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Microstructure-Sensitive Crystal Viscoplasticity for Ni-base Superalloys

(with application to long-term creep-fatigue interactions)

Award DE-FE0011722
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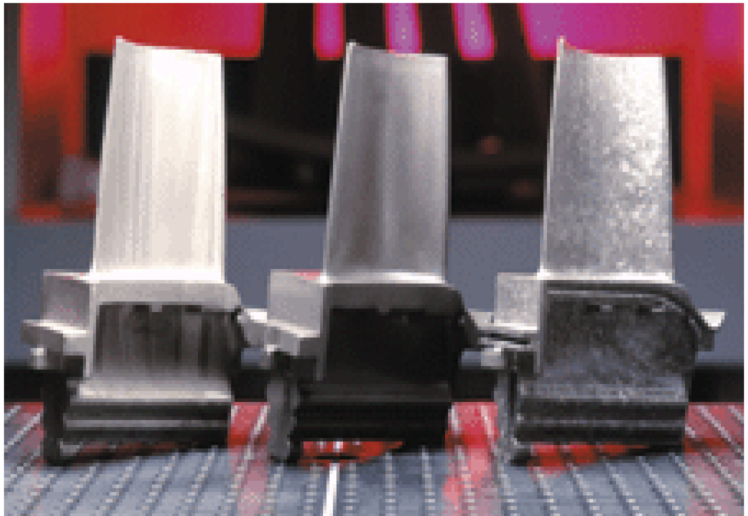
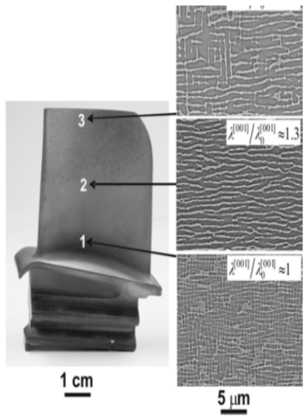
University Turbine Systems Research Workshop
Virginia Tech
November 1-3, 2016

Hot Section Gas Turbine Materials

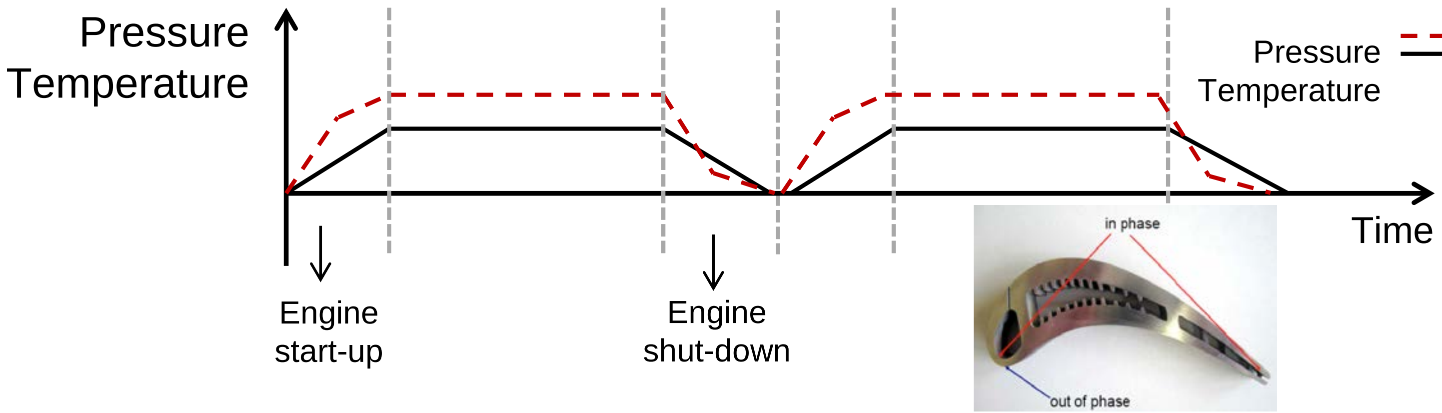
Land-based gas turbines

- 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

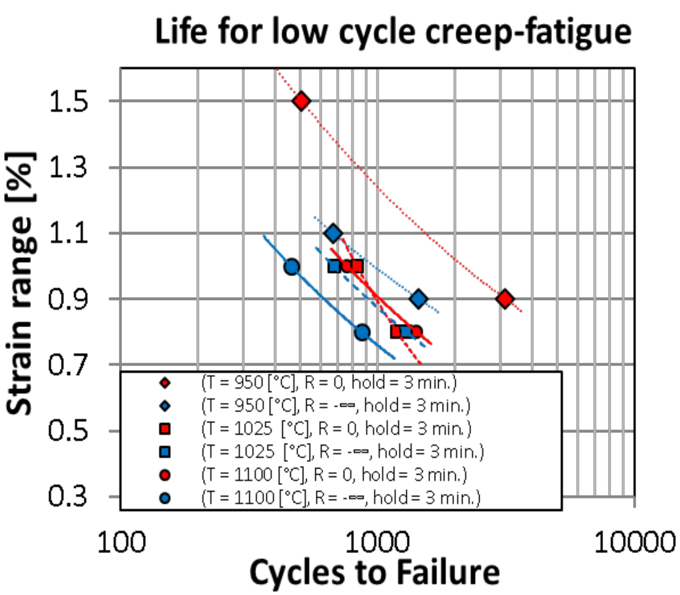


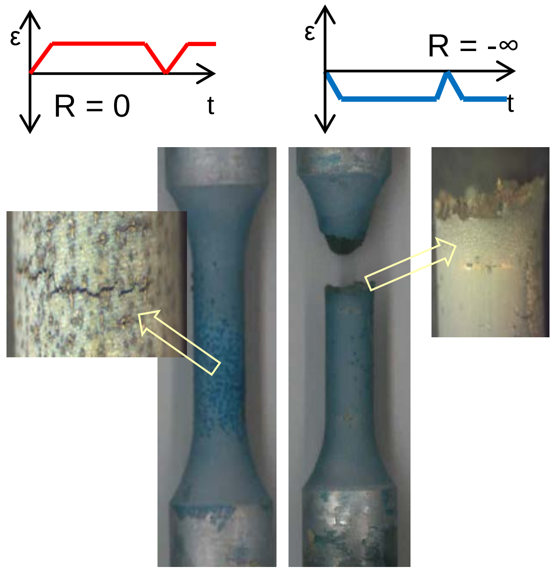


[Epishin et al., 2010]



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

Continuation of "Process" During Service

- Load profile
- Temperature profile
- Environment profile

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

Dislocations
- Density in γ and γ'
- 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

Influence of Service Conditions on Microstructure, Properties, & Performance

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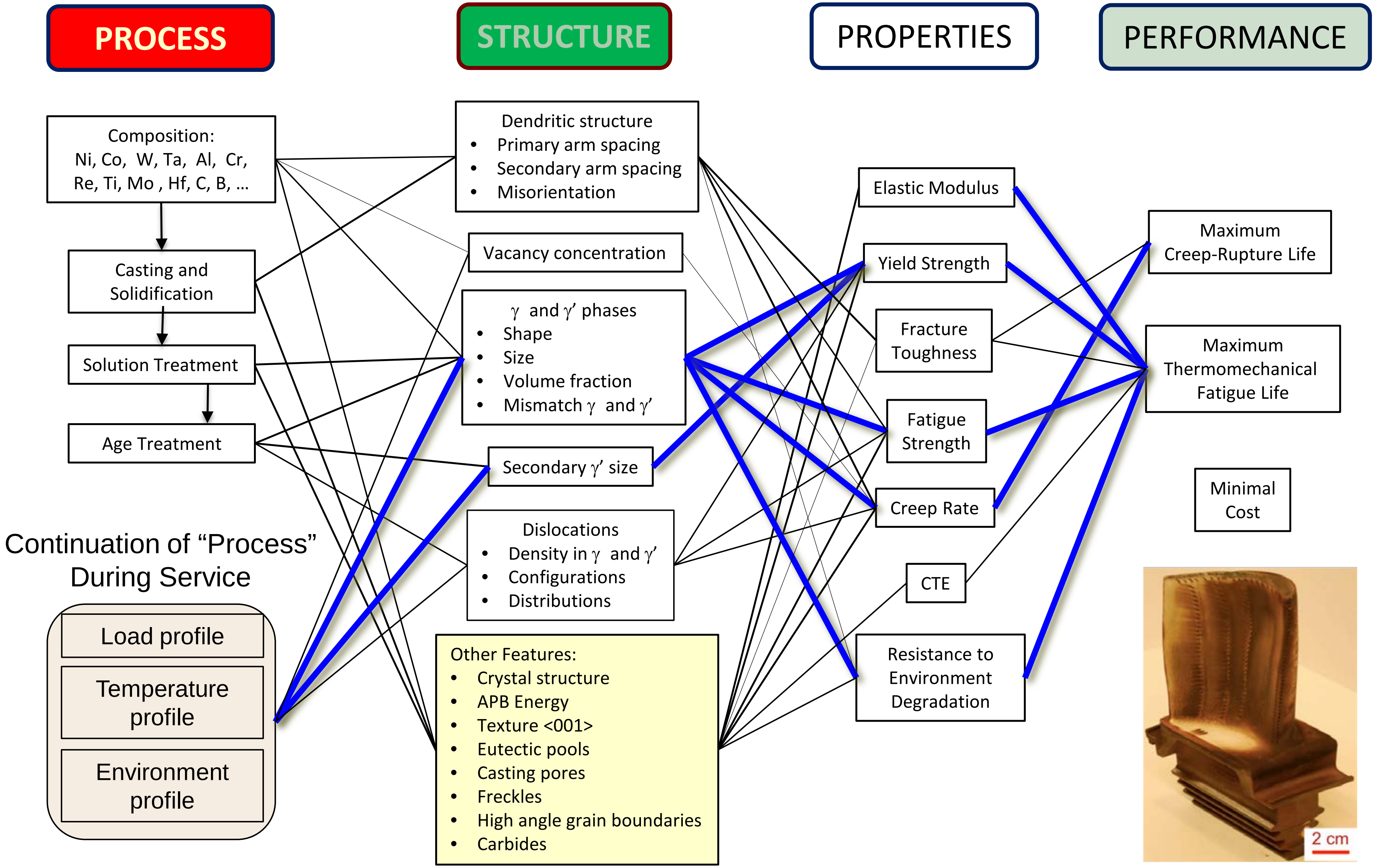

Role of Chemical Composition

PROCESS

- Composition: Ni, Co, W, Ta, Al, Cr, Re, Ti, Mo , Hf, C, B, …
- Casting and Solidification
- Solution Treatment
- Age Treatment

Continuation of "Process" During Service

- Load profile
- Temperature profile
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- Resistance to Environment Degradation

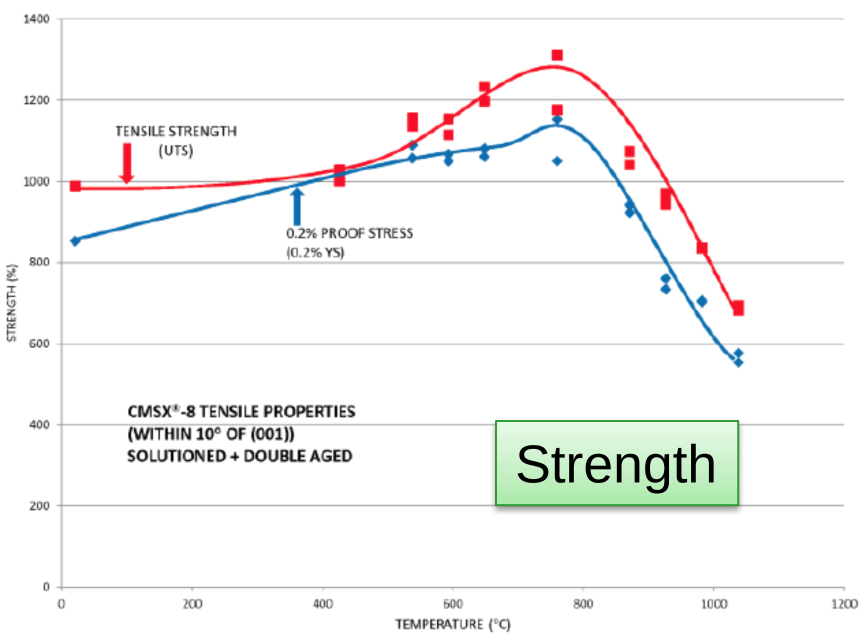
PERFORMANCE

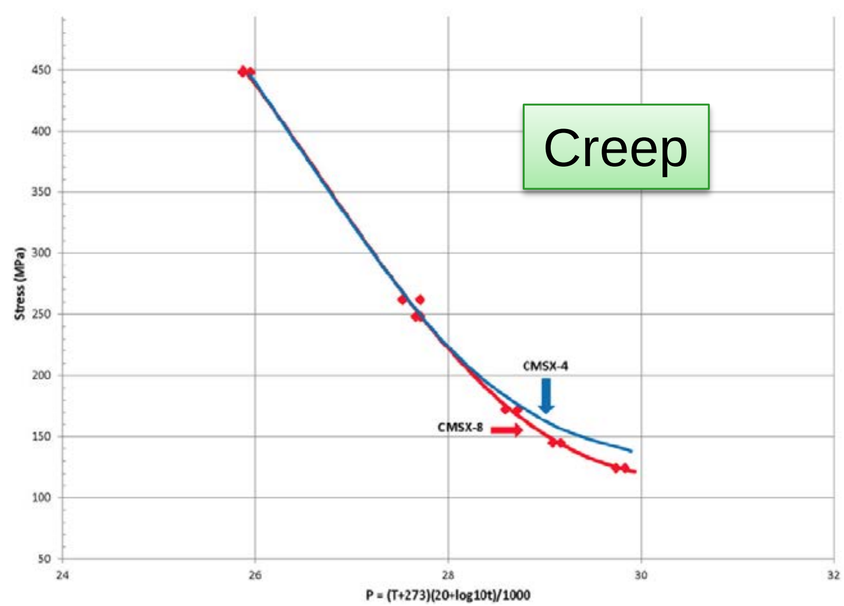
- Maximum Creep-Rupture Life
- Maximum Thermomechanical Fatigue Life
- Minimal Cost

Single Crystal Alloy being Investigated for IGT Applications

CMSX-8: 1.5% Re "alternative 2nd gen alloy" replacing 3.0% Re containing alloys (e.g., CMSX-4, PWA1484)

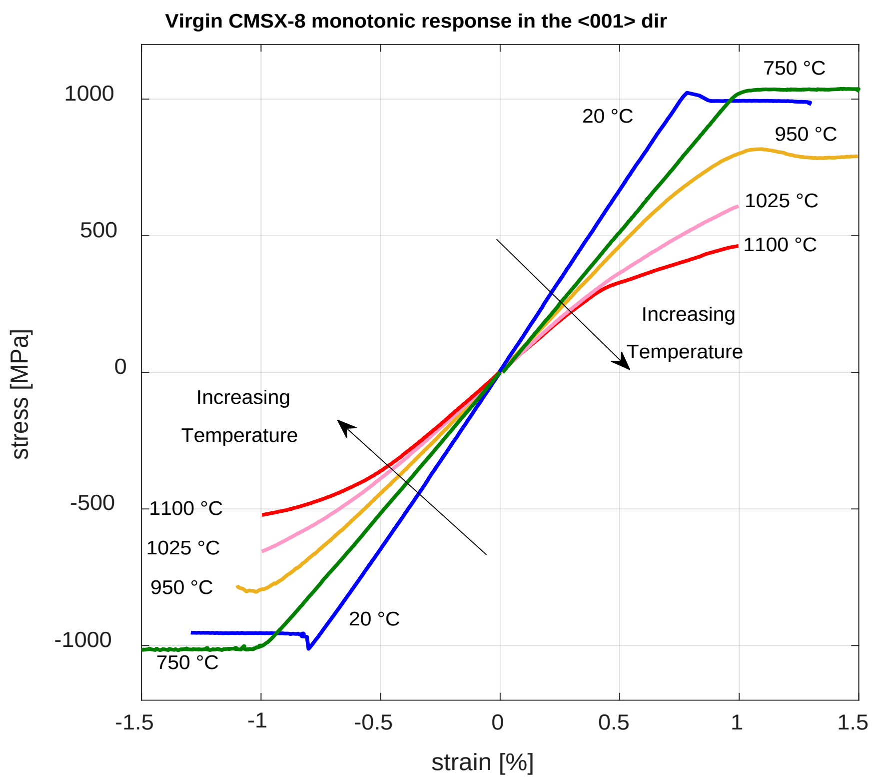
Alloy	Cr	Co	Mo	W	Al	Ti	Ta	Re	Hf	C	B	Zr	Ni
Mar-M247LC-DS	8.4	10.0	0.7	10.0	5.5	1.0	3.0	-	1.5	0.07	0.015	0.05	Bal
CM247LC-DS	8.1	9.2	0.5	9.5	5.6	0.7	3.2	-	1.4	0.07	0.015	0.01	Bal
CMSX-4	6.5	9.0	0.6	6.0	5.6	1.0	6.5	3.0	0.1	-	-	-	Bal
SC16	16	0.17	3.0	0.16	3.5	3.5	3.5	-	-	-	-	-	Bal
PWA1484	5.0	10.0	2.0	6.0	5.6	-	9.0	3.0	0.1	-	-	-	Bal
CMSX-8	5.4	10.0	0.6	8.0	5.7	0.7	8.0	1.5	0.2	-	-	-	Bal

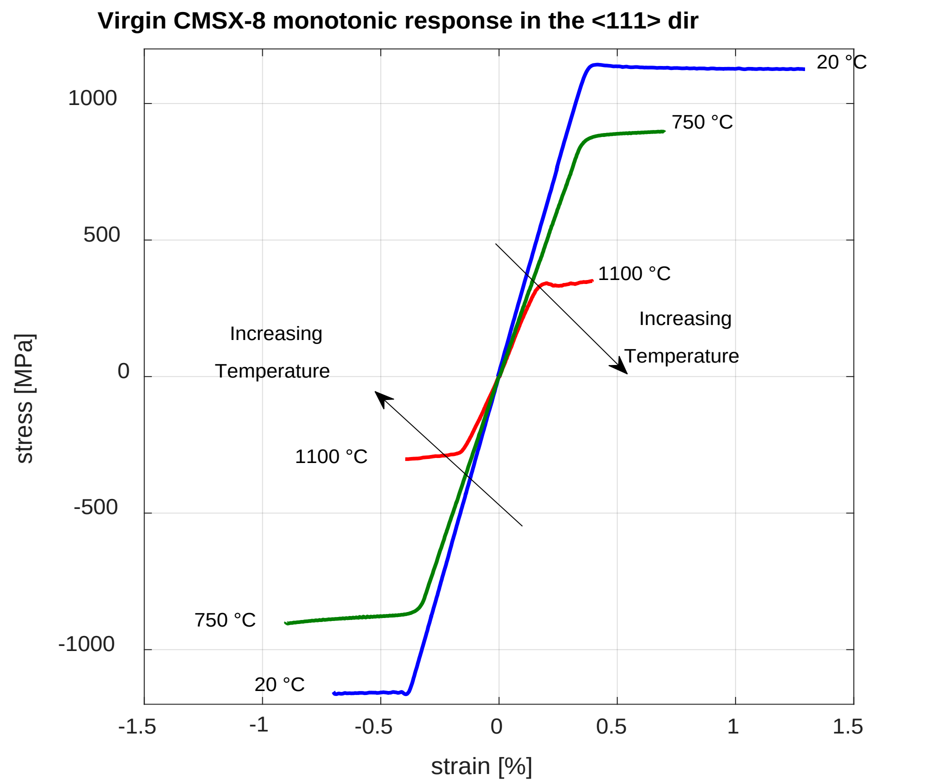




[Wahl and Harris, 2012]

Influence of Temperature, Loading Direction and Crystal Orientation on Modulus and Strength





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Thermomechanical Fatigue (TMF)

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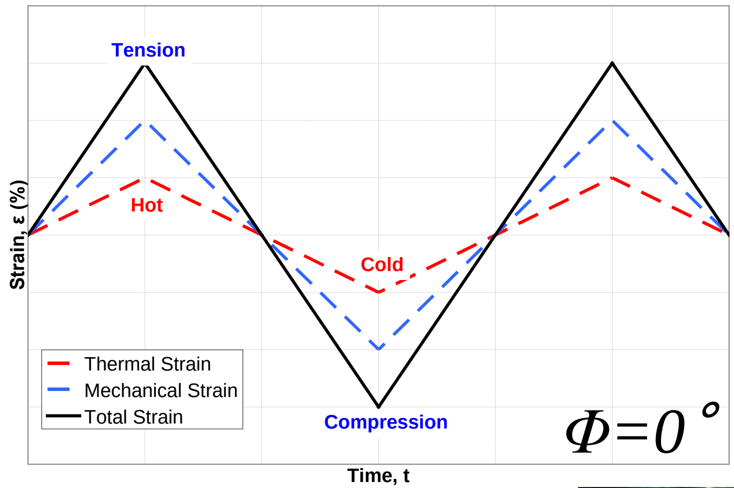
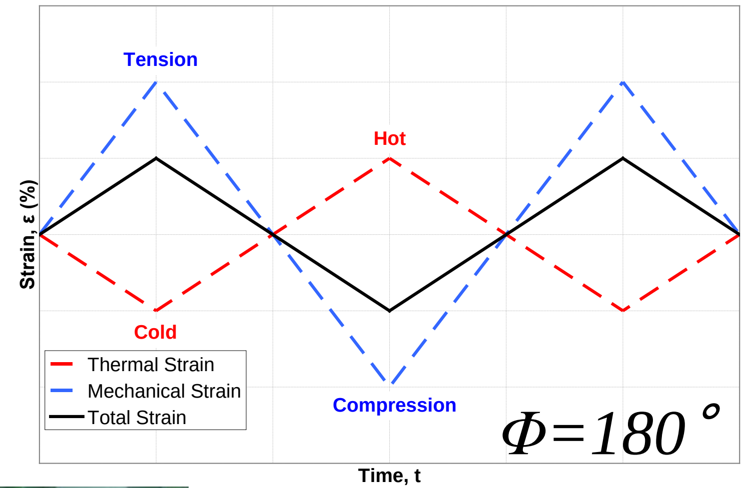
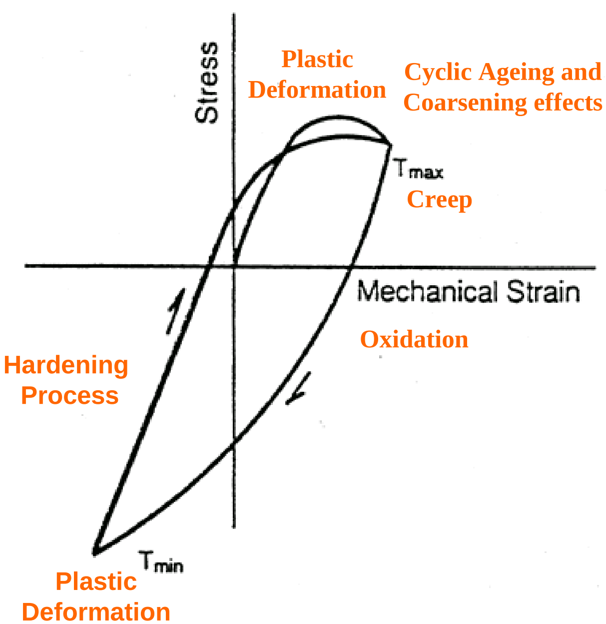
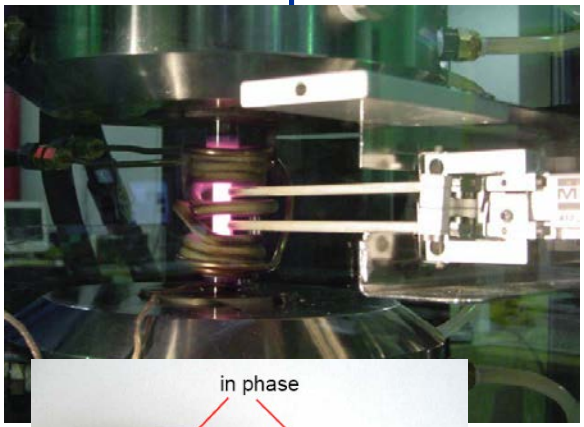
Linear In-Phase (IP)

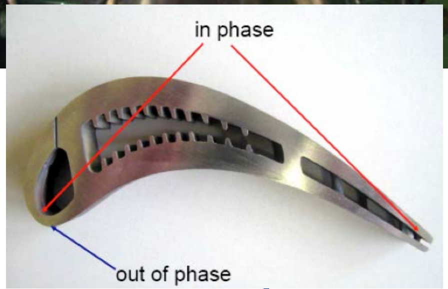


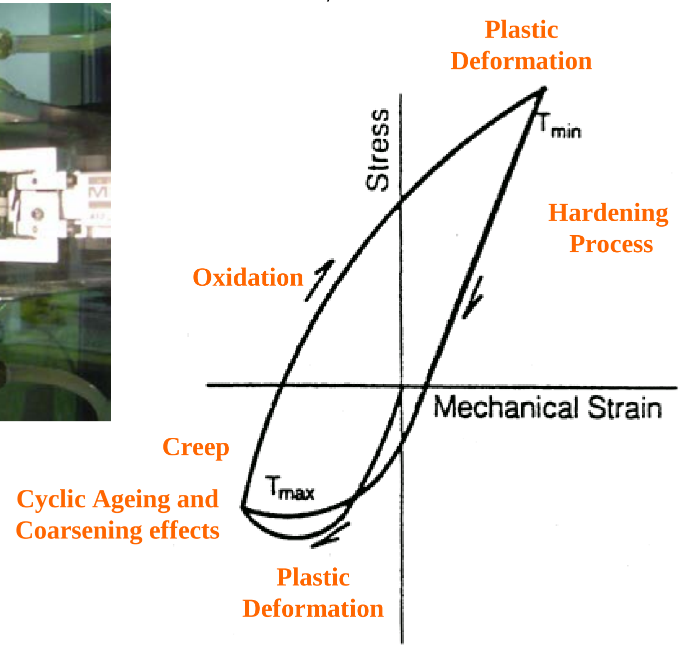
Linear Out-of-Phase (OP)





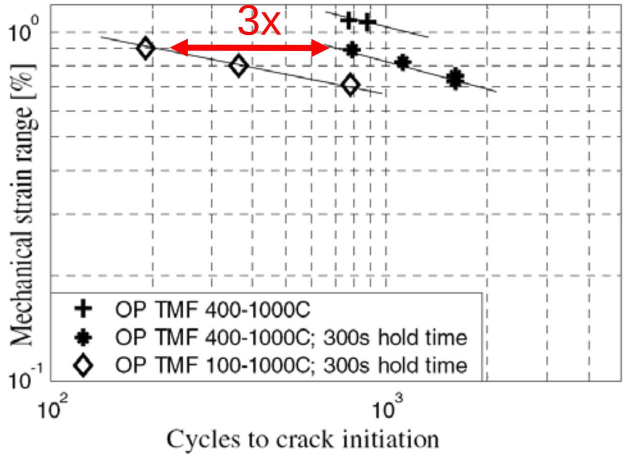


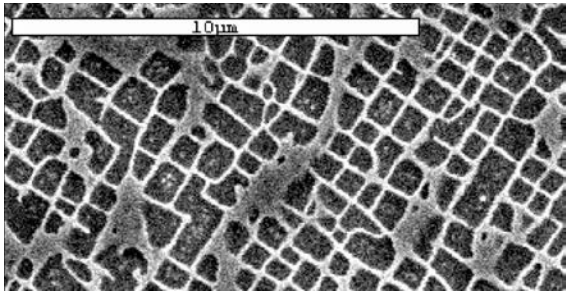


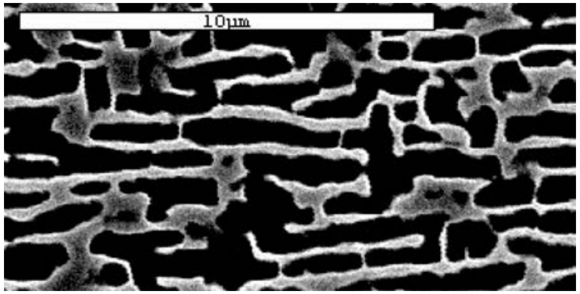


Effect of T_{min} on OP TMF of CMSX-4

CMSX-4 [001]

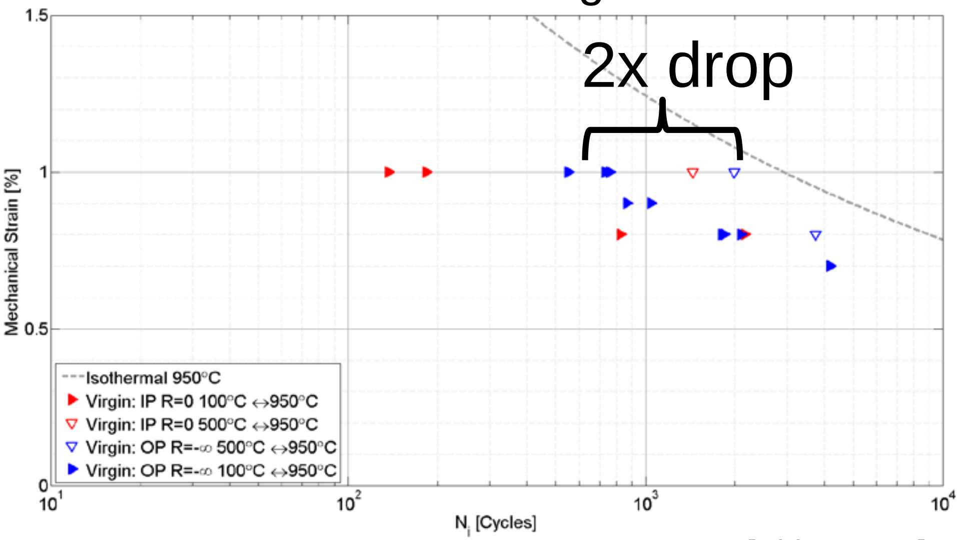




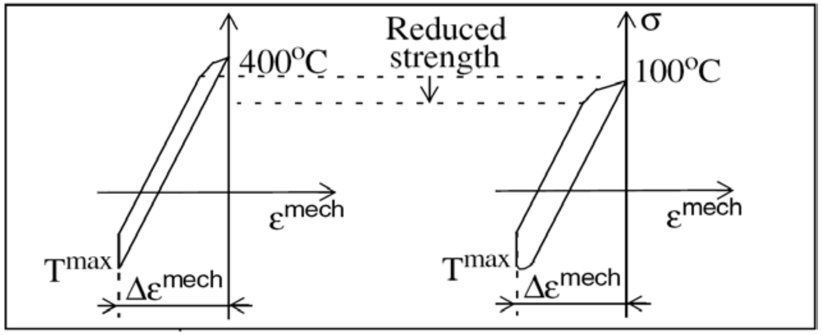


[Arrell et al., 2004]

CM247LC DS in Longitudinal Dir.

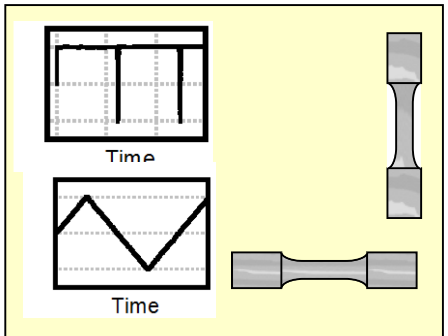


[Kirka, 2014]

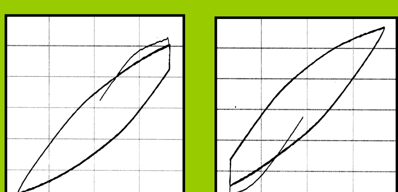


Life Modeling Approach

Damage Mechanism Modules



Deformation Response



Fatigue → N_i^{fat}

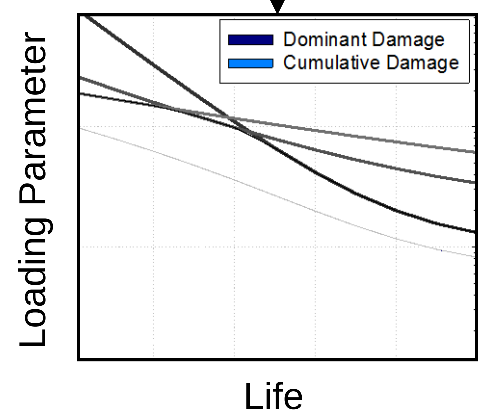
Creep-Fatigue → N_i^{cr}

Environment-Fatigue → N_i^{env}

Creep Ratchetting → N_i^{rat}

Dominant Damage

$$N_i = \min\left\{N_i^{fat}, N_i^{cr}, N_i^{env}, \ldots\right\}$$



Accurrate representations of the deformation response highly critical for predicting crack formation

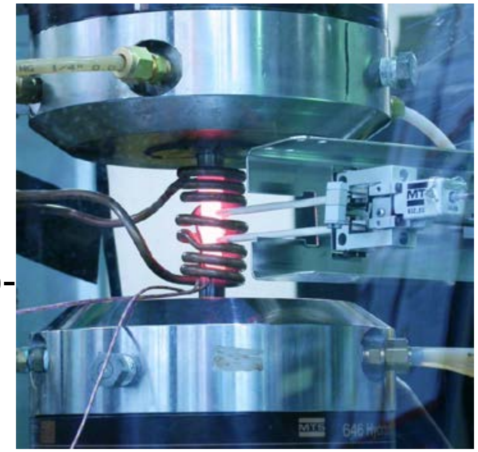
Primary Objectives of UTSR Project

- 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

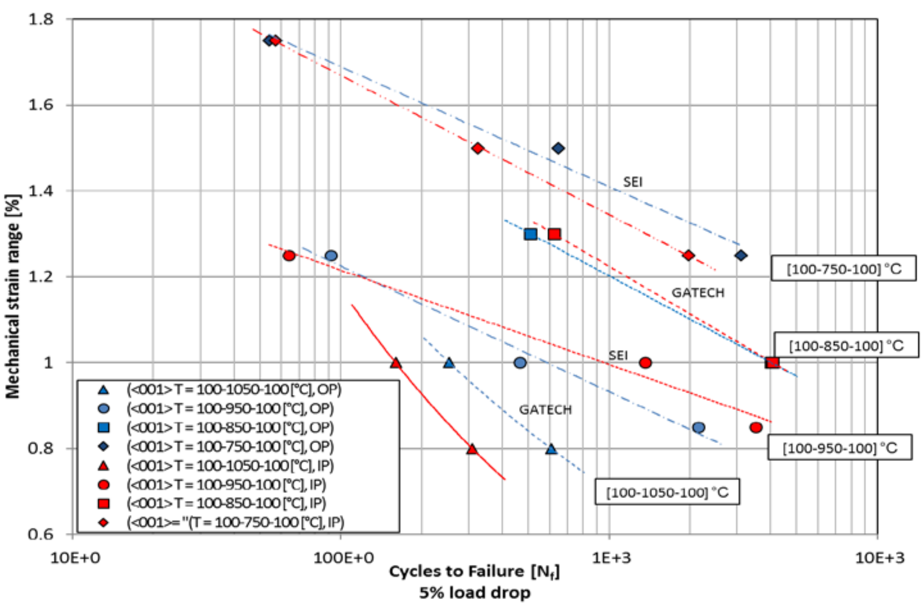
Major Activities and Accomplishments

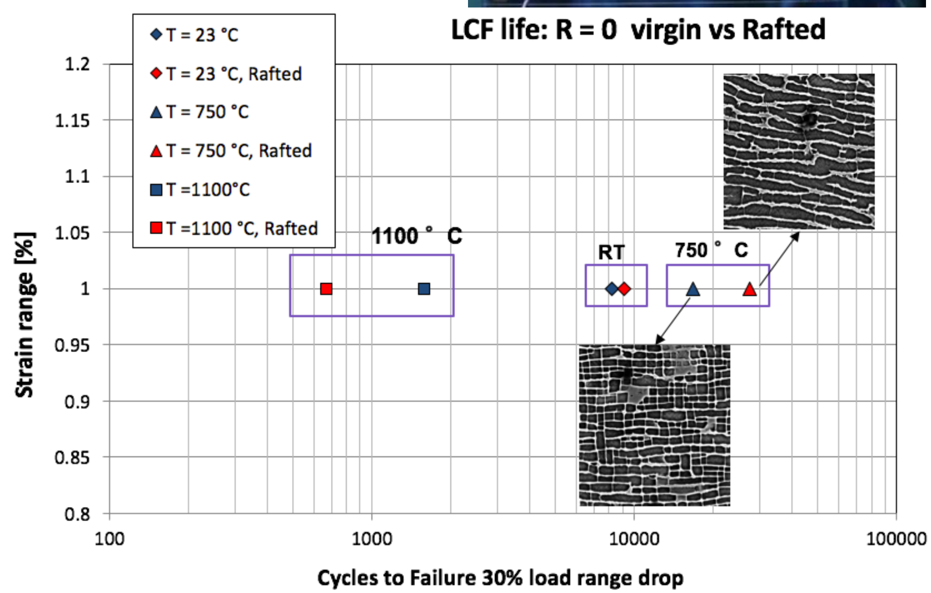
Experimentally establish the creep-fatigue interactions in a single-crystal Ni-base superalloy that is being targeted for use in industrial gas turbines (CMSX-8)

- 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

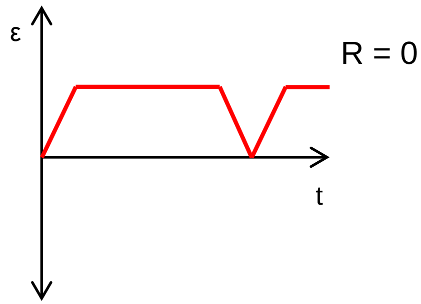


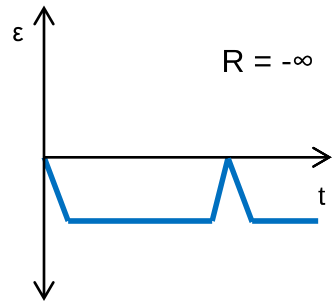
TMF life: In-Phase (R=0) vs Out-of-Phase (R=-inf)

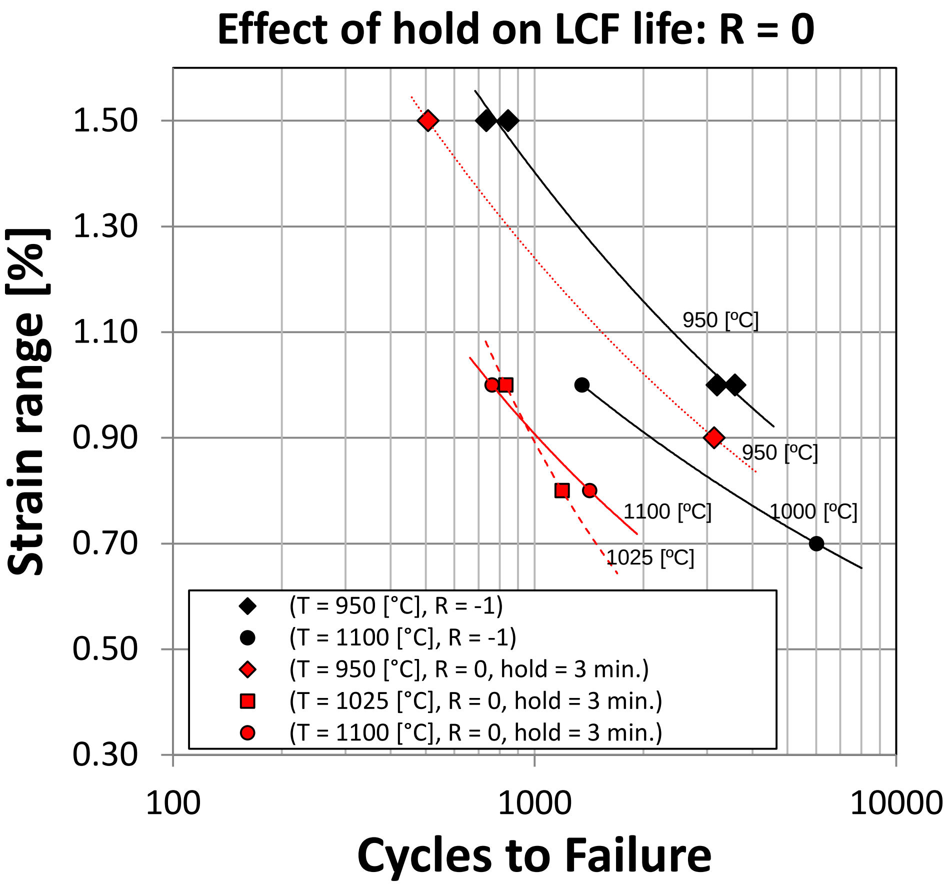


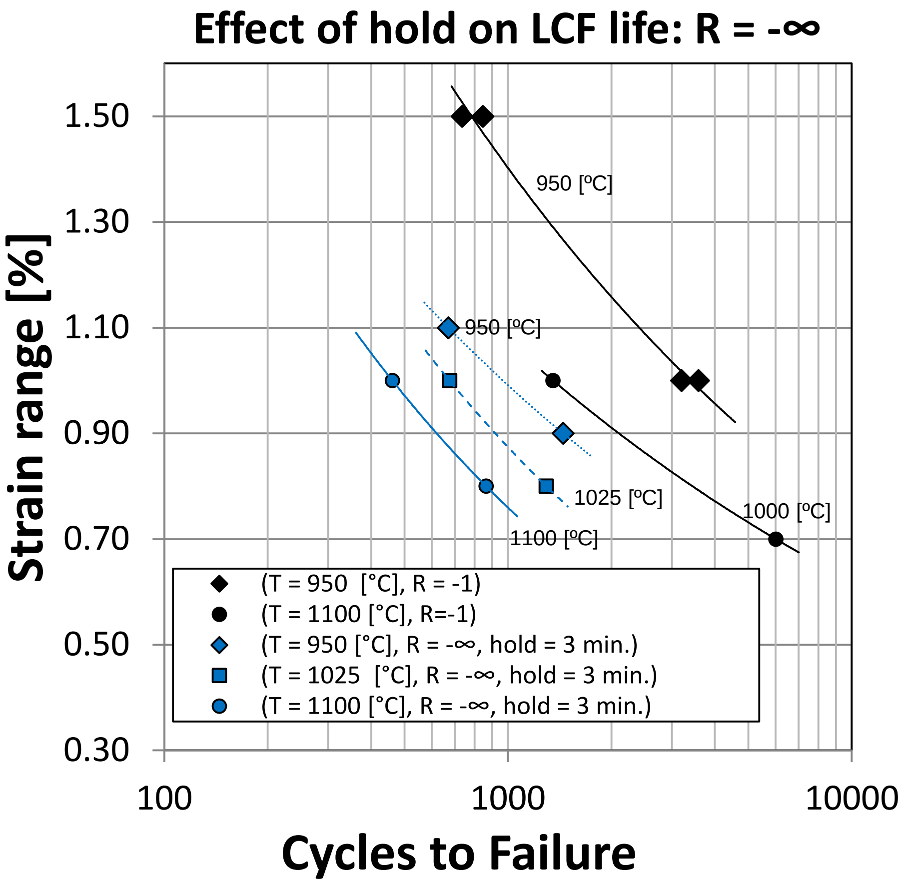


Conventional Creep-Fatigue (baseline)

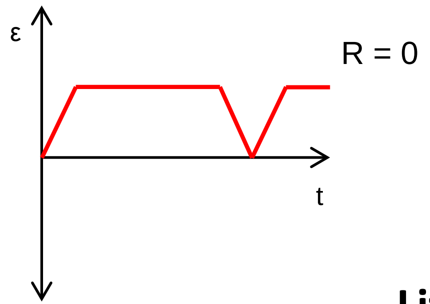


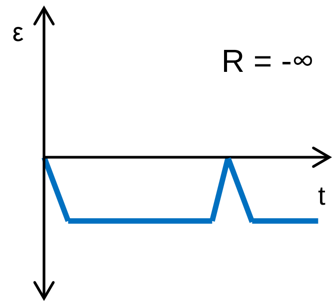


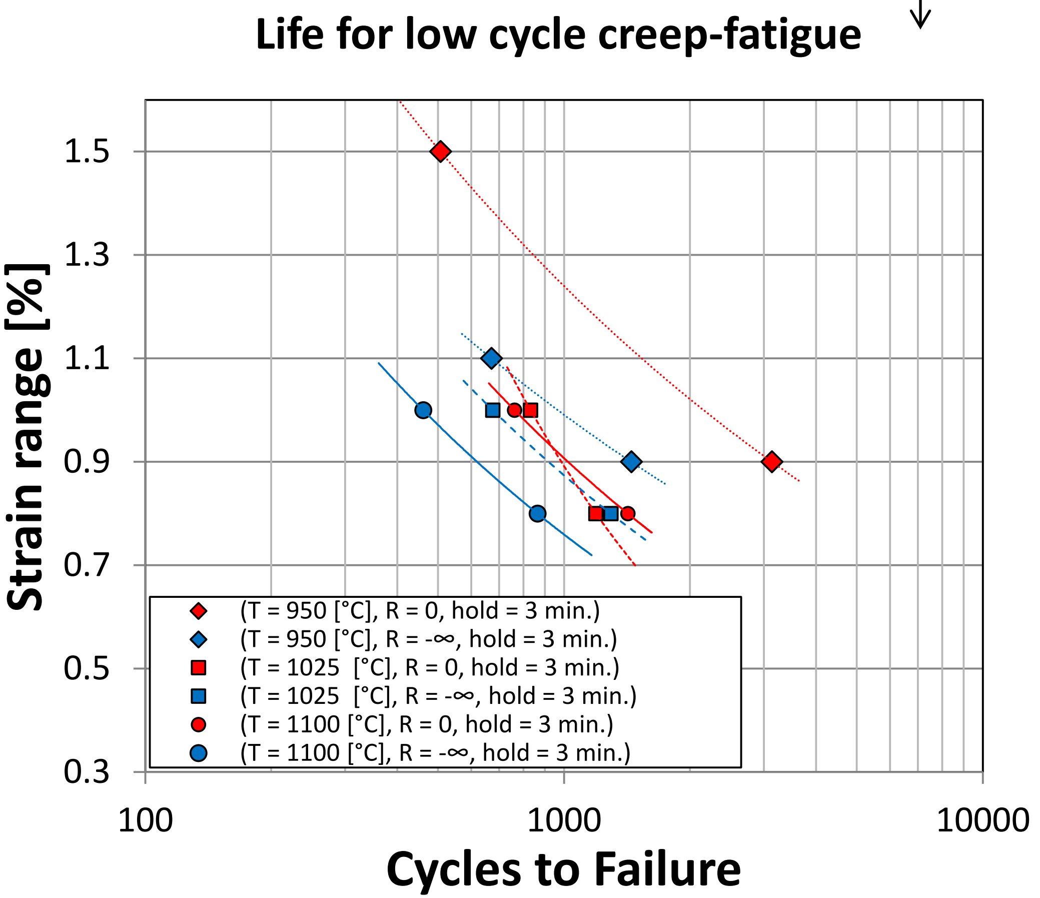




Conventional Creep-Fatigue (baseline)

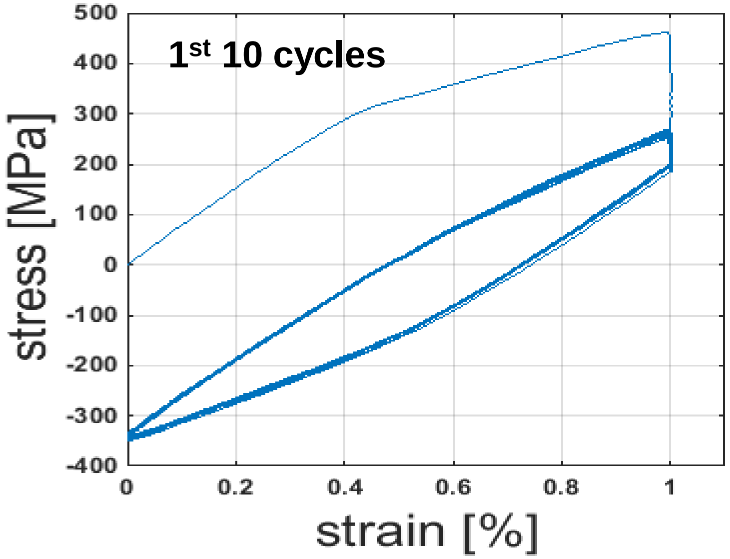


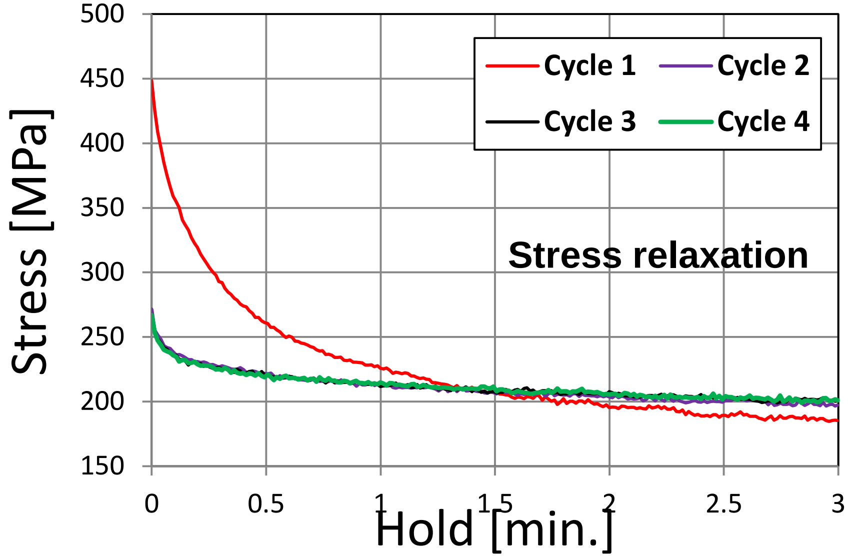


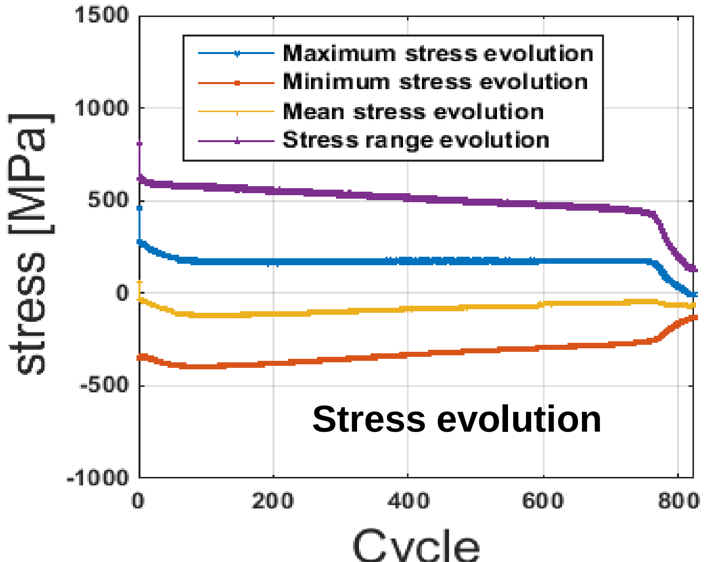


Cycle Evolution

T = 1100 ºC, R = 0, Δε = 1.0 %

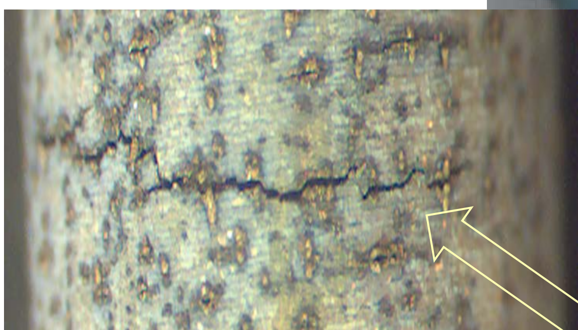


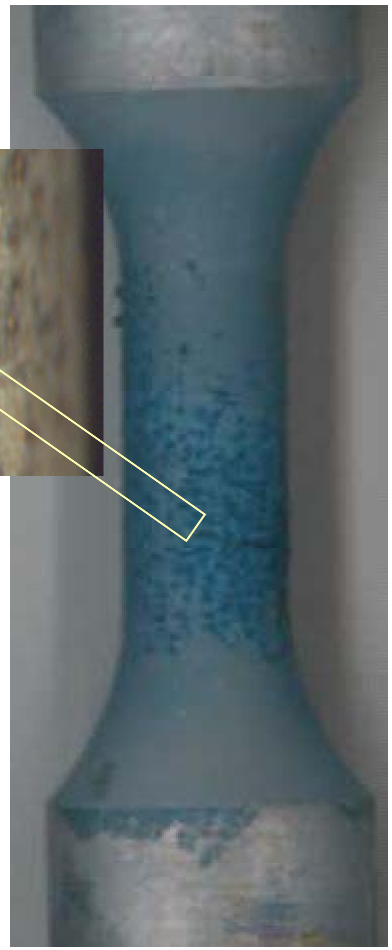


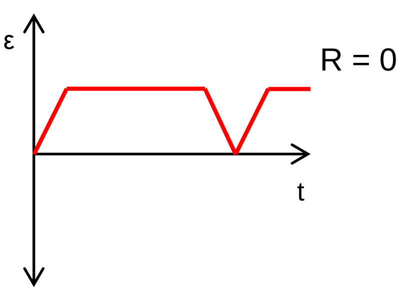


Crack Characteristics

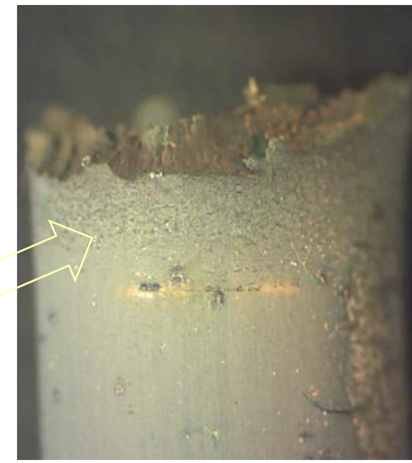
$R = 0$, $T = 1100°C$, $\Delta\varepsilon = 0.8\%$
$N_f = 1420$

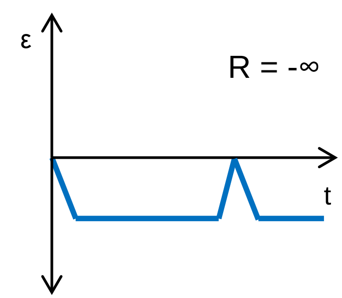




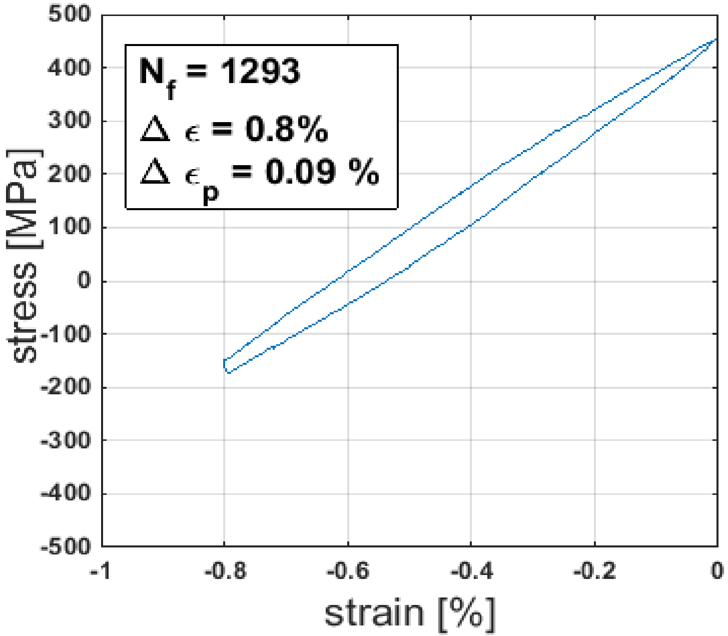


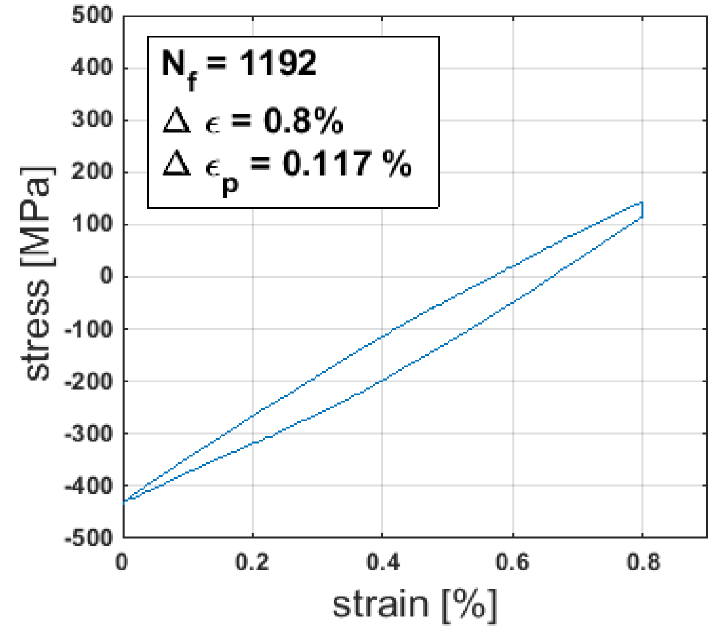
$R = -\infty$, $T = 1100°C$, $\Delta\varepsilon = 0.8\%$
$N_f = 980$



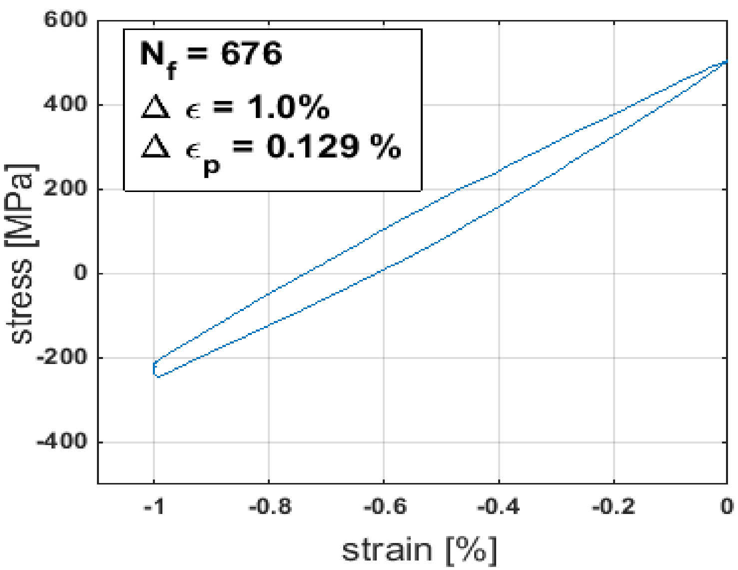


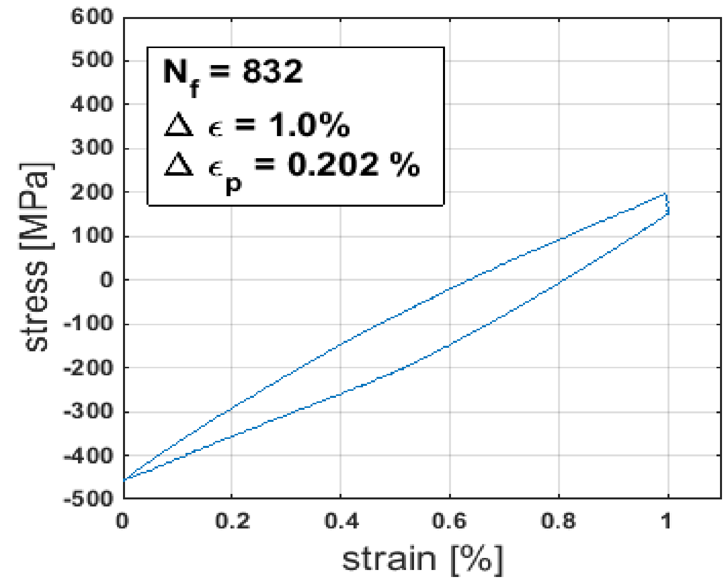
Half-life at 1025 ºC





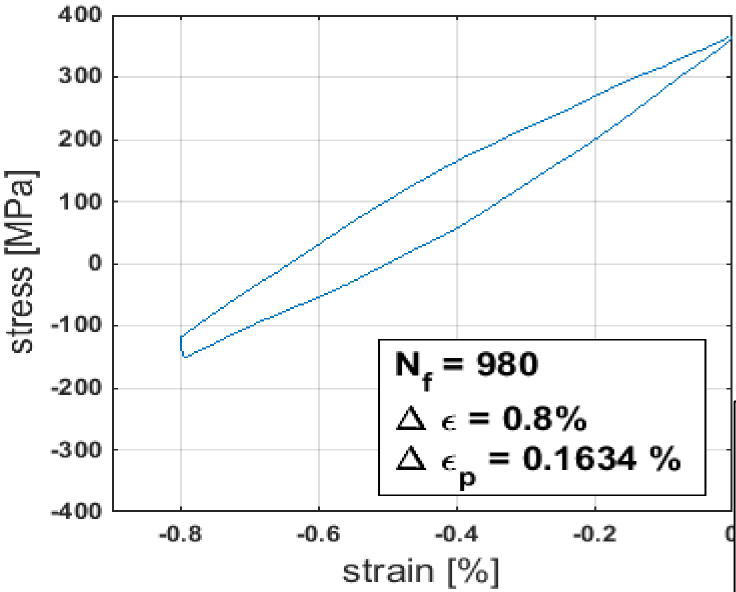
$\Delta\varepsilon$ = 0.8 [%]

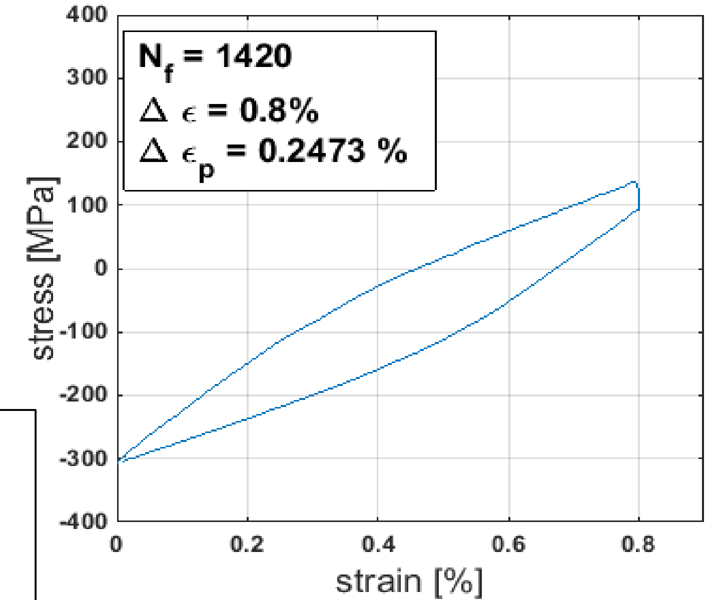




$\Delta\varepsilon$ = 1.0 [%]

Half-life at 1100 ºC

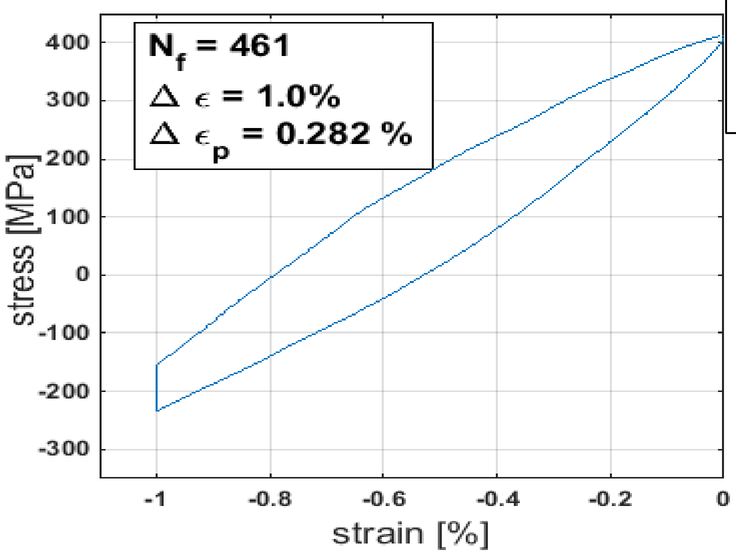


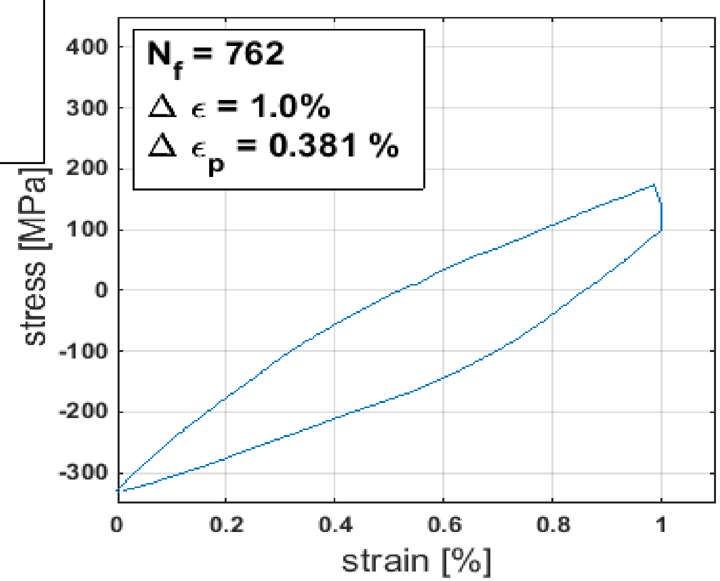


$\Delta\varepsilon$ = 0.8 [%]

Plastic strain range alone does not explain life data at high temperatures. A Coffin-Manson relations would not be sufficient

$\Delta\varepsilon$ = 1.0 [%]





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- 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

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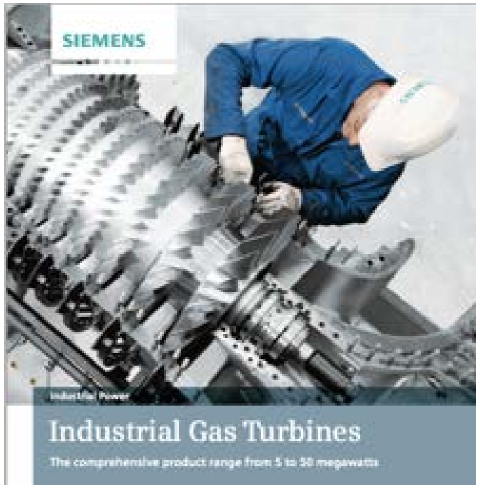
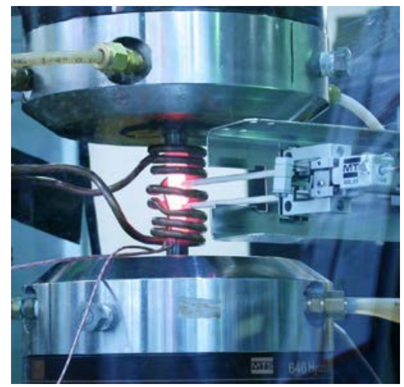


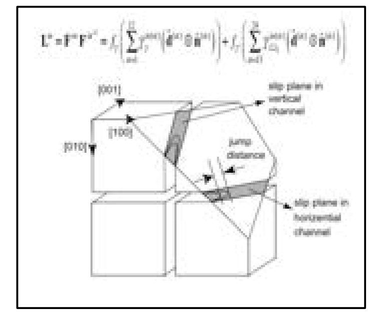
Microstructure-sensitive Crystal Viscoplasticity (CVP) Model to Determine Service "Process"-Structure-Property Linkages

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

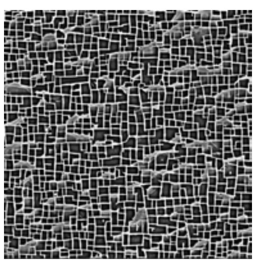
γ deformation

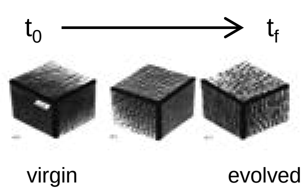


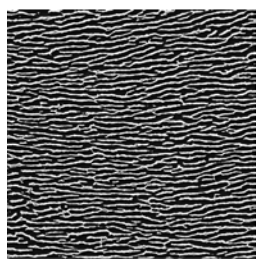
γ' deformation



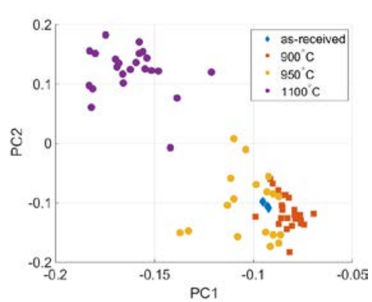
Experiments & Models to Predict Current State of Microstructure (Service Process-Structure Linkages)







- 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

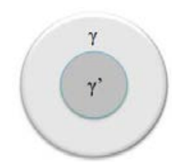


Sensitivity of Local Composition on Diffusivity for Input in Aging and Viscoplasticity Models

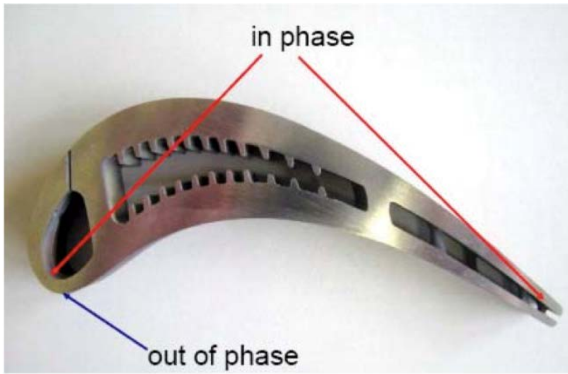
Thermo-Calc
DICTRA
Databases: TCNi5 / MOBNi2

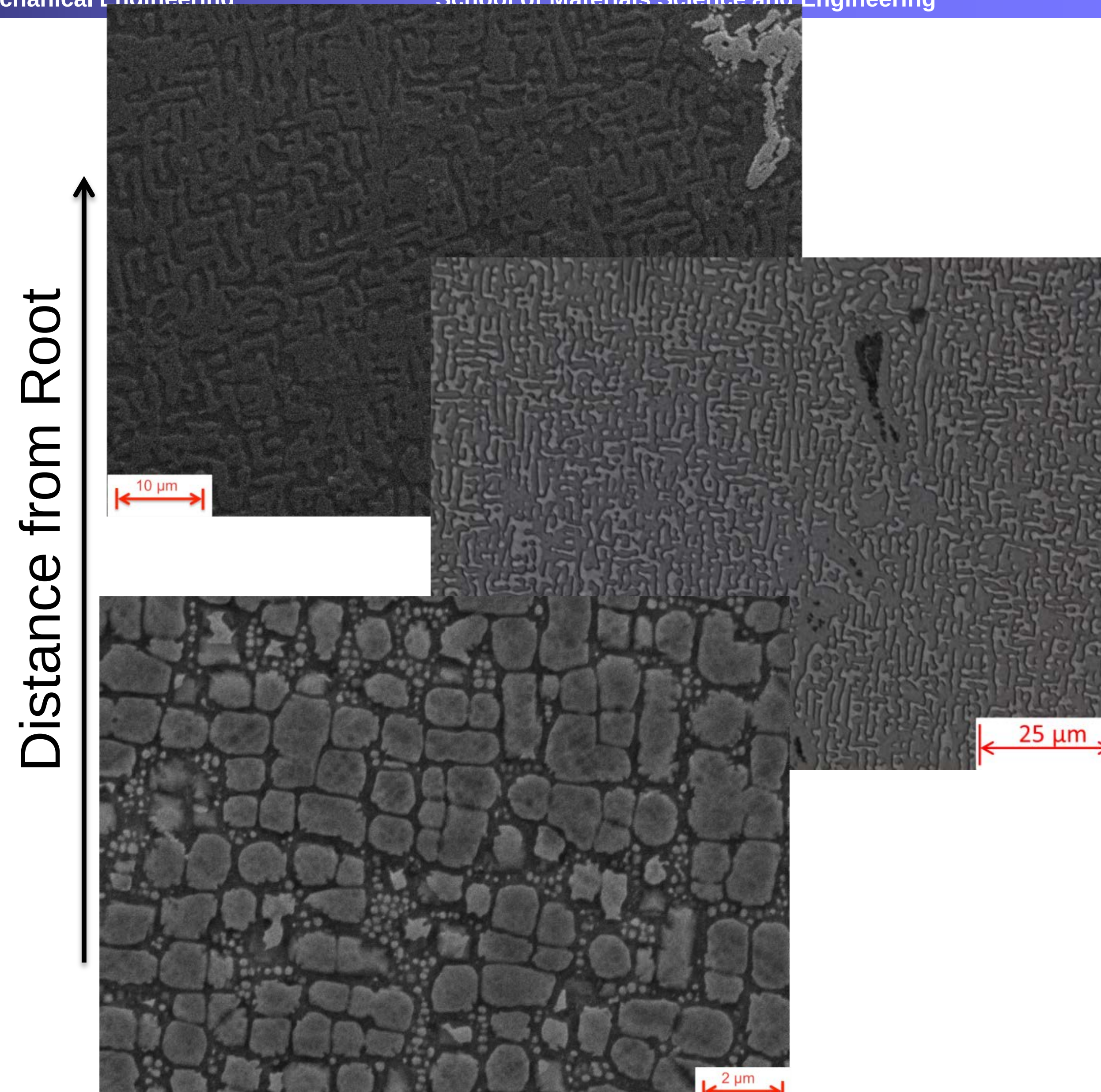
Thermo-Calc Software

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

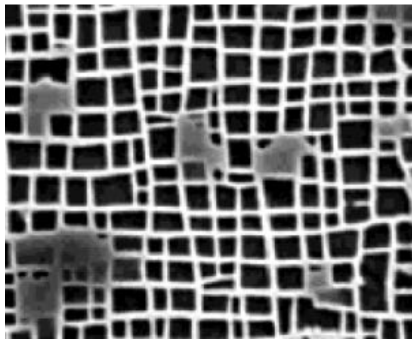


Microstructure Evolution in Blades

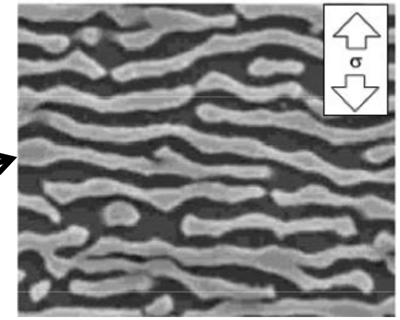




Rafting and Coarsening of γ’

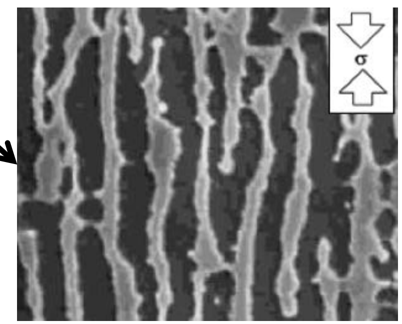


Tension



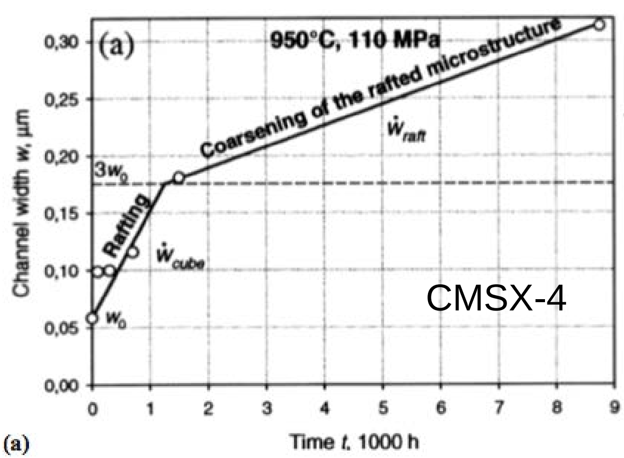
N-raft

Compression



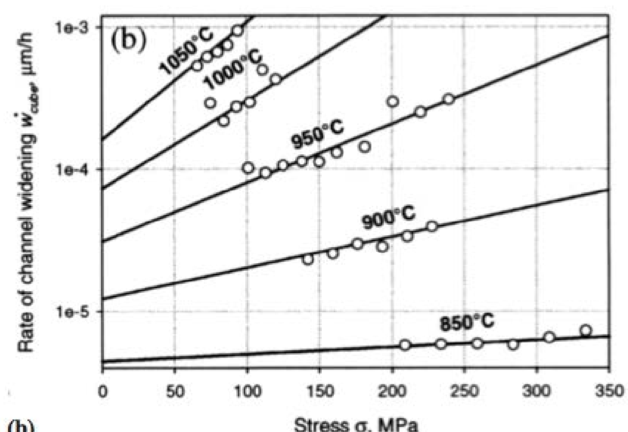
P-raft

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



CMSX-4

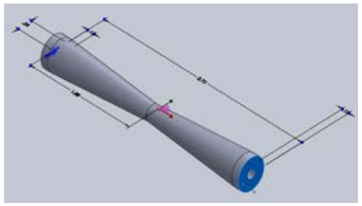
(a)

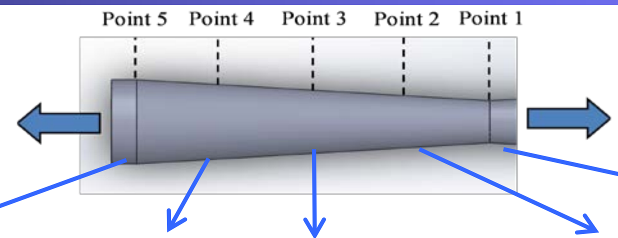


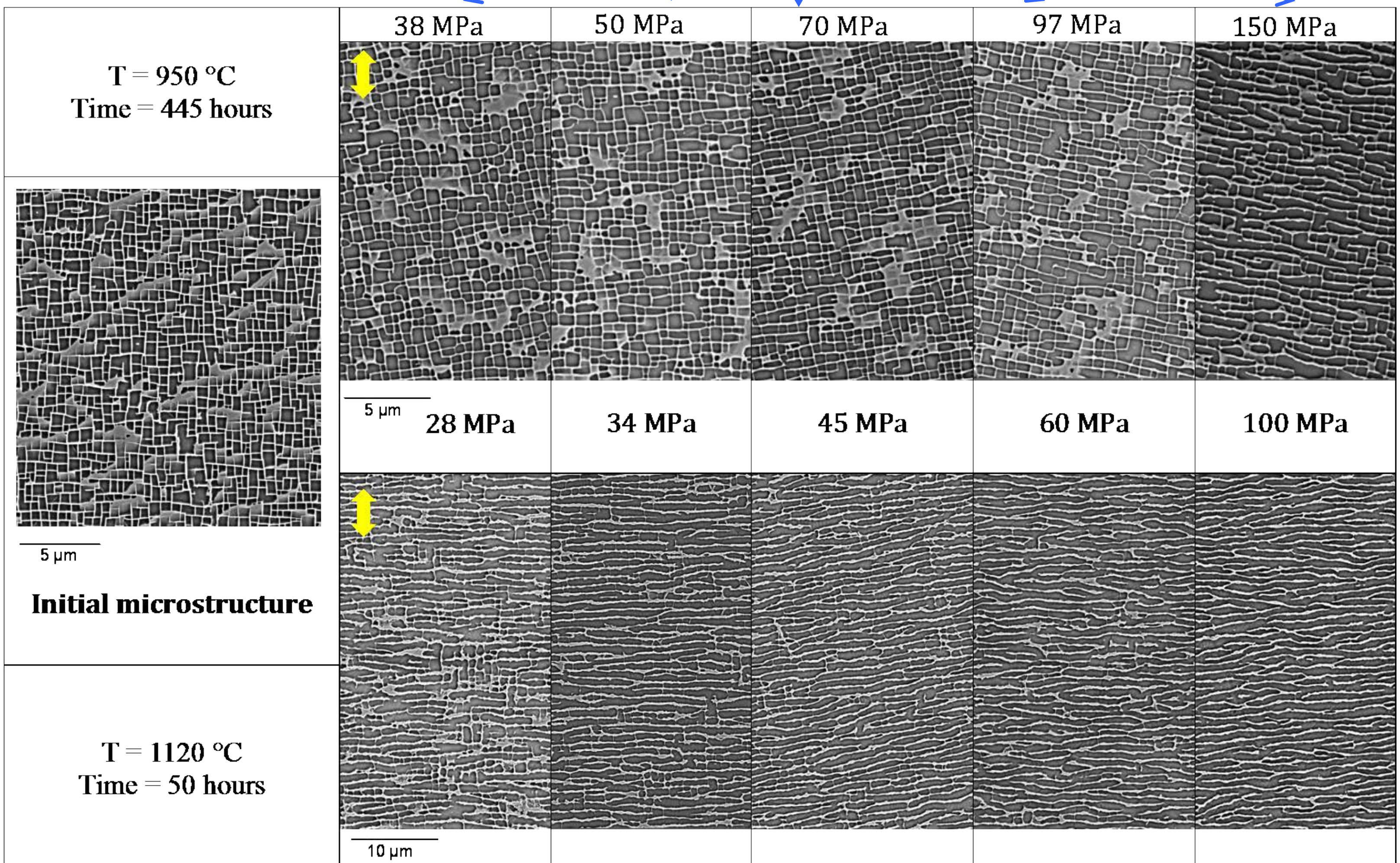
(b)

[Epishin et al., 2008]

High-Throughput Stress-assisted Aging

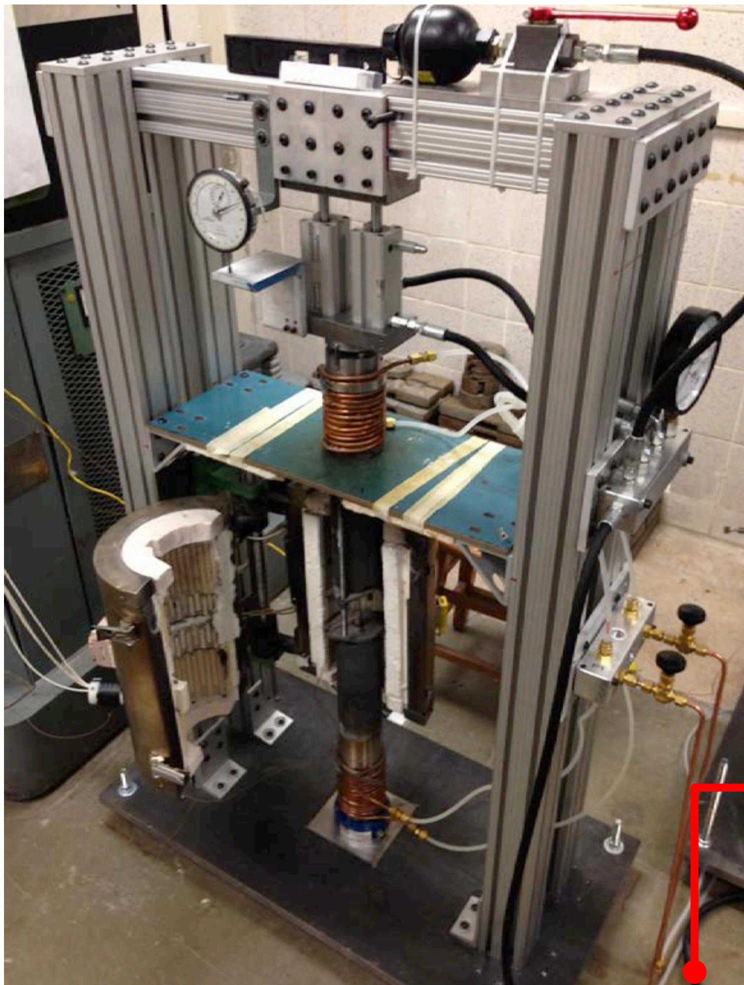


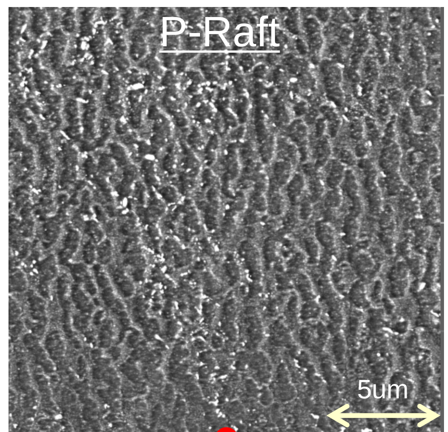




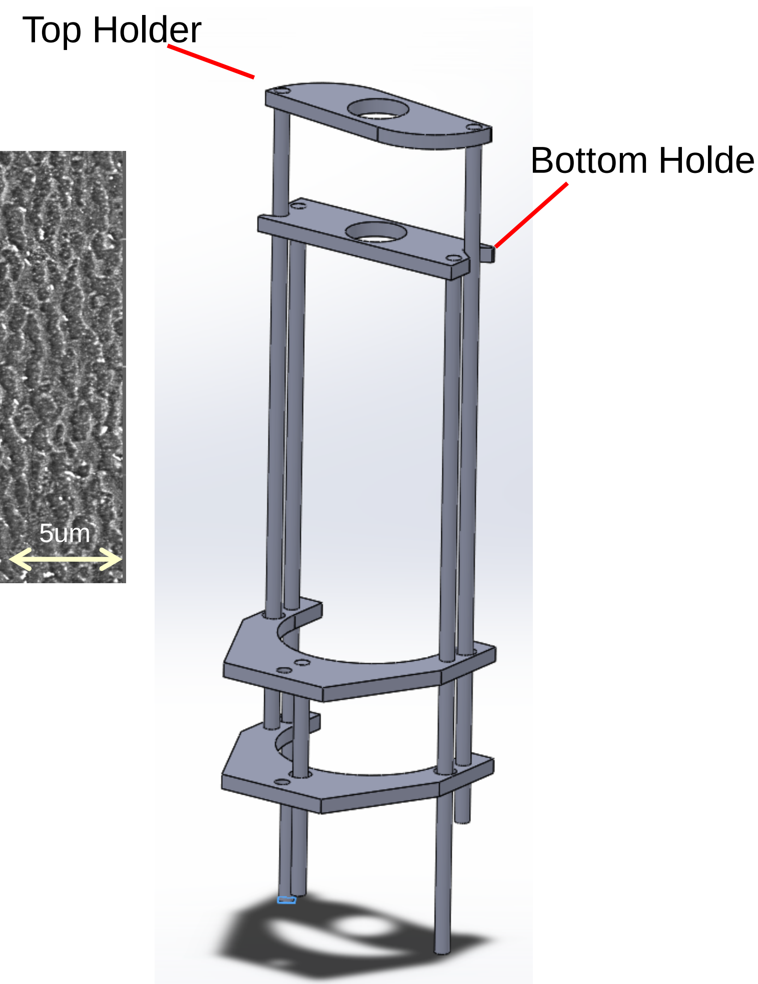
Aged Microstructure under Compressive Stress

Compression Creep Frame





Ceramic Compression Creep Extensometer



Physical Models to Describe Aging Behavior

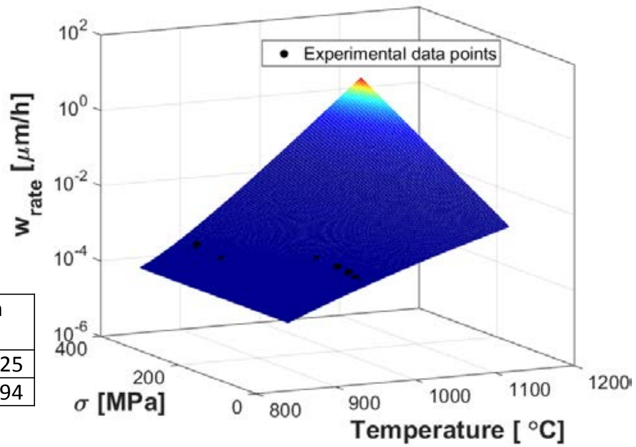
Physical aging models

Rafting

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

$$U(T) = U_T(T - T_0)^n$$

	A (µm/h)	Q (kJ/mol)	U_T(J/mol.MPa.K^n)	n
CMSX-8	2.0×10^5	206	0.033	1.525
CMSX-4	9.31×10^4	222	0.19	1.294

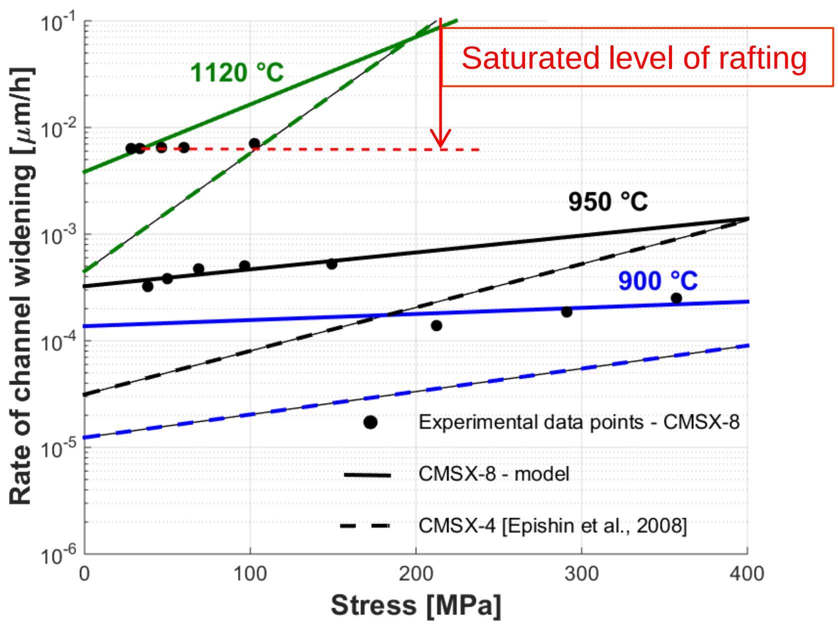


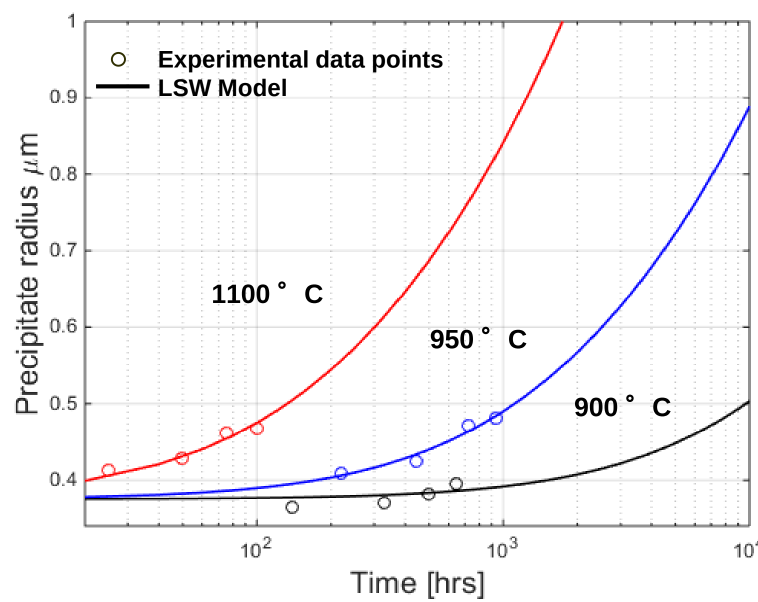
Coarsening

LSW model: $(r)^3$- $(r_0)^3 = Kt$

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

$$\boxed{Q_{coar}\ (CMSX-8) = 269.4\ kJ/mol}$$





2-point Correlation Method

- 2-point correlation – A statistical representation of the microstructure that provides a magnitude measure in addition to the associated spatial correlation.

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

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

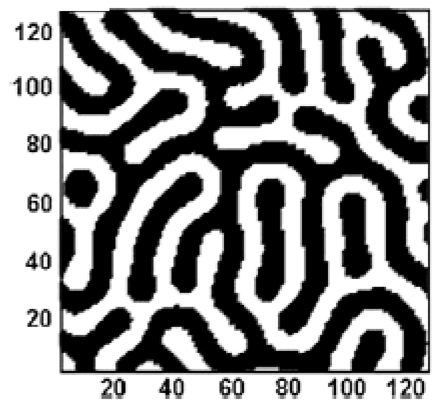
$$f(h,h'|\mathbf{r}) = \frac{1}{vol(\Omega)} \int_{\Omega} m(\mathbf{x},h) m(\mathbf{x}+\mathbf{r},h' d\mathbf{x})$$

$$^{np}F_{\mathbf{k}} = \Im(^{np}f_{\mathbf{t}}) = \frac{1}{S}\ {}^{n}M^{*}_{\mathbf{k}}\ {}^{p}M_{\mathbf{k}}$$

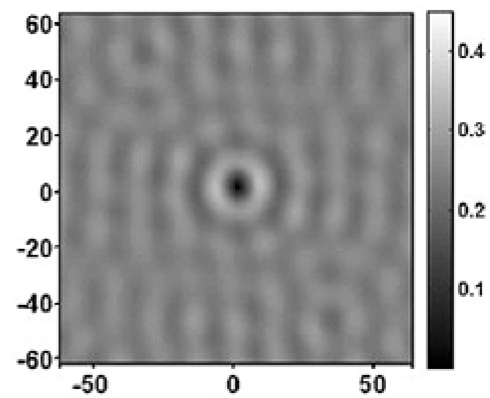
$$= \frac{1}{S} |{}^{n}M_{\mathbf{k}}||{}^{p}M_{\mathbf{k}}| e^{-i\ {}^{n}\theta_{\mathbf{k}}} e^{i\ {}^{p}\theta_{\mathbf{k}}}$$

[Niezgoda, Fullwood and Kalidindi, 2008]

(a)

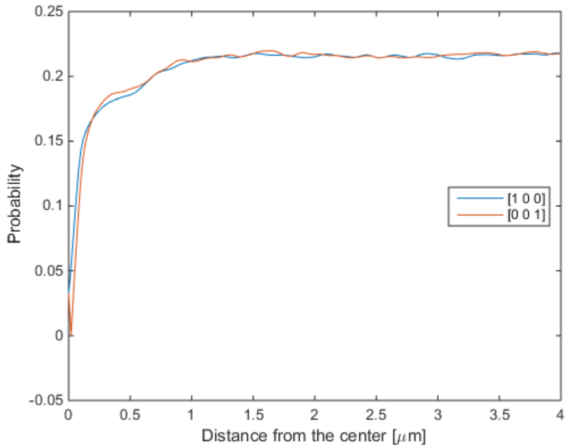


(b)

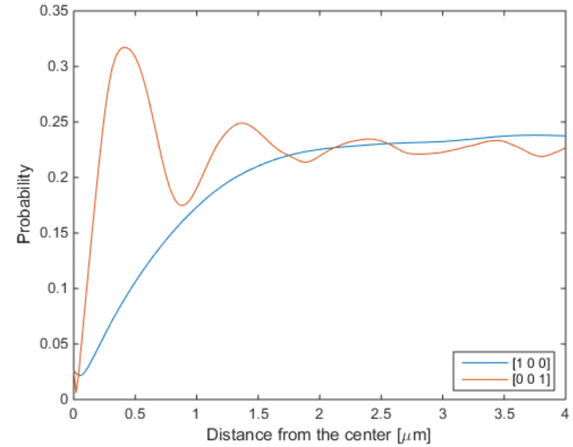


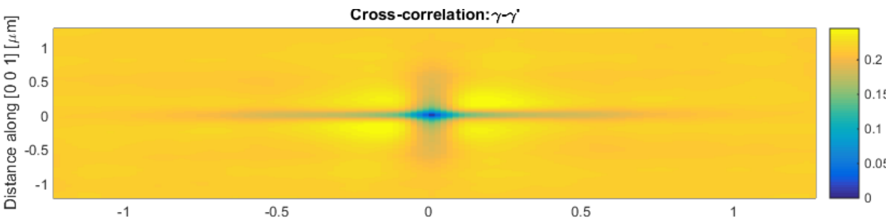
(a) An example of two phase microstructure (b) Cross-correlation for the black and white phases at the head and tail of a vector [Fullwood, Niezgoda, Adams, Kalidindi, 2010].

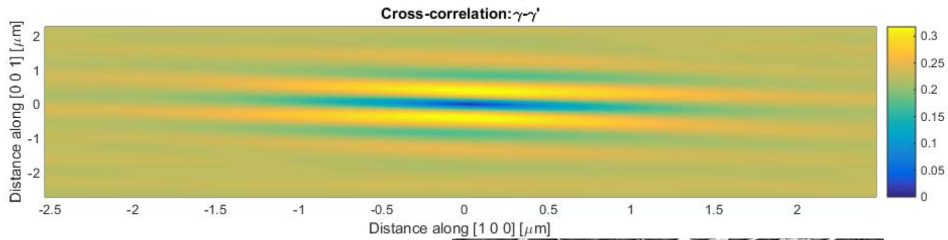
2-point Correlation Application to CMSX-8

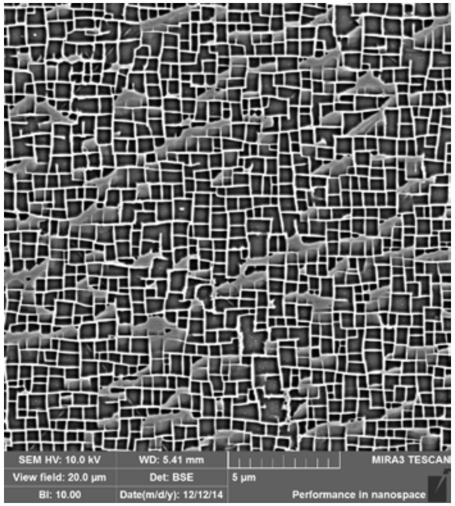


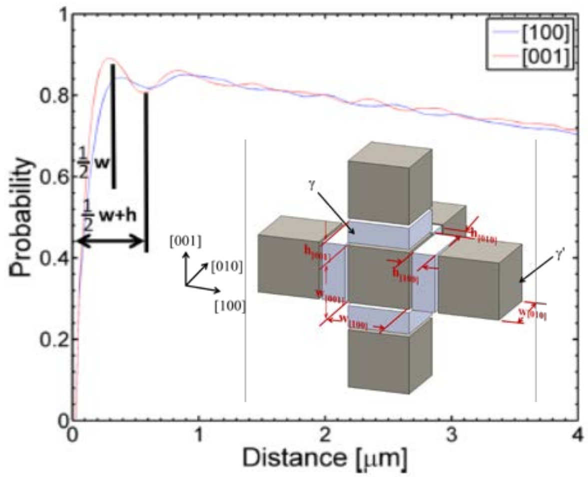
γ' precipitate and γ channel sizes are determined from the first peak and valley of the probabilistic curve of the corresponding micrograph.

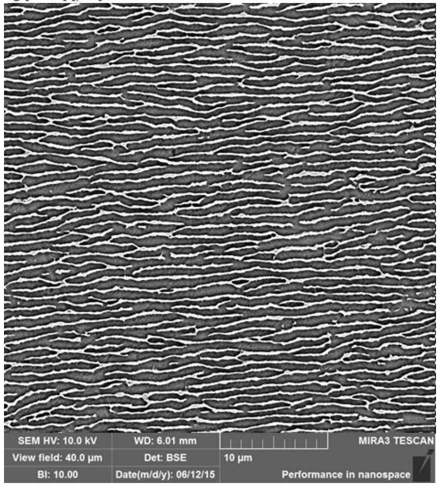








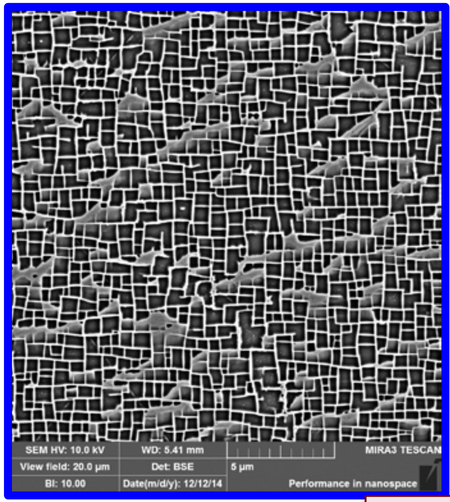


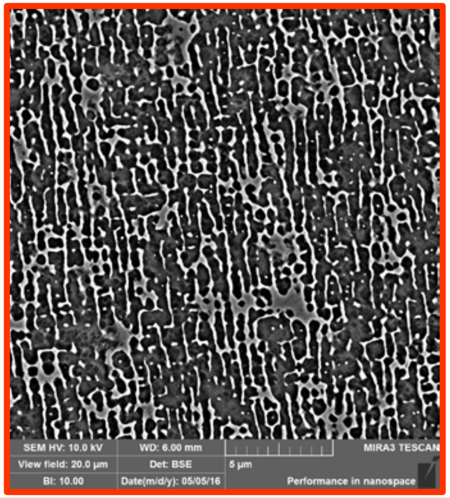


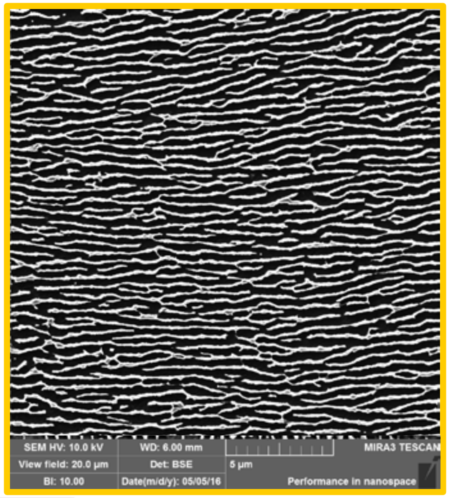
Quantifying the Current Aged State

The George W. Woodruff School of Mechanical Engineering

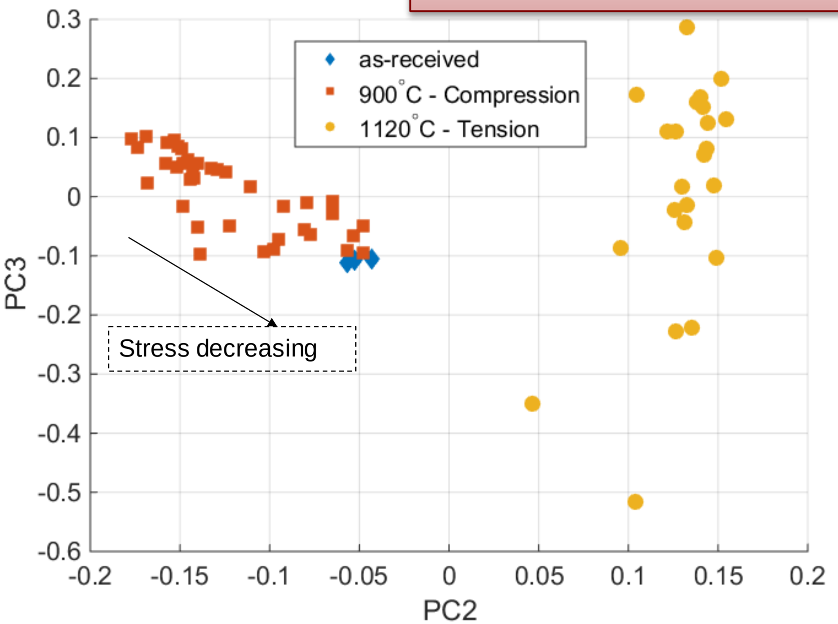
School of Materials Science and Engineering

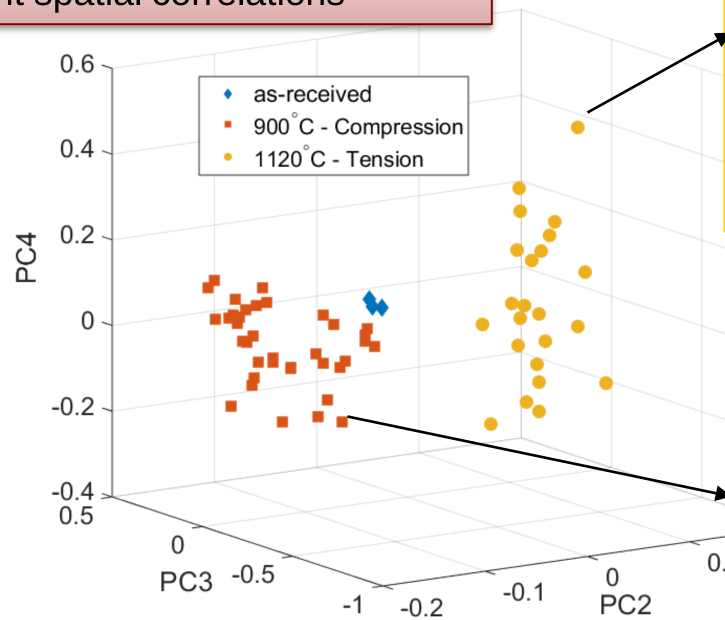


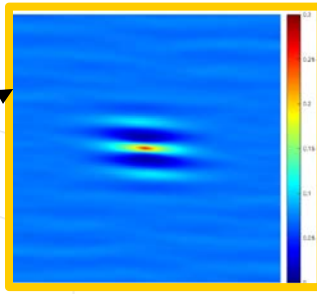


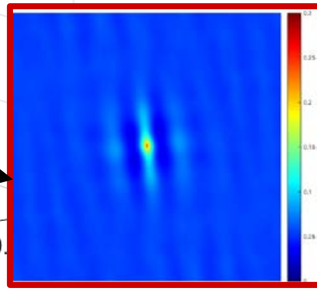


Reduced order representation of aged microstructures using PCA of 2-point spatial correlations

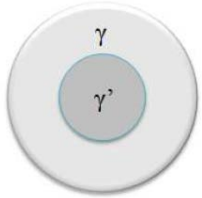








Influence of Variation in Composition



Thermo-Calc

DICTRA

Databases: TCNi5 / MOBNi2

Composition sensitive diffusivity parameter

Aging behavior

Temperature-dependent constitutive models

LSW model

$$r^3 - r_o^3 = K\left(t - t_o\right)$$

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

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

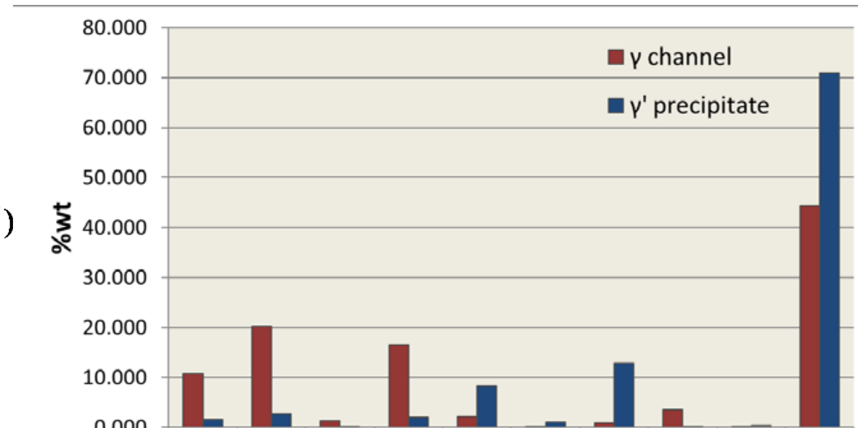
Coarsening effective diffusivity

$$\dot{\gamma}^\alpha = \dot{\gamma}_0 \Theta(T) \left\langle \frac{\tau_\upsilon^\alpha}{D^\alpha} \right\rangle^n \exp\left\{ B_0 \left\langle \frac{\tau_\upsilon^\alpha}{D^\alpha} \right\rangle^{n+1} \right\} \mathrm{sgn}(\tau^\alpha - \chi^\alpha)$$

$$\Theta(T) = \exp\left(-\frac{Q_0}{RT}\right)$$

Diffusivity parameter

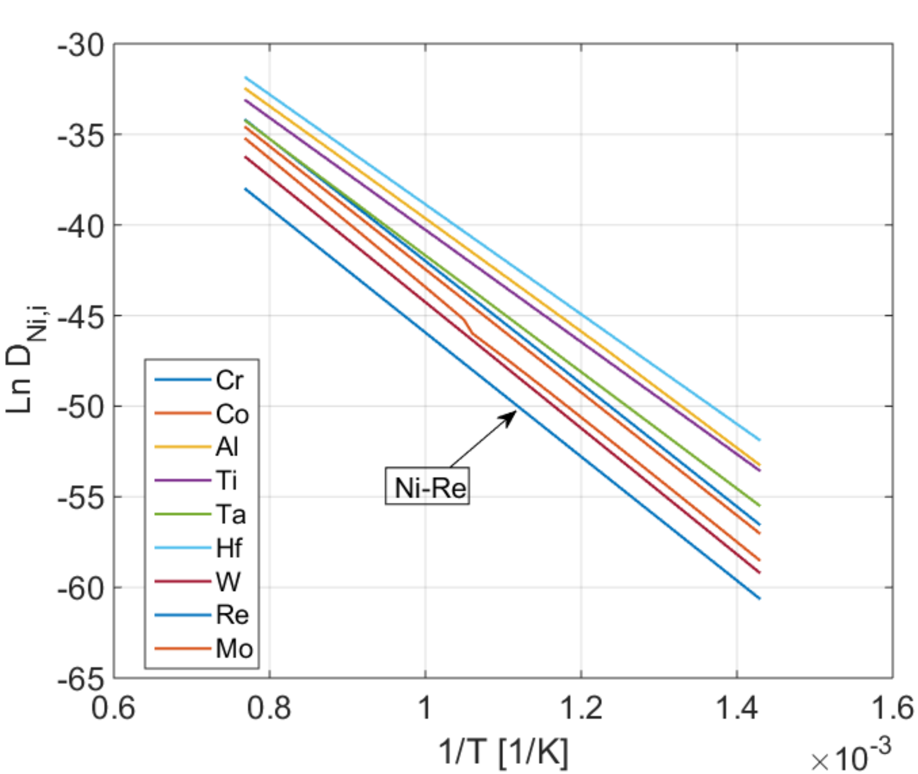
Composition segregation
Thermo-Calc



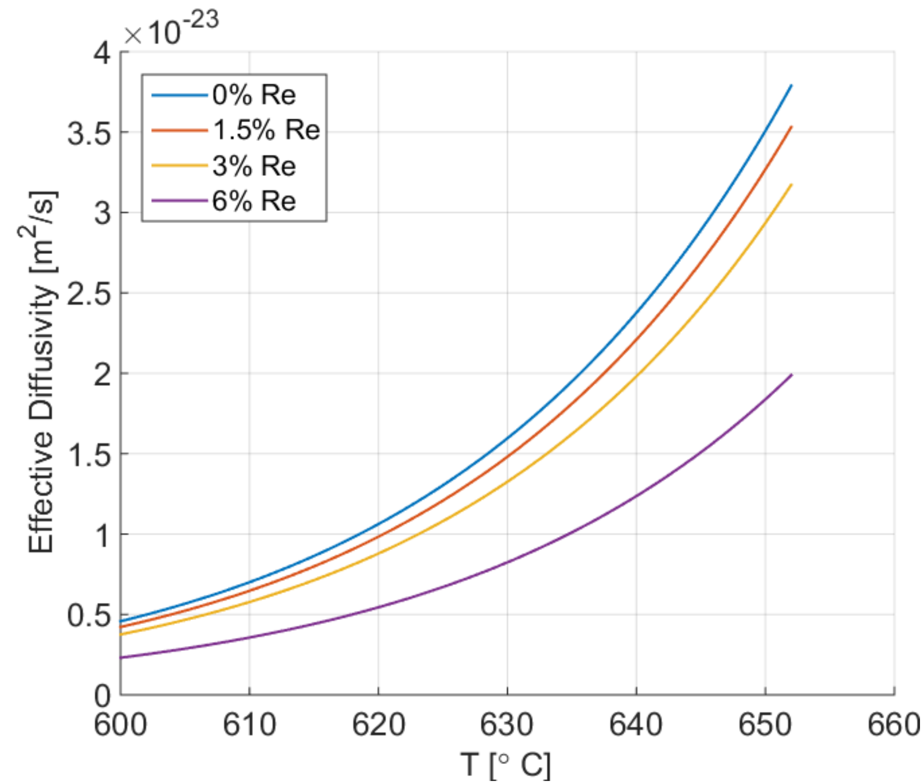
	Cr	Co	Mo	W	Al	Ti	Ta	Re	Hf	Ni
γ channel	10.82	20.31	1.260	16.52	2.080	0.170	0.940	3.520	0.012	44.38
γ' precipitate	1.610	2.690	0.130	2.030	8.230	1.070	12.93	0.110	0.330	70.87

Influence of Composition on Diffusivity

Interdiffusion coefficients of Ni-x binary systems
DICTRA



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



$$D_{Ni-x} = D_{0,Ni-x}\left(-\frac{Q_{Ni-x}}{RT}\right) \qquad Q_{eff} = \sum_{i=1}^{n} x_x \, Q_{Ni-x}$$

Molar fraction of element x

Effective activation energy/
Coarsening activation energy

= 275.9 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

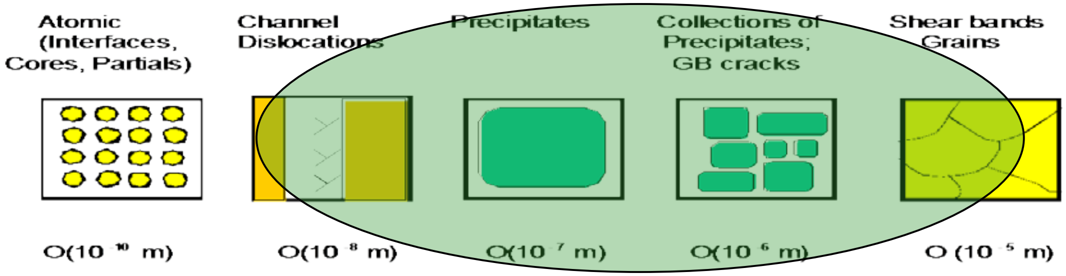
Microstructure-sensitive Crystal Viscoplasticity for Single-Crystal Ni-base Superalloys

Georgia Institute of Technology

The George W. Woodruff School of Mechanical Engineering

School of Materials Science and Engineering

Alloy structure

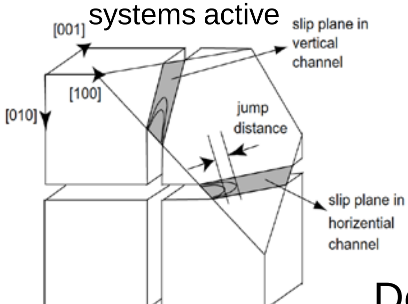


[Shenoy, Tjipowidjojo, and McDowell, 2008]

+

γ deformation

In γ : 12 octahedral slip systems active



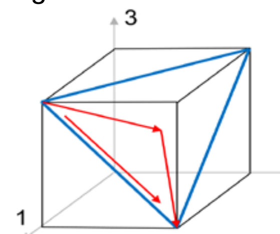
[Ma, Dye, and Reed, 2008]

Distinct deformation in the γ and γ' phases

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

γ □ deformation

In γ': 12 octahedral slip systems moving as dislocation ribbons



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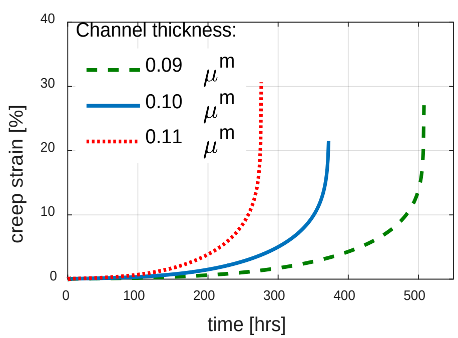
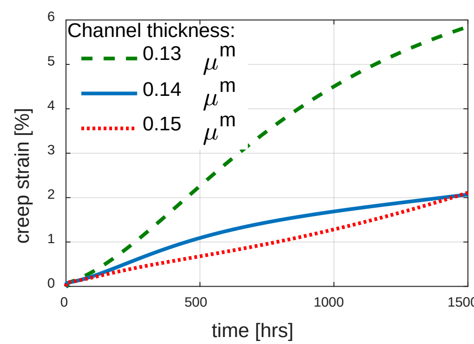
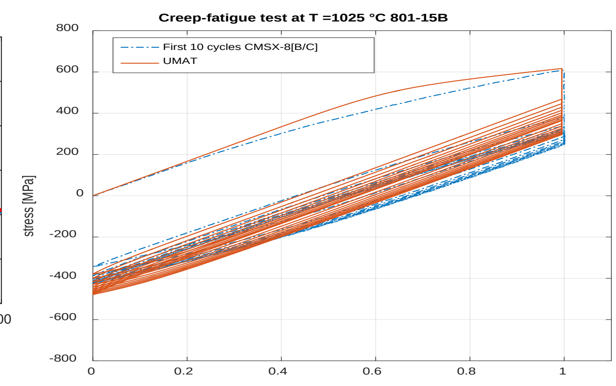
Deformation predictions sensitive to the γ and γ' phase attributes



Tertiary creep: 950 °C, Stress = 400 MPa

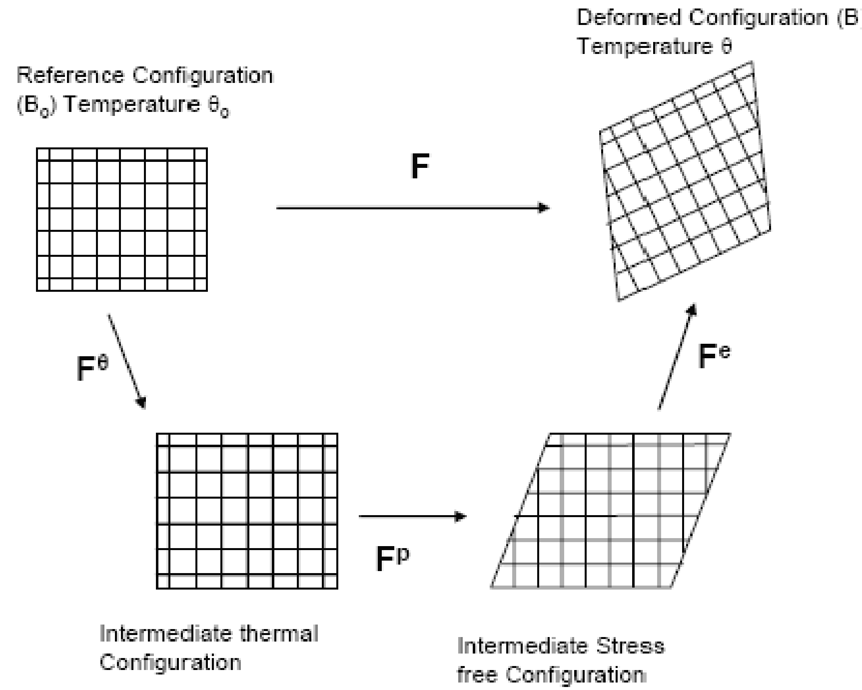


Primary creep: 750 °C, Stress = 680 MPa



Crystal Viscoplasticity – Kinematic Relations

Kinematic relations including temperature dependence



Deformation gradient

$$\mathbf{F} = \frac{\partial \mathbf{x}}{\partial \mathbf{X}} = \mathbf{F}^e \cdot \mathbf{F}^p \cdot \mathbf{F}^\theta$$

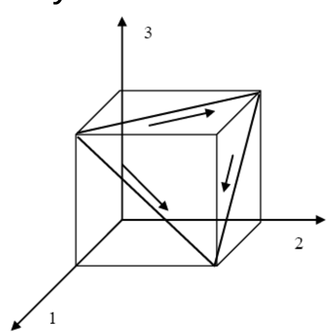
Velocity gradient

$$\mathbf{L} = \dot{\mathbf{F}} \cdot \mathbf{F}^{-1}$$

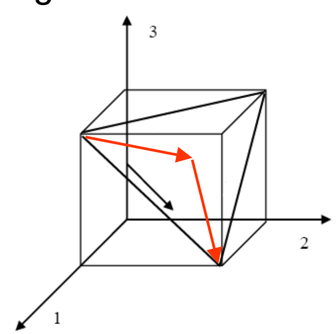
Macroscopic plastic velocity gradient

$$\mathbf{L}^p = \dot{\mathbf{F}}^p \, \mathbf{F}^{p^{-1}} = \sum_{\alpha=1}^{N_{slip}} \dot{\gamma}^{(\alpha)} \left(\mathbf{s}_o^{(\alpha)} \otimes \mathbf{n}_o^{(\alpha)} \right)$$

In γ : 12 octahedral slip systems active

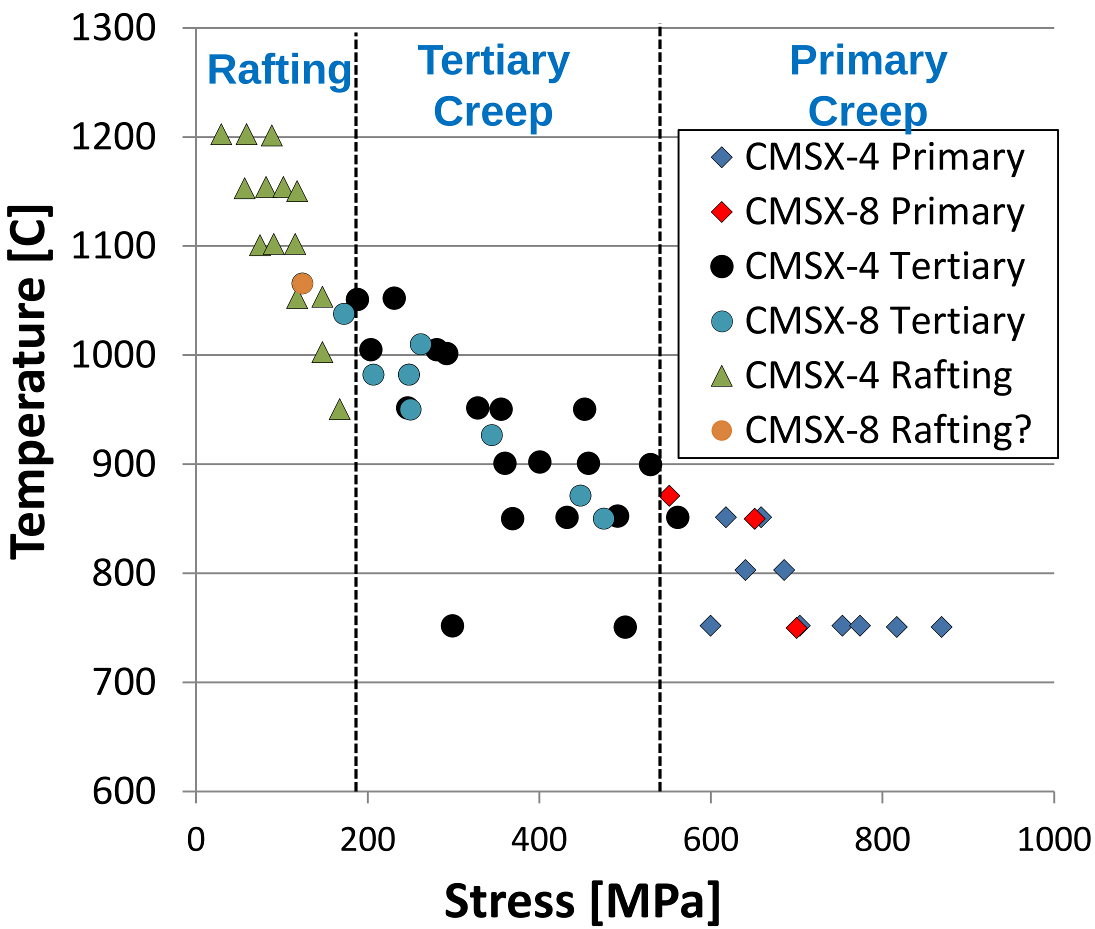


In γ': 12 octahedral slip systems moving as dislocation ribbons



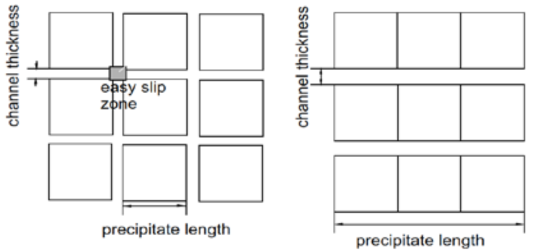
Creep Deformation Mechanisms of Superalloys

Influence of stress and temperature on modes of creep deformation



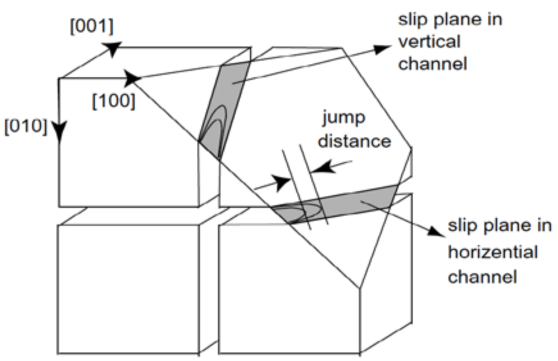
[Reed, 2006; Ma, Dye, and Reed, 2008, CMSX-8 Data]

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



[Ma, Dye, and Reed, 2008]

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



[Ma, Dye, and Reed, 2008]

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)

Crystal Viscoplasticity (CVP) – Rate Eqn

Inelastic Velocity Gradient

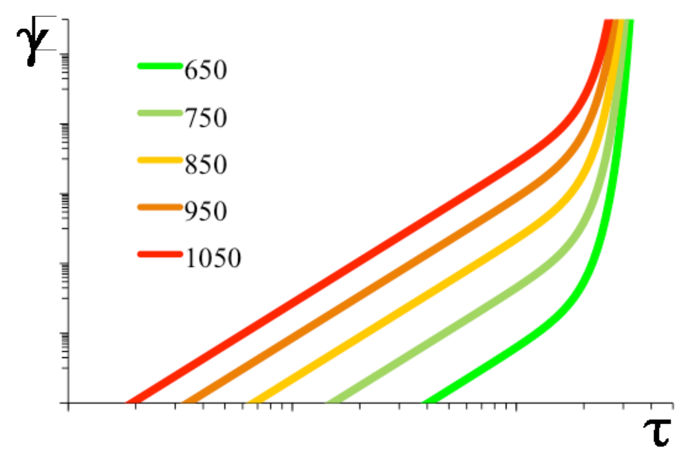
$$\mathbf{L}^{in} = \dot{\mathbf{F}}^{in}\,\mathbf{F}^{in^{-1}} = f_\gamma \left(\sum_{\alpha=1}^{12} \dot{\gamma}_\gamma^{\,in(\alpha)} \left(\hat{\mathbf{d}}^{(\alpha)} \otimes \hat{\mathbf{n}}^{(\alpha)} \right) \right) + f_{\gamma'} \left(\sum_{\alpha=13}^{24} \dot{\gamma}_{L1_2}^{\,in(\alpha)} \left(\hat{\mathbf{d}}^{(\alpha)}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

Inelastic Shear Strain Rate

$$\begin{cases} \dot{\gamma}_\gamma^{\,in(\alpha)} = \rho^{(\alpha)}_{\ \gamma}\, b\, \lambda_\gamma^{(\alpha)} F_{attack}\, sign\left(\tau^{(\alpha)} + \tau^{(\alpha)}_{\ mis} - \chi^{(\alpha)} \right) \exp\left\{ \dfrac{-Q_{slip}^{110} + \left(\left| \tau^{(\alpha)} + \tau^{(\alpha)}_{\ mis} - \chi^{(\alpha)} \right| - \tau^{(\alpha)}_{\ \gamma pass} - \tau^{(\alpha)}_{\ oro} \right) V_{c1}^{(\alpha)}}{kT} \right\} \\[2ex] \dot{\gamma}_{L1_2}^{\,in(\alpha)} = \rho_{L1_2}^{(\alpha)}\, b\, \lambda_{L1_2}^{(\alpha)} F_{attack}\, sign\left(\tau^{(\alpha)} - \chi^{(\alpha)} \right) \exp\left\{ \dfrac{-Q_{slip}^{112} + \left(\left| \tau^{(\alpha)} - \chi^{(\alpha)} \right| - \tau^{(\alpha)}_{\ L1_2 pass} - \tau_{APB} \right) V_{c2}^{(\alpha)}}{kT} \right\} \end{cases}$$

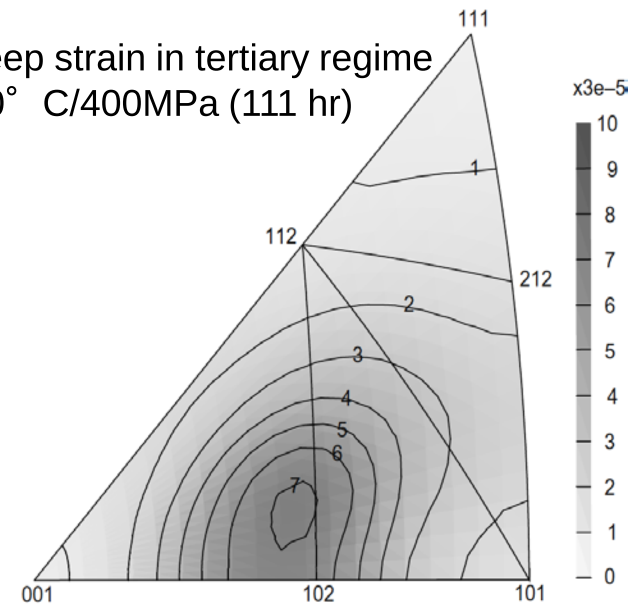
Evolution Equations

$$\begin{cases} \dot{\rho}_\gamma^{(\alpha)} = \dfrac{1}{b} \left(\dfrac{c_{mult1}}{\lambda_\gamma^{(\alpha)}} - c_{annh1}\, \rho_\gamma^{(\alpha)} \right) \left| \dot{\gamma}_\gamma^{\,in(\alpha)} \right| \\[2ex] \dot{\rho}_{L1_2}^{(\alpha)} = c_{mult21}\, \rho_{pb}^{(\alpha)}\, \Gamma + \dfrac{c_{mult22}}{b\, \lambda_{\gamma'}^{(\alpha)}} \left| \dot{\gamma}_{\gamma'}^{(\alpha)} \right| - c_{annh2}\, \rho_{\gamma'}^{(\alpha)} \left| \dot{\gamma}_{\gamma'}^{(\alpha)} \right| \\[2ex] \dot{\rho}_{pb}^{(\alpha)} = \dfrac{c_{mult}^{pb}}{b L_\gamma} \left| \dot{\gamma}_\gamma^{\,in(\alpha)} \right| - c_{annh}^{pb}\, \rho_{pb}^{(\alpha)} \left| \dot{\gamma}_\gamma^{\,in(\alpha)} \right| \end{cases}$$



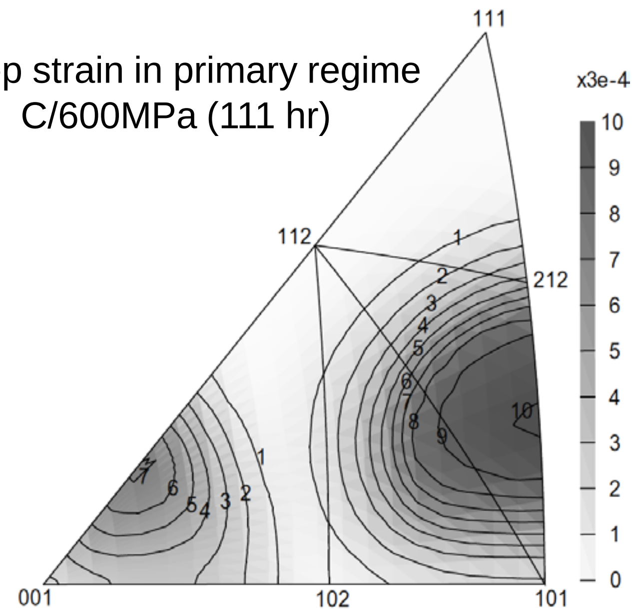
CMSX-4 Model Predictions

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

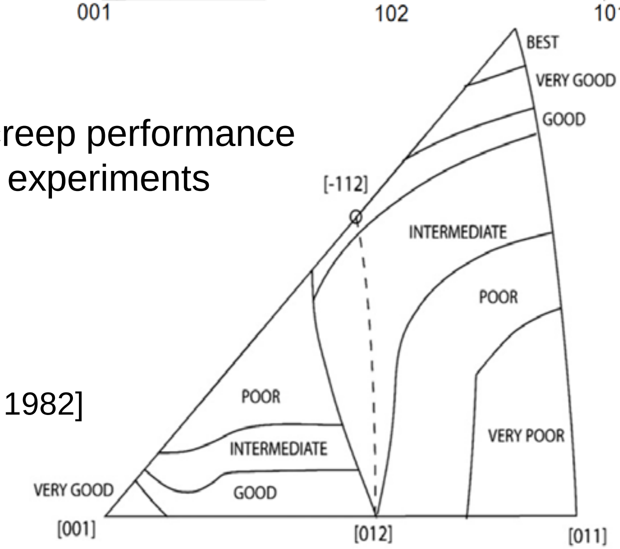


[Ma, Dye, and Reed, 2008]

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

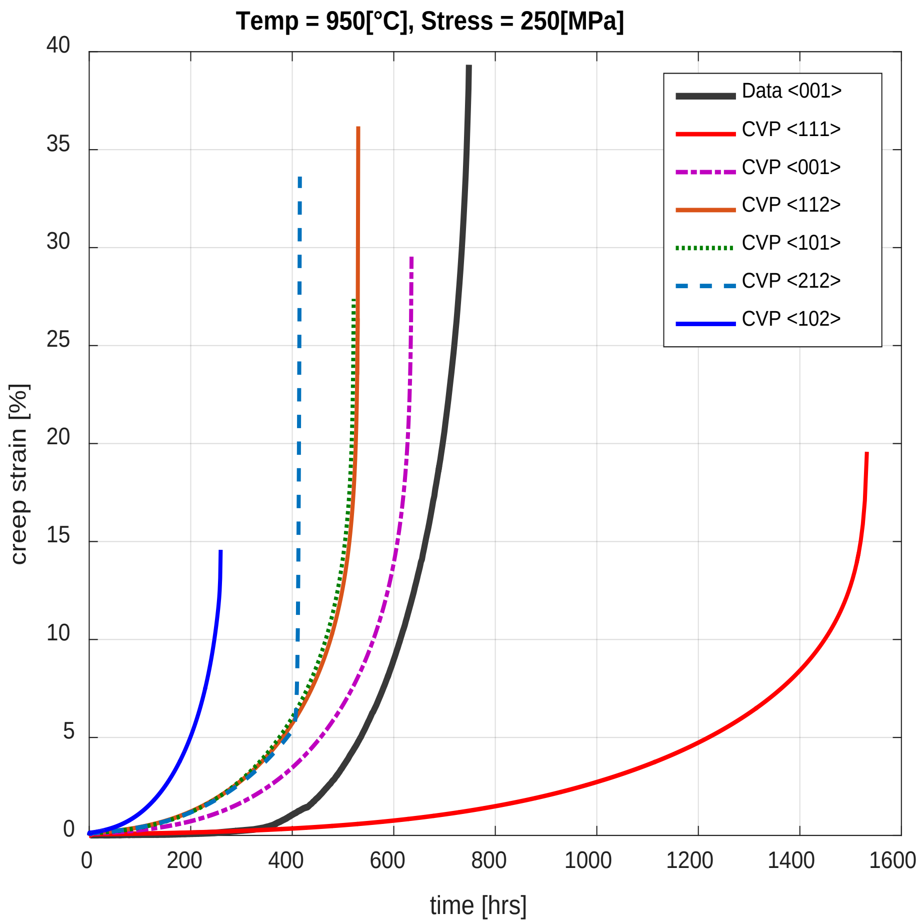


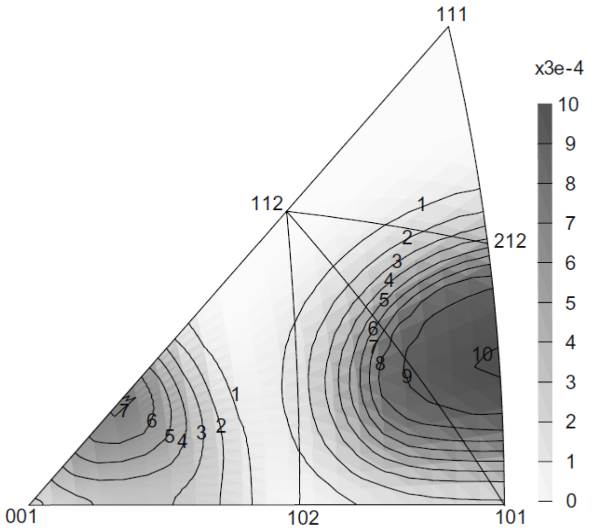
Primary creep performance
based on experiments

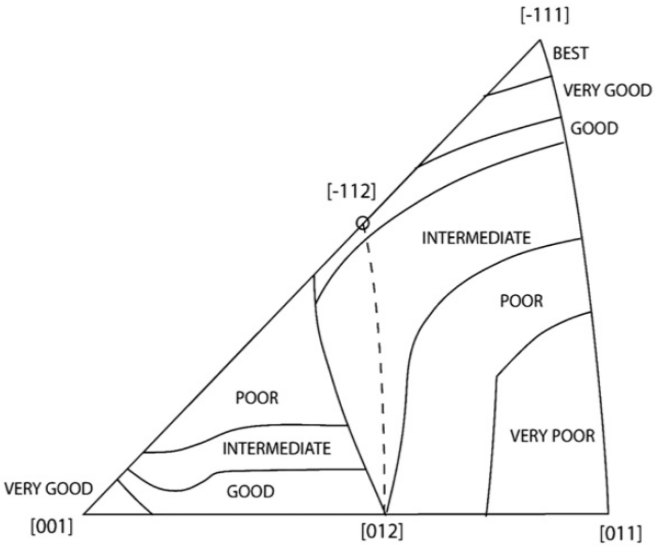


[MacKay and Meier, 1982]

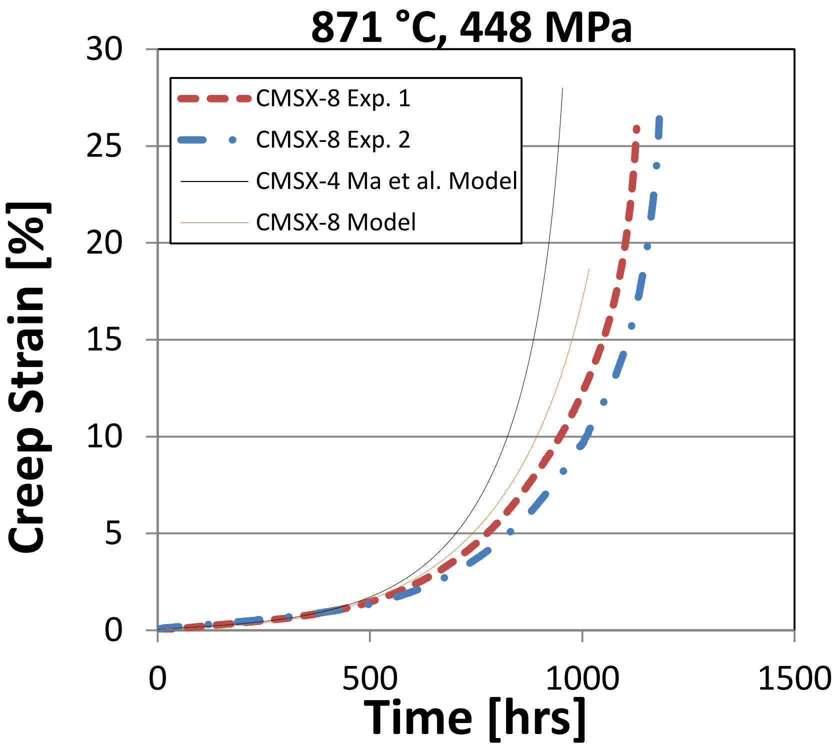
Creep in different orientations

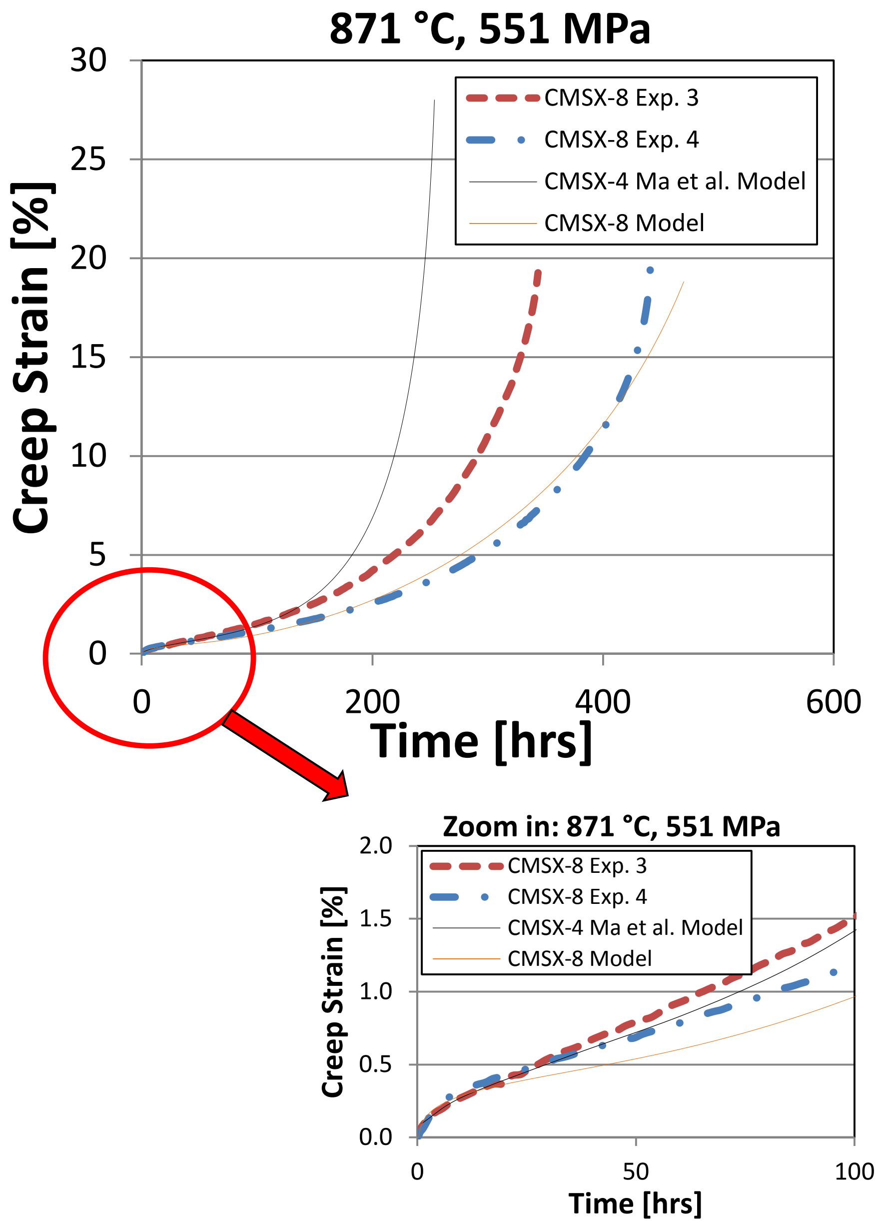






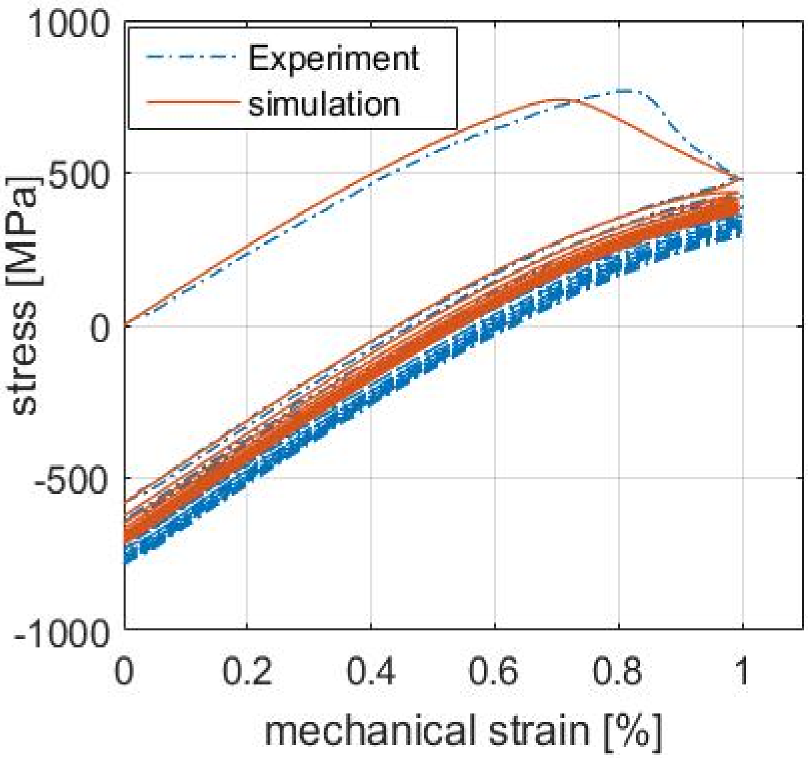
Primary and Tertiary Creep



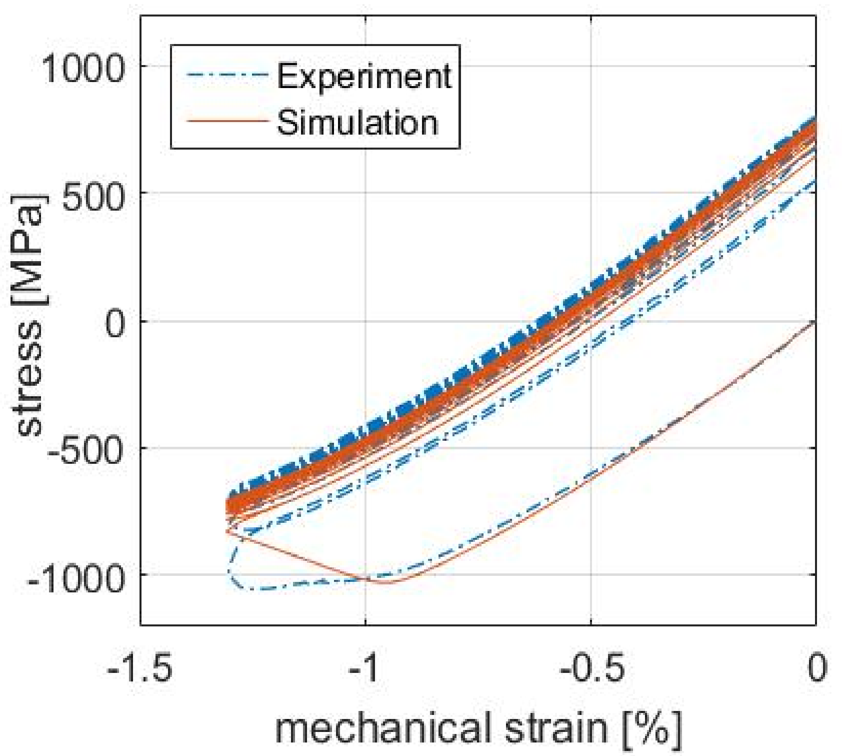


Primary, secondary and tertiary creep can be captured with the model

TMF validation



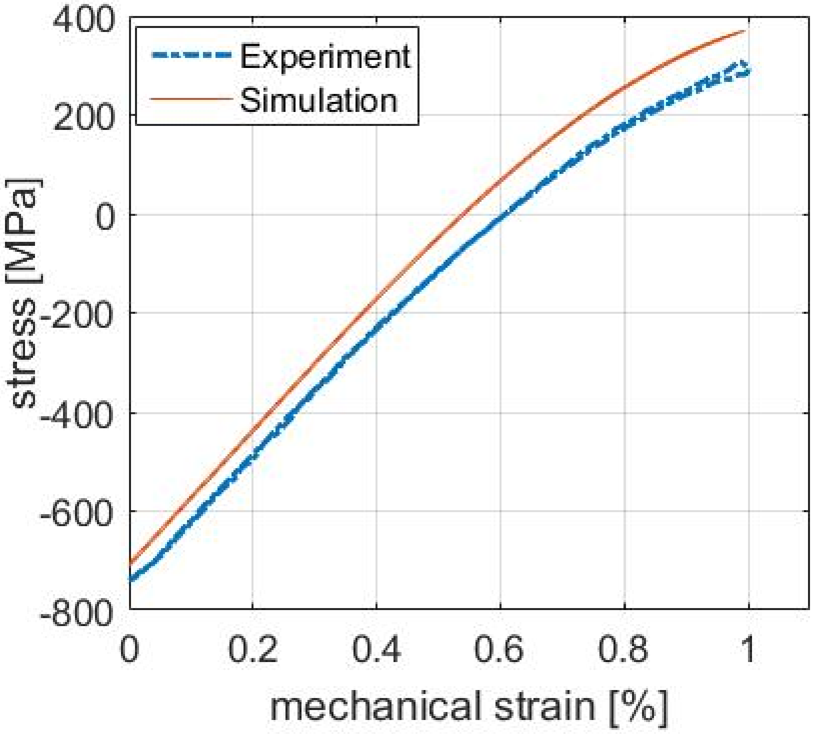
First 10 cycles: IP-TMF
[100-1100-100] ºC, R = 0, $\dot{T} = 2.83[°K/s]$



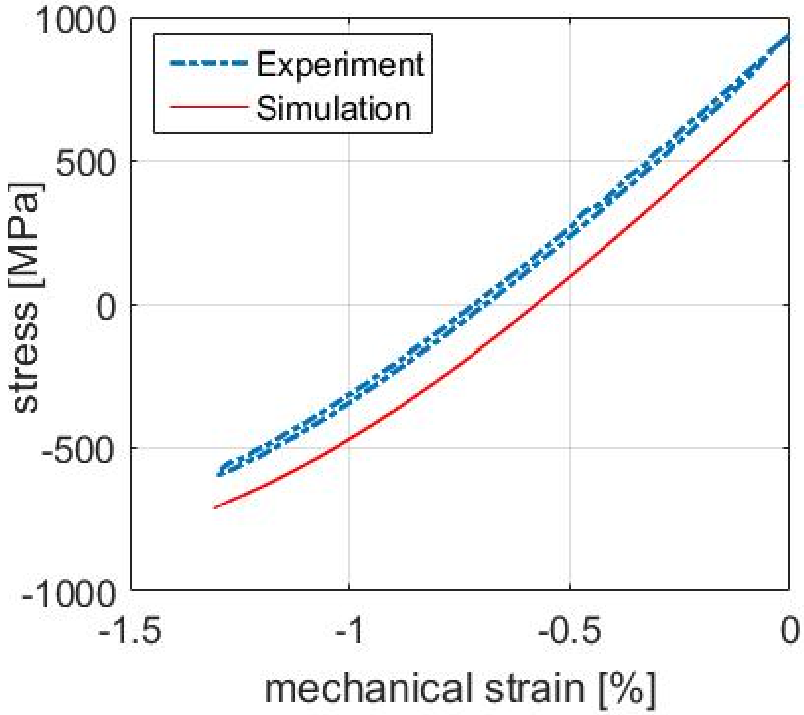
Stabilized hysteresis: OP-TMF
[100-850-100] ºC, R = -∞, $\dot{T} = 2.83[°K/s]$

Very good agreement predicting TMF

TMF validation



Stabilized hysteresis: IP-TMF
[100-1100-100] ºC, R = 0, $\dot{T} = 2.83[°K/s]$



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

Very good agreement predicting TMF

Incorporating the Influence of Re Content

Since Re segregates almost exclusively in the γ channels, the Activation energy in the γ phase can be modified to account for Re content as follows:

$$\begin{cases} \dot{\gamma}_{\gamma}^{\,in(\alpha)} = \Theta(T)\,\rho^{(\alpha)}_{\gamma}\; b\,\lambda_{\gamma}^{(\alpha)} F_{attack}\, sign\left(\tau^{(\alpha)} + \tau^{(\alpha)}_{mis} - \chi^{(\alpha)}\right) \exp\left\{ \dfrac{-Q_{slip}^{110} + \left(\left|\tau^{(\alpha)} + \tau^{(\alpha)}_{mis} - \chi^{(\alpha)}\right| - \tau^{(\alpha)}_{\gamma pass} - \tau^{(\alpha)}_{oro} \right) V_{c1}^{(\alpha)}}{kT} \right\} \\ \dot{\gamma}_{L1_2}^{\,in(\alpha)} = \rho^{(\alpha)}_{L1_2}\, b\,\lambda_{L1_2}^{(\alpha)} F_{attack}\, sign\left(\tau^{(\alpha)} - \chi^{(\alpha)}\right) \exp\left\{ \dfrac{-Q_{slip}^{112} + \left(\left|\tau^{(\alpha)} - \chi^{(\alpha)}\right| - \tau^{(\alpha)}_{L1_2 pass} - \tau_{APB} \right) V_{c2}^{(\alpha)}}{kT} \right\} \end{cases}$$

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

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

[Miller, 1976; Shenoy et al., 2005]

Remaining Plans for Project

- 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