New Mechanistic Models of Creep-Fatigue Interactions for Gas Turbine Components (DE-FE0011796)

Thomas Siegmund
School of Mechanical Engineering, Purdue University
Email: siegmund@purdue.edu

Vikas Tomar
School of Aerospace and Aeronautical Engineering, Purdue University
Jamie Kruzic
Oregon State University

TEAM - DOE

Purdue University

- Thomas Siegmund with Dr. Trung Nugyen (post doc)
- Vikas Tomar with Devendra Verma (PhD student)

Oregon State University

- Jay Kruzic with Halsey Ostergaard (PhD Student)

DOE-NETL Program Management

- PM Dr. Rin Burks

DOE-NETL Collaboration

- Dr. Jeff Hawk NETL Albany

OSU Oregon State UNIVERSITY

PURDUE UNIVERSITY

TIMELINE

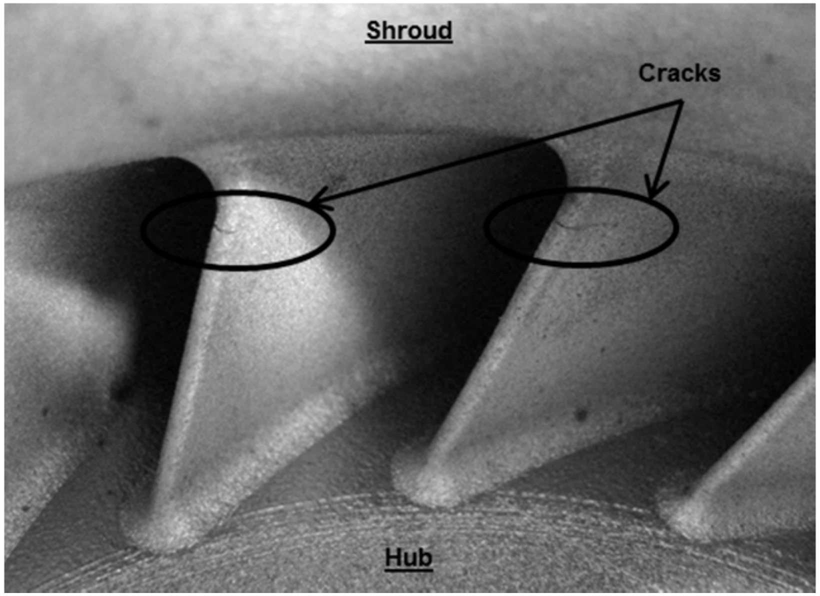
Project Milestone Description	Project Duration - Start: 2/15/2015 End: 12/1/2017												Planned Start Date	Planned End Date	Actual Start Date	Actual End Date
	Project Year (PY) 1				Project Year (PY) 2				Project Year (PY) 3							
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12				
Project Management Plan	x												2/15/15	3/1/15	2/15/15	3/1/15
Literature Assessment	x	x											2/15/15	5/1/15	2/15/15	5/1/15
Material Acquisition	x	x											2/15/15	5/1/15	2/15/15	5/1/15
Definition of Strain Gradient Visco-Plasticity	x	x	x										2/15/15	7/1/15	2/15/15	7/1/15
Definition of Cohesive Zone Model			x	x									7/1/15	12/1/15	7/1/15	
HT Nanoindentation		x	x	x									5/1/15	12/1/15	8/1/15	
Uniaxial Cyclic Deformation Data and Parameters		x	x	x									5/1/15	12/1/15	8/1/15	
Model Implementation of UMAT and UEL				x	x	x							12/1/15	5/1/16	8/1/15	
Model Verification				x	x	x							12/1/15	5/1/16	8/1/15	

Oregon State University

Purdue University

BACKGROUND

Cracks: In conventional and AM parts



[1] 2006 Los Angeles Incident, PROBABLE CAUSE: "The HPT stage 1 disk failed from an intergranular fatigue crack …."
http://aviation-safety.net/database/record.php?id=20060602-0

[2] Direct Metal Laser Sintering: Karl Wygant et al.; Pump and Turbine 2014

BACKGROUND

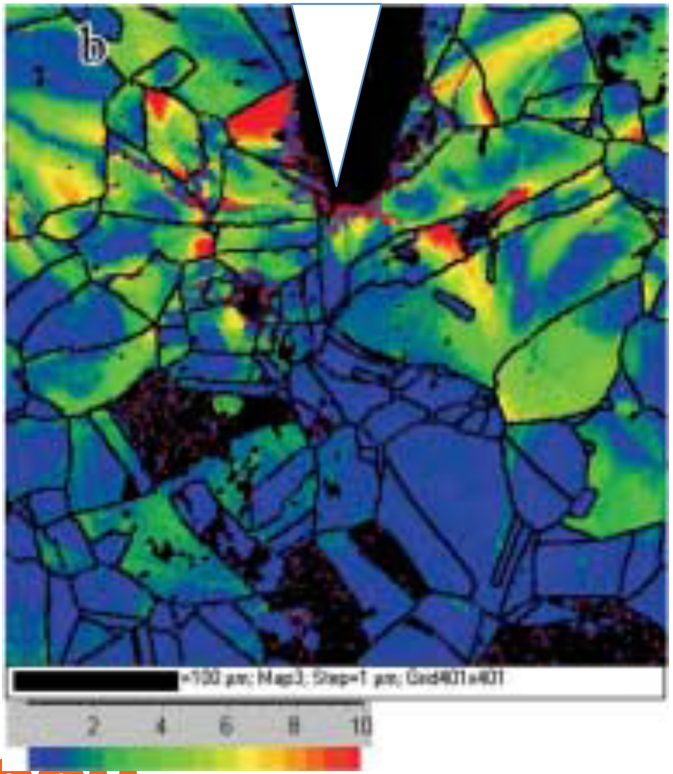
Views on Fatigue Failure

- *S-N*: stress only, no cracks
- Fracture Mechanics: global description, cracks
  Rule based (Paris law and beyond)
- **Micromechanics: local description**
  Aims to avoid rules and become predictive in complex loading scenarios

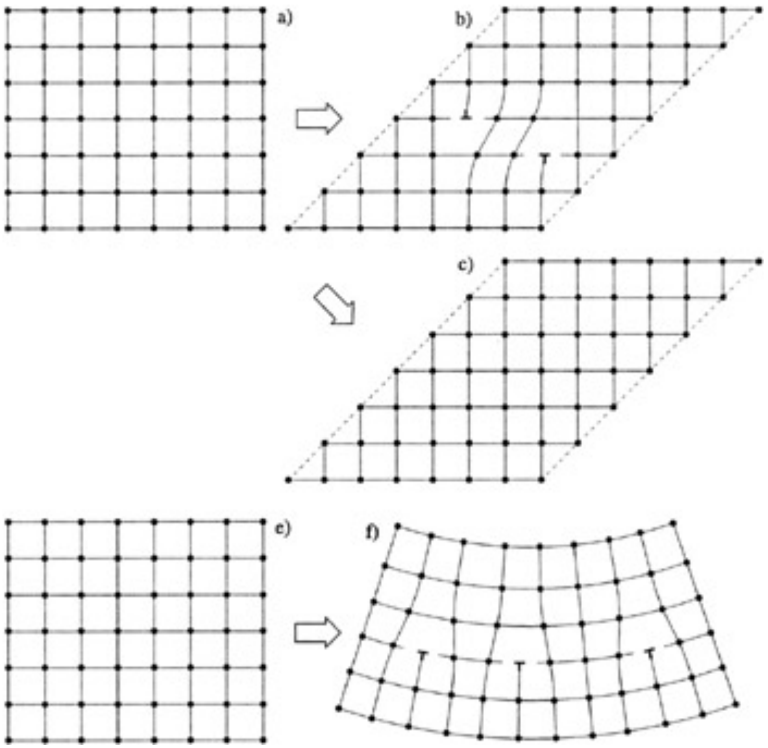
BACKGROUND

Plasticity

EBSD misorientation to reference at crack tip



Misorientation=GND Strain gradients



Brewer et al. Microsc. Microanal. 12, 85–91, 2006

BACKGROUND: RATE INDEP.

$$r_m = \frac{1}{3\pi}\frac{K}{(\sigma_0)^2} \rightarrow r_c = \frac{1}{3\pi}\frac{K}{(4\sigma_0)^2}$$ ......cyclic plastic zone size

$$\eta = \frac{\Delta\varepsilon_{pl}}{r_c}$$ .... strain gradient, therefore a length $\Lambda[m]$

$$\boxed{\varepsilon_{pl},\eta \quad \rightarrow \quad \sigma_0 = f(\varepsilon_{pl},\eta,microstr.)}$$

$$\boxed{\Delta a \approx \Delta CMOD = \frac{J}{2\sigma_0} \quad \rightarrow \quad \left(\frac{J}{2\sigma_0}/\Lambda\right) \text{......non-dim.}}$$

BACKGROUND

Hypothesis

Strain Gradient effects of viscoplastic deformation play a relevant role in the failure response of IN 718 at use temperature (650°C).

- Conventional viscoplasticity is incomplete in its description of rate dependent deformation as effects of gradients of strain are ignored.
- Gradient theories predict higher crack tip stresses, and thus stronger activation of stress dependent processes
- Gradient theories alter the tip deformation fields, an thus not only a cyclic plastic zone but also a cyclic gradient zone exist in fatigue

BACKGROUND

Research Question 1

How do we formulate a constitutive framework that accounts for gradient viscoplasticity and other observed specific features of plasticity in IN 718.

BACKGROUND

Research Question 2

What are the experimental methods to determine the lengthscale parameters inherent to a gradient theory through experimentation?

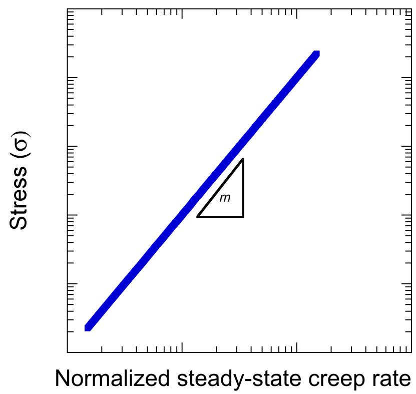
BACKGROUND

Research Question 3

How is a Local-Approach to material failure best be used to predict crack growth in IN 718 under creep-fatigue-environmental loading conditions?

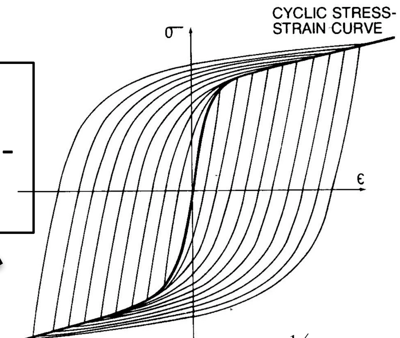
OVERVIEW: ORIGINAL PLAN

Research on Constitutive Parameters



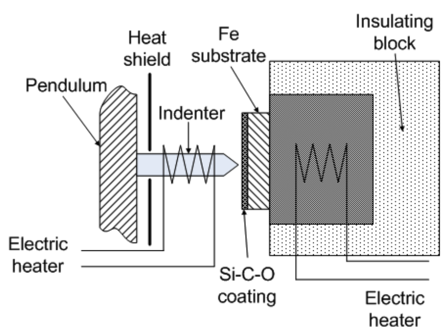
Uniaxial Creep at 650°C
@ multiple stress levels

Tensile cyclic stress-strain at 650°C

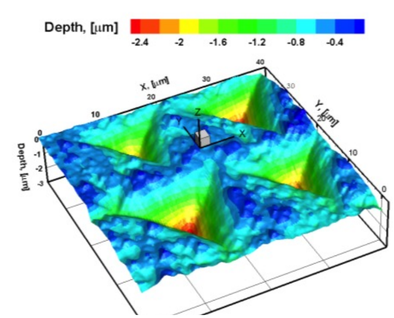


$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2A'}\right)^{1/n}$$

Experimentally determined parameter	Symbol	Experiment
Reference stress	A'	Cyclic tensile tests
Cyclic strain hardening exponent	n	Cyclic tensile tests
Strain rate exponent	m	Uniaxial creep & Nanoindentation
Reference strain rate	$\dot{\varepsilon}_0$	Uniaxial creep & Nanoindentation
Characteristic length scale	$\boldsymbol{l}$	Nanoindentation
Dislocation-strain softening	ρ_i	Nanoindentation post creep



Nano-indentation at 650°C



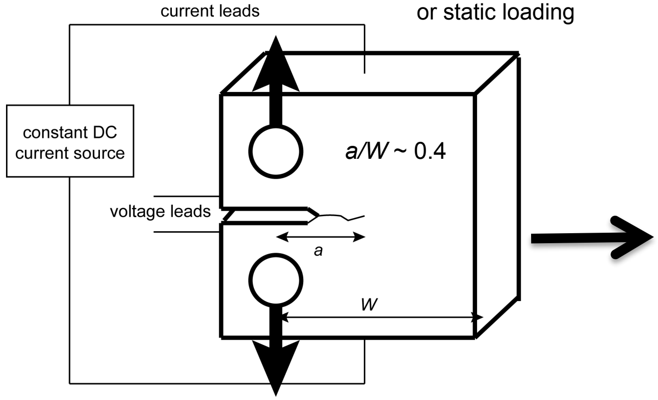
OSU Oregon State University

PURDUE UNIVERSITY

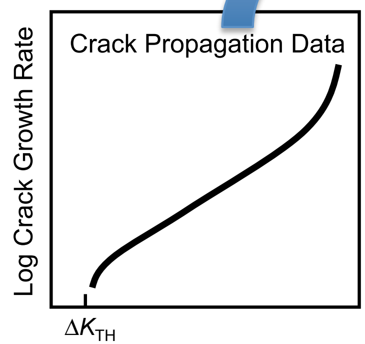
OVERVIEW: ORIGINAL PLAN

Research on Crack Propagation Models

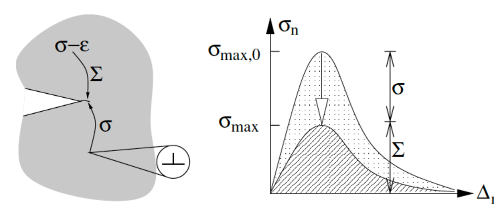
Low frequency cyclic (f < 0.25 Hz), high load ratio (R ~ 0.5) or static loading



Creep crack growth &
Creep-fatigue crack growth at 650°C

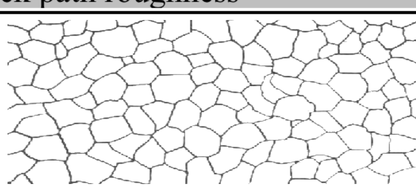


Cohesive Zone Model



Iterate to converge on model parameters

Experimentally determined parameter	Symbol	Experiment
Cohesive zone threshold	σ_f	Long crack fatigue threshold
Cohesive zone strength and length	$\sigma_{\max,0}, \delta_\Sigma$	Long crack fatigue – Paris law Overload retardation
Creep damage parameters	Ω , p	Creep crack growth
Crack path roughness	R_A	ASTM E112 grain size analysis



Grain size to estimate crack path

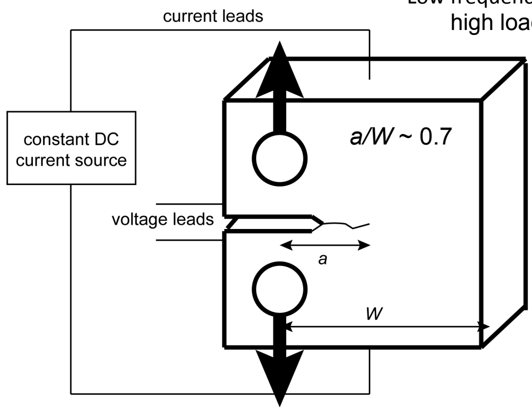
OSU Oregon State UNIVERSITY

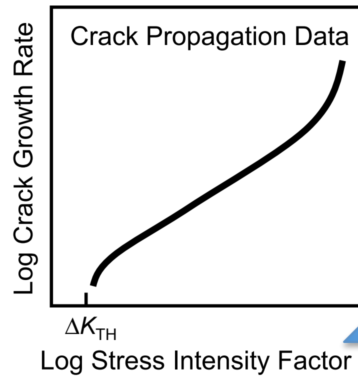
PURDUE UNIVERSITY

OVERVIEW: ORIGINAL PLAN

Initial Validation & Model Refinement

Low frequency cyclic (f < 0.25 Hz), high load ratio (R ~ 0.5)

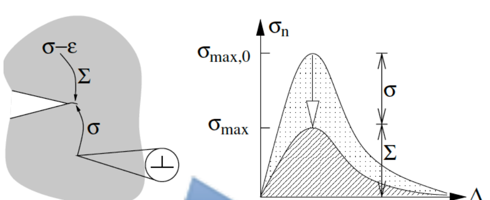


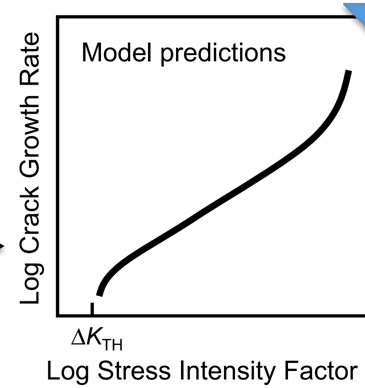


Model must achieve transferability across ***changing crack tip constraint conditions***

Compare results

- Creep-fatigue crack growth at 650°C using both experiment and model
- Crack tip constraint is changed from previous experiments (a/W now ~0.7)



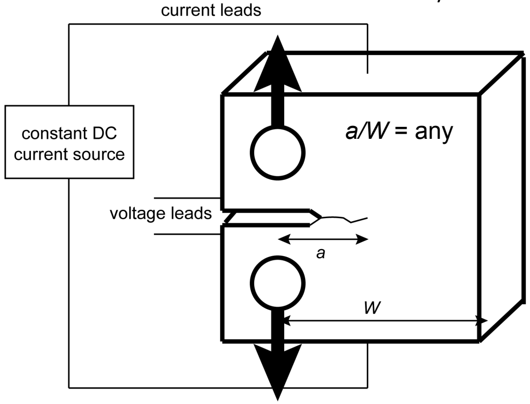


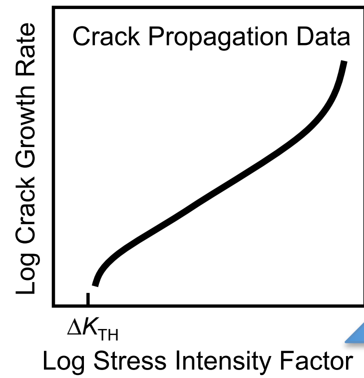
If needed, refine model and iterate to converge on improved model framework & parameters

OVERVIEW: ORIGINAL PLAN

Final Validation & Model Refinement

Variable cyclic loading frequency and dwell times

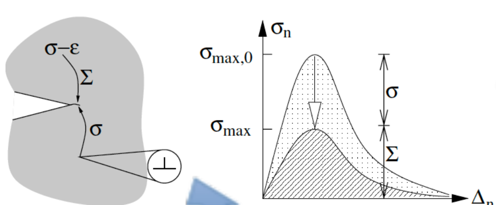


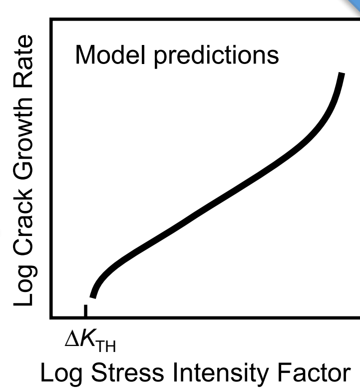


Model must achieve transferability across ***changing cyclic loading frequencies and dwell times***

Compare results

- Finally the full creep-fatigue interaction will be modeled
- Cyclic frequency will be varied and dwell times introduced

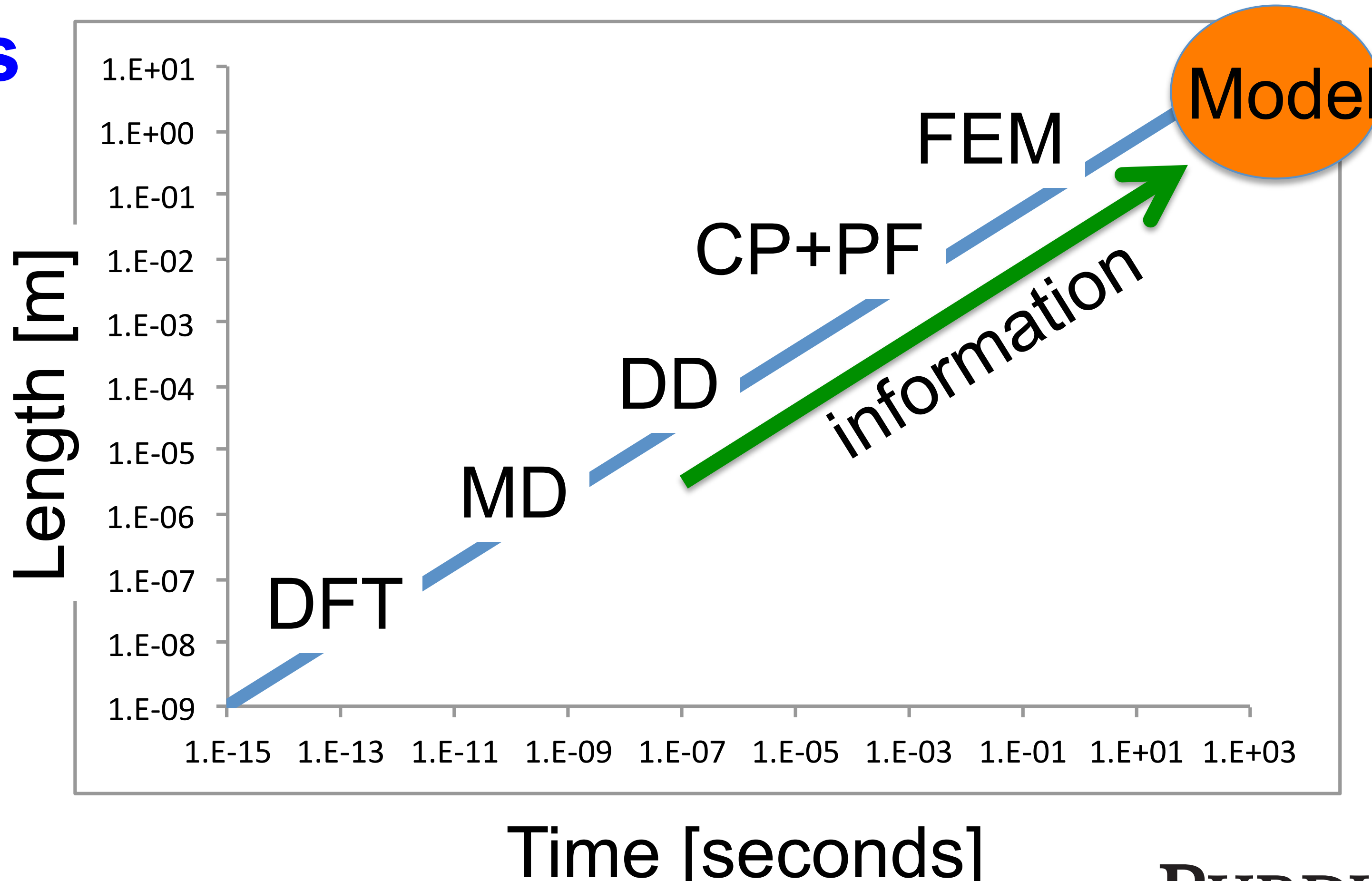




If needed, refine model and iterate to converge on improved model framework & parameters

OVERVIEW: LENGTH AND TIME

Small Scales and Long Times can only be addressed with advanced continuum models



PROGRESS: LEAD KRUZIC

Material Acquisition and Collaboration

- **IN 718**
- **Provided by Jeff Hawk, NETL Albany**
- **Processing (at NETL)**

  Step forging and squaring (from round slab D=8.5” to plate t=1.25”; Hot rolling into a plate t=0.616”; solution annealed.

  Received a plate roughly 27” x 5 5/8 “ x 0.616”.

- **Processing (at OSU)**

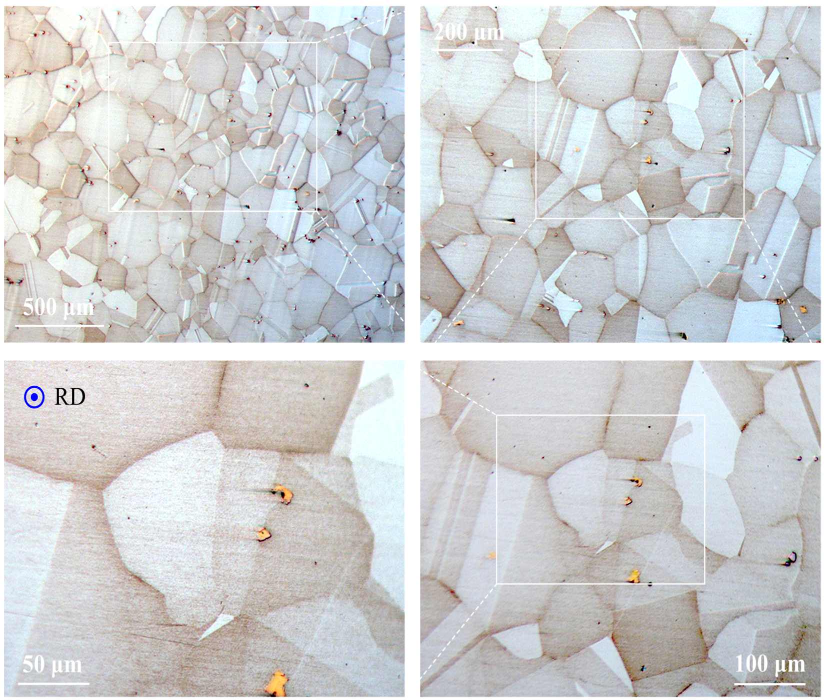
  Solution annealed at 982°C, 1hr, air cooled Hardened by holding at 718°C for 8hrs, then furnace cooled to 621°C and held for 10 hrs, then air cooled.

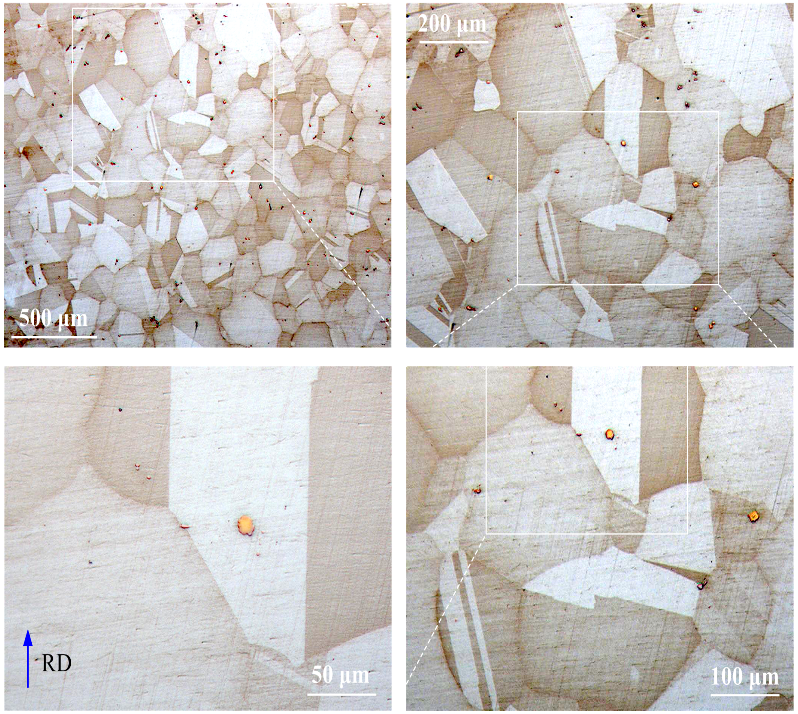
Oregon State UNIVERSITY

PURDUE UNIVERSITY

PROGRESS

Optical Microstructure Characterization



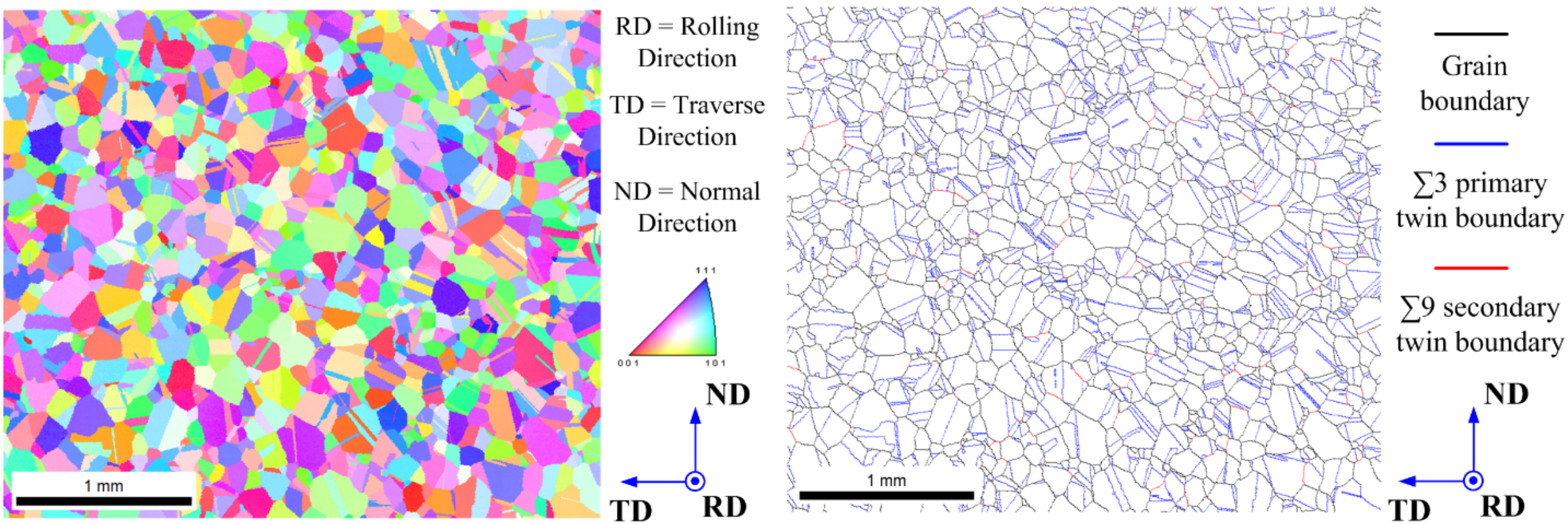


Uniform and equiaxed microstructure

Oregon State University

Purdue University

EBSD on Transverse Section



(a) Crystal orientation map (b) Grain/twin boundary map

Highly twinned

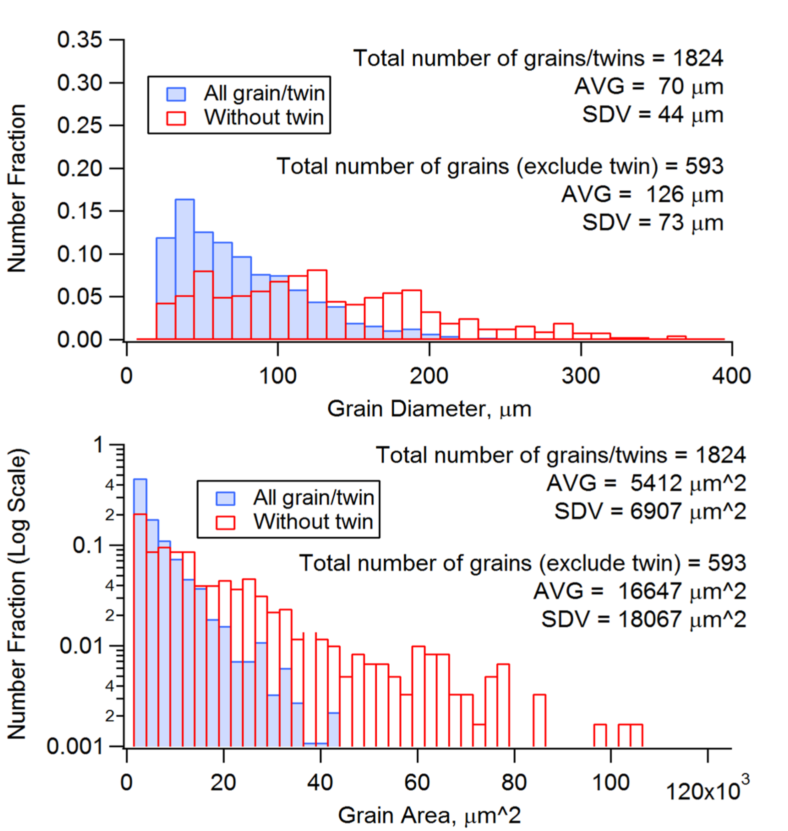
Most twins as ∑3 (from recrystallization)

Oregon State University

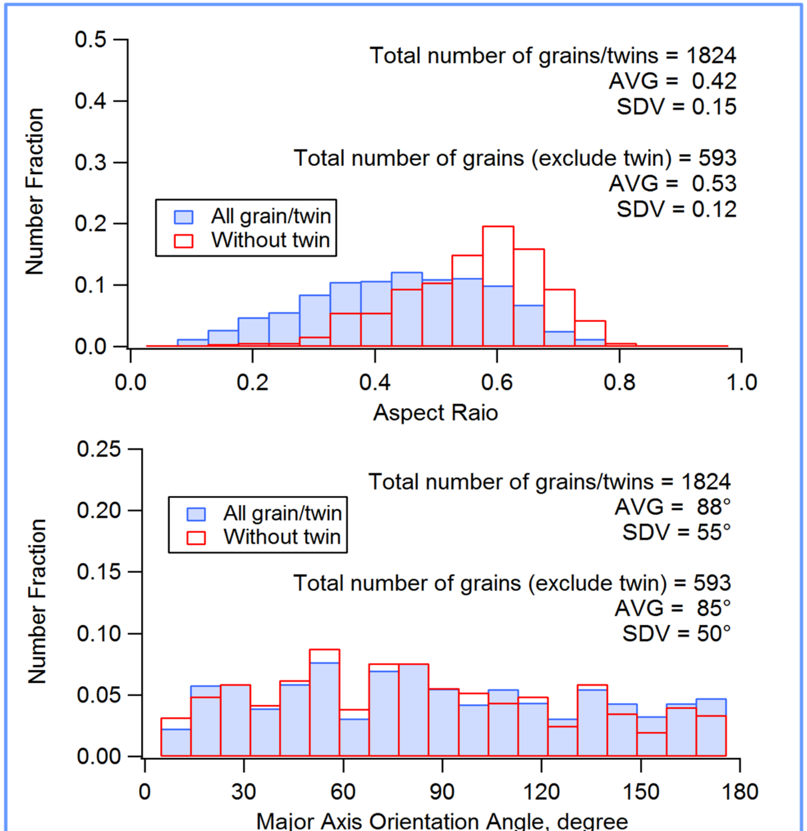
Purdue University

PROGRESS

Grains & Twins: Grain Size and Orientation



(a) Grain size



(b) Grain shape

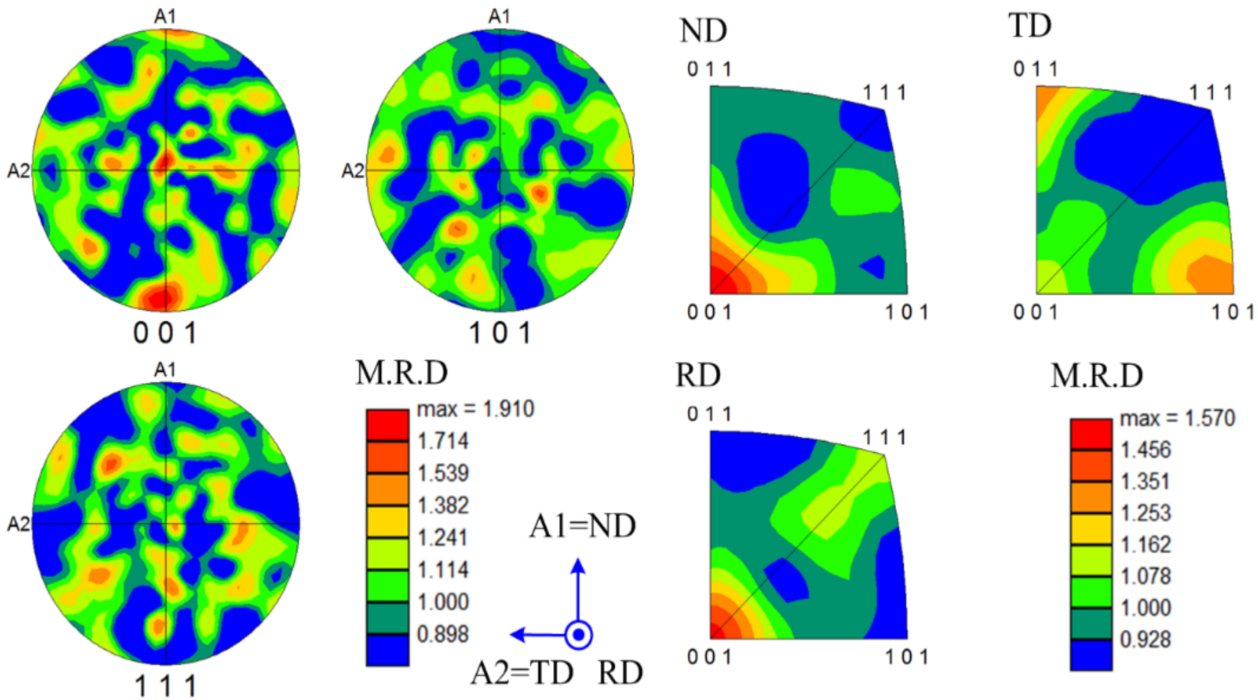
Analysis with and without twins

Oregon State UNIVERSITY

PURDUE UNIVERSITY

PROGRESS

Texture



(a) Pole figure (b) Inverse pole figure

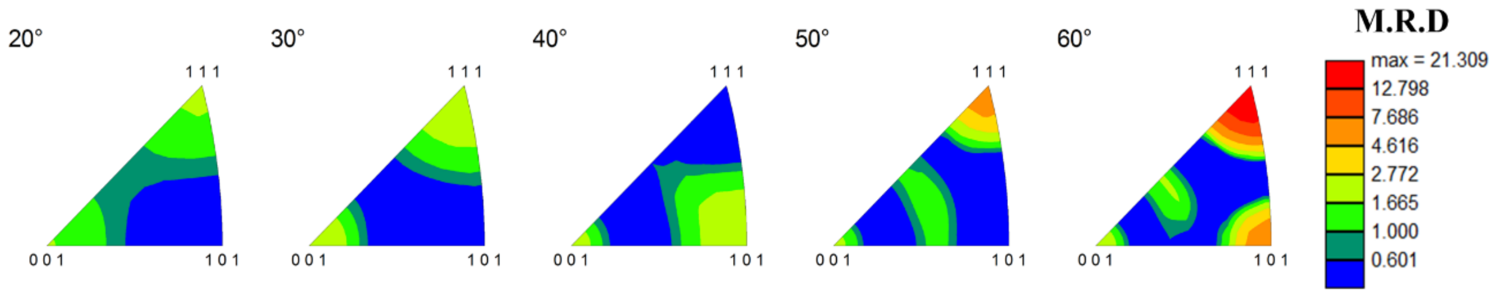
Only weak initial texture, remnants of a cube (100)[001] and even weaker fiber <111> texture exist

Oregon State University

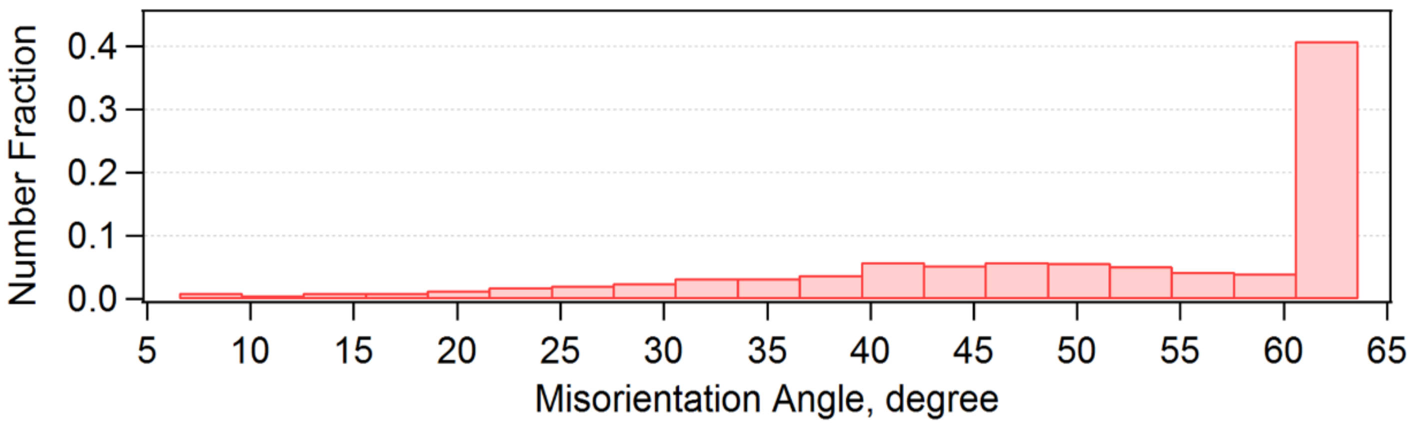
Purdue University

PROGRESS

Grain and Twin Boundaries



(a) Misorientation axis distribution



(b) Misorientation angle distribution

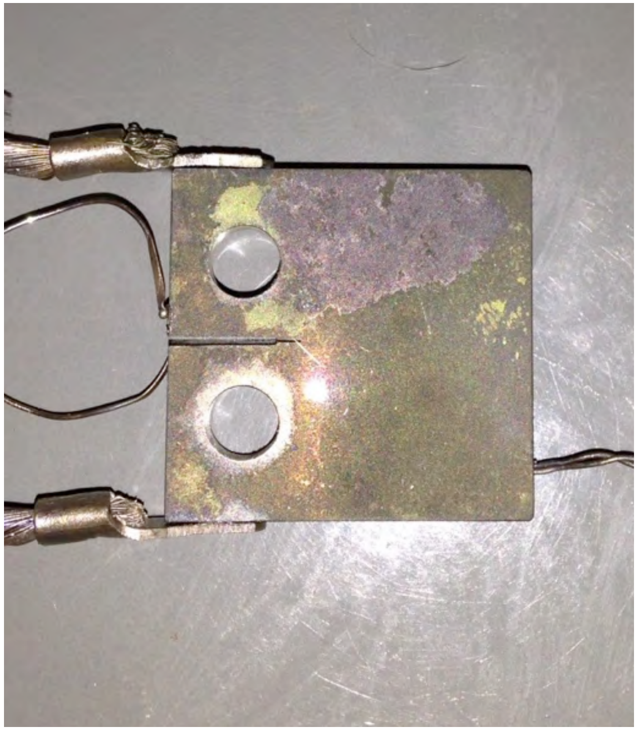
Strongly influenced by S3 twins

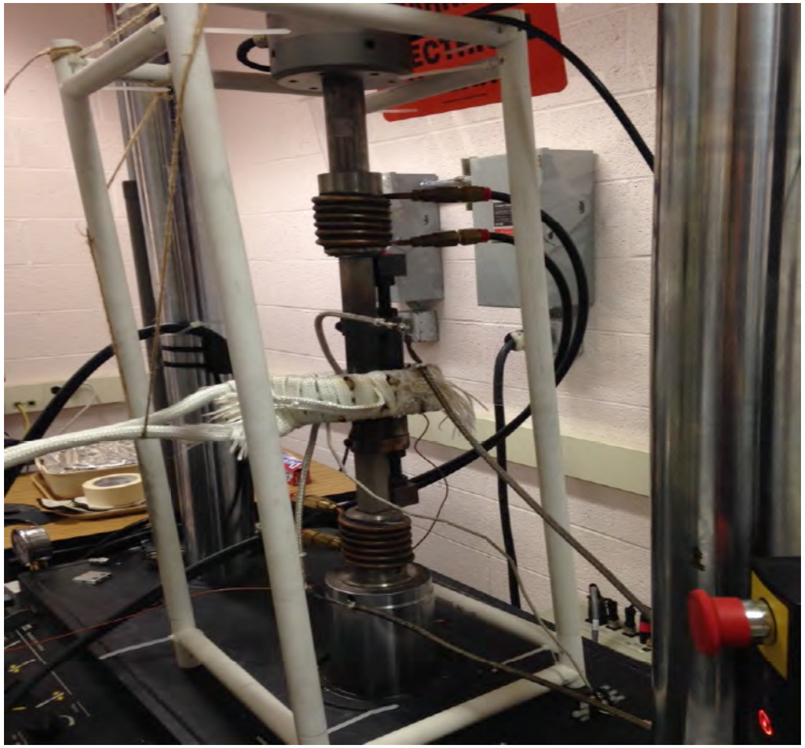
Oregon State University

Purdue University

PROGRESS

Creep Experiment: In progress



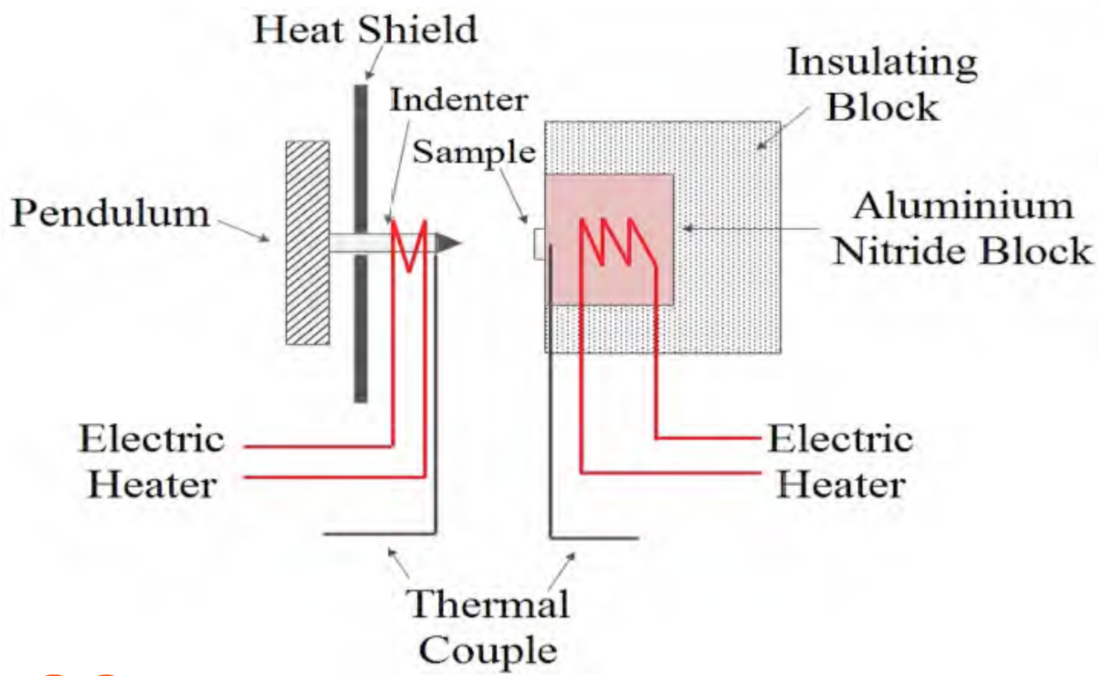


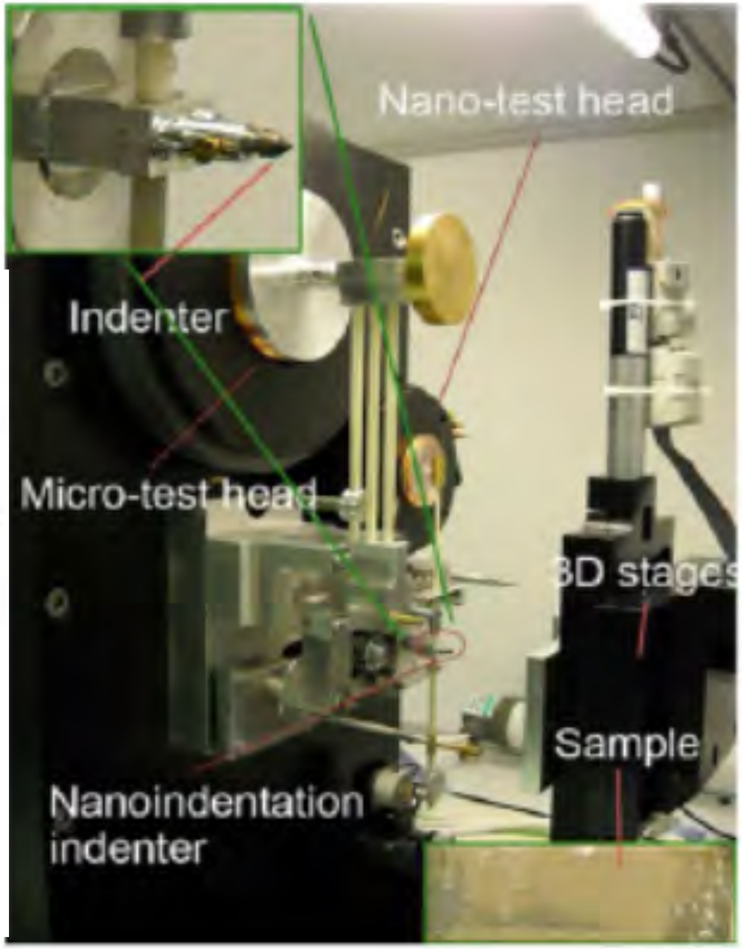
HT Experiments on CT specimens with potential drop measurements

PROGRESS: LEAD TOMAR

High Temperature Nanoindentation

Probe plasticity at small length scales



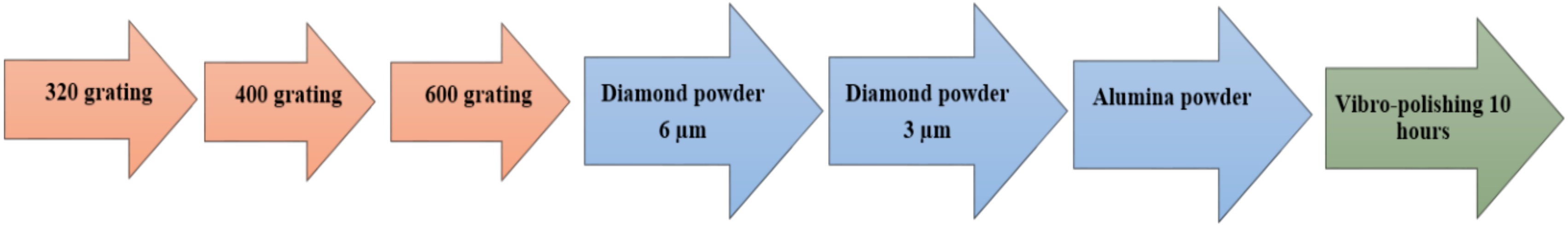


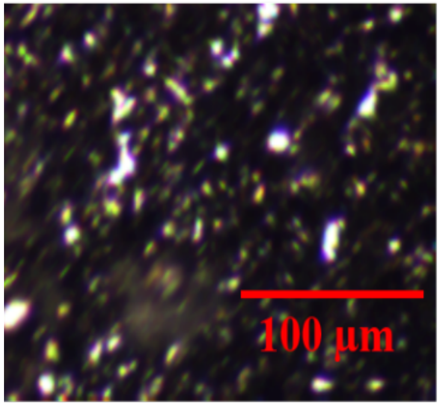
OSU Oregon State University

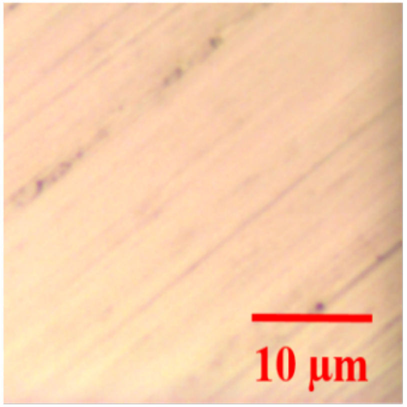
PURDUE UNIVERSITY

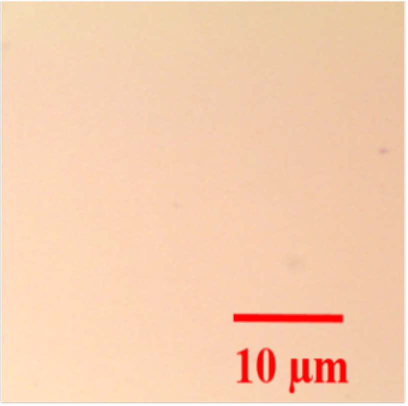
PROGRESS

HT Nanoindentation: Specimen preparation









OSU Oregon State University

Purdue University

PROGRESS

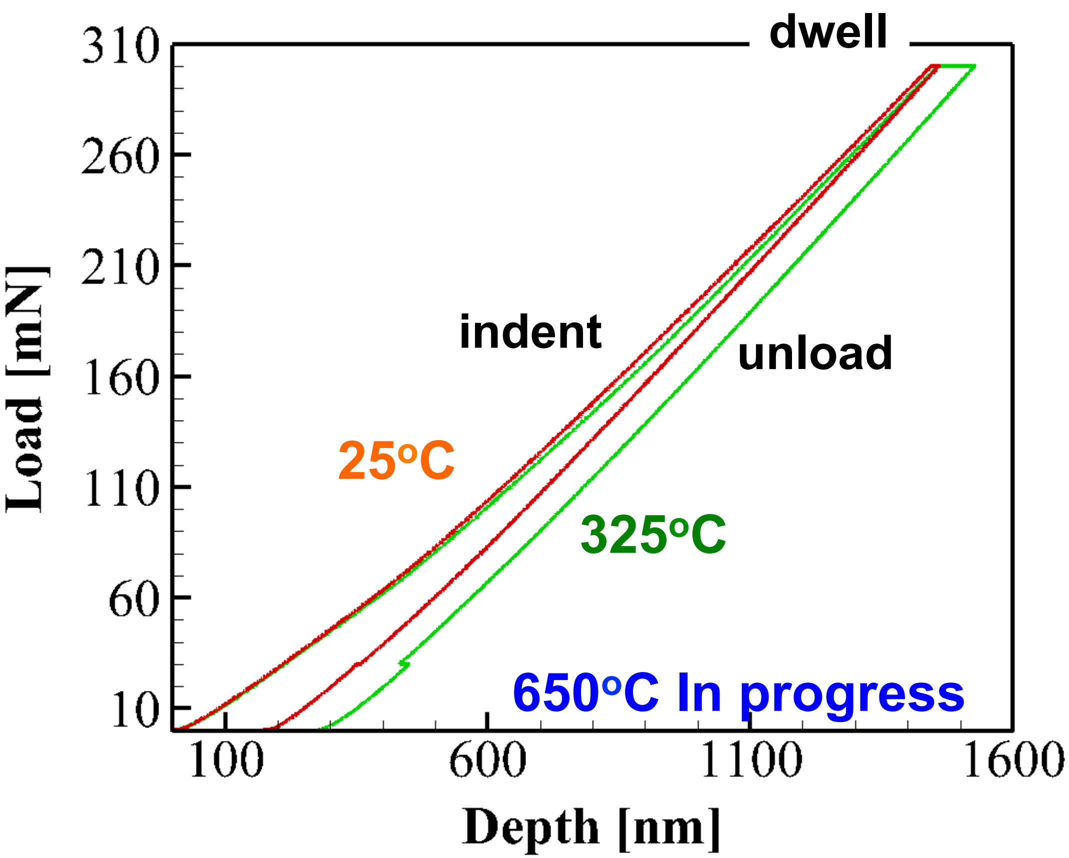
HT Nanoindentation: Experimental plan

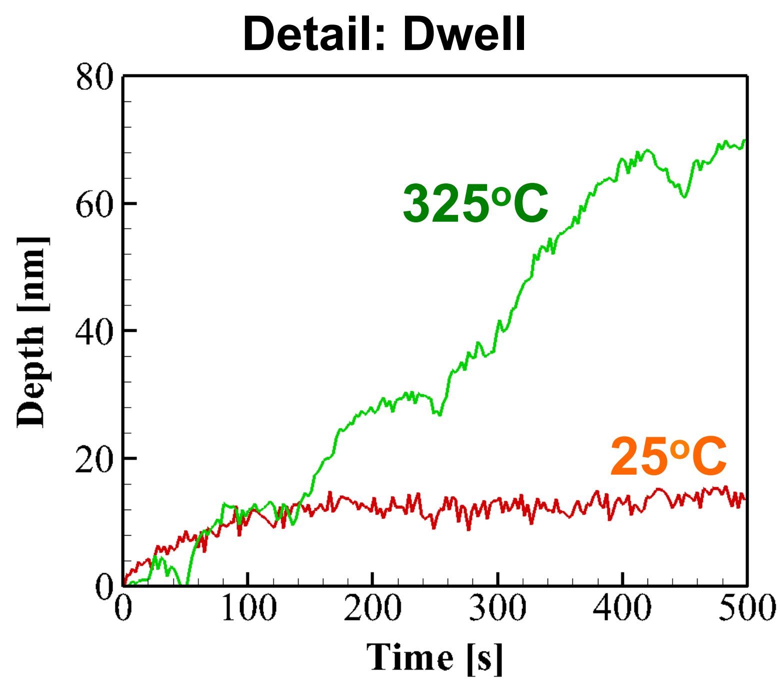
Through change in indent depth the ratio of **viscoplast. strain & viscoplast. strain gradient** is altered → obtain the relevant length scale

Load (mN)	25 °C (no. of points)	350 °C (no. of points)	650 °C (no. of points)	Post oxidation (no. of points)	Dwell time (s)
50	10	10	10	10	500
100	10	10	10	10	500
200	10	10	10	10	500
300	10	10	10	10	500
400	10	10	10	10	500

PROGRESS

HT Nanoindentation: 1st data on IN 718





Oregon State University

Purdue University

PROGRESS: LEAD SIEGMUND

Constitutive Models: Gradient Effects

Flow stress

$$\sigma_{\text{flow}} = \sigma_0 + M\alpha\mu b\sqrt{\rho}$$

σ_0: stress related to lattice friction and solute contents

M: average Taylor factor ($M \approx 3$)

α: weighting factor of dislocation interactions ($\alpha \approx 1/3$)

μ: shear modulus

b: Burgers vector

PROGRESS

Constitutive Models

Dislocation density: $\rho = \rho_S + \rho_G$

- Statistically stored dislocation:

$$\rho_S = \frac{\sqrt{3}\bar{\varepsilon}^{vp}}{b\Lambda}$$

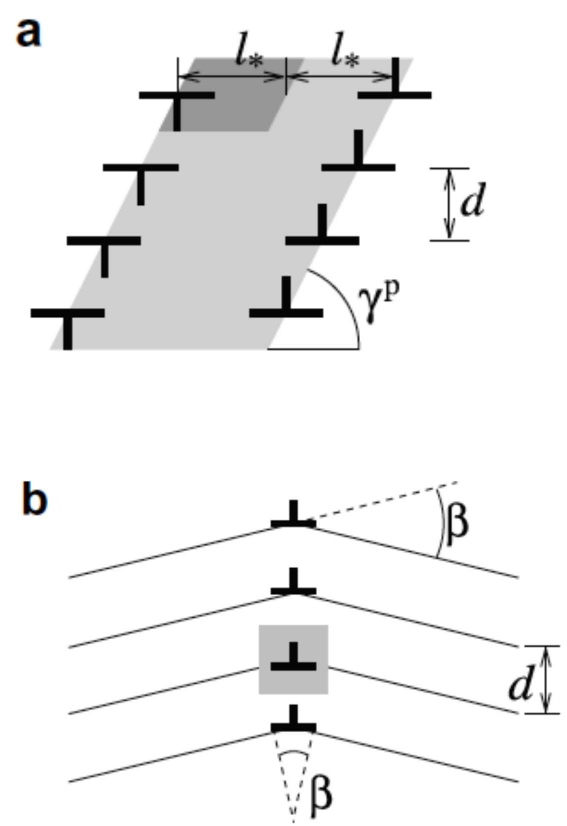
Λ: mean free path

- Geometrically necessary dislocation:

$$\rho_G = \bar{r}\frac{\bar{\eta}}{b}$$

$\bar{\eta}$: effective plastic strain gradient

$\bar{r}$: Nye-factor ($\bar{r} = 1.90$)



Oregon State University

Purdue University

PROGRESS

Constitutive Models: Flow Stress

$$\sigma_{\text{flow}} = \sigma_0 + M\alpha\mu b\sqrt{\rho_S + \rho_G} = \sigma_0\left(1 + \frac{\sqrt{3}\alpha\mu b}{\sigma_0}\sqrt{\frac{\sqrt{3}\bar{\varepsilon}^{vp}}{b\Lambda} + \frac{\bar{\eta}}{b}}\right)$$

$$\Delta\dot{\bar{\varepsilon}}^{vp} = g(\boldsymbol{\sigma}, \mathbf{q})$$

$\mathbf{q}$: state variable vector

$$\Delta\bar{\varepsilon}^{vp} = \Delta t\dot{\bar{\varepsilon}}^{vp} = \Delta t \cdot g(\boldsymbol{\sigma}, \mathbf{q}) = \Delta t\dot{\bar{\varepsilon}}_0\left(\frac{\bar{\boldsymbol{\sigma}}}{\boldsymbol{\sigma}_{\text{flow}}}\right)^m$$

$$\boxed{\left(\frac{J}{2\sigma_0}/\Lambda\right), (b/\Lambda), \left(\frac{\dot{J}}{2\sigma_y}/\dot{\varepsilon}_0\Lambda\right)}$$

OSU Oregon State University

PURDUE UNIVERSITY

PROGRESS

Computational Implementation

$$\dot{\varepsilon}_{ij} = \frac{\dot{\sigma}_{ij}}{9K}\delta_{ij} + \frac{\dot{s}_{ij}}{2\mu} + \frac{3\dot{\bar{\varepsilon}}^{vp}}{2\bar{\sigma}}\dot{s}_{ij} = \frac{\dot{\sigma}_{ij}}{9K}\delta_{ij} + \frac{\dot{s}_{ij}}{2\mu} + \frac{3\dot{\bar{\varepsilon}}_0}{2\bar{\sigma}}\left(\frac{\bar{\sigma}}{\sigma_0\left(1+\frac{\sqrt{3}\alpha\mu b}{\sigma_0}\sqrt{\frac{\sqrt{3}\bar{\varepsilon}^{vp}}{b\Lambda}+\frac{\bar{\eta}}{b}}\right)}\right)^m \dot{s}_{ij}$$

$$\dot{\sigma}_{ij} = K\dot{\varepsilon}_{ij}\delta_{ij} + 2\mu\left\{\dot{\varepsilon}'_{ij} - \frac{3\dot{\bar{\varepsilon}}_0}{2\bar{\sigma}}\left[\frac{\bar{\sigma}}{\sigma_0\left(1+\frac{\sqrt{3}\alpha\mu b}{\sigma_0}\sqrt{\frac{\sqrt{3}\bar{\varepsilon}^{vp}}{b\Lambda}+\frac{\bar{\eta}}{b}}\right)}\right]^m \dot{s}_{ij}\right\}$$

PROGRESS

Computational Implementation

Euler implicit scheme + Newton-Raphson iteration

- Nonlinear equations

$$f_1\left(\Delta\bar{\varepsilon}^{vp},\bar{\sigma}\right)=\Delta\bar{\varepsilon}^{vp}-\Delta t\dot{\bar{\varepsilon}}_0\left(\frac{\bar{\sigma}}{\sigma_{\text{flow}}}\right)^m=0$$

$$f_2\left(\Delta\bar{\varepsilon}^{vp},\bar{\sigma}\right)=3\mu\left(\bar{\varepsilon}^{*}-\Delta\bar{\varepsilon}^{vp}\right)-\bar{\sigma}=0$$

- Trial state

$$\boldsymbol{\varepsilon}_{n+1}^{trial}=\boldsymbol{\varepsilon}_{n}^{el}+\Delta\boldsymbol{\varepsilon};\quad \bar{\varepsilon}^{*}=\sqrt{\frac{2}{3}\boldsymbol{\varepsilon}_{n+1}^{trial}:\boldsymbol{\varepsilon}_{n+1}^{trial}}$$

Oregon State University

Purdue University

Computational Implementation

- Iteration

$$\begin{Bmatrix} \Delta\bar{\varepsilon}^{vp} \\ \bar{\sigma} \end{Bmatrix}_{n+1} = \begin{Bmatrix} \Delta\bar{\varepsilon}^{vp} \\ \bar{\sigma} \end{Bmatrix}_{n} - \mathbf{J}_n^{-1} \begin{Bmatrix} f_1\left(\Delta\bar{\varepsilon}^{vp}, \bar{\sigma}\right) \\ f_2\left(\Delta\bar{\varepsilon}^{vp}, \bar{\sigma}\right) \end{Bmatrix}_{n}$$

$$\mathbf{J}_n = \begin{bmatrix} \dfrac{\partial f_1}{\partial \Delta\bar{\varepsilon}^{vp}} & \dfrac{\partial f_1}{\partial \bar{\sigma}} \\ \dfrac{\partial f_2}{\partial \Delta\bar{\varepsilon}^{vp}} & \dfrac{\partial f_2}{\partial \bar{\sigma}} \end{bmatrix}_n$$

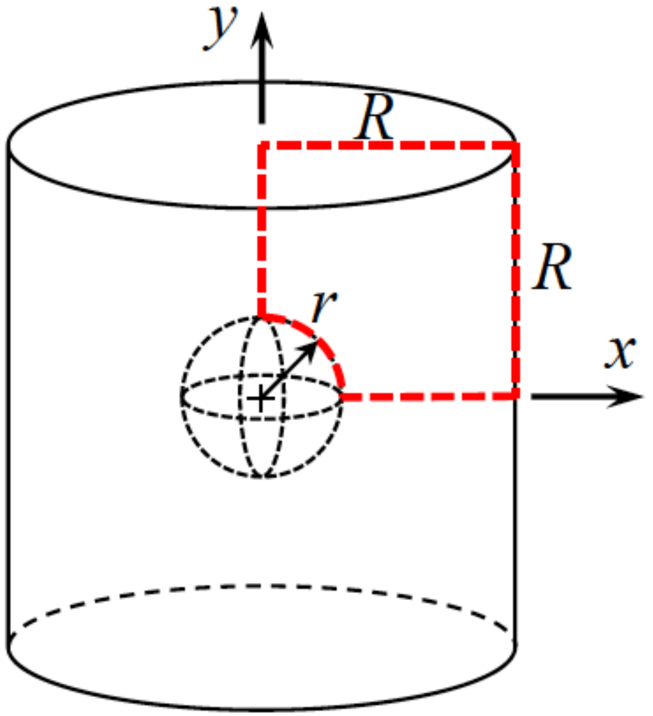
$$\bar{\varepsilon}_{n+1}^{vp} = \bar{\varepsilon}_n^{vp} + \Delta\bar{\varepsilon}^{vp}$$

- Stress update follows a standard procedure upon convergence of the above iteration.

OUTCOMES

Results: Creep Rupture

Relates to issue of voids in DMLS materials



E (GPa)	ν	σ_{y0} (MPa)	$\dot{\bar{\varepsilon}}_0$ (s^{-1})	m	b (nm)
200	0.3	250	0.005	5	0.25

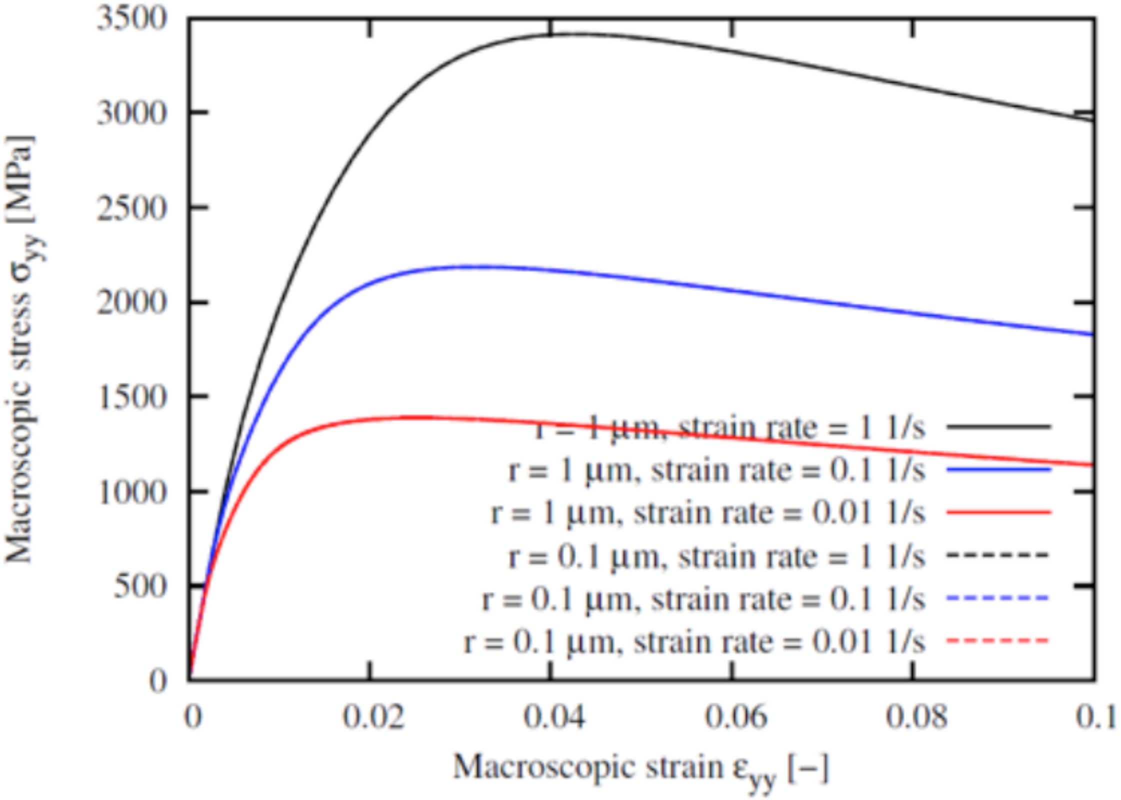
OSU Oregon State University

PURDUE UNIVERSITY

PROGRESS

Void Growth conventional plasticity

No size effect only rate effect



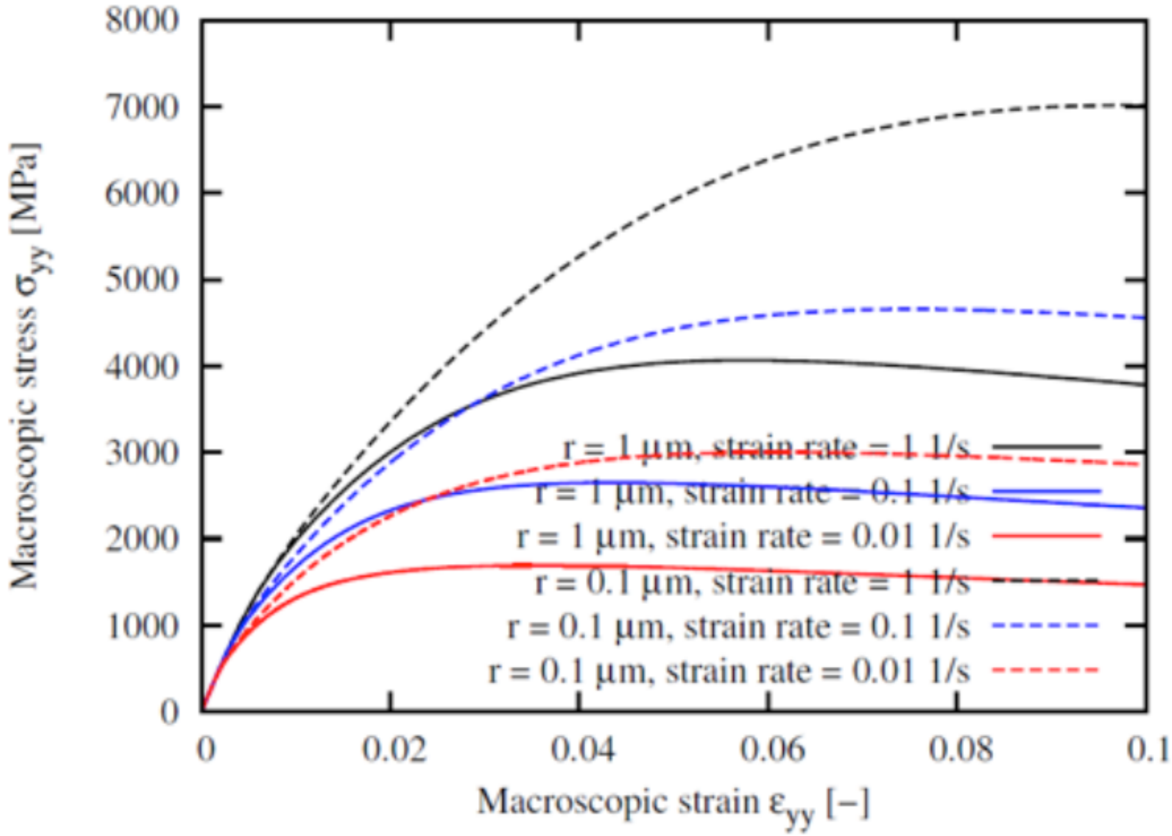
Oregon State University

Purdue University

PROGRESS

Void Growth with SGP:

Void Size Effect combined with a rate effect



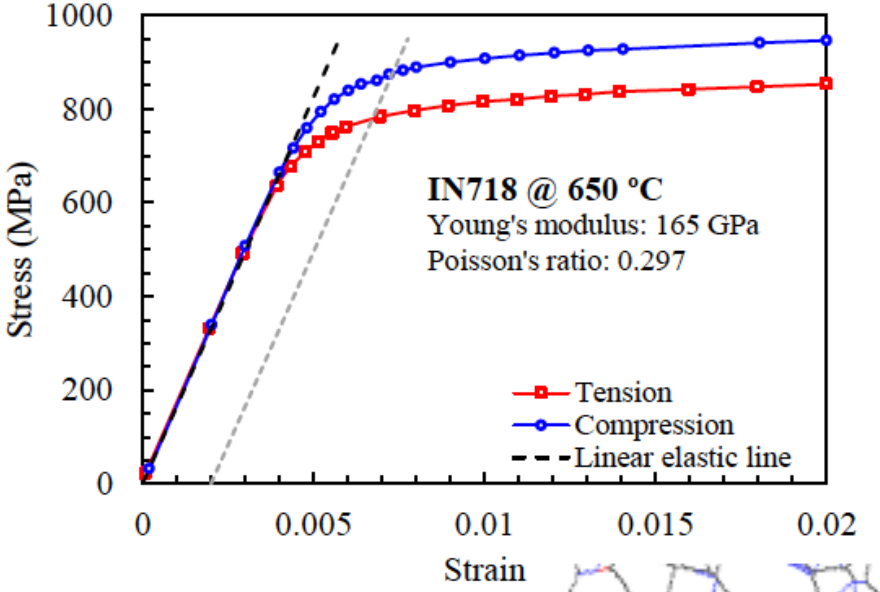
- Smaller voids lead to higher stresses
- Smaller voids are more sensitive to rate

Oregon State University

Purdue University

PROGRESS

Strength Differential Effect (Data by Lissenden et al)



$$SD = 2\frac{|\sigma_C| - |\sigma_T|}{|\sigma_C| + |\sigma_T|} = 0.12$$

$$SR = \frac{|\sigma_T|}{|\sigma_C|} = 0.88$$

Oregon State University

Purdue University

Strength Differential Effect: Yield Function

$$\Phi(s_1, s_2, s_3) = (|s_1| - k \cdot s_1)^m + (|s_2| - k \cdot s_2)^m + (|s_3| - k \cdot s_3)^m$$

m, k

$m = 2, k = 0 \ldots \text{von Mises}$

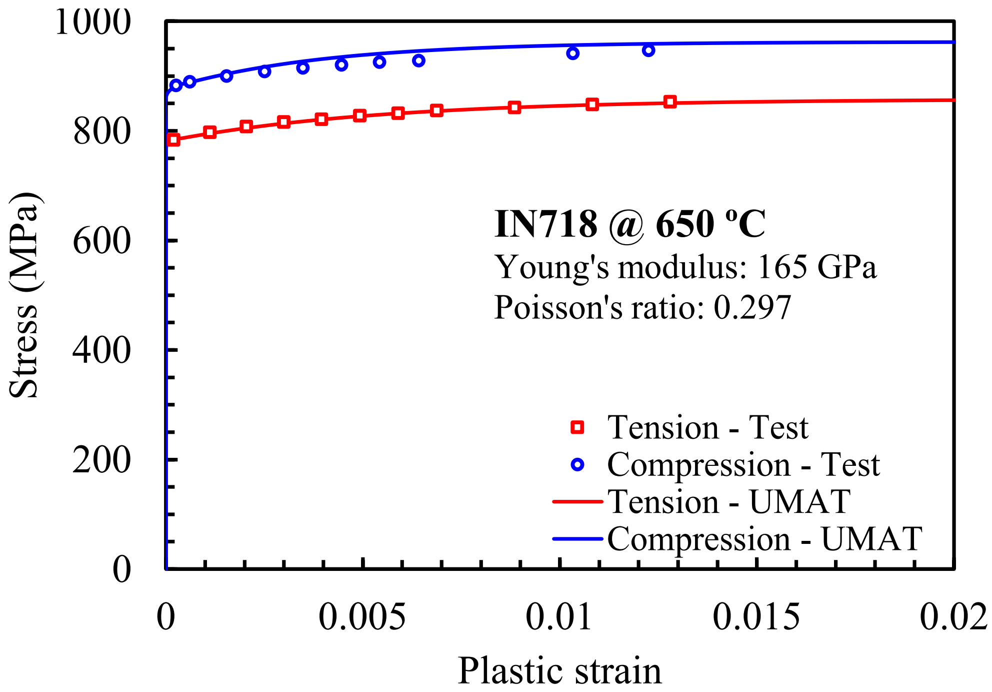
$$k = \frac{1 - \left\{ \dfrac{2^m - 2 \cdot (\sigma_T / \sigma_C)^m}{(2 \cdot \sigma_T / \sigma_C)^m - 2} \right\}^{(1/m)}}{1 + \left\{ \dfrac{2^m - 2 \cdot (\sigma_T / \sigma_C)^m}{(2 \cdot \sigma_T / \sigma_C)^m - 2} \right\}^{(1/m)}}$$

PROGRESS

Strength Differential Effect: UMAT

E (GPa)	ν	σ_T (MPa)	σ_C (MPa)	K (MPa)	ε_0	n
165	0.297	779	876	1003	0.0013	0.038

$$\sigma = K\left(\varepsilon_0 + \bar{\varepsilon}\right)^n$$

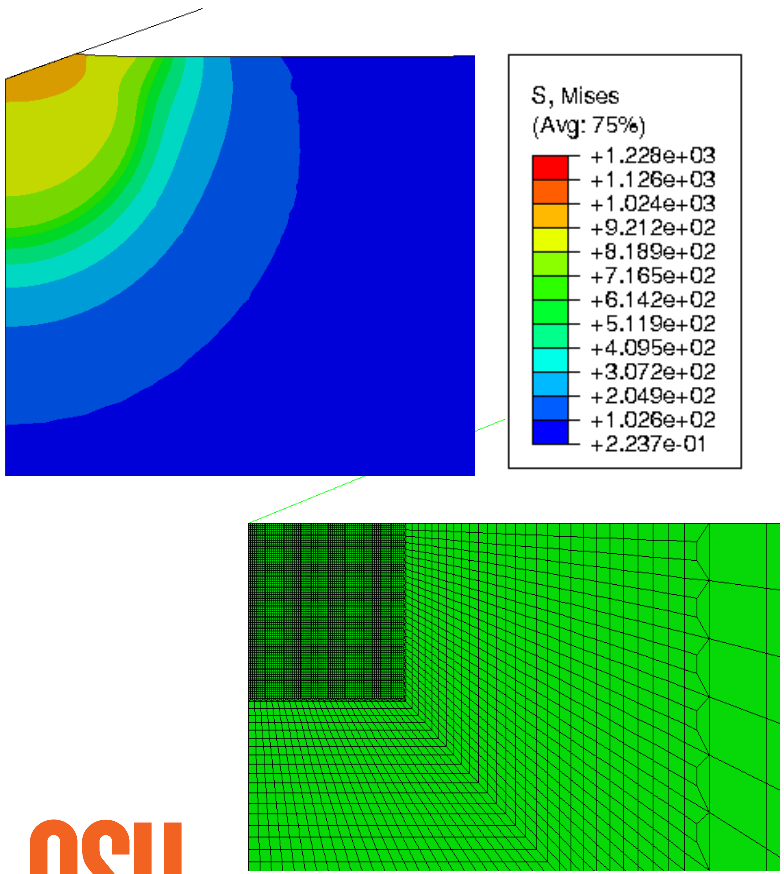


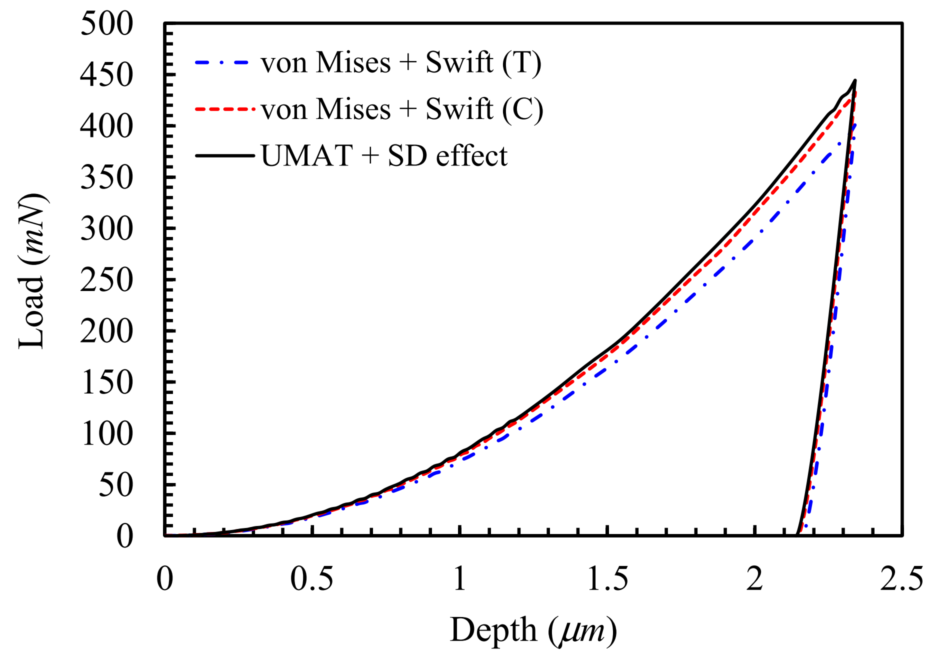
Oregon State University

Purdue University

PROGRESS

Strength Differential & Indentation





Von Mises + Swift (T)	Von Mises + Swift (C)	UMAT w/ SD
1.0	1.09	1.12

Oregon State University

Purdue University

PROGRESS

Crack Growth: Cohesive Zone Models

$$T_n = \sigma_{\max,0}\, e\left(\frac{\Delta_n}{\delta_0}\right)\exp\left(-\frac{\Delta_n}{\delta_0}\right)$$

$$\sigma_{\max} = \sigma_{\max,0}\left(1 - D_C\right)$$

$$\Delta D_C = \max\left\{0, \frac{\left|\dot{\Delta}_n\right|}{\delta_\Sigma}\left[\frac{T_n}{\sigma_{\max}} - \frac{\sigma_f}{\sigma_{\max,0}}\right] H\left(\Delta_{n,acc} - \delta_0\right)\right\}$$

$$\Delta_{n,acc} = \int_t \left|\dot{\Delta}_n\right| dt$$

$$D_C = D_C + \Delta D_C$$

$$\boxed{\left(\frac{J}{2\sigma_0} / \Lambda\right), (b / \Lambda), \left(\frac{\dot{J}}{2\sigma_y} / \dot{\varepsilon}_0 \Lambda\right), (\delta / \Lambda)}$$

Oregon State University

Purdue University

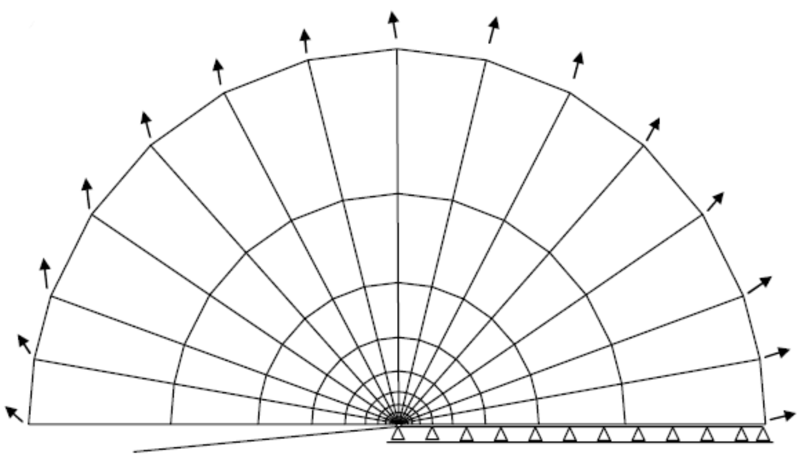
PROGRESS

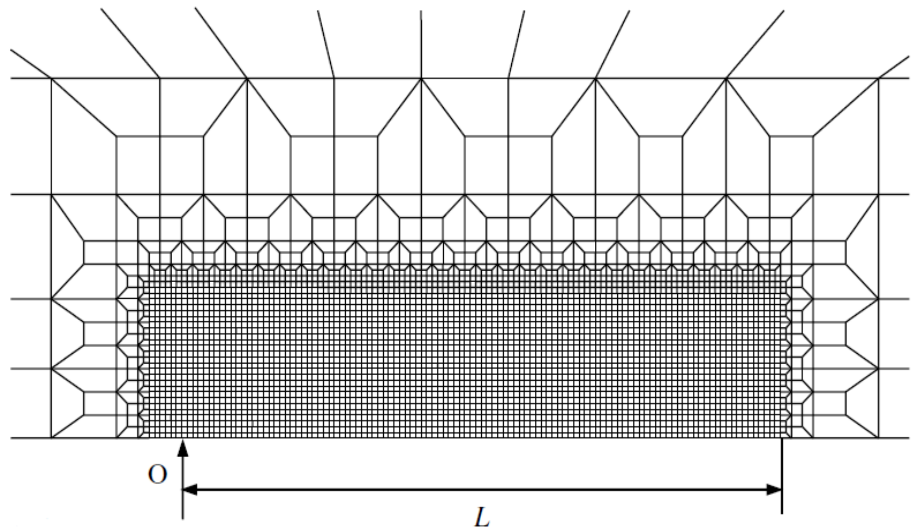
Modified Boundary Layer Model

$$u_x(t) = K_I(t)\sqrt{\frac{r}{2\pi}}\frac{1+\nu}{E}\left(3-4\nu-\cos\theta\right)\cos\frac{\theta}{2}$$

$$u_y(t) = K_I(t)\sqrt{\frac{r}{2\pi}}\frac{1+\nu}{E}\left(3-4\nu-\cos\theta\right)\sin\frac{\theta}{2}$$

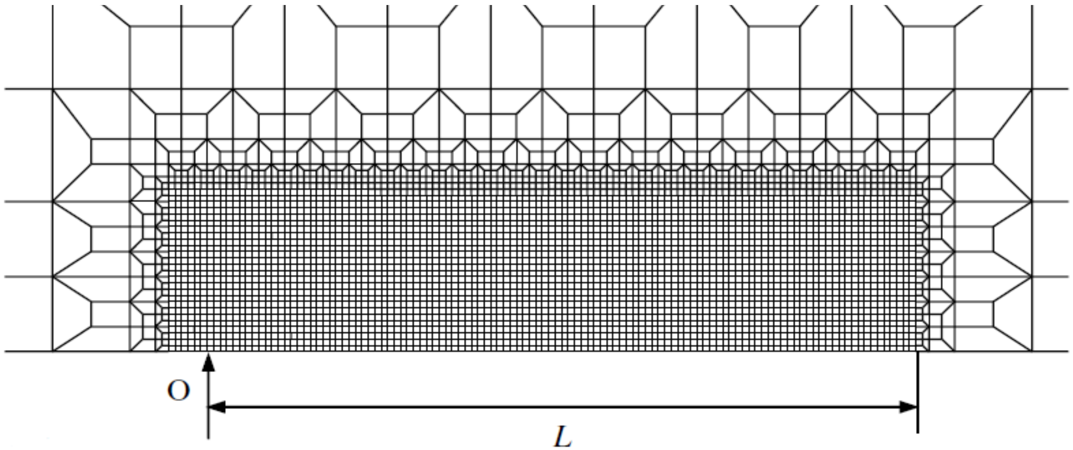
$$K(t) = \sqrt{\frac{EG(t)}{\left(1-\nu^2\right)}}$$

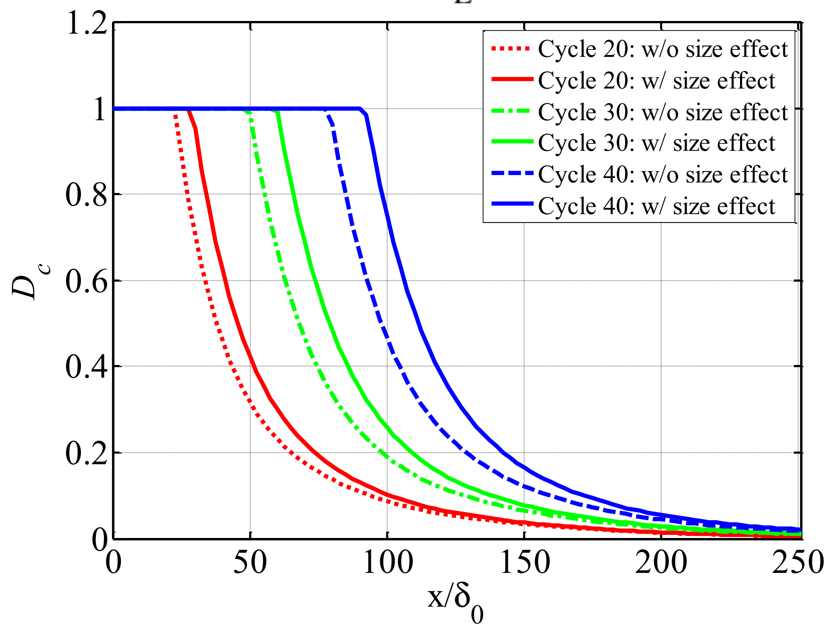




PROGRESS

Strain Gradients and FCG

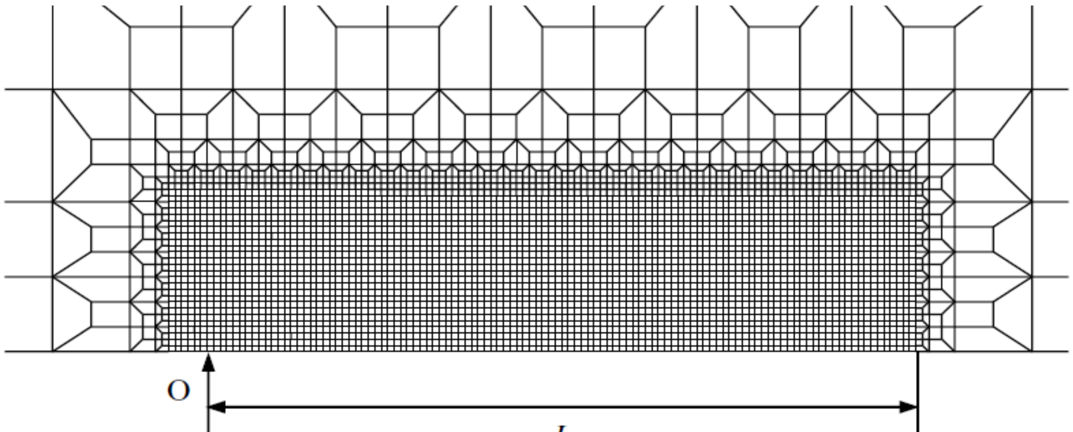


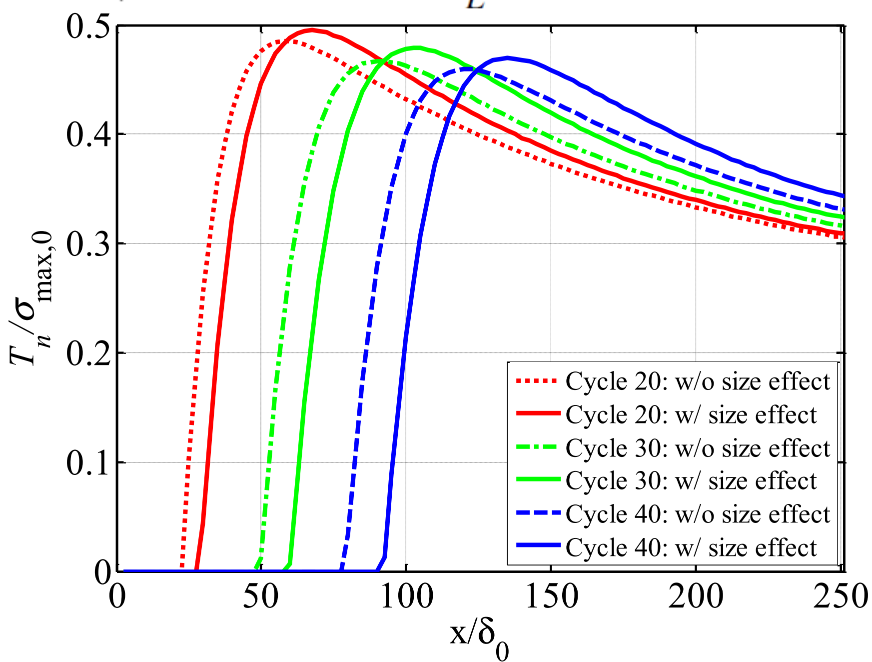


- FCG Rates with SGP are larger than without

PROGRESS

Strain Gradients and FCG





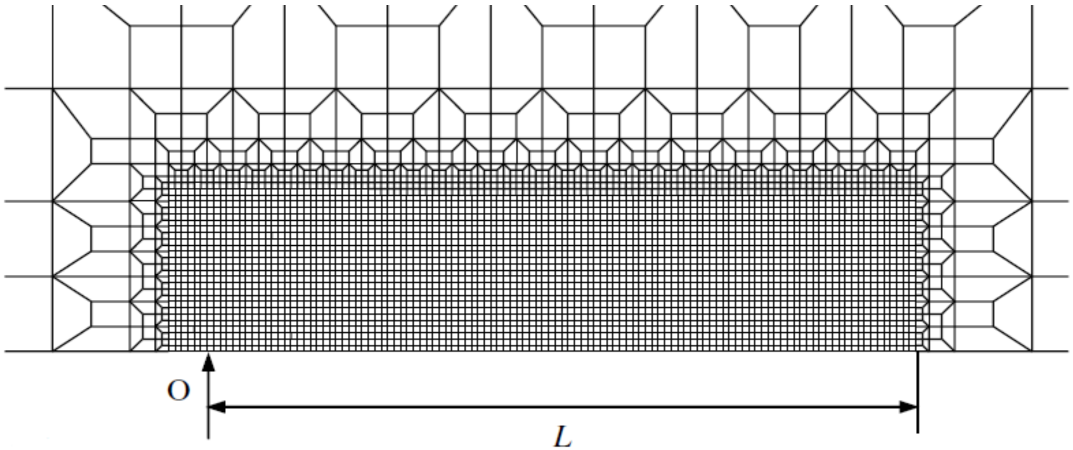
- Opening stresses with SGP are larger than without

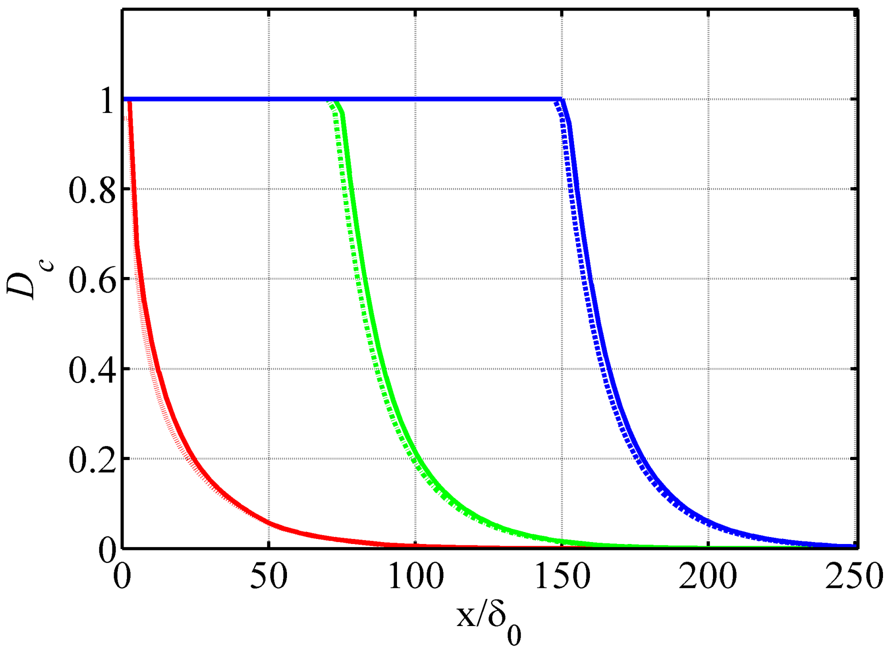
Oregon State University

Purdue University

PROGRESS

Strength Differential and FCG

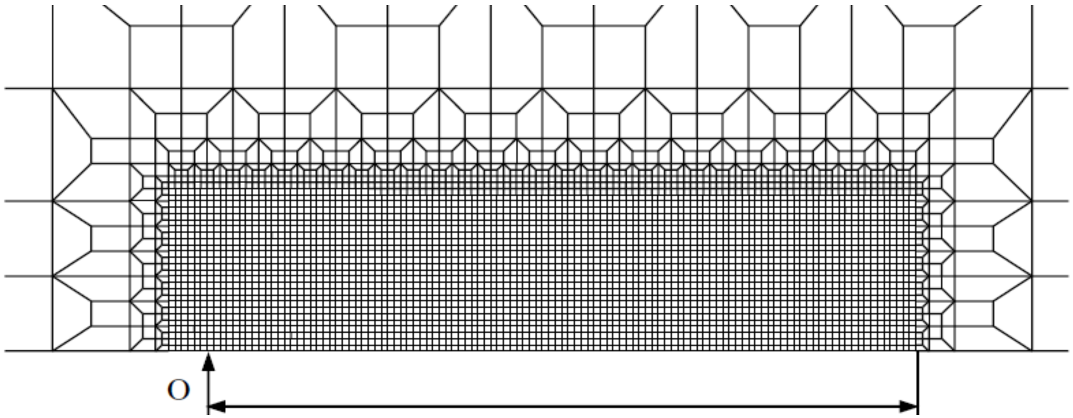


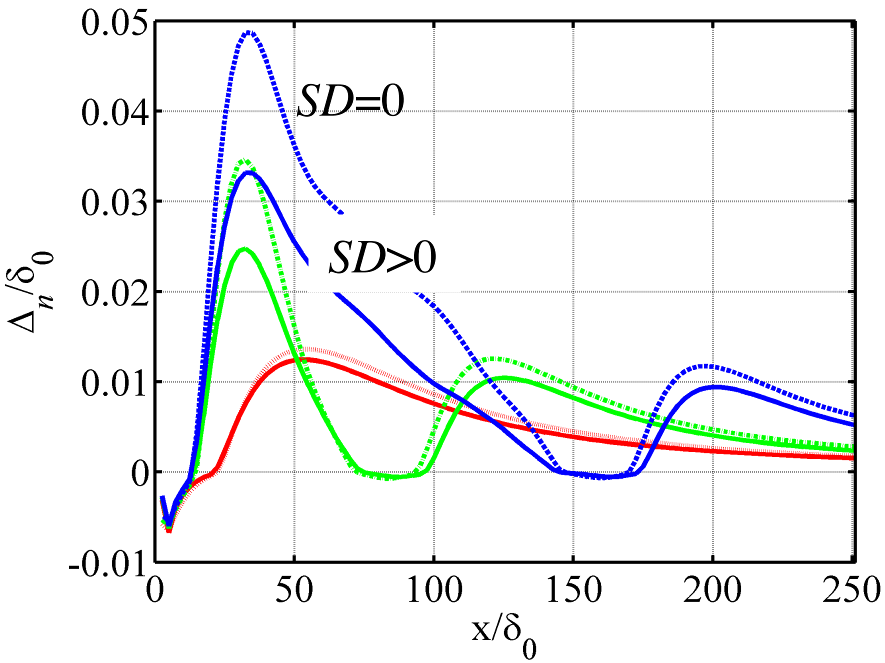


- FCG Rates appear as little affected by SD alone

PROGRESS

Strength Differential and FCG





- Crack closure appear as affected by SD alone

Oregon State University

Purdue University

TRAINING

Computational Fracture Mechanics

Full semester course
Online

https://engineering.purdue.edu/ProEd/

CONCLUSION

- **Procured and characterized materials**
- **Established interaction with Jeff Hawk, NETL Albany**
- **Property measurements are forthcoming**
- **Computational mechanics: Advanced model implementation on several fronts**
  - Strain gradients raise the open stress level and appear to accelerate crack growth
  - Strength differential alters the crack closure conditions but appears to not accelerate crack growth
- **Mechanics indicates the SGP and SD effects alter the crack tip stress state which would alter crack growth in creep and environmental degradation**