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

Award DE-FE0011722
August 2013 – August 2016
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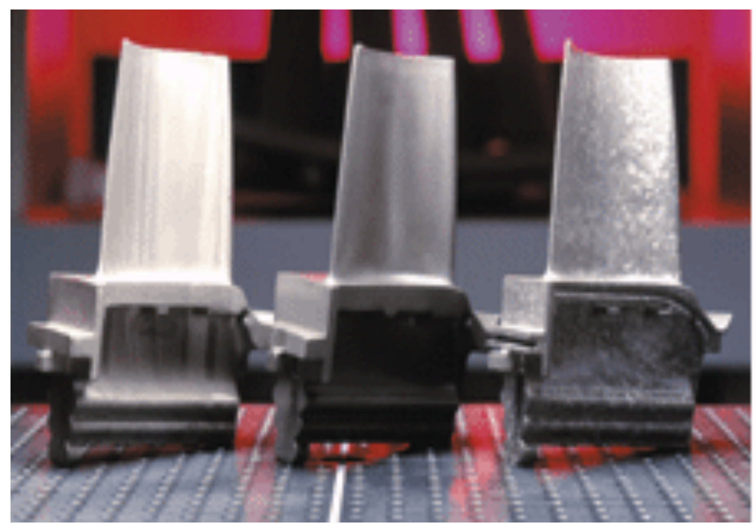
University Turbine Systems Research Workshop
Purdue University
October 21-23, 2014

Hot Section Gas Turbine Materials

Power Output: 375 MW



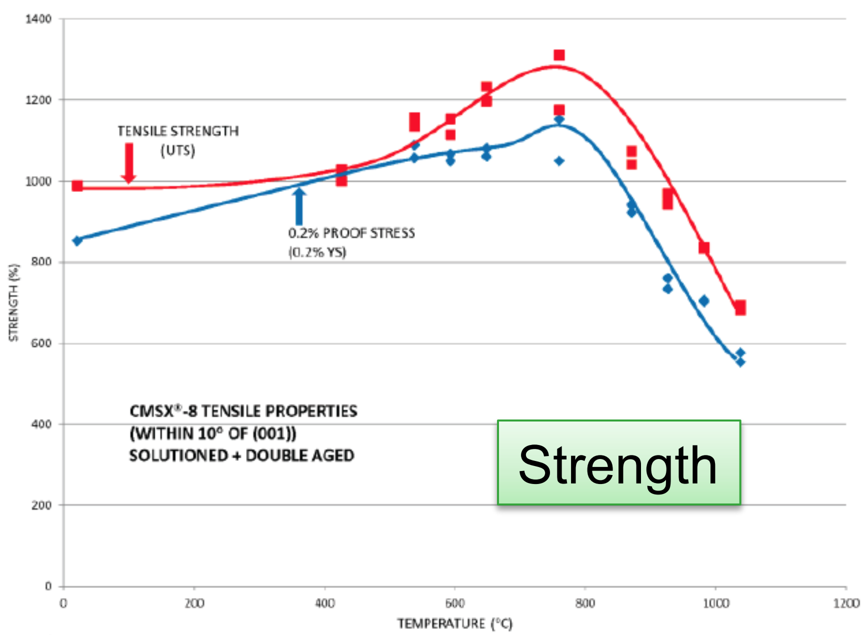
Land-based gas turbines

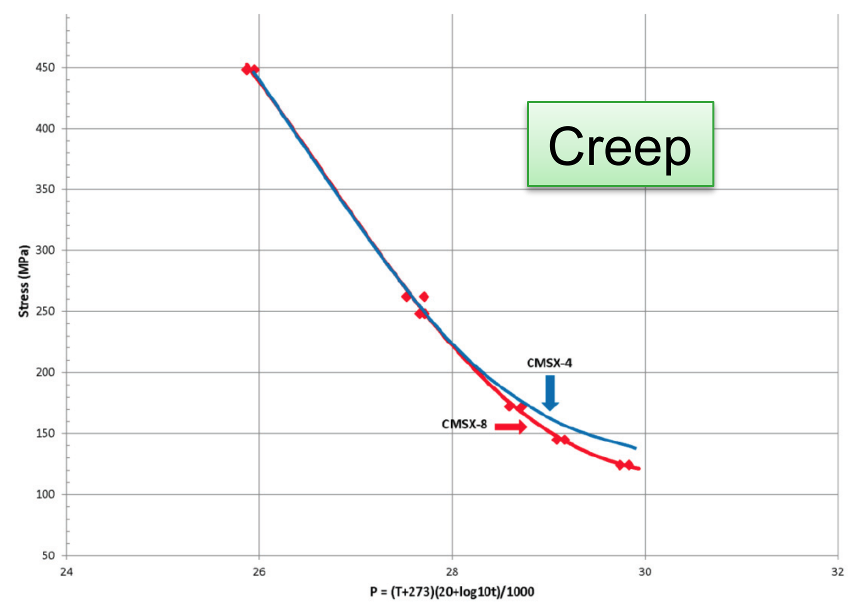
- drive to increase service temperature to improve efficiency; increase life
- replace large directionally-solidified Ni-base superalloys with single crystal superalloys

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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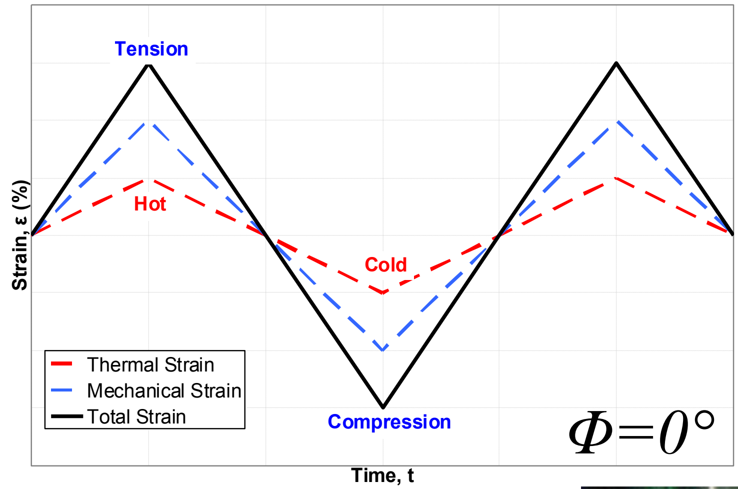
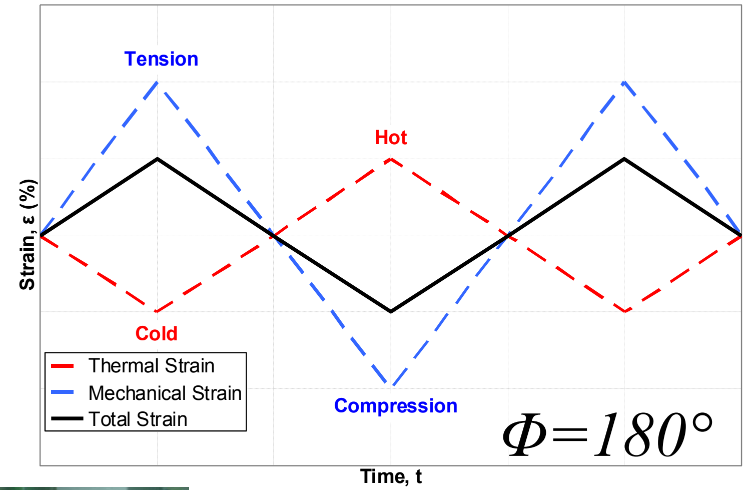
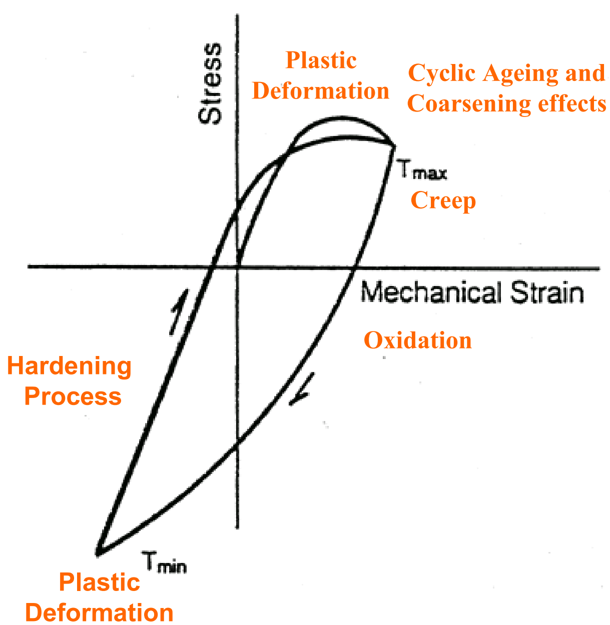
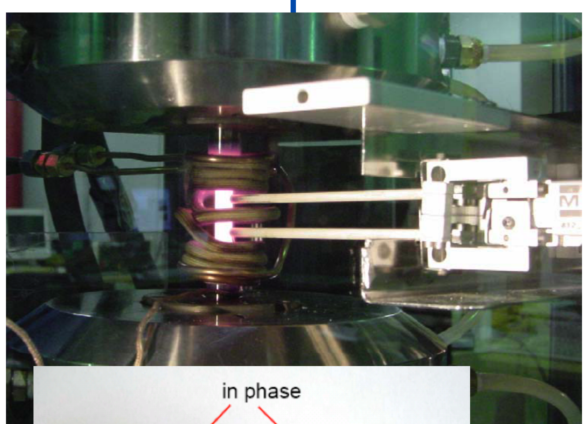
Linear In-Phase (IP)

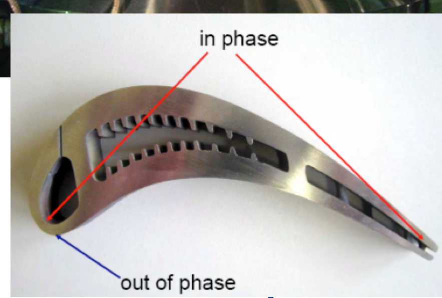


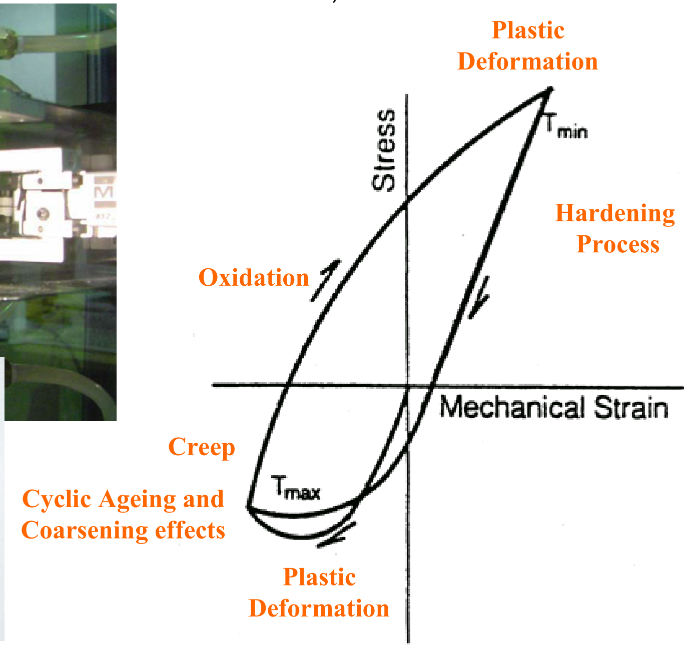
Linear Out-of-Phase (OP)





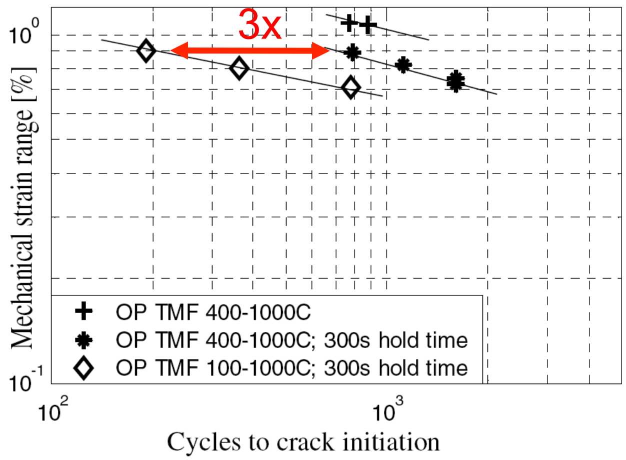


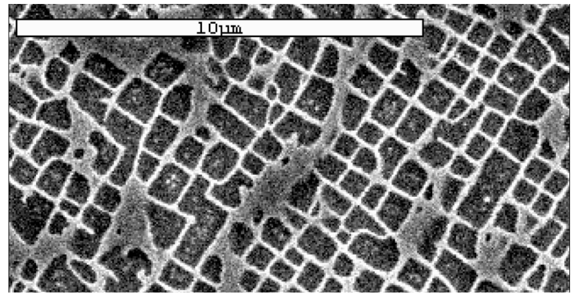


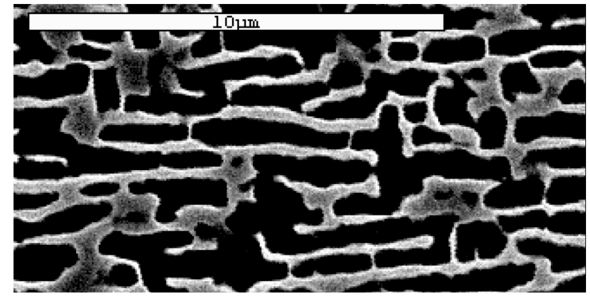


Effect of T_{min} on OP TMF of CMSX-4

CMSX-4 [001]

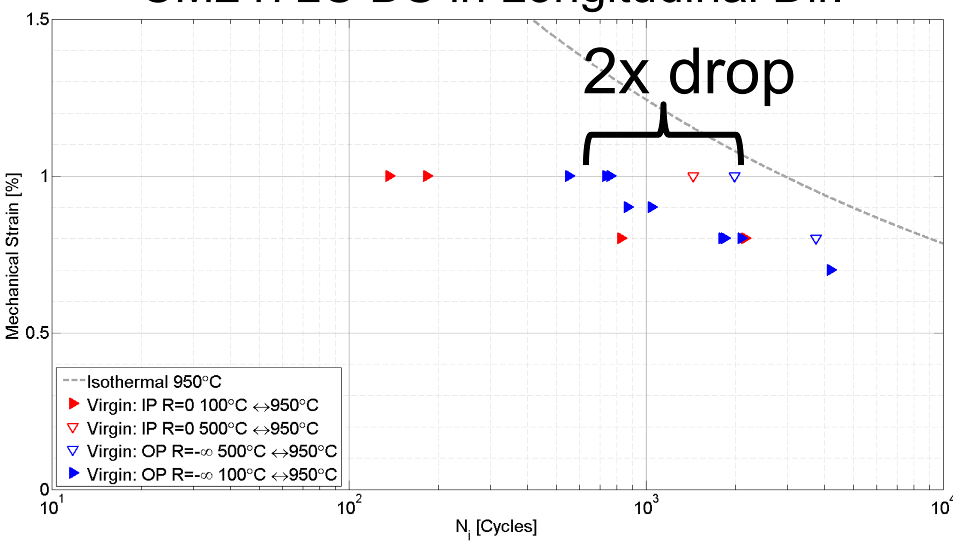




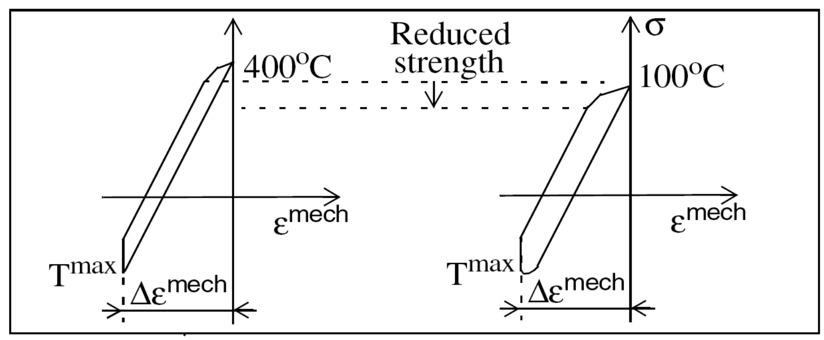


[Arrell et al., 2004]

CM247LC DS in Longitudinal Dir.

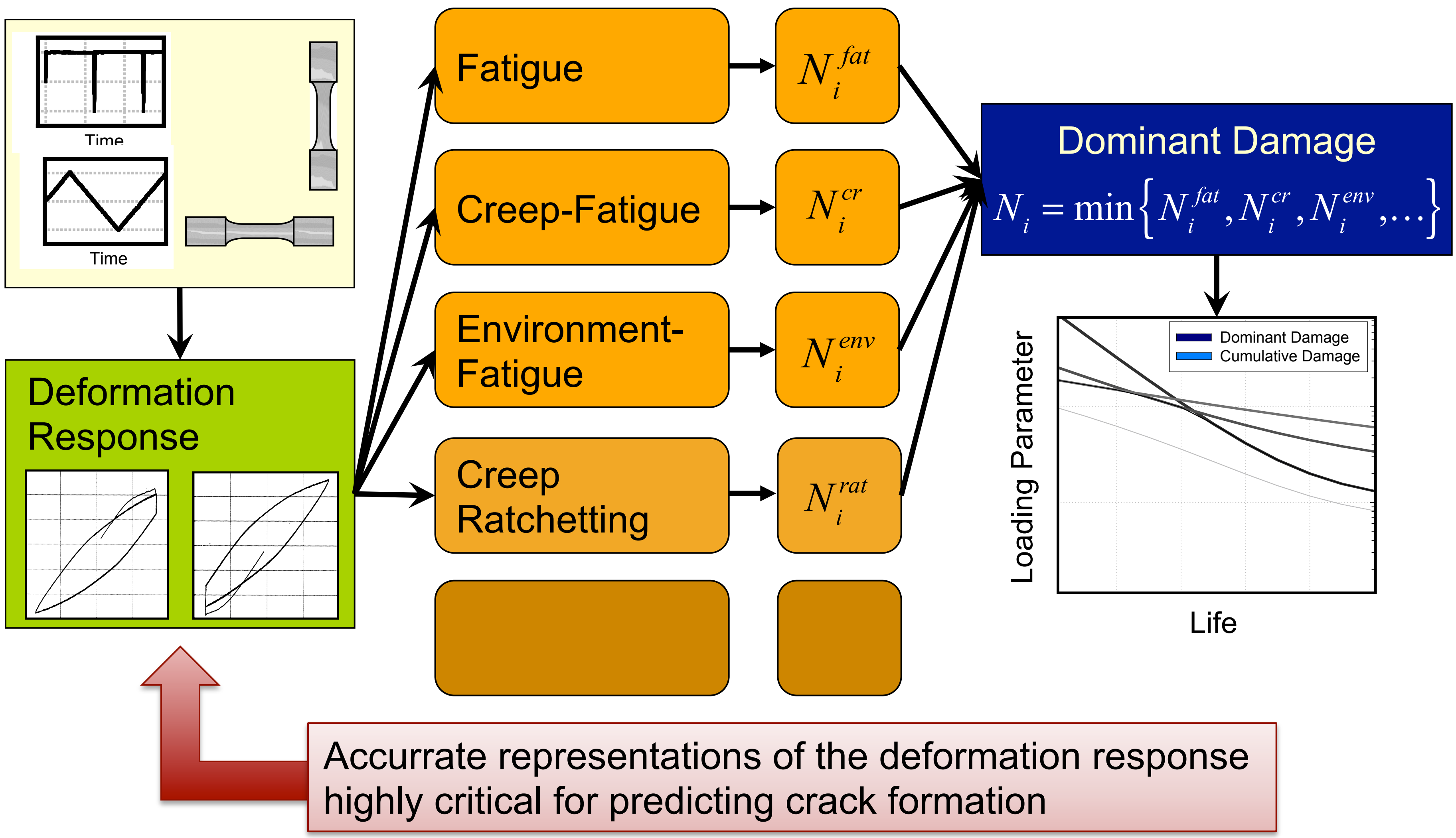


[Kirka, 2014]



Life Modeling Approach

Damage Mechanism Modules

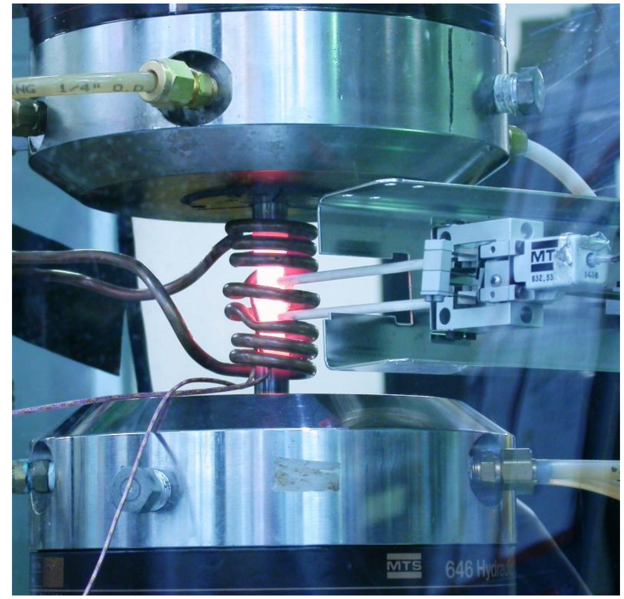


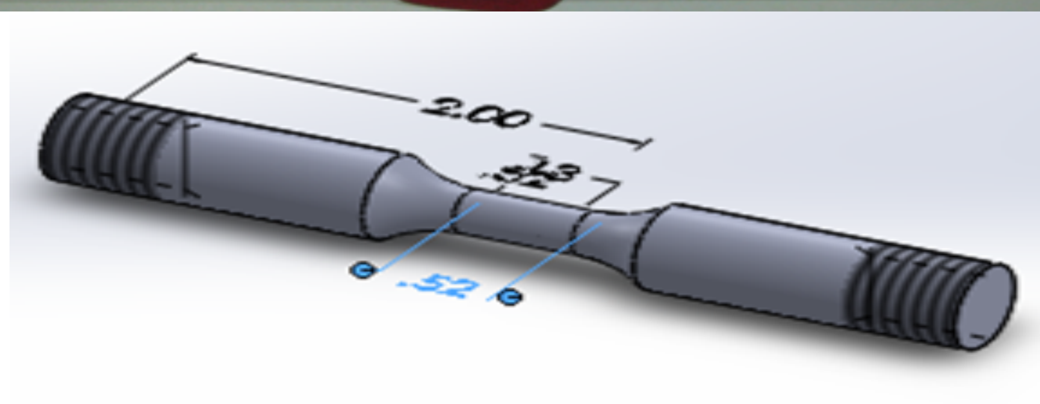
Primary Objectives of UTSR Project

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

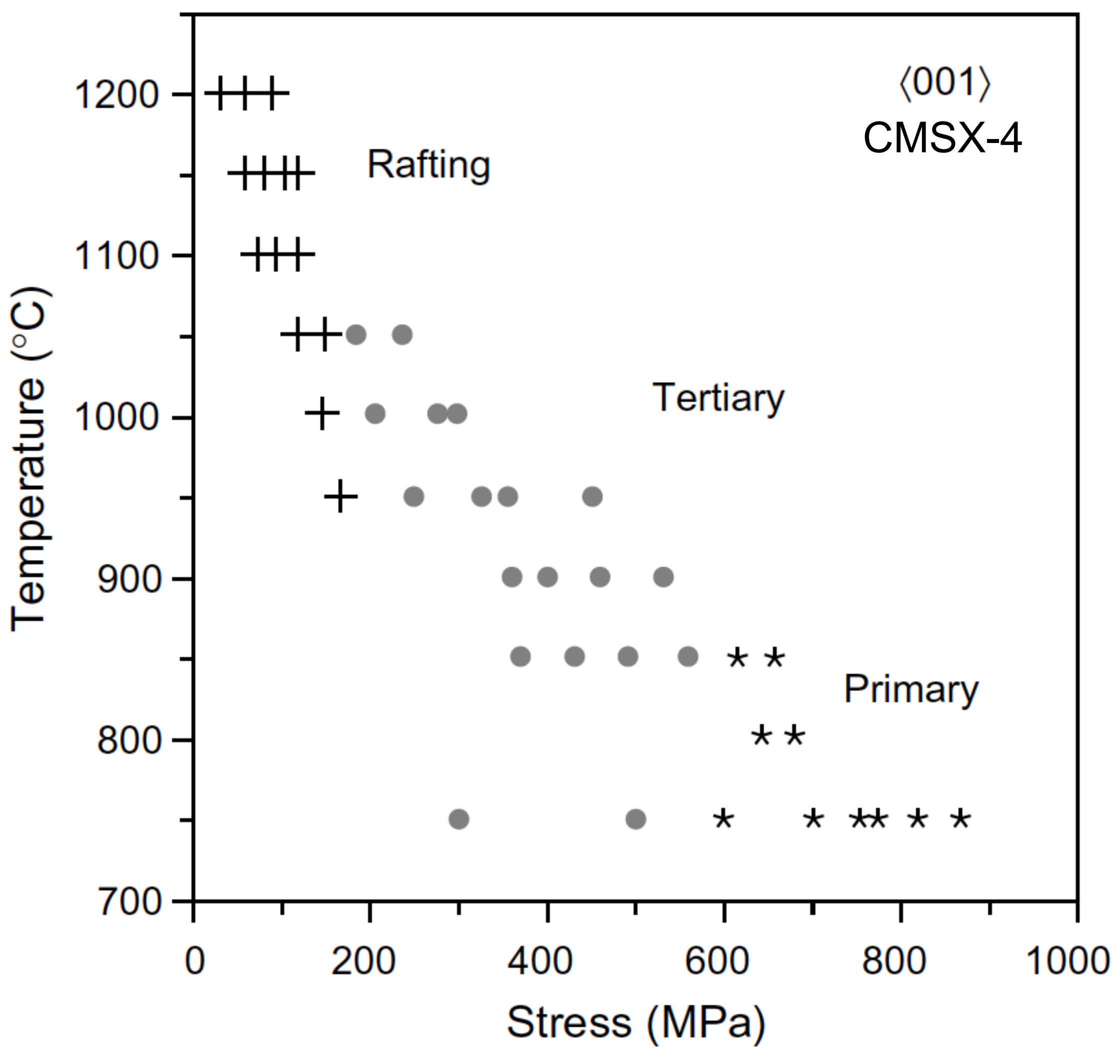
Creep-Fatigue Interaction Studies

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



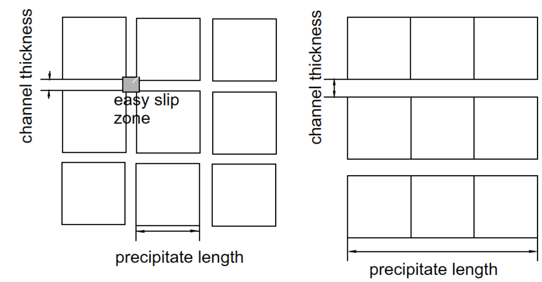


Influence of stress and temperature on modes of creep deformation

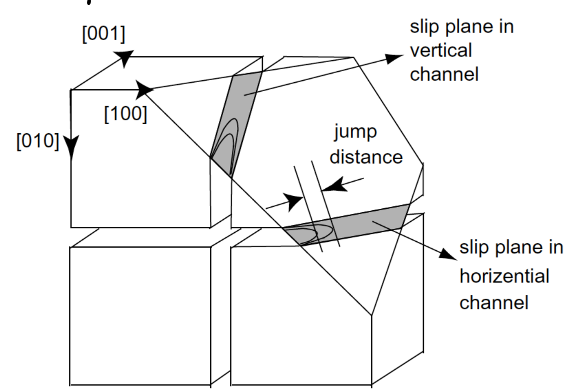


[Reed, 2006; Ma, Dye, and Reed, 2008]

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

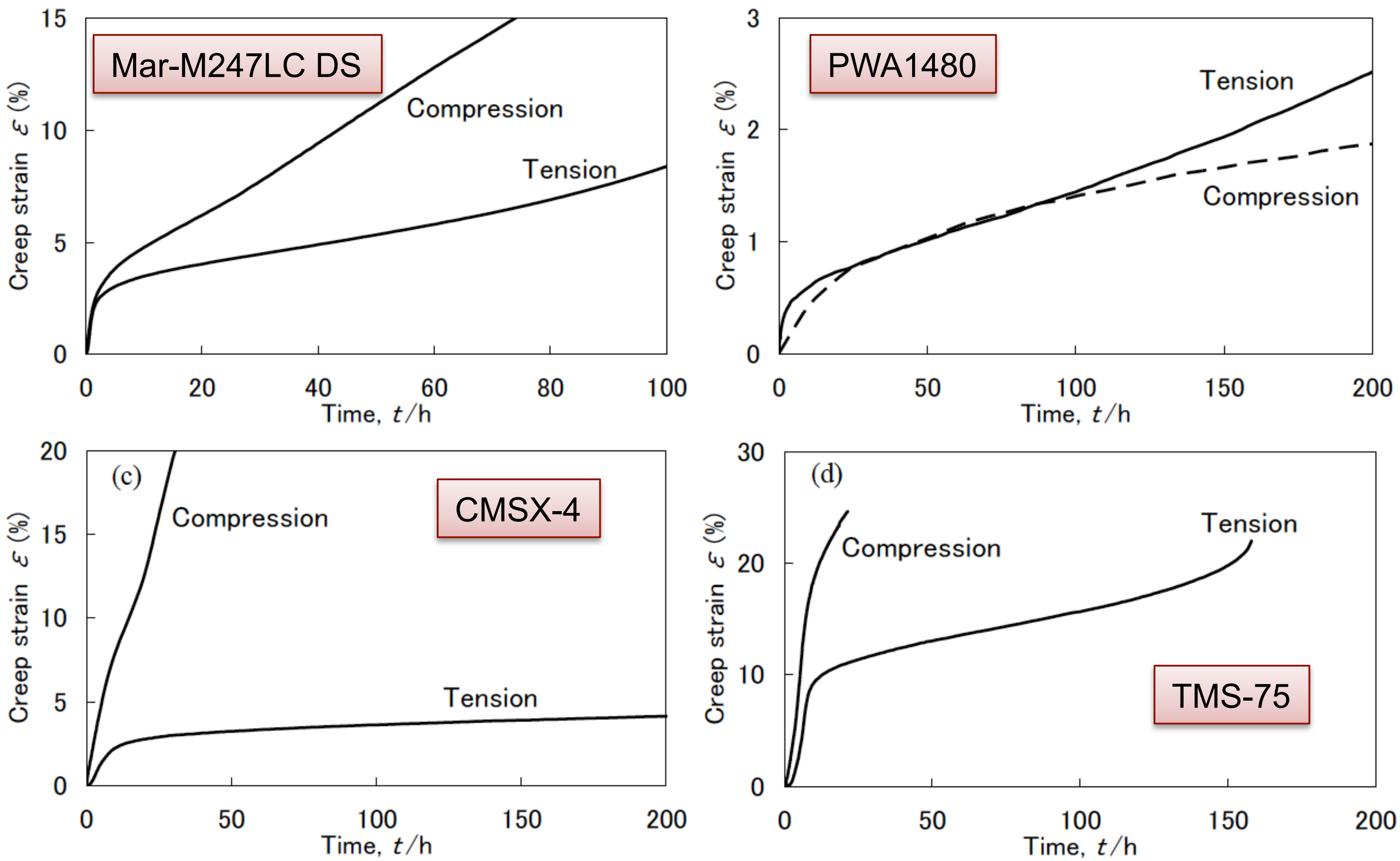


Tertiary – dislocation activity restricted to a/2<110> form operating on {111} slip planes in the γ channels



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

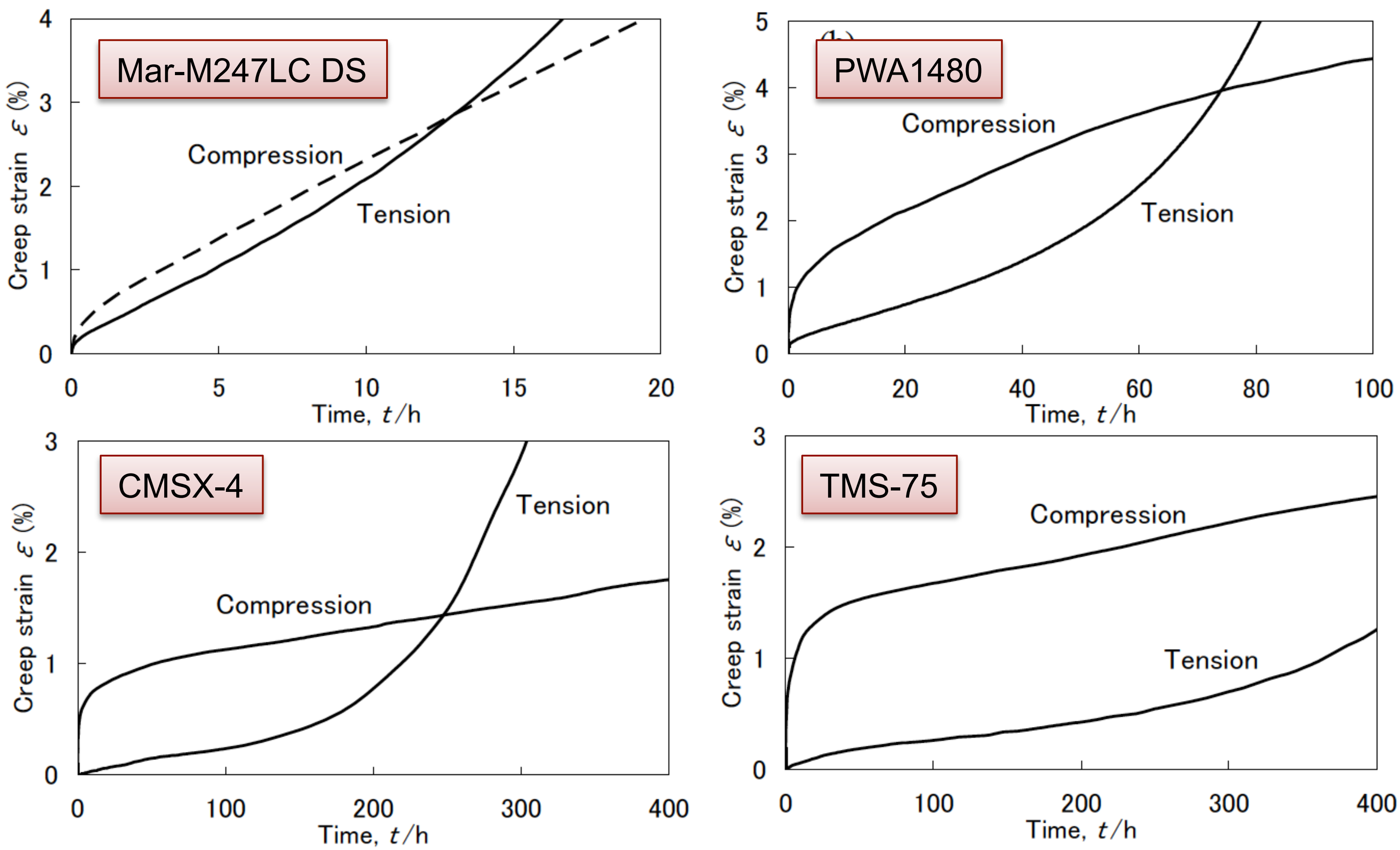
Asymmetry in Creep at 750°C/750 MPa



Note: Primary Creep Regime (based on tension)

[Tsuno et al., 2008]

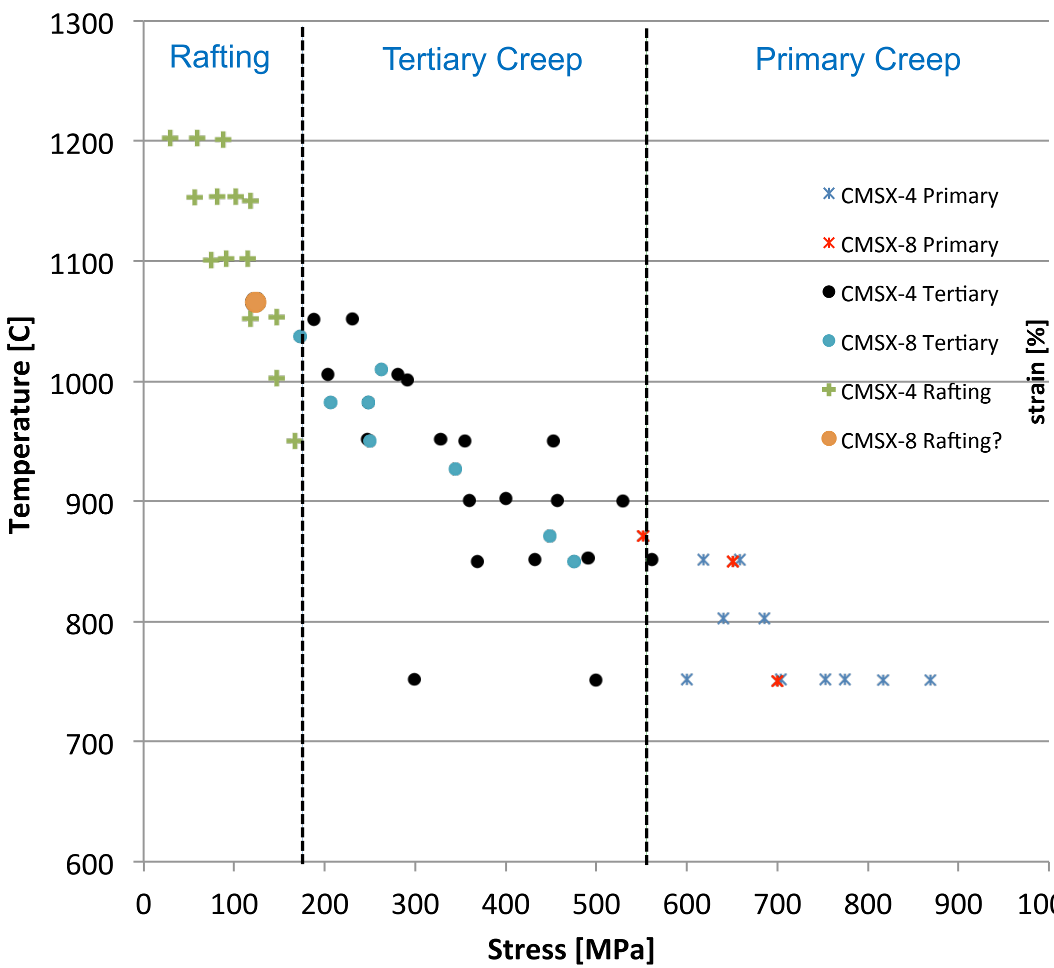
Asymmetry in Creep at 900°C/392 MPa

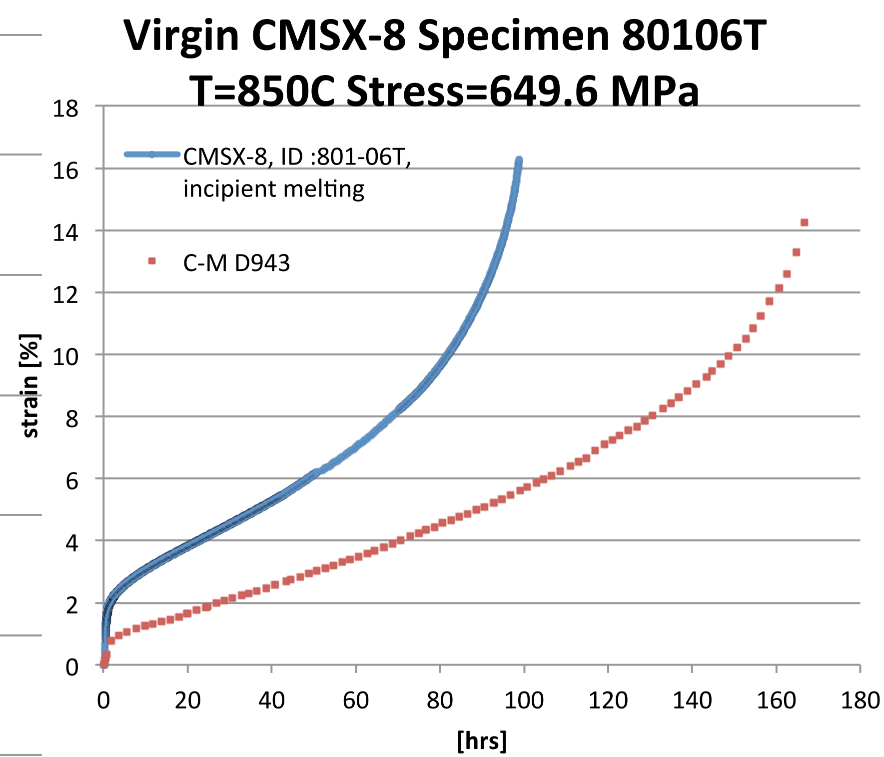


Note: Tertiary Creep Regime (based on tension)

[Tsuno et al., 2008]

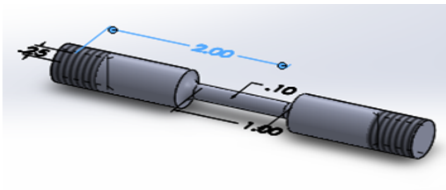
Creep of CMSX-8





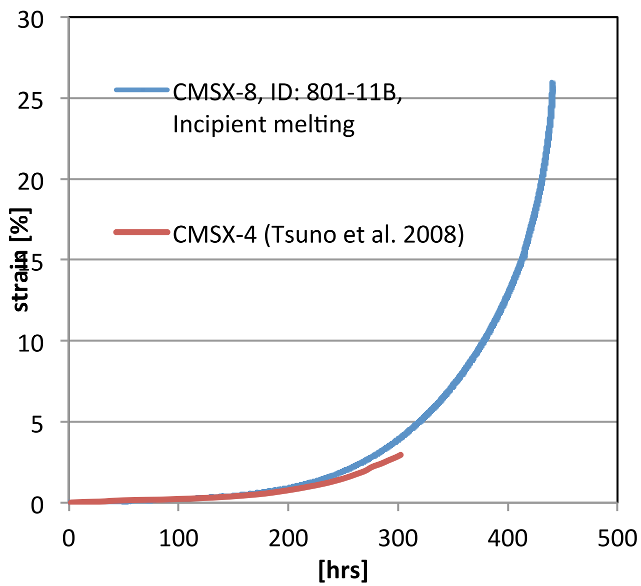
- LMP = 24.70
- Life to rupture = 98.90 hrs.
- Temp = 850 C
- Stress = 650 MPa
- Alpha = 4.1

Creep of CMSX-8 – Tertiary Creep Regime



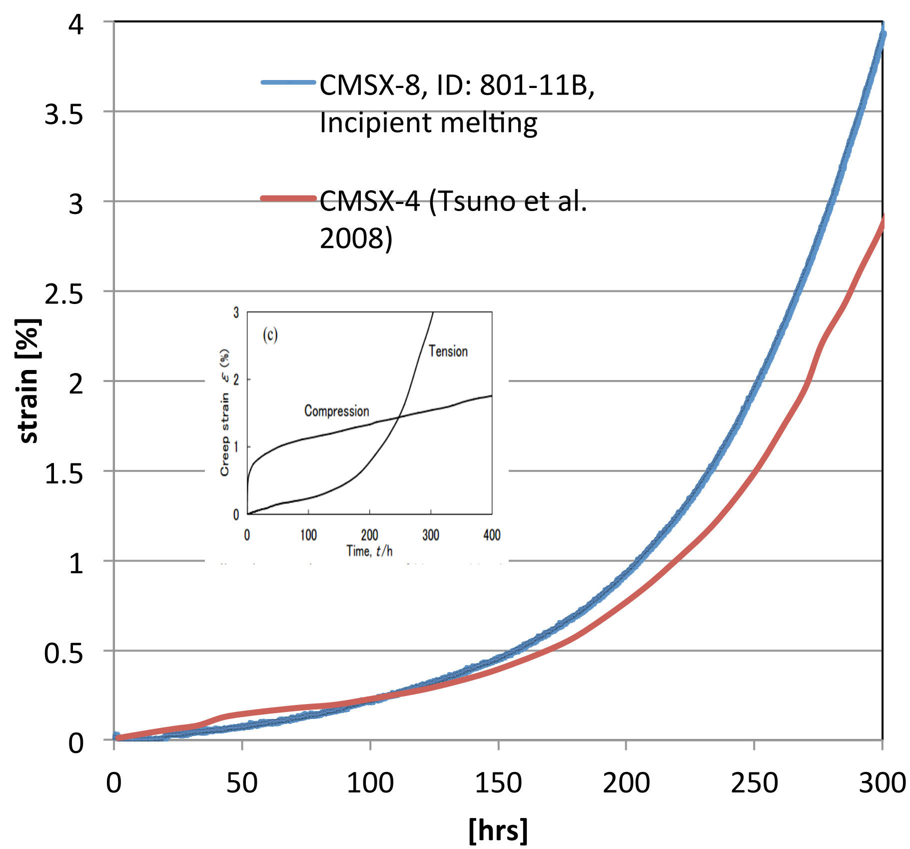
801-11B

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



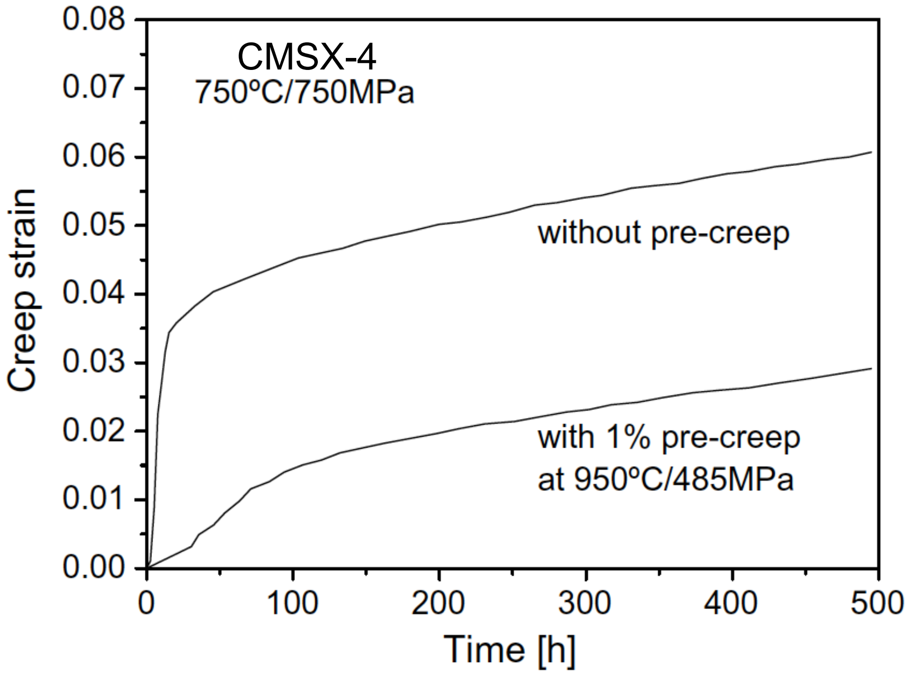
Zoom-in

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

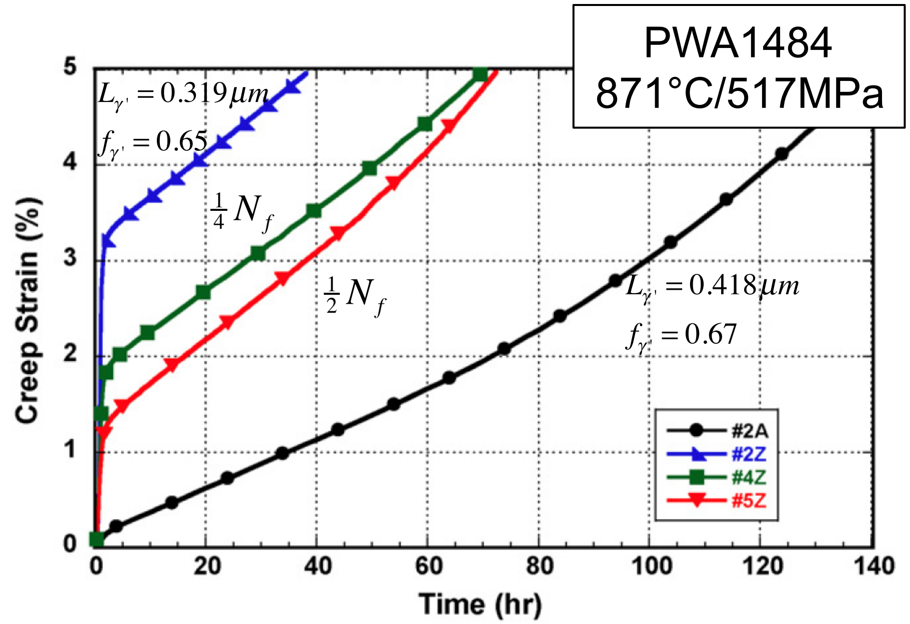


- LMP=26.57
- Life to rupture = 451.78 hrs.
- Temp = 900 C
- Stress = 392 MPa
- Alpha = 5.8

Influence of prior creep & fatigue on creep



[Ma, Dye, and Reed, 2008]



[Pierce, Palazotto, & Rosenberger, 2010]

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

[Wilson & Fuchs, Superalloys 2008]

Microstructure Evolution in Blades

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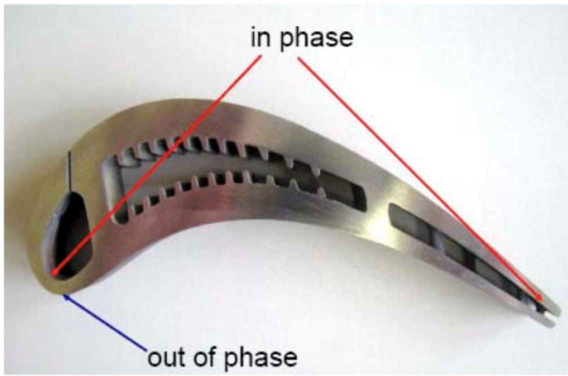
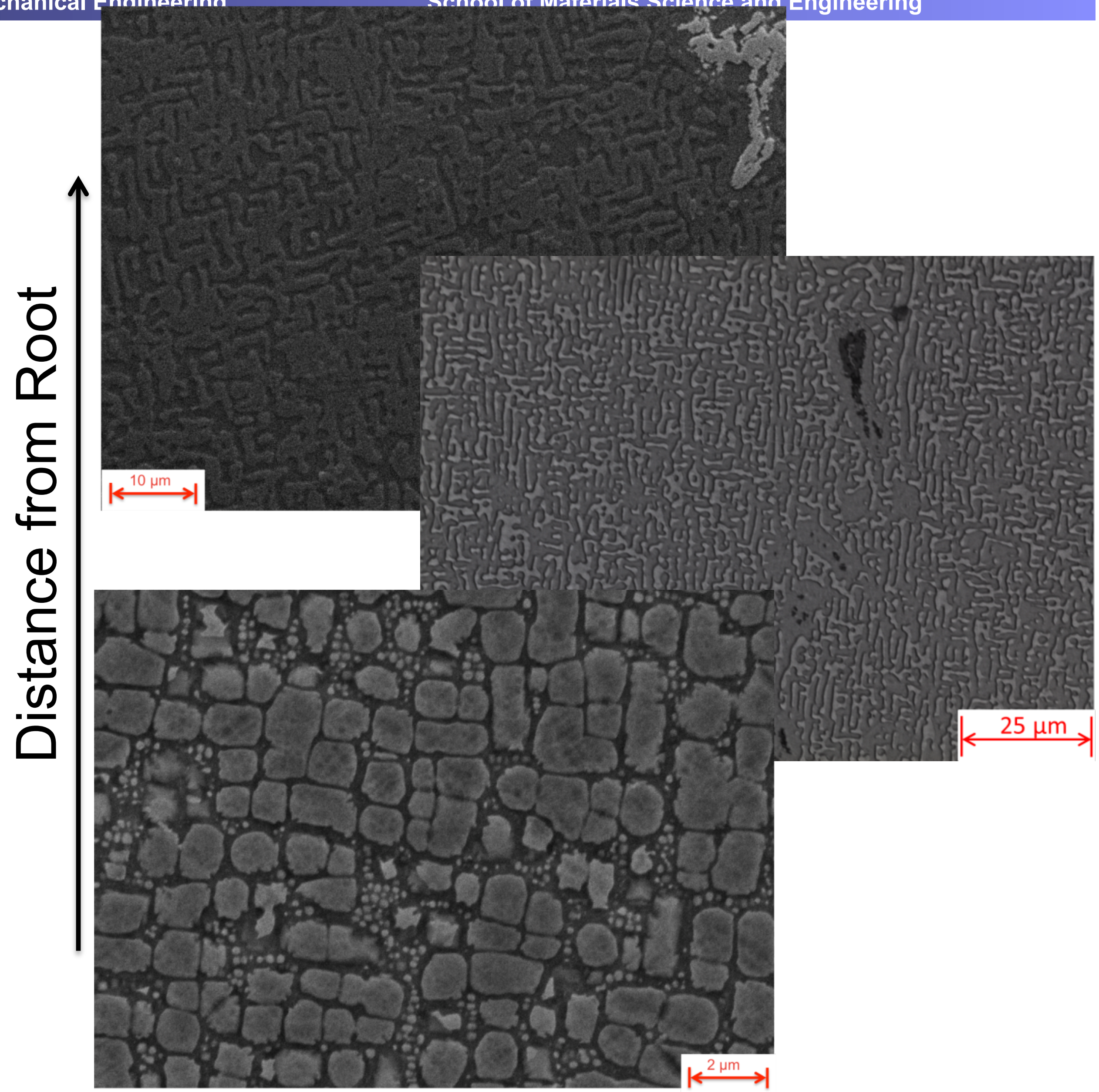
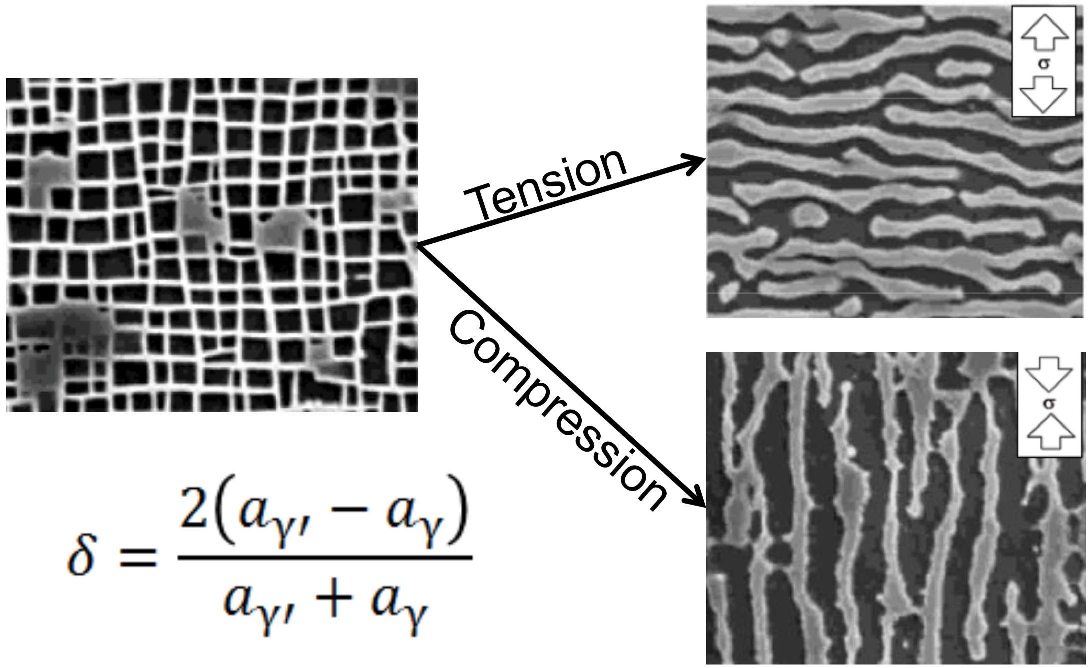




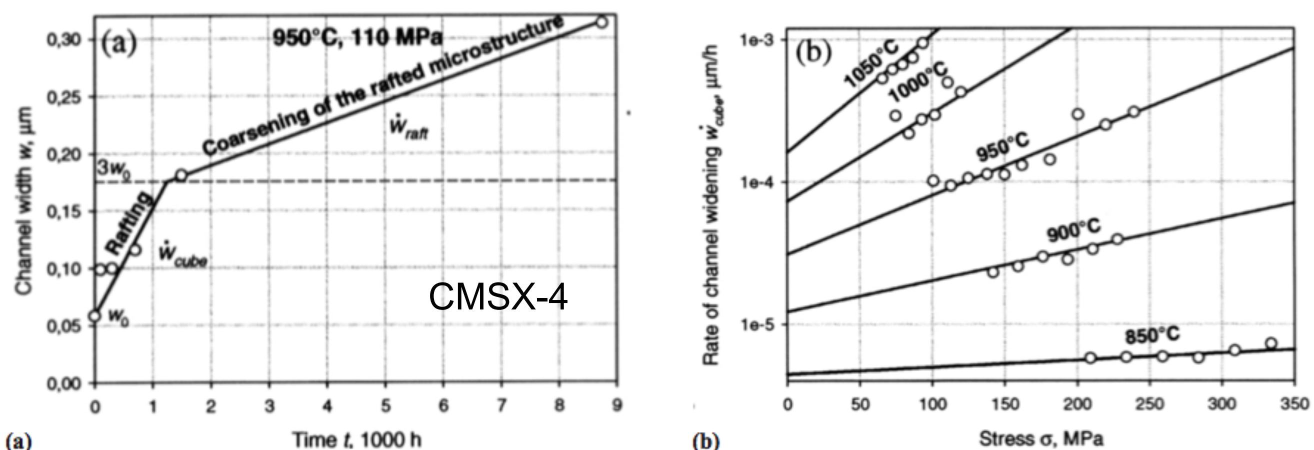
Rafting and Coarsening of γ'



N-raft

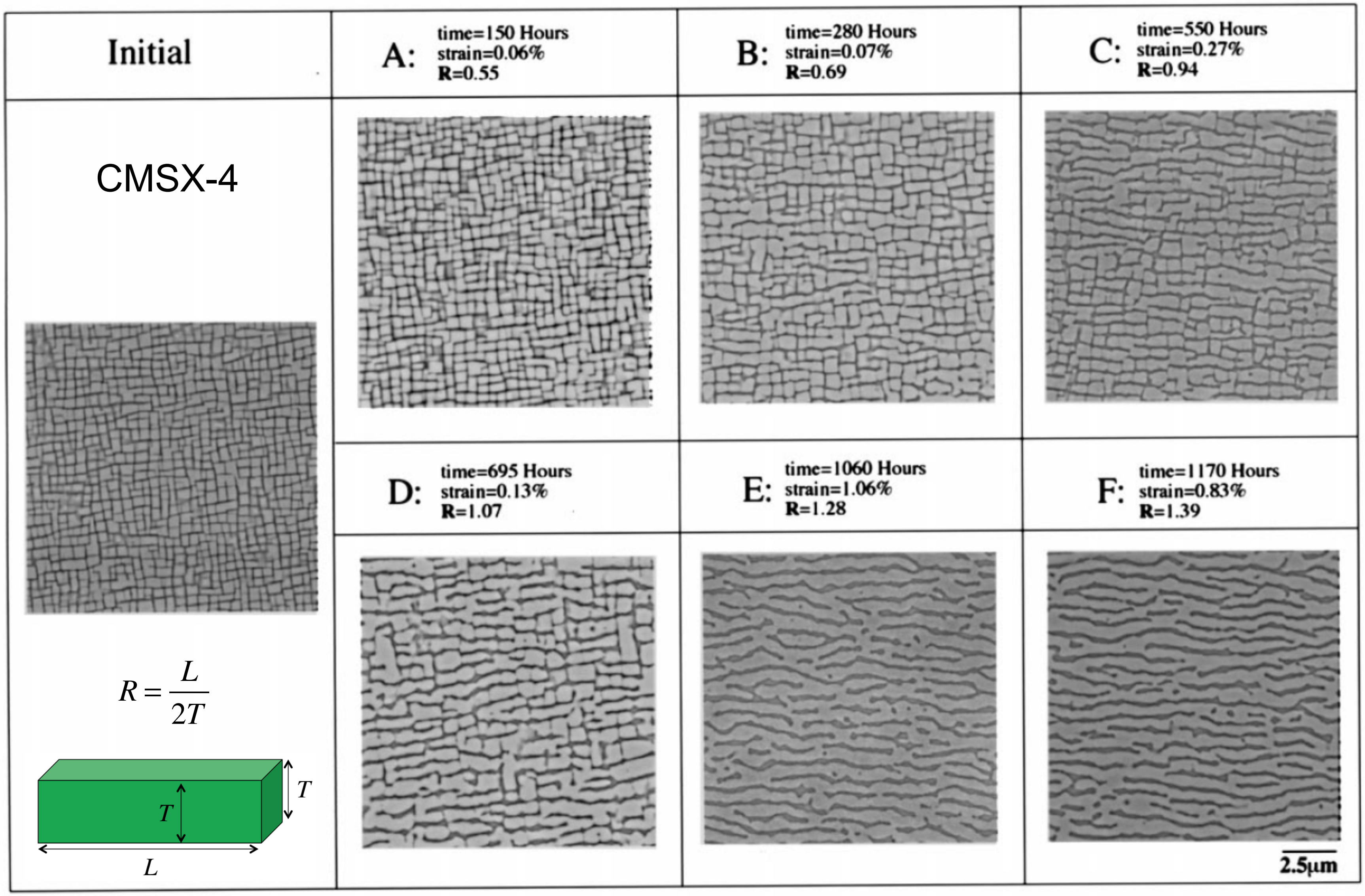
P-raft

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



[Epishin et al., 2010]

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

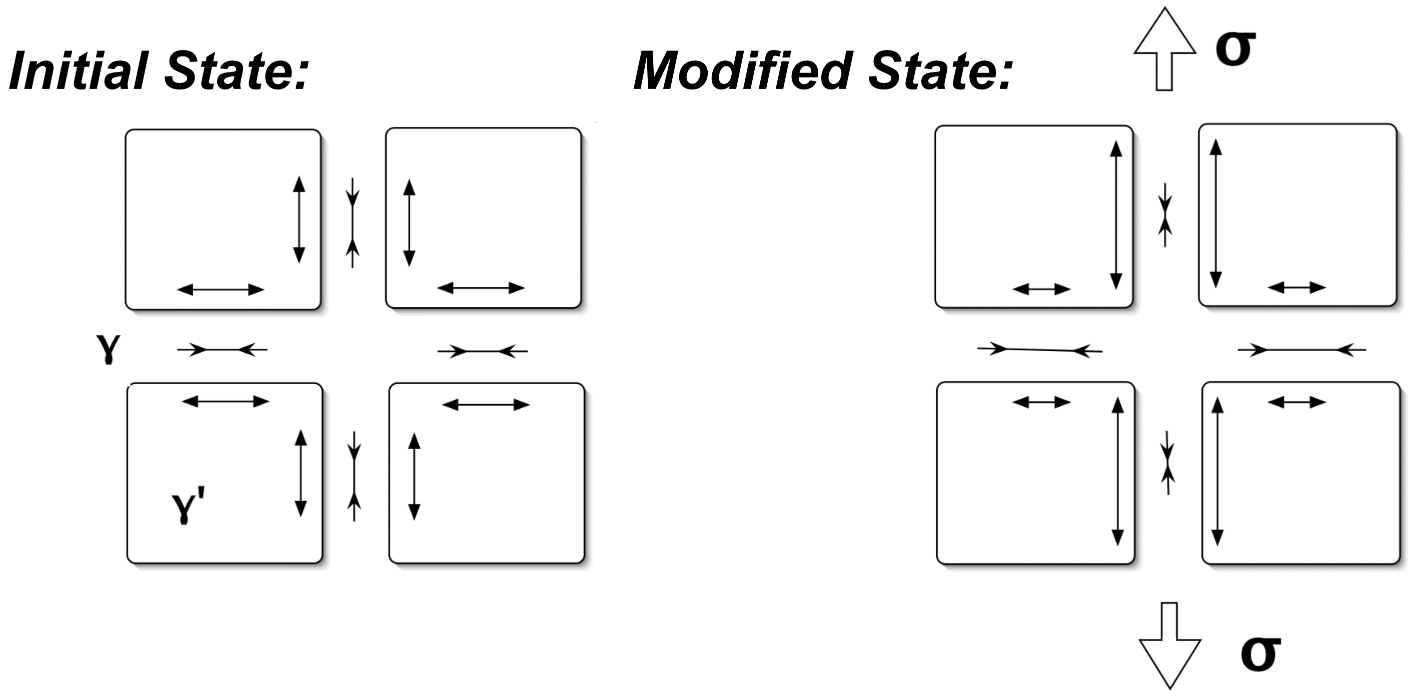


[Matan, Cox, Rae, & Reed, 1999]

Rafting in the "elastic" regime

For negative mismatch alloys

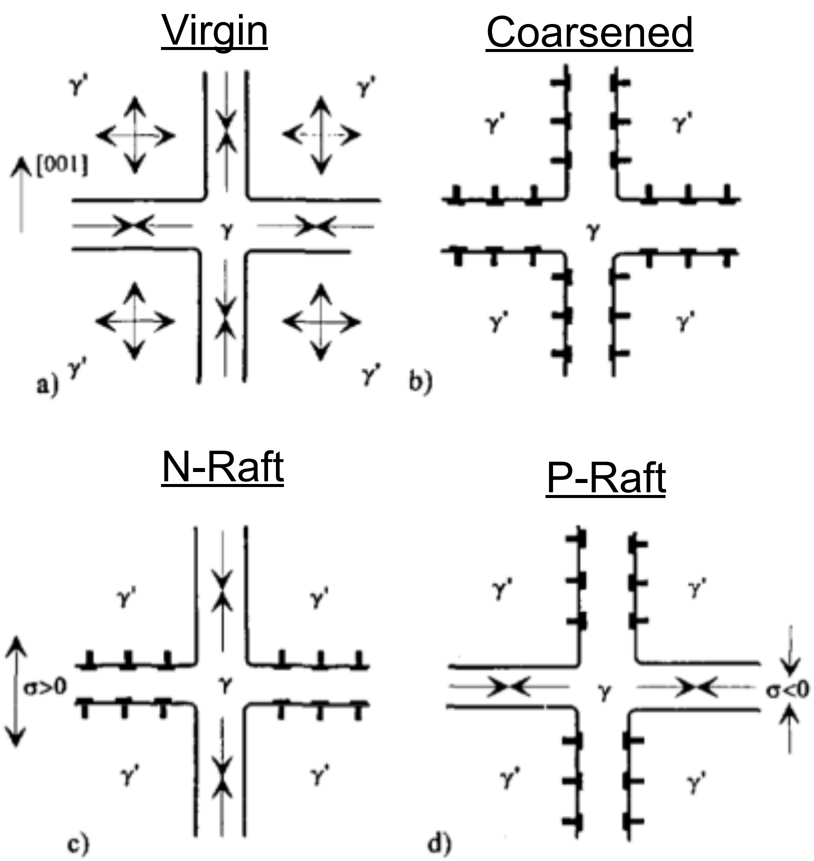
$$\delta = \frac{2\left(a_{\gamma'} - a_{\gamma}\right)}{a_{\gamma'} + a_{\gamma}}$$



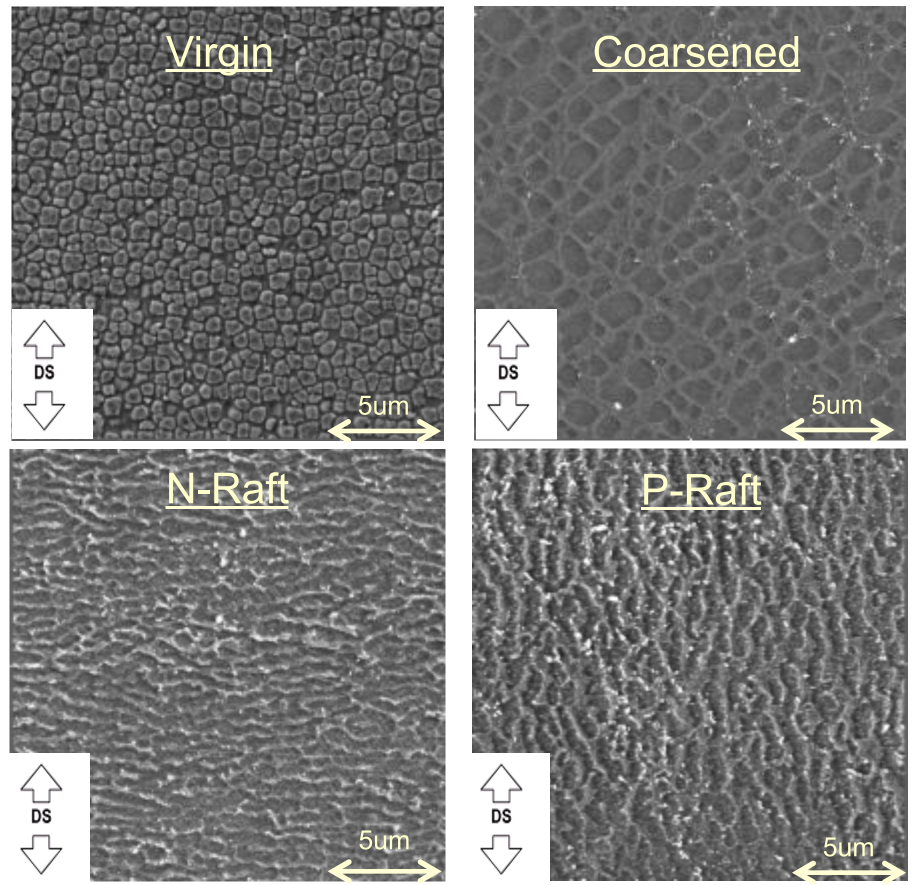
superposition of applied and misfit stresses drive deformation in horizontal channels promoting N-raft formation

- Controlled by difference between the elastic strain energy in the horizontal and vertical γ channels
- Material transport driven by gradient in elastic strain energy density ("elastic" regime when plastic strain < 0.1%)

Rafting in the “plastic” regime



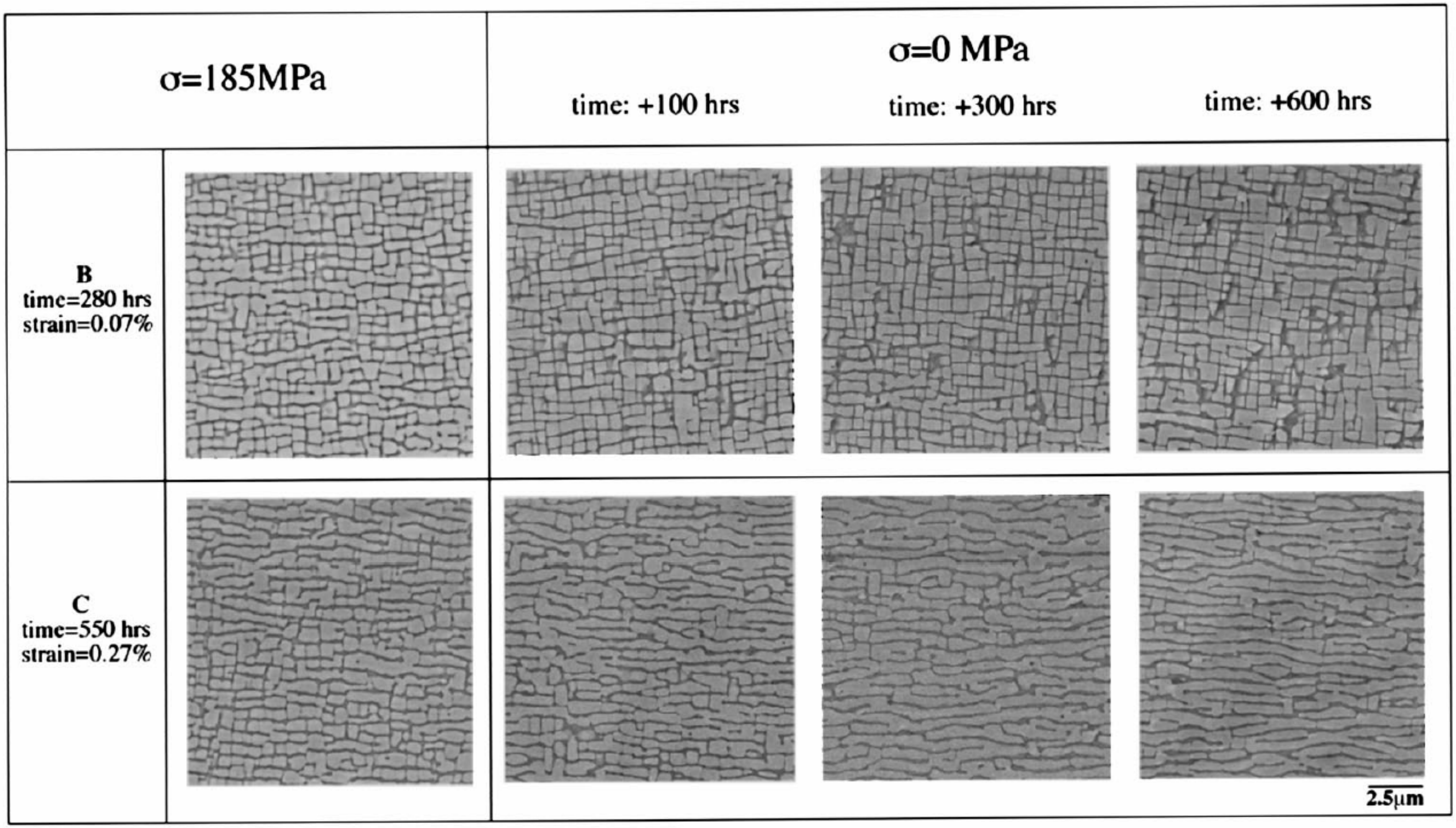
[Mughrabi et al., 1997]



- Dislocations in the horizontal channels (tensile creep case) and their adsorption at the γ/γ' interfaces, resulting in loss of perfect coherency and reduction in elastic misfit strains, is responsible for providing the kinetic path to enable rafting to occur at a reasonable rate.
- Rate in this regime is largely independent of whether the applied stress remains acting or not.

Influence of aging without applied stress

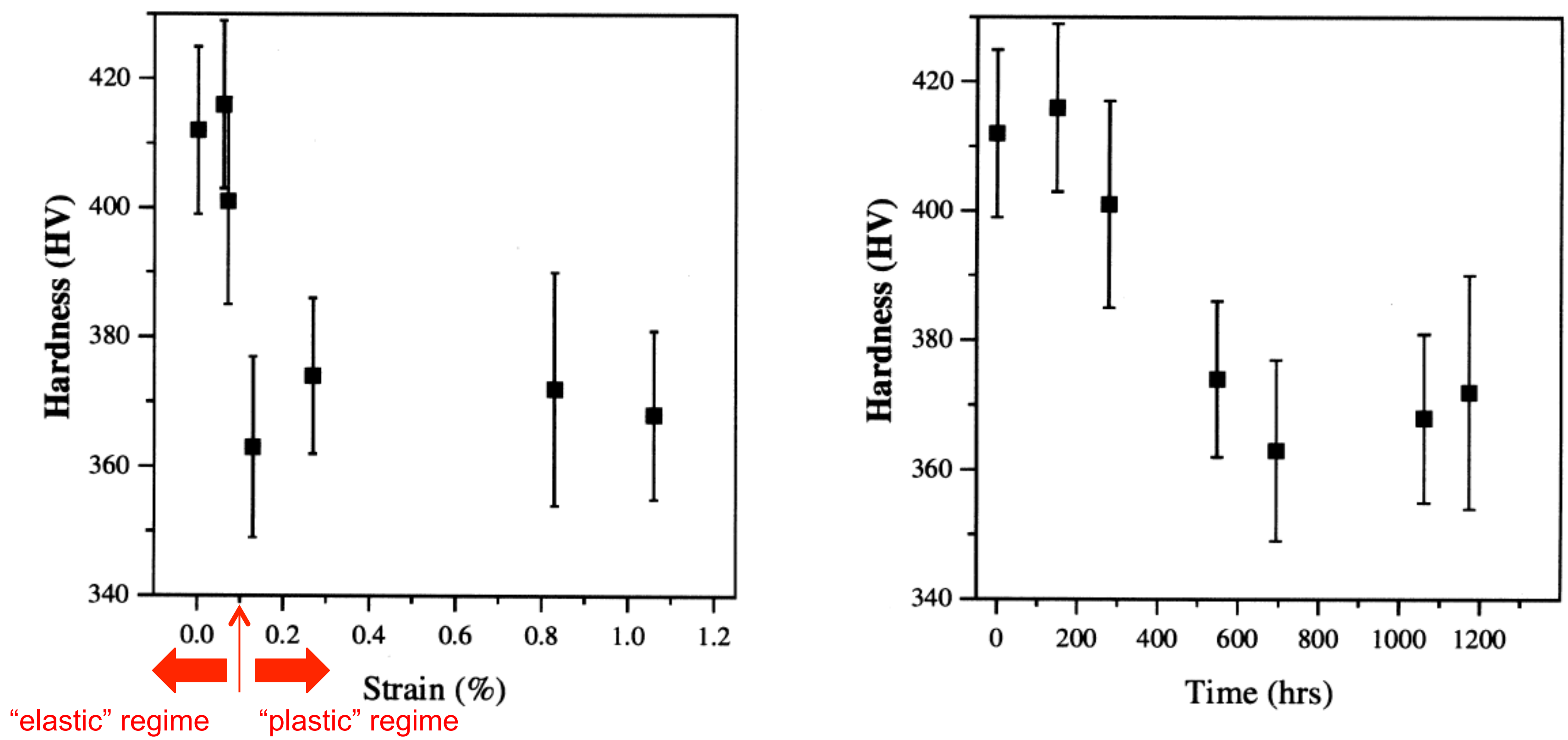
CMSX-4



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

Influence of aging on hardness

CMSX-4
950°C/185MPa

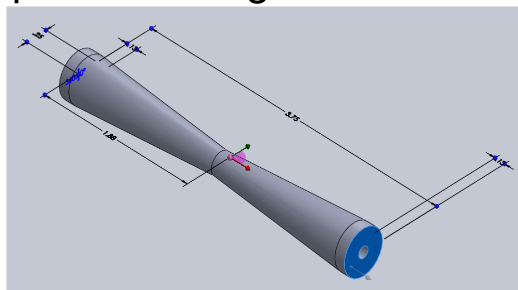


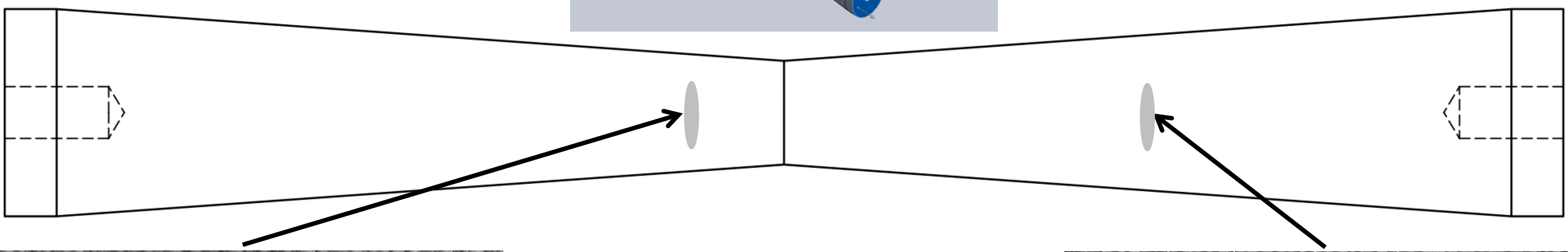
Note: The significant drop in hardness at 0.1% creep strain, representing the threshold strain, is attributed to the loss of coherency of the γ/γ' interfaces because of misfit dislocations present on these interfaces; hence termed "plastic" regime.

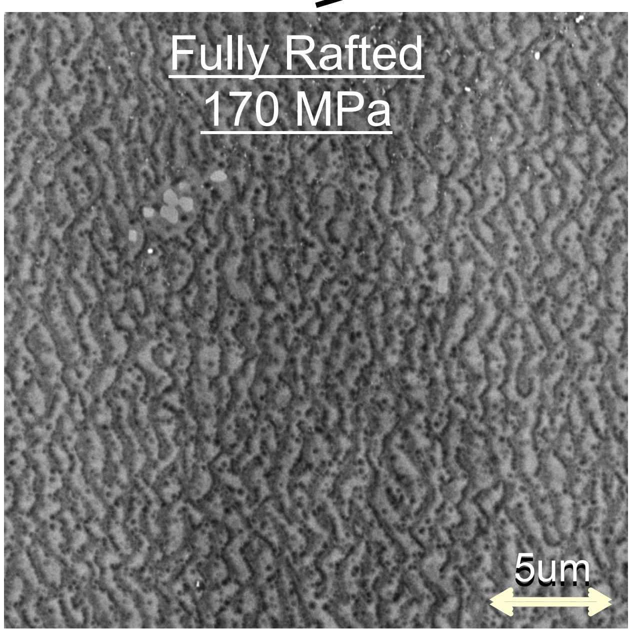
[Matan, Cox, Rae, & Reed, 1999]

Aging Studies under Stress

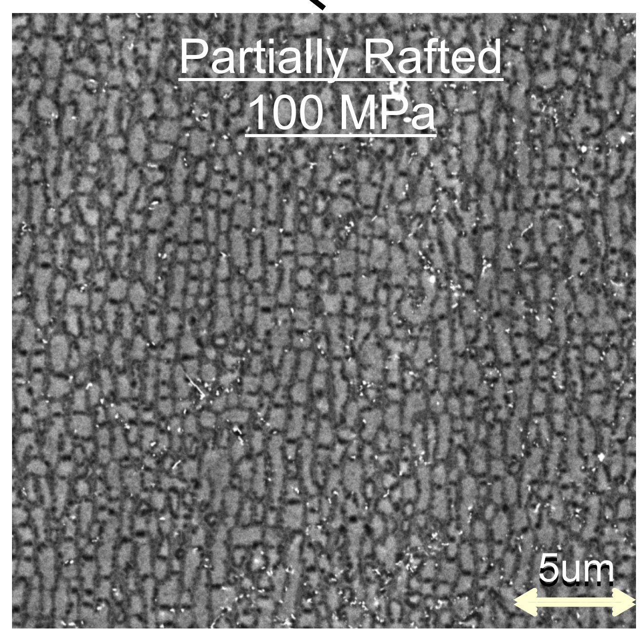
Objective: Obtain kinetic data to predict rafting and coarsening as a function of temperature, stress, microstructure and time







Test conditions
CM247LC-DS
Temperature: 950°C
Force: 1260kN
Time: 500 hrs



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Artificial Aged Microstructure Generation

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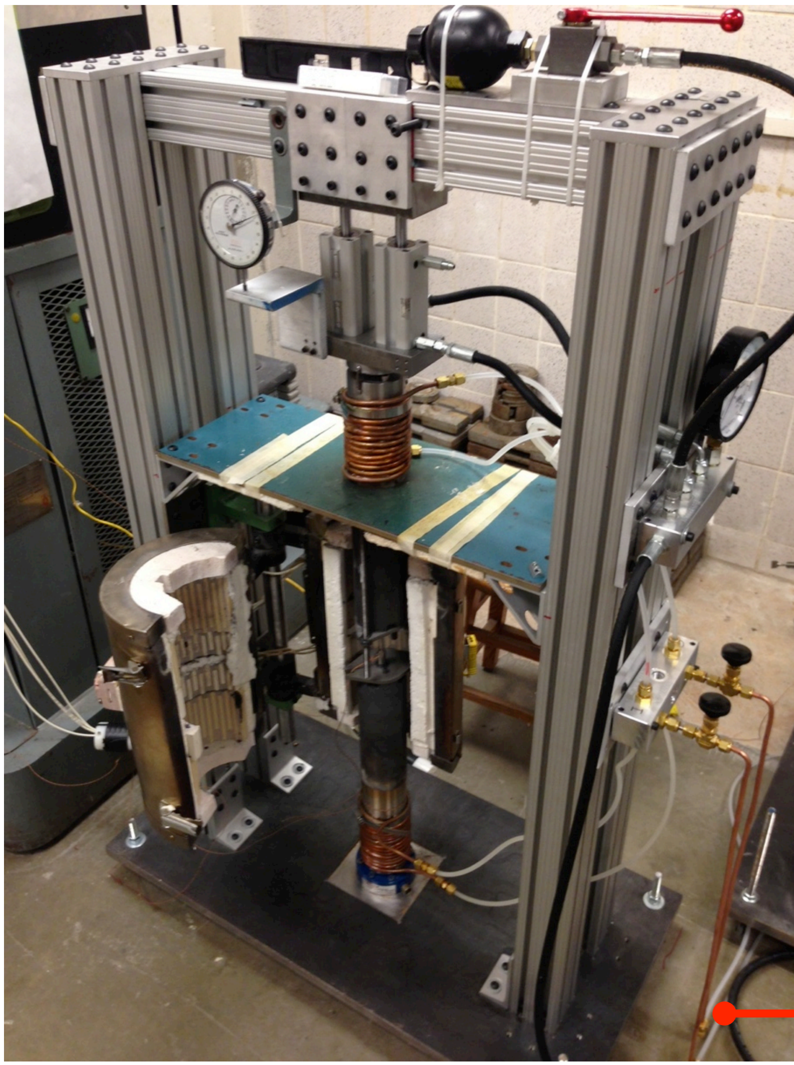
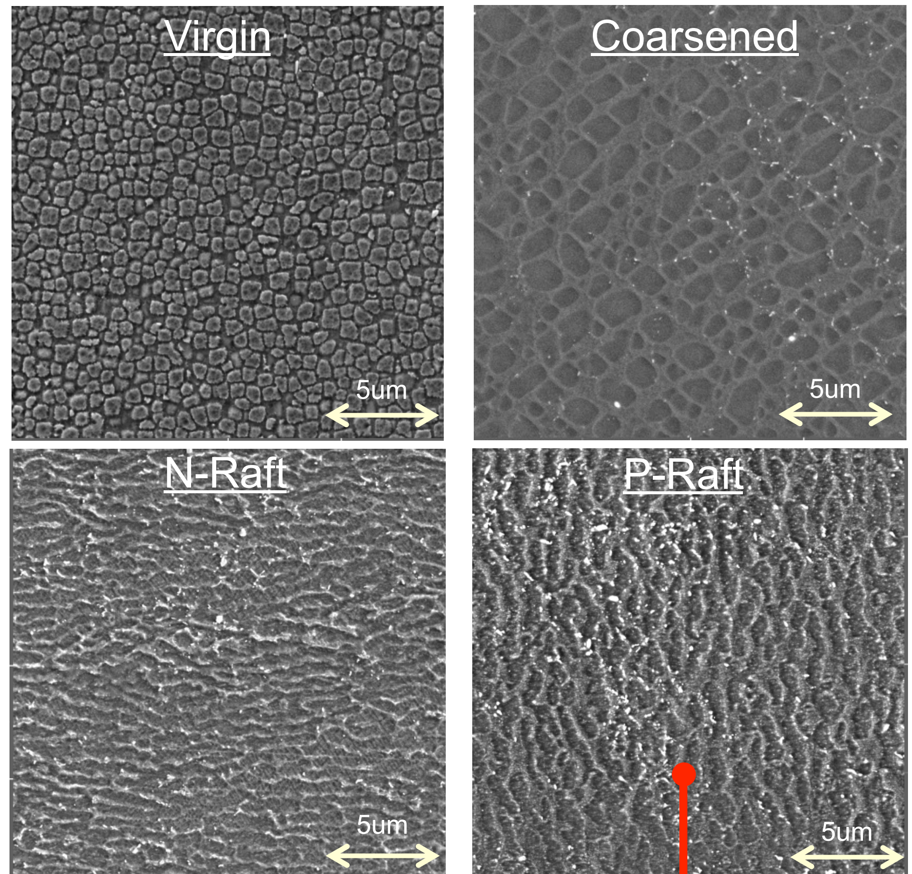
Compression Creep Frame



Four Different Microstructures



MICROSTRUCTURE-SENSITIVE CRYSTAL VISCOPLASTICITY MODELS

Length Scales in Ni-base Superalloys

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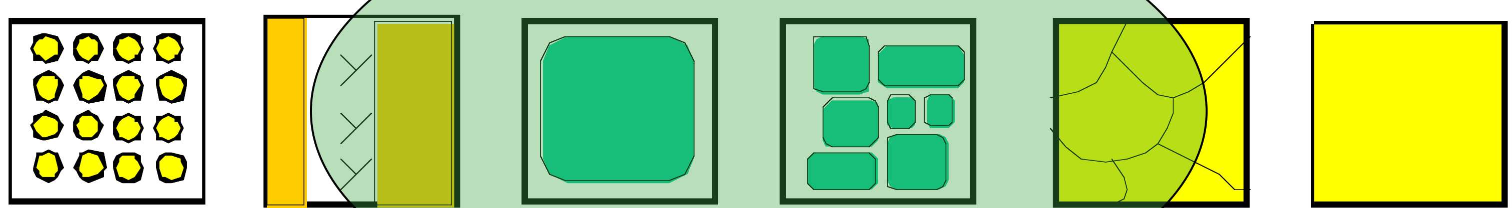
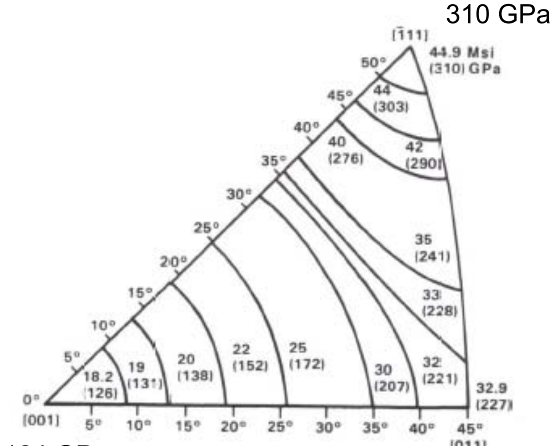
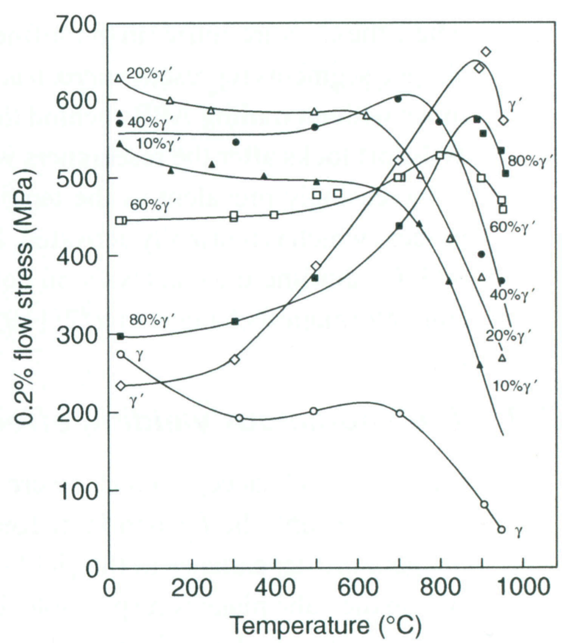
Atomic (Interfaces, Cores, Partials)	Channel Dislocations	Precipitates	Collections of Precipitates; GB cracks	Shear bands Grains	
$O(10^{-10}$ m)	$O(10^{-8}$ m)	$O(10^{-7}$ m)	$O(10^{-6}$ m)	$O(10^{-5}$ m)	

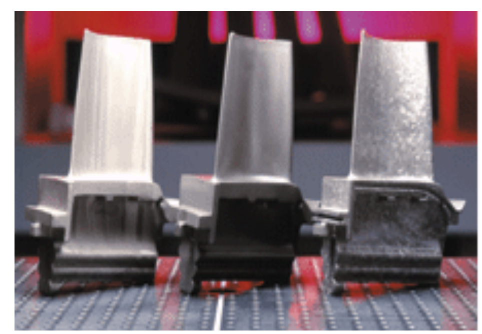


[Shenoy, Tjipowidjojo, and McDowell, 2008]





[Reed, 2008]



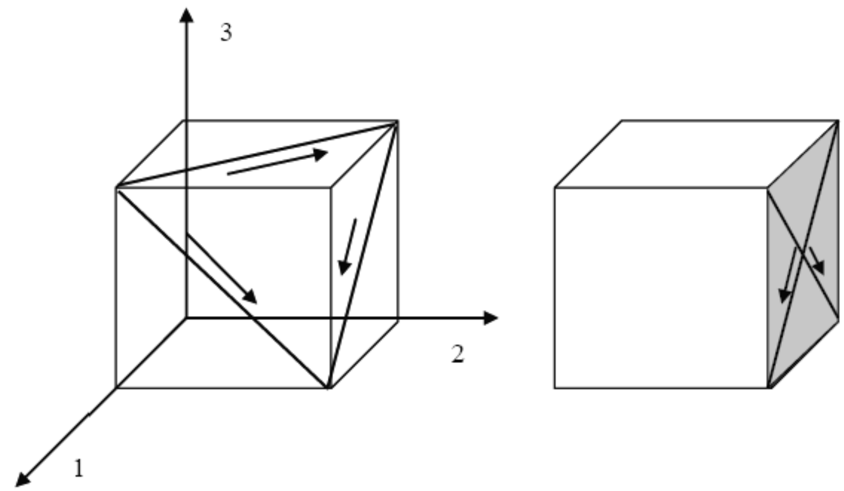
components

Slip systems

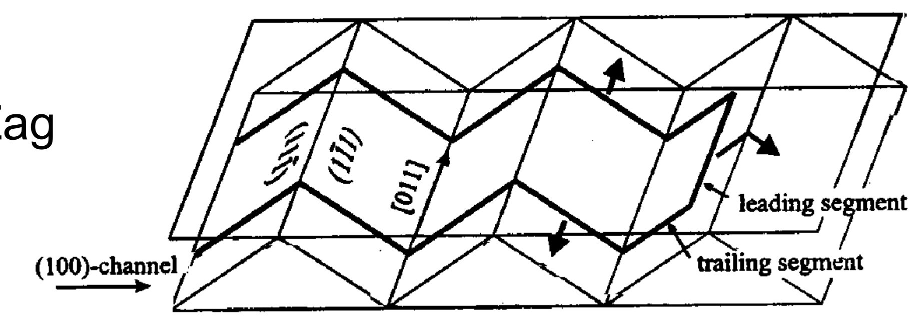
<u>Slip Systems</u>

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

- Cube slip systems
  - ➢ Active at higher temperatures
  - ➢ [111] loading orientation
  - ➢ Less T/C asymmetry
  - ➢ Macroscopic manifestation of "Zig-Zag mechanism," [Bettge and Osterle, 1999]



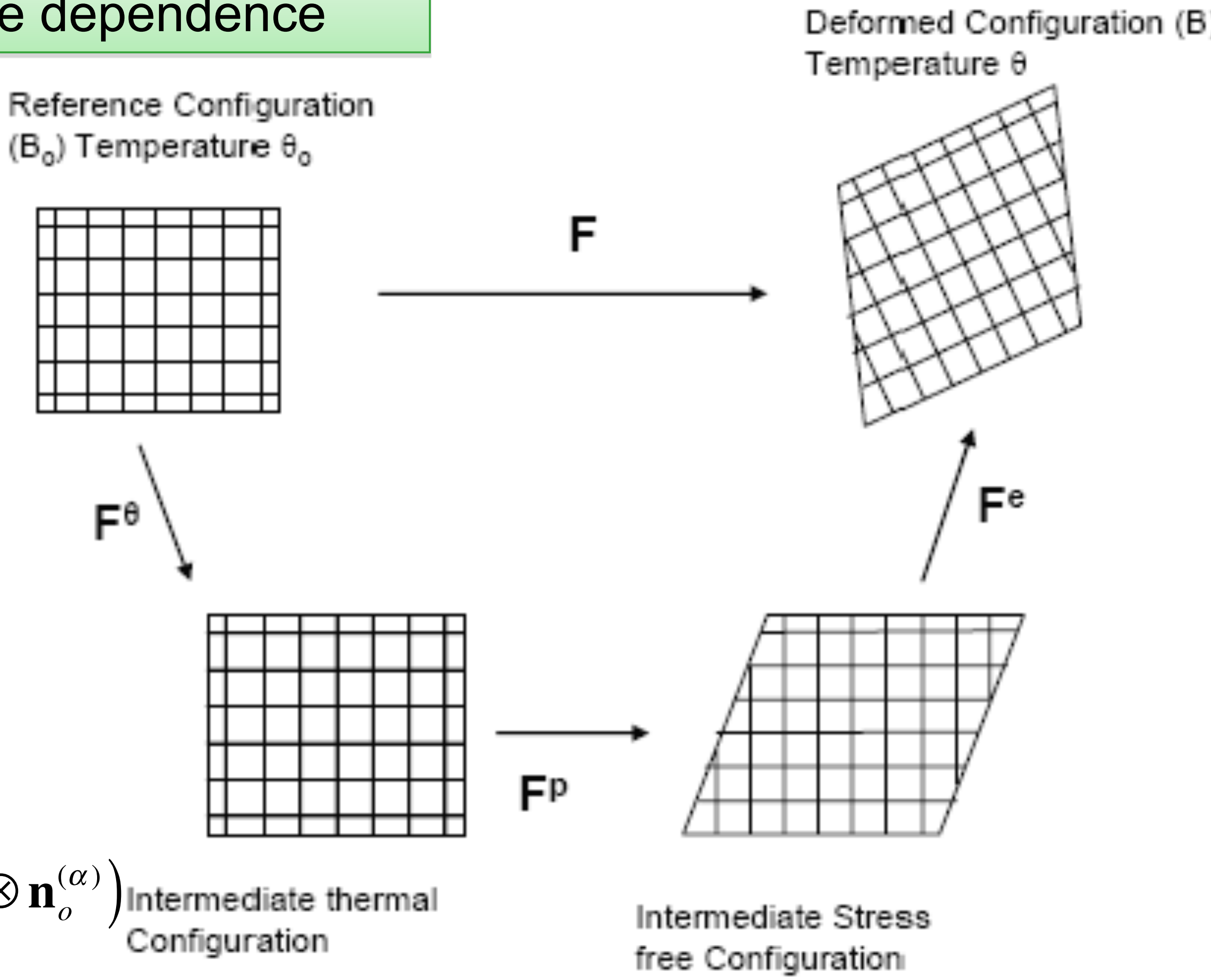
Octahedral slip system Cube slip system



Cube slip [Bettge and Osterle, 1999]

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

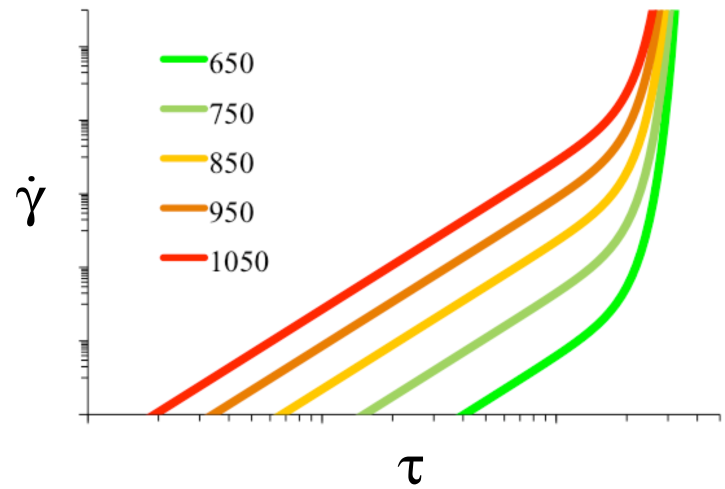
$$\mathbf{L} = \dot{\mathbf{F}} \cdot \mathbf{F}^{-1}$$

Macroscopic plastic velocity gradient

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

Crystal viscoplasticity (CVP) – rate eqn

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



Inelastic Shear Strain Rate

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

where

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

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

[Shenoy et al., 2005]

CVP Models for Ni-base Superalloys

Shenoy, Gordon, McDowell, & Neu (2005)

Creep-fatigue and TMF (temperature-dependent)

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

Shenoy, Tjiptowidjojo, & McDowell (2008)

Creep-fatigue using dislocation-based ISV

$$\dot{\gamma}^{in(\alpha)} = \left[\dot{\gamma}_o \left\langle \frac{\left|\tau^{(\alpha)} - \chi^{(\alpha)}\right| - \kappa^{(\alpha)}}{D^{(\alpha)}} \right\rangle^{n_1} + \dot{\gamma}_1 \left\langle \frac{\left|\tau^{(\alpha)} - \chi^{(\alpha)}\right|}{D^{(\alpha)}} \right\rangle^{n_2} \right] \mathrm{sgn}\left(\tau^{(\alpha)} - \chi^{(\alpha)}\right)$$

MacLachlan, Wright, Gunturi, & Knowles (2001)

Limited to CMSX-4 at 950°C in tertiary regime (stress ≤ 450 MPa) – coupled CVP with damage mechanics

Ma, Dye, & Reed (2008)

Dislocation-based ISV considering primary and tertiary creep regimes (limited to creep of CMSX-4 at 950°C)

$$\dot{\gamma}_{\gamma}^{in(\alpha)} = \rho_{\gamma}^{(\alpha)} b \lambda_{\gamma}^{(\alpha)} F_{attack} \exp\left\{ \frac{-Q_{slip}^{110} + \left(\left|\tau^{(\alpha)} + \tau_{mis}^{(\alpha)}\right| - \tau_{\gamma pass}^{(\alpha)} - \tau_{oro}^{(\alpha)} \right) V_{c1}^{(\alpha)}}{kT} \right\} sign\left(\tau^{(\alpha)} + \tau_{mis}^{(\alpha)}\right)$$

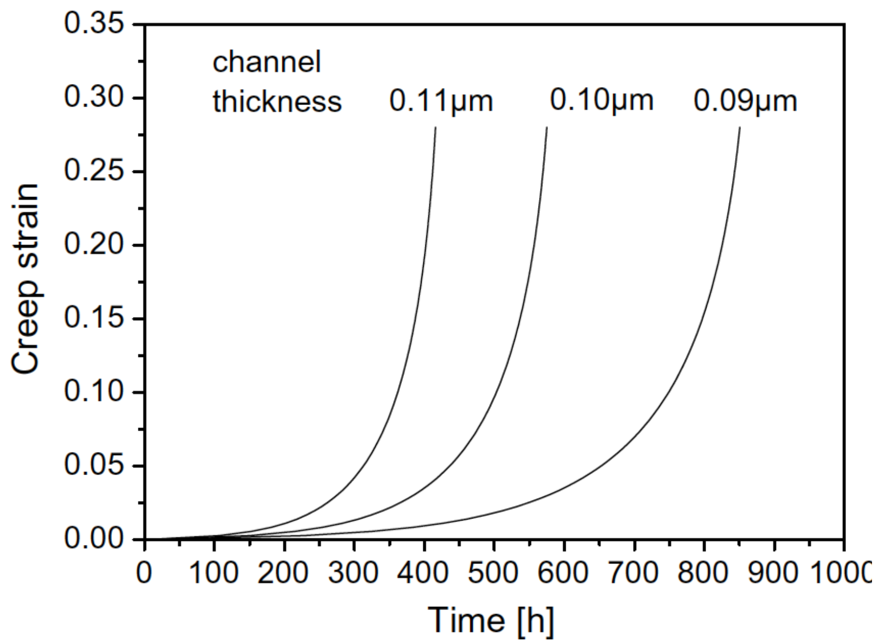
$$\dot{\gamma}_{L1_2}^{in(\alpha)} = \rho_{P}^{(\alpha)} b \lambda_{L1_2}^{(\alpha)} F_{attack} \exp\left\{ \frac{-Q_{slip}^{112} + \left(\left|\tau^{(\alpha)}\right| - \tau_{L1_2\, pass}^{(\alpha)} \right) V_{c2}^{(\alpha)}}{kT} \right\} sign\left(\tau^{(\alpha)}\right)$$

Kirka & Neu (2014)

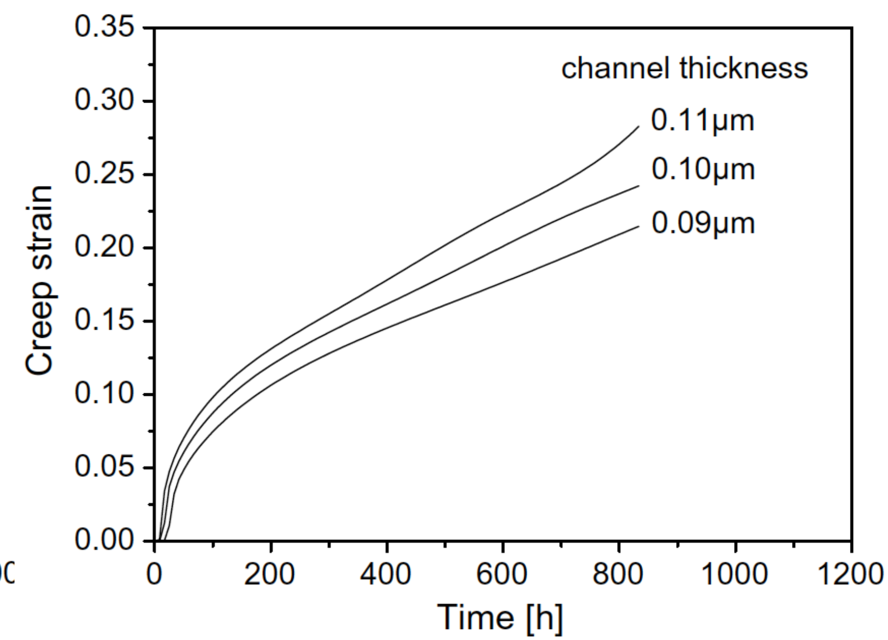
Added state variables to account for state of aged microstructure in temperature-dependent formulation

Ma et al. model predictions showing microstructure sensitivity

Tertiary creep
950°C/400MPa



Primary creep
750°C/770MPa



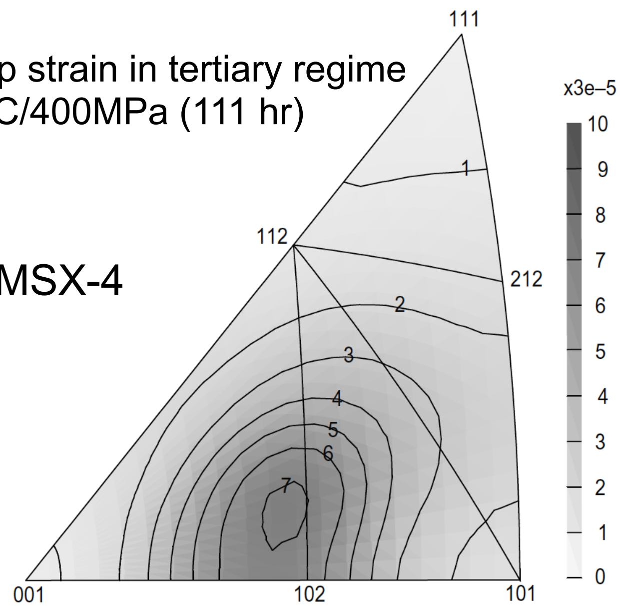
Deformation along [001]
Volume fraction of γ' fixed at 0.7

[Ma, Dye, and Reed, 2008]

Ma et al. model predictions showing orientation sensitivity

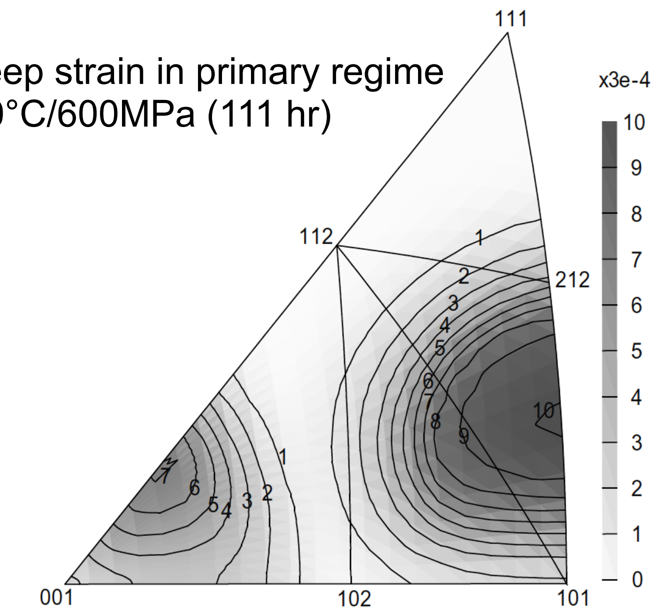
Creep strain in tertiary regime
900°C/400MPa (111 hr)

CMSX-4

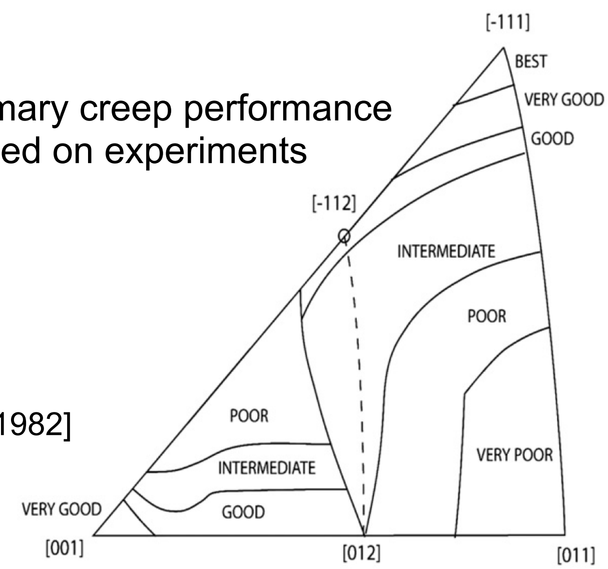


[Ma, Dye, and Reed, 2008]

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



Primary creep performance
based on experiments



[MacKay and Meier, 1982]

Kirka (2014) modifications to capture evolution of γ' precipitates

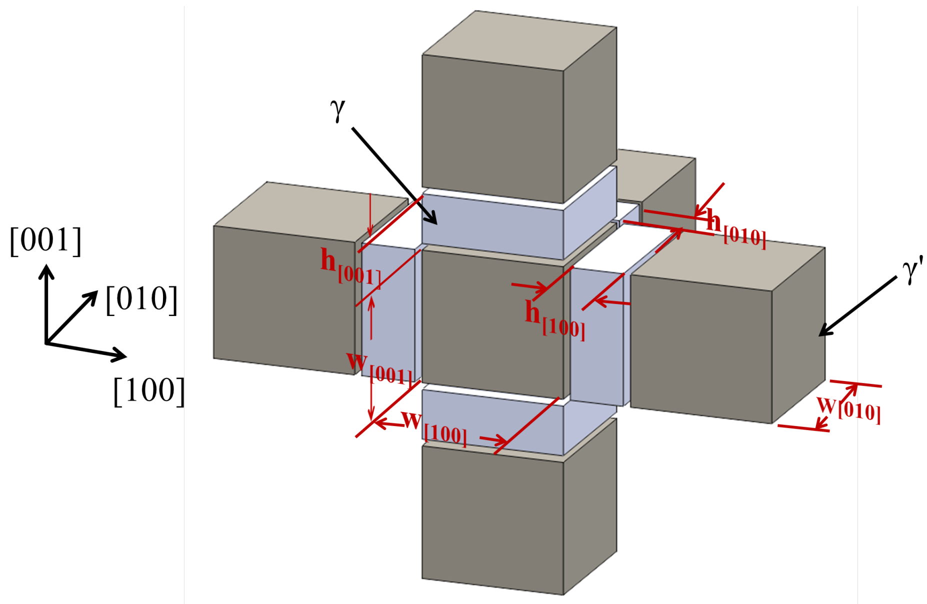
- Directional coarsening is roughly a constant volume process
- Stress-free coarsening maintains proportionality between all precipitate/channel dimensions
- Microstructure uniqueness is defined by 2 independent dimensions

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

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



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

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

Sensitivity of Composition on Diffusivity

Prediction of Aging

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

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

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

$$K = \frac{8\sigma D C_o \left(V_m\right)^2}{9\nu RT} \qquad D = D_o \exp\left(-\frac{Q}{RT}\right)$$

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

Temperature-Dependent Constitutive Models

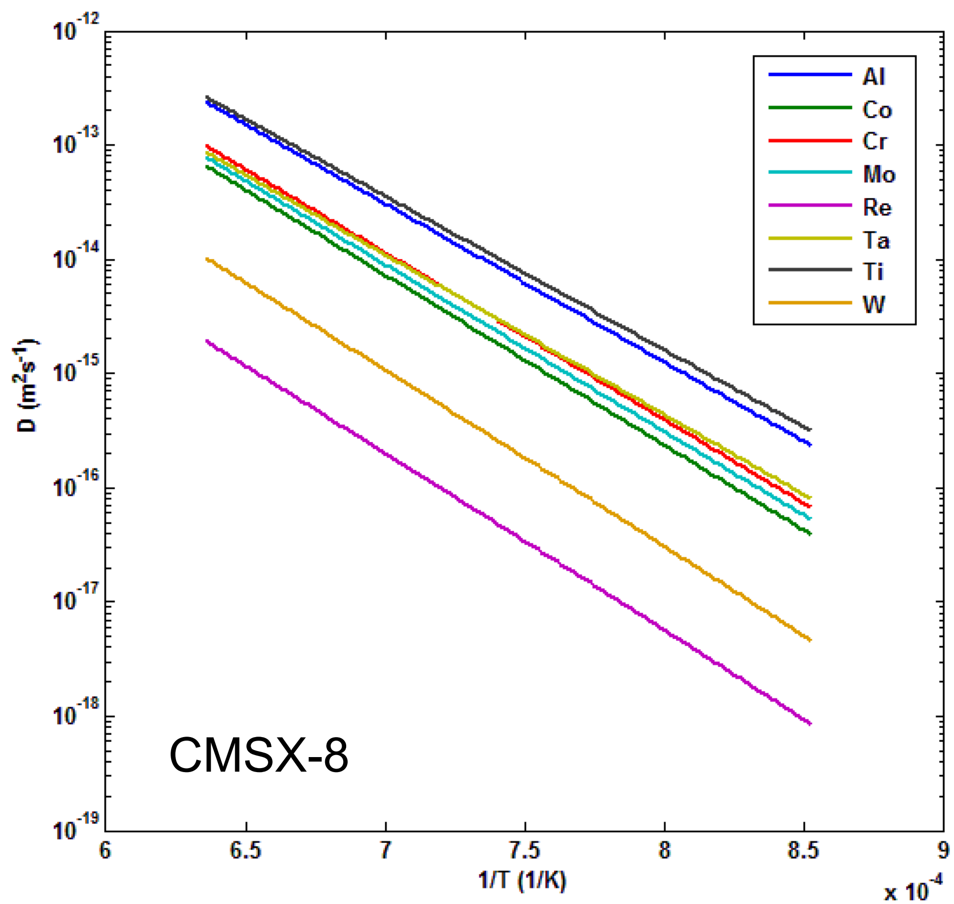
$$\dot{\gamma}^\alpha = \dot{\gamma}_0 \Theta(T)\left\langle \frac{\tau_\upsilon^\alpha}{D^\alpha} \right\rangle^n \exp\left\{ B_0 \left\langle \frac{\tau_\upsilon^\alpha}{D^\alpha} \right\rangle^{n+1} \right\} \mathrm{sgn}(\tau^\alpha - \chi^\alpha)$$

$$\Theta(T) = \exp\left(-\frac{Q_0}{RT}\right) \qquad T \geq \frac{T_m}{2}$$

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

Thermo-Calc / DICTRA

Databases: TCNi5 / MOBNi2



Composition Segregation ---- Results

Composition:

CMSX-10		wt%Cr	wt%Co	wt%Mo	wt%W	wt%Ta	wt%Re	wt%Al	wt%Ti	wt%Ni
overall	nominal	2	3	0.4	5	8	6	5.7	0.2	69.7
γ	experiment (dendrite)	3.64	4.95	0.73	9.74	2.34	16.58	1.99	0.06	59.98
	calculation from DICTRA	3.64	6.39	0.67	8.54	0.94	14.2	2.39	0.06	63.17
γ'	experiment (dendrite)	1.29	2.64	0.34	6.96	8.92	4.7	6.93	0.15	68.08
	calculation from DICTRA	1.06	1.07	0.25	2.99	12	1.34	7.59	0.28	73.42
CMSX-8		wt%Cr	wt%Co	wt%Mo	wt%W	wt%Ta	wt%Re	wt%Al	wt%Ti	wt%Ni
	nominal	5.4	10	0.6	8	8	1.5	5.7	0.7	60.1
T=1223K	γ	10.7	20.1	1.3	16.5	0.93	3.47	2.1	0.17	44.73
	γ'	1.6	2.67	0.13	2.05	12.97	0.11	8.28	1.08	71.11
CMSX-4		wt%Cr	wt%Co	wt%Mo	wt%W	wt%Ta	wt%Re	wt%Al	wt%Ti	wt%Ni
	nominal	6.5	10	0.6	6	6	3	5.6	1	61.3
T=1223K	γ	12.15	18.42	1.21	11.57	0.66	6.54	2.16	0.19	47.1
	γ'	1.91	2.95	0.16	1.56	10.37	0.23	8.39	1.72	72.71

CVP Model Development Plans

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