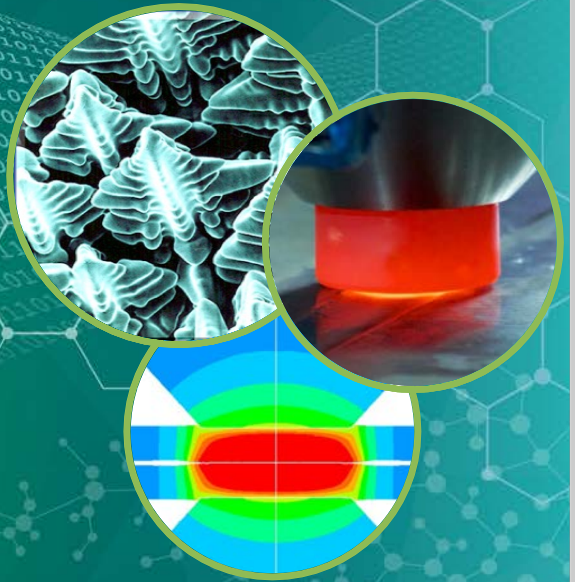
Oak Ridge National Laboratory

Weldability of Creep-Resistant Alloys for Advanced Fossil Power Plants

Zhili Feng, Yiyu Jason Wang, Wei Zhang, Yanli Wang, Doug Kyle

Oak Ridge National Laboratory



2021 DOE/FE Spring R&D Project Review Meeting

June 3, 2021

Program Manager: Vito Cedro III

fengz@ornl.gov

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

U.S. DEPARTMENT OF ENERGY

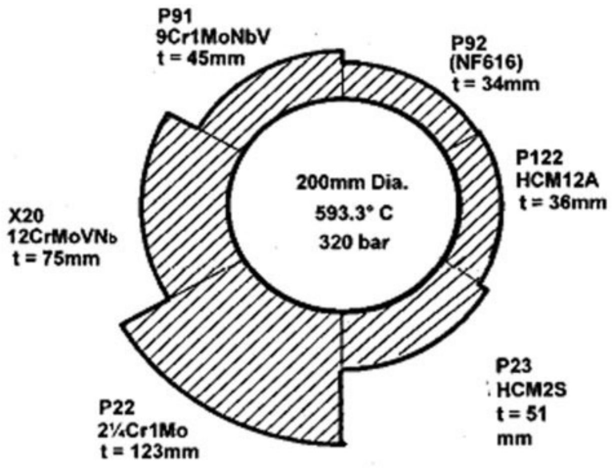
- **Acknowledgment:** This material is based upon work supported by the Department of Energy Award Number FWP-FEAA118

- **Disclaimer:** This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

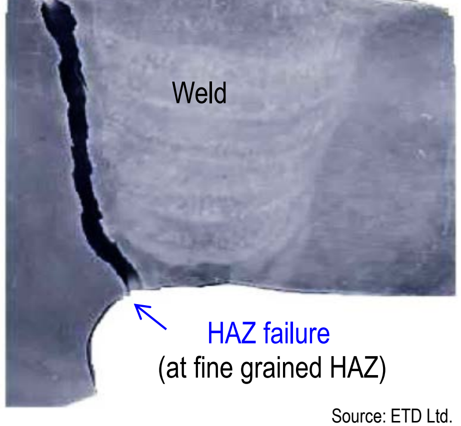
Project Goal and Scope

- Address the critical **creep strength reduction** (aka Type IV Cracking) **in weldment** of CSEF Steels that negates the benefits of P91, P92 etc.
  - Develop, validate, and apply an Integrated Computational Welding Engineering (ICWE) prediction tool for creep deformation and failure in CSEF structure 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 creep testing system and experimental approach necessary to quantify the highly nonuniform creep deformation and failure in a weldment to validate and refine the models

- 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



Type IV HAZ cracking in a 9-12Cr steel

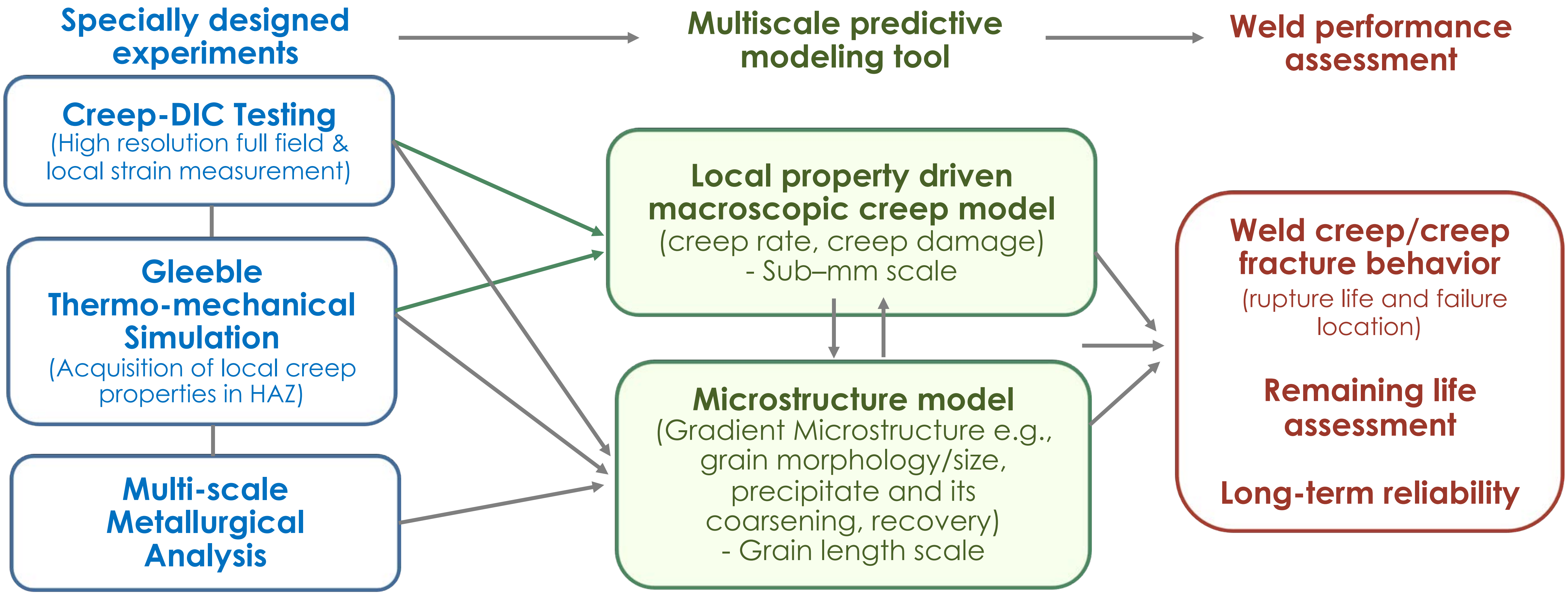


Source: ETD Ltd.

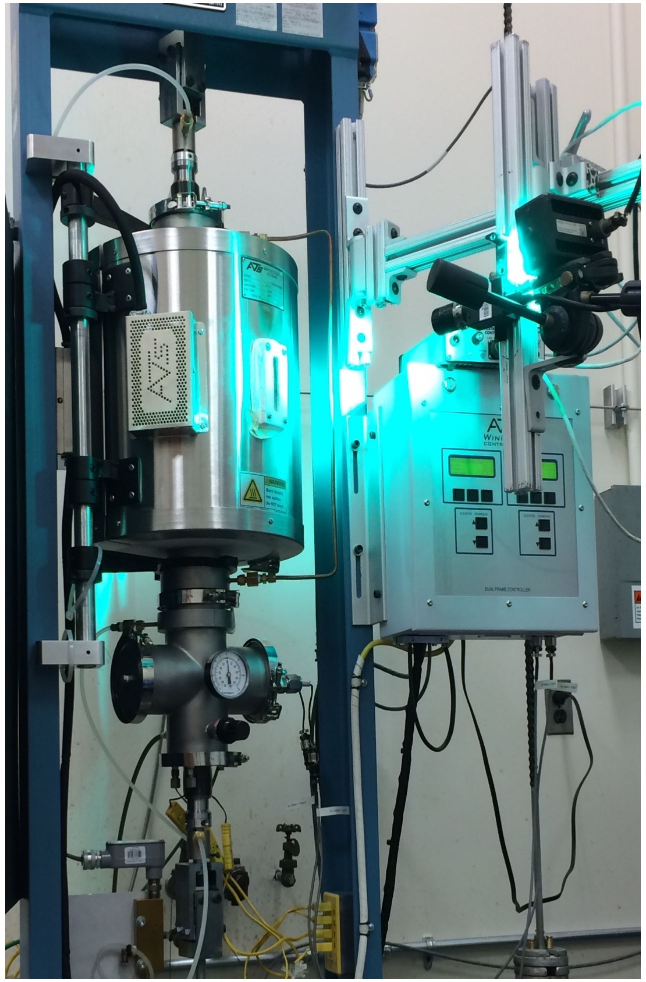
Up to 50% life reduction compared to base metal

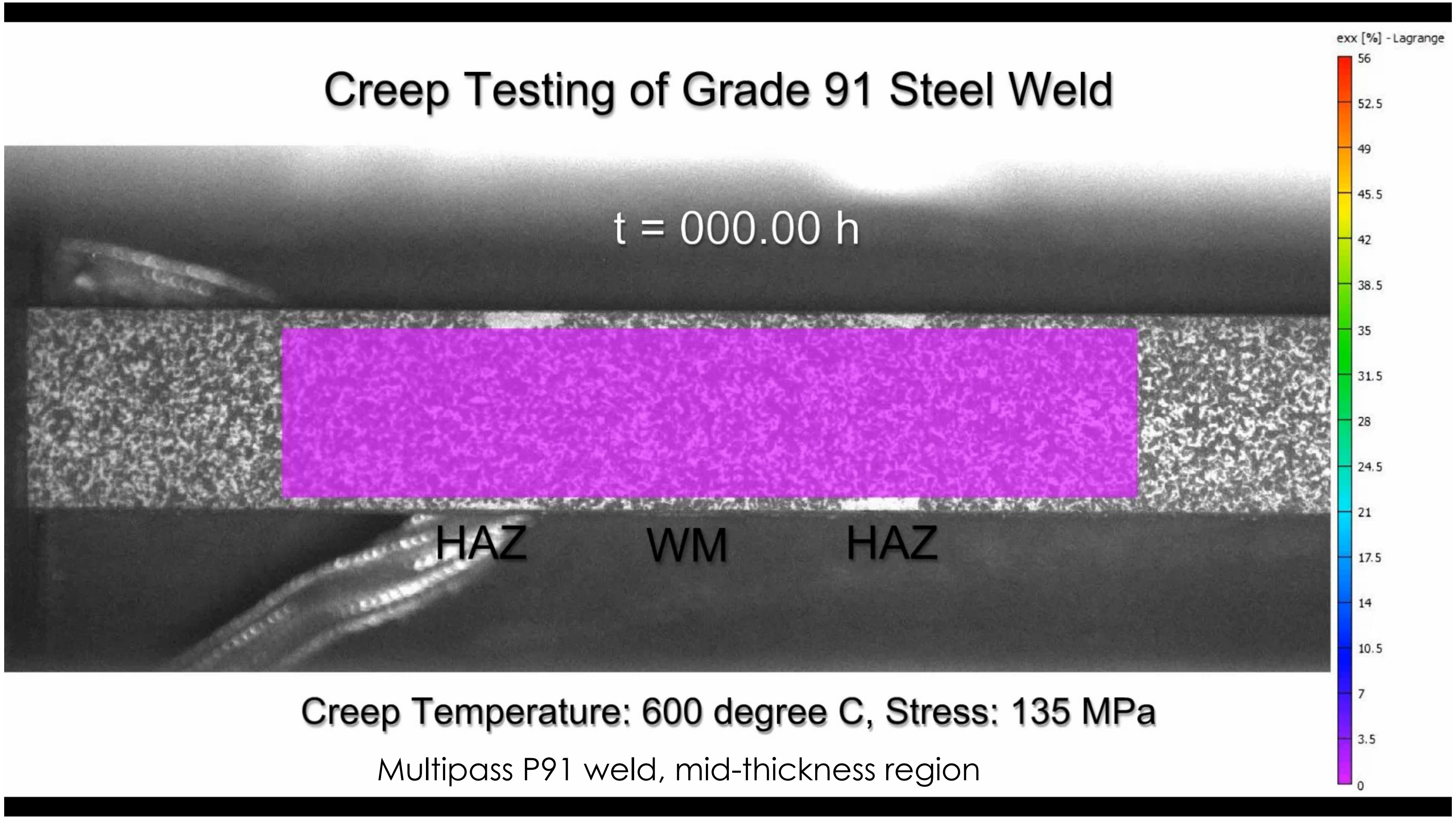
Integrated Approach for Weld Life/Performance Prediction

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

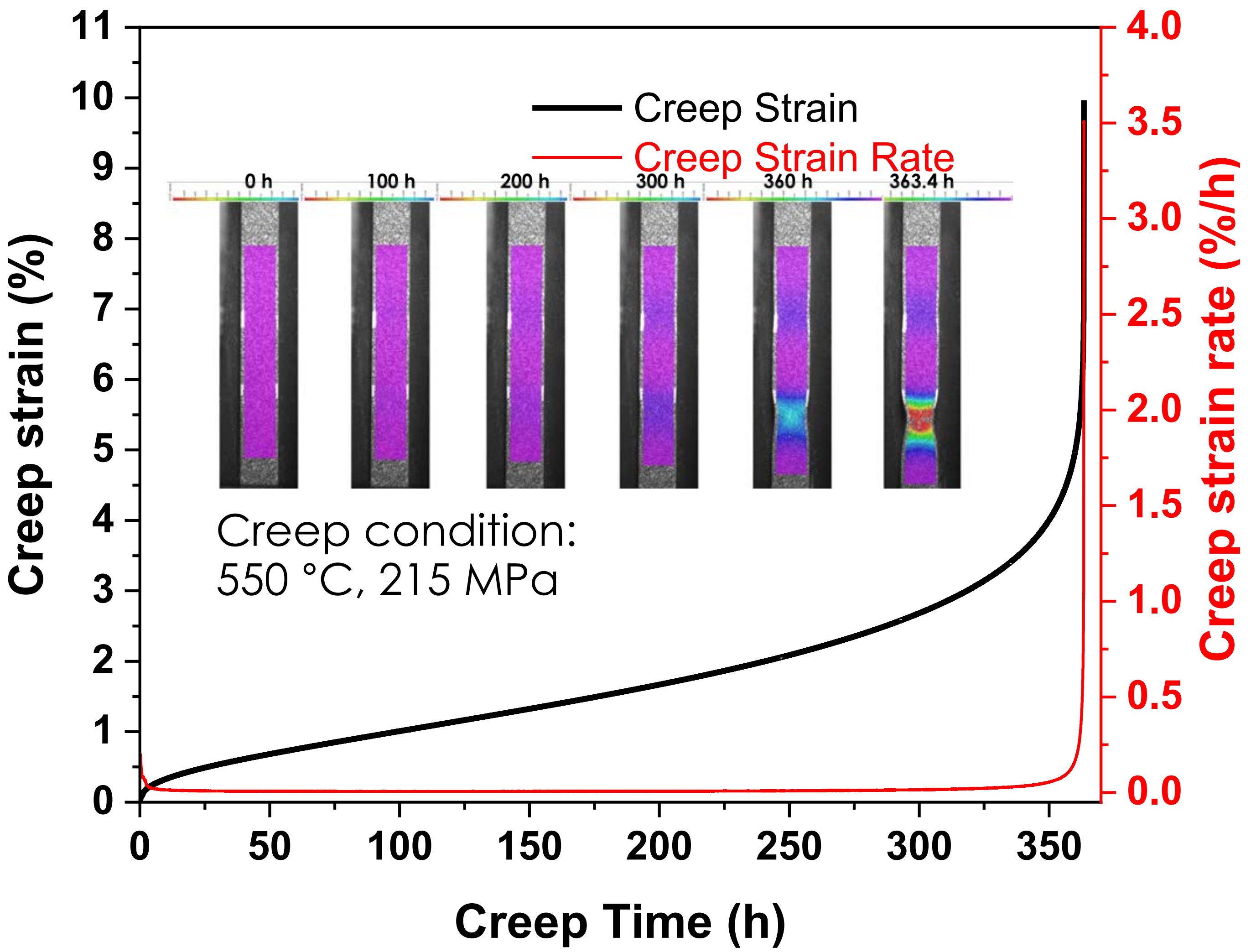


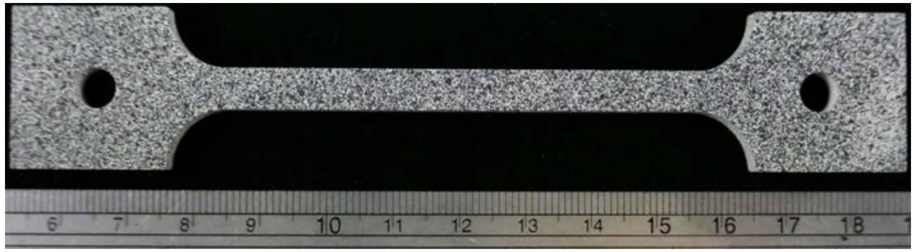
Designed and built a special in-situ full-field creep strain measurement system with high temperature DIC to determine the heterogenous creep deformation in Grade 91 steel weld



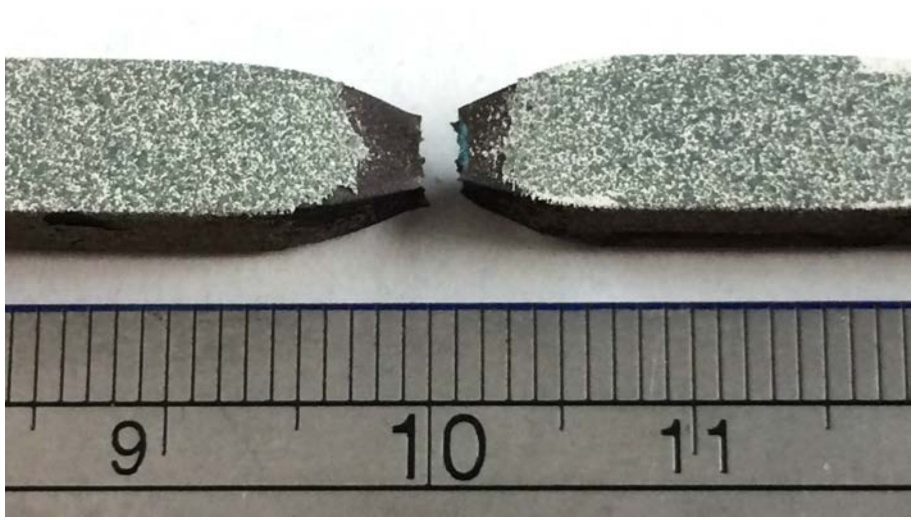


Creep measurement using "standard" extensometer shows very low creep strain before ternary creep leading to failure





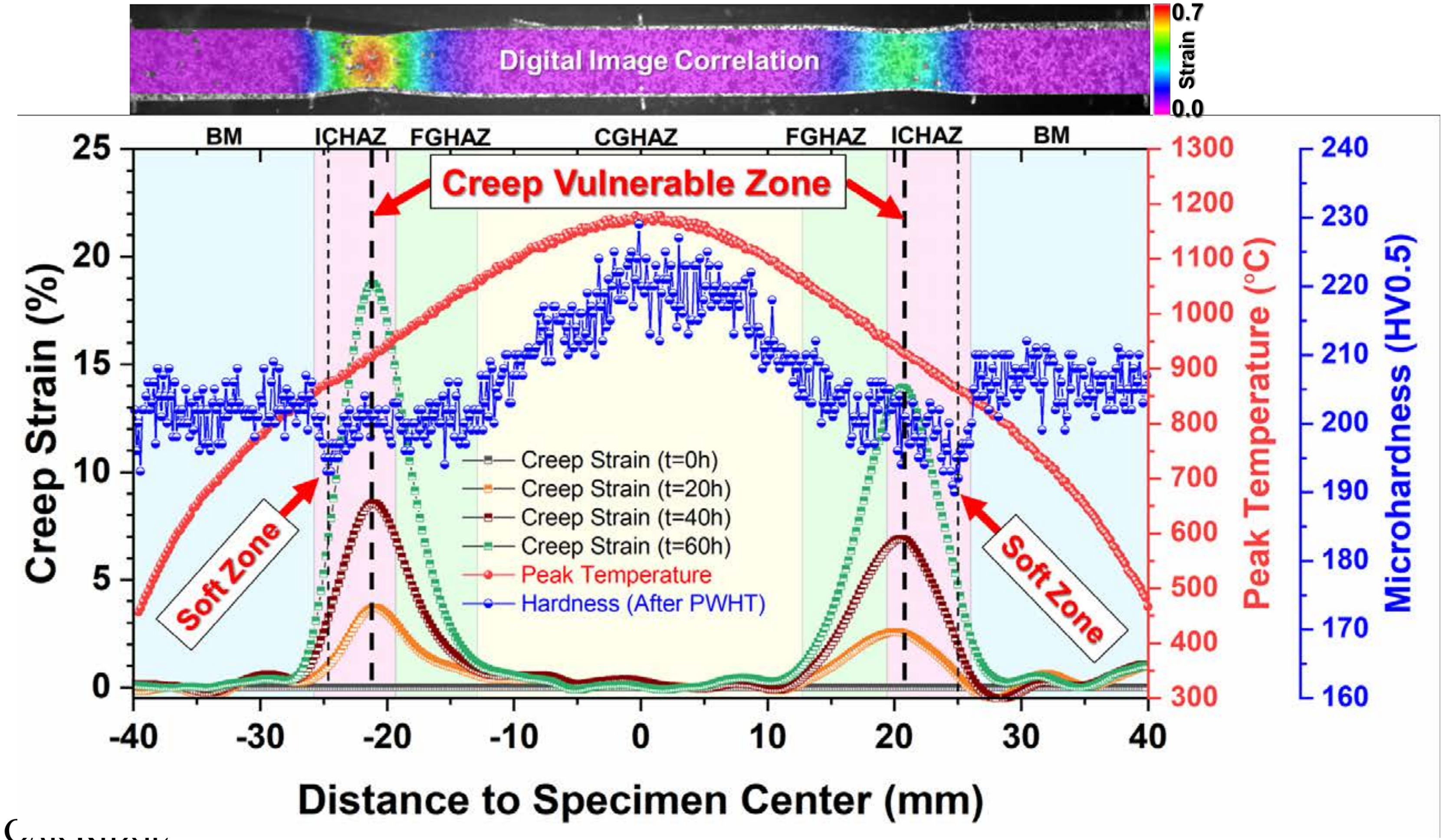
Before creep testing

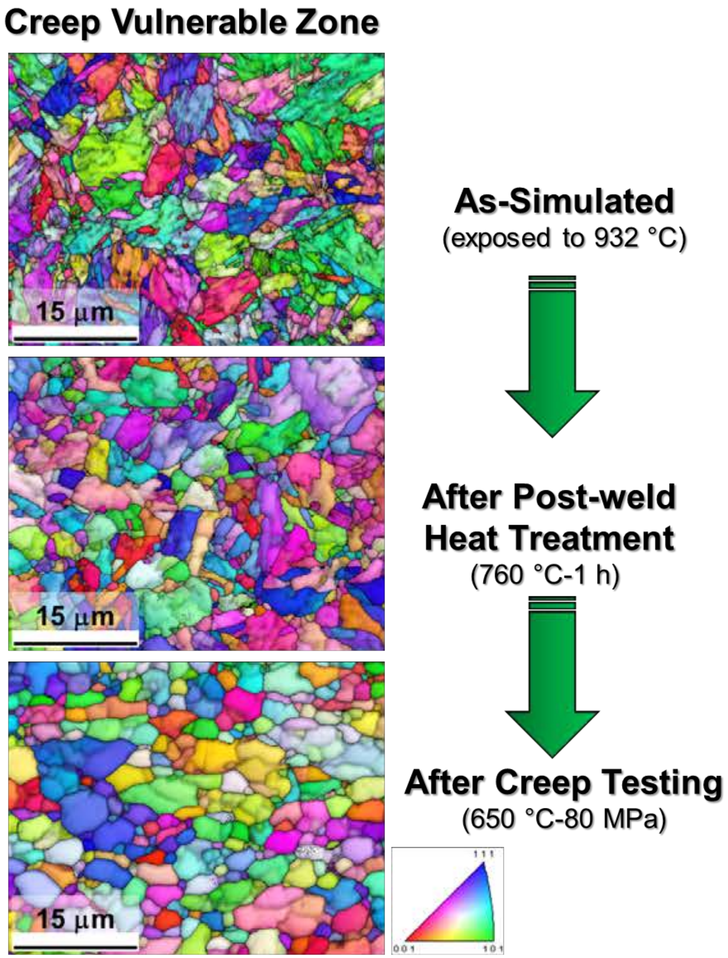


After creep testing

Extended the novel testing system and approach connected creep deformation and failure with underlying microstructure features

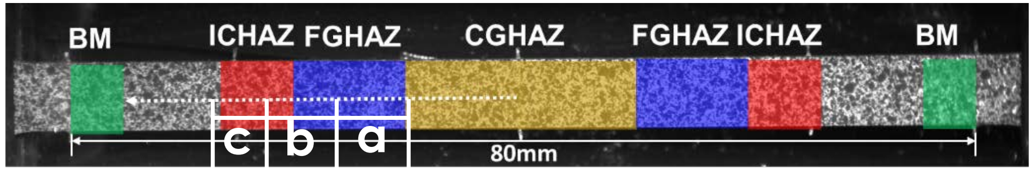
- **Positively identified the most vulnerable region for Type IV cracking is ICHAZ**



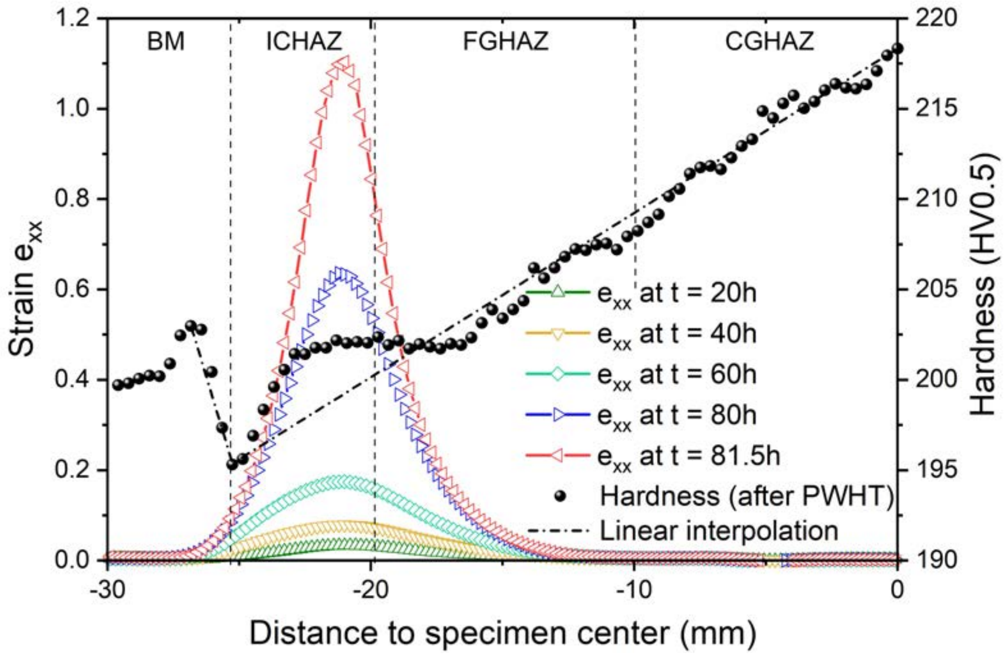


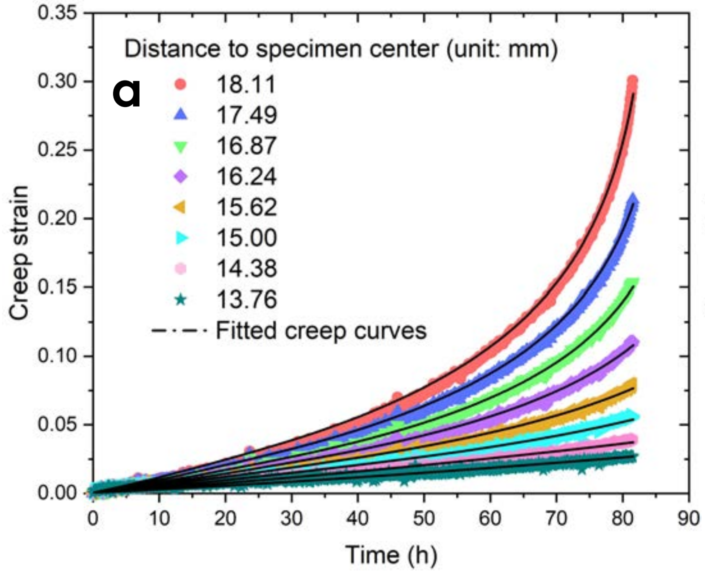
ORNL Invention Disclosure, 2020

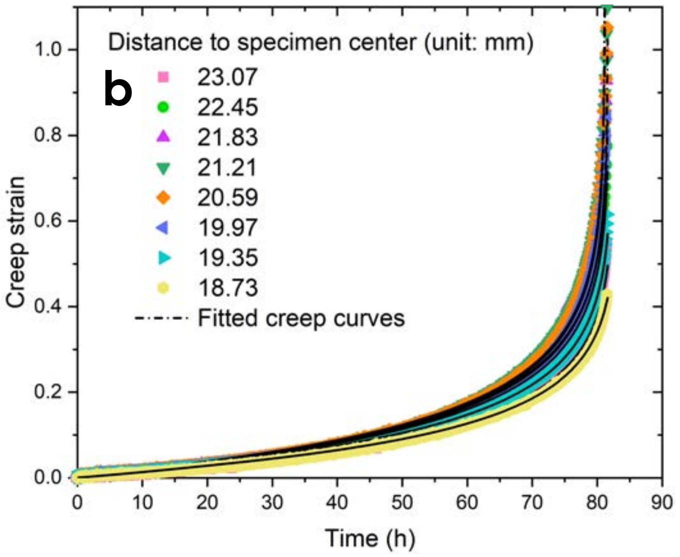
ORNL's special testing system make it possible to extract material property parameters in different subregions of HAZ with sufficient spatial resolution that are necessary for use in ICWE creep model



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



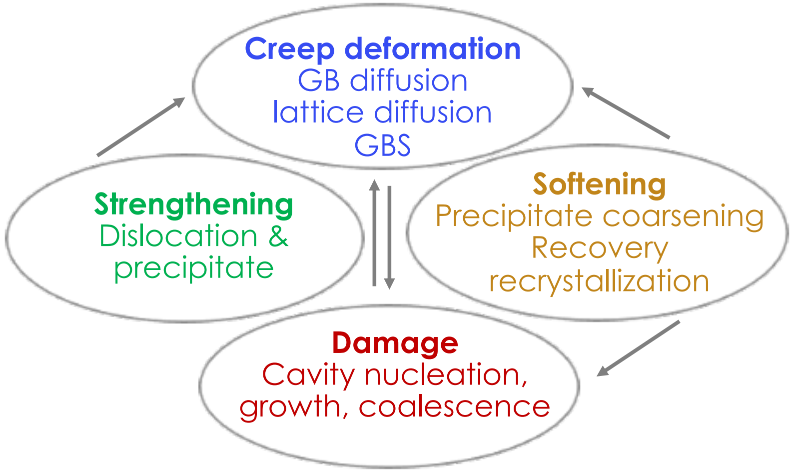


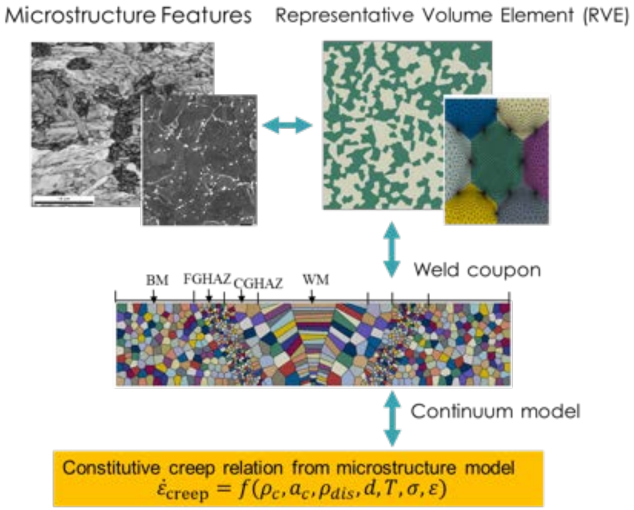


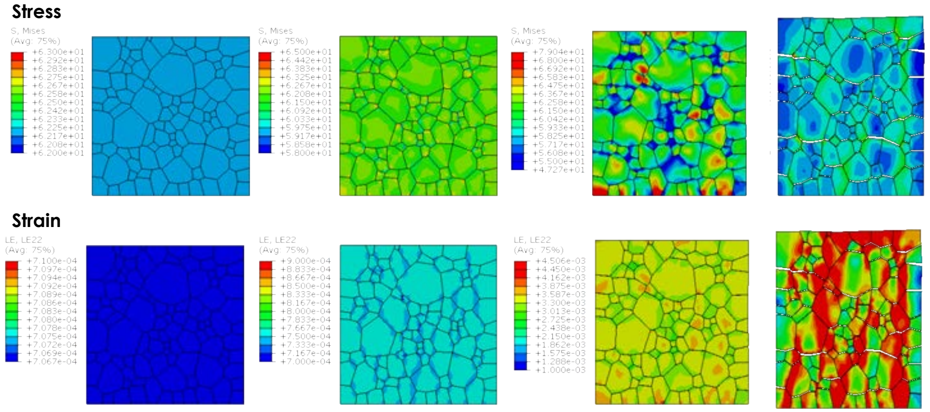
ORNL Invention Disclosure, 2020

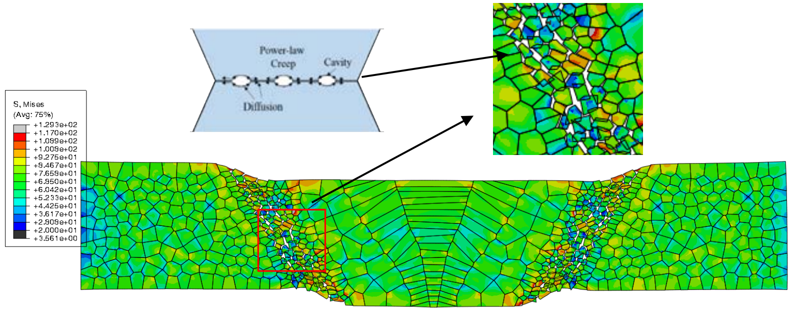
Microstructure informed Level II Model provided the foundation for Level 1 practical engineering modeling tool for creep modeling of large welded structures

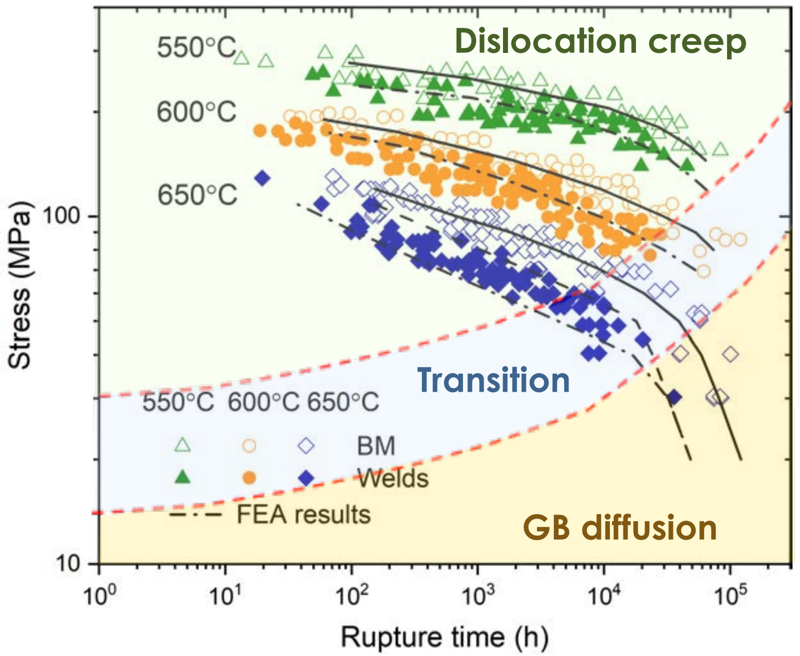
- Leve II Model: A mechanistic constitutive model was developed to account for the effects of microstructure, stress and temperature on the creep deformation and damage mechanisms of high temperature alloy weldments.







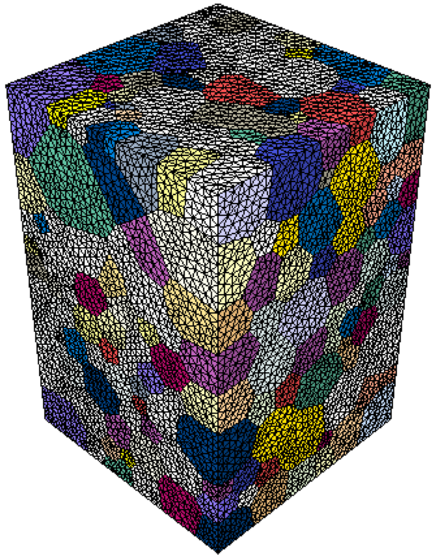




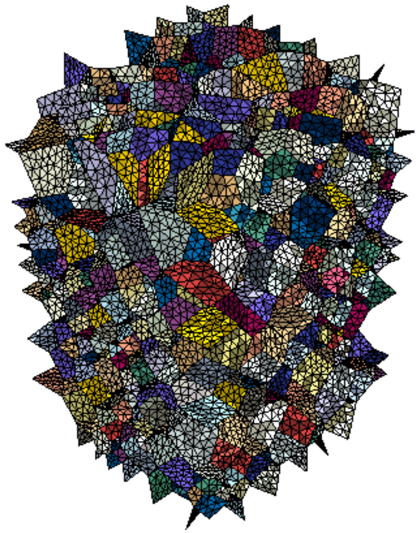
Oak Ridge National Laboratory

Three Dimensional Model

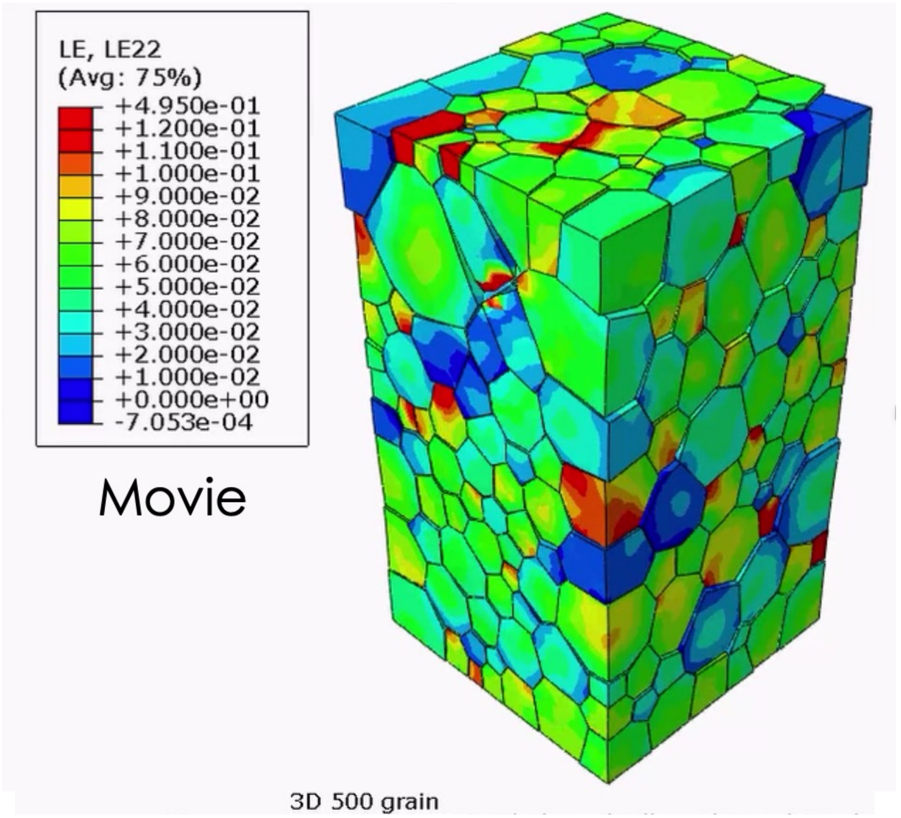
- To obtain more realistic localized and macroscopic deformation of the critical subregions in the weldment.



Model: 500 grains
~ 600,000 elements



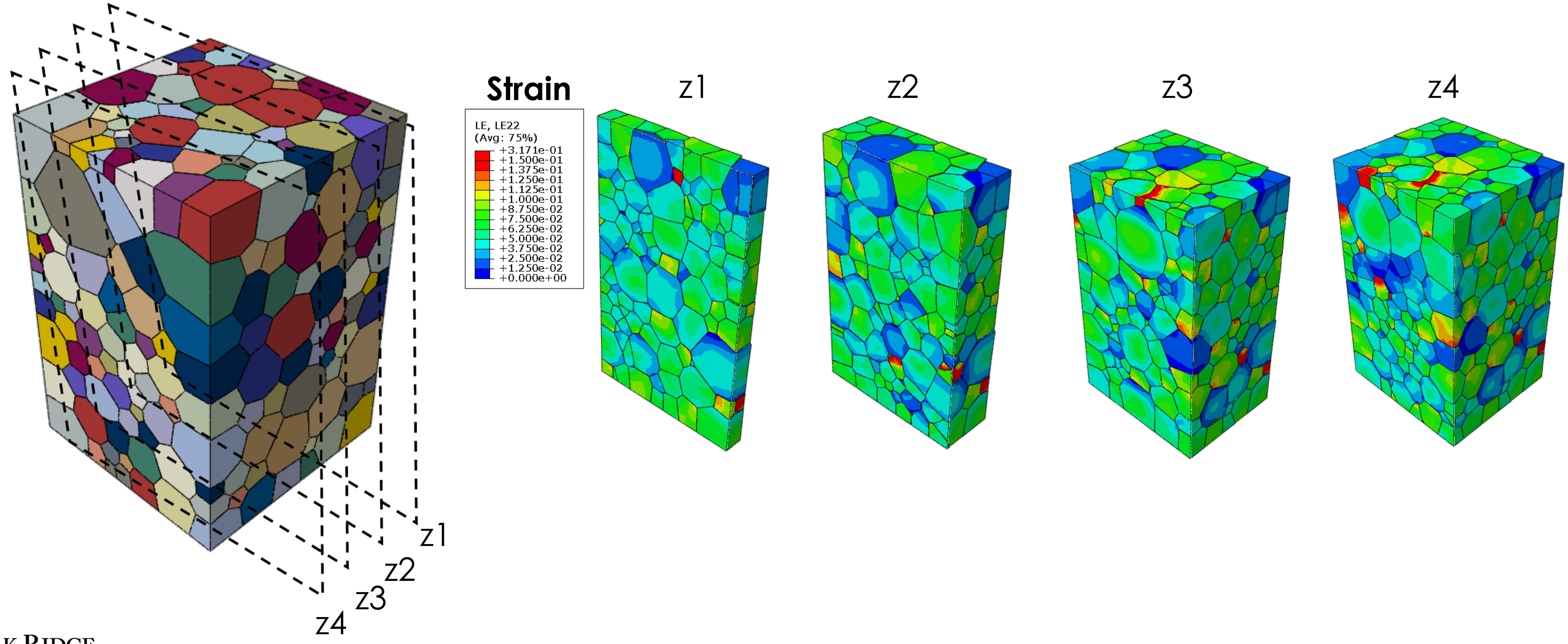
Grain boundary
Cohesive element



Strain evolution and intergranular fracture

Three Dimensional Model

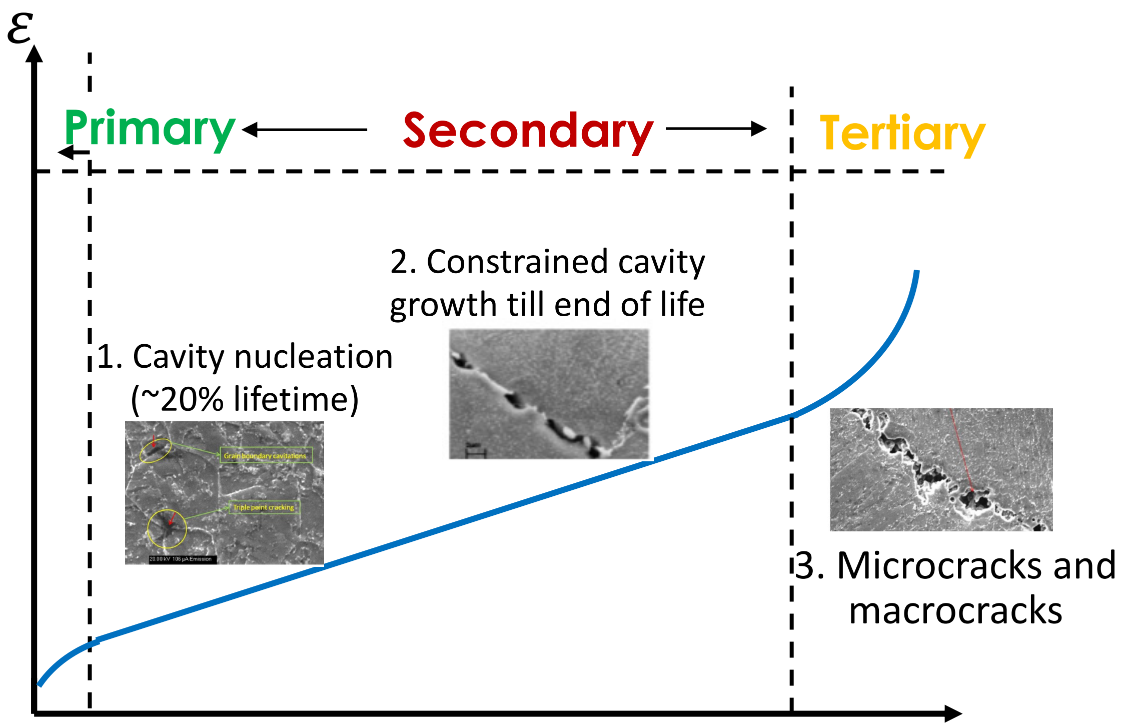
- Inner strain distribution



Level 1 Model: Cavity-evolution based constitutive model

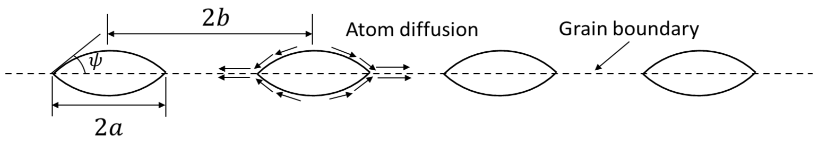
- **Three stages of damage evolution determines the lifetime:**

$$t_f = t_n + t_g + t_p$$



Grain boundary cavitation in HAZ

- **Cavity evolution-based creep model**



- **Cavity nucleation**

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

- **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**

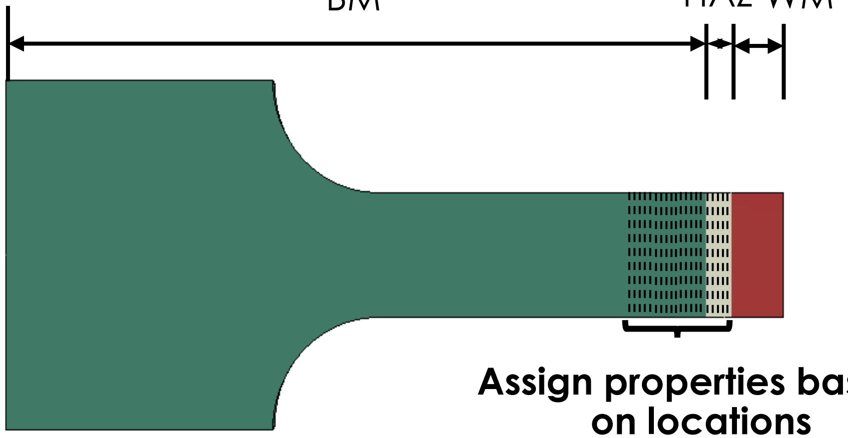
$$\dot{\varepsilon}^c = A_{\mathrm{dis}} \frac{EbD_{\mathrm{l}}}{k_{\mathrm{B}} T} \left(\frac{\sigma_e}{\sigma_0 (1 - \omega(t))} \right)^n, \quad \omega(t) = (a(t)/b(t))^2$$

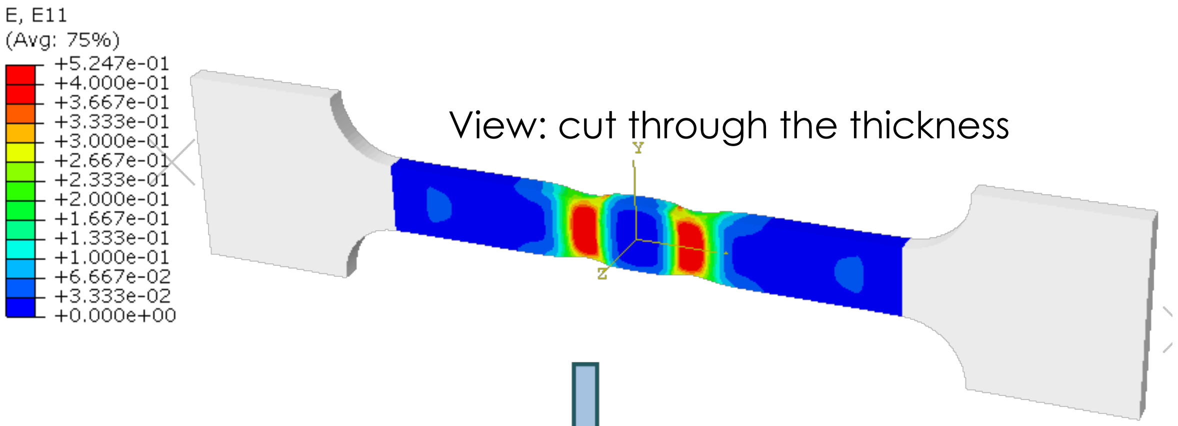
Microcracking $a/b \to 0.75$

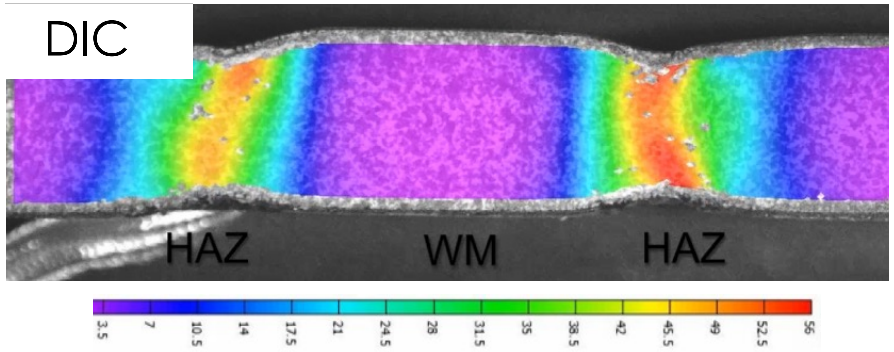
Needleman and Rice, 1980; Onck and van der Giessen, 1998, 1999;

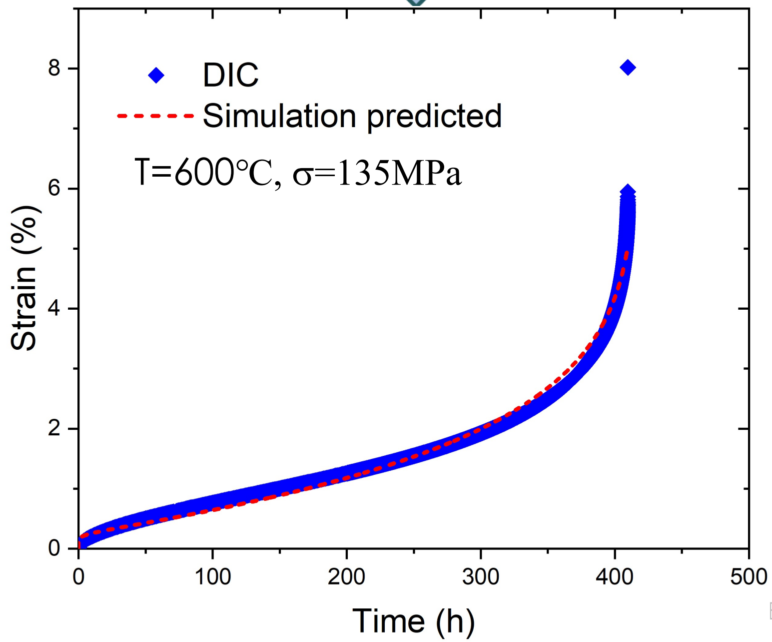
Validation of ORNL's Level I ICWE Creep Model with DIC Experiment

- Finite element model





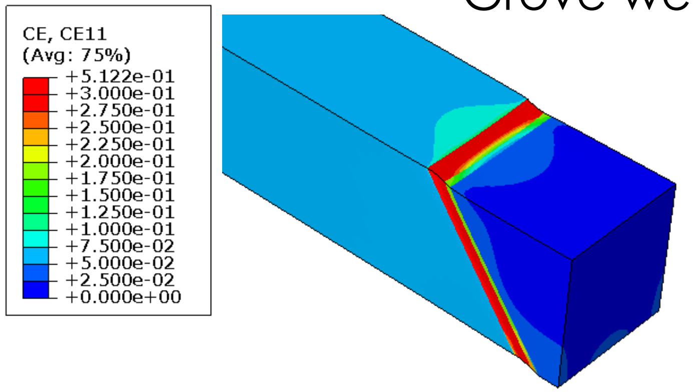




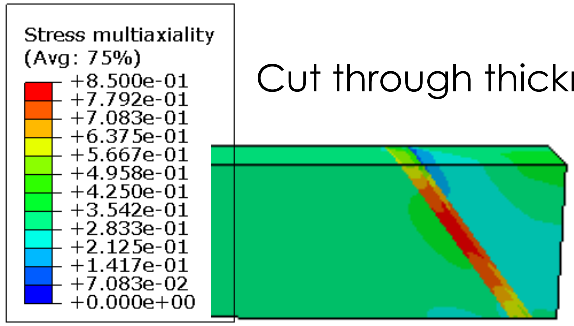
Application of ICWE Creep Model: EPRI's improved weld configuration

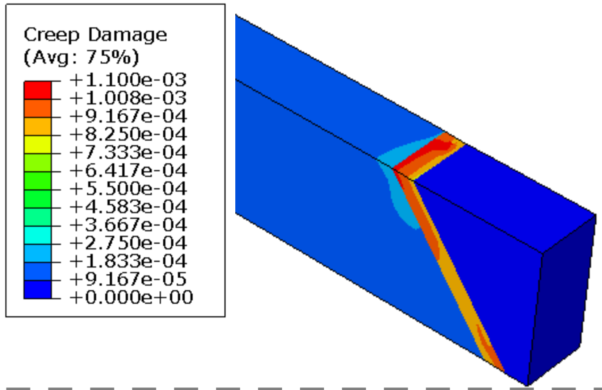
- **Creep strain**
- **Stress triaxiality**
- **Creep damage parameter ω**

Grove weld

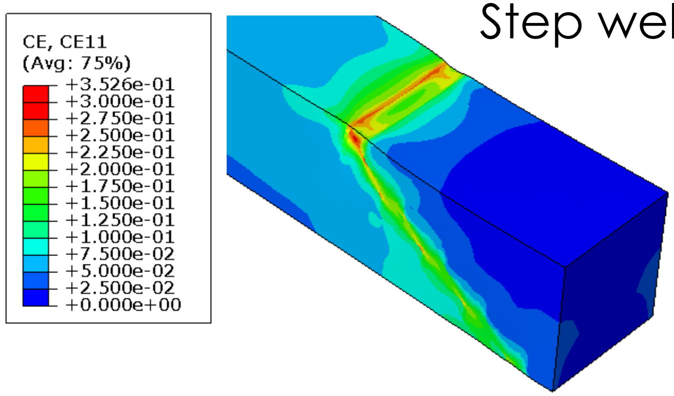


Cut through thickness

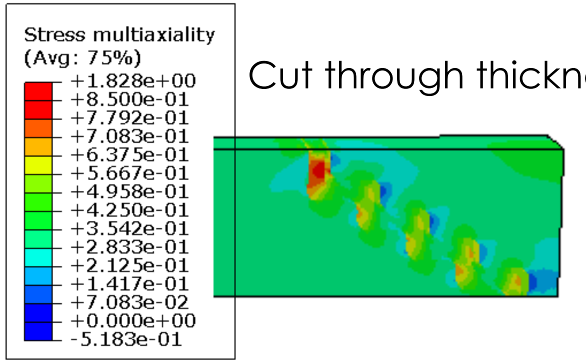


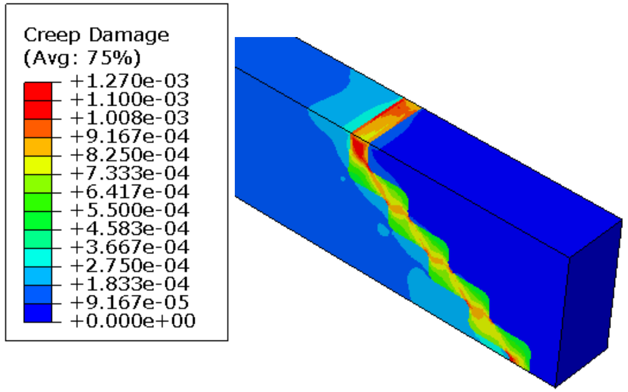


Step weld



Cut through thickness

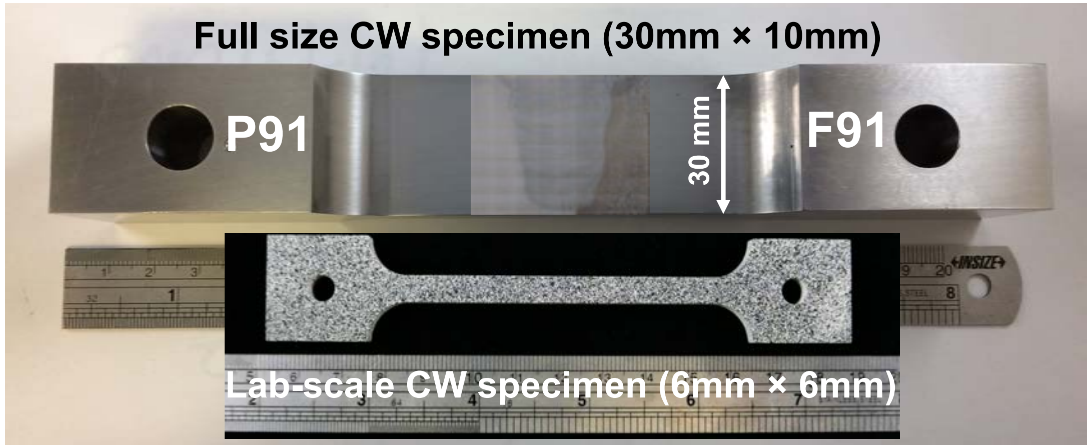


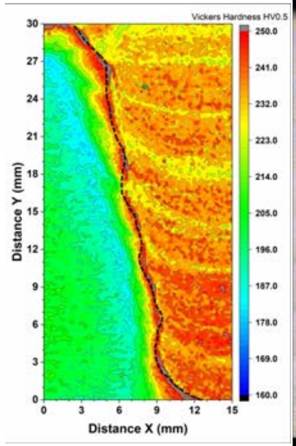


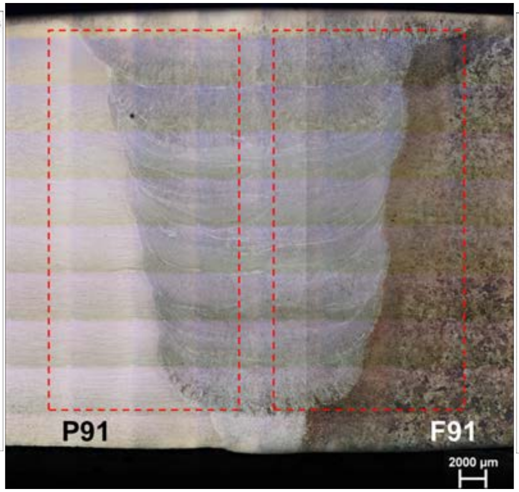
(Same contour scale for grove and step weld)

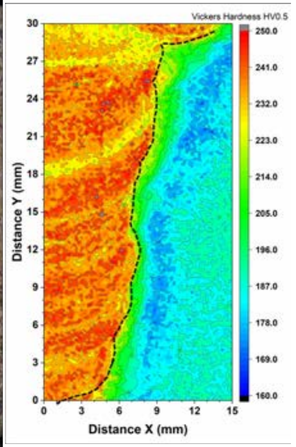
EPRI EEM project: Ex-service Grade 91 forging (F91)-Grade 91 piping (P91) header

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



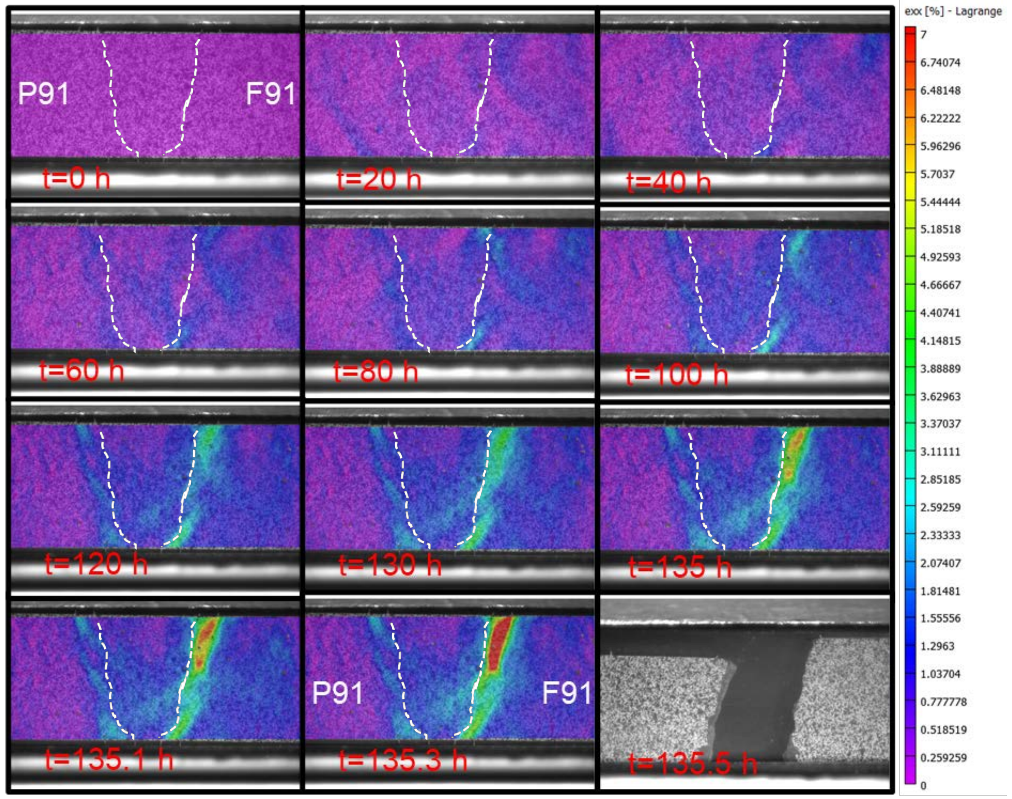




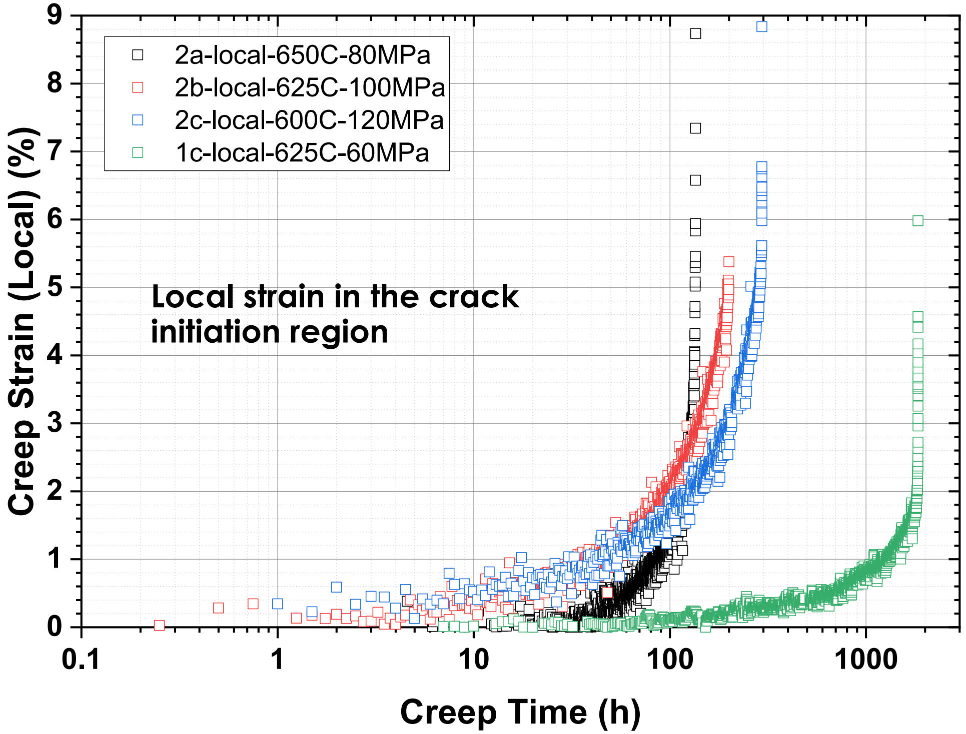


- Need for full size cross-weld test necessitated upgrade of testing system
  - ✓ Constraint effect plays a significant role in creep deformation mechanism
  - ✓ Nonuniform weld configuration and microstructure along the wall thickness direction

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**

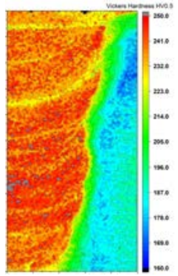
OAK RIDGE National Laboratory

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

Inputs

- Creep property measured on lab samples
- Hardness mapping of actual P91-F91 welds
- Weld geometry



Service condition 575℃, steam pressure of 17.85MPa, running hour 141,000 hours

Level-1model $\dot{\varepsilon} \sim a_0, N_0$

Cavity evolution during service (a^*, N^*)

Remaining life assessment

Level-1model $\dot{\varepsilon} \sim a^*, N^*$

Outputs

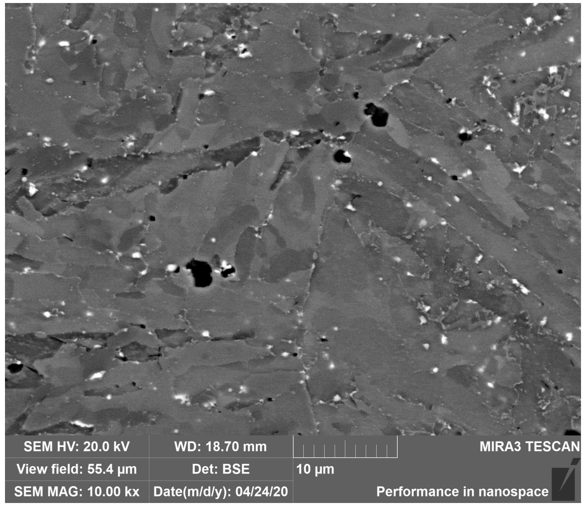
Creep strain map

Failure location

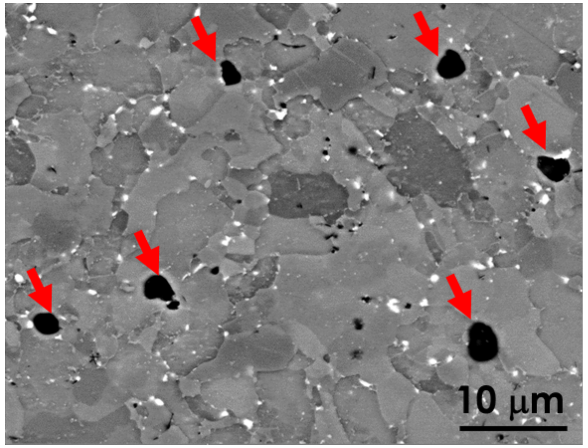
Remaining life

ICWE Level 1 Model is capable to predict creep voids formed during 140,000hrs service

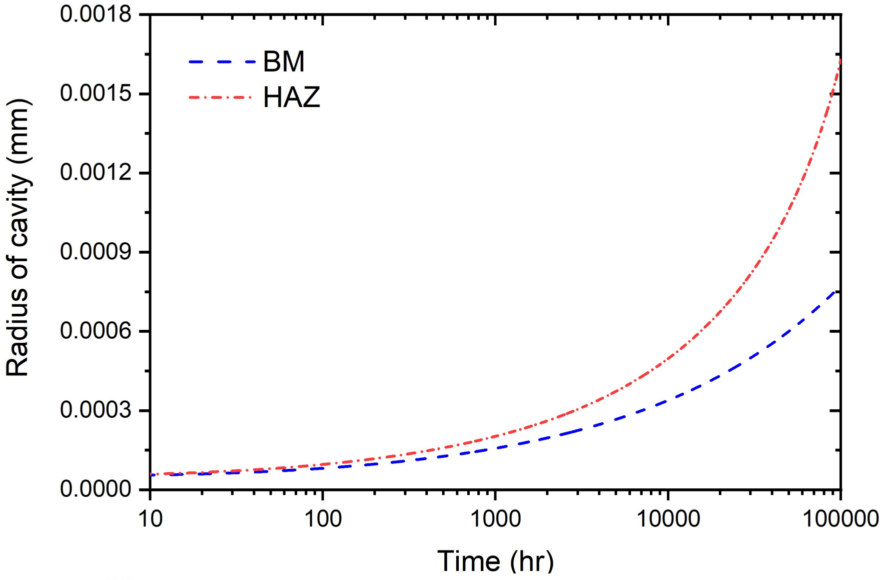
BM

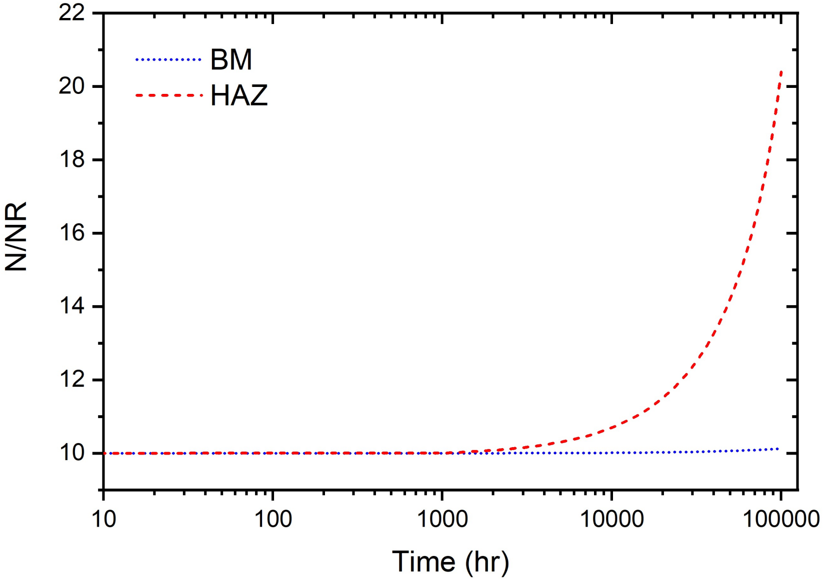


HAZ

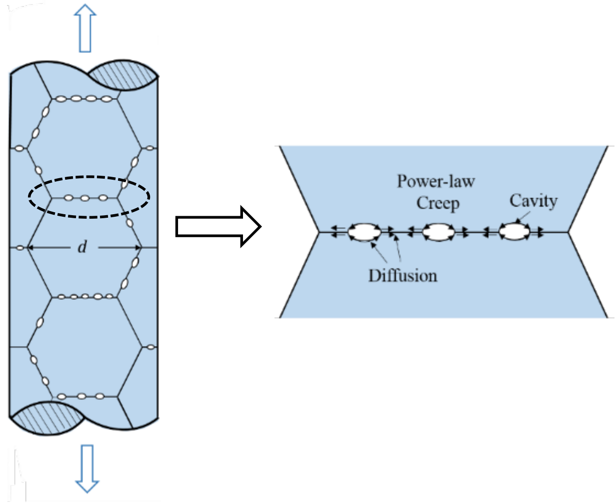


575℃, 25MPa for 100,000 hours





- **Level-1 model predicts the creep cavitation behavior by accounting for the cavity nucleation and growth**



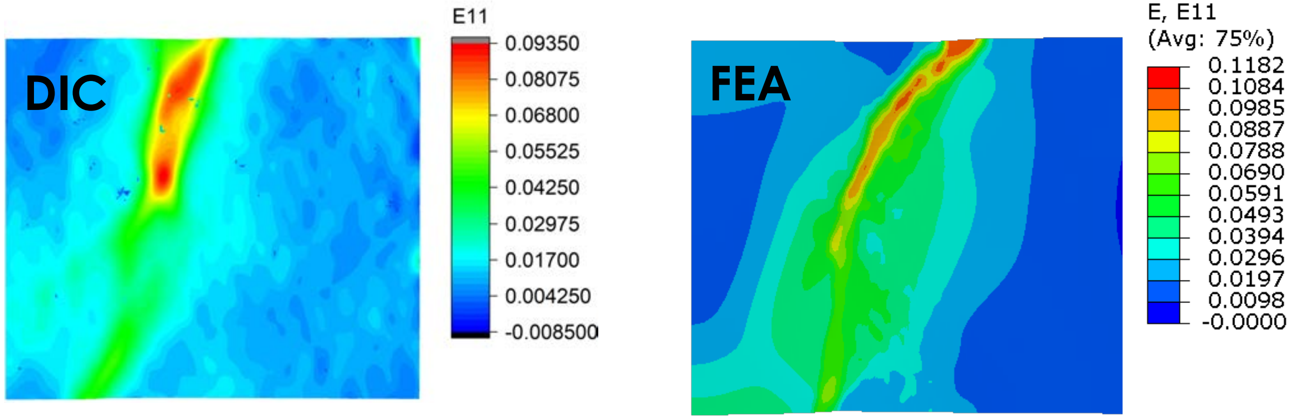
Initial condition

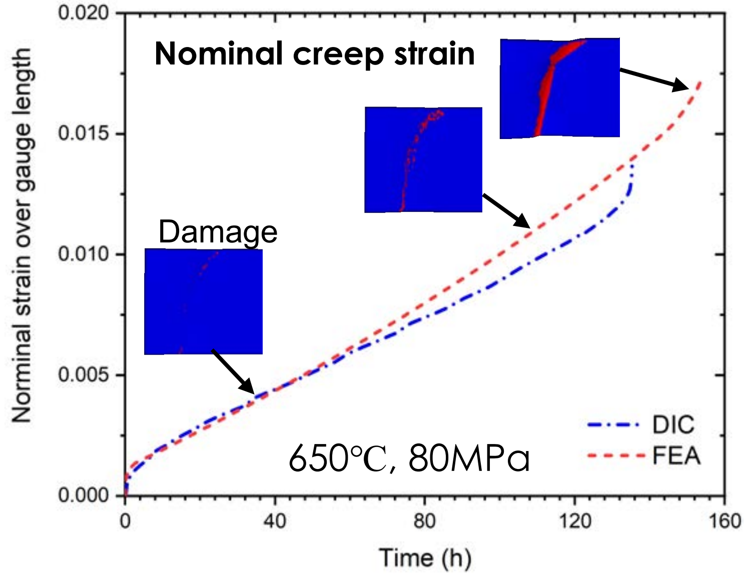
$a_0 = 0.05\ \mu m,\ b_0 = d,$

$d_{BM} = 10\mu m, d_{FGHAZ} = 2\mu m$

OAK RIDGE National Laboratory

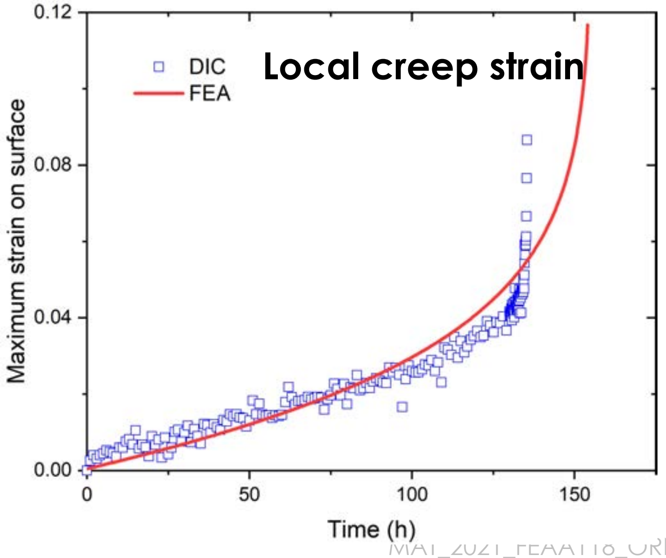
Level 1 Model is capable to predict the deformation and remaining life of the P91-F91 cross weld after service conditions



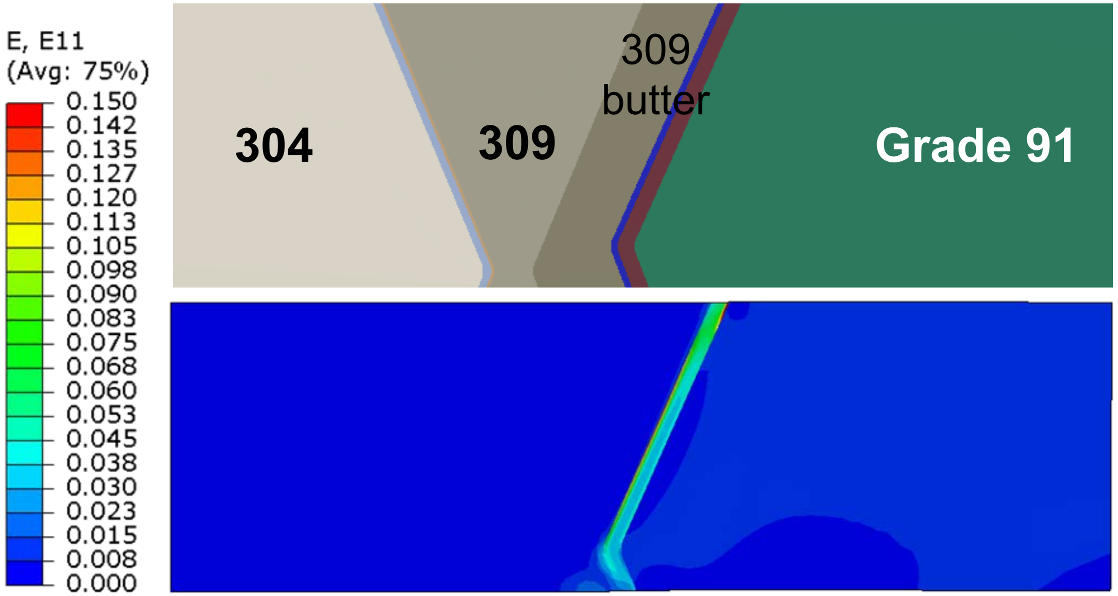


Test ID	Temperature (℃)	Stress (MPa)	Failure life, hrs experiment	Predicted Life, hrs
2a	650	80	135.5	154.1
2b	625	100	200.0	296.8
2c	600	120	294.5	419.3
1c	625	60	1843.0	2702.3

- 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

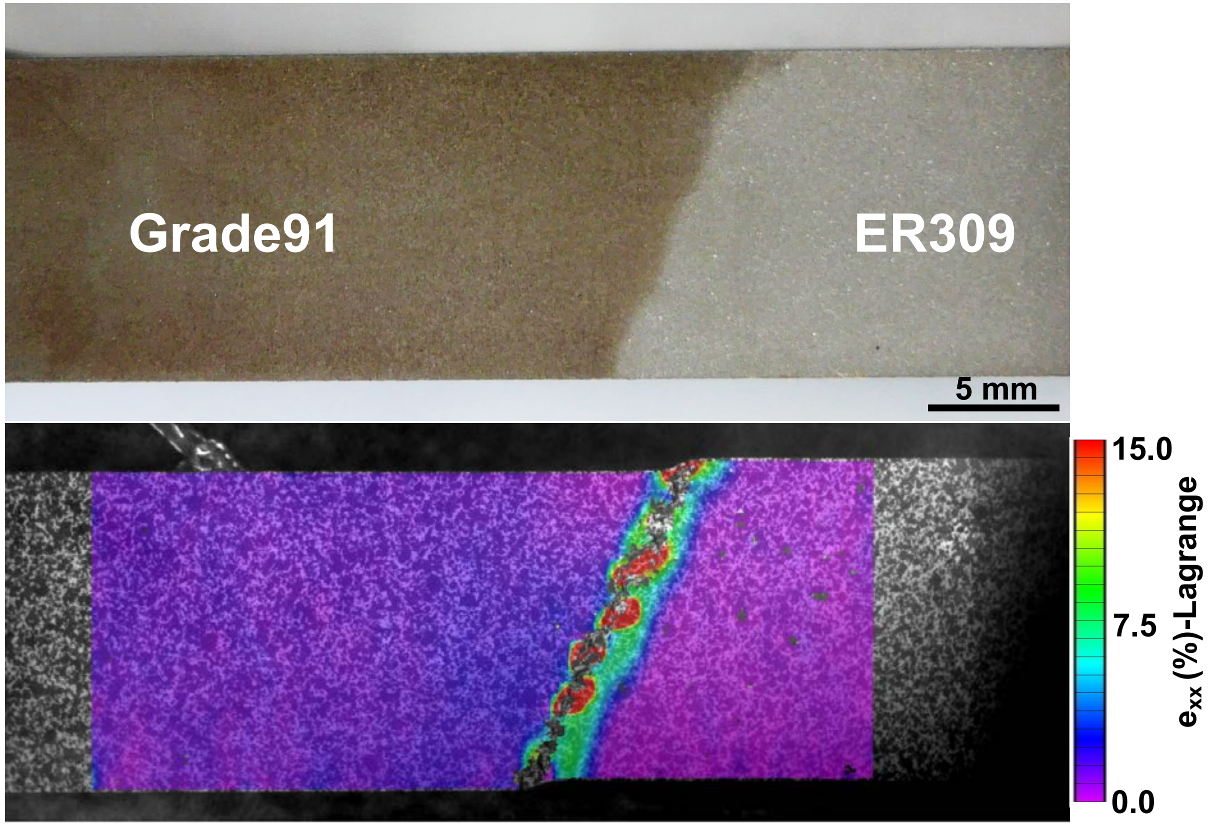


Application to prediction of creep strain accumulation and rupture life of dissimilar metal weld at 650 °C and 90 MPa



t = 200 h

Predicted life of conventional DMW: **230** hrs, failure at the weld interface in the G91 HAZ



Actual Experiment: Failed at **214** hrs in the G91 HAZ at the interface

Summary

- **Accomplishments so far**
  - Successfully developed and demonstrated an ICWE modeling tool for creep deformation and failure in CSEF structure welds
  - Developed new experimental approach and testing systems to understand the highly inhomogeneous creep deformation and failure of CSEF welds, and to determine the local creep properties essential for ICWE model
  - Applied the ICWE modeling tool in this and several other related projects and with plan to expand for industry applications
- **FY21 Activity**
  - Complete the remaining creep testing planned for EPRI EMM. Why P91 is better than F91?
  - EPRI $45K contribution

Publications:

- Total 23 journal and conference proceedings from this project so far, working on 5-6 journal papers
- Selected Journal Publications
  - Yiyu Wang, Wei Zhang, Yanli Wang, Yong Chae Lim, Xinghua Yu, and Zhili Feng. Experimental Evaluation of Localized Creep Deformation in Grade 91 Steel Weldments. *Materials Science and Engineering A*, 799 (2021) 140356.
  - Yiyu Wang, Wei Zhang, Hui Huang, Yanli Wang, Weicheng Zhong, Jian Chen, Zhili Feng. Clarification of Creep Deformation Mechanism in Heat-Affected Zone of 9Cr Steels with In Situ Experiments. *Scripta Materialia, 194 (2021) 113640*.
  - Yiyu Wang, Wei Zhang, Yanli Wang, and Zhili Feng. Microstructure and Mechanical Properties of Intercritically Treated Grade 91 Steel. Materials, 13 (2020) 3985.
  - Zhang, W., Wang, X., Wang, Y., Yu, X., Gao, Y. and Feng, Z., 2020. "Type IV failure in weldment of creep resistant ferritic alloys: I. Micromechanical origin of creep strain localization in the heat affected zone". Journal of the Mechanics and Physics of Solids, 134, p.103774.
  - Zhang, W., Wang, X., Wang, Y., Yu, X., Gao, Y. and Feng, Z., 2020. "Type IV failure in weldment of creep resistant ferritic alloys: II. Creep fracture and lifetime prediction". Journal of the Mechanics and Physics of Solids, 134, p.103775.

Impact to Other Projects

- ICWE model and special weld creep testing system played key role to the success of FEAA372 “Innovative Solid-State AM transition joint”
  - Modeling tool was used to design the transition joint for both creep life and thermal fatigue life improvement
  - Weld creep testing system confirmed the model prediction and improved life compared to reference conventional DM weld
- The ICWE model developed in this project was extended to include creep-fatigue and thus provided a more detailed model than was originally planned in FEAA115
- EPRI plans to develop fitness for service based life prediction tool based on ORNL’s ICWE modeling approach

Thank you!

ORNL is managed by UT-Battelle, LLC for the US Department of Energy