT, or reheating
Strain age cracking (SAC): longer term at service temperature and stresses

Stress Relief cracking (SRC)

- Intergranular cavitation and fracture – same failure process as in Type IV cracking
  - Possible to extend the ICWE model for SRC/SAC
- But two major developments are needed
  - **Accurate** simulation of weld residual stresses during welding, and the subsequent relaxation/relief process during PWHT and service.
    - Based on dynamic strain hardening laws developed at ORNL
  - **Time dependent** local ductility/failure resistance degradation that are functions of precipitation kinetics and stress evolution.
    - Requiring integrated experiment and modeling effort (analogous to Type IV cracking modeling in G91 welds, but with different experiment designs)
- Modeling and experiment need to be integrated

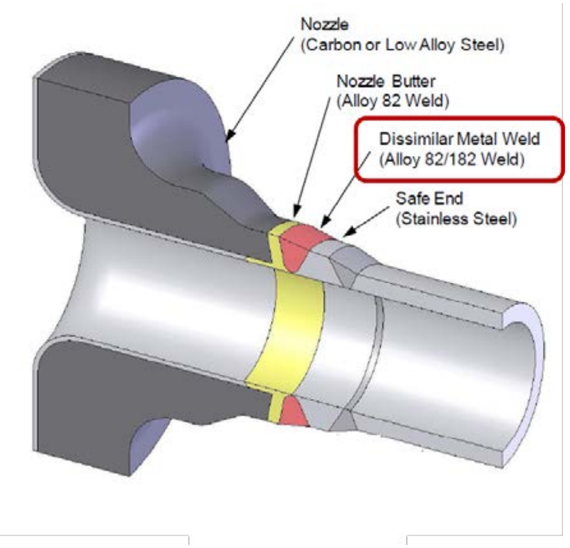
REV model for precipitate Effects on grain boundary sliding and failure



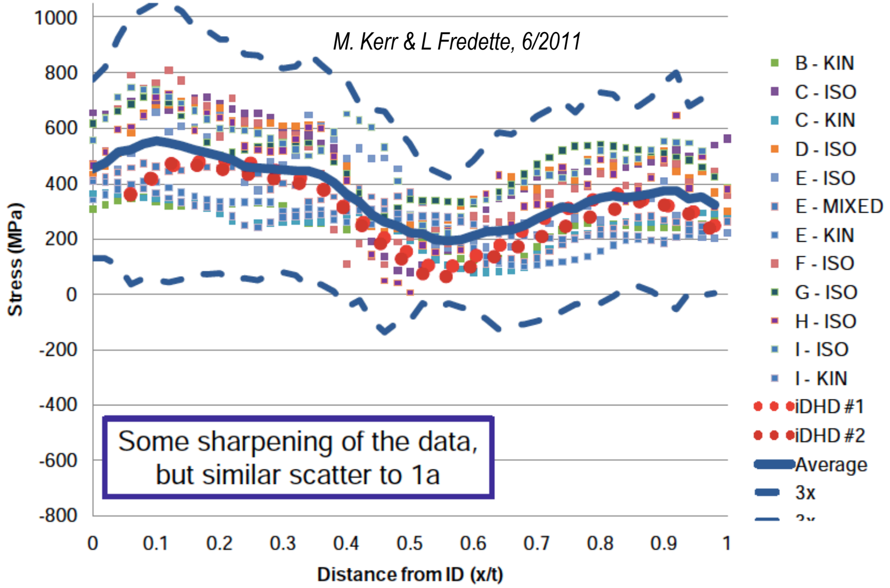
Size effect:
Larger precipitates promote cavity nucleation
Number effect:
Greater number of precipitates result in lower load carrying capability.

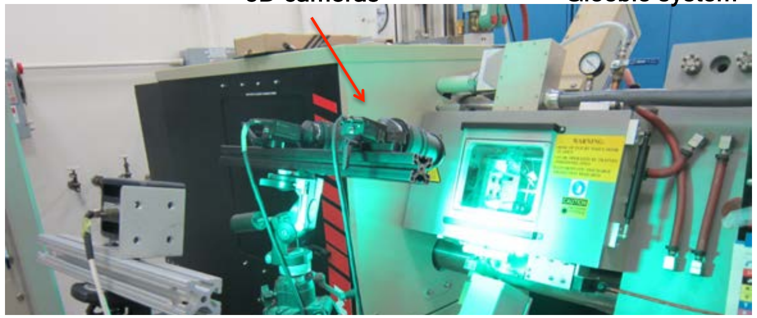
Accurate weld residual stress modeling

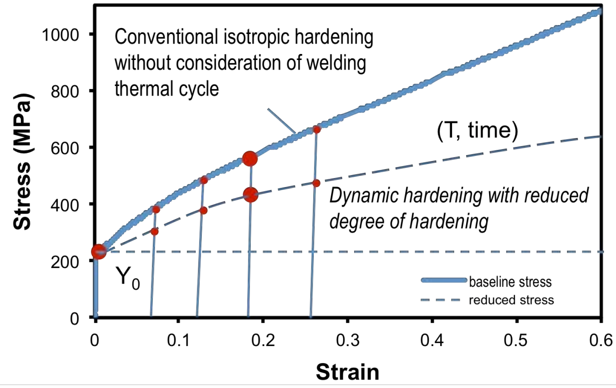
- "Of highest significance (among all factors) is the assumed weld **material hardening behavior**." Rathbun et al., *NRC Welding Residual Stress Validation Program International Round Robin Program and Findings*, 2011 ASME PVP.

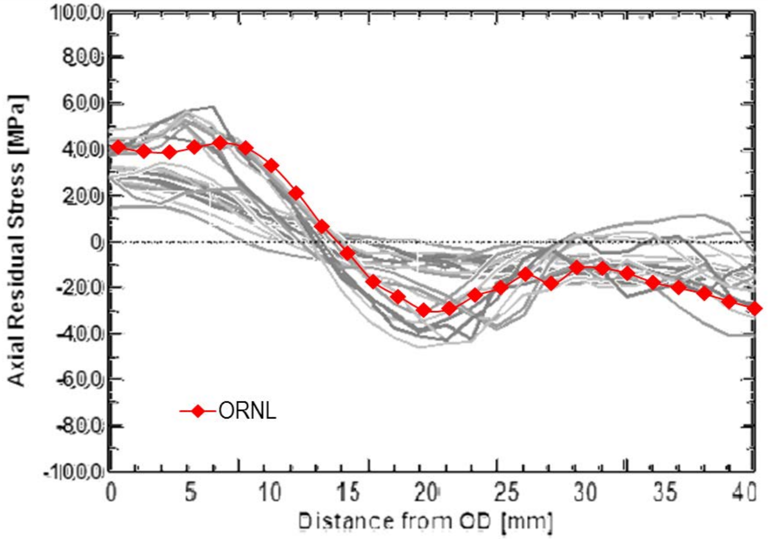


DM weld in a nuclear reactor





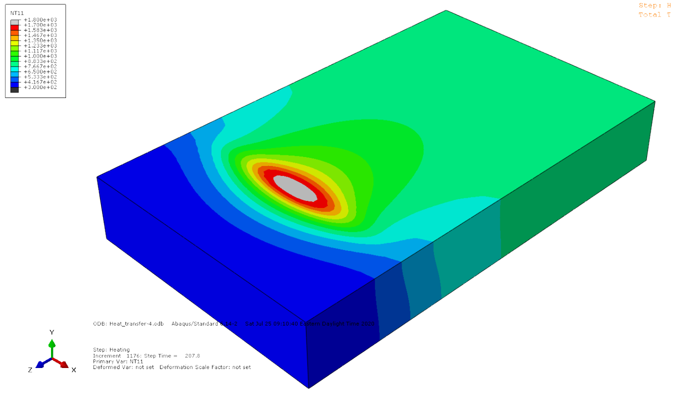




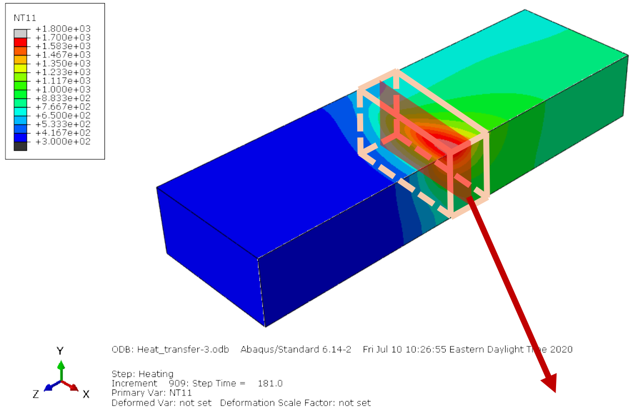
Feng, Chen, Yu, Qiao et al, 2013

Preliminary results

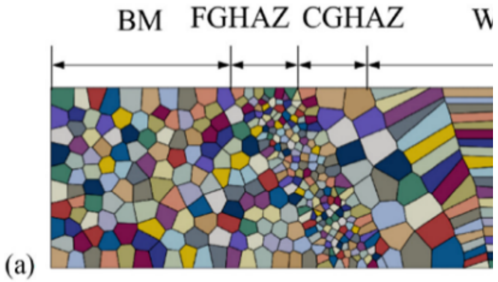
1. **Transient heat flow analysis** -- 3D plate to simulate welding procedure

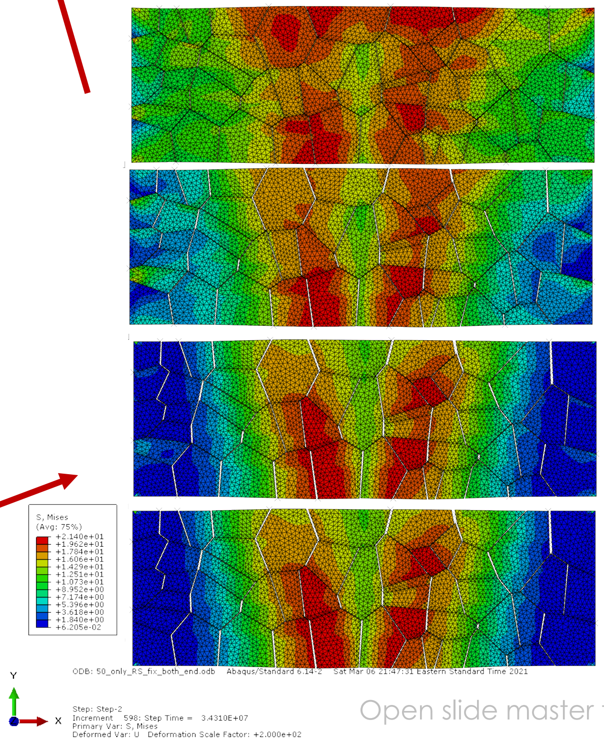


2. **Mechanical solution** Temperature distribution as input file for mechanical analysis

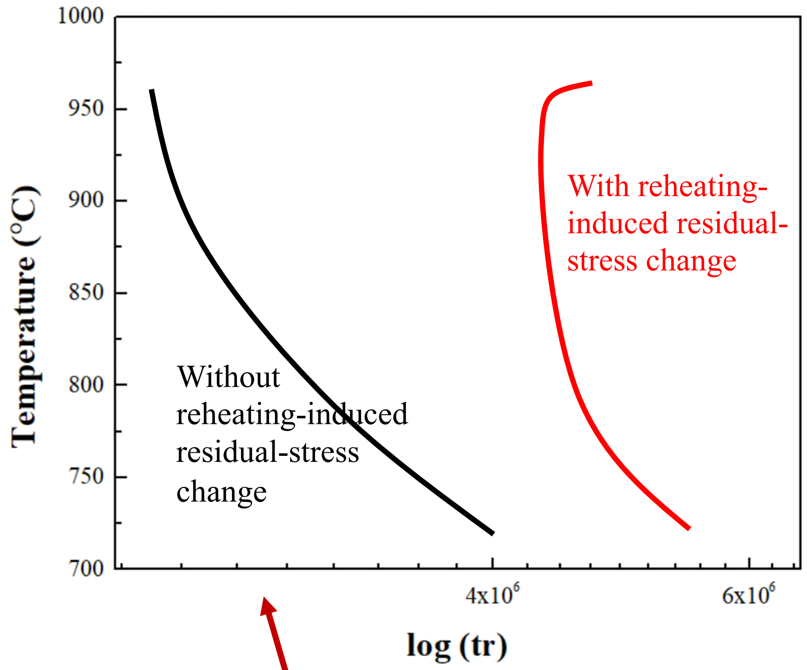


3. **Lifetime predication--2D failure model** Residual stress field obtained from 3D model (after-welding & PWHT)

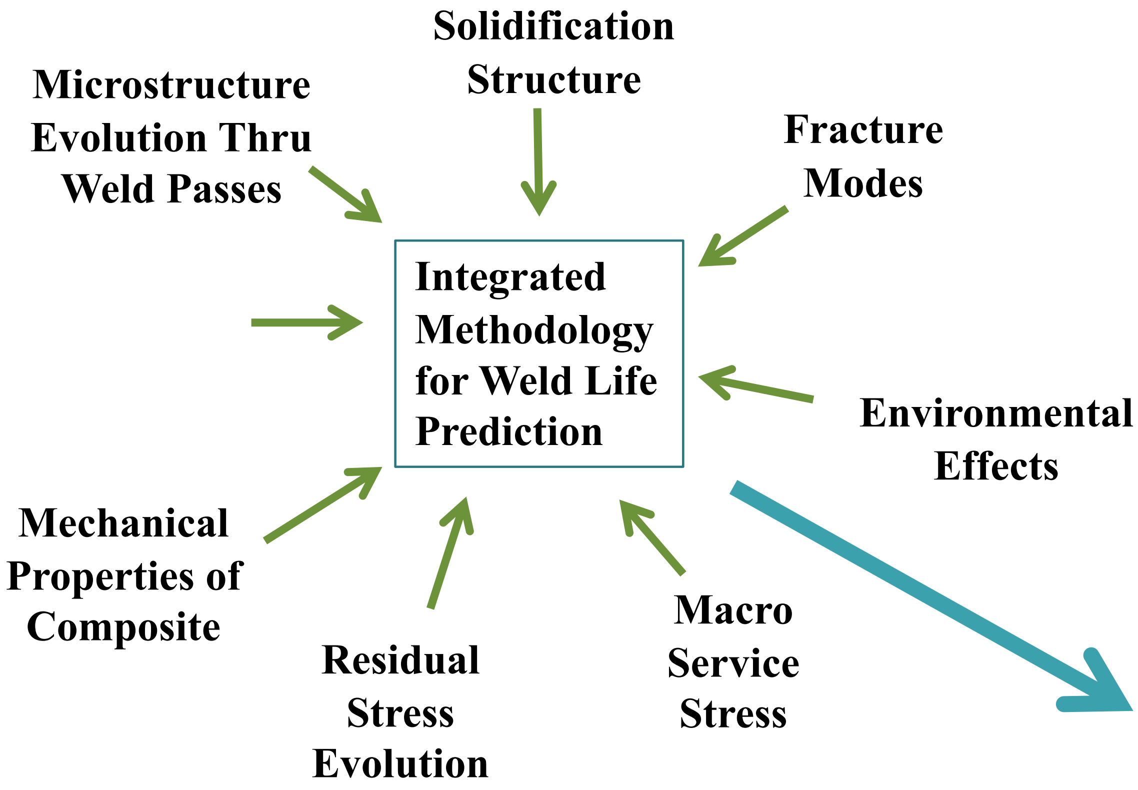


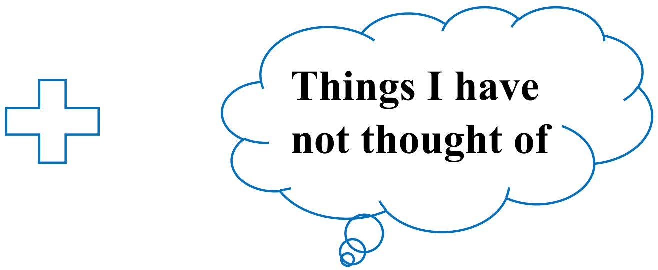


4. **Obtain the relationship between reheating temperature & lifetime**



Framework for Collaborative R&D





Enabled Actions

- Life Prediction
- Weld Process Dev't
- PWHT Dev't
- NDT Strategies
- Code Enhancements
- Repair Strategies
- Alloy Dev't

Jack de Barbadillo (Special Metals, 2015)

Thank you!