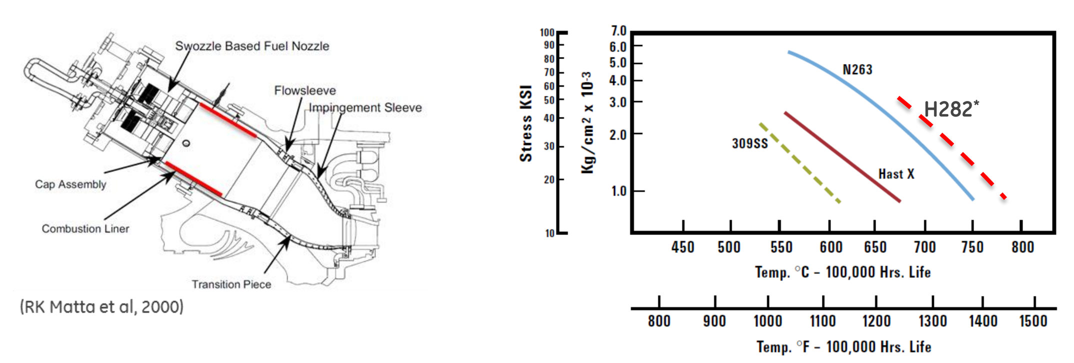
Modeling Long-term Creep Performance for Welded Nickel-base Superalloy Structures for Power Generation Systems

Chen Shen[1], Monica Soare[1], Pengyang Zhao[2], Akane Suzuki[1], Vipul Gupta[1], Timothy Hanlon[1], Yunzhi Wang[2], Samuel Thamboo[1]

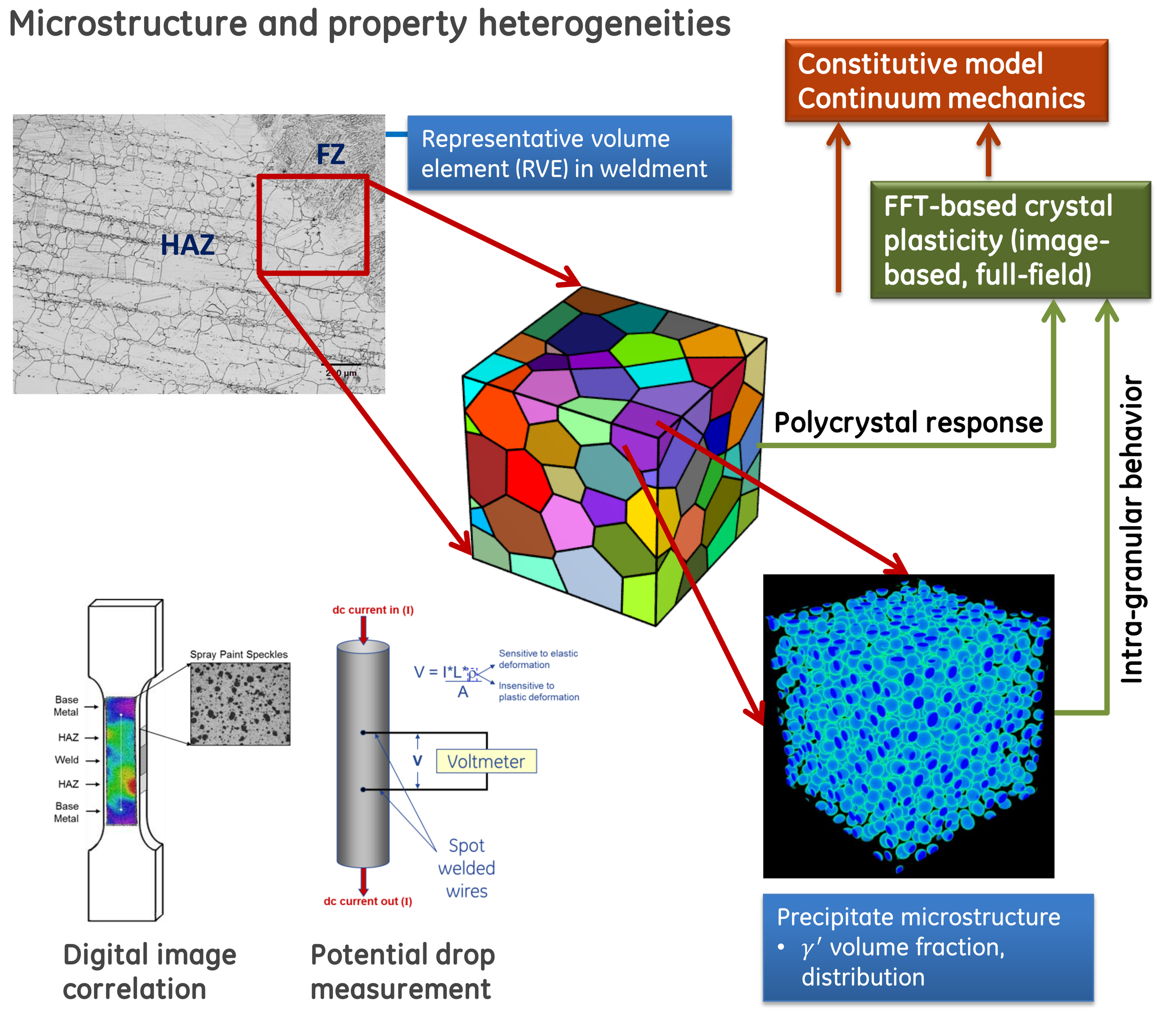
[1] GE Global Research, 1 Research Circle, Niskayuna, NY 12309; [2] Ohio State University, 2041 College Road, Columbus, OH 43210

INTRODUCTION

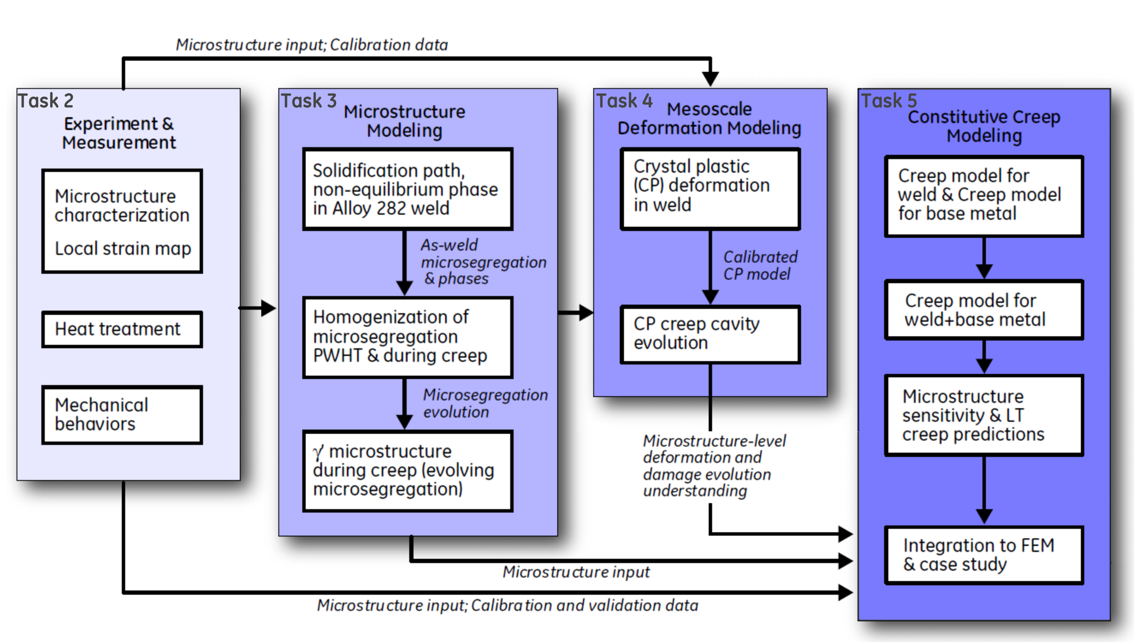


- High firing temperature for improved fuel efficiency
- Combustor materials - creep strength, oxidation & corrosion resistance
- Long-term creep prediction a key challenge
- Physics-based modeling of creep life for AUSC steam turbine rotor alloy HA282 in prior DOE program
- Challenge: heterogeneous (weld) microstructure, higher temperature (1500-1700˚F)

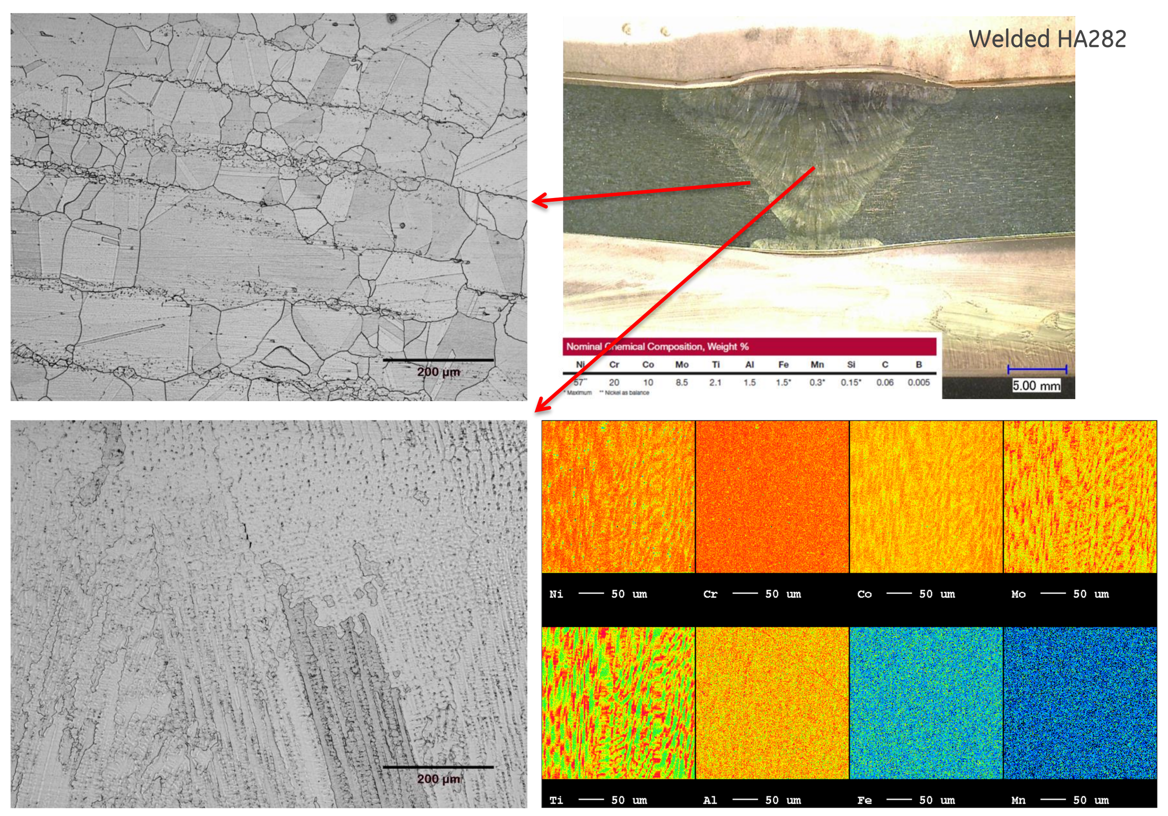
Microstructure and property heterogeneities

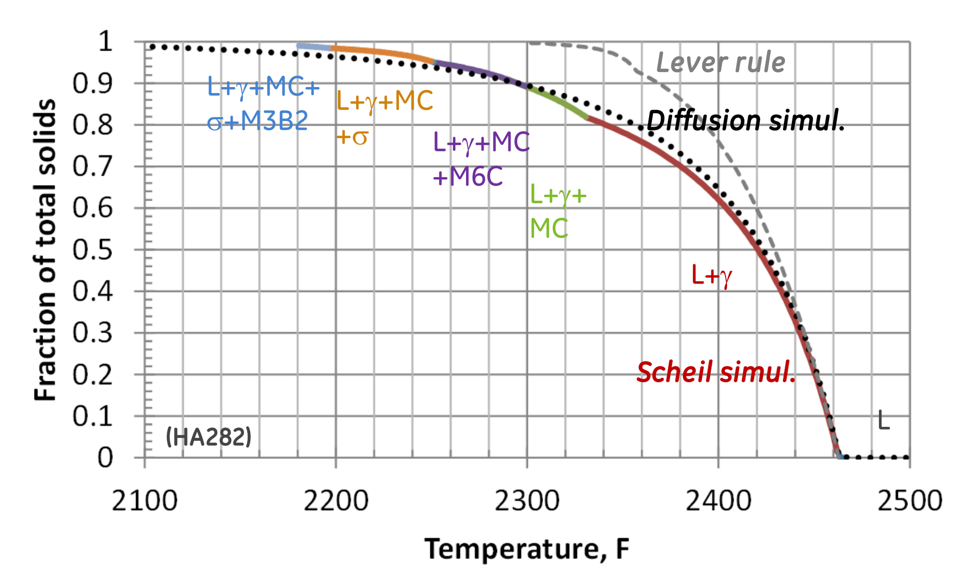


Develop a physics-based, microstructure-informed model for accurately predicting long-term creep behavior for heterogeneous weld structure



MICROSTRUCTURE



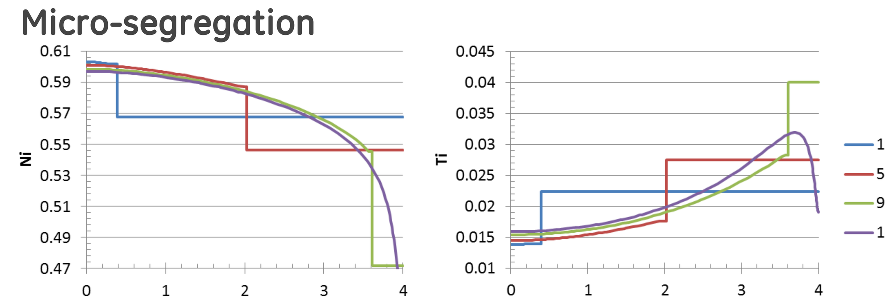


As-solidified phase observation (VIM + Investment casting)*

Phase identified	Description	Spatial characteristics
γ'	Primary strengthening precipitates, $Ni_3(Al,Ti)$ type	Dendrite core: spherical Interdendritic: coarser, cuboidal
TiN	Primary nitrides (MN)	Homogeneously disperse
(TiMoCr)C	Primary carbides (MC)	Preferentially interdendritic
σ	TCP phase, rich in Cr,Mo,Ni Detrimental intermetallic Depletes refractory elements	Globular, preferentially interdendritic
$(TiMo)_2SC$	Carbosulphide	Adjacent to σ
Mo,Cr-carbides	Lamellar γ/carbide, Secondary carbides $M_{23}C_6$, M_6C	

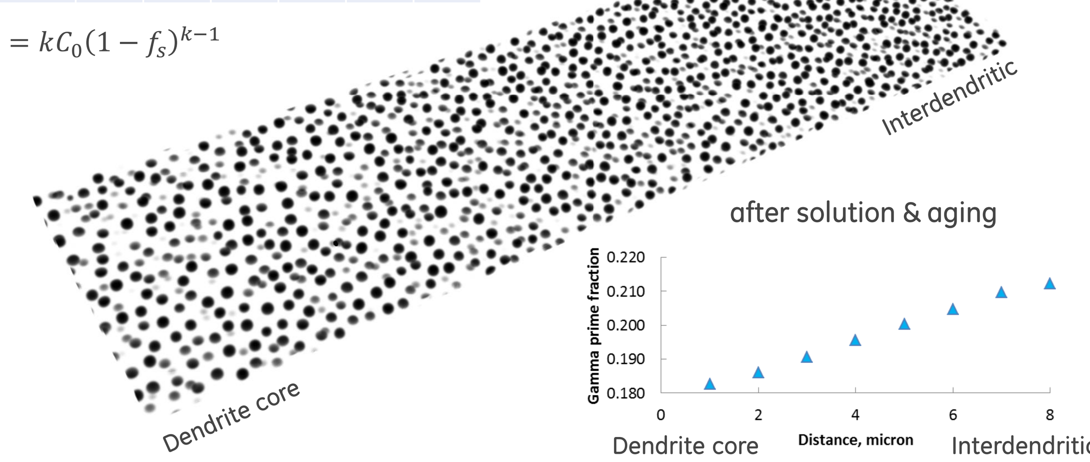
(* Matysiak, H. et al, 2013)

Micro-segregation



	Ni	Cr	Co	Mo	Ti	Al
EPMA fit k	1.04	0.97	1.08	0.86	0.74	0.90
Scheil	1.06	0.98	1.04	0.68	0.62	1.14

$$C_s = kC_0(1-f_s)^{k-1}$$

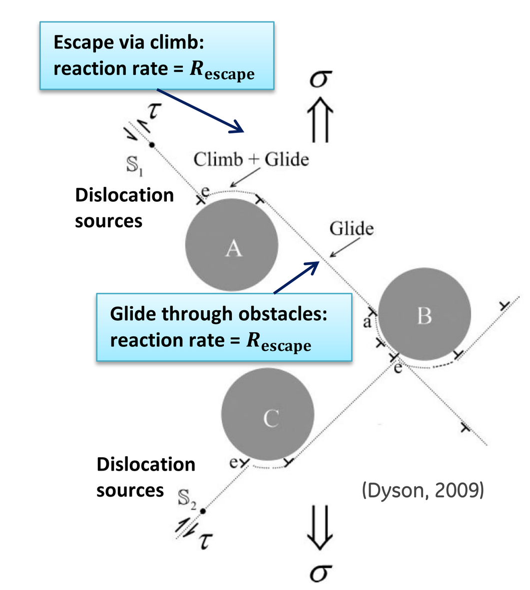


MESOSCALE DEFORMATION

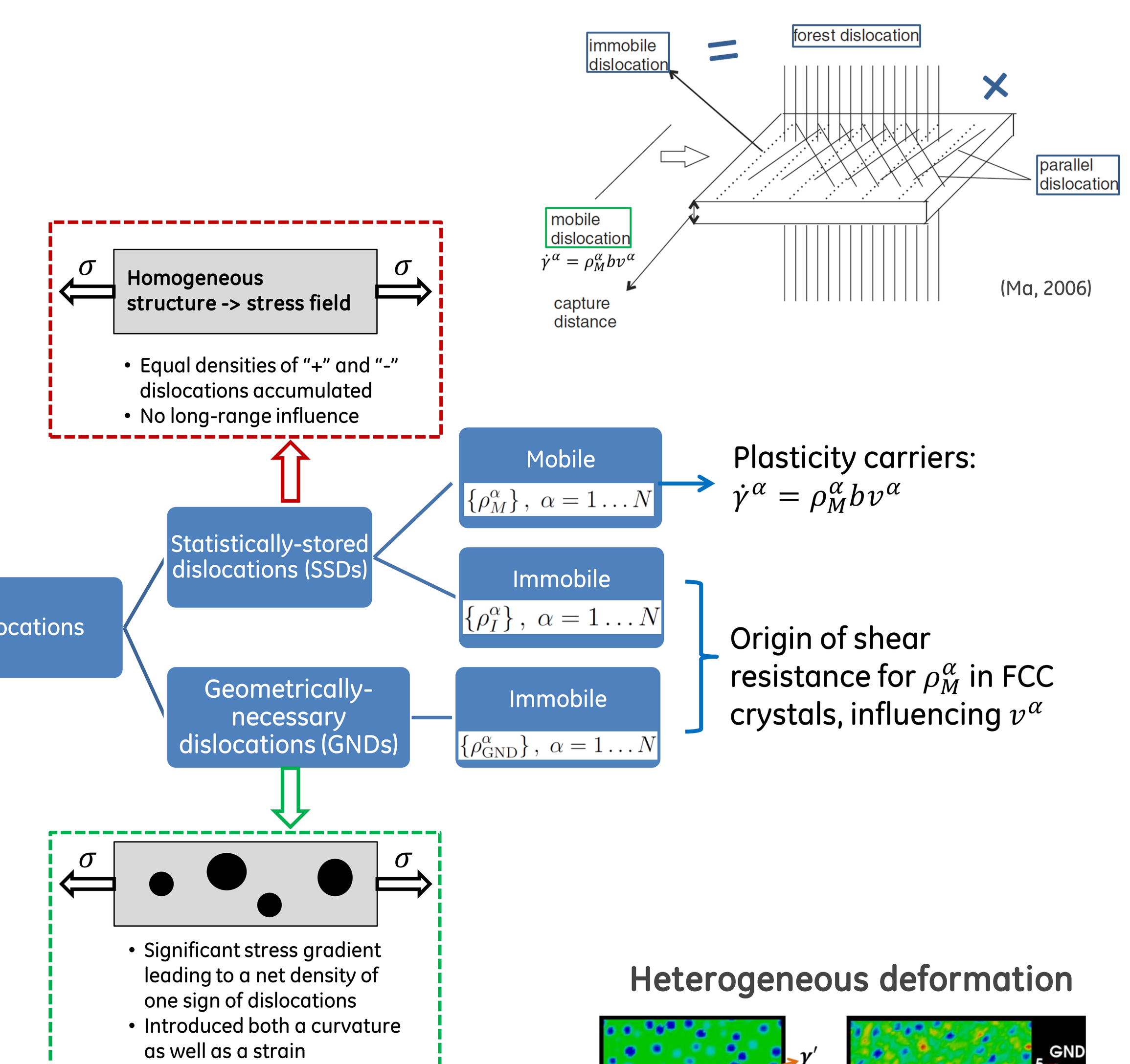
Orowan equation serves as the kinetic equation linking the macroscopic shear rate and microscopic dislocation activities:

$$\dot{\gamma}^\alpha = \rho_M^\alpha b v^\alpha = \rho_M^\alpha b v^\alpha(\sigma, T, S_i, P_i, \ldots)$$

- $\dot{\gamma}^\alpha$ - Shear rate on slip system α
- ρ_M^α - Mobile dislocation density of slip system α
- σ - Applied stress
- T - Temperature
- S_i - State variables, e.g., dislocation densities and γ' volume fraction
- P_i - Material properties, e.g., modulus and APB energy.

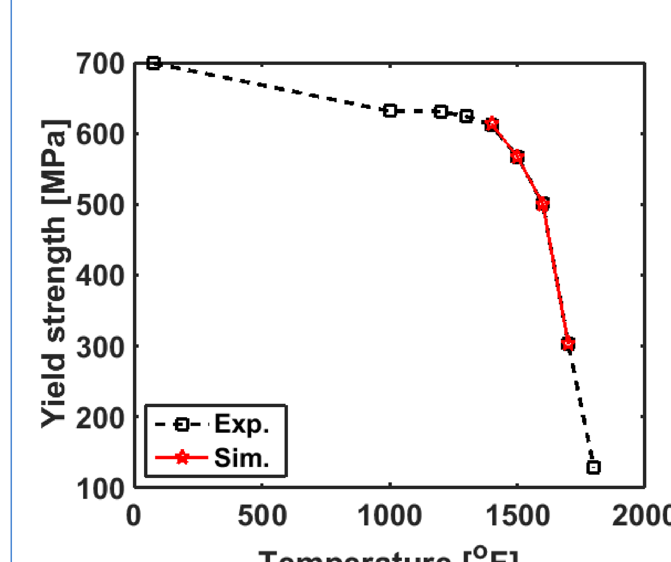


$$v^\alpha(\sigma, T, S_i, P_i, \ldots) = \begin{cases} v^\alpha_{\text{glide}}(\sigma, T, S_i, P_i, Q^\alpha_{\text{slip}}), & \text{if } R_{\text{escape}} \gg R_{\text{glide}}, \text{ e.g. tensile} \\ v^\alpha_{\text{climb}}(\sigma, T, S_i, P_i, Q^\alpha_{\text{self}}), & \text{if } R_{\text{escape}} \ll R_{\text{glide}}, \text{ e.g. creep} \end{cases}$$

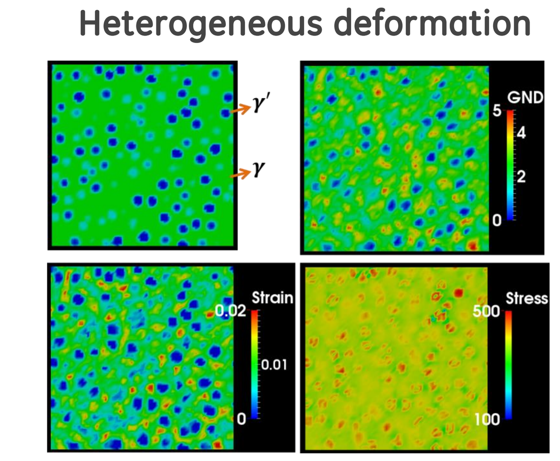


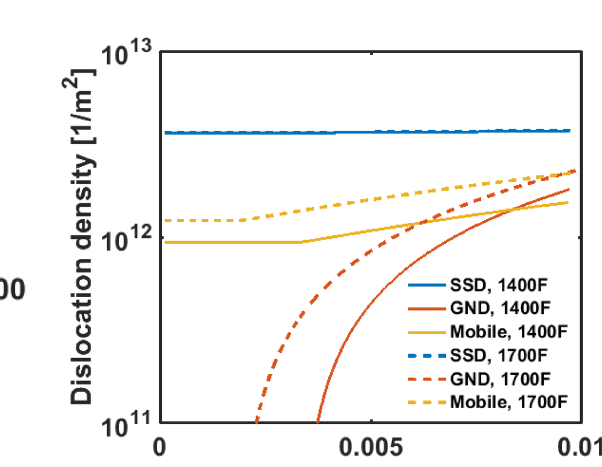
Plasticity carriers: $\dot{\gamma}^\alpha = \rho_M^\alpha b v^\alpha$

Origin of shear resistance for ρ_M^α in FCC crystals, influencing v^α



Heterogeneous deformation

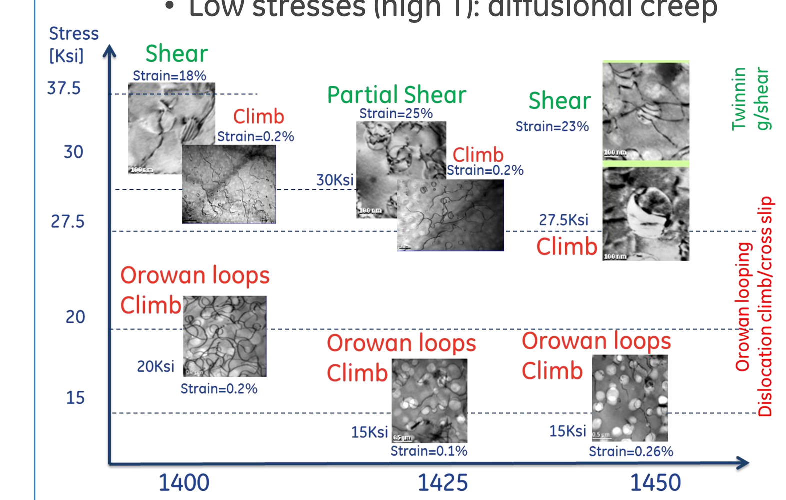


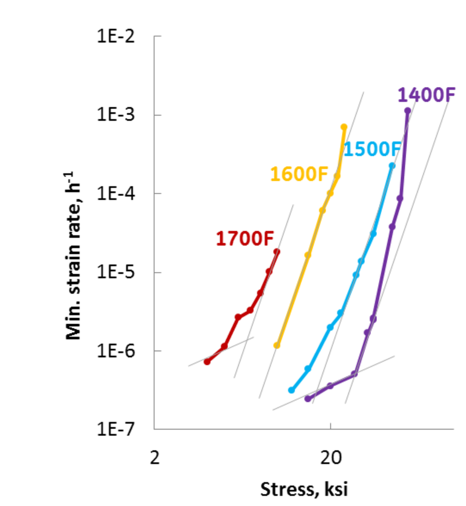


MACROSCALE DEFORMATION

Creep deformation modes

- Intermediate stresses: dislocation climb-bypass
- High stresses: γ' shearing
- Low stresses (high T): diffusional creep





Constitutive creep model

$$\varepsilon^{creep} = \varepsilon^{disloc} + \varepsilon^{diffusion}$$

$$\dot{\varepsilon}^{disloc} = A\rho(C)\, f(1-f)\left(\sqrt{\frac{\pi}{4f}} - 1\right) \sinh\left(B\frac{\sigma_{eff} - \sigma_p - \sigma_0}{MkT}\lambda b^2\right)$$

$$\sigma_{eff} = \frac{\sigma_{applied}(1+\varepsilon^{creep})}{1-D_s}$$ (Dyson, 2009)

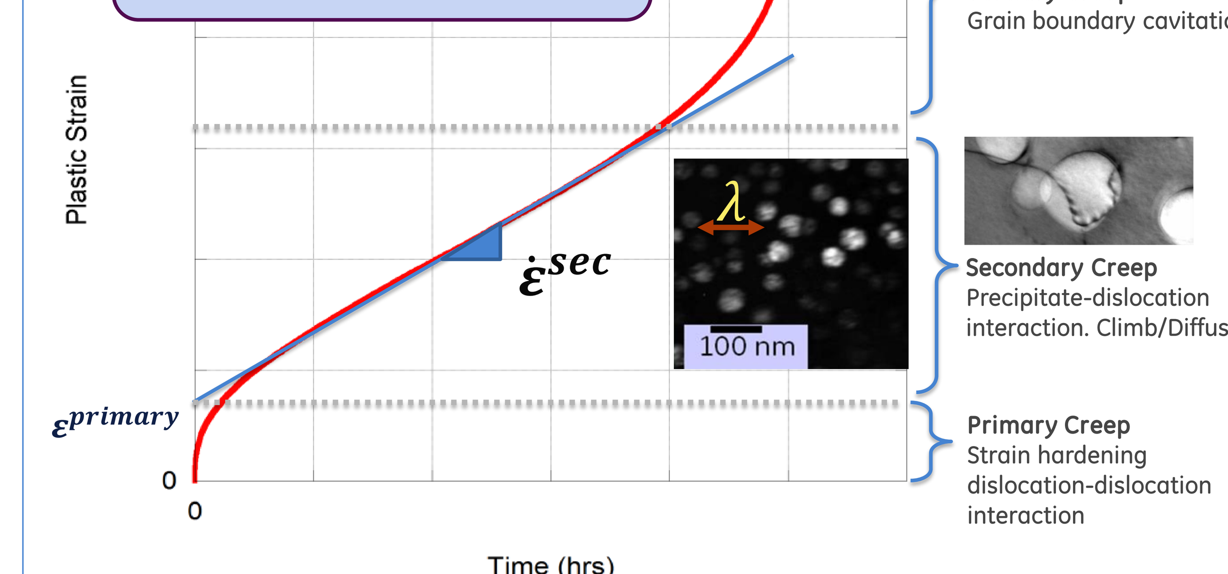
$$\dot{\sigma_p} = E\frac{f}{1-f}\dot{\varepsilon}^{disloc}\left(1-(1+2f)\frac{\sigma_p}{2f\sigma_{eff}}\right)$$ For climb

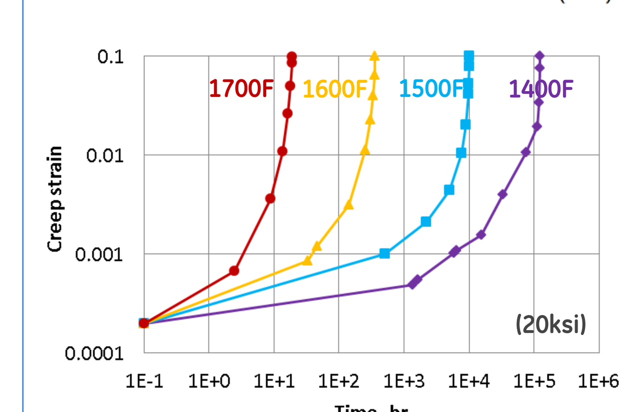
$$\sigma_p = \frac{\gamma_{APB}}{2b}\left[\sqrt{\frac{12\gamma_{APB} f r}{\pi G b^2}} - f\right]$$ For precipitate shearing

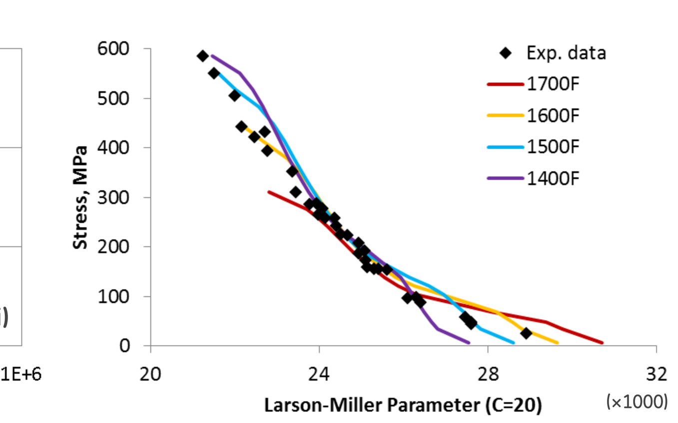
$\sigma_o = 0.25MG(T)b\sqrt{\rho}$, $\rho = \rho(C)$ For D-D interaction

$$\dot{\varepsilon}^{diffusion} = c_L\sigma + c_B\,\sigma + \dot{\varepsilon}^{BD} + \dot{\varepsilon}^{SD}$$

$$c_L = F\frac{12D_v\Omega}{k_B T d^2} \qquad c_B = 3\pi F\frac{4D_B\delta_B\Omega}{dk_B T}$$







ACKNOWLEDGMENT

This work is supported by Department of Energy (Award # DE-FE0024027) and GE Power & Water. We gratefully thank Vito Cedro, Steve Pope, Srikanth Kottilingam, Jeffrey Roberts, Deepak Saha, Michael Knussman, Rebecca Casey, Michael Gilhooly, Thomas Bigelow for technical discussions and support.