Modeling Creep-Fatigue-Environment Interactions in Steam Turbine Rotor Materials for Advanced Ultrasupercritical Coal Power Plants

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High temperature rotor application

- High temperature steam
- High stress concentration at bucket connection
- DOE's goal: A-USC 1400F capability (5000 psi steam, 20+years)
- Candidate alloy: 282
Overall goal and tasks of the program

Creep-fatigue-environment interactions of Alloy 282

• Fatigue performance in steam and air environment
  • Hold-time fatigue experiment (Task 2)
  • Hold-time fatigue FEM modeling (Task 6)
  • Fundamental understanding at crack tip (Task 2,3)
• Creep performance
  • Creep modeling & prediction (Task 5)
  • Long-term microstructure stability & interaction with defects (Task 4)
Tasks of the program

Creep-fatigue-environment interactions of Alloy 282

• Fatigue performance in steam and air environment
  • **Hold-time fatigue experiment (Task 2)**
    • Establish relationship between crack growth and LCF for Alloy 282
    • Predict LCF behaviors in steam and air
  • Hold-time fatigue FEM modeling (Task 6)
  • Fundamental understanding at crack tip (Task 2,3)

• Creep performance
  • Creep modeling & prediction (Task 5)
  • Long-term microstructure stability & interaction with defects (Task 4)
Alloy 282 hold-time fatigue mechanism understanding (Task 2)

Time Dependent Fatigue Crack Propagation

Hold time fatigue can generally be categorized into cycle dependent behavior, time dependent behavior, and in some cases, a combination of the two.
If we have crack growth data like this:

Then we expect LCF data to be:

Hold-time effect can manifest itself in LCF as well.

- Coarse grain Ni-base superalloy @ 1000°F
- 1s load/unload period + hold time
- 0.75% strain range
Need to establish:
• Initiation criteria and short crack growth behavior
• Upper bound of time independent and time dependent curves

Goal: Calculate smooth bar LCF life by integrating time-independent and time-dependent crack growth curves
Hold-Time-Sweep Testing

**Alloy 282 Air**

- **ΔK = 25ksi*in^{1/2}**
  - Load Ratio: 0.1
  - 1600°F
  - 1400°F
  - 1200°F

**Alloy 282 Steam**

- **ΔK = 25ksi*in^{1/2}**
  - Load Ratio: 0.1
  - 1400°F
  - 1200°F

- **Effect of steam** apparent at 1200°F, for cyclic periods greater than 100 seconds
- **Effect of steam** apparent at 1400°F, for cyclic periods greater than 3 seconds
- **1600°F air behavior** shows fully time dependent crack growth beyond 1000sec cyclic period

**1600°F/Air selected to evaluate the relationship between crack growth and LCF**
Preliminary Results: Building LCF/FCGR Correlation

1600F/Air

Hold-time effect manifested in Alloy 282 FCGR and LCF behavior
Tasks of the program

Creep-fatigue-environment interactions of Alloy 282

- Fatigue performance in steam and air environment
  - Hold-time fatigue experiment (Task 2)
- Hold-time fatigue FEM modeling (Task 6)
  - Calibrate 282 bulk material response for ANSYS
  - Predict crack propagation with/without hold-time, different strain ratios
  - Fundamental understanding at crack tip (Task 2,3)
- Creep performance
  - Creep modeling & prediction (Task 5)
  - Long-term microstructure stability & interaction with defects (Task 4)
Hold-time fatigue FE modeling (Task 6)

Constitutive material modeling

Finite Element simulations

Crack tip plasticity history

Identify material's cyclic, SPLCF elastic-plastic response

Perform ONE Fatigue Crack Growth Test (CT geometry)

Goal: Predict crack growth rate for different R-ratio conditions, with and without hold time
Fatigue and crack propagation FE modeling (Task 6)

**Calibrate Chaboche rate-dependent material model in ANSYS**
- SPLCF: 4 RB specimens
- 20CPM ramps w/ 6hr holds at max strain
- Strain ranges: [0, 0.0125], [0, 0.01], [0, 0.008], and [0, 0.007]
- Strain ratio: \( R = 0 \)
- 1400F

**Calibrate Chaboche rate-independent material model in ANSYS**
- LCF: 15 RB specimens
- Strain ranges*: [0.011], [0.0085], [0.0065], [0.005], [0.004]
- Strain ratio: \( R = 0 \)
- 1400F

*Strain ranges: \([0, \varepsilon_0, \varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4] \) for LCF

**Confined crack-tip plasticity model to predict crack growth rate**
- FCP: 11 CT specimens
- 20Hz, Environment: Lab air
- K increase and K shed tests
- Load ratio: \( R = 0.05, 0.25, 0.5, 0.9 \)
- 1200F, 1300F, 1400F
- Crack measurement technique: DC Potential drop (ASTM E647-08)

Calibrate model and predict crack growth
Tasks of the program

Creep-fatigue-environment interactions of Alloy 282

• Fatigue performance in steam and air environment
  • Hold-time fatigue experiment (Task 2)
  • Hold-time fatigue FEM modeling (Task 6)

• Fundamental understanding at crack tip (Task 2,3)
  • FIB/TEM: oxidation characteristics in air & steam
  • Ab initio/atomistic:
    • Oxidation-crack tip interaction, controlling mechanisms to hold-time effect
    • Oxygen diffusivities, energetics & kinetics (input to Tasks 4,6)

• Creep performance
  • Creep modeling & prediction (Task 5)
  • Long-term microstructure stability & interaction with defects (Task 4)
Crack-tip characterization (Task 2), ab initio/atomic modeling (Task 3)

FIB/Lift-out at crack front from 1400F steam specimen
- $\alpha$-Al2O3 filled surface cracks
- Very thin Co-rich oxide at surface
- Bulk of Cr2O3 with lesser Ti

Ab initio/atomic modeling is pursuing:
- Crack tip oxide formation
- Oxygen diffusion in Cr2O3 and paths along GBs & interfaces

Provide microscopic mechanisms and parameters to high-level models
Tasks of the program

Creep-fatigue-environment interactions of Alloy 282

• Fatigue performance in steam and air environment
  • Hold-time fatigue experiment (Task 2)
  • Hold-time fatigue FEM modeling (Task 6)
  • Fundamental understanding at crack tip (Task 2,3)

• Creep performance
  • Creep modeling & prediction (Task 5)
    • Microstructure-based constitutive model
    • Creep curve simulation and present shortcoming
  • Long-term microstructure stability & interaction with defects (Task 4)
Alloy 282 creep mechanism understanding (Task 5)

- Low stress: dislocation looping & climb,
- Higher stress: γ' shearing
- Microtwinning at very low stress, low temperature

Dislocation climb-bypass is the main observation at low stresses
Creep experiment

- Historical test data 1375~1450°F, 15,000-40,000 psi
- New testing aimed at low stresses ≤ 15,000 psi
Modeling creep curves

- Current model (Oruganti, 2011) fits rupture times of Alloy 282 at different temperatures
- Does not fit well at low stress regime

→ current focus
Constitutive creep models

Empirical power law
\[ \dot{\varepsilon} \sim A\sigma^n \exp \left( -\frac{Q}{RT} \right) \]

Microstructure based constitutive model of Dyson (climb-bypass)
\[ \dot{\varepsilon} \sim A' \exp \left( -\frac{Q}{RT} \right) \sinh \left( -\frac{\sigma\Omega}{RT} \right) \]

Back stress: \( \sigma \rightarrow \sigma - \sigma_B \)
Activation volume: \( \Omega \sim \lambda_p b^2 \)
Prefactor: \( A' \sim \rho b (b/r_p) \phi_p \lambda_p / \bar{M} \)

<table>
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<tr>
<th>Cond</th>
<th>Stress (Ksi)</th>
<th>Temper (F)</th>
<th>Min. strain rate (10^{-7}/s)</th>
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\( Q \sim 515\text{KJ/mol} \)

Model creep strain curve with microstructure evolution

![Model creep strain curve with microstructure evolution](image)
Microstructure dependence

Solution Annealed

PA = SA + 8h @ 1450°F

Cond. | γ' (nm)
--- | ---
SA | 5-15
PA | 20-50
OA | 40-70

OA = PA + 250h @ 1425°F

Creep strain vs. time curves

PA SA

1400F, 37.5ksi

PA OA

1425F, 27.5ksi

→ more plots

Courtesy Jeff Hawk
Tasks of the program

Creep-fatigue-environment interactions of Alloy 282

• Fatigue performance in steam and air environment
  • Hold-time fatigue experiment (Task 2)
  • Hold-time fatigue FEM modeling (Task 6)
  • Fundamental understanding at crack tip (Task 2,3)
• Creep performance
  • Creep modeling & prediction (Task 5)
  • Long-term microstructure stability & interaction with defects (Task 4)
    • Precipitate size (coarsening)
    • Precipitate spatial distribution & inter-particle spacing
    • Precipitate-dislocation interactions
Microstructure modeling (Task 4)

- Precipitate ($\gamma'$) strengthening
- Size and inter-spacing distributions
- Long-term (>20yr) $\gamma'$ stability

Can predict long-term precipitate size (coarsening)

Precipitation (Langer-Schwartz) model
- $\gamma'$ nucleation, growth, coarsening
- Calibrated to short-term data

(1840F solution + 5C/min cooling + isothermal aging)
Microstructure modeling (Task 4)

- **Phase field model**, nucleation, growth and coarsening
- Actual heat treatment (cooling, aging)
- Length scale: \(2\mu m\) box
- GPU accelerated, 50:1 time ratio at 1400F

Can predict long-term precipitate spatial distribution
Microstructure modeling (Task 4)

- Use same parameters of precipitation model
- No additional calibration

Validate statistical distributions
**Microstructure-dislocation interactions (Task 4)**

- **Creep model:** Back stress, microstructure dependence

- **Mean γ’ size, Inter-particle spacing**
- **Dislocation climb-bypass (one particle)**
- **Many-particle, spatial distribution**

Develop means to incorporate microstructure (evolution) into constitutive creep model
Backup slides
**Phase 1: Hold Time Sweep**
- Establish fully time dependent crack growth rates at four temperatures, three stress levels
- Establish critical cyclic period (for transition to fully time dependent behavior) at four temperatures, three stress levels

**Phase 2: FCP and HTFCP**
- Establish hold time crack propagation threshold at four temperatures
- Establish continuous cycling FCP data at four temperatures

**Phase 3: LCF**
- Establish fully time independent (20cpm) LCF lives at four temperatures
- Establish fully time dependent LCF lives at three temperatures, three hold times
- Construct $N_f$ vs. hold time curves at three temperatures, one strain level

**Goal:** Calculate smooth bar LCF life by integrating time-independent and time-dependent crack growth curves
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Advanced Ultra-Supercritical Steam Turbine

2 Percentage Point Efficiency Gain = 5% CO₂ Reduction

CO₂ Reduction (%)

Net Plant Efficiency (%) (Bituminous Coal, Without CO₂ Capture)

20% reduction in CO₂ corresponds with similar reductions (per MWh) in consumables including coal and limestone (reducing front-end equipment size), flue gas volume (reducing back-end and emission control equipment size), and overall emissions, water use, and waste generation

R. Romanosky, 2010
A-USC Rotor Materials

Projected Alloy 282


Operating Temperatures for SC and USC Technologies