Creep-Fatigue-Oxidation Interactions: Predicting Alloy Lifetimes Under Fossil Energy Service Conditions

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Power Plants Will Need to be Capable of Flexible Operation

- Frequent (~daily) load cycling will result in significant creep-fatigue interaction

Project focus on 3 key areas
- Long term creep fatigue testing and lifetime modeling
- Interactions among creep fatigue and oxidation
- Study of microstructurally small cracks under creep-fatigue loading
Interaction of Creep & Fatigue Damages in Gr.91

Sub grain coarsening / Dislocation density decrease
Creep performance significantly affected by strain cycling*

Effect of oxidation on crack initiation during Creep-Fatigue

- Fast crack initiation due to cracking of the scale & propagation in the alloy
- Much thicker non protective scale in air due to cracking

*Fournier et al., Int. J. Fatigue 2008, M&M Trans A 2009
Decrease of $N_f$ with Hold Time for Creep-fatigue Tests at 625°C, ±0.5%

- Faster softening with increasing hold time
- Significant decrease of number of cycles to failure with longer hold time (>3000h test)
Significant Stress Relaxation During 10h Hold Time

- Need ~ 1.5h to reach a nearly steady state stress
- Creep lifetime at 625°C, 100MPa ~5000h
Linear Decrease of “Steady Stress” for 10h Hold Time Test After ~30 cycles

Significant softening due to cycling
Significant Effect of Cycling on Scale Growth

130h, 720 cycles

3,500h, 350 cycles

±0.5%, 10min

500 μm

100 μm

±0.5%, 10h
Multi-Layer Oxide Scale for 10min Hold Time Test

Inner Cr-Rich Scale

Outer Fe-Rich Scale

Affected zone

Oxide scale at specimen surface
Interaction Between Crack Propagation & Creep Cavitation for ±0.5%, 10h Hold

Lower cycle to failure for 10h hold time test is likely due to
- Fast crack initiation due to oxide scale cracking
- Effect of creep cavitation on crack propagation
New Test Facility to Evaluate LCF Resistance in Aggressive Environments

Stress-strain curve, 9Cr-1Mo ferritic steel, 625°C, fully reversed 1% total deformation, Steam

Sealed chamber inside furnace and extensometer to provide feedback signal for system operation under strain control
Limited Effect of Steam on the HCF Behavior of Gr.91

- Very similar softening in air and steam
- Gr91 oxidation rate is known to be drastically affected by H$_2$O
- New batch of Gr.91 alloy showing lower N$_f$
Decrease of Nf for Creep-Fatigue Test in Steam with 10min hold time

Still working on testing procedure to improve post test microstructure characterization
Very Oxidized Cracks in Steam

42h Air

±0.5%, 10min

20h Steam

Affected area
Further Curve Analysis + Upgrading the Steam Rig

- Scale growth depends on environment and cycling time
- Fournier et al. simple assumption that crack initiates at t=0 when thicker scale is observed
- Crack initiation leads to more complex stress state
- Lowering noise + Making the steam rig operator-friendly
Limited Effect of Load Cycling on Gr.91 Creep Properties

- 0MPa
- 21MPa
- 210MPa
- 10h
- 10min
- Cyclic
- Standard
- Cyclic
- Standard
- 15,000h interrupted

Strain(%)

Time(h)
Significant Variation of Gr.91 Creep Properties

ORNL Gr.91 development program

\[ \log t_r = C_h - 0.0231\delta - 2.385 \log \sigma + 31,080/T, \]

550°C, 210MPa

Leftover specimens from original Gr. 91 program
Switching from Standard to Cyclic Testing Does Not Impact Creep Rate

- No effect of load cycling: cyclic damage requires strain cycling
- Best testing conditions would be fully reverse creep-fatigue testing using thermomechanical machines
- Ongoing microstructure characterization

Standard, $7.4 \times 10^{-5} \, \%/h$
Cyclic $7.1 \times 10^{-5} \, \%/h$
New Set up to Study Microstructurally Small Crack Growth at High T°C

- Sumit Bahl’s work (Indian Institute of Science)
- Slower propagation for small cracks
- Crack initiation at room temperature
- High cyclic fatigue & creep fatigue testing
- In Situ imaging of crack propagation
- Tests conducted at Room and 550°C
Crack Growth Imaging at Room T°C

300μm
No Effect of Frequency & Hold Time on Small Crack Propagation

Crack arrest with 100s or 10min hold time

Effect of oxidation or decrease of dislocation density at crack tip?
No Acceleration or Retardation & Arrest of Crack Growth in Grade 91 Steel is Unusual

Jha and Caton, Int J Fatigue 2010

Strong effect of dwell time (6 s) in IN100
Plastic Relaxation at the Crack-tip a Possible Mechanism?

Low cycle fatigue  Low cycle creep-fatigue (10 s hold time)

(a) Cycle # 1  Cycle # 100

(b) Cycle # 1  Cycle # 100

Stress (MPa)  Strain (%)

-400 -200 0 200 400
-0.4 -0.2 0.0 0.2 0.4

All high temp data at 550°C
Near the racture surface the dislocation densities are lower (cyclic softening)

EBSD IQ + KAM maps for 550°C FCG tested specimens

Faster decrease of dislocation density at crack tip for creep-fatigue specimens?
The average sub-grain size measured using the TEM micrographs for the as-received, low cycle fatigue and low cycle creep-fatigue tested specimens (10 sec hold time) are 220 ± 80 nm, 310 ± 130 nm and 360 ± 120 nm.
Significant Oxidation at the Crack Tip During Testing

Depending on the scale (Fe or Cr-rich), oxidation at 550ºC can be very fast. Oxidation-induced crack closure?
Modeling can show why 3 factors are important

- Stress relaxation may reduce monotonic crack tip displacement, oxide scale may wedge the crack and microstructural coarsening may reduce the crack tip displacement density.

- All three mechanisms lead to reduction of monotonic and cyclic crack tip displacements that can lead to retardation and/or arrest.

* Shyam et al. FFEMS 2014 for tool steels
Conclusion

Significant effect of hold time on Gr.91 fatigue lifetime

- Fast crack initiation due to oxide formation and cracking

Combined effects of strain cycling and environment. No existing model?

- Interaction between cavity formation & crack propagation

Collaboration with FEAA118 (next presentation) on modeling microstructure evolution and its effect on cavity formation

Long term cyclic creep has limited effect on Gr.91 creep strength

Relevant testing requires strain-controlled cycling with electro-mechanical machines

No effect of hold time on small crack growth

Demonstrated thermo-mechanical testing

Temperature variation during hold time