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

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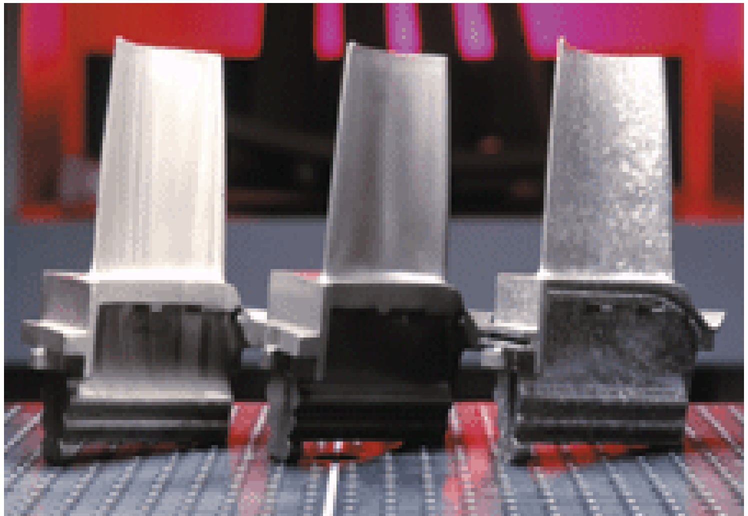
University Turbine Systems Research Workshop
Georgia Institute of Technology
November 3-5, 2015

Hot Section Gas Turbine Materials

Land-based gas turbines

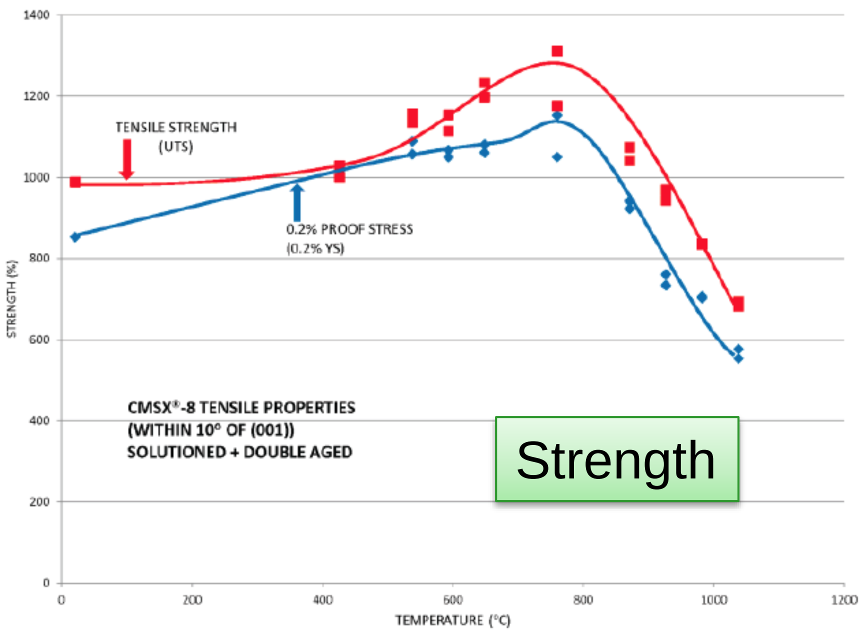
- drive to increase service temperature to improve efficiency; increase life
- replace large directionally-solidified Ni-base superalloys with single crystal superalloys

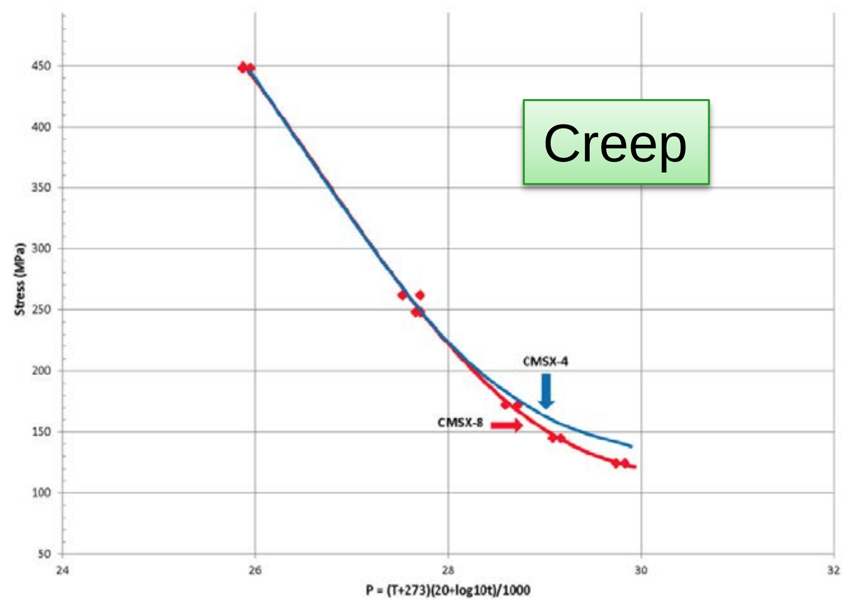


Single Crystal Alloy being Investigated for IGT Applications

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]

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Thermomechanical Fatigue (TMF)

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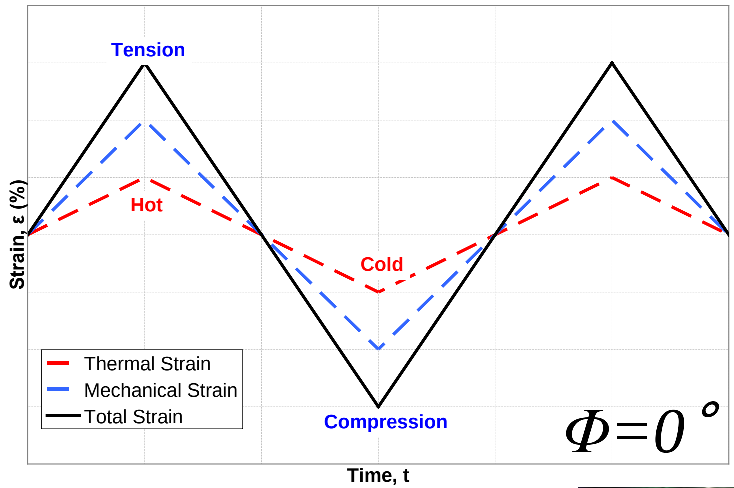
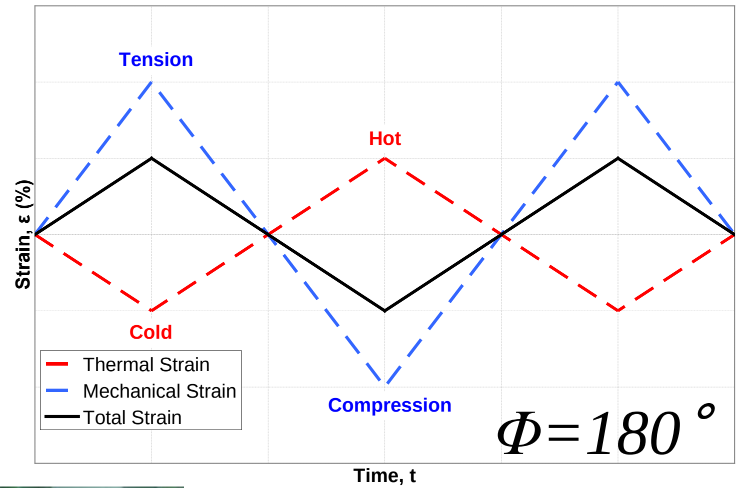
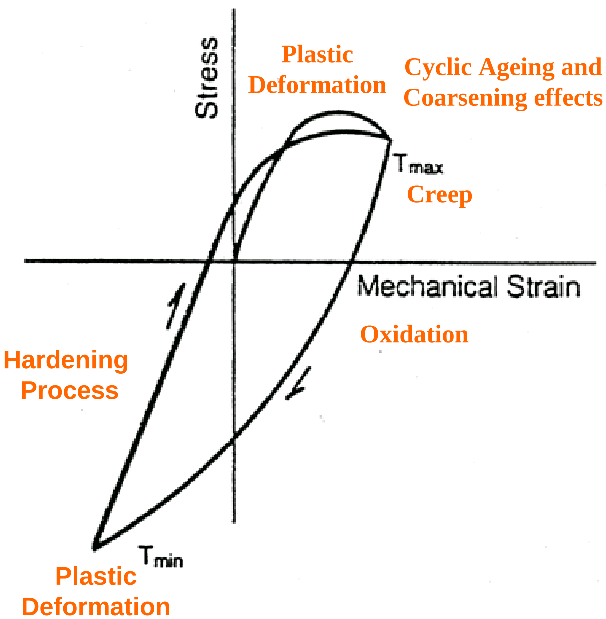
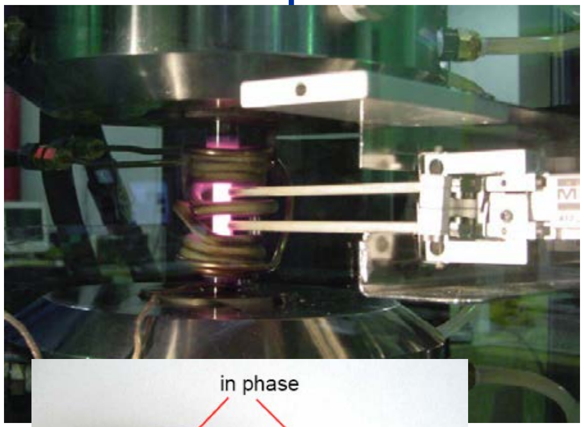
Linear In-Phase (IP)

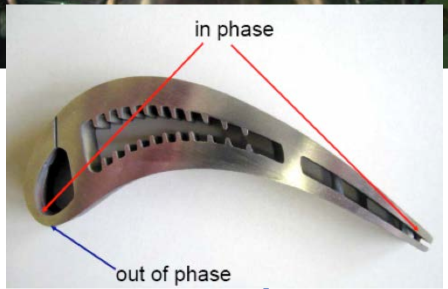


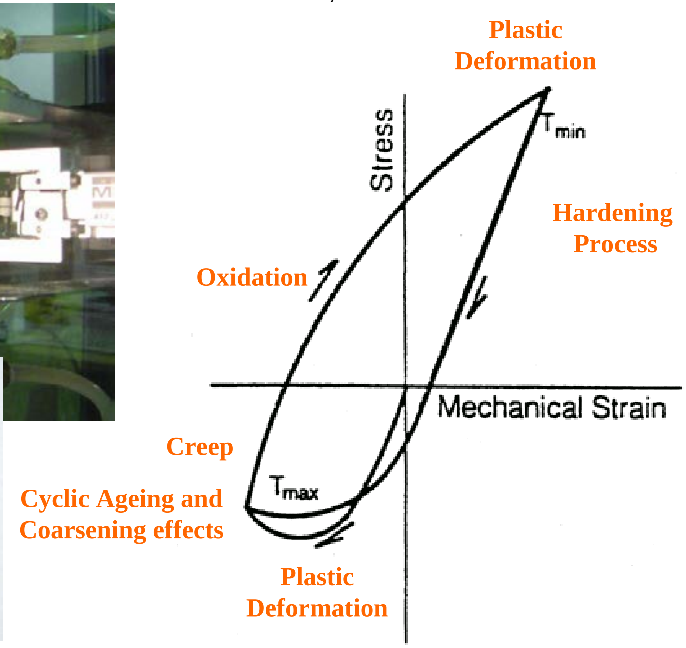
Linear Out-of-Phase (OP)





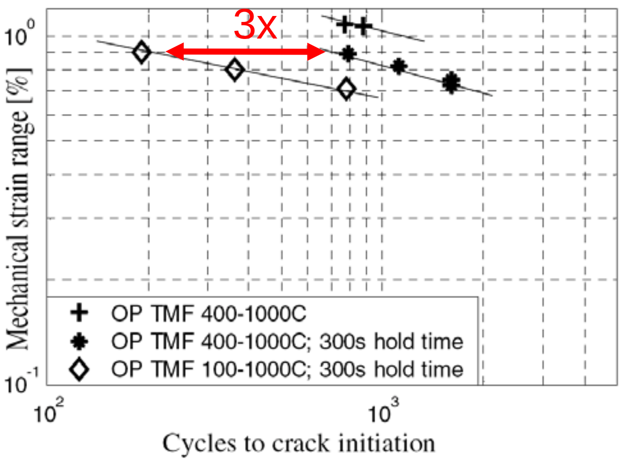


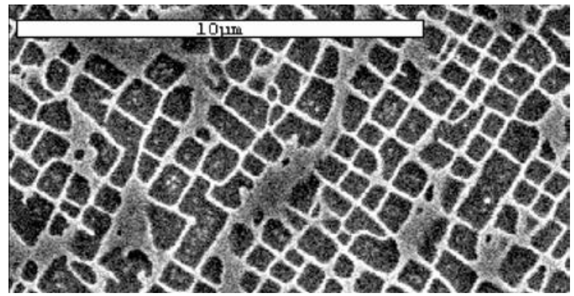


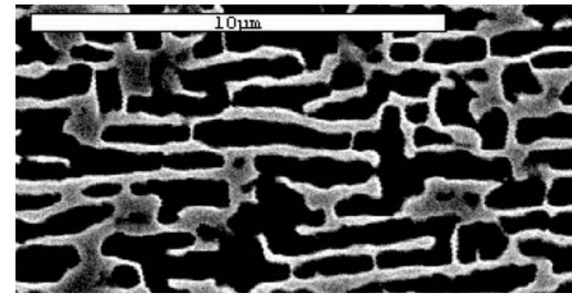


Effect of T_{min} on OP TMF of CMSX-4

CMSX-4 [001]

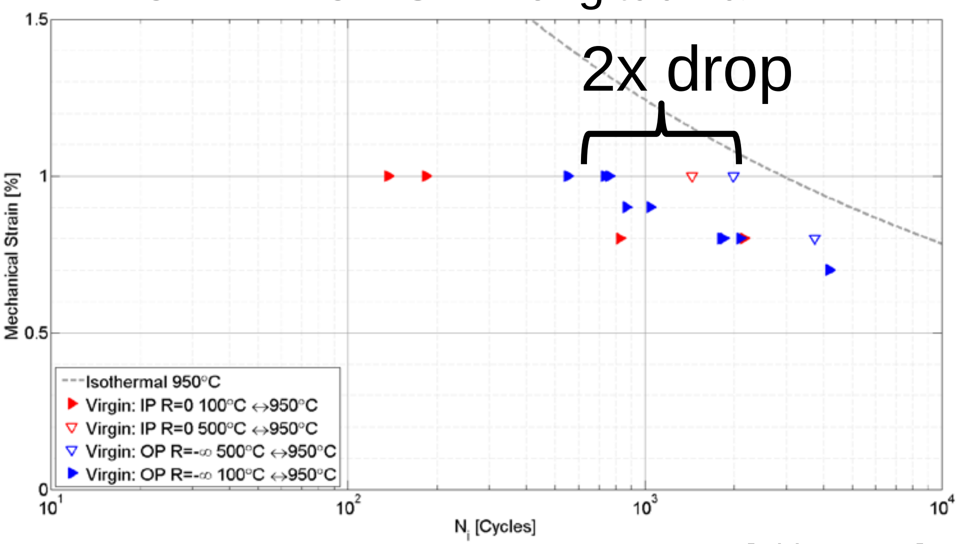


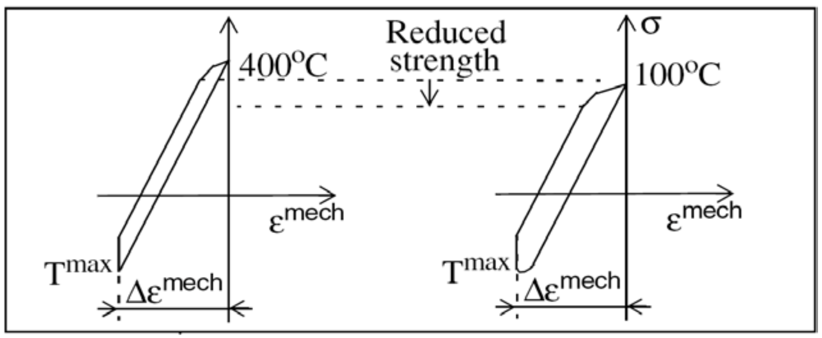




[Arrell et al., 2004]

CM247LC DS in Longitudinal Dir.

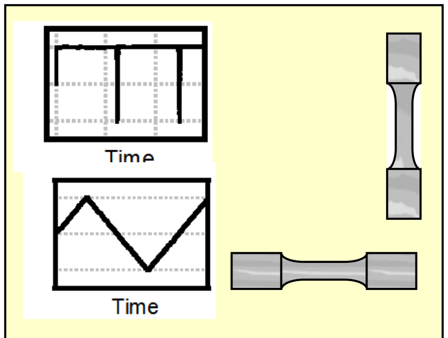




[Kirka, 2014]

Life Modeling Approach

Damage Mechanism Modules



Deformation Response

Fatigue → N_i^{fat}

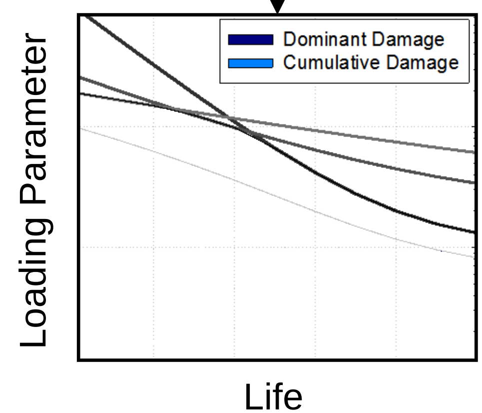
Creep-Fatigue → N_i^{cr}

Environment-Fatigue → N_i^{env}

Creep Ratchetting → N_i^{rat}

Dominant Damage

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



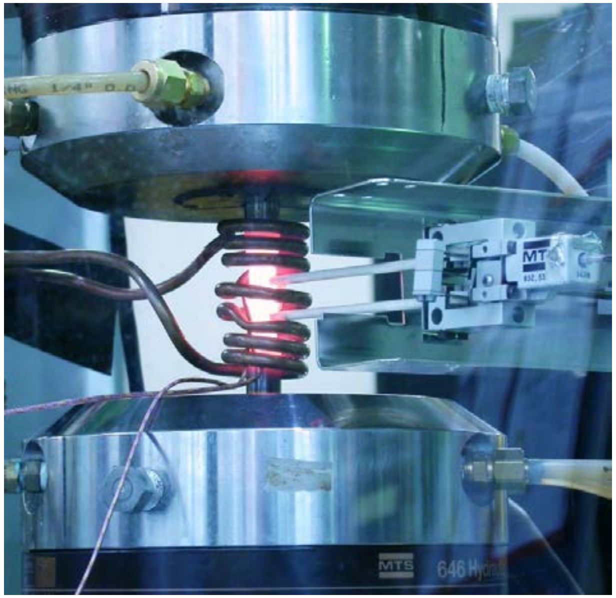
Accurrate representations of the deformation response highly critical for predicting crack formation

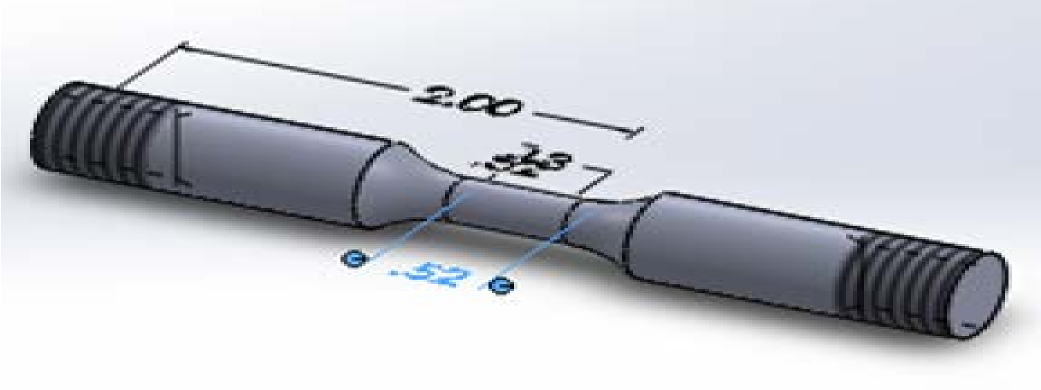
Primary Objectives of UTSR Project

- 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

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





Conventional Creep-Fatigue (baseline)

In a creep-fatigue interaction test, life can be controlled by:

- Plastic strain range
- Environmental effects
- Influence of mean stress / stress range
- Creep damage (dwell)
- Microstructure / crystal orientation

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Conventional Creep-Fatigue (baseline)

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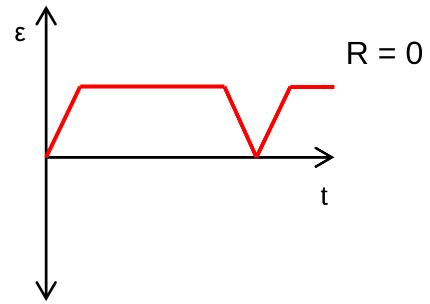
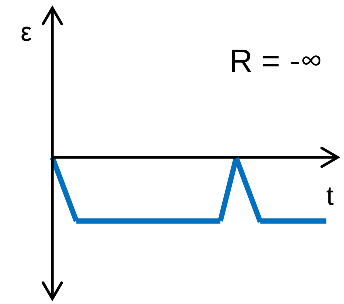
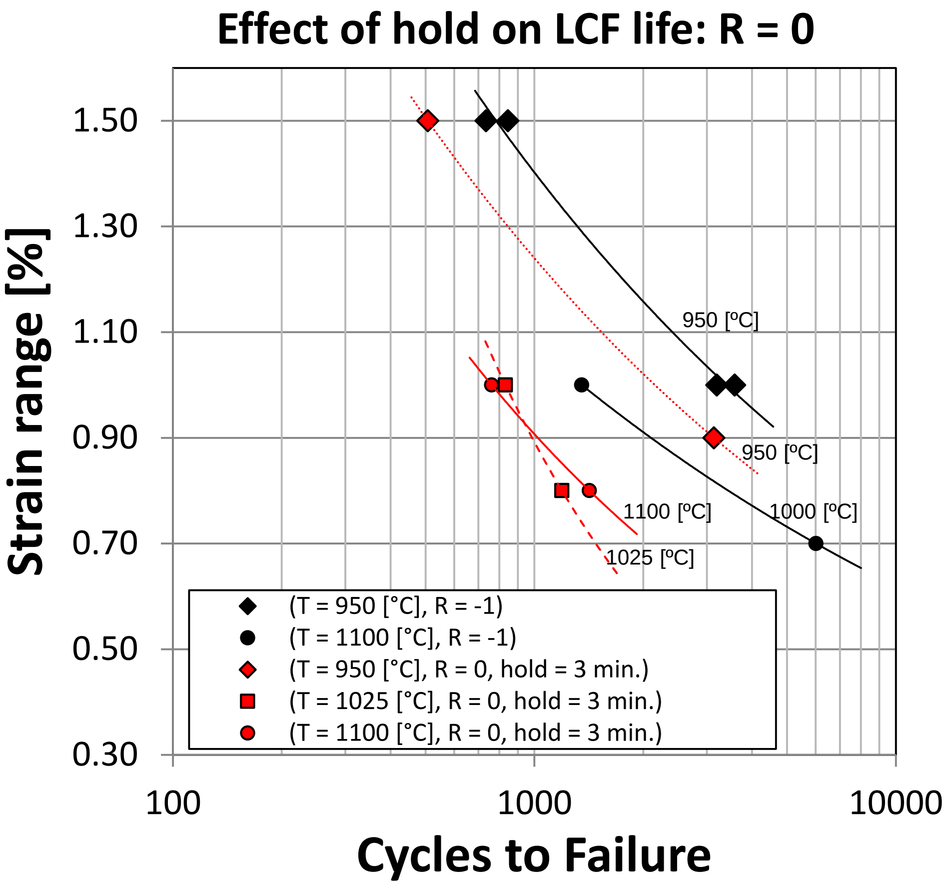
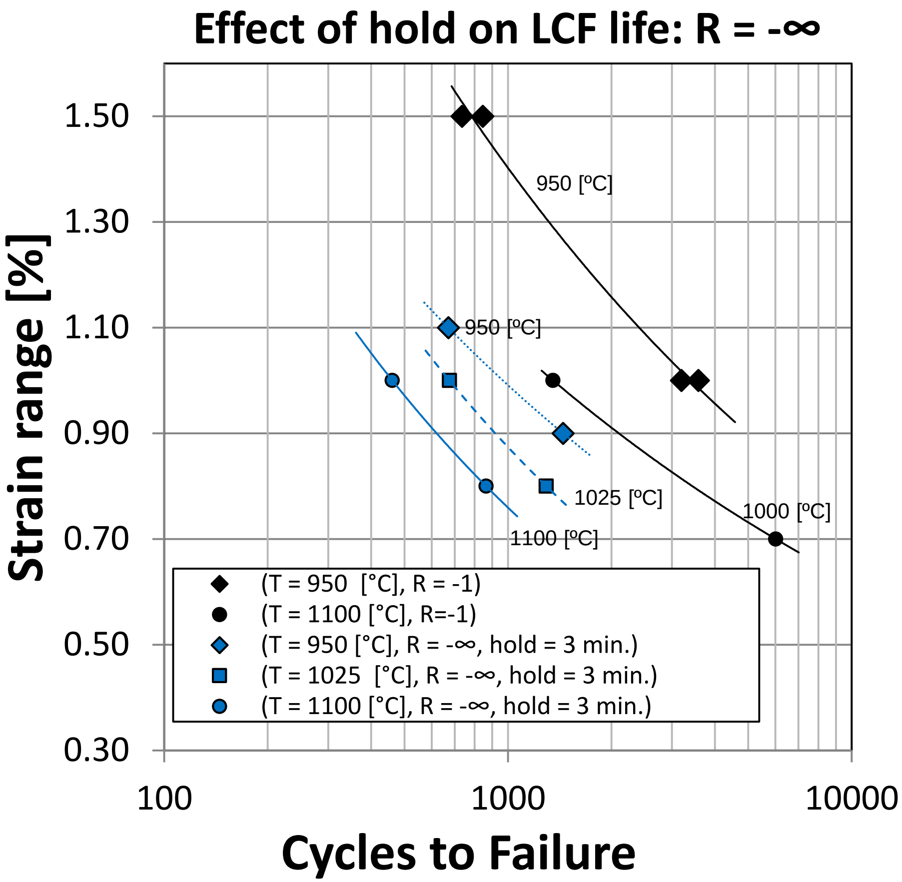
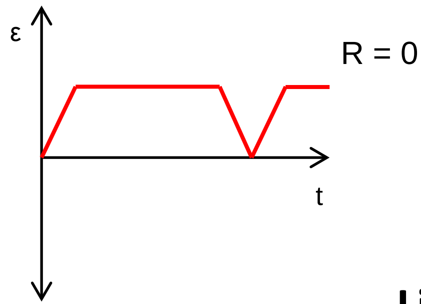


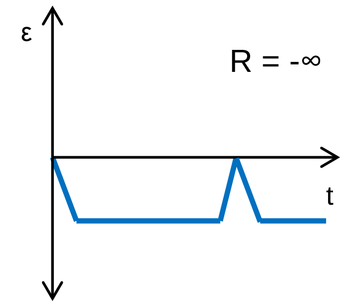


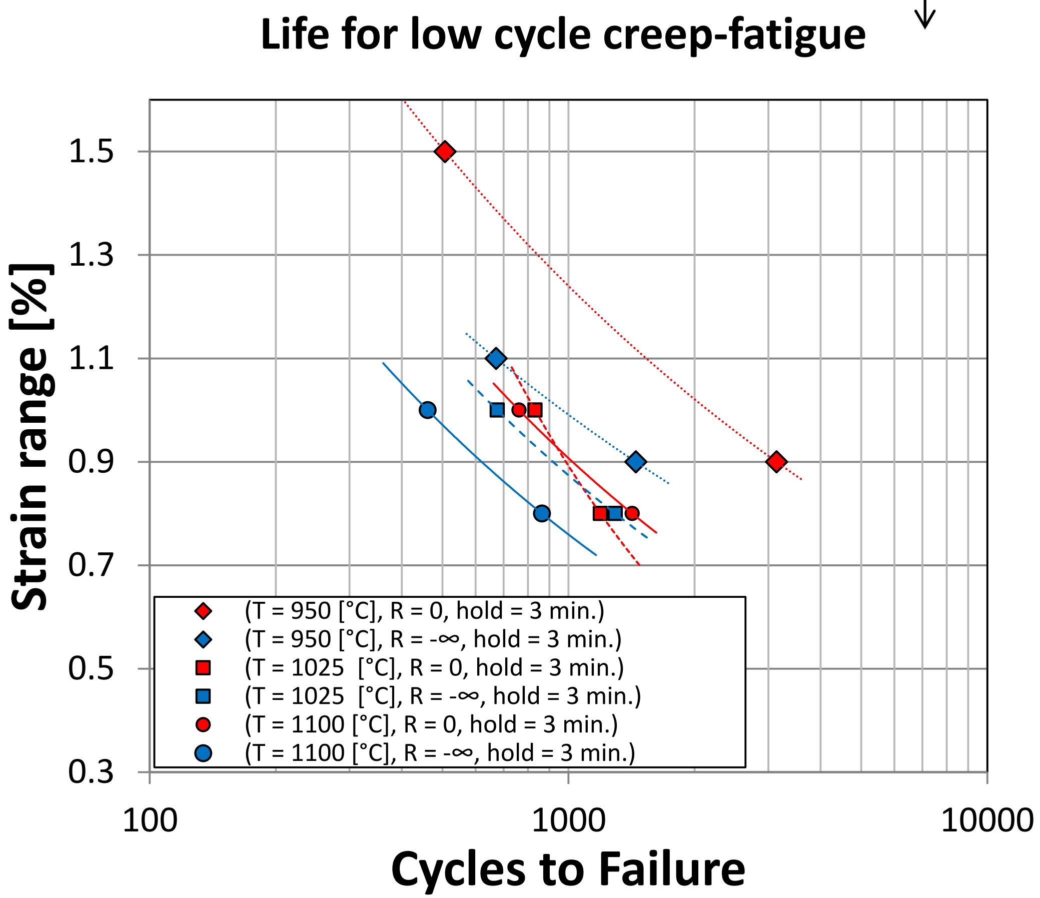




Conventional Creep-Fatigue (baseline)

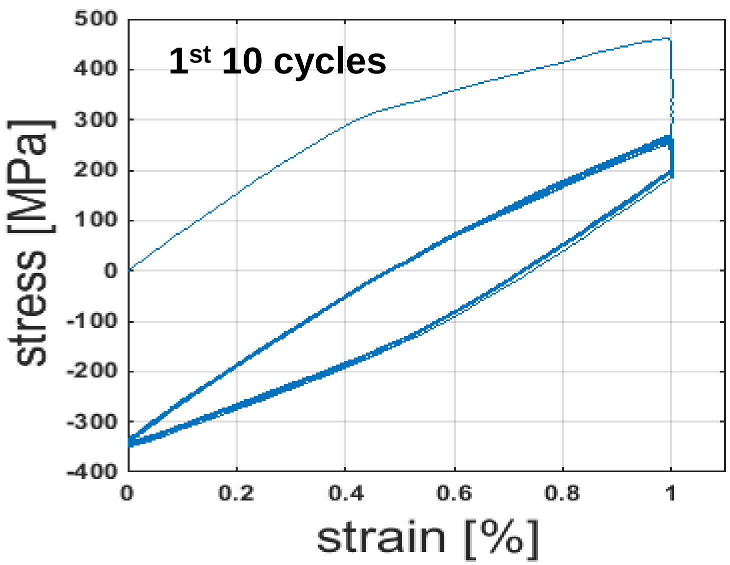


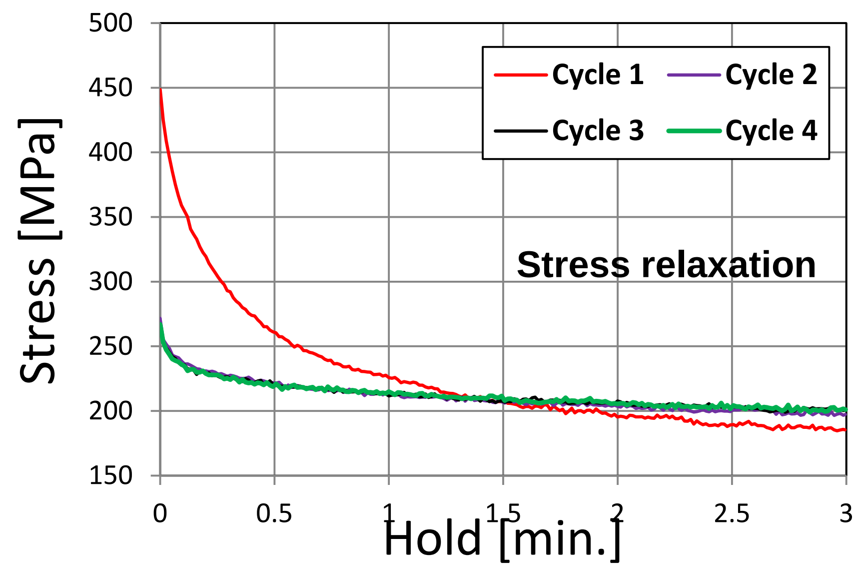


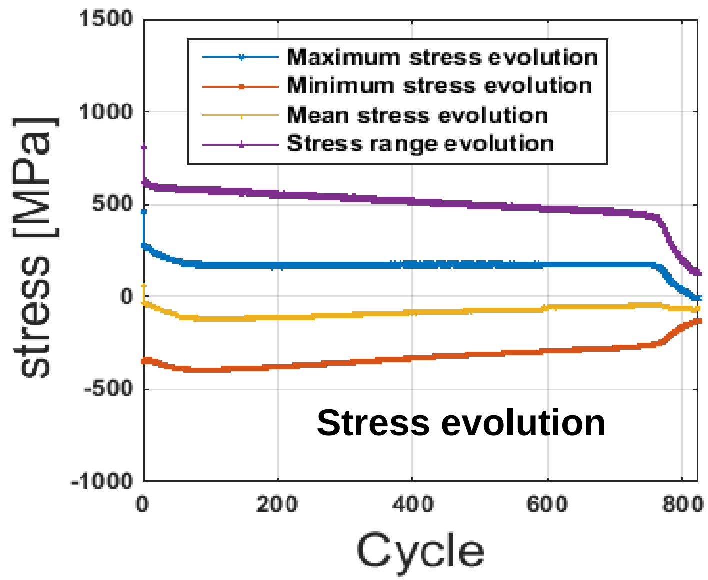


Cycle Evolution

T = 1100 °C, R = 0, $\Delta\varepsilon$ = 1.0 %



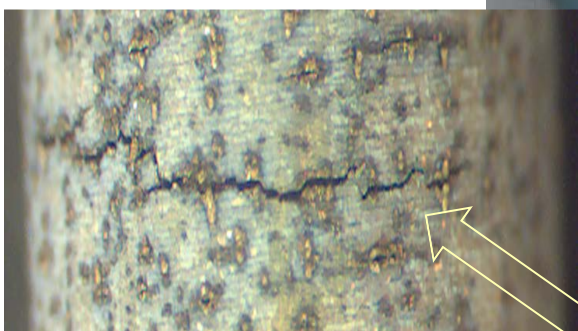


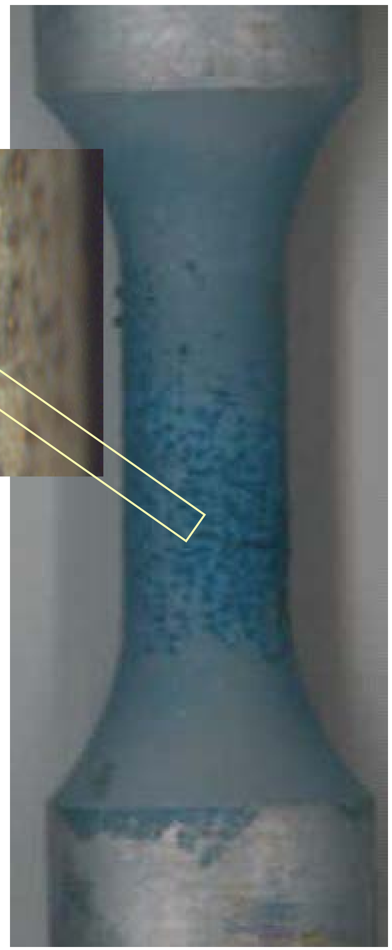


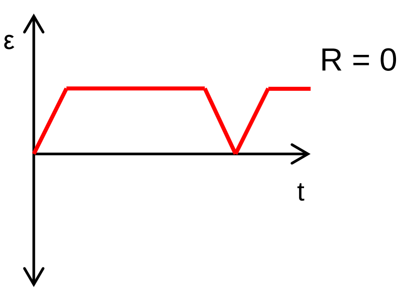
Crack Characteristics

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

$N_f = 1420$

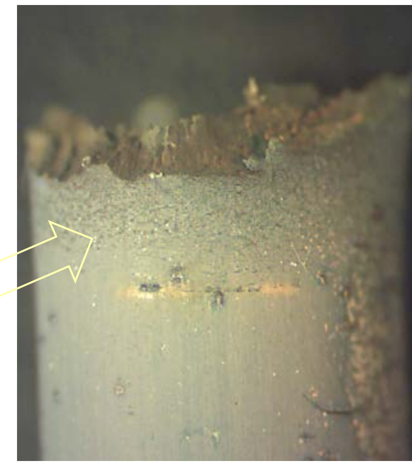


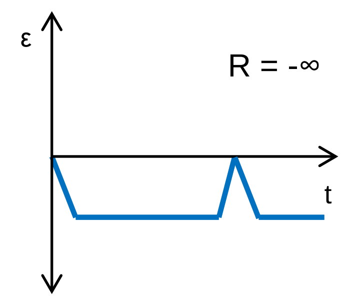




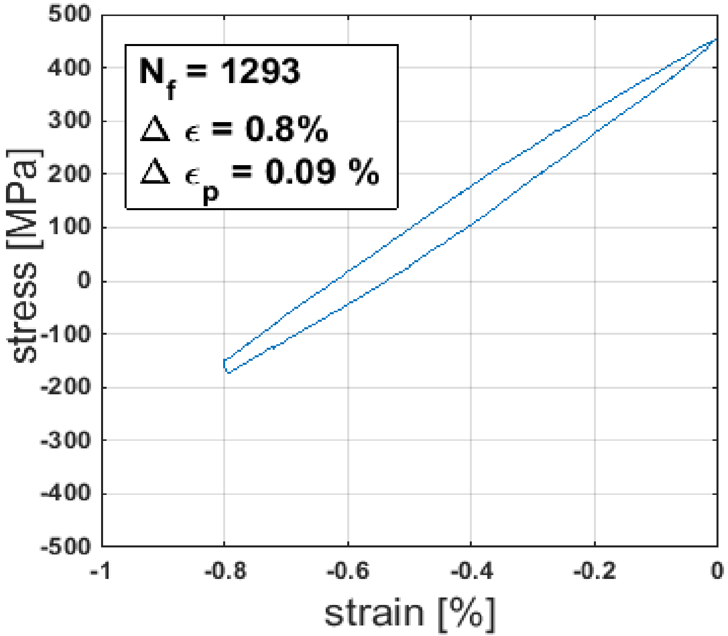
$R = -\infty$, $T = 1100^{\circ}C$, $\Delta\varepsilon = 0.8\%$

$N_f = 980$

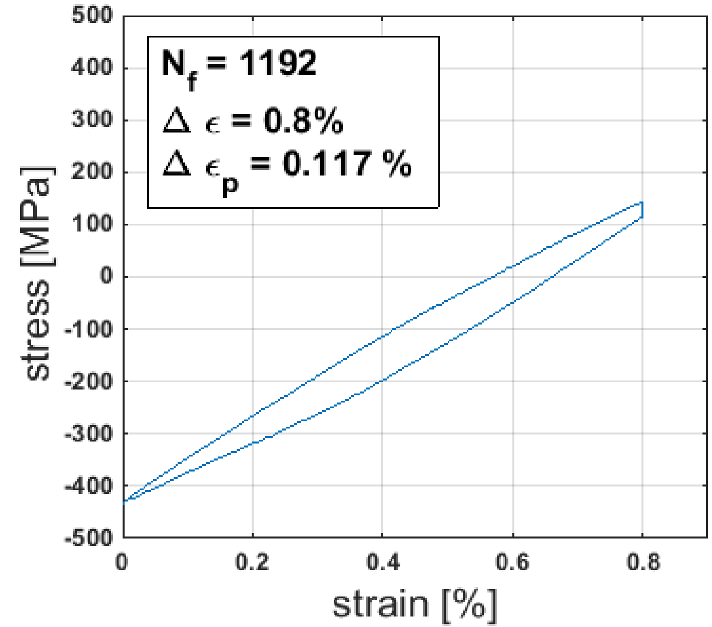


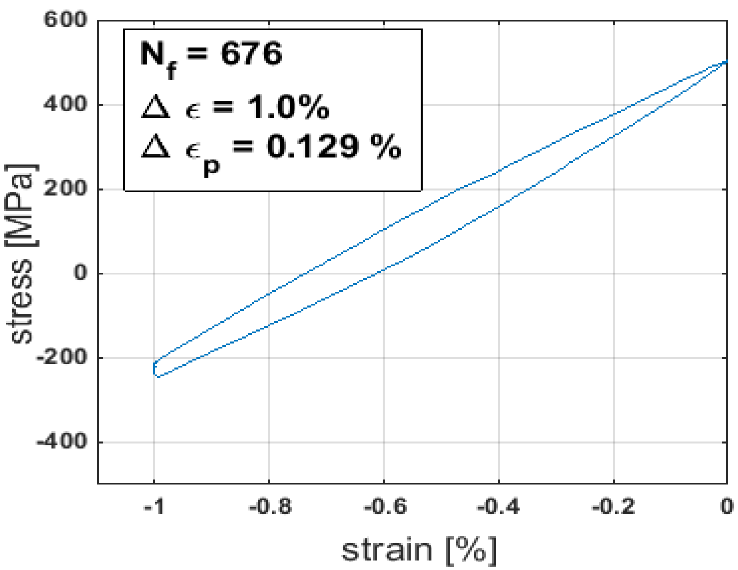


Half-life at 1025 ºC

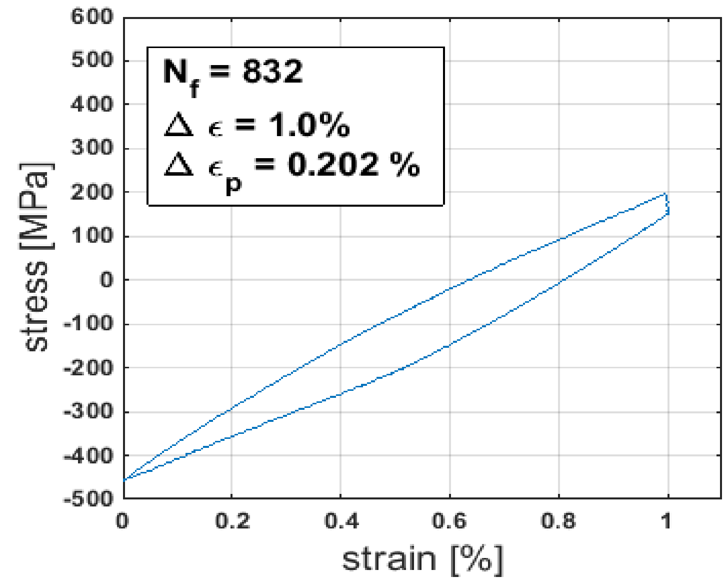


$\Delta\varepsilon = 0.8$ [%]

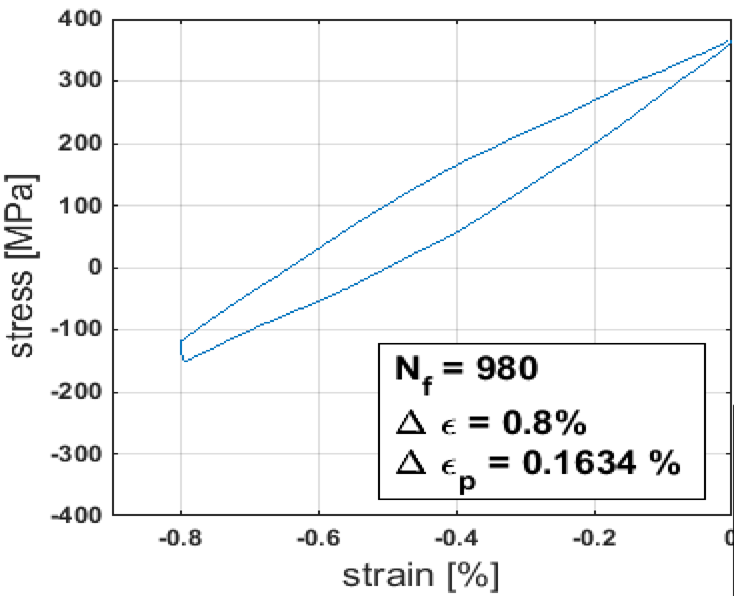


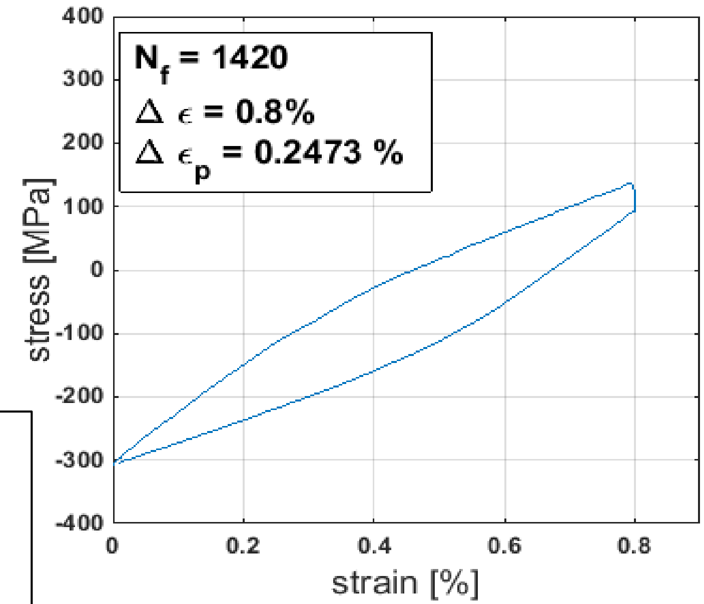


$\Delta\varepsilon = 1.0$ [%]



Half-life at 1100 ºC

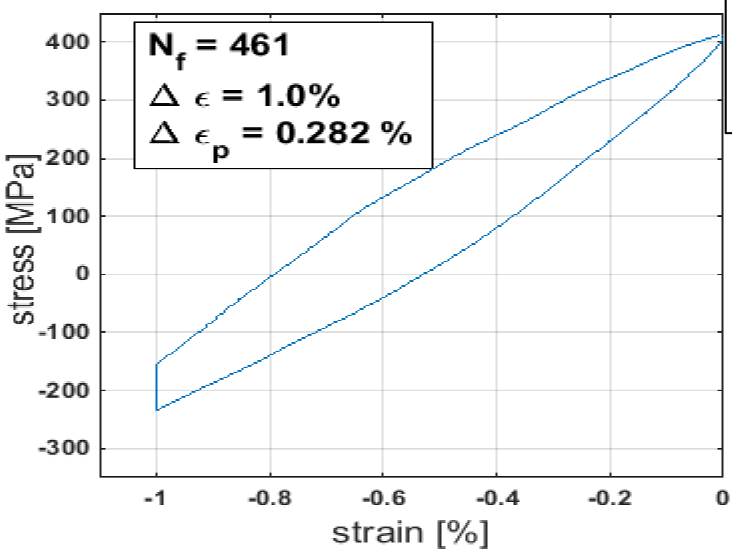


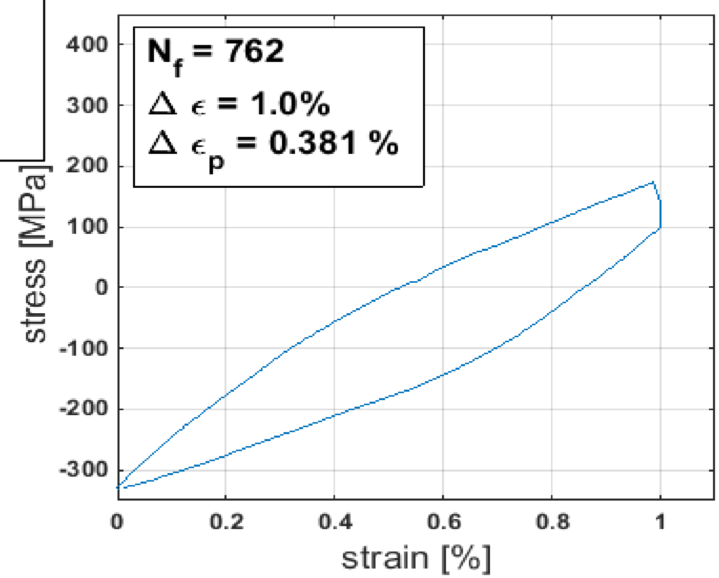


Δε = 0.8 [%]

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

Δε = 1.0 [%]





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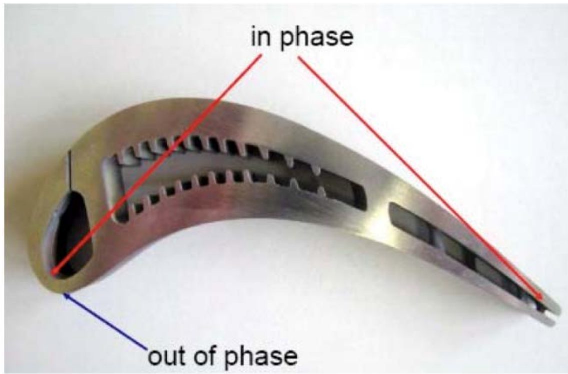
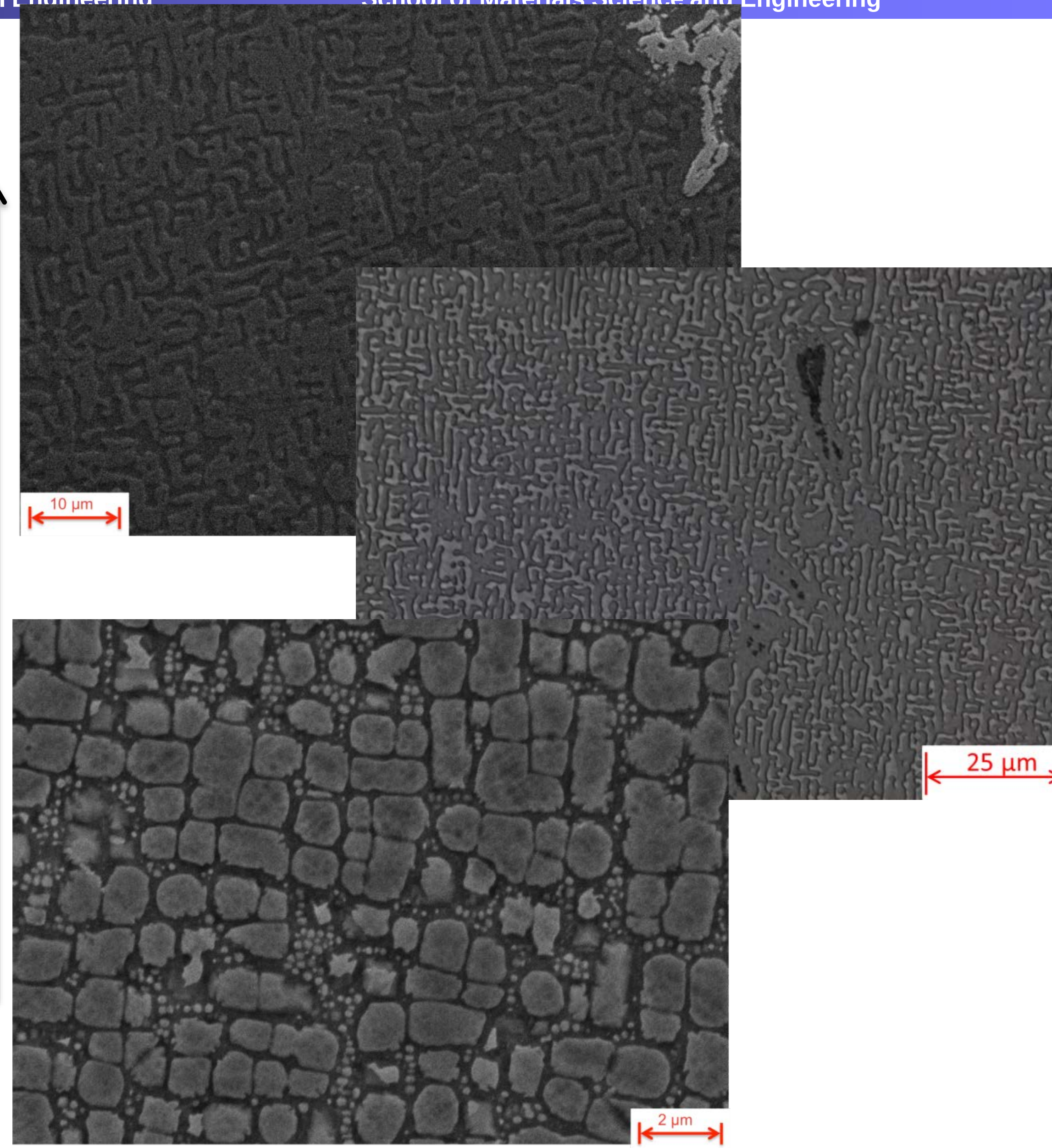
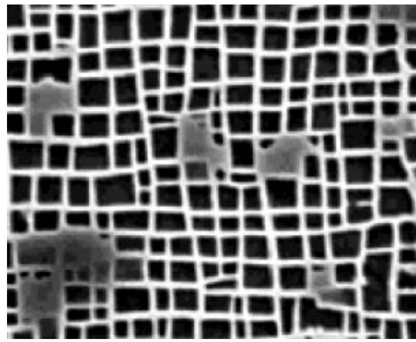
Microstructure Evolution in Blades

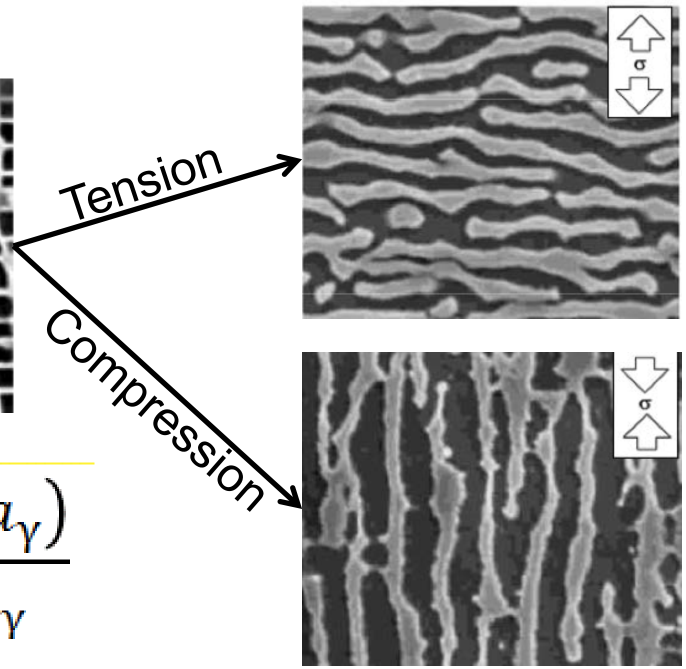


Distance from Root



Rafting and Coarsening of γ’

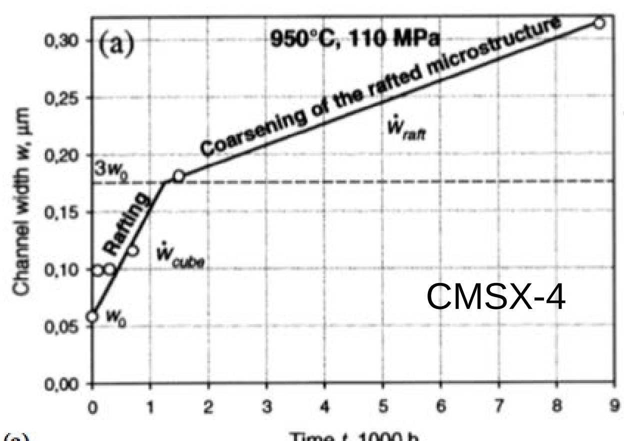




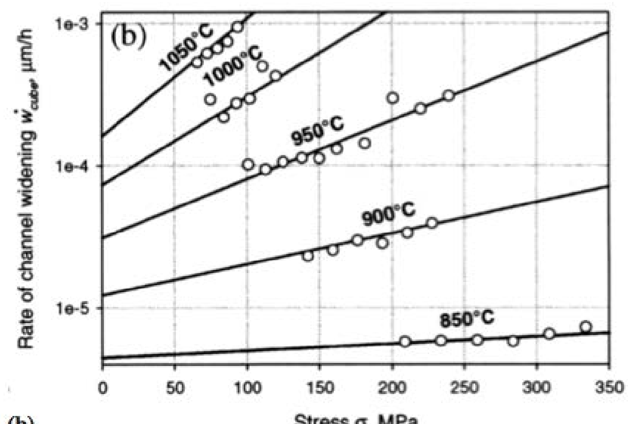
N-raft

P-raft

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



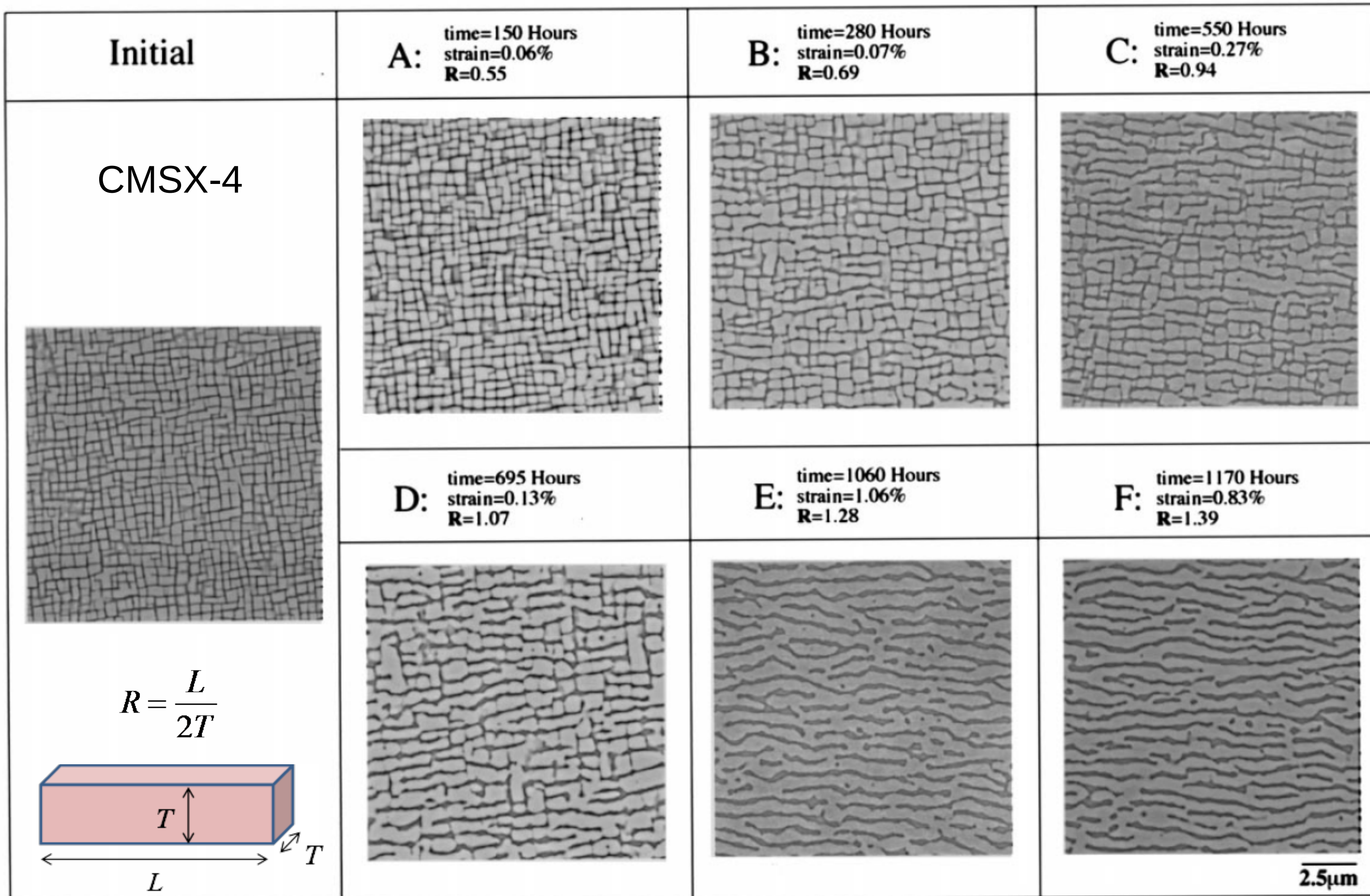
(a)



(b)

[Epishin et al., 2008]

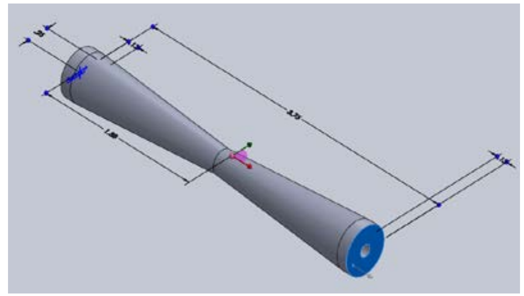
Microstructure after tensile creep at 950° C/185MPa for different times

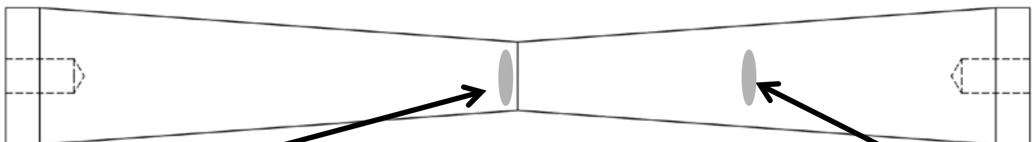


[Matan, Cox, Rae, & Reed, 1999]

Stress-dependent Aging Study – CMSX-8

Objective: Obtain kinetic data to predict rafting and coarsening as a function of temperature, stress, microstructure and time



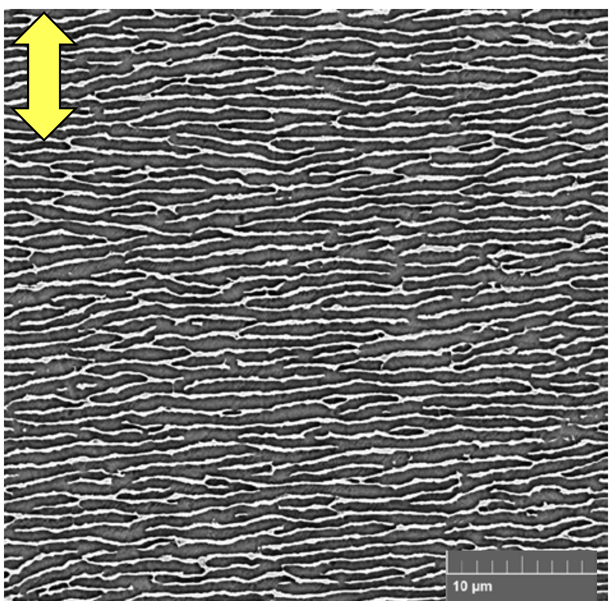


Fully Rafted

100 MPa

Partially Rafted

50 MPa



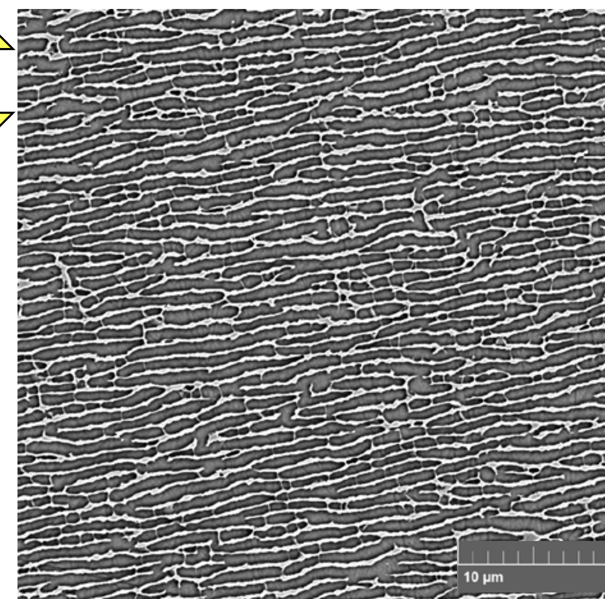
Test conditions

CMSX-8

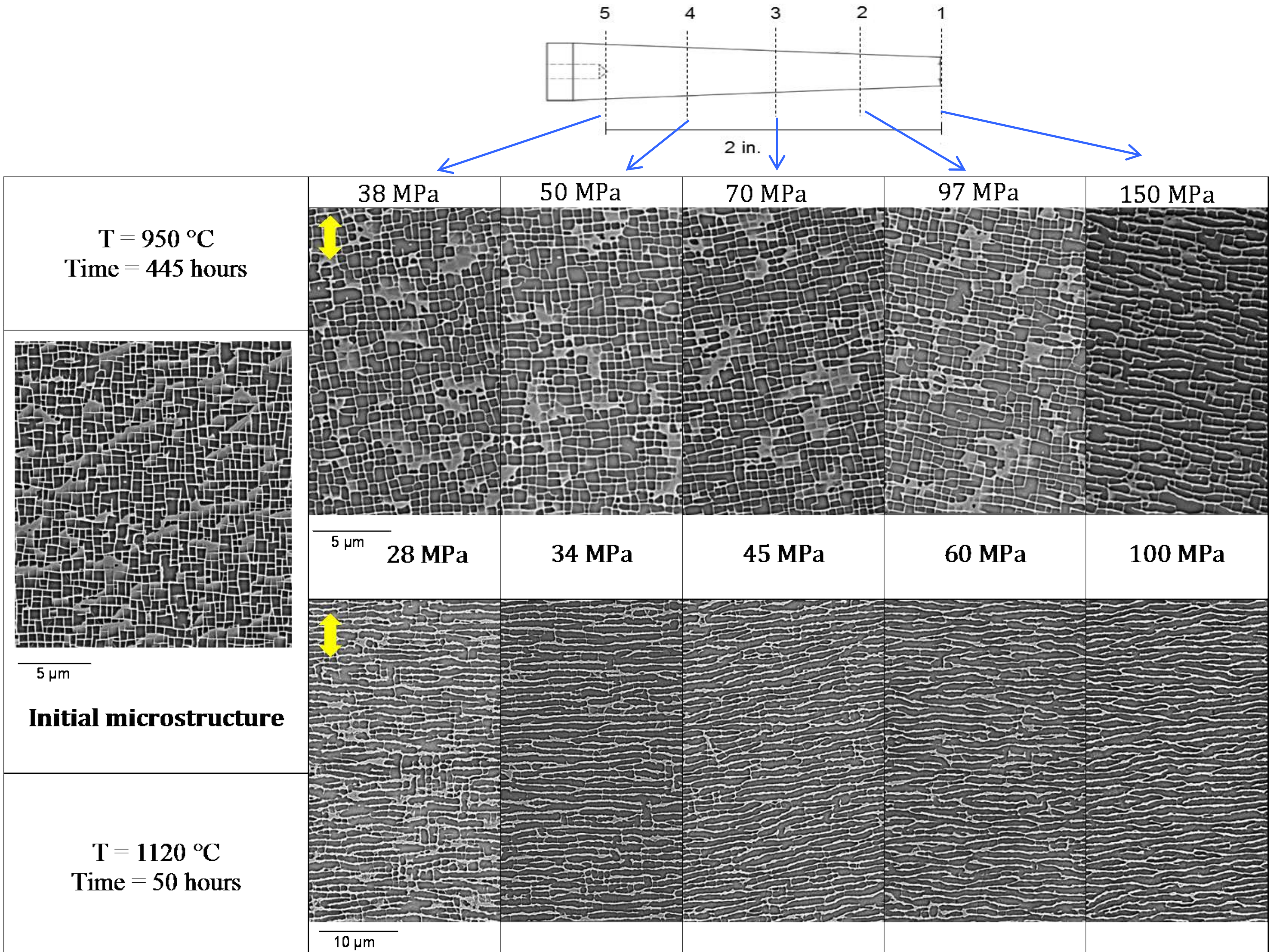
Temperature: 1120° C

Force: 3.24kN

Time: 50 hrs



CMSX-8 Rafted Microstructure



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.

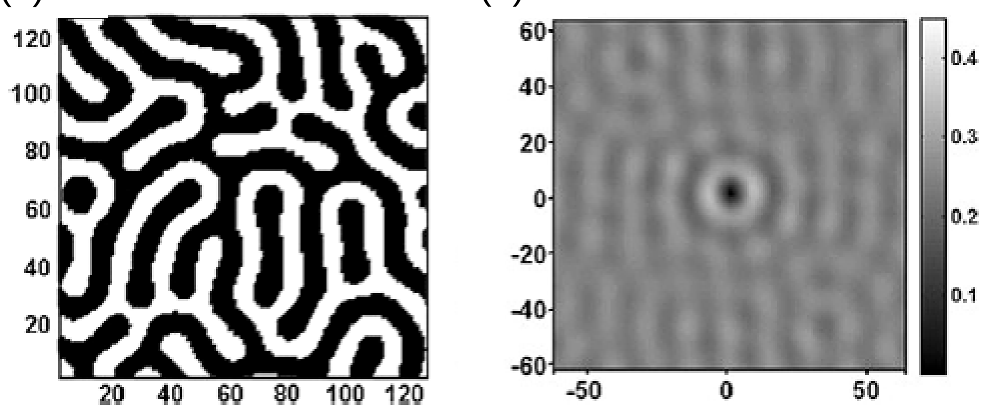
- **Cross-correlation**
  Defined by $f(h, h' \neq h \mid \boldsymbol{r})$**.** The function gives the probability that a random vector of length x start in one phase and end in the other.

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

$$\begin{aligned} {}^{np}F_{\mathbf{k}} &= \Im({}^{np}f_{\mathbf{t}}) = \frac{1}{S}\, {}^{n}M_{\mathbf{k}}^{*}\, {}^{p}M_{\mathbf{k}} \\ &= \frac{1}{S} |{}^{n}M_{\mathbf{k}}||{}^{p}M_{\mathbf{k}}| e^{-i\, {}^{n}\theta_{\mathbf{k}}} e^{i\, {}^{p}\theta_{\mathbf{k}}} \end{aligned}$$

[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

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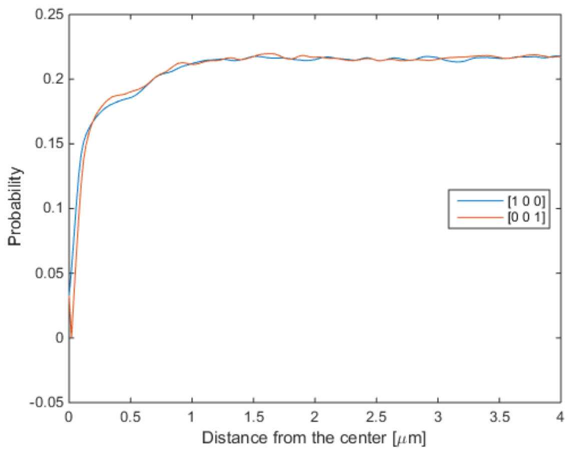
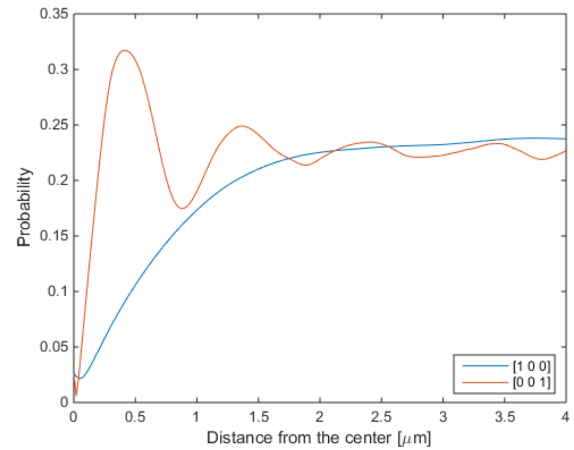
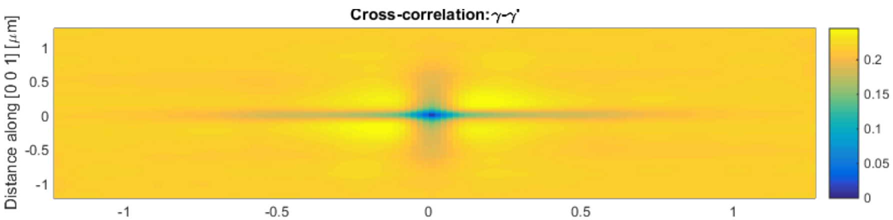
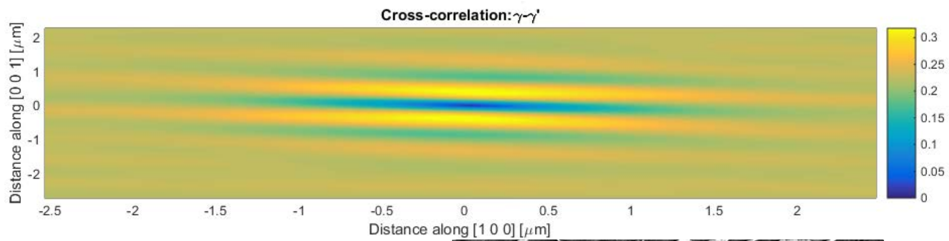
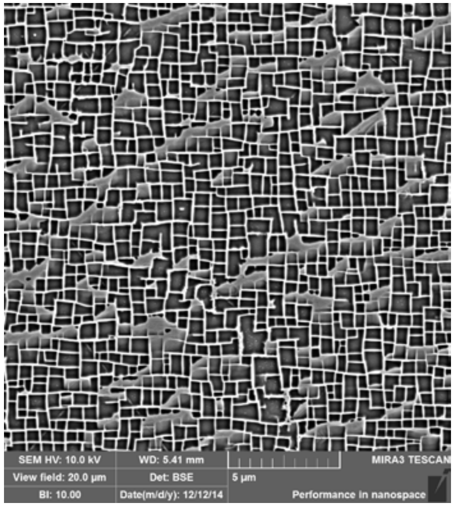


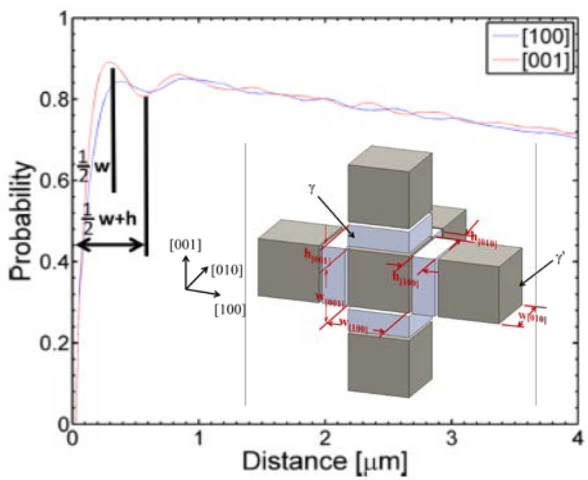
γ’ precipitate and γ channel sizes are determined from the first peak and valley of the probabilistic curve of the corresponding micrograph.

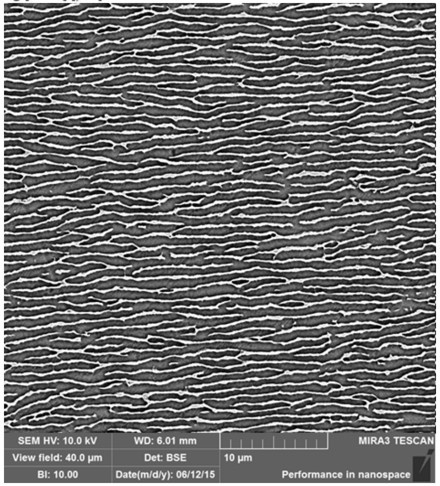




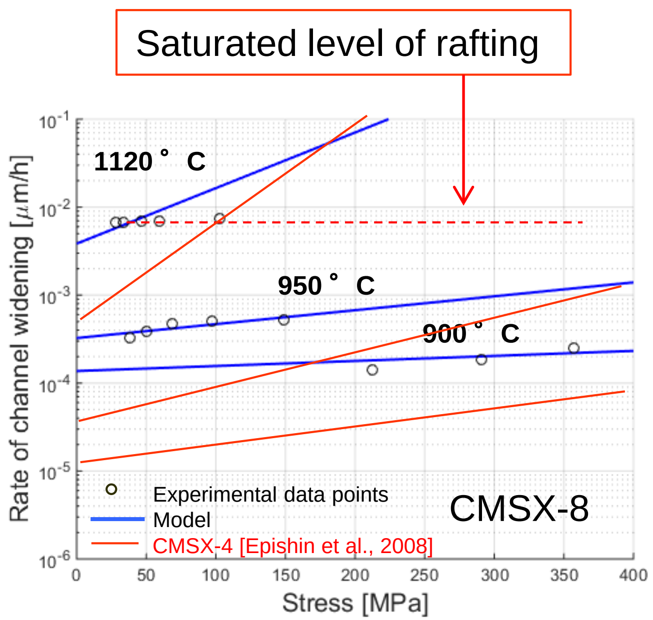


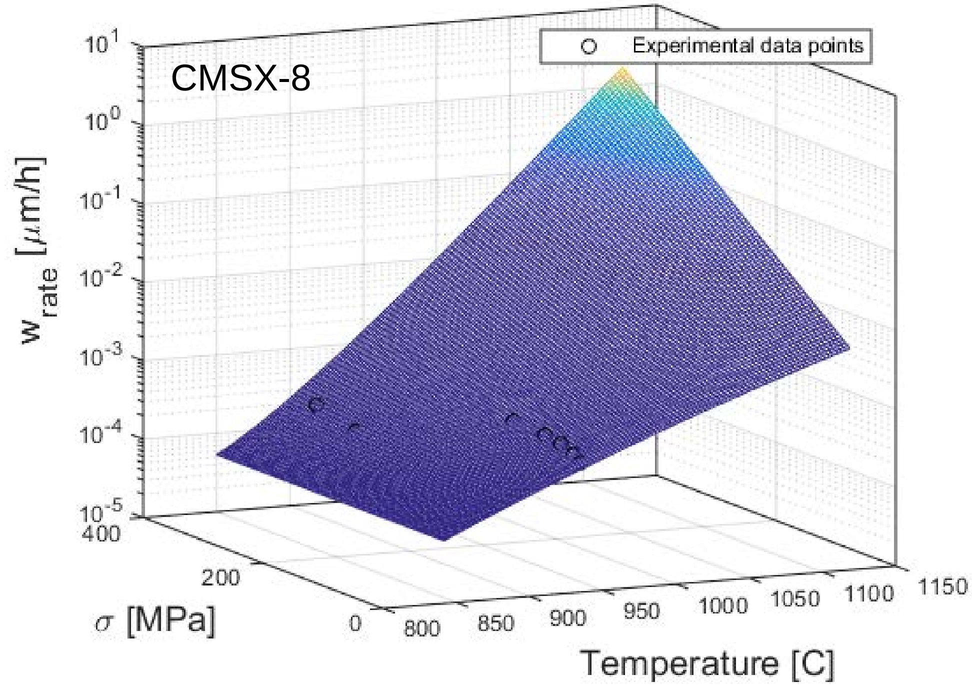


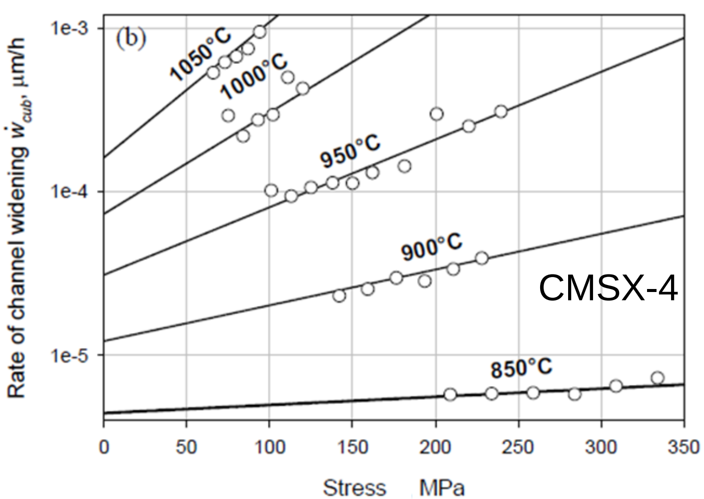




Kinetics of Rafting – CMSX-8 and CMSX-4







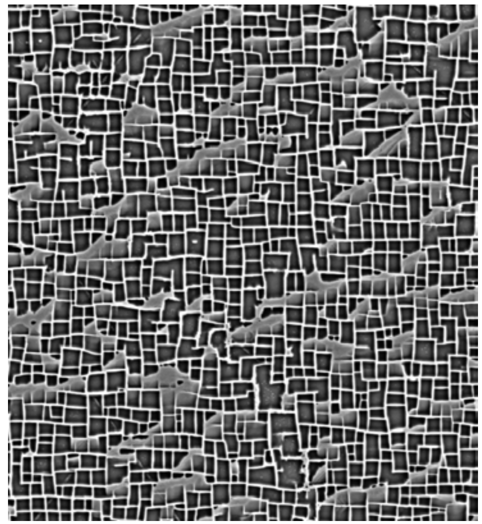
	A (μm/h)	Q (KJ/mol)	U_T (J/mol.Mpa.K^n)	n
CMSX-8	2.0×10^5	205.80	0.033	1.525
CMSX-4	9.31×10^4	221.78	0.19	1.294

$$\dot{w}(T,\sigma) = A.exp\left[-\frac{Q - U(T).\sigma}{RT}\right] \qquad U(T) = U_T(T - T_0)^n$$

[Epishin et al., 2008]

Stress-free Aging – CMSX-8

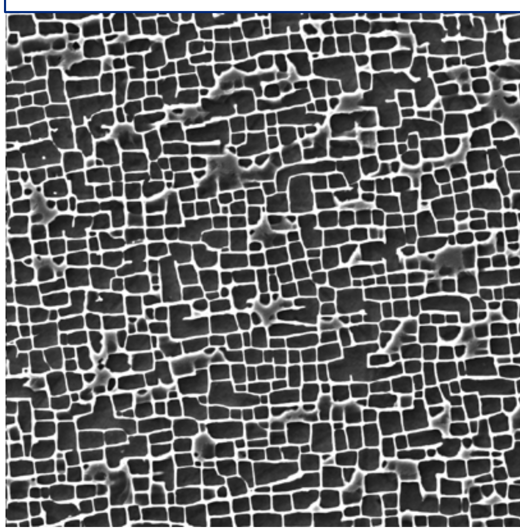
Initial Microstructure



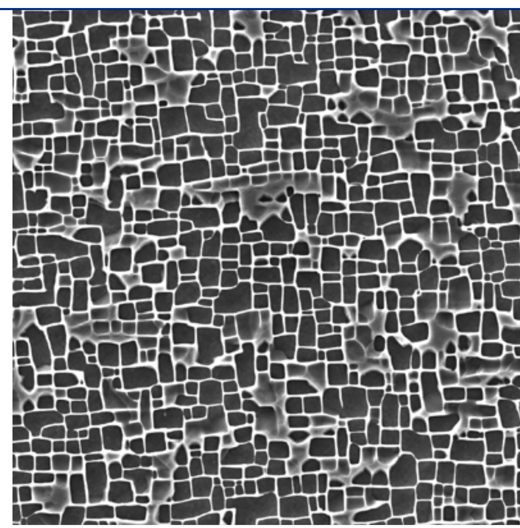
σ = 0 Mpa
T = 950 ° C

5µm

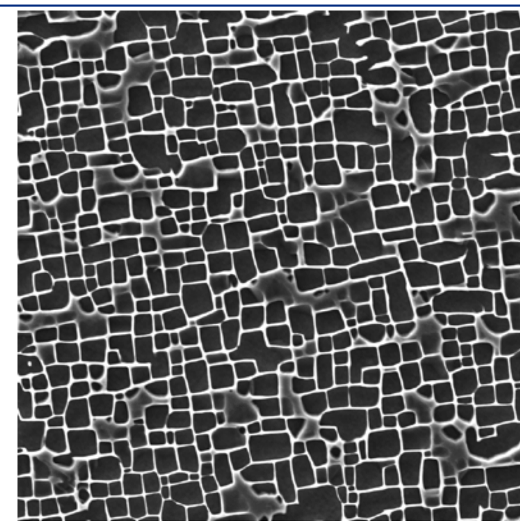
t = +400 hours



t = +700 hours



t = +900 hours

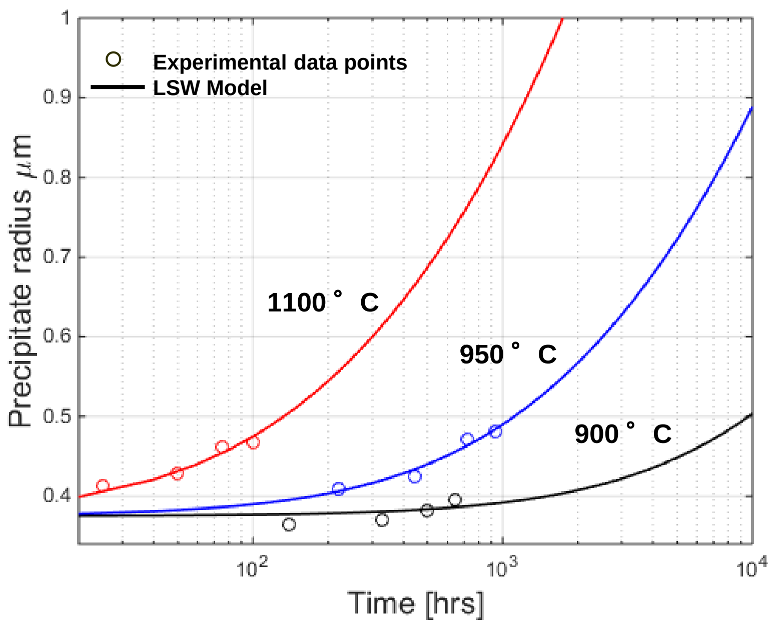


LSW model – Describe and Predict Coarsening Behavior

- According to Lifshitz-Slyozov-Wagner (LSW) theory particle coarsening process involves growth of the larger particles at the expense of the smaller ones to dissolve, with the driving force of reduction in interfacial energy of the system.

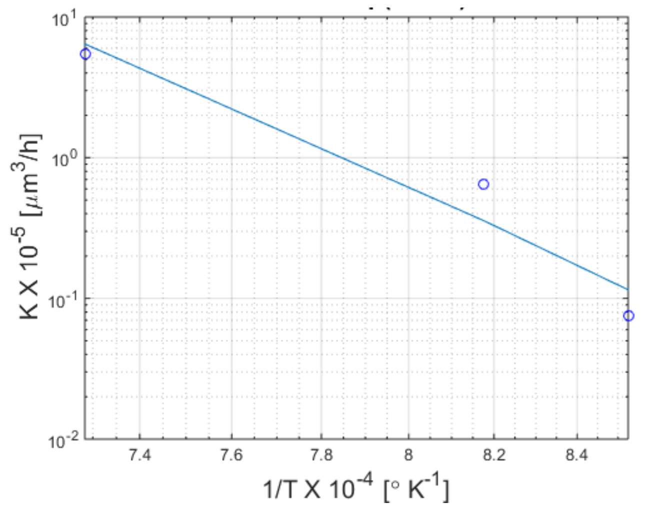
- Cube rate law indicates the volume diffusion

$$(r)^3 - (r_0)^3 = Kt \qquad K = K_0 \exp\left(-\frac{Q_{coar}}{RT}\right)$$

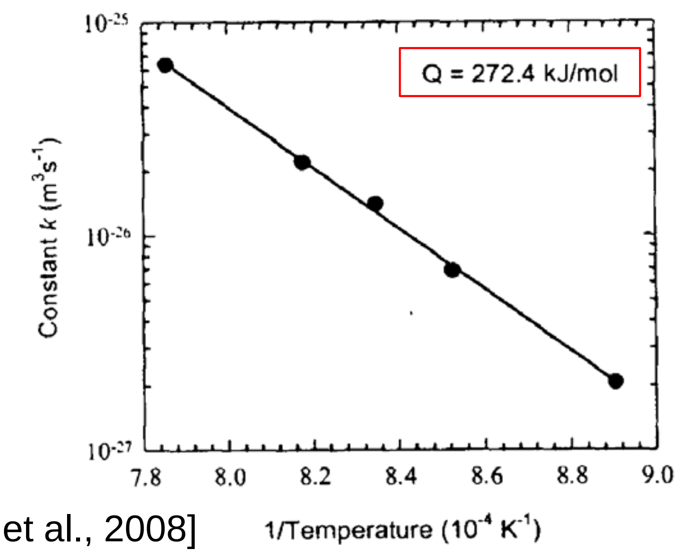


$$Q_{coar}\,(CMSX-8) = 269.4\ kJ/mol$$

CMSX-8



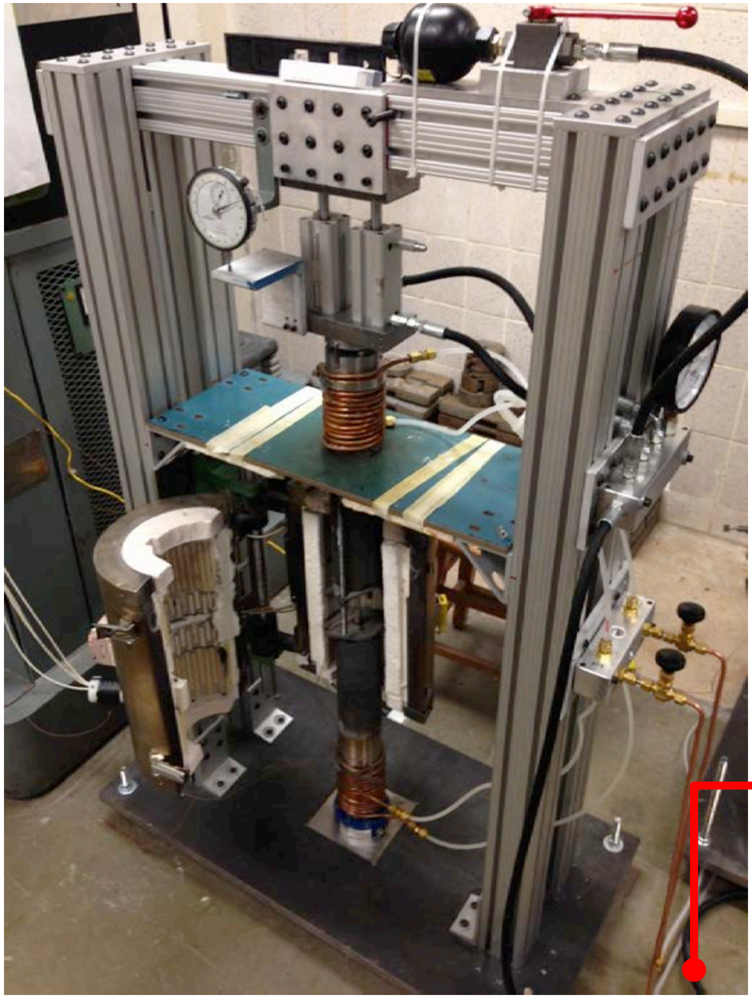
CMSX-4

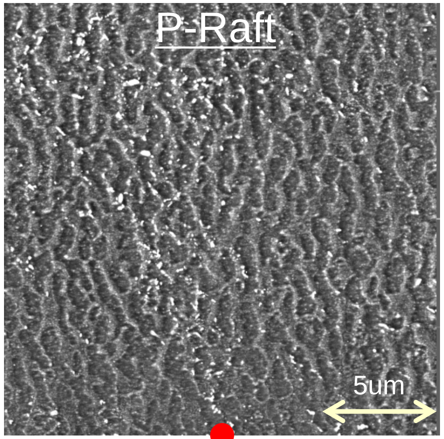


[Lapin et al., 2008]

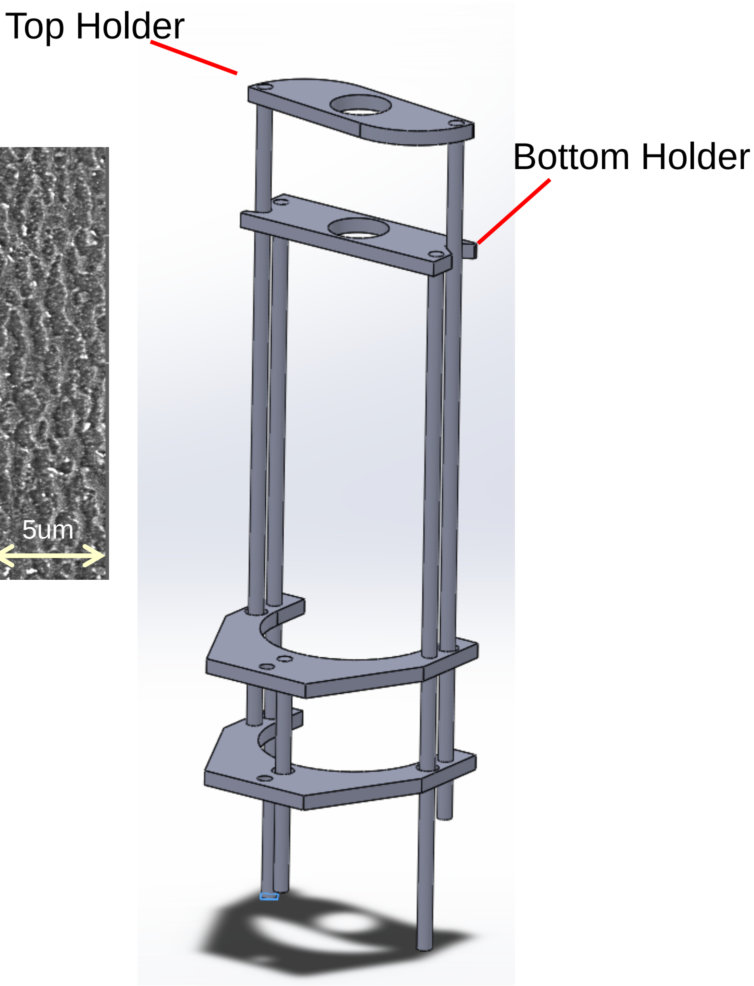
Aged Microstructure under Compressive Stress

Compression Creep Frame





Ceramic Compression Creep Extensometer



Composition Sensitive Effective Diffusivity

Flux of all n components in CMSX-8 system during a diffusion controlled process can be described by the **effective diffusion coefficient** , D_{eff}

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

[Ai et al., 2015]

Prediction of Aging

Effective diffusion coefficient term embedded in LSW model of isotropic coarsening,

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

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

Coarsening activation energy

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

Temperature-Dependent Constitutive Models

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

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

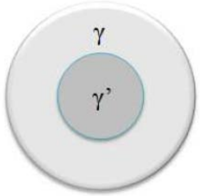
Composition dependent diffusivity parameter

Inter-diffusion coefficient of Ni-m binary system can be determined by DICTRA software

Effective Activation Energy for CMSX-8

Georgia Institute of Technology
The George W. Woodruff School of Mechanical Engineering
School of Materials Science and Engineering

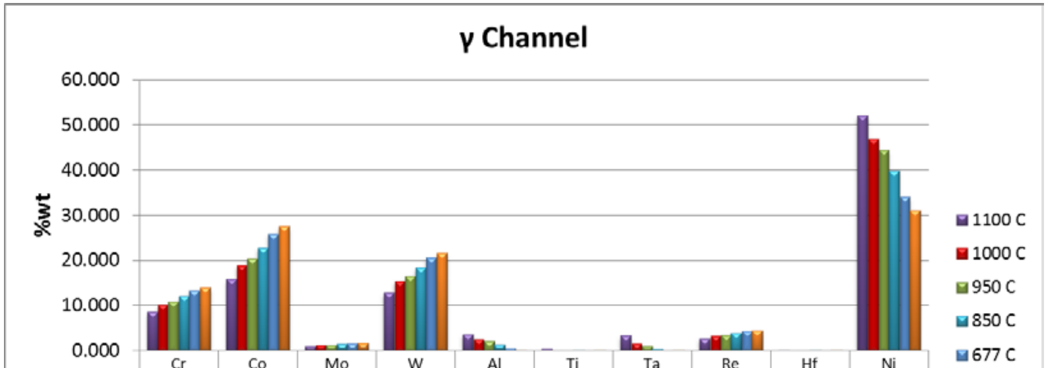
Equilibrium chemical composition of the γ phase is calculated at each temperature.



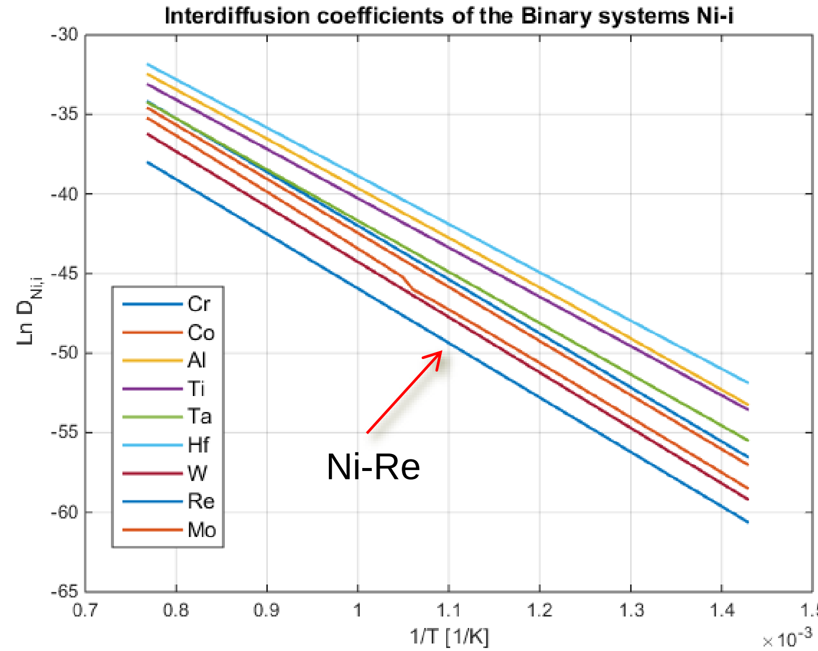
DICTRA

Databases:
TCNi5 / MOBNi2

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



	Cr	Co	Mo	W	Al	Ti	Ta	Re	Hf	Ni
1100 C	8.472	15.764	0.977	12.807	3.596	0.415	3.272	2.628	0.029	52.037
1000 C	10.110	18.900	1.170	15.380	2.540	0.024	1.510	3.250	0.016	46.870
950 C	10.820	20.310	1.260	16.520	2.080	0.170	0.940	3.520	0.012	44.380
850 C	12.000	22.720	1.382	18.400	1.303	0.081	0.305	3.922	0.006	39.880
677 C	13.370	25.830	1.510	20.560	0.450	0.018	0.026	4.300	0.001	33.920
550 C	13.918	27.417	1.559	21.476	0.149	0.005	0.003	4.417	0.000	31.057



Binary System	Ni-Cr	Ni-Co	Ni-Mo	Ni-W	Ni-Al	Ni-Ti	Ni-Ta	Ni-Re	Ni-Hf	Ni-Ni
Q Ni,i (KJ/mol)	2.81E+02	2.95E+02	2.82E+02	2.89E+02	2.60E+02	2.57E+02	2.67E+02	2.85E+02	2.52E+02	2.67E+02
D_0 Ni,i (m2 /s)	2.75E-04	3.35E-04	2.02E-04	7.23E-05	5.18E-05	8.86E-05	7.23E-05	8.27E-06	1.91E-04	7.25E-08
X_i	1.27E-01	2.10E-01	7.97E-03	5.47E-02	6.15E-02	3.28E-04	5.45E-03	1.14E-02	5.86E-05	5.22E-01
$X_iQ_{Ni,i}$	3.57E+01	6.18E+01	2.25E+00	1.58E+01	1.60E+01	8.43E-02	1.46E+00	3.25E+00	1.48E-02	1.40E+02

$$Q_{eff} = \sum_{i=1}^{n} x_i\, Q_{Ni-i}$$

Effective Activation energy /
Coarsening Activation energy

= 275.89 kJ/mol

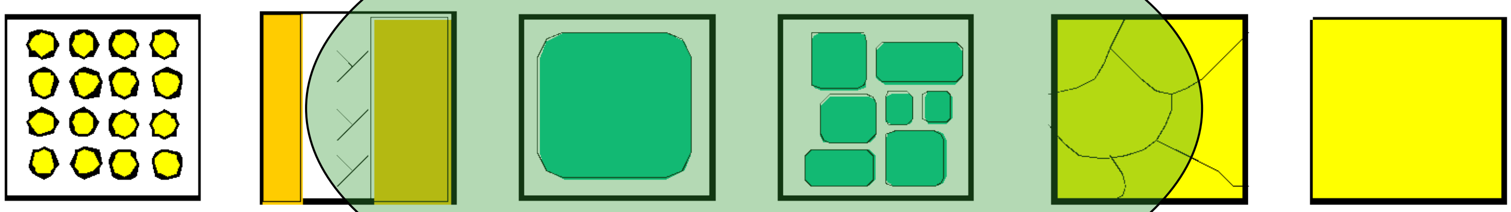
The influence of perturbations in composition on aging and diffusion-controlled processes is feasible with this methodology.

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

Length Scales in Ni-base Superalloys

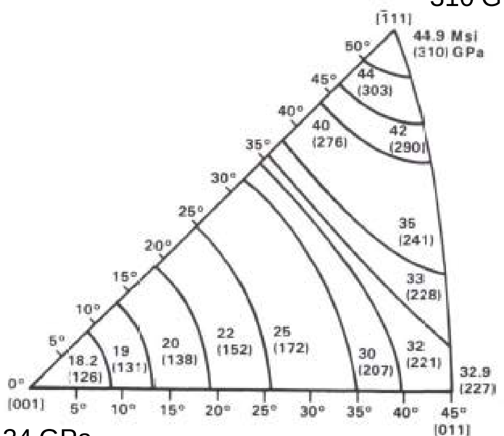
Atomic (Interfaces, Cores, Partials)	Channel Dislocations	Precipitates	Collections of Precipitates; GB cracks	Shear bands Grains	



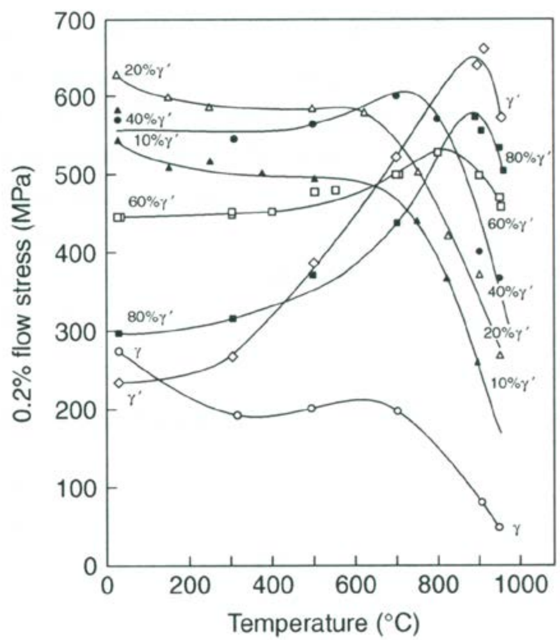
[Shenoy, Tjipowidjojo, and McDowell, 2008]

$O(10^{-10}$ m)	$O(10^{-8}$ m)	$O(10^{-7}$ m)	$O(10^{-6}$ m)	$O(10^{-5}$ m)

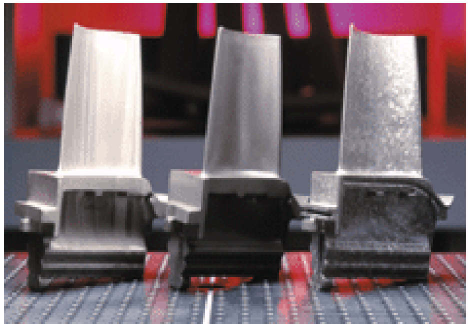
310 GPa



124 GPa



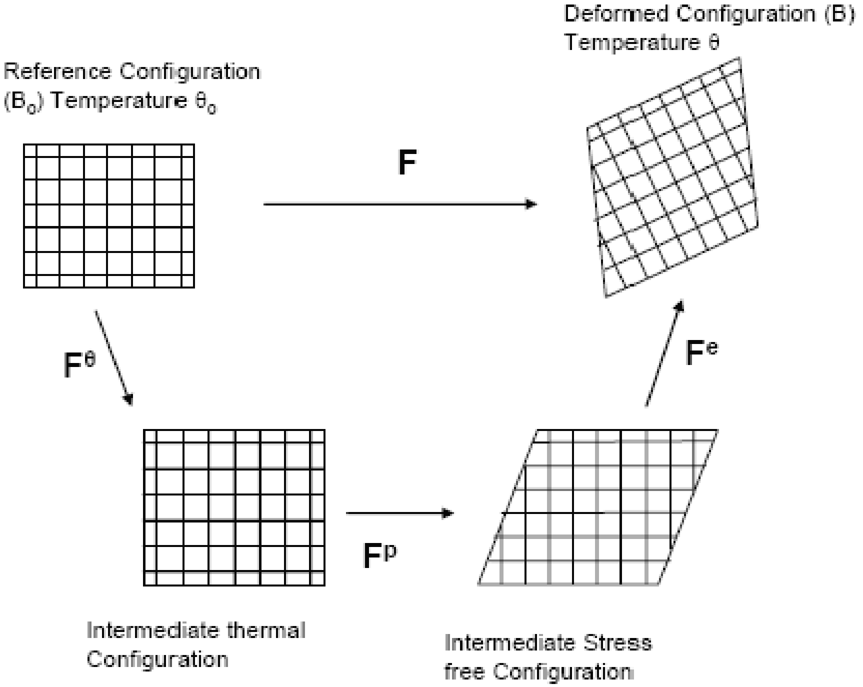
[Reed, 2008]



components

Crystal Viscoplasticity – Kinematic Relations

Kinematic relations including temperature dependence



Deformation gradient

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

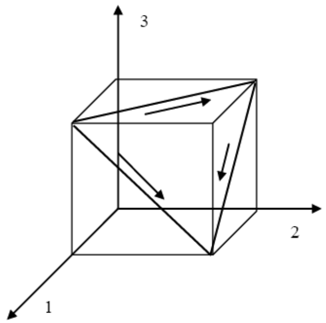
Velocity gradient

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

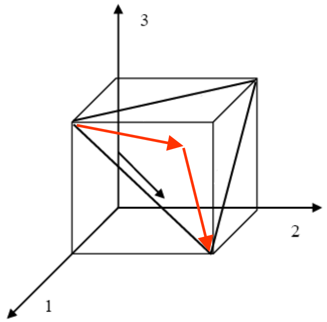
Macroscopic plastic velocity gradient

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

In γ : 12 octahedral slip systems active

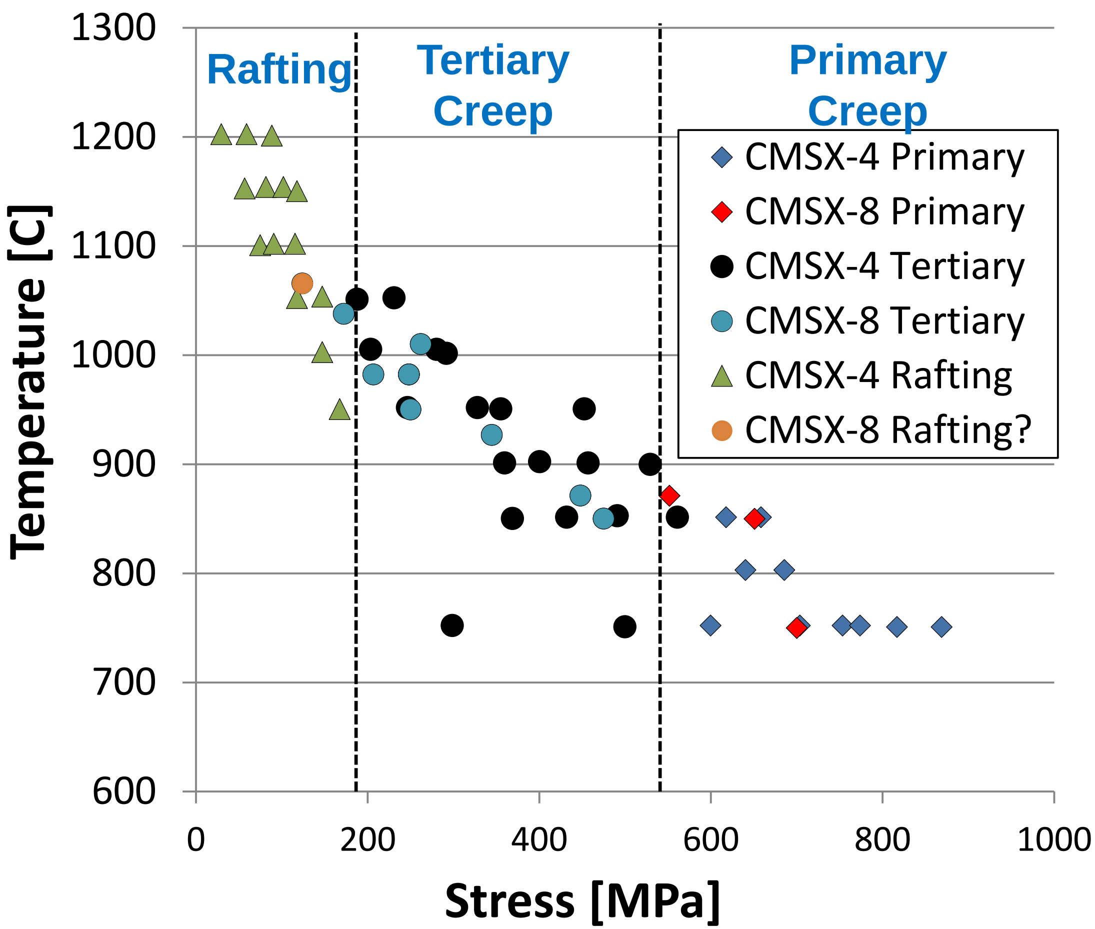


In γ': 12 octahedral slip systems moving as dislocation ribbons



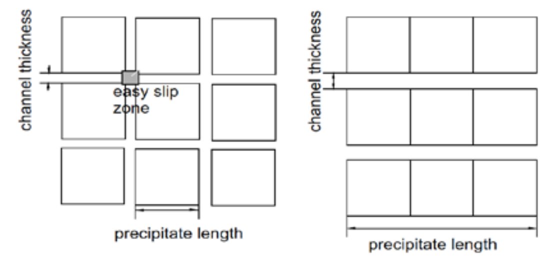
Creep Deformation Mechanisms of Superalloys

Influence of stress and temperature on modes of creep deformation



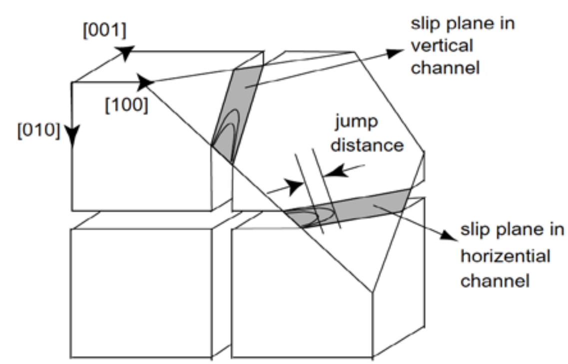
[Reed, 2006; Ma, Dye, and Reed, 2008, CMSX-8 Data]

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

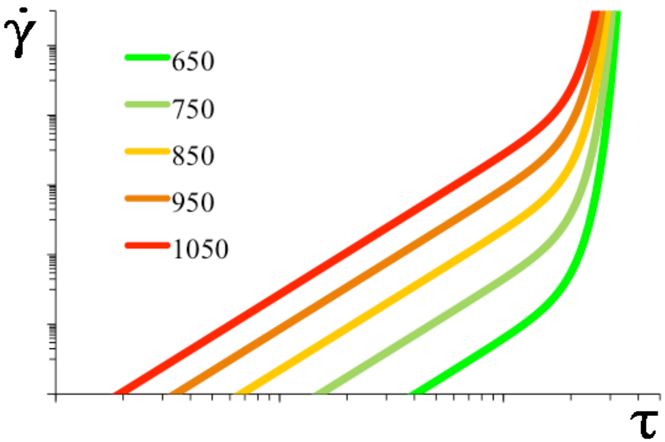
$$\mathbf{L}^{in} = \dot{\mathbf{F}}^{in}\mathbf{F}^{in^{-1}} = f_{\gamma}\left(\sum_{\alpha=1}^{12}\dot{\gamma}_{\gamma}^{in(\alpha)}\left(\hat{\mathbf{d}}^{(\alpha)}\otimes\hat{\mathbf{n}}^{(\alpha)}\right)\right) + f_{\gamma'}\left(\sum_{\alpha=13}^{24}\dot{\gamma}_{L1_2}^{in(\alpha)}\left(\hat{\mathbf{d}}^{(\alpha)}\otimes\hat{\mathbf{n}}^{(\alpha)}\right)\r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

Inelastic Shear Strain Rate

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

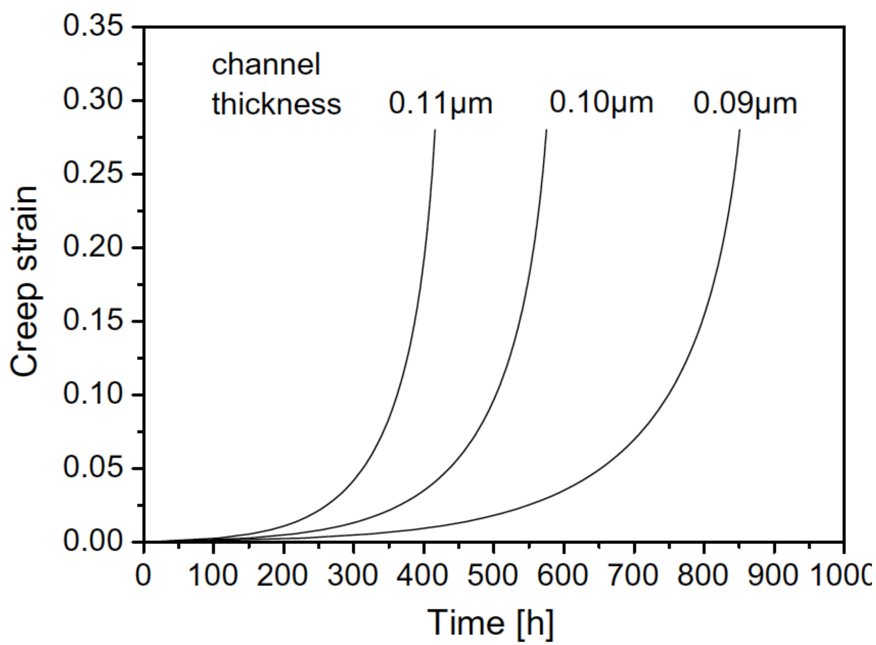
Evolution Equations

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

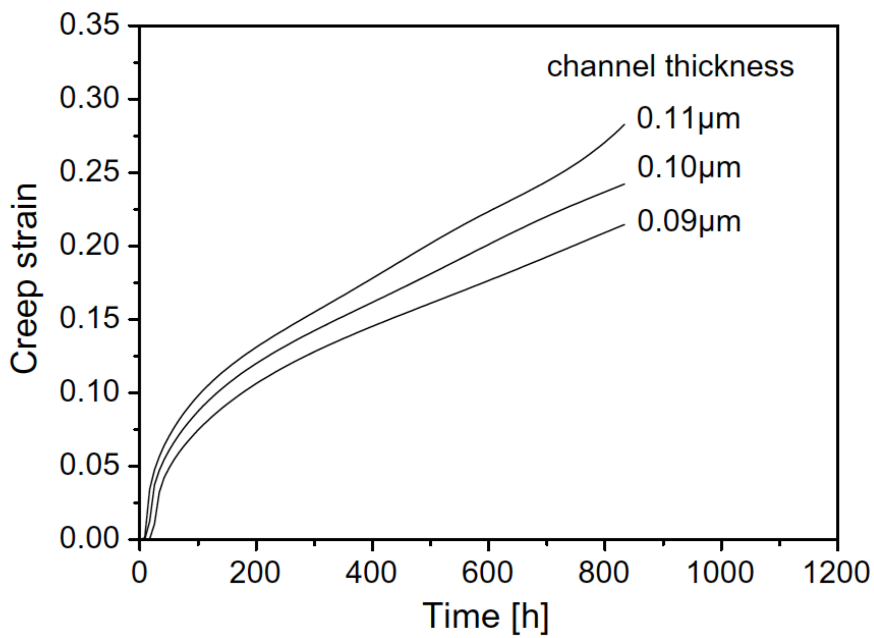


CMSX-4 Model Predictions

Tertiary creep
950° C/400MPa



Primary creep
750° C/770MPa

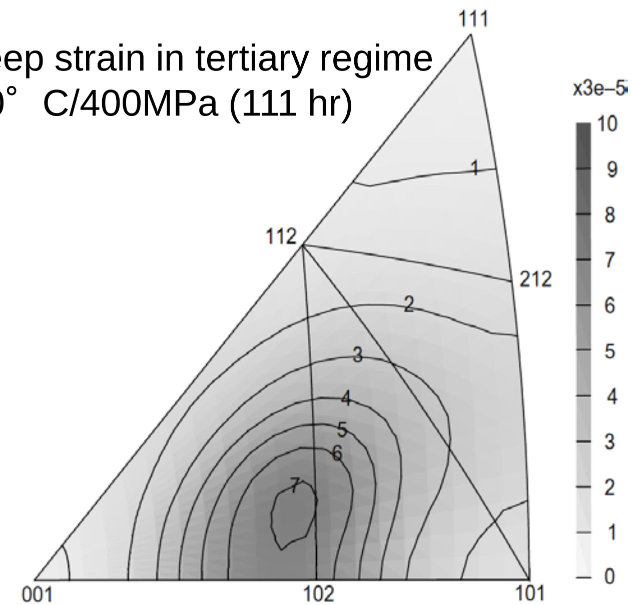


Deformation along [001]
Volume fraction of ©' fixed at 0.7

[Ma, Dye, and Reed, 2008]

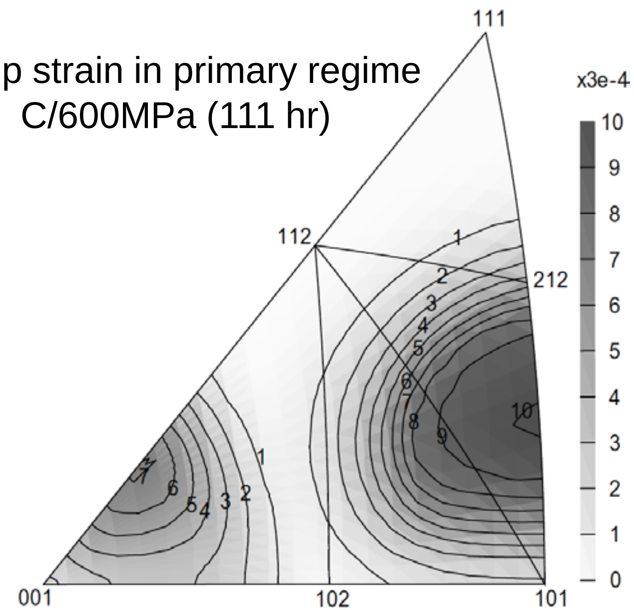
CMSX-4 Model Predictions

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

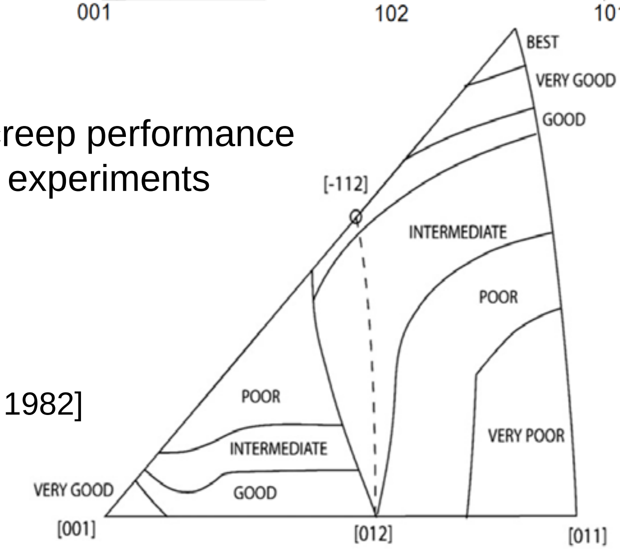


[Ma, Dye, and Reed, 2008]

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

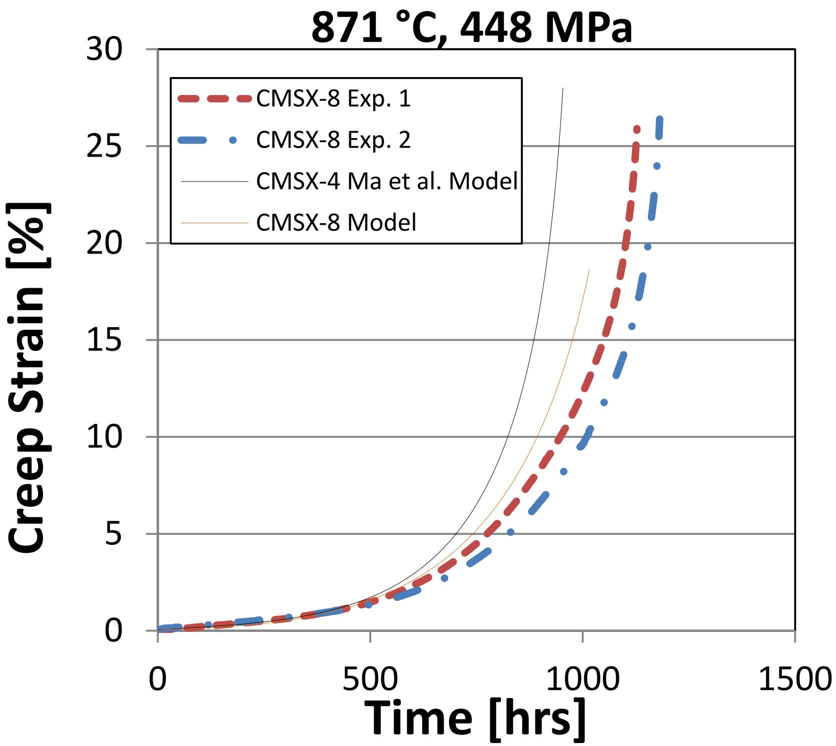


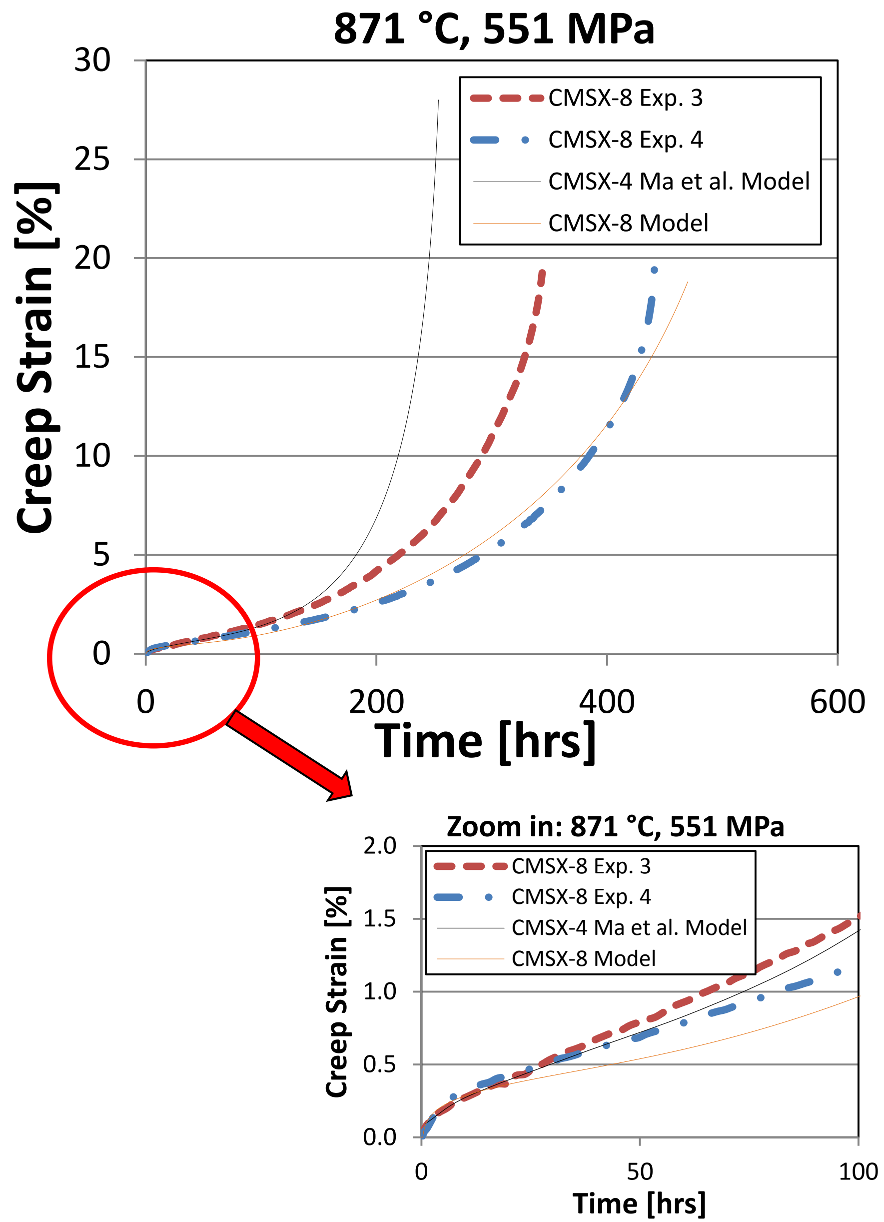
Primary creep performance
based on experiments



[MacKay and Meier, 1982]

Initial Calibration to CMSX-8 Creep Data





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

Modifications to Capture Evolution of γ' Precipitates

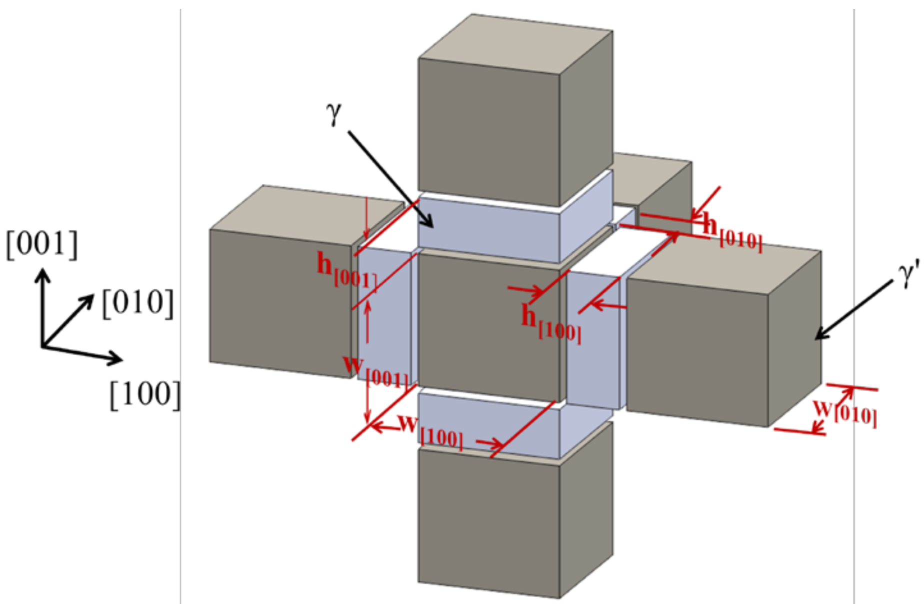
- Directional coarsening is roughly a constant volume process
- Stress-free coarsening maintains proportionality between all precipitate/channel dimensions
- Microstructure uniqueness is defined by 2 independent dimensions

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

[Tinga, Brekelmans, and Geers, 2009]

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

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



$$\eta = \frac{h_{[001]} - h^o_{[001]}}{h^o_{[001]}}$$

$$\zeta = \frac{h_{[100]} - h^o_{[100]}}{h^o_{[100]}}$$

[Kirka, 2014]

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:

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

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]