Weldability of Creep-Resistant Alloys for Advanced Fossil Power Plants

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Objectives

• Focus on two critical welding challenges for creep-resistant alloys for A-USC/USC
  – Reduced creep strength in the weld regions of CSEF (primary focus)
  – Joining of dissimilar metals

• Develop a modeling tool to predict local creep deformation and failure in welded structures in operation
  – Development of localized creep deformation measurement (ORNL weld creep test)
  – Understand phase transformation and failure mechanism of welded CSEF steels
  – Expand Integrated Computational Welding Engineering (ICWE) modeling capability for creep performance
  – Develop practice solutions to address weld degradation and predict life of welded structures.
Outline

– Limitations in conventional cross-weld creep testing
– Full-field creep deformation measurement
– Failure mechanism of welded CSEF steels
– Integrated Computational Welding Engineering (ICWE) modeling capability for creep performance
– Conclusions
Type IV failure of Grade 91 steels

- Life of weldments shorter than Base Metal.
  - Type IV failure shortens the material life, caused by weakened microstructure at HAZ.

Due to localized deformation, conventional cross-weld testing has limitations.
Minimum Creep Rate in Cross-Weld Creep Testing

Monkman-Grant relationship

\[ \dot{\varepsilon}_{ss}^m t_R = C_{MG} \]
Full Field Creep Strain Mapping is Needed

• To capture creep behaviors in different regions
  – “True” weld minimum creep rate
• To obtain creep parameters in different regions for modeling
• To validate model results
• To correlate creep deformation to microstructure and mechanical properties
ORNL’s weld creep test technique
Strain Distribution Measurement in Literature

Measuring indents distance by interrupted creep tests

Time-consuming
Low accuracy
1D distribution
Indentation may affect the final result
Our Approach: Digital Image Correlation (DIC)

• DIC, a full-field deformation measurement method can be applied to measure strain distribution in a cross-weld sample

• “DIC is an optical method that employs tracking and image registration techniques for accurate 2D and 3D measurements of changes in images”*

Experimental Setup (Gleeble + DIC)

• Samples were painted with speckles for surface strain measurement
• Images were taken 1 image/60s for the first 12 hours and 1 image/300s for the rest 78 hours.
Creep Strain Evolution

Significant strain concentration is shown after 30 hours of test
Creep Strain Distribution Comparison

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

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

70MPa @ 650C
Creep deformation evolution in different locations

Graph showing strain over time for different locations and conditions:

- **Non-Standard overall**
- **Standard overall**
- **Standard HAZ**
- **Non-Standard HAZ**
- **Standard BaseMetal**
- **Non-Standard BaseMetal**
- **Non-Standard WeldMetal**
- **Standard WeldMetal**

Conditions: 650°C/70 MPa

Markers:

1. **Standard WM**
2. **Standard HAZ**
3. **Standard BM**
4. **Non-Standard WM**
5. **Non-Standard HAZ**
6. **Non-Standard BM**
Traverse Creep Strain Distribution Comparison

Standard heat treatment (1040/760/760)

Modified heat treatment (1040/650/760)
Micro-hardness vs. Creep Strain

Highest creep deformation region is not the weakest.
Strain-Microstructure Correlation

Coarse carbides in “standard” weld and fine carbides in “modified” weld
Minimum Creep Rate in Cross-Weld Creep Testing

Monkman-Grant relationship

\[ \dot{\varepsilon}_{ss}^m t_R = C_{\text{MG}} \]
Minimum Creep Rate in Cross-Weld Creep Testing

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\[ \dot{\varepsilon}^m_{SS} t_R = C_{MG} \]
Advantages of ORNL weld creep test

- Localized creep deformation measurement

Total creep strain after 90 hours

Local creep strain after 90 hours

- Local creep strain can be easily correlated to local microstructure
Understanding Failure Mechanism of Welded CSEF Steels
Previous Study on Grade 91 Show Dispersion of Fine Carbides is the Key

Simulated HAZ heat profile during high energy X-ray diffraction scan

In-situ Diffraction Study at SPring-8 showed carbide evolution in FGHAZ

Does martensite sub-structure play a role in creep?
Orientation Maps of Crept Sample

BM
WM
FGHAZ
Misorientation Angles

BM before creep

BM after creep

WM after creep

FGHAZ after creep
Develop ICWE Modeling Capability
Integrated Modeling of Materials, Processes and Properties

Friction stir welding: Mechanic deformation
Ultrasonic welding: 20~50 kHz vibration
Advanced fusion welding: Heat & melt flow
MagPulse welding: Electromagnetic force

Process & materials
Fluid flow
Mechanics
Metallurgy
Electromagnetics
Heat transfer
Property & performance

Non-destructive evaluation
Cost modeling: Design for assembly & manufacturing
Model automation for technology transfer

Expend our capability to cross-weld creep modeling
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

Performance simulation of a high strength steel weld
Initial FEA model

• 2-dimension axisymmetric model
• 4 distinct regions: WM, CGHAZ, FGHAZ, WM
• Power law creep
FEA model

- Initial feasibility 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)](image)

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

![Graph showing equivalent creep strain distribution with distance from the middle (mm) for different times: 0 hour, 1000 hour, 2022 hour, and 2763 hour. The graph includes regions labeled WM, CGHAZ, and FGHAZ, representing different zones within the material.](image-url)
Steep stress gradient at the interface between different regions. Gradual properties transition need to be considered.
Next step model development

- Include gradual mechanical properties transition from WM to BM.
- Establish the relation between microstructure and creep properties in different region of the weld.
- The mechanical properties used in the model, especially creep properties of different regions need to be further re-evaluated by experiments.
Power Law Parameters Obtained by DIC

Strain rate can be extracted from each individual location
Creep constitutive equation parameters can be obtained
Milestones

• 9/30/14 Demonstrate ICWE modeling capability to capture local creep deformation and failure in a representative cross weld tensile ✔

• 3/31/15 Improve and standardize the ORNL weld creep test procedure and demonstrate its effectiveness to quantify the non-uniform creep deformation behavior in Grade 91 steel weldments ✔

• 6/30/15 Establish the relationship between the local microstructure/stress evolution to creep deformation in weldments in Grade 91 steels using ORNL weld creep test and in-situ neutron/synchrotron techniques. (depends on beam time allocation)

• 9/30/15 Complete next stage of ICWE model development and demonstrate its capability to predict local creep deformation and failure in ORNL weld creep test (on track)
Conclusions

• ORNL weld creep test has successfully been used to measure localized creep deformation.

• Local strain is correlated to hardness and microstructure.

• FEA model of cross-weld sample is being established with consideration of gradual properties change

• Stability of martensite substructure and higher angle boundaries play an important role in Type IV failure
Backup Slides
HAZ Creep Rate

![Graph showing HAZ creep rate over time](image)
New Sample Geometry
Dissimilar Metal Welds

316L  82  2.25Cr1Mo
Dissimilar Metal Welds

316L  82  2.25Cr1Mo

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The graph shows the temperature (°C) over time (s) for different materials: SS316, Alloy 82, and T22.
Damage prediction

\[
\frac{d\varepsilon_c}{dt} = \frac{3}{2} A \left[ \frac{\sigma_{eq}}{1 - \omega} \right]^n \frac{S_{ij}}{\sigma_{eq}} t^m
\]

\[
\frac{d\omega}{dt} = \frac{M \left[ \alpha \sigma_1 + (1 - \alpha) \sigma_{eq} \right]^\kappa}{(1 + \phi)(1 - \omega)^\phi} t^m
\]
Hot Tensile Testing

Original painting

Improved painting