Long-term Creep-Fatigue Interactions in Ni-base Superalloys

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Land-based gas turbines

- drive to increase service temperature to improve efficiency; increase life
- replace large directionally-solidified Ni-base superalloys with single crystal superalloys
CMSX-8: 1.5% Re "alternative 2nd gen alloy" replacing 3.0% Re containing alloys (e.g., CMSX-4, PWA1484)

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Cr</th>
<th>Co</th>
<th>Mo</th>
<th>W</th>
<th>Al</th>
<th>Ti</th>
<th>Ta</th>
<th>Re</th>
<th>Hf</th>
<th>C</th>
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</table>

[Wahl and Harris, 2012]
Thermomechanical Fatigue (TMF)

**Linear In-Phase (IP)**
- Strain, $\varepsilon$ (%)
- Thermal Strain
- Mechanical Strain
- Total Strain
- Time, $t$

**Linear Out-of-Phase (OP)**
- Strain, $\varepsilon$ (%)
- Thermal Strain
- Mechanical Strain
- Total Strain
- Time, $t$

- Plastic Deformation
- Creep
- Oxidation
- Hardening Process
- Cyclic Ageing and Coarsening effects
Effect of $T_{min}$ on OP TMF of CMSX-4

CMSX-4 [001]

CM247LC DS in Longitudinal Dir.

[Kirka, 2014]
Accurate representations of the deformation response highly critical for predicting crack formation
Primary Objectives of UTSR Project

- Creep-fatigue interaction experiments on CMSX-8
- Aging studies and influence of aging on creep-fatigue interactions
- Crystal viscoplasticity to capture the deformation response
Creep-Fatigue Interaction Studies

- Conventional creep-fatigue (baseline)
  - ASTM E2714-09
- Long-term creep followed by fatigue
- Fatigue followed by long-term creep
- Impact of pre-aging
- Creep-fatigue interaction life analysis
- Orientations: <001>, <111>, <011>
- Application to TMF with long dwells
Influence of stress and temperature on modes of creep deformation

Rafting – transport of matter constituting the γ phase out of the vertical channels and into the horizontal ones (tensile creep case)

Tertiary – dislocation activity restricted to a/2<110> form operating on {111} slip planes in the γ channels

Primary – γ' particles are sheared by dislocation ribbons of overall Burgers vector a<112> dissociated into superlattice partial dislocations separated by a stacking fault; shear stress must above threshold stress (about 550 MPa – uniaxial normal stress)

[Reed, 2006; Ma, Dye, and Reed, 2008]
Asymmetry in Creep at 750°C/750 MPa

Note: Primary Creep Regime (based on tension)

[Tsuno et al., 2008]
Asymmetry in Creep at 900°C/392 MPa

Note: Tertiary Creep Regime (based on tension)

[Tsuno et al., 2008]
Creep of CMSX-8

- LMP = 24.70
- Life to rupture = 98.90 hrs.
- Temp = 850°C
- Stress = 650 MPa
- Alpha = 4.1
Creep of CMSX-8 – Tertiary Creep Regime

801-11B

Virgin CMSX-8 Specimen 801-11B
T=900°C Stress=392 MPa

- LMP=26.57
- Life to rupture = 451.78 hrs.
- Temp = 900°C
- Stress = 392 MPa
- Alpha = 5.8
Influence of prior creep & fatigue on creep

PWA1484 exposed to 871°C for 32 hrs also reduces primary creep

[Wilson & Fuchs, Superalloys 2008]
Microstructure Evolution in Blades

Distance from Root

in phase
out of phase

2 cm

25 μm
10 μm
2 μm
Rafting and Coarsening of $\gamma'$

Rafting and coarsening of $\gamma'$ is a microstructural transformation observed in superalloys. The image shows different macroscopic states of $\gamma'$ precipitation under tension and compression. The mathematical equation for the rafting parameter $\delta$ is given by:

$$\delta = \frac{2(a_{\gamma'} - a_\gamma)}{a_{\gamma'} + a_\gamma}$$

where $a_{\gamma'}$ and $a_\gamma$ are the misfit misfits of the $\gamma'$ phase with the matrix.

The CMSX-4 alloy is used in the experiments, and the results are compared under different conditions such as temperature, stress, and time.

[Epishin et al., 2010]
Microstructure after tensile creep at 950°C/185MPa for different times

<table>
<thead>
<tr>
<th>Initial</th>
<th>A: time=150 Hours strain=0.06% R=0.55</th>
<th>B: time=280 Hours strain=0.07% R=0.69</th>
<th>C: time=550 Hours strain=0.27% R=0.94</th>
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<td>CMSX-4</td>
<td><img src="image1.png" alt="Image" /></td>
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<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
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</tbody>
</table>

$R = \frac{L}{2T}$

[Matan, Cox, Rae, & Reed, 1999]
Rafting in the “elastic” regime

Controlled by difference between the elastic strain energy in the horizontal and vertical $\gamma$ channels.

Material transport driven by gradient in elastic strain energy density (“elastic” regime when plastic strain < 0.1%).
Rafting in the “plastic” regime

- Dislocations in the horizontal channels (tensile creep case) and their adsorption at the γ/γ' interfaces, resulting in loss of perfect coherency and reduction in elastic misfit strains, is responsible for providing the kinetic path to enable rafting to occur at a reasonable rate.
- Rate in this regime is largely independent of whether the applied stress remains acting or not.
### Influence of aging without applied stress

**CMSX-4**

<table>
<thead>
<tr>
<th>$\sigma = 185\text{MPa}$</th>
<th>$\sigma = 0\text{ MPa}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>time</strong> = +100 hrs</td>
<td><strong>time</strong> = +300 hrs</td>
</tr>
<tr>
<td><strong>time</strong> = +600 hrs</td>
<td></td>
</tr>
</tbody>
</table>

**B**
- time = 280 hrs
- strain = 0.07%

**C**
- time = 550 hrs
- strain = 0.27%

[Matan, Cox, Rae, & Reed, 1999]
Note: The significant drop in hardness at 0.1% creep strain, representing the threshold strain, is attributed to the loss of coherency of the $\gamma/\gamma'$ interfaces because of misfit dislocations present on these interfaces; hence termed “plastic” regime.

[Matan, Cox, Rae, & Reed, 1999]
Objective: Obtain kinetic data to predict rafting and coarsening as a function of temperature, stress, microstructure and time.
Artificial Aged Microstructure Generation

Compression Creep Frame

Four Different Microstructures

Virgin

Coarsened

N-Raft

P-Raft
MICROSTRUCTURE-SENSITIVE CRYSTAL VISCOPLASTICITY MODELS
Length Scales in Ni-base Superalloys

- Atomic Channel Precipitates
- Channel Dislocations
- Precipitates
- Collections of Precipitates; Grains
- Shear bands; GB cracks

Min. Length Scale, L
- $O(10^{-10} \text{ m})$
- $O(10^{-8} \text{ m})$
- $O(10^{-7} \text{ m})$
- $O(10^{-6} \text{ m})$
- $O(10^{-5} \text{ m})$

- Components

310 GPa
124 GPa

[Shenoy, Tjipowidjojo, and McDowell, 2008]
[Reed, 2008]
Slip Systems

- Octahedral slip systems
  - Active over entire temperature range
  - [100] loading orientation
  - T/C asymmetry in precipitates
  - Anomalous temperature dependence

- Cube slip systems
  - Active at higher temperatures
  - [111] loading orientation
  - Less T/C asymmetry
  - Macroscopic manifestation of “Zig-Zag mechanism,” [Bettge and Osterle, 1999]
Crystal viscoplasticity – kinematic relations

Kinematic relations including temperature dependence

Deformation gradient
\[ F = \frac{\partial x}{\partial X} = F^e \cdot F^p \cdot F^\theta \]

Velocity gradient
\[ L = \dot{F} \cdot F^{-1} \]

Macroscopic plastic velocity gradient
\[ L^p = \dot{F}^p \cdot F^{p^{-1}} = \sum_{\alpha=1}^{N_{\text{slip}}} \gamma^{(\alpha)} \left( s^{(\alpha)}_o \otimes n^{(\alpha)}_o \right) \]
\[
\mathbf{L}^p = \dot{\mathbf{F}}^p \mathbf{F}^p = \sum_{\alpha=1}^{N_{\text{slip}}} \dot{\gamma}^{(\alpha)} \left( \mathbf{s}_{o}^{(\alpha)} \otimes \mathbf{n}_{o}^{(\alpha)} \right)
\]

**Inelastic Shear Strain Rate**

\[
\dot{\gamma}^{(\alpha)} = \dot{\gamma}_o \Theta(T) \left( \frac{\tau_v^{(\alpha)}}{D^{(\alpha)}} \right)^n \exp \left\{ B_o \left( \frac{\tau_v^{(\alpha)}}{D^{(\alpha)}} \right)^{n+1} \right\} \text{sgn} \left( \tau^{(\alpha)} - \chi^{(\alpha)} \right)
\]

where

\[
\tau_v^{(\alpha)} = \left| \tau^{(\alpha)} - \chi^{(\alpha)} \right| - \kappa^{(\alpha)} \frac{\mu}{\mu_o} \quad \text{and} \quad D^{(\alpha)} = D_o \frac{\mu}{\mu_o}
\]

\[
\Theta(T) = \exp \left( -\frac{Q_o}{RT} \right) \quad \text{for} \quad T \geq \frac{T_m}{2} \quad \Theta(T) = \exp \left( -\frac{2Q_o}{RT} \left[ \ln \left( \frac{T_m}{2T} \right) + 1 \right] \right) \quad \text{for} \quad T \leq \frac{T_m}{2}
\]

[Shenoy et al., 2005]
CVP Models for Ni-base Superalloys

**Shenoy, Gordon, McDowell, & Neu (2005)**
Creep-fatigue and TMF (temperature-dependent)
\[ \dot{\gamma}^{in(\alpha)} = \dot{\gamma}_o \Theta(T) \left( \frac{\tau^{(\alpha)} - \chi^{(\alpha)} - \kappa^{(\alpha)}}{D^{(\alpha)}} \right)^n \exp \left( B_0 \left( \frac{\tau^{(\alpha)} - \chi^{(\alpha)} - \kappa^{(\alpha)}}{D^{(\alpha)}} \right)^{n+1} \right) \text{sgn}(\tau^{(\alpha)} - \chi^{(\alpha)}) \]

**Shenoy, Tjiptowidjojo, & McDowell (2008)**
Creep-fatigue using dislocation-based ISV
\[ \dot{\gamma}^{in(\alpha)} = \left[ \dot{\gamma}_o \left( \frac{\tau^{(\alpha)} - \chi^{(\alpha)} - \kappa^{(\alpha)}}{D^{(\alpha)}} \right)^n + \dot{\gamma}_1 \left( \frac{\tau^{(\alpha)} - \chi^{(\alpha)}}{D^{(\alpha)}} \right)^{n_1} \right] \text{sgn}(\tau^{(\alpha)} - \chi^{(\alpha)}) \]

**MacLachlan, Wright, Gunturi, & Knowles (2001)**
Limited to CMSX-4 at 950°C in tertiary regime (stress ≤ 450 MPa) – coupled CVP with damage mechanics

**Ma, Dye, & Reed (2008)**
Dislocation-based ISV considering primary and tertiary creep regimes (limited to creep of CMSX-4 at 950°C)
\[ \dot{\gamma}_\gamma^{in(\alpha)} = \rho_{\gamma}^{(\alpha)} b \lambda_{\gamma}^{(\alpha)} F_{\text{attack}} \exp \left\{ \frac{-Q_{\text{slip}}^{110} + \left[ \tau^{(\alpha)} + \tau^{(\alpha)}_{\text{mis}} - \tau^{(\alpha)}_{\gamma \text{pass}} - \tau^{(\alpha)}_{\gamma \text{oro}} \right] V_{\gamma}^{(\alpha)}}{kT} \right\} \text{sgn}(\tau^{(\alpha)} + \tau^{(\alpha)}_{\text{mis}}) \]
\[ \dot{\gamma}_{L12}^{in(\alpha)} = \rho_{\alpha}^{(\alpha)} b \lambda_{L12}^{(\alpha)} F_{\text{attack}} \exp \left\{ \frac{-Q_{\text{slip}}^{112} + \left[ \tau^{(\alpha)} - \tau^{(\alpha)}_{L12 \text{pass}} \right] V_{L12}^{(\alpha)}}{kT} \right\} \text{sgn}(\tau^{(\alpha)}) \]

**Kirka & Neu (2014)**
Added state variables to account for state of aged microstructure in temperature-dependent formulation
Ma et al. model predictions showing microstructure sensitivity

Tertiary creep
950°C/400MPa

Primary creep
750°C/770MPa

Deformation along [001]
Volume fraction of γ fixed at 0.7

[Ma, Dye, and Reed, 2008]
Ma et al. model predictions showing orientation sensitivity

Creep strain in tertiary regime
900°C/400MPa (111 hr)

CMSX-4

Creep strain in primary regime
750°C/600MPa (111 hr)

Primary creep performance based on experiments

[Ma, Dye, and Reed, 2008]

[MacKay and Meier, 1982]
Directional coarsening is roughly a constant volume process

- Stress-free coarsening maintains proportionality between all precipitate/channel dimensions
- Microstructure uniqueness is defined by 2 independent dimensions

Rafting: $\dot{w}_i^{raft}(T, \sigma) = - \left( \frac{3A\omega_i}{2\omega_o} \right) \left( \frac{\sigma_i^{dcv}}{\sigma_{VM} + \delta} \right) \exp \left( - \frac{Q_{raft} - \sigma_{VM}U(T)}{RT} \right)$

[Tinga, Brekelmans, and Geers, 2009]

Isotropic Coarsening: 

$\dot{w}_i^{coar} = \frac{8K}{3} \left( w_o^3 + 8Kt \right)^{-\frac{2}{3}}$

$\dot{w}_i = \dot{w}_i^{coar} + \dot{w}_i^{raft}$

$\eta = \frac{h_{[001]} - h_o^{[001]}}{h_{[001]}^o}$

$\zeta = \frac{h_{[100]} - h_o^{[100]}}{h_{[100]}^o}$
Sensitivity of Composition on Diffusivity

**Prediction of Aging**

\[
\dot{\omega}_i = \dot{\omega}_i^{\text{coar}} + \dot{\omega}_i^{\text{raft}}
\]

\[
\dot{\omega}_i^{\text{coar}} = \frac{8K}{3}\left(\omega_i^{*} + 8Kt\right)^{-2/3}
\]

\[
r^3 - r_i^3 = K(t - t_i)
\]

\[
K = \frac{8\sigma D C_o (V_m)^2}{9\nu RT}
\]

\[
D = D_o \exp\left(-\frac{Q}{RT}\right)
\]

\[
\dot{\omega}_i^{\text{raft}} = -\left(\frac{3A\omega}{2\omega_o}\right)\left(\frac{\sigma_i^{\text{dev}}}{\sigma_{VM} + \delta}\right) \exp\left(-\frac{Q_{\text{raft}} - \sigma_{VM} U(T)}{RT}\right)
\]

**Temperature-Dependent Constitutive Models**

\[
\dot{\gamma}^\alpha = \dot{\gamma}_0 \Theta(T)\left[\frac{\tau^\alpha}{D^\alpha}\right]^a \exp\left\{B_0\left[\frac{\tau^\alpha}{D^\alpha}\right]^{n+1}\right\} \text{sgn}(\tau^\alpha - \dot{\chi}^\alpha)
\]

\[
\Theta(T) = \exp\left(-\frac{Q_0}{RT}\right) \quad \text{for } T \geq \frac{T_m}{2}
\]

\[
\Theta(T) = \exp\left\{-\frac{2Q_0}{RT_m}\left[\ln\left(\frac{T_m}{2T}\right) + 1\right]\right\} \quad \text{for } T \leq \frac{T_m}{2}
\]

**Thermo-Calc / DICTRA**

Databases: TCNi5 / MOBNi2

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**CMSX-8**
### Composition Segregation ---- Results

**Composition:**

<table>
<thead>
<tr>
<th></th>
<th>wt%Cr</th>
<th>wt%Co</th>
<th>wt%Mo</th>
<th>wt%W</th>
<th>wt%Ta</th>
<th>wt%Re</th>
<th>wt%Al</th>
<th>wt%Ti</th>
<th>wt%Ni</th>
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<td>10.37</td>
<td>0.23</td>
<td>8.39</td>
<td>1.72</td>
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</table>
CVP Model Development Plans

- Implement Ma et al. (2008) model
  - add kinematic hardening to improve cyclic loading response
  - CMSX-8 (How much different than CMSX-4? Can it be tied to %Re?)
- Theoretical extensions to embed aging in CVP
- Implementation of CVP model in UMAT/ABAQUS
- Calibration experiments on each microstructure (i.e., artificially aged conditions) of CMSX-8
- Calibration of CVP parameters to CMSX-8
- Validation and demonstration
- Reduced-order formulations for material definition
  - using built in ABAQUS models (uncoupled creep and plasticity; two-layer viscoplasticity)