Microstructure-Sensitive Crystal Viscoplasticity for Ni-base Superalloys
(with application to long-term creep-fatigue interactions)

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University Turbine Systems Research Workshop
Pittsburgh
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Hot Section Gas Turbine Materials

Land-based gas turbines

- drive to increase service temperature to improve efficiency; increase life; with minimal increase in cost
- replace large directionally-solidified Ni-base superalloys with single crystal superalloys

Power Output: 375 MW
Complexities in evaluating creep-fatigue interaction

Microstructure Changes during Service

Complex Temperature and Loading Profiles

[Epishin et al., 2010]

[Attari et al., 2013]

[Vardar et al., 2007]
<table>
<thead>
<tr>
<th>Atomic structure</th>
<th>Channel dislocations</th>
<th>Precipitate</th>
<th>Groups of precipitates</th>
<th>Dendrites</th>
<th>Bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td>O($10^{-10}$ m)</td>
<td>O($10^{-8}$ m)</td>
<td>O($10^{-7}$ m)</td>
<td>O($10^{-6}$ m)</td>
<td></td>
<td>O($10^{-1}$ m)</td>
</tr>
</tbody>
</table>

- Γ deformation
- Γ′ deformation
- Dendrites
- Bulk
PSPP Map for Ni-base Superalloy Airfoils

**PROCESS**

- Composition:
  - Ni, Co, W, Ta, Al, Cr, Re, Ti, Mo, Hf, C, B, ...

- Casting and Solidification
- Solution Treatment
- Age Treatment

**STRUCTURE**

- Dendritic structure
  - Primary arm spacing
  - Secondary arm spacing
  - Misorientation

- Vacancy concentration

- \(\gamma\) and \(\gamma'\) phases
  - Shape
  - Size
  - Volume fraction
  - Mismatch \(\gamma\) and \(\gamma'\)

- Secondary \(\gamma'\) size

- Dislocations
  - Density in \(\gamma\) and \(\gamma'\)
  - Configurations
  - Distributions

- Other Features:
  - Crystal structure
  - APB Energy
  - Texture <001>
  - Eutectic pools
  - Casting pores
  - Freckles
  - High angle grain boundaries
  - Carbides

**PROPERTIES**

- Elastic Modulus
- Yield Strength
- Fracture Toughness
- Fatigue Strength
- Creep Rate
- CTE
- Resistance to Environment Degradation

**PERFORMANCE**

- Maximum Creep-Rupture Life
- Maximum Thermomechanical Fatigue Life
- Minimal Cost

Continuation of “Process” During Service

- Load profile
- Temperature profile
- Environment profile
Influence of Service Conditions on Microstructure, Properties, & Performance

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Composition:
Ni, Co, W, Ta, Al, Cr, Re, Ti, Mo, Hf, C, B, ...

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Age Treatment

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Fracture Toughness

Fatigue Strength

Creep Rate

Resistance to Environment Degradation

CTE

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Maximum Creep-Rupture Life

Maximum Thermomechanical Fatigue Life

Minimal Cost

Load profile

Temperature profile

Environment profile

Composition:
Ni, Co, W, Ta, Al, Cr, Re, Ti, Mo, Hf, C, B, ...

Age Treatment

Continuation of "Process" During Service
Role of Chemical Composition

**PROCESS**
- Composition: Ni, Co, W, Ta, Al, Cr, Re, Ti, Mo, Hf, C, B, ...
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- Age Treatment

**STRUCTURE**
- Dendritic structure
  - Primary arm spacing
  - Secondary arm spacing
  - Misorientation
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- $\gamma$ and $\gamma'$ phases
  - Shape
  - Size
  - Volume fraction
  - Mismatch $\gamma$ and $\gamma'$
- Secondary $\gamma'$ size
- Dislocations
  - Density in $\gamma$ and $\gamma'$
  - Configurations
  - Distributions
- Other Features:
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  - APB Energy
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**PROPERTIES**
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- Maximum Thermomechanical Fatigue Life
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Continuation of “Process” During Service
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- Temperature profile
- Environment profile
Single Crystal Alloy being Investigated for IGT Applications

CMSX-8: 1.5% Re "alternative 2\textsuperscript{nd} 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>
<th>B</th>
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<th>Ni</th>
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<tr>
<td>Mar-M247LC-DS</td>
<td>8.4</td>
<td>10.0</td>
<td>0.7</td>
<td>10.0</td>
<td>5.5</td>
<td>1.0</td>
<td>3.0</td>
<td>-</td>
<td>1.5</td>
<td>0.07</td>
<td>0.015</td>
<td>0.05</td>
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<td>0.7</td>
<td>3.2</td>
<td>-</td>
<td>1.4</td>
<td>0.07</td>
<td>0.015</td>
<td>0.01</td>
<td>Bal</td>
</tr>
<tr>
<td>CMSX-4</td>
<td>6.5</td>
<td>9.0</td>
<td>0.6</td>
<td>6.0</td>
<td>5.6</td>
<td>1.0</td>
<td>6.5</td>
<td>3.0</td>
<td>0.1</td>
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<td>9.0</td>
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<td>0.1</td>
<td>-</td>
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<td>-</td>
<td>Bal</td>
</tr>
<tr>
<td>CMSX-8</td>
<td>5.4</td>
<td>10.0</td>
<td>0.6</td>
<td>8.0</td>
<td>5.7</td>
<td>0.7</td>
<td>8.0</td>
<td>1.5</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Bal</td>
</tr>
</tbody>
</table>

[C Wahl and Harris, 2012]
Influence of Temperature, Loading Direction and Crystal Orientation on Modulus and Strength

Virgin CMSX-8 monotonic response in the <001> dir

Virgin CMSX-8 monotonic response in the <111> dir
Primary Objectives of UTSR Project

• Creep-fatigue interaction experiments on CMSX-8
• Influence of aging on microstructure and creep-fatigue interactions
• Microstructure-sensitive, temperature-dependent crystal viscoplasticity to capture the creep and cyclic deformation response
Creep-Fatigue Interaction Experiments

Experimentally establish the creep-fatigue interactions in a single-crystal Ni-base superalloy that is being targeted for use in industrial gas turbines (CMSX-8)

- Characterize creep-fatigue interactions on CMSX-8
  - Creep-fatigue
  - Thermomechanical fatigue
  - Creep (either tension or compression) followed by fatigue
  - Fatigue followed by creep

- Characterize the influence of aging on microstructure and creep-fatigue interactions

![Image of experiment setup]
Conventional Creep-Fatigue (baseline)

Effect of hold on LCF life: $R = 0$

- $(T = 950 \, ^\circ C, R = -1)$
- $(T = 1100 \, ^\circ C, R = -1)$
- $(T = 950 \, ^\circ C, R = 0, \text{hold} = 3 \text{ min.})$
- $(T = 1025 \, ^\circ C, R = 0, \text{hold} = 3 \text{ min.})$
- $(T = 1100 \, ^\circ C, R = 0, \text{hold} = 3 \text{ min.})$

Effect of hold on LCF life: $R = -\infty$

- $(T = 950 \, ^\circ C, R = -1)$
- $(T = 1100 \, ^\circ C, R = -1)$
- $(T = 950 \, ^\circ C, R = -\infty, \text{hold} = 3 \text{ min.})$
- $(T = 1025 \, ^\circ C, R = -\infty, \text{hold} = 3 \text{ min.})$
- $(T = 1100 \, ^\circ C, R = -\infty, \text{hold} = 3 \text{ min.})$
Conventional Creep-Fatigue (baseline)

Life for low cycle creep-fatigue

Strain range [%] vs Cycles to Failure

- (T = 950 °C, R = 0, hold = 3 min.)
- (T = 950 °C, R = -∞, hold = 3 min.)
- (T = 1025 °C, R = 0, hold = 3 min.)
- (T = 1025 °C, R = -∞, hold = 3 min.)
- (T = 1100 °C, R = 0, hold = 3 min.)
- (T = 1100 °C, R = -∞, hold = 3 min.)
Plastic strain range alone does not explain life data at high temperatures. A Coffin-Manson relations would not be sufficient.

\( \Delta \varepsilon = 0.8 \% \)

\( \Delta \varepsilon = 1.0 \% \)

\( \Delta \varepsilon_p = 0.1634 \% \)

\( \Delta \varepsilon_p = 0.2473 \% \)

\( \Delta \varepsilon_p = 0.282 \% \)

\( \Delta \varepsilon_p = 0.381 \% \)
Crack Characteristics

- $R = 0$, $T = 1100^\circ\text{C}$, $\Delta \varepsilon = 0.8\%$
  
  - $N_f = 1420$

- $R = -\infty$, $T = 1100^\circ\text{C}$, $\Delta \varepsilon = 0.8\%$
  
  - $N_f = 980$
Ostergren Model

- Energy-based life prediction model based on the net hysteretic energy.
- Accounts for the mean stress and cycle time (frequency) effect.
- The accuracy of prediction relies on precision of inelastic strain measurement.

\[ \sigma_T \Delta \varepsilon_p \ N_f^\beta \ y_{\beta(\kappa-I)} = C \]

[Ostergren, 1976]
Zamrik and Renauld Model

- Introducing hold-time and elevated temperature function to account for creep effect and exponentially increasing creep/or environmental damage with increasing temperature, respectively.

- Substituting inelastic strain with maximum tensile strain range.

\[
N = A \left[ \left( \frac{\varepsilon_{\text{ten}}}{\varepsilon_f} \right) \left( \frac{\sigma_{\text{max}}}{\sigma_u} \right) \right]^B \left( 1 + \frac{t_h}{t_c} \right)^C \exp \left( \frac{-Q}{R(T_{\text{max}} - T_0)} \right)
\]

- \(\sigma_{\text{max}}\): maximum tensile stress in mid-life hysteresis loop
- \(\varepsilon_{\text{ten}}\): tensile strain range in mid-life hysteresis loop for which the stress is tensile
- \(\sigma_u\): ultimate strength measured under monotonic tensile loading
- \(\varepsilon_f\): elongation to failure measured under monotonic tensile loading
- \(t_h\): length of compressive hold-time
- \(t_c\): length of total time including hold-time
- \(Q\): activation energy for high temperature damage

[Zamrik and Renauld, 2000]
Kulawinski et al. Model

- The model is based on Zamrik model and the energy density term includes:
  - Zamrik damage parameter
  - Inelastic strain range
  - Stress range
  - Arrhenius term

\[ N_f = A \left[ \Delta \sigma_{eq} \cdot \Delta \varepsilon_{eq}^{in} \cdot W_{zam} \cdot \exp \left( \frac{-Q}{RT} \right) \right]^B \]

- The goodness of fit plot shows majority of life predictions using Kulawinski model lie within the scatter band of factor two.

- 95% of the variance of the low cycle fatigue (LCF) and creep-fatigue (CFI) life data is captured by this lifetime model.

[Kulawinski et al., 2015]
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Microstructure Evolution in Blades

Distance from Root

in phase
out of phase

2 cm
10 μm
25 μm
2 μm
CMSX-4 via Scanning Laser Epitaxy (SLE)

As-built
After Heat Treatment

[Basak and Das (Georgia Tech), 2017]
Rafting and Coarsening of $\gamma'$

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

[N-raft]

[P-raft]

[Epishin et al., 2008]
### High-Throughput Stress-assisted Aging

#### Initial microstructure

**T = 1120 °C**  
**Time = 50 hours**

<table>
<thead>
<tr>
<th>5 µm</th>
<th>28 MPa</th>
<th>34 MPa</th>
<th>45 MPa</th>
<th>60 MPa</th>
<th>100 MPa</th>
</tr>
</thead>
</table>

#### T = 950 °C  
**Time = 445 hours**

<table>
<thead>
<tr>
<th>34 MPa</th>
<th>45 MPa</th>
<th>60 MPa</th>
<th>100 MPa</th>
<th>28 MPa</th>
</tr>
</thead>
</table>

#### T = 1120 °C  
**Time = 50 hours**

<table>
<thead>
<tr>
<th>150 MPa</th>
<th>97 MPa</th>
<th>70 MPa</th>
<th>50 MPa</th>
<th>38 MPa</th>
</tr>
</thead>
</table>

---

*Images of microstructures with varying stress levels and temperatures.*
Comόression Creep Frame

Ceramic Compression Creep Extensometer

Top Holder

Bottom Holder
Aging Behavior of CMSX-8

Physical aging models

Directional coarsening (Rafting)

\[
\dot{w}(T, \sigma) = A \cdot \exp \left( -\frac{Q - U(T) \cdot \sigma}{RT} \right)
\]

\[
U(T) = U_T (T - T_0)^n
\]

[Epishin et al., 2008]

Isotropic Coarsening

Lifshitz-Slyozov-Wagner (LSW) model:

\[
(r)^3 - (r_0)^3 = Kt
\]

\[
K = K_0 \exp \left( -\frac{Q_{coar}}{RT} \right)
\]

\[
Q_{coar} (CMSX - 8) = 269.4 \text{ kJ/mol}
\]

High-throughput experimental technique

Stress gradient in longitudinal direction resulting in morphology evolution gradient

Influence of Variation in Composition

Thermo-Calc
DICTRA
Databases: TCNi5 / MOBNi2

Composition sensitive diffusivity parameter

Aging behavior

Temperature-dependent constitutive models

LSW model

\[ r^3 - r_o^3 = K(t - t_o) \]

\[ (T) = \exp\left(\frac{Q_0}{RT}\right) \]

\[ D_{eff} = D_{0,eff} \left(-\frac{Q_{eff}}{RT}\right) \]

Composition segregation

Thermo-Calc
• Effective diffusivity of system is equivalent to effective diffusivity in $\gamma$ channels.

• Diffusivity of Ni-m binary systems computed from mobility databases using DICTRA from Thermo-Calc.

$$D_{\text{eff}} = D_{0,\text{eff}} \exp \left( -\frac{Q_{\text{eff}}}{kT} \right)$$

$$Q_{\text{eff}} = \sum_{m} C_{m} Q_{\text{Ni}-m}$$

$$D_{0,\text{eff}} = \frac{1}{\sum_{m} \frac{C_{m}}{D_{0,\text{Ni}-m}}}$$

$C_{m}$: atomic concentration of element $m$.

[Strada Rodas, Gorgannejad, Neu, et al., Superalloys 2016]
A database comprising of coarsened and rafted (P-type and N-type) microstructure as a result of various aging histories is generated.
• The 2-point statistical correlation is a rigorous quantification method that describes spatial correlation and critical structural information with microstructure reconstruction capability.

• It is computed based on the probability density associated with finding an ordered pair of specific phase at the head and tail of a randomly placed vector $r$ into the microstructure.
Data Visualization of Aged CMSX-8 in PC Space

- Application of PCA to the high dimension 2-point spatial correlation results in a reduced-order representation of microstructure ensemble.

- The axes are ordered descendingly by the extent of variation each explain.

- Powerful classification and visualization tool: Micrographs with similar microstructures are grouped in PC space automatically. The ones with significant different structures are located far from each other.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Temperature [°C]</th>
<th>Stress [MPa] (min, max)</th>
<th>Dwell time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>23</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>AT1-1</td>
<td>1120</td>
<td>95</td>
<td>50</td>
</tr>
<tr>
<td>AT1-2</td>
<td>1120</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>AT2-1</td>
<td>950</td>
<td>206</td>
<td>450</td>
</tr>
<tr>
<td>AT2-2</td>
<td>950</td>
<td>112</td>
<td>450</td>
</tr>
<tr>
<td>AC1</td>
<td>900</td>
<td>-208</td>
<td>850</td>
</tr>
<tr>
<td>AF1</td>
<td>950</td>
<td>0</td>
<td>940</td>
</tr>
</tbody>
</table>

PCA is a linear approach to dimensionality reduction by coordinate transform.

The axes are defined by the directions of the highest variance.
Effect of Aging on Creep-Fatigue

**Pre-Aging**

\[
\sigma = 130 \text{ MPa}, \quad T = 1100 \degree \text{C}, \quad t = 50 - 60 \text{ hours}, \quad \varepsilon_{\text{creep}} < 2 \%
\]

**Pre-Creeping**

\[
\sigma = 392 \text{ MPa}, \quad T = 900 \degree \text{C}, \quad \varepsilon = 5 - 6 \%
\]

Removal of Oxide and γ' depleted zone

Initial as-heat-treated microstructure

γ' depleted zone

Oxide layer

Removal of Oxide and γ' depleted zone
Role of Microstructure on LCF – Three Critical Temperature Regimes to Study

**Room Temperature**
- The primary mechanism is the dislocation ribbons shearing through the $\gamma'$ precipitates

**750 °C**
- Material exhibits its highest strength at this temperature

**1100 °C**
- The dominated mechanism is cross slip and thermally assisted glide and climb of dislocations in $\gamma$ channels
No notable microstructure influence when $R_\varepsilon = -\infty$.

Fatigue-environment interaction likely explanation when $R_\varepsilon = -\infty$. 

Influence of Microstructure
$R_\varepsilon = 0$ versus $R_\varepsilon = -\infty$ at 1100 °C
Fracture surface topology – Low cycle fatigue at 1100°C

$R_\varepsilon = 0$

- **As-heat-treated**
  - $N_f = 1545$

- **Pre-aged**
  - $N_f = 600$

- **Pre-crept**
  - $N_f = 398$

$R_\varepsilon = -\infty$

- **Necking: 20% reduction in area at fractured point**
  - $N_f = 1288$

- **Necking: 25% reduction in area at fractured point**
  - $N_f = 1197$

- **Crack propagation**
  - $N_f = 1376$
Low Cycle Fatigue Response of CMSX-8 [001]

\[ R_e = 0, \text{ strain rate} = 1 \times 10^{-3} \, 1/s \]

Only observe significant influence of microstructure on LCF at 1100° C
First 10 cycles – RT and 750 °C

RT

Elastic dominated cyclic response

750 °C

Elastic dominated cyclic response - Peak strength
Low Cycle Fatigue at **Room Temperature**

As-heat-treated

Pre-crept

Low Cycle Fatigue at **750 °C**

As-heat-treated

Pre-aged

Pre-crept
LCF at **Room temperature**

*Pre-aged microstructure*

CFI at **750 °C**

*As–heat–treated microstructure*
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Creep Deformation REGIMES

Microstructure Evolution Dominant Regime

Tertiary – dislocation activity restricted to \(a/2\langle110\rangle\) form operating on \(\{111\}\) slip planes in the \(\gamma\) channels

Primary – \(\gamma'\) particles are sheared by dislocation ribbons of overall Burgers vector \(a\langle112\rangle\) dissociated into superlattice partial dislocations separated by a stacking fault; shear stress must above threshold stress (about 550 MPa)

[Reed, 2006; Ma, Dye, and Reed, 2008; our CMSX-8 Data]
Distinct deformation in the $\gamma$ and $\gamma'$ phases

$$L^\text{in} = f_\gamma \left( \sum_{\alpha=1}^{12} j_{\gamma}^{\text{in}}(\alpha) \left( \hat{d}(\alpha) \otimes \hat{n}(\alpha) \right) \right) + f_{\gamma'} \left( \sum_{\alpha=13}^{24} j_{L_{12}}^{\text{in}}(\alpha) \left( \hat{d}(\alpha) \otimes \hat{n}(\alpha) \right) \right)$$

Deformation predictions sensitive to the $\gamma$ and $\gamma'$ phase attributes
Kinematic relations including temperature dependence

**Deformation gradient**

\[
F = \frac{X}{x} = F^e \times F^p \times \mathcal{F}
\]

**Velocity gradient**

\[
L = \dot{F} \times F^{-1}
\]

**Macrophysical plastic velocity gradient**

\[
L^p = \dot{F}^p F^p \times F^{-1} = \sum_{\text{slip}} \left( \begin{array}{c} s_{o} \\ n_{o} \end{array} \right)
\]

In \( \gamma \): 12 octahedral slip systems active

In \( \gamma' \): 12 octahedral slip systems moving as dislocation ribbons
Inelastic Velocity Gradient

\[ \mathbf{L}^{\text{in}} = \mathbf{F}^{\text{in}} \mathbf{F}^{-1} = \mathbf{f} \sum_{\alpha=1}^{12} \gamma^{\text{in(\alpha)}} \left( \mathbf{d}^{(\alpha)} \otimes \mathbf{n}^{(\alpha)} \right) + \mathbf{f}_{\alpha} \sum_{\alpha=13}^{24} \gamma_{12} \left( \mathbf{d}^{(\alpha)} \otimes \mathbf{n}^{(\alpha)} \right) \]

Inelastic Shear Strain Rate

\[ \dot{\gamma}^{\text{in}(\alpha)} = \rho^{(\alpha)} \gamma \lambda^{(\alpha)} F_{\text{attack}} \text{sign} \left( \tau^{(\alpha)} + \tau^{(\alpha)}_{\text{mis}} - \chi^{(\alpha)} \right) \exp \left( \frac{-Q_{\text{slip}}^{110} + \left( \tau^{(\alpha)} + \tau^{(\alpha)}_{\text{mis}} - \chi^{(\alpha)} \right) \exp \left( \frac{Q_{\text{slip}}^{110}}{kT} \right)} {kT} \right) \]

\[ \dot{\gamma}_{12}^{\text{in}(\alpha)} = \rho_{12}^{(\alpha)} \gamma \lambda_{12}^{(\alpha)} F_{\text{attack}} \text{sign} \left( \tau^{(\alpha)} - \chi^{(\alpha)} \right) \exp \left( \frac{-Q_{\text{slip}}^{112} + \left( \tau^{(\alpha)} - \chi^{(\alpha)} \right) \exp \left( \frac{Q_{\text{slip}}^{112}}{kT} \right)} {kT} \right) \]

Dislocation Density Evolution Equations

\[ \dot{\rho}_{\gamma}^{(\alpha)} = \frac{1}{b} \left( \frac{c_{\text{mult1}}}{\lambda^{(\alpha)}} - c_{\text{annh1}} \rho_{\gamma}^{(\alpha)} \right) \left| \dot{\gamma}^{\text{in}(\alpha)} \right| \]

\[ \dot{\rho}_{12}^{(\alpha)} = c_{\text{mult21}} \rho_{pb}^{(\alpha)} \Gamma + \frac{c_{\text{mult22}}}{b \lambda^{(\alpha)}} \left| \dot{\gamma}^{(\alpha)} \right| - c_{\text{annh2}} \rho_{\gamma}^{(\alpha)} \left| \dot{\gamma}^{(\alpha)} \right| \]

\[ \dot{\rho}_{pb}^{(\alpha)} = \frac{c_{pb}}{b L_{\gamma}} \left| \dot{\gamma}^{\text{in}(\alpha)} \right| - c_{\text{annh} pb} \rho_{pb}^{(\alpha)} \left| \dot{\gamma}^{\text{in}(\alpha)} \right| \]
Evolution of dislocation densities

\[ \dot{\rho}_{\gamma}(\alpha) = \frac{1}{b} \left( \frac{c_{\text{mult}}}{\lambda_{\gamma}(\alpha)} - c_{\text{annh}} \rho_{\gamma}(\alpha) \right) \dot{\gamma}_{\gamma}^{\text{in}}(\alpha) \]

\[ \dot{\rho}_{pb}(\alpha) = \frac{c_{\text{mult}}^{pb}}{b L_{\gamma}} \dot{\gamma}_{\gamma}^{\text{in}}(\alpha) - c_{\text{annh}}^{pb} \rho_{pb}(\alpha) \dot{\gamma}_{\gamma}^{\text{in}}(\alpha) \]

\[ \dot{\rho}_{L12}(\alpha) = c_{\text{mult}}^{21} \rho_{pb}(\alpha) \Gamma + \frac{c_{\text{mult}}^{22}}{b \lambda_{\gamma}(\alpha)} \dot{\gamma}_{\gamma}^{\text{in}}(\alpha) - c_{\text{annh}}^{2} \rho_{\gamma'}(\alpha) \dot{\gamma}_{\gamma'}^{\text{in}}(\alpha) \]
Creep in different orientations

Temp = 950[°C], Stress = 250[MPa]
Various Creep Predictions

(a) 750 °C

(b) 850 °C

(c) 871 °C

(d) 1037 °C
Effect of Channel Size on Creep

$T = 750^\circ C$
$\sigma = 700$ [MPa]

$T = 1037^\circ C$
$\sigma = 172$ [MPa]
Effect of APB Energy on Creep

$T = 750^\circ C$
$\sigma = 700$ [MPa]

$T = 850^\circ C$
$\sigma = 475$ [MPa]

$\gamma_{APB} = 0.11$ [J/m$^2$]
$\gamma_{APB} = 0.13$ [J/m$^2$]
$\gamma_{APB} = 0.15$ [J/m$^2$]
Primary, secondary and tertiary creep can be captured with the model.
First 10 cycles: IP-TMF
[100-1100-100] °C, R = 0, $\dot{T} = 2.83[{^\circ}K/s]$ 

Stabilized hysteresis: OP-TMF
[100-850-100] °C, R = -∞, $\dot{T} = 2.83[{^\circ}K/s]$

Very good agreement predicting TMF
Since Re segregates almost exclusively in the $\gamma$ channels, the Activation energy in the $\gamma$ phase can be modified to account for Re content as follows:

\[
\dot{\gamma}^{in(\alpha)} = \Theta(T) \rho(\alpha)_{\gamma} b \lambda(\alpha)_{\gamma} F_{\text{attack}} \text{sign} \left( \tau^{(\alpha)} + \tau_{\text{mis}}^{(\alpha)} - \chi(\alpha) \right) \exp \left\{ -Q_{110}^{\text{slip}} + \frac{\left[ \tau^{(\alpha)} + \tau_{\text{mis}}^{(\alpha)} - \chi(\alpha) \right]}{kT} - \frac{\tau^{(\alpha)}_{\gamma\text{pass}} - \tau_{\gamma\text{cor}}^{(\alpha)}}{V_{c1}} \right\}
\]

\[
\dot{\gamma}^{in(\alpha)}_{L_2} = \rho_{L_2} \lambda_{L_2} F_{\text{attack}} \text{sign} \left( \tau^{(\alpha)} - \chi(\alpha) \right) \exp \left\{ -Q_{112}^{\text{slip}} + \frac{\left[ \tau^{(\alpha)} - \chi(\alpha) \right] - \tau^{(\alpha)}_{L_2\text{pass}} - \tau_{\text{APB}}}{kT} \right\} V_{c2}
\]

If we considering activation energy for plastic flow $Q_0$ a function of $\%$Re, the diffusivity parameter could take the form of:

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

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

[Miller, 1976; Shenoy et al., 2005]
Creep-Fatigue Interaction Experiments and Lifetime Models

Microstructure-sensitive Crystal Viscoplasticity (CVP) Model to Determine Service “Process”-Structure-Property Linkages

\[
L^{in} = F^{in} F^{-1} = f_\gamma \left( \sum_{\alpha=1}^{12} \gamma^{in(\alpha)} \left( \hat{d}^{(\alpha)} \otimes \hat{n}^{(\alpha)} \right) \right) + f_{\gamma'} \left( \sum_{\alpha=13}^{24} \gamma'^{in(\alpha)} \left( \hat{d}^{(\alpha)} \otimes \hat{n}^{(\alpha)} \right) \right)
\]

Experiments & Models (both physically-based and data analytics) to Predict Current State of Microstructure (Service Process-Structure Linkages)

- Stress-free and stress-assisted (rafting) aging experiments under tensile and compressive stresses
- Establishing process-structure linkages using physical models, 2-point statistics and PCA

Established Method to Determine Sensitivity of Local Composition on Diffusivity for Input in Aging and Viscoplasticity Models

Thermo-Calc
DICTRA
Databases: TCNi5 / MOBNi2

- Composition segregation in γ and γ’ phase
- Determination of composition sensitive effective diffusivity to characterize aging activation energy and diffusivity parameter in viscoplasticity models
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