Models of Long-Term Creep Behavior of High Performance Structural Alloys

Abhinav Saboo

Changning Niu, Qiaofu Zhang, Jiadong Gong, Greg B Olson

QuesTek Innovations LLC, Evanston, IL

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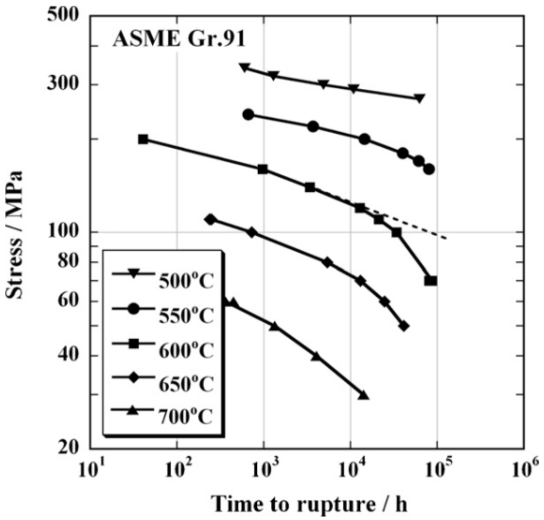
What do we want to model?

Creep Strength

- Answers **when** a material will fail
- Maximum allowable stress that will cause creep rupture in a given time
- Usually characterized as maximum allowable stress for a creep life of 100,000 hrs

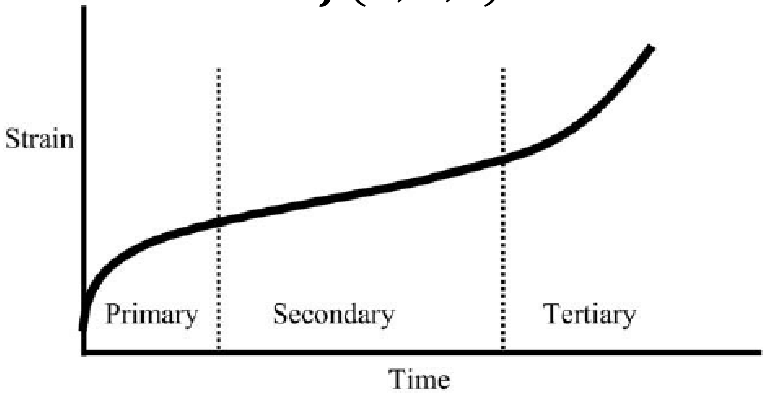
Creep Ductility

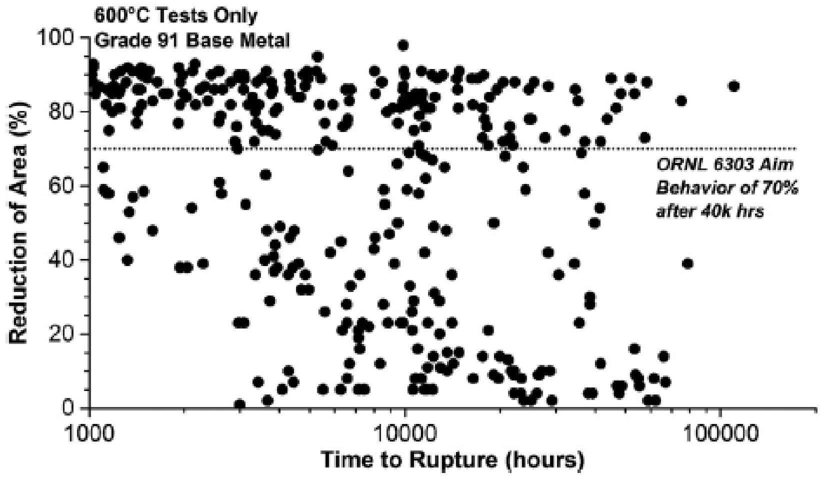
- Answers **how** a material will fail
- Characterized by reduction of area on fracture
- Low ductility failures can lead to catastrophic failures (Leak-before-break)



K. Sawada, et al., Mater. Sci. Eng. A (2011) 528

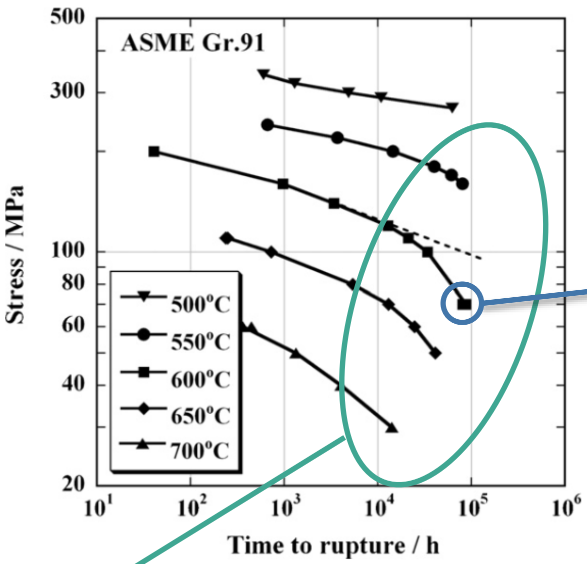
$$\dot{\epsilon} = f(T, \sigma, t)$$



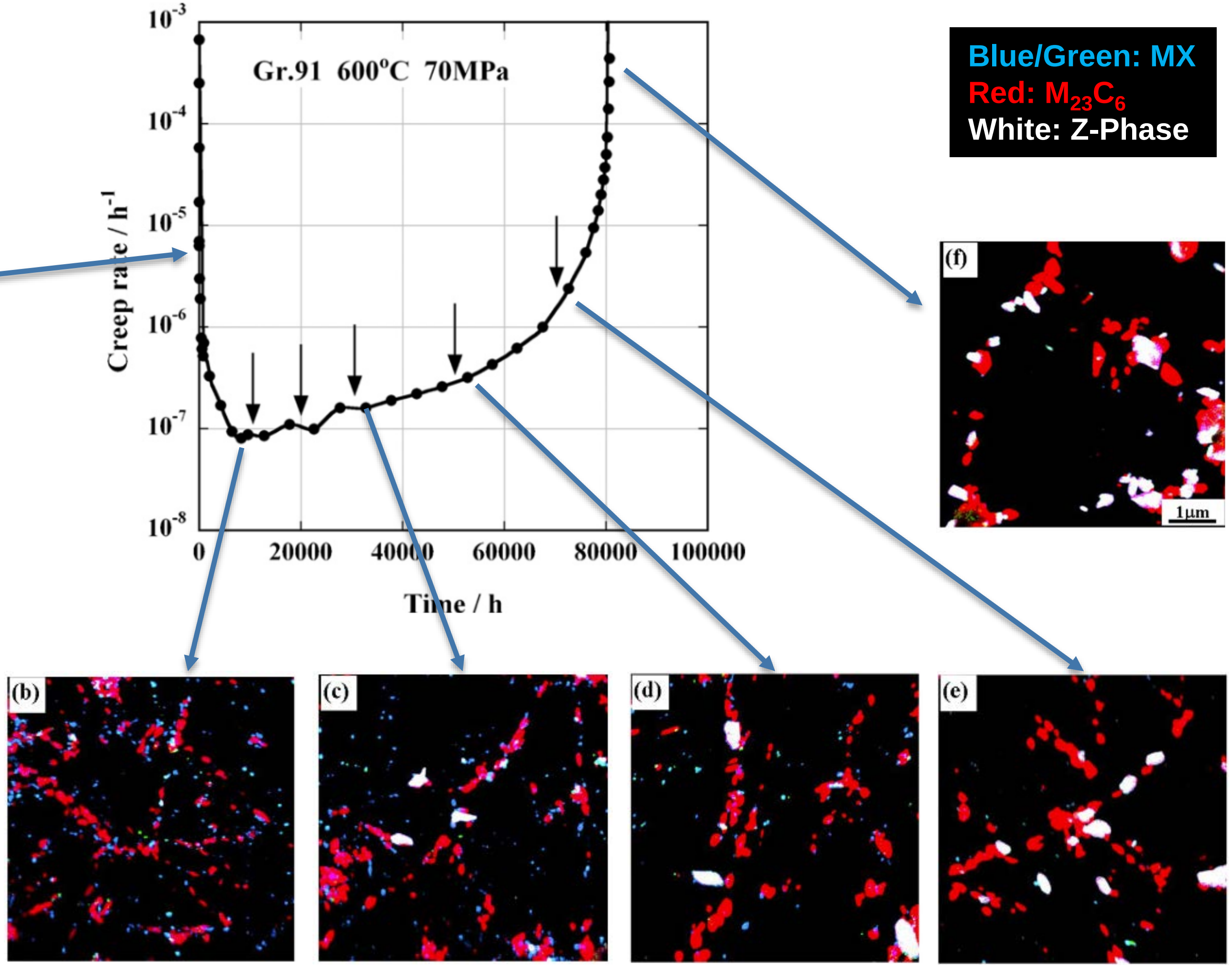


Siefert et al, 32 Intl. J. of Pressure Vessels and Piping 138 (2016) 31-44

CSEF steels and accelerated creep



Accelerated strength reduction in long term creep



Accelerated strength reduction accompanied by microstructural degradation.

K. Sawada, et al., Mater. Sci. Eng. A (2011) 528

Comparison of Creep Models

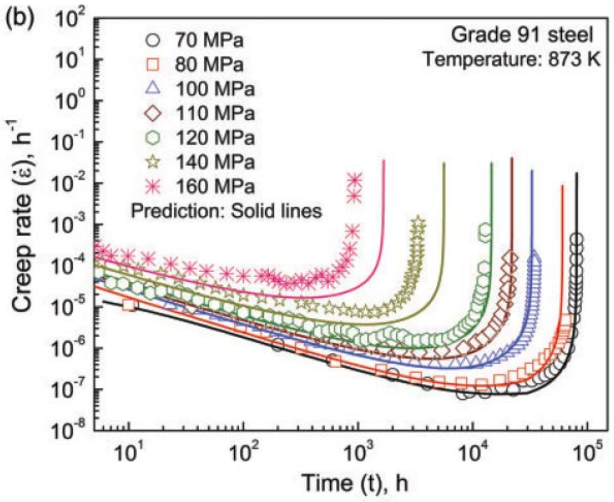
Hyperbolic Sine Model

- State-of-the-art solution to model creep behavior
- Phenomenological model involving direct fitting to experimental data
- Extension to other materials would require the same amount of data used in the first fitting

QuesTek's Creep Model

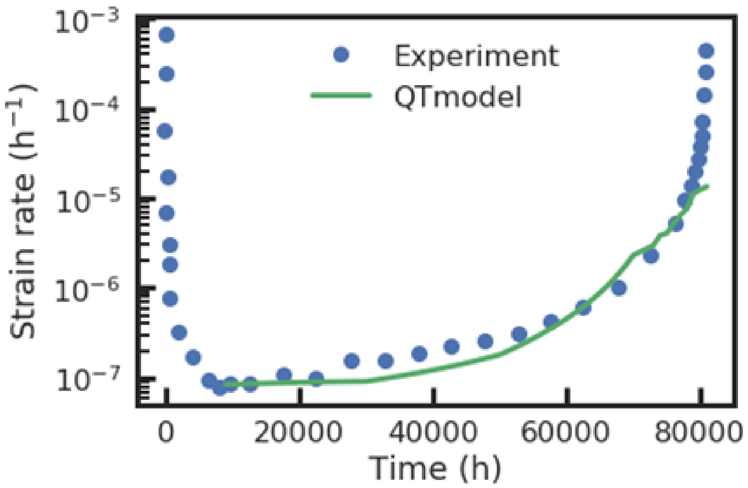
- Mechanistic model capturing the climb mechanism in play
- Easy extension to same material with different compositions or even other materials

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \frac{D_d}{1-\left(1-\frac{c_e}{c_0}\right)D_s}\sinh\left[\frac{\sigma(1-H)}{\sigma_0(1-D_C)}\right]$$

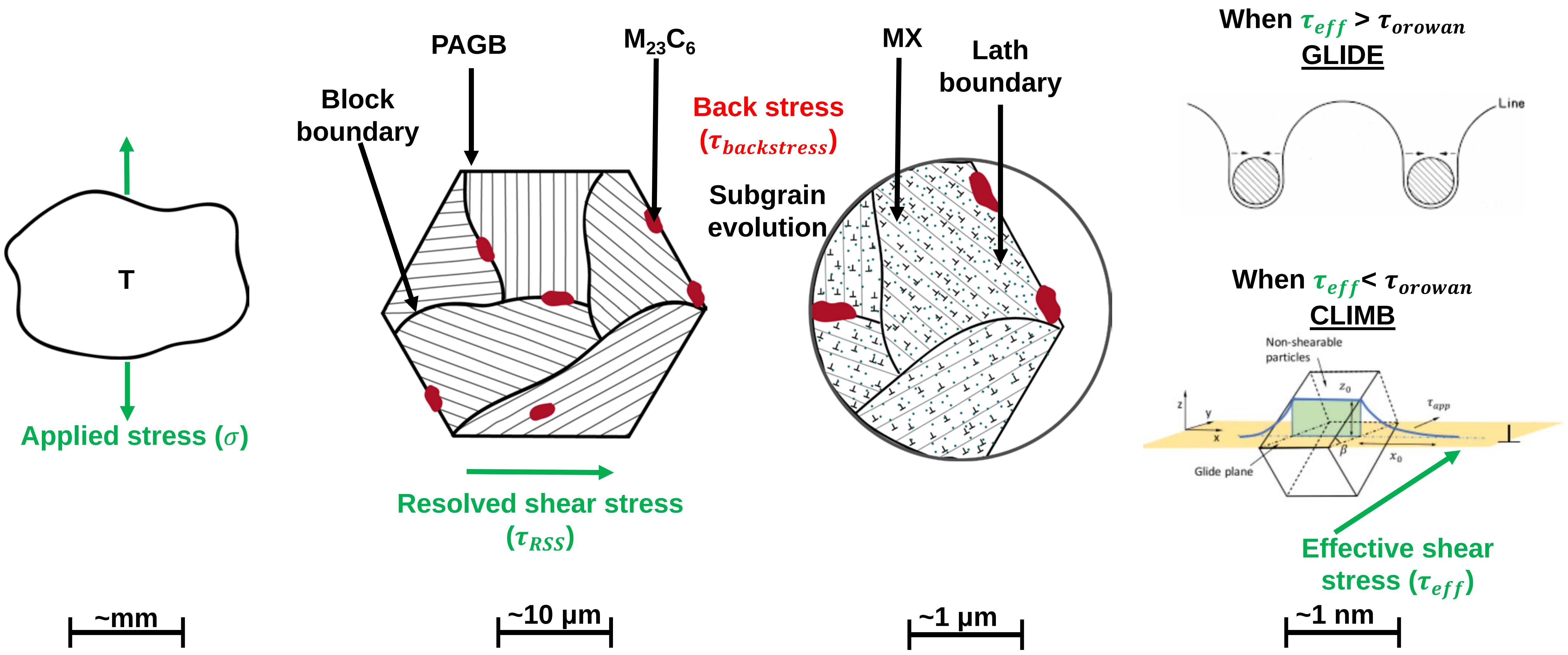


J Christopher, et al., Int. J. Damage Mech. (2018)

$$\dot{\epsilon} = \rho_m b v = \rho_m b \frac{\lambda}{t} = \rho_m\, b \frac{\lambda}{t_c + t_g}$$



QuesTek's creep model – Dislocation creep



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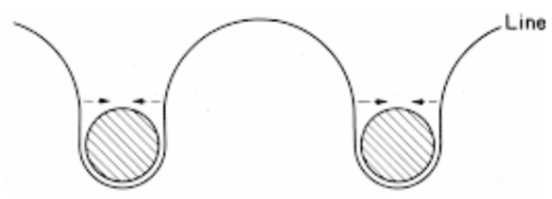
QuesTek's Creep Model: Cont.

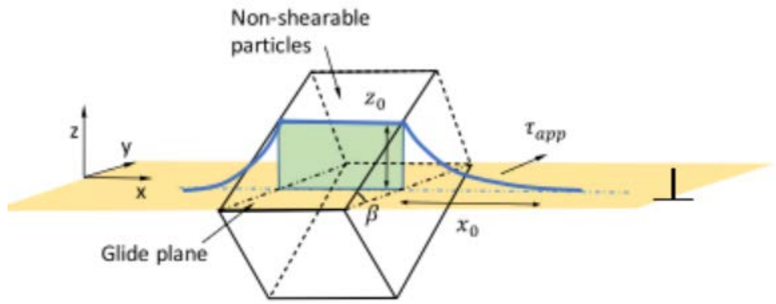
Decreasing stress

When $\tau_{eff} > \tau_{orowan}$: Glide



$$v_g = f(T, \tau)$$

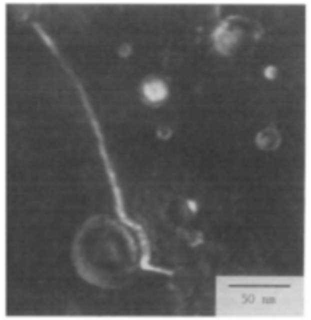
When $\tau_{eff} < \tau_{orowan}$: Climb



$$t_c = \int_{y_{min}}^{y_{max}} \frac{dy}{dy/dt}$$

$$\frac{dy}{dt} = C_i \frac{\mu}{dA/dy} = \frac{\text{Driving force for adding vacancies}}{\text{Number of vacancies required to climb}}$$

When $\tau_{eff} < \tau_{threshold}$: No climb (or glide)



$$\tau_{threshold} = f(T, \tau)$$

$$t_{detach} = 1 \Big/ \frac{3D_v}{b^2} exp\left(-\frac{Gb^2 r\left[(1-k)\left(1-\frac{\tau_{eff}}{\tau_d(T)}\right)\right]^{3/2}}{k_B T}\right)$$

- J Rosler, et al., Acta Metal. (1988)
- E Arzt, et al., Acta Metal. (1988)
- J Zhao, et al., Acta Mater. (2018)

Overall Dislocation creep

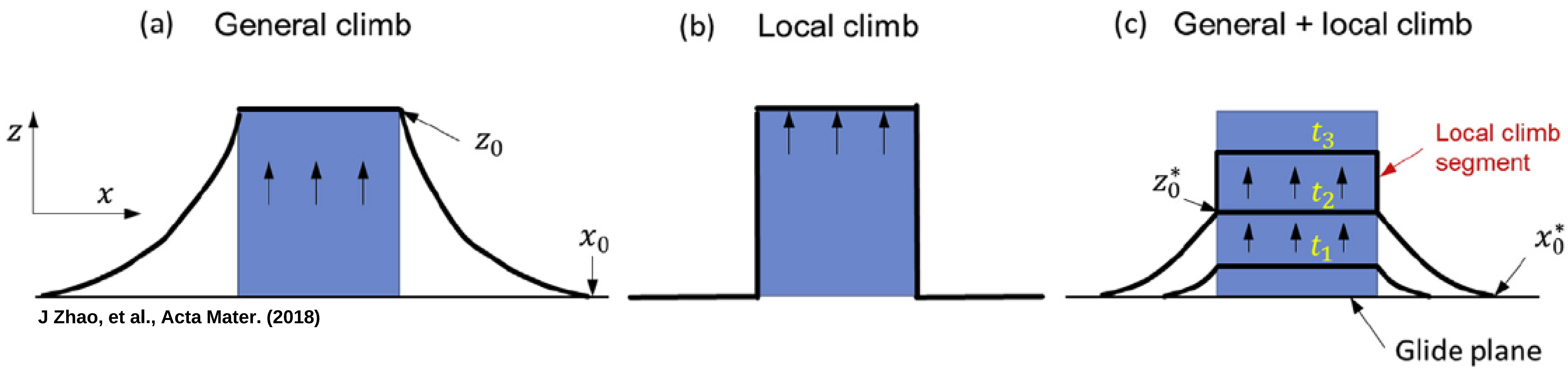
$$\dot{\epsilon}_{dis} = \rho_m b v = \rho_m b \frac{\lambda}{t} = \rho_m\, b \frac{\lambda}{t_c + t_g + t_{detach}}$$

+

Diffusional creep (Coble)

$$\dot{\epsilon}_{diff} = A\left(\frac{D_{gb}}{d^3}\right)\sigma$$

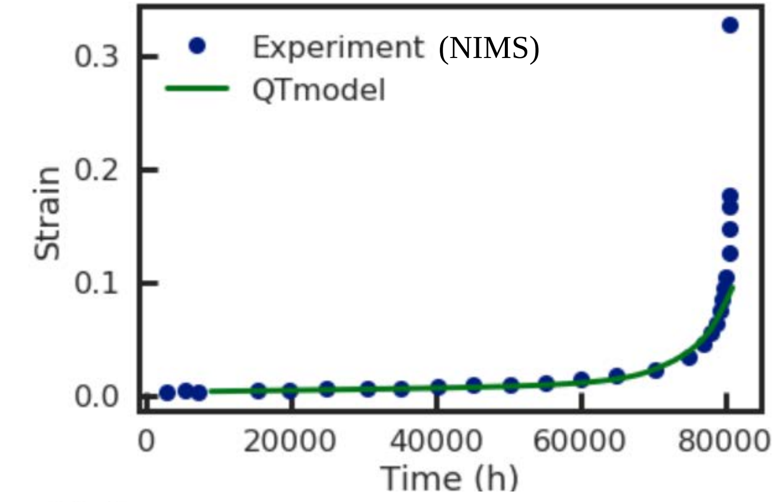
General climb and local climb modes

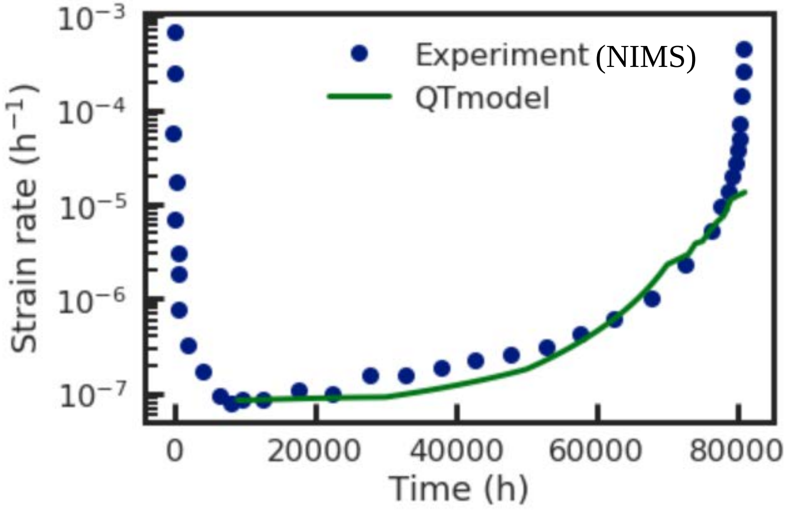


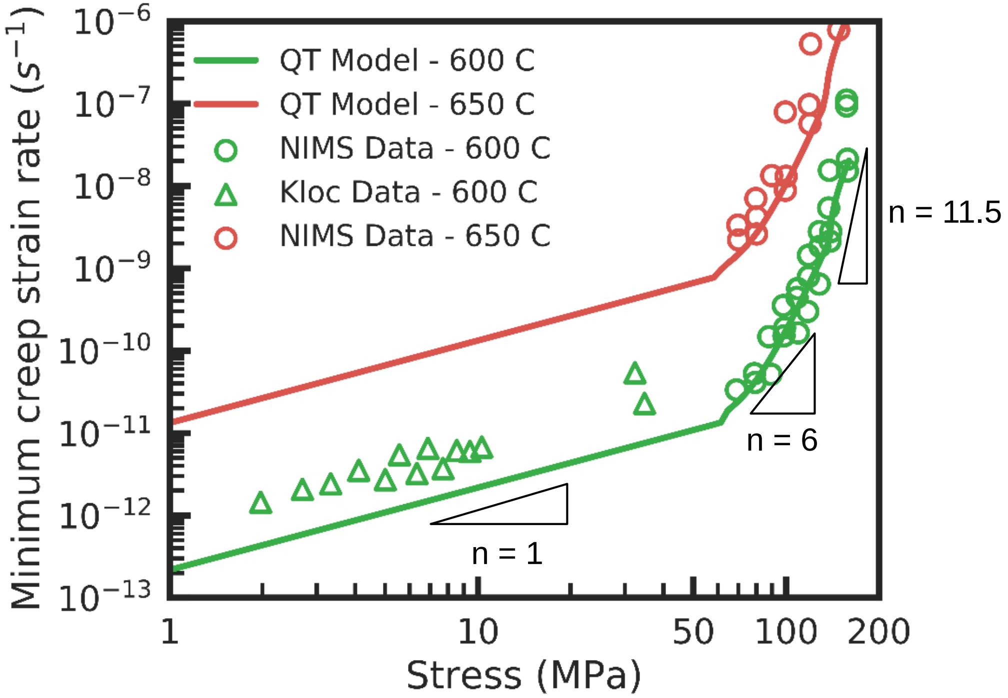
J Zhao, et al., Acta Mater. (2018)

General Climb	Local Climb	General + Climb
• Enabled at low stress • Larger driving force • More vacancies needed • Usually slower	• Enabled at high stress • Low driving force • Fewer vacancies needed • Usually faster	• Used in this model • Captures both modes • Needs to find equilibrium/transition point

Model application to Grade 91 steel



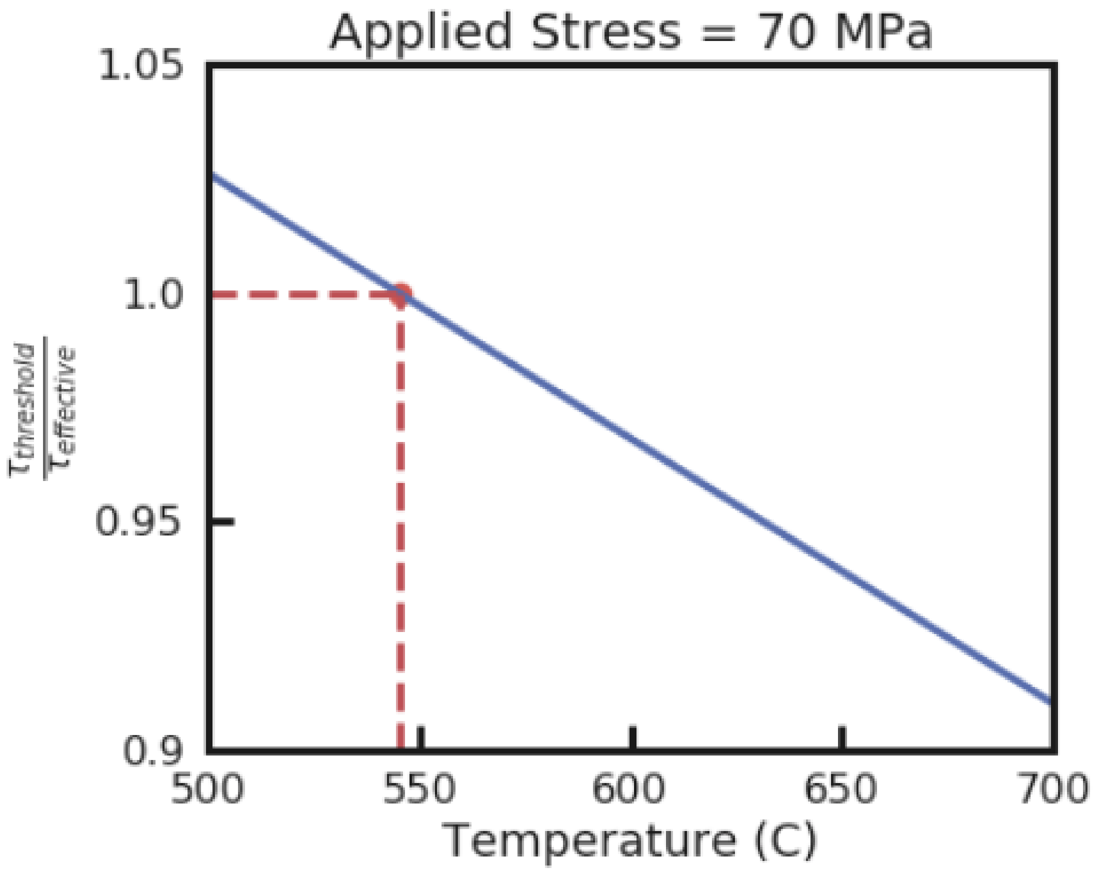




- **Accurate prediction of strain and creep rate at 70 MPa**
- **Prediction made using experimental data from [1]**
- **Tertiary creep region was modeled by a necking model**
- **Captures stress dependence in min. creep rate predictions**
- **Transition from general → local climb mode observed**

[1] K. Sawada, et al., Mater. Sci. Eng. A (2011) 528

Transition from dislocation to diffusional creep



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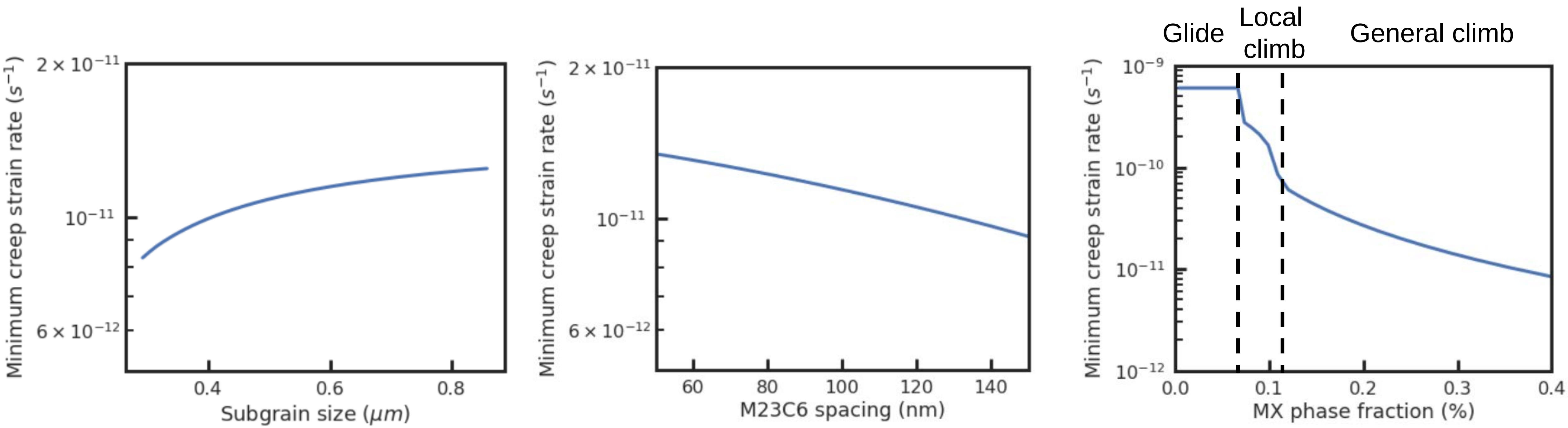
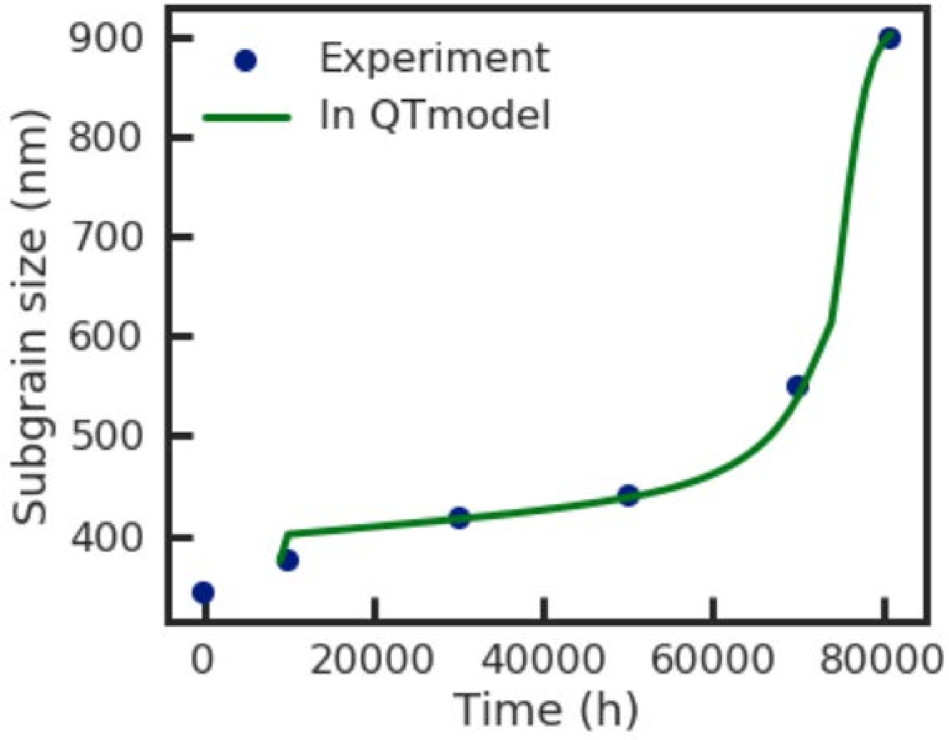
Effect of different microstructural variables



- **Creep strain rate most sensitive to MX phase fraction**
- **Microstructurally sensitive model enables application to different conditions (eg – weld regions)**

Modeling microstructural evolution



Subgrain size model [1]

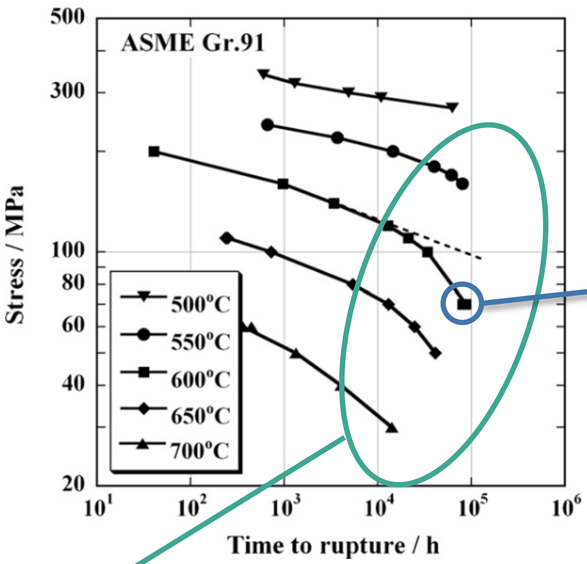
$$\ln\left(\frac{d}{d_{ST}}\right) = \ln\left(\frac{d_0}{d_{ST}}\right)\exp\left(-\frac{\varepsilon}{k_{sg}}\right)$$

Dislocation number density

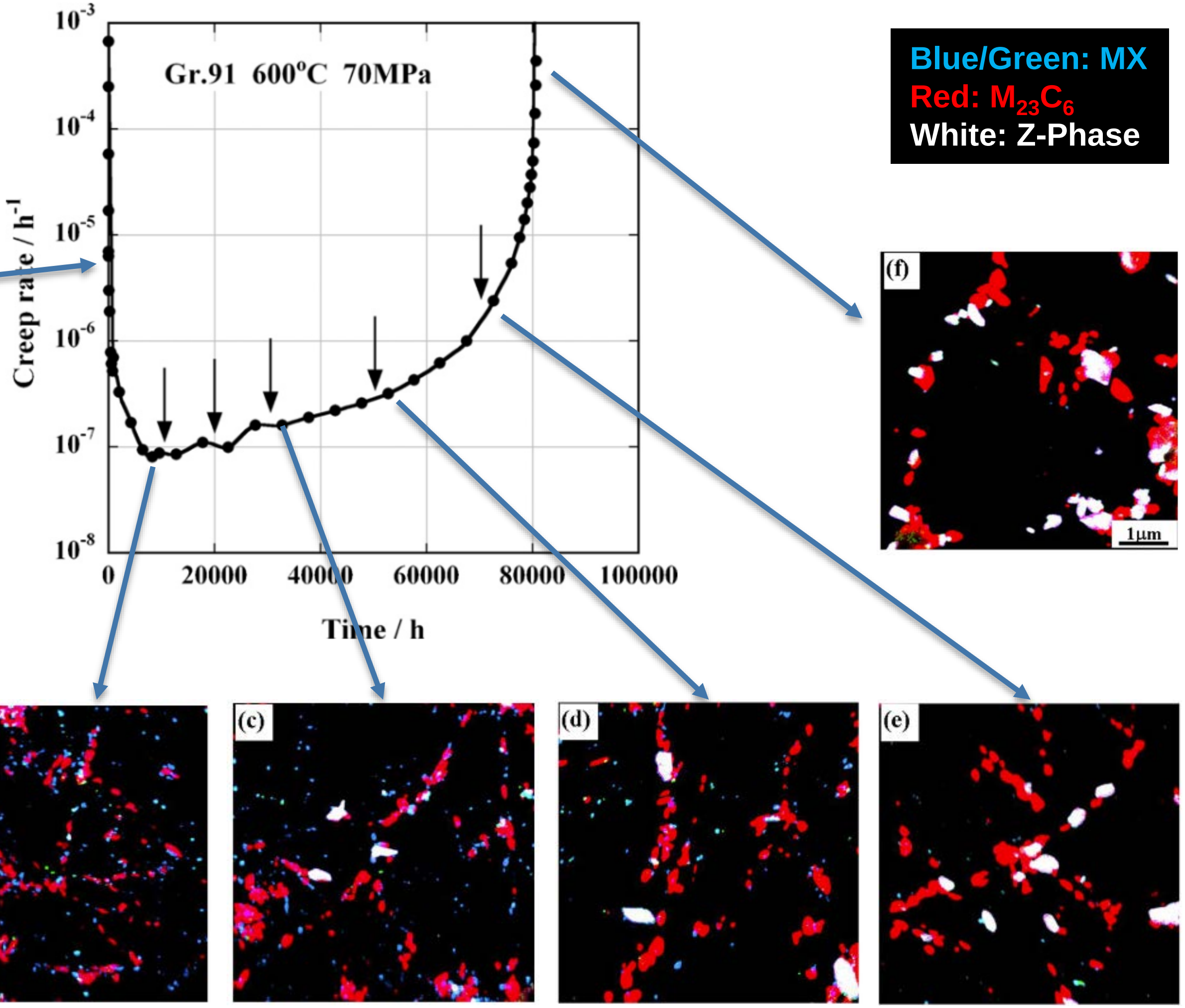
- **Currently using experimental data values**
- **Working on dislocation evolution model**

[1] A. Orlova, et al., Mater. Sci. Eng. A (1998) 245

Accelerated creep deformation



Accelerated strength reduction in long term creep



Accelerated strength reduction accompanied by microstructural degradation.

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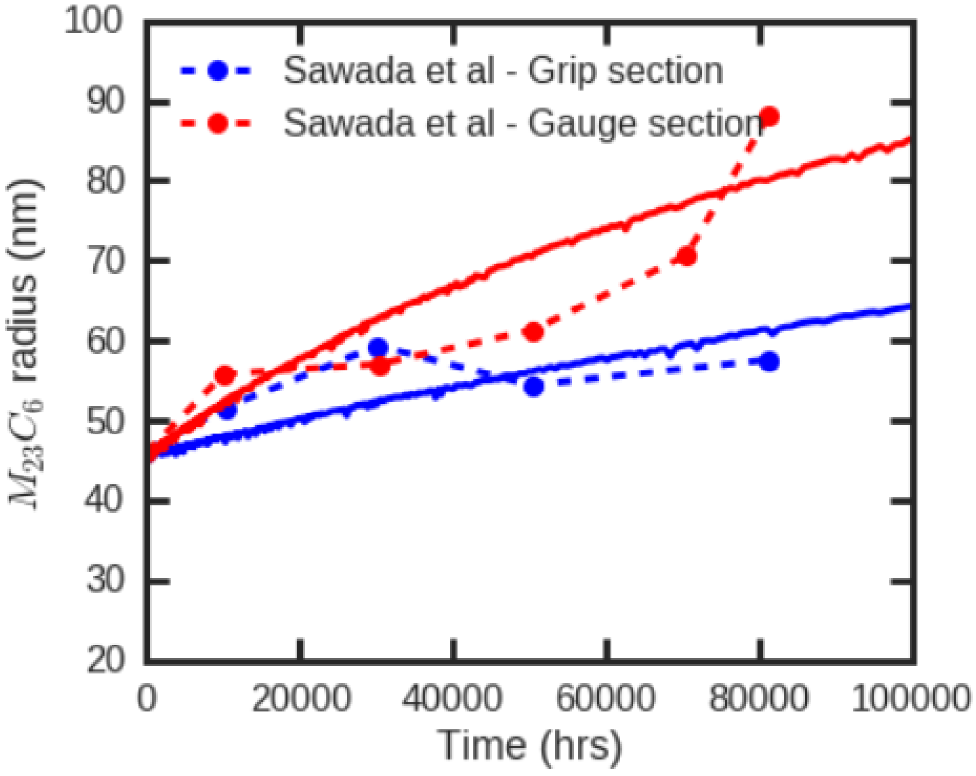
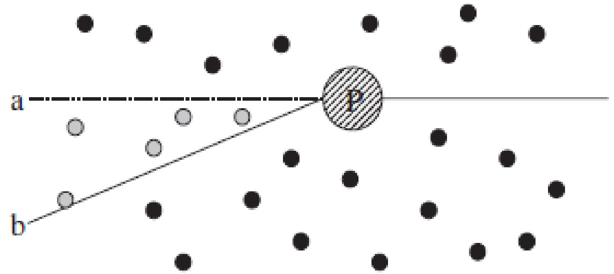
Evolution of $M_{23}C_6$ precipitate



Scavenging effect[1]

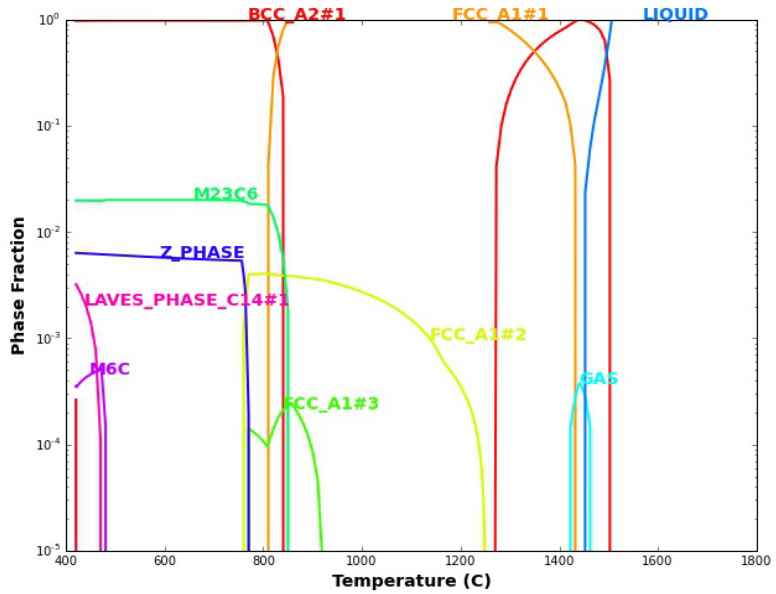
$$D_{eff} \propto \dot{\epsilon}$$



- **Accelerated coarsening explained by increase in diffusion coefficients due Scavenging effect**
- **A closed loop simulation between creep model and precipitation model will be more accurate**

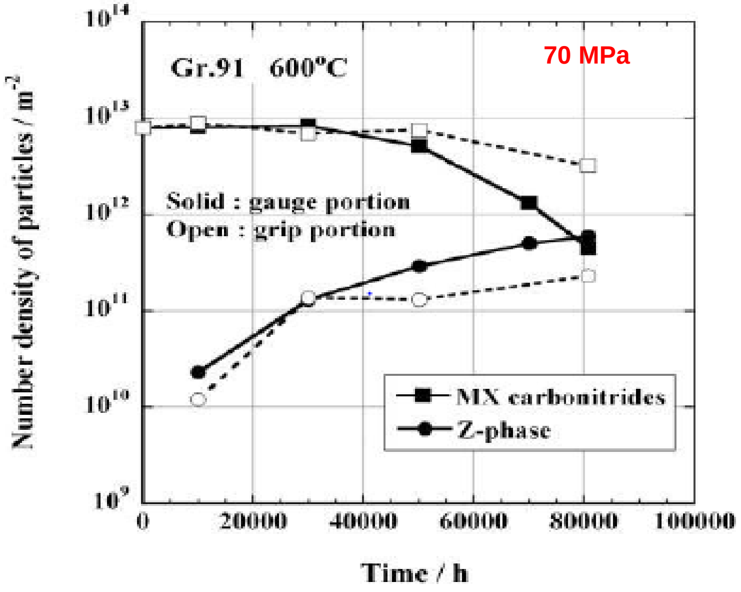
[1] Taneike et al, ISIJ Int. Vol. 4 (2001)

Evolution of MX→Z-Phase precipitation



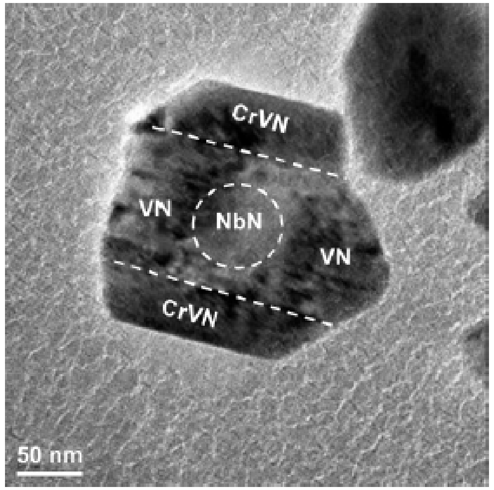
Z-Phase is a thermodynamically stable phase.

K. Sawada, et al., Mater. Sci. Eng. A (2011) 528



Z-Phase Precipitation consumes beneficial MX precipitates.

H. K. Danielsen, Mater. Sci. Tech. (2016) 32



Heterogeneous nucleation on MX precipitates

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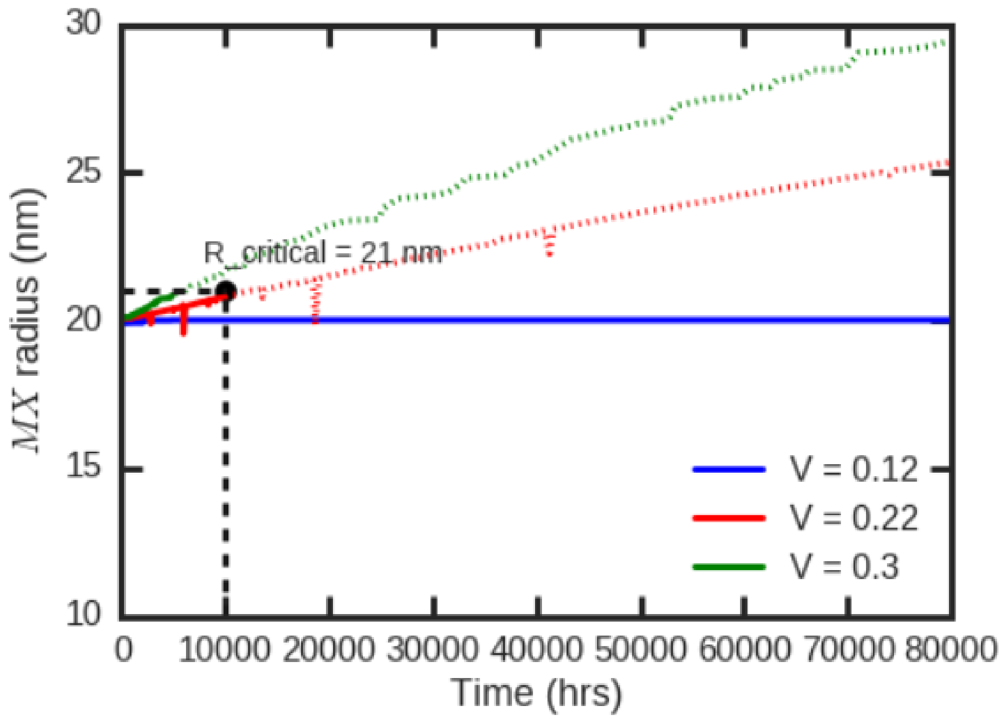
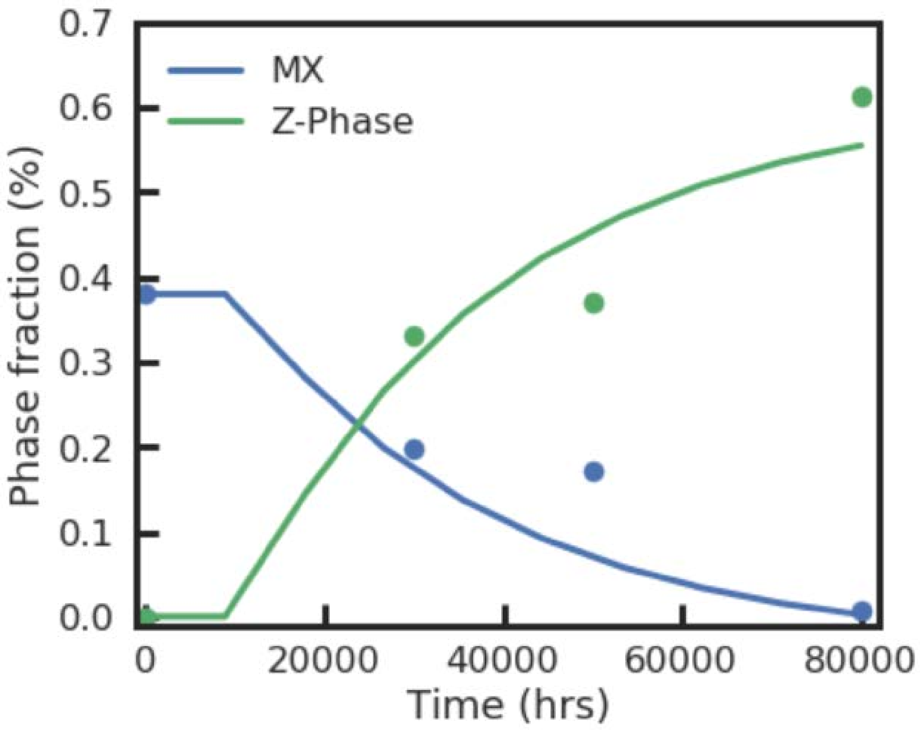
MX→Z-Phase precipitation

Critical radius for Z-phase nucleation



Once critical radius is reached, phase fraction is modeled using a JMAK equation with driving force of Z-Phase as input



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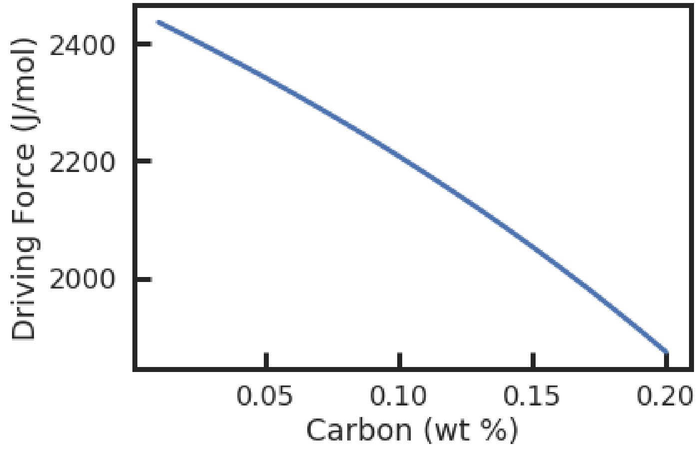
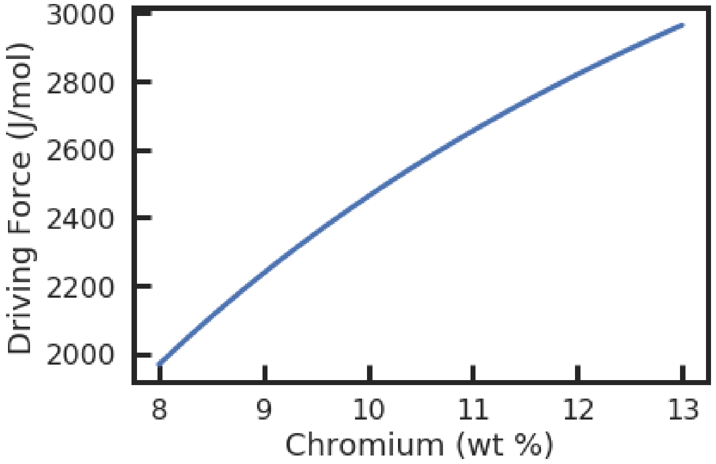
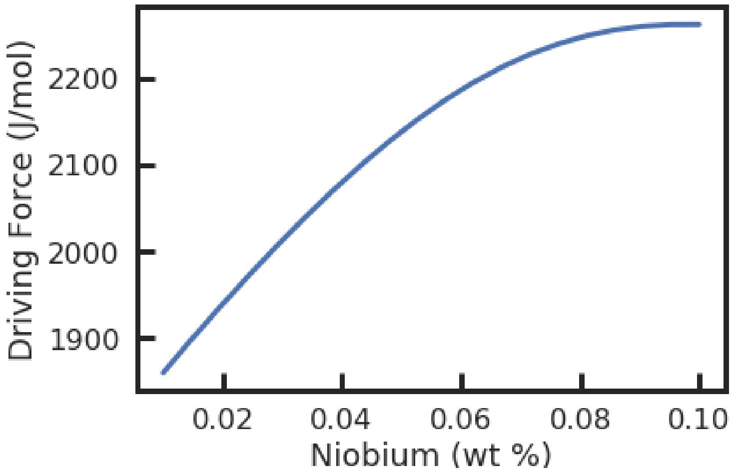
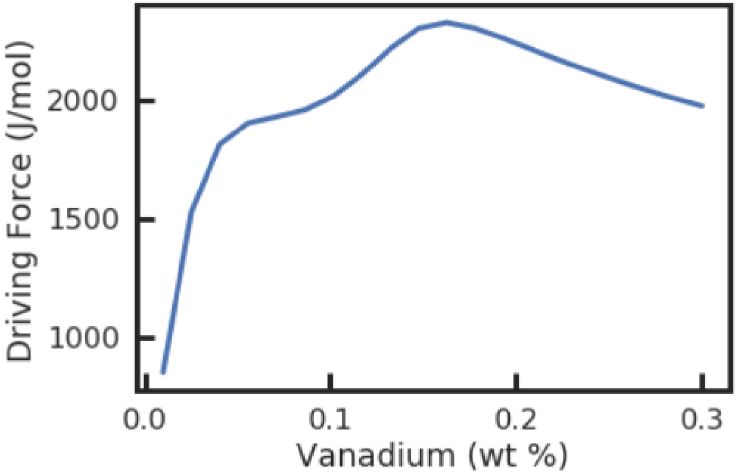
Effect of composition on Z-phase driving force

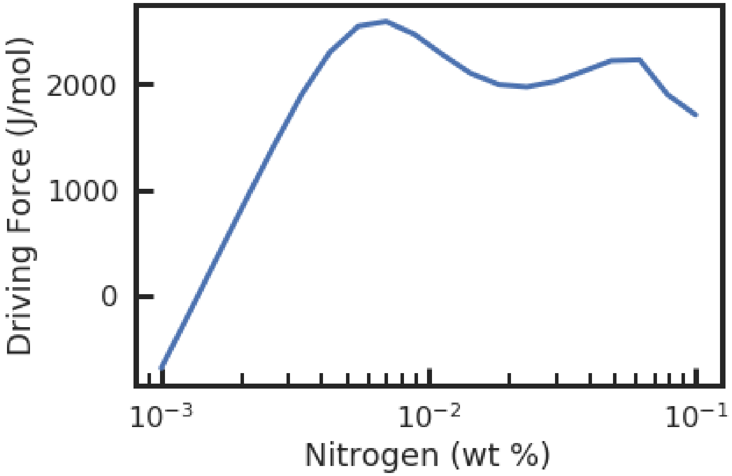








CALPHAD method enables prediction of Z-Phase stability as a function of composition



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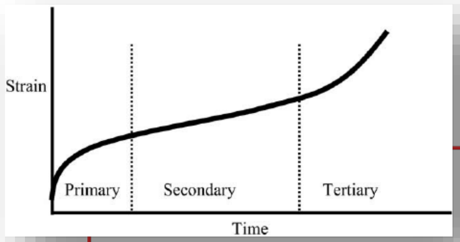
Modeling creep ductility

- Important to model the tertiary creep region accurately to get accurate prediction of creep ductility
- Kachanov-type damage evolution most widely used method for describing tertiary creep

$$\dot{D}_{CV} = C \cdot \dot{\varepsilon}_{eq}^{cr} \left(\frac{\sigma_1}{\sigma_{eq}} \right)^{\nu}$$

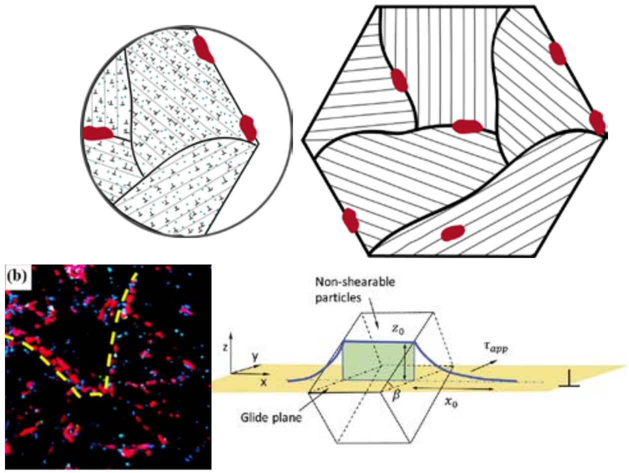
- Damage evolution governed by maximum principle stress
- Phenomenological approach not based on actual creep cavitation and growth mechanism
- QuesTek's efforts will be based on developing damage evolution model using an extension of Gurson-type model (GTN model) for modeling ductile failure in porous material
- Plastic deformation in Gurson model can directly be replaced by creep deformation. Void nucleation and growth relation will be taken from Needleman and Tvergaad formulation of Gruson model
- Such a mechanistic approach will enable prediction of damage evolution as a function of composition, specifically the inclusion content. (Strong dependence of inclusion on void nucleation reported by EPRI)

Landscape of long term creep modeling for CSEF steels



	PRIMARY CREEP	SECONDARY CREEP	TERTIARY CREEP
Mechanism	Dislocation density evolution	Dislocation climb and glide Precipitate evolution Martensite microstructure evolution	Creep cavitation
State-of-art modeling approach	Hardening parameter	Hyperbolic sine model with damage parameters Precipitate damage parameter	Cavitation damage parameter (Kachanov-type damage model)
QuesTek's modeling approach	Hardening parameter or dislocation density evolution model	Dislocation dynamics based microstructure sensitive model Precipitation model Subgrain evolution model	Gurson-type damage evolution model

A multiscale modeling framework



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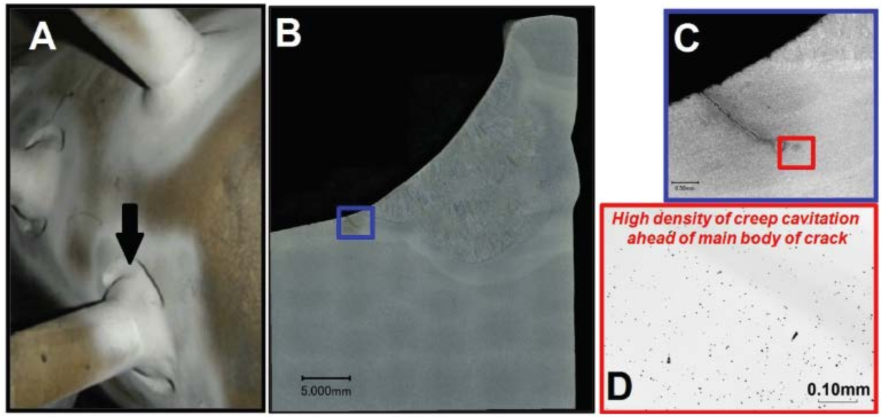
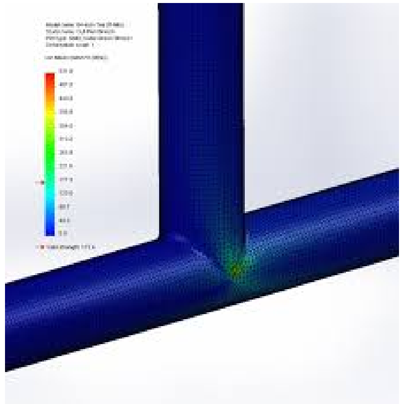


EPRI 3002003472 (2014)



QT creep strain rate model + microstructure evolution model

+

QT creep damage evolution model

Convert →

Composition dependent CDM models

Summary

- QuesTek's creep model
  - Captures diffusional and power law creep behavior for Grade 91 steels
  - Good agreement with experiments
  - Mechanistic approach enables easy application to other (CSEF) alloys
- Ongoing efforts at QuesTek
  - Application of model to weld metal and HAZ
  - Creep damage evolution model
  - QT model to CDM model converter
- Contacts

  - Abhinav Saboo (PM), asaboo@questek.com
  - Jiadong Gong (PI), jgong@questek.com

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