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
Virginia Tech
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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
Superalloys airfoils are subject to a continuation of “process” during service due to sustained hostile environment and loading. Understanding the influence of the microstructure and its evolution on TMF, creep and fatigue and their interactions is key to delivering better turbine designs.
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
- γ and γ' phases
  - Shape
  - Size
  - Volume fraction
  - Mismatch γ and γ'

- Secondary γ' size

**PROPERTIES**

- Elastic Modulus
- Yield Strength
- Fracture Toughness
- Fatigue Strength
- Creep Rate
- Resistance to Environment Degradation
- CTE
- Maximum Creep-Rupture Life
- Maximum Thermomechanical Fatigue Life
- Minimal Cost

**PERFORMANCE**

Continuation of “Process” During Service

- Load profile
- Temperature profile
- Environment profile

Other Features:
- Crystal structure
- APB Energy
- Texture <001>
- Eutectic pools
- Casting pores
- Freckles
- High angle grain boundaries
- Carbides
Influence of Service Conditions on Microstructure, Properties, & Performance

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- Secondary γ' size
- Dendritic structure
  - Dislocations
    - Density in γ and γ'
    - Configurations
    - Distributions
- Other Features:
  - Crystal structure
  - APB Energy
  - Texture <001>
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- Load profile
- Temperature profile
- Environment profile
Role of Chemical Composition

**PROCESS**
- Composition: Ni, Co, W, Ta, Al, Cr, Re, Ti, Mo, Hf, C, B, ...
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**STRUCTURE**
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**Continuation of “Process” During Service**
- Load profile
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- 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>
<th>Zr</th>
<th>Ni</th>
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<td>0.7</td>
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<td>0.05</td>
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<td>0.01</td>
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<td>CMSX-4</td>
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<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>
<td>-</td>
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<td>3.5</td>
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<td>Bal</td>
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<tr>
<td>PWA1484</td>
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<td>2.0</td>
<td>6.0</td>
<td>5.6</td>
<td>-</td>
<td>9.0</td>
<td>3.0</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Bal</td>
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<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>

[Strength and Creep properties]

[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
Thermomechanical Fatigue (TMF)

**Linear In-Phase (IP)**

- **Time, t**
- **Strain, ε (%)**
- **Thermal Strain**
- **Mechanical Strain**
- **Total Strain**

- **Cold**
- **Tension**
- **Compression**

- **Φ = 0°**

**Linear Out-of-Phase (OP)**

- **Time, t**
- **Strain, ε (%)**
- **Thermal Strain**
- **Mechanical Strain**
- **Total Strain**

- **Cold**
- **Tension**
- **Compression**

- **Φ = 180°**

**Plastic Deformation**

**Cyclic Ageing and Coarsening effects**

**Hardening Process**

**Creep**

**Oxidation**

**Plastic Deformation**

**Creep**

**Oxidation**

**Plastic Deformation**

**Cyclic Ageing and Coarsening effects**
Effect of $T_{min}$ on OP TMF of CMSX-4

CMSX-4 [001]

Effect of $T_{min}$ on OP TMF of CMSX-4

CM247LC DS in Longitudinal Dir.
Accurate representations of the deformation response highly critical for predicting crack formation.
• 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
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

TMF life: In-Phase (R=0) vs Out-of-Phase (R=-inf)
Conventional Creep-Fatigue (baseline)

Effect of hold on LCF life: R = 0

- (T = 950 °C, R = -1)
- (T = 1100 °C, R = -1)
- (T = 950 °C, R = 0, hold = 3 min.)
- (T = 1025 °C, R = 0, hold = 3 min.)
- (T = 1100 °C, R = 0, hold = 3 min.)

Effect of hold on LCF life: R = -∞

- (T = 950 °C, R = -1)
- (T = 1100 °C, R = -1)
- (T = 950 °C, R = -∞, hold = 3 min.)
- (T = 1025 °C, R = -∞, hold = 3 min.)
- (T = 1100 °C, R = -∞, hold = 3 min.)
The George W. Woodruff School of Mechanical Engineering
School of Materials Science and Engineering

Conventional Creep-Fatigue (baseline)

Life for low cycle creep-fatigue

Strain range [%]

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.)
$T = 1100 \, ^\circ C, \, R = 0, \, \Delta \varepsilon = 1.0 \, \%$
Crack Characteristics

R = 0, T = 1100°C, \(\Delta \varepsilon = 0.8\%\)
\(N_f = 1420\)

R = -\(\infty\), T = 1100°C, \(\Delta \varepsilon = 0.8\%\)
\(N_f = 980\)
Half-life at 1025 °C

- N_f = 1293
- \( \Delta \varepsilon = 0.8\% \)
- \( \Delta \varepsilon_p = 0.09\% \)

- N_f = 1192
- \( \Delta \varepsilon = 0.8\% \)
- \( \Delta \varepsilon_p = 0.117\% \)

- N_f = 676
- \( \Delta \varepsilon = 1.0\% \)
- \( \Delta \varepsilon_p = 0.129\% \)

- N_f = 832
- \( \Delta \varepsilon = 1.0\% \)
- \( \Delta \varepsilon_p = 0.202\% \)
Plastic strain range alone does not explain life data at high temperatures. A Coffin-Manson relations would not be sufficient.

\[ \Delta \varepsilon = 0.8 \% \]

\[ \Delta \varepsilon = 1.0 \% \]

\[ N_f = 980 \]
\[ \Delta \varepsilon = 0.8 \% \]
\[ \Delta \varepsilon_p = 0.1634 \% \]

\[ N_f = 461 \]
\[ \Delta \varepsilon = 1.0 \% \]
\[ \Delta \varepsilon_p = 0.282 \% \]

\[ N_f = 762 \]
\[ \Delta \varepsilon = 1.0 \% \]
\[ \Delta \varepsilon_p = 0.381 \% \]
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
Major Activities and Accomplishments

- 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
- Microstructure-sensitive Crystal Viscoplasticity (CVP) Model to Determine Service “Process”-Structure-Property Linkages
  
  \[ L^\text{in} = \mathbf{F}^\text{in} \mathbf{F}^\text{mat}^{-1} = f_y \left( \sum_{\alpha=1}^{12} \gamma_{y}^{\text{in}(\alpha)} \left( \mathbf{d}^{(\alpha)} \otimes \hat{n}^{(\alpha)} \right) \right) + f_{y'} \left( \sum_{\alpha=13}^{24} \gamma_{y'}^{\text{in}(\alpha)} \left( \mathbf{d}^{(\alpha)} \otimes \hat{n}^{(\alpha)} \right) \right) \]

- Experiments & Models to Predict Current State of Microstructure (Service Process-Structure Linkages)

- 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
Microstructure Evolution in Blades
Rafting and Coarsening of $\gamma'$

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

CMSX-4

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

<table>
<thead>
<tr>
<th>Stress Level</th>
<th>Initial microstructure</th>
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<tbody>
<tr>
<td>38 MPa</td>
<td><img src="image1" alt="Initial microstructure" /> 5 μm</td>
</tr>
<tr>
<td>50 MPa</td>
<td><img src="image2" alt="Initial microstructure" /> 5 μm</td>
</tr>
<tr>
<td>70 MPa</td>
<td><img src="image3" alt="Initial microstructure" /> 5 μm</td>
</tr>
<tr>
<td>97 MPa</td>
<td><img src="image4" alt="Initial microstructure" /> 5 μm</td>
</tr>
<tr>
<td>150 MPa</td>
<td><img src="image5" alt="Initial microstructure" /> 5 μm</td>
</tr>
</tbody>
</table>

Initial microstructure

T = 950 °C
Time = 445 hours

T = 1120 °C
Time = 50 hours
Aged Microstructure under Compressive Stress

Compression Creep Frame

Ceramic Compression Creep Extensometer

Top Holder

Bottom Holder

P-Raft

5μm
Physical Models to Describe Aging Behavior

Rafting

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

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

Coarsening

LSW model:

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

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

<table>
<thead>
<tr>
<th>Material</th>
<th>A (\mu m/h)</th>
<th>Q (kJ/mol)</th>
<th>( U_T ) (J/mol.MPa.K^n)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMSX-8</td>
<td>2.0 \times 10^{5}</td>
<td>206</td>
<td>0.033</td>
<td>1.525</td>
</tr>
<tr>
<td>CMSX-4</td>
<td>9.31 \times 10^{4}</td>
<td>222</td>
<td>0.19</td>
<td>1.294</td>
</tr>
</tbody>
</table>

Saturated level of rafting

\[ Q_{coar} (CMSX - 8) = 269.4 \text{ kJ/mol} \]
• 2-point correlation – A statistical representation of the microstructure that provides a magnitude measure in addition to the associated spatial correlation.

\[ f(h, h'|r) = \frac{1}{vol(\Omega)} \int_{\Omega} m(x, h)m(x + r, h'dx) \]

\[ ^n p F_k = \mathbb{E}(^n p f_i) = \frac{1}{S} ^n M_k^p M_k \]

\[ = \frac{1}{S} ^n M_k^p M_k e^{-i ^n \theta_k} e^{i ^n \theta_k} \]

[Niezgoda, Fullwood and Kalidindi, 2008]

• 2-point correlations \( f(h, h' \mid r) \) capture the probability density associated with finding an ordered pair of specific local state at the head and tail of a randomly placed vector \( r \) into the microstructure.

• **Cross-correlation**
  Defined by \( f(h, h' \neq h \mid r) \). The function gives the probability that a random vector of length \( x \) start in one phase and end in the other.

(a) An example of two phase microstructure (b) Cross-correlation for the black and white phases at the head and tail of a vector [Fullwood, Niezgoda, Adams, Kalidindi, 2010].
γ' precipitate and γ channel sizes are determined from the first peak and valley of the probabilistic curve of the corresponding micrograph.
Quantifying the Current Aged State

Reduced order representation of aged microstructures using PCA of 2-point spatial correlations
Influence of Variation in Composition

Thermo-Calc
DICTRA
Databases: TCNi5 / MOBNi2

Composition sensitive diffusivity parameter

Aging behavior

Temperature-dependent constitutive models

LSW model

\[ r^3 - r_0^3 = K(t - t_0) \]

\[ \dot{T}_\phi = \dot{\theta}(T) \left( \frac{\tau^a}{D^a} \right)^\eta \exp \left\{ B_0 \left( \frac{\tau^a}{D^a} \right)^{n+1} \right\} \text{sgn}(r^a - \chi^a) \]

\[ K = \frac{64D_{\text{eff}}C_\infty\sigma\Omega^2}{9RT} \]

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

Composition segregation

Thermo-Calc

Coarsening effective diffusivity

Temperature-dependent constitutive models

\[ \dot{T} = \dot{\theta}(T) \left( \frac{\tau^a}{D^a} \right)^\eta \exp \left\{ B_0 \left( \frac{\tau^a}{D^a} \right)^{n+1} \right\} \text{sgn}(r^a - \chi^a) \]

\[ \Theta(T) = \exp(-\frac{Q}{RT}) \]

Diffusivity parameter

<table>
<thead>
<tr>
<th>Element</th>
<th>wt%</th>
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</thead>
<tbody>
<tr>
<td>Cr</td>
<td>10.82</td>
</tr>
<tr>
<td>Co</td>
<td>20.31</td>
</tr>
<tr>
<td>Mo</td>
<td>1.260</td>
</tr>
<tr>
<td>W</td>
<td>16.52</td>
</tr>
<tr>
<td>Al</td>
<td>2.080</td>
</tr>
<tr>
<td>Ti</td>
<td>0.170</td>
</tr>
<tr>
<td>Ta</td>
<td>0.940</td>
</tr>
<tr>
<td>Re</td>
<td>3.520</td>
</tr>
<tr>
<td>Hf</td>
<td>0.012</td>
</tr>
<tr>
<td>Ni</td>
<td>44.38</td>
</tr>
<tr>
<td>Y channel</td>
<td>2.690</td>
</tr>
<tr>
<td>Y' precipitate</td>
<td>0.130</td>
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</tbody>
</table>
Influence of Composition on Diffusivity

Interdiffusion coefficients of Ni-x binary systems

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

\[ Q_{eff} = \sum_{i=1}^{n} x_i Q_{Ni-x} \]

Composition variation (Re) effect on effective diffusivity of the complex Superalloy system

\[ = 275.9 \text{ KJ/mol} \]
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
Distinct deformation in the $\gamma$ and $\gamma'$ phases

In $\gamma$: 12 octahedral slip systems active

$\gamma'$: 12 octahedral slip systems moving as dislocation ribbons

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

Deformation gradient

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

Velocity gradient

\[ L = \bar{F} \cdot \bar{F}^{-1} \]

Macroscopic plastic velocity gradient

\[ L^p = F^p \cdot F^p = \sum_{\alpha=1}^{N_{\text{slip}}} \lambda^{(\alpha)} \left( s^{(\alpha)} \otimes n^{(\alpha)} \right) \]

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

In \( \gamma' \): 12 octahedral slip systems moving as dislocation ribbons
Creep Deformation Mechanisms of Superalloys

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)

[Reed, 2006; Ma, Dye, and Reed, 2008, CMSX-8 Data]
Inelastic Velocity Gradient

\[ \mathbf{L}^{in} = \mathbf{F}^{in} \mathbf{F}^{in^{-1}} = f_{\gamma'} \left( \sum_{\alpha=1}^{12} \gamma^{\gamma} \dot{\gamma}^{\gamma} \left( \hat{\mathbf{d}}^{(\alpha)} \otimes \hat{\mathbf{n}}^{(\alpha)} \right) \right) + f_{\gamma'} \left( \sum_{\alpha=13}^{24} \gamma^{L1_2} \dot{\gamma}^{L1_2} \left( \hat{\mathbf{d}}^{(\alpha)} \otimes \hat{\mathbf{n}}^{(\alpha)} \right) \right) \]

Inelastic Shear Strain Rate

\[
\begin{align*}
\dot{\gamma}^{\gamma} &= \rho^{(\alpha)} \beta^{\gamma} F_{\text{attack}} \text{sign} \left( \tau^{(\alpha)} + \tau^{(\alpha)}_{\text{mis}} - \chi^{(\alpha)} \right) \exp \left( -Q_{\text{slip}}^{110} + \frac{\left| \tau^{(\alpha)} + \tau^{(\alpha)}_{\text{mis}} - \chi^{(\alpha)} \right| - \tau^{(\alpha)}_{\gamma \text{pass}} - \tau^{(\alpha)}_{\text{oro}}}{kT} \right) \frac{V^{(\alpha)}_{c1}}{} \\
\dot{\gamma}^{L1_2} &= \rho^{(\alpha)}_{L1_2} \beta^{L1_2} F_{\text{attack}} \text{sign} \left( \tau^{(\alpha)} - \chi^{(\alpha)} \right) \exp \left( -Q_{\text{slip}}^{112} + \frac{\left| \tau^{(\alpha)} - \chi^{(\alpha)} \right| - \tau^{(\alpha)}_{L1_2 \text{pass}} - \tau^{(\alpha)}_{\text{AFB}}}{kT} \right) \frac{V^{(\alpha)}_{c2}}{}
\end{align*}
\]

Evolution Equations

\[
\begin{align*}
\dot{\rho}^{(\alpha)}_{\gamma} &= \frac{1}{b} \left( \frac{c_{\mu11}}{\beta^{(\alpha)}_{\gamma}} - c_{\text{annh1}} \rho^{(\alpha)}_{\gamma} \right) \left| \dot{\gamma}^{\gamma} \right| \\
\dot{\rho}^{(\alpha)}_{L1_2} &= c_{\mu21} \rho^{(\alpha)}_{pb} \Gamma + \frac{c_{\mu22}}{b} \beta^{(\alpha)}_{\gamma} \left| \dot{\gamma}^{\gamma} \right| - c_{\text{annh2}} \rho^{(\alpha)}_{\gamma} \beta^{(\alpha)}_{\gamma} \left| \dot{\gamma}^{\gamma} \right| \\
\dot{\rho}^{(\alpha)}_{pb} &= \frac{c_{\mu2}}{b} \beta^{(\alpha)}_{\gamma} \left| \dot{\gamma}^{\gamma} \right| - c_{\text{annh}} \rho^{(\alpha)}_{pb} \beta^{(\alpha)}_{\gamma} \left| \dot{\gamma}^{\gamma} \right|
\end{align*}
\]
Orientation Sensitivity

CMSX-4 Model Predictions

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

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]
Creep in different orientations

Temp = 950[°C], Stress = 250[MPa]

Data <001>, CVP <111>, CVP <001>, CVP <112>, CVP <101>, CVP <212>, CVP <102>
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 = -\( \infty \), \( \dot{T} = 2.83[{^\circ}K/s] \)

Very good agreement predicting TMF
Stabilized hysteresis: IP-TMF
[100-1100-100] °C, R = 0, \( \dot{T} = 2.83[^\circ K/s] \)

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

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:

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

$$
\dot{\gamma}_{L_2}^\text{in}(\alpha) = \rho^{(\alpha)}_{L_2} b \lambda^{(\alpha)}_{L_2} F^\text{attack} \text{sign}(\tau^{(\alpha)} - \chi^{(\alpha)}) \exp\left[\frac{-Q_{\text{slip}}^{112} + \left|\tau^{(\alpha)} - \chi^{(\alpha)}\right| - \tau^{(\alpha)}_{L_2\text{pass}} - \tau_{\alpha\beta \gamma}}{kT} \right] V_{c2}^{(\alpha)}
$$

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]
• Exercise new CVP codes
  • (1) displacement-controlled algorithm coded in FORTRAN as UMAT for ABAQUS (suitable for 3D analysis of detailed features, but computationally expensive)
  • (2) stress-controlled algorithm coded in MATLAB (limited to 1D loadings, but computationally cheap; utility in alloy design; early design iterations)
• Characterize aged microstructure and its analysis
  • Establish protocols for reduced-order modeling of the current state of the microstructure using spatial correlations and principal component analysis
  • Develop PSP linkage models using PC values for describing current state of the microstructure
• Creep-fatigue interaction life analysis relationships using all new data
• Disseminate research
  • Archival journal articles
  • Intern with Siemens Energy
  • Workshops and Conferences (UTSR, ASME, …)
• Ernesto Estrada Rodas – complete Ph.D. studies in 2017