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

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TEAM AND COLLABORATION

Purdue University

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

Oregon State University

- Jay Kruzic with Halsey Ostergaard (PhD Student)

NETL Collaboration

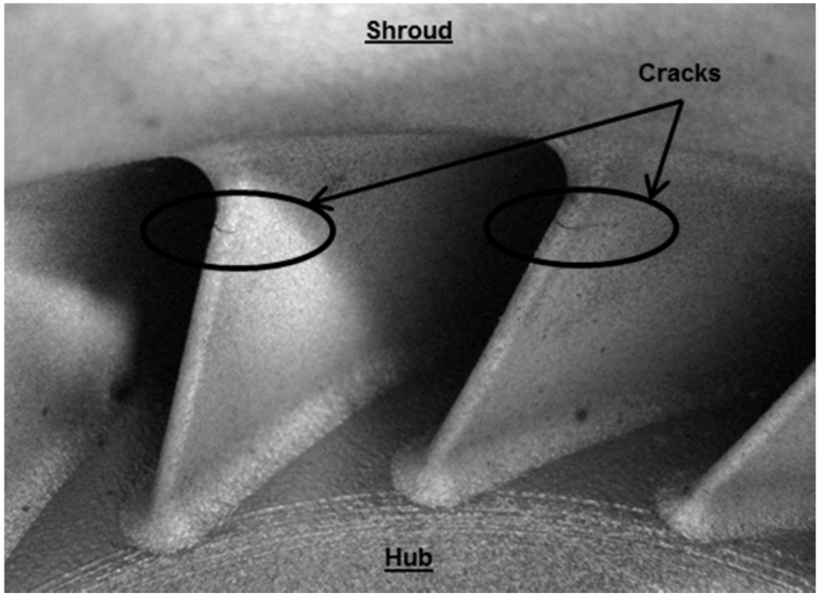
- Jeff Hawk, Albany OR: Material and creep experiments

Industry

- i3D MFG, Bend OR: EOS AM Material

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

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BACKGROUND

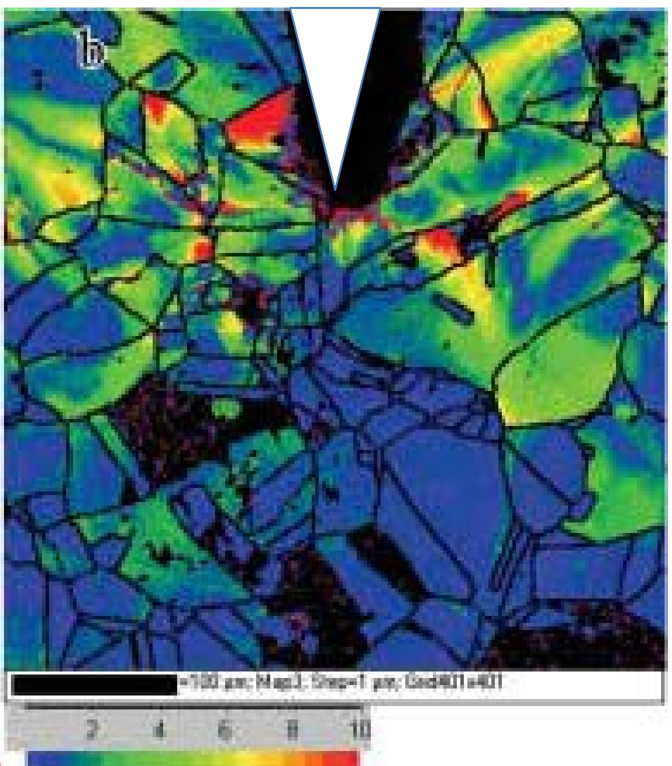
Views on Fatigue Failure

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

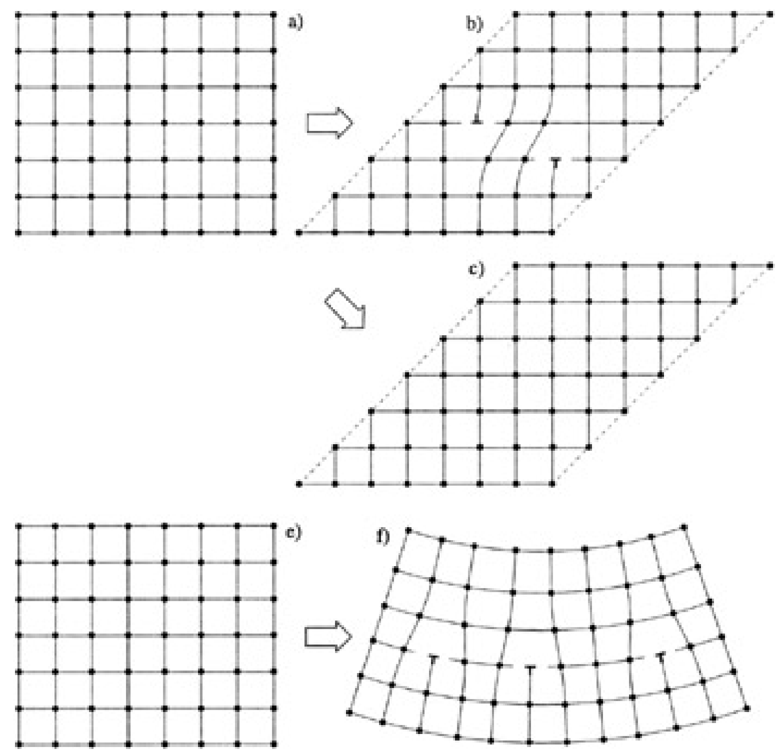
BACKGROUND

Plasticity

EBSD misorientation to reference at crack tip



Misorientation=GND Strain gradients



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

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BACKGROUND

Crack Tip Plastic Zones

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

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

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

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

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BACKGROUND

Hypothesis

Strain Gradient effects of viscoplastic deformation play a relevant role in the failure response of IN718 at 650ºC and affect creep-fatigue interaction processes

- 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 Questions

- How do we formulate a constitutive framework that accounts for gradient viscoplasticity and other observed specific features of plasticity in IN718.
- What are the experimental methods to determine the lengthscale parameters inherent to a gradient theory through experimentation?
- How is a Local-Approach to material failure best be used to predict crack growth in IN718 under creep-fatigue-environmental loading conditions?
- How does IN718-CONV differ from IN718-AM?

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OVERVIEW: METHODS

Uniaxial Constitutive Parameters

- Uniaxial tensile tests at various rates and with rate jumps
- Uniaxial creep at various loads and with load jump
- Uniaxial tensile deformation followed by creep

Size Dependent Constitutive Parameters

- High temperature nanoindentation with mN loads
- Hardness and Creep
- Load rate

OVERVIEW: METHODS

Fracture Mechanics

- Fatigue crack growth at 650^{o}C
- Creep crack growth at 650^{o}C
- Creep-Fatigue crack growth at at 650^{o}C
- Fractography

OVERVIEW: METHODS

Computational Mechanics

- Constitutive models for viscoplasticity in IN 718
- Norton-law based models
- Dislocation mechanics based models
- Viscoplastic strain gradients
- Structural mechanics
- Crack growth models for fatigue
- Crack growth models for creep
- Crack growth models for creep-fatigue

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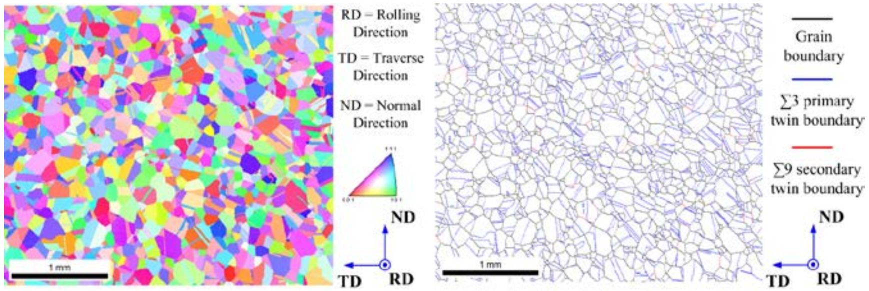
IN 718 Procurement and heat treat

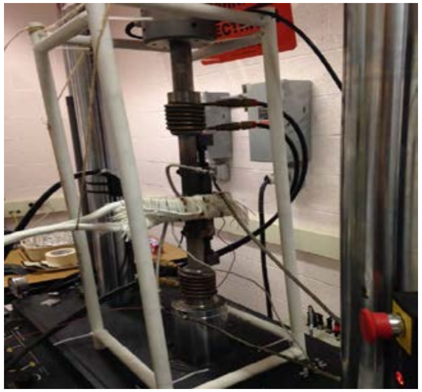
- NETL-Albany provided rolled plate from forged slab
- OSU standard heat treat

IN 718 Microstructure Characterization



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

HT Fracture Mechanics Set up



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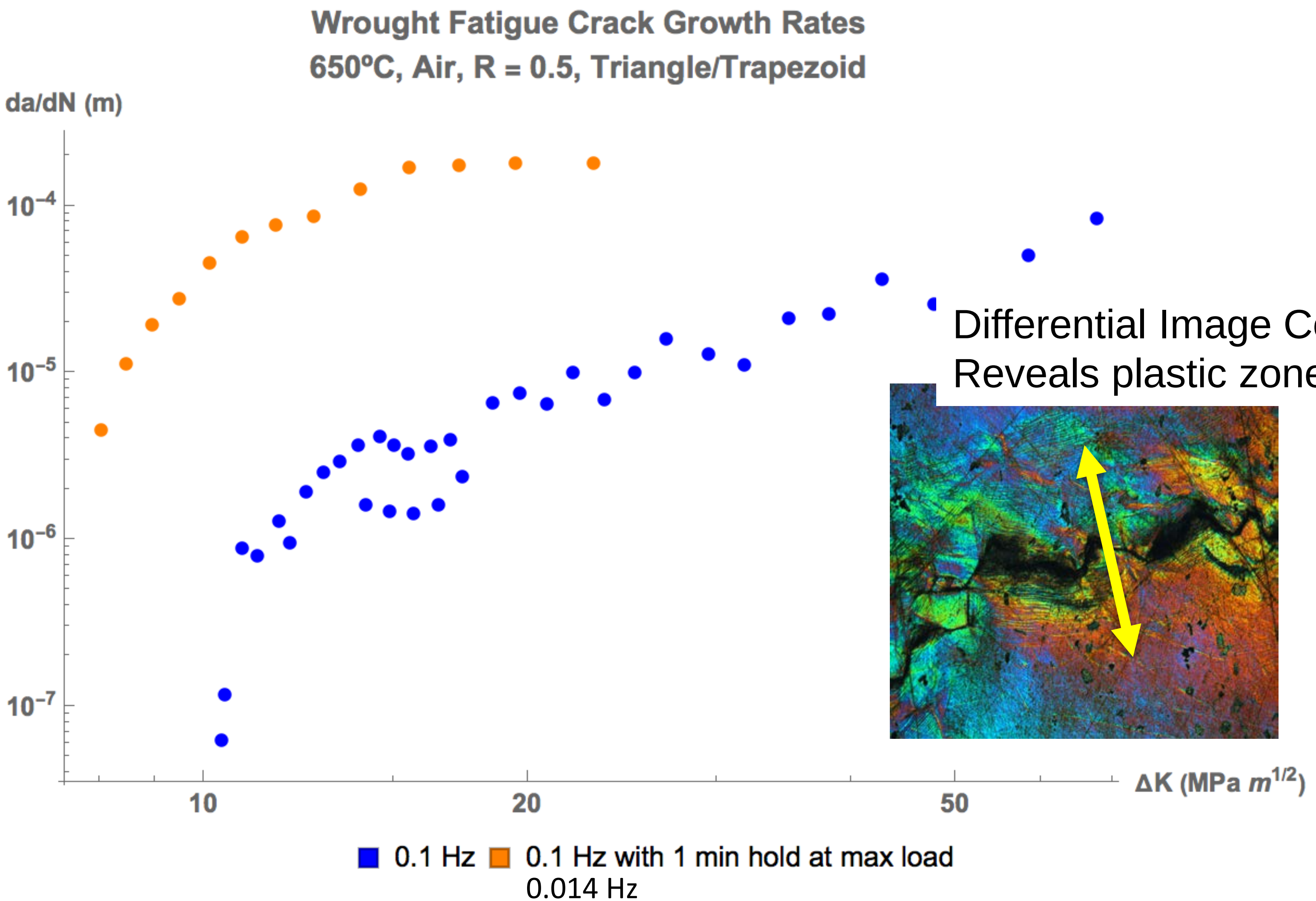

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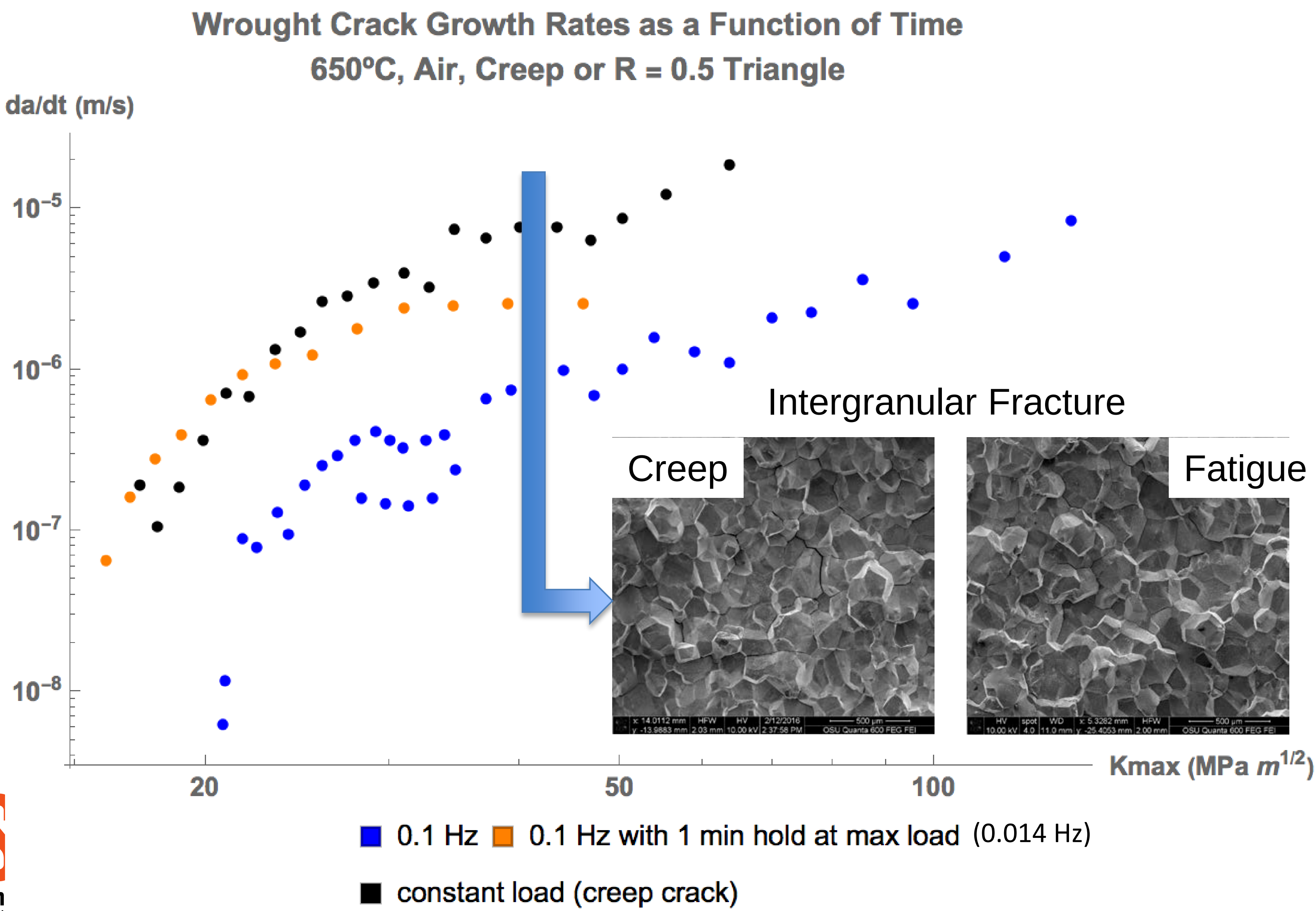
Wrought Crack Growth Rates as a Function of Time
650ºC, Air, Creep or R = 0.5 Triangle
da/dt (m/s)
10^-5
10^-6
10^-7
10^-8
20
50
100
Kmax (MPa m^1/2)
Intergranular Fracture
Creep
Fatigue
0.1 Hz
0.1 Hz with 1 min hold at max load (0.014 Hz)
constant load (creep crack)

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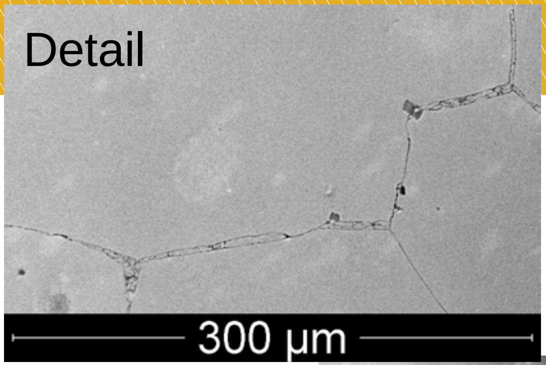
Crack growth mechanism

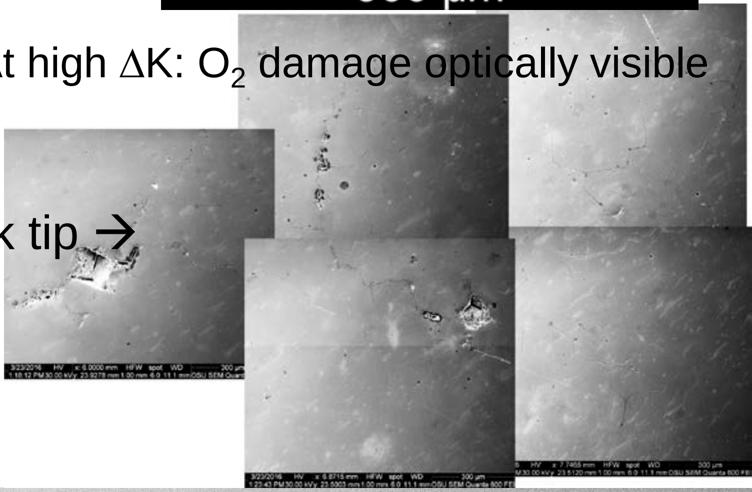
(for CREEP AND LOW FREQ.)

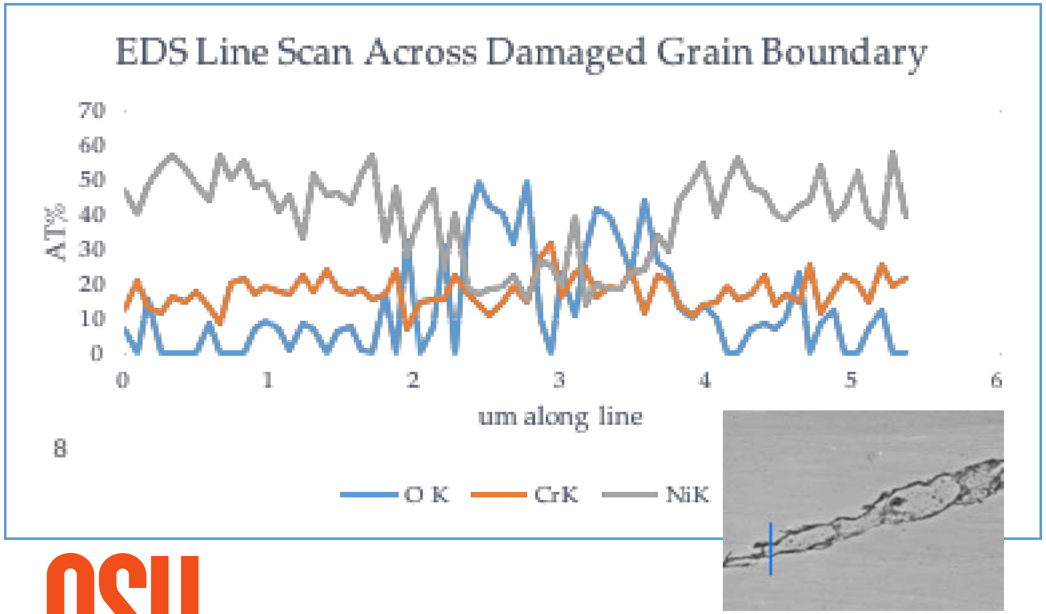
- **stress assisted grain boundary oxidation (SAGBO)**
- **Coupled with plastic deformation**

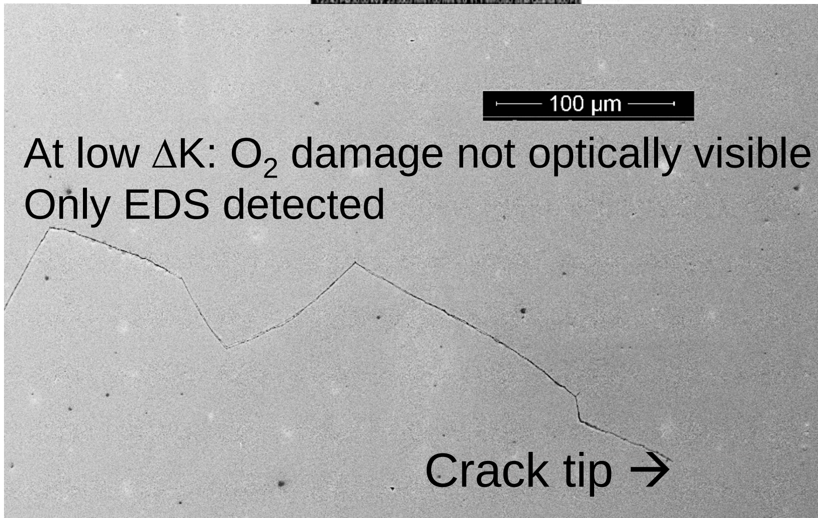


At high ΔK: O_2 damage optically visible

Crack tip →







At low ΔK: O_2 damage not optically visible
Only EDS detected

Crack tip →

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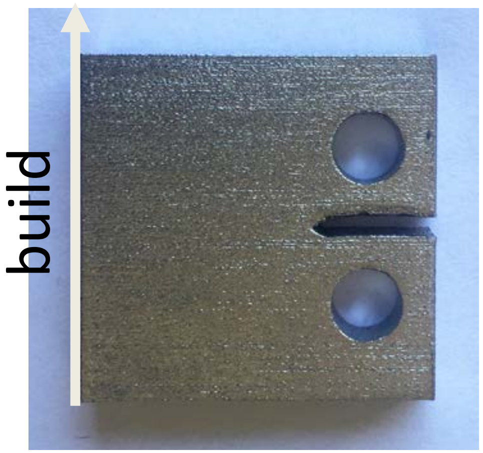

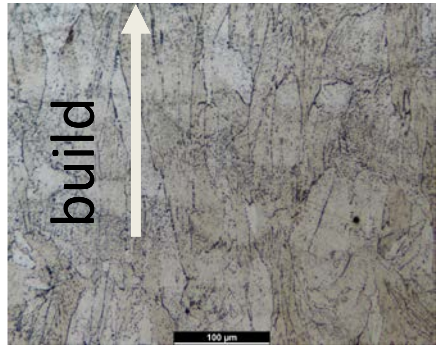

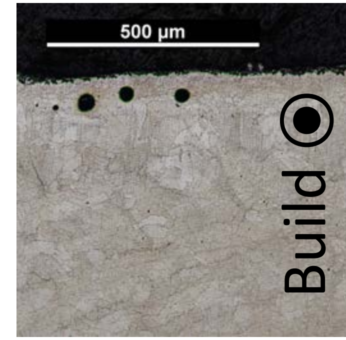

Direct metal laser sintered (DMLS) alloy 718 samples:

- EOS M290 printer
- Pre-alloyed 718 powder supplied by EOS
- Argon build environment
- 40 m layer height
- EOS proprietary scan pattern (63º rotation between layers)

- For this work: heat treatment steps identical to wrought material tested here (AMS 5662)

- We believe this is representative of commercially available high quality prints

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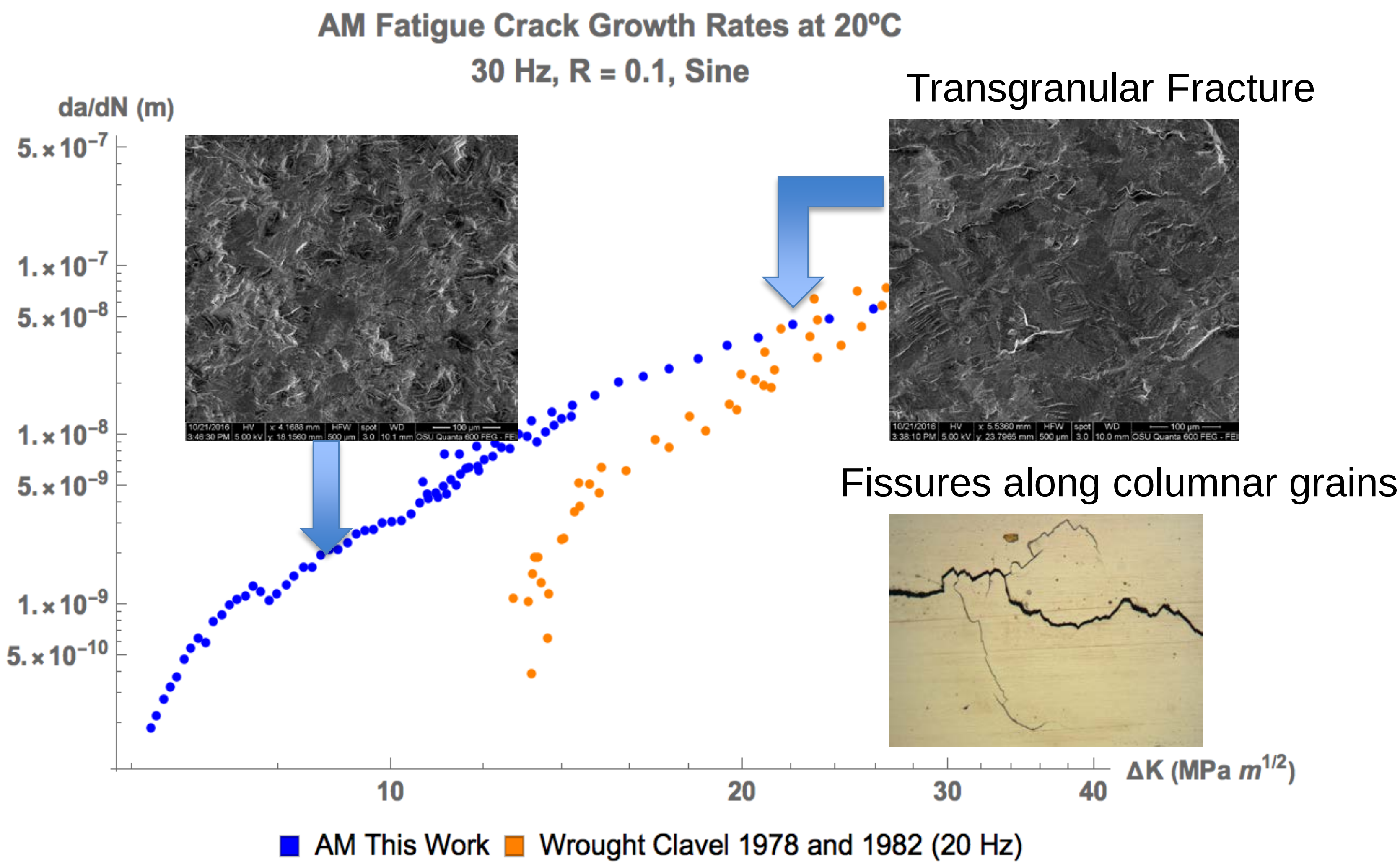
AM Fatigue Crack Growth Rates at 20ºC
30 Hz, R = 0.1, Sine
da/dN (m)
5.×10^-7
1.×10^-7
5.×10^-8
1.×10^-8
5.×10^-9
1.×10^-9
5.×10^-10
10
20
30
40
ΔK (MPa m^1/2)
AM This Work
Wrought Clavel 1978 and 1982 (20 Hz)
Transgranular Fracture
Fissures along columnar grains

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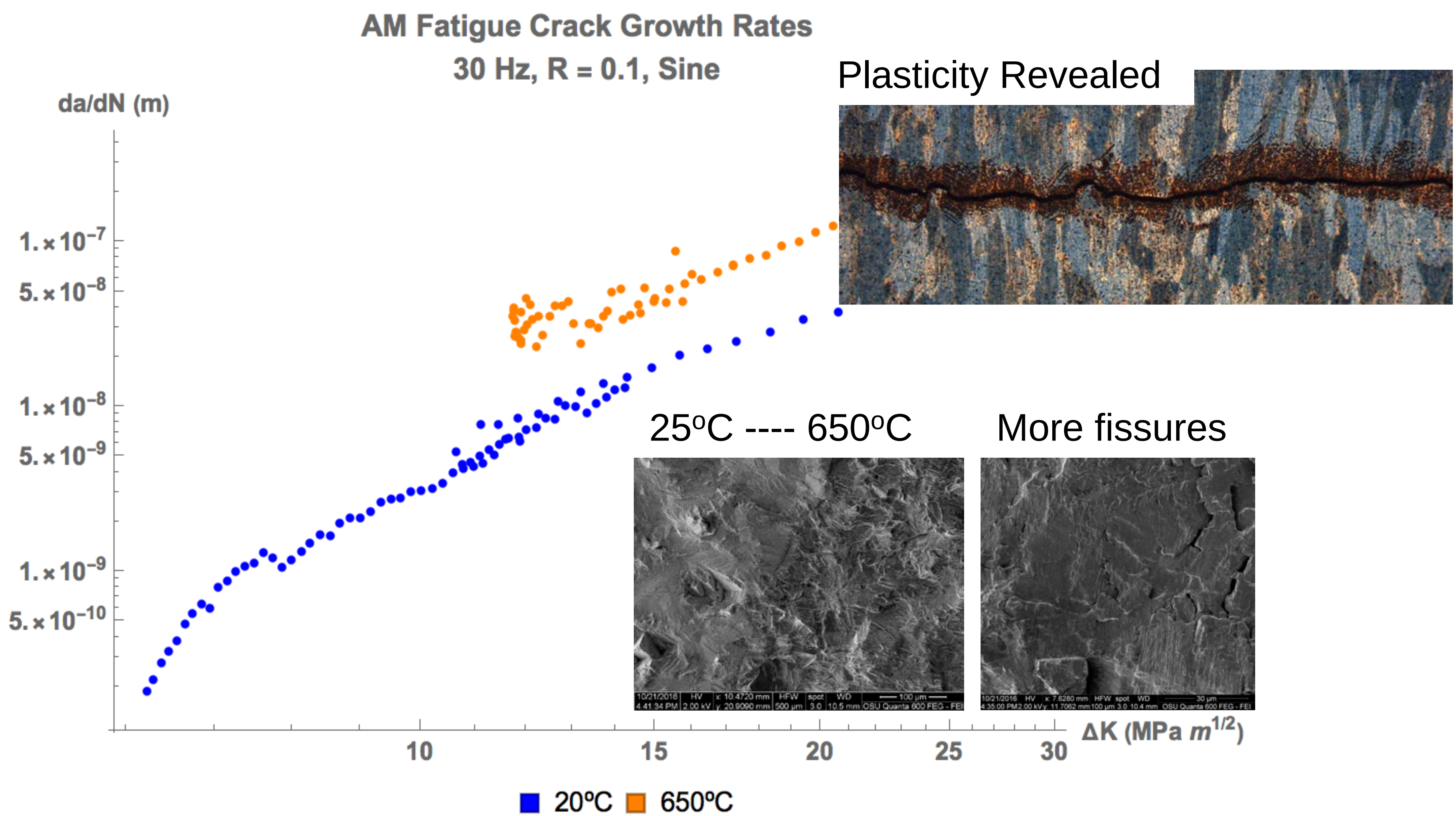

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Crack Growth Experiments

- **At low frequency (for IN718CONV):**
- **Intergranular fracture together with plasticity**
- **Time dominates**

- **At high frequency (for IN718AM):**
- **Transgranular fracture together with plasticity**
- **Cycling dominates**

- **CONV vs. AM:**
- **Equiaxed grains vs. columnar grains**
- **ΔK_{th} is much reduced in AM & $\Delta a/\Delta N$ elevated in AM even if tensile properties are good**

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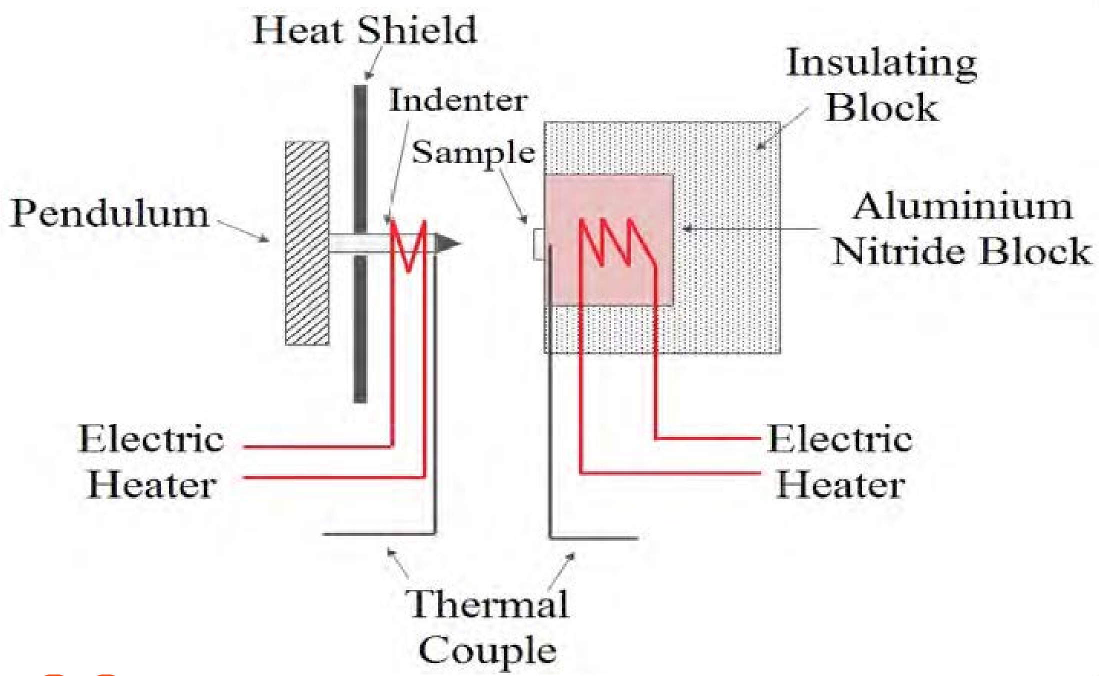
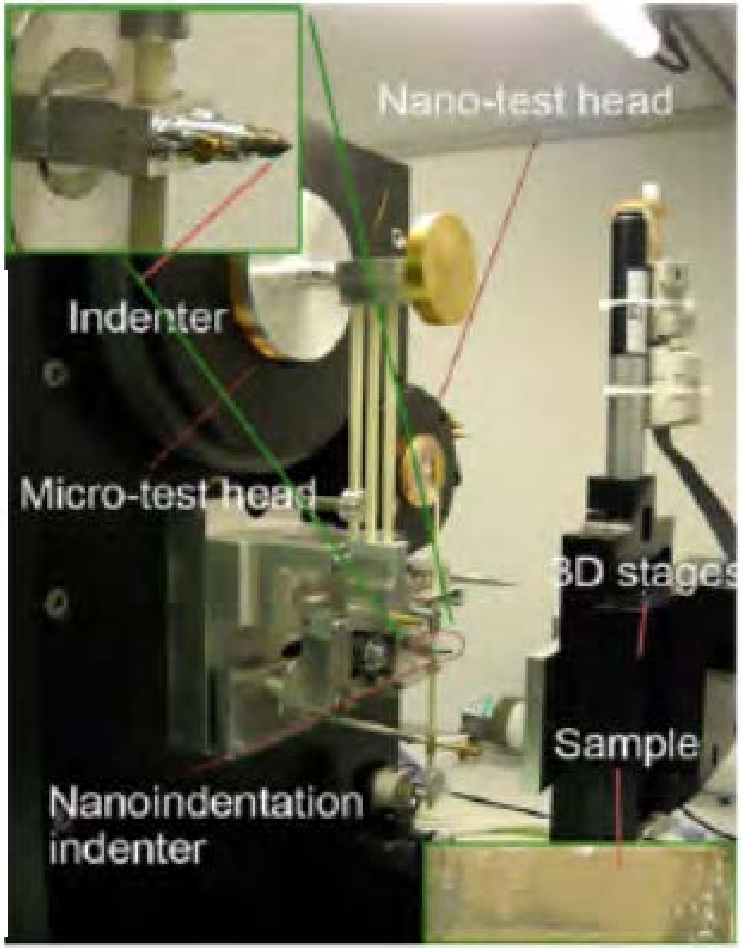
High Temperature Nanoindentation

Probe viscoplasticity at small length scales





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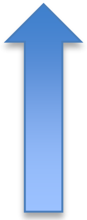
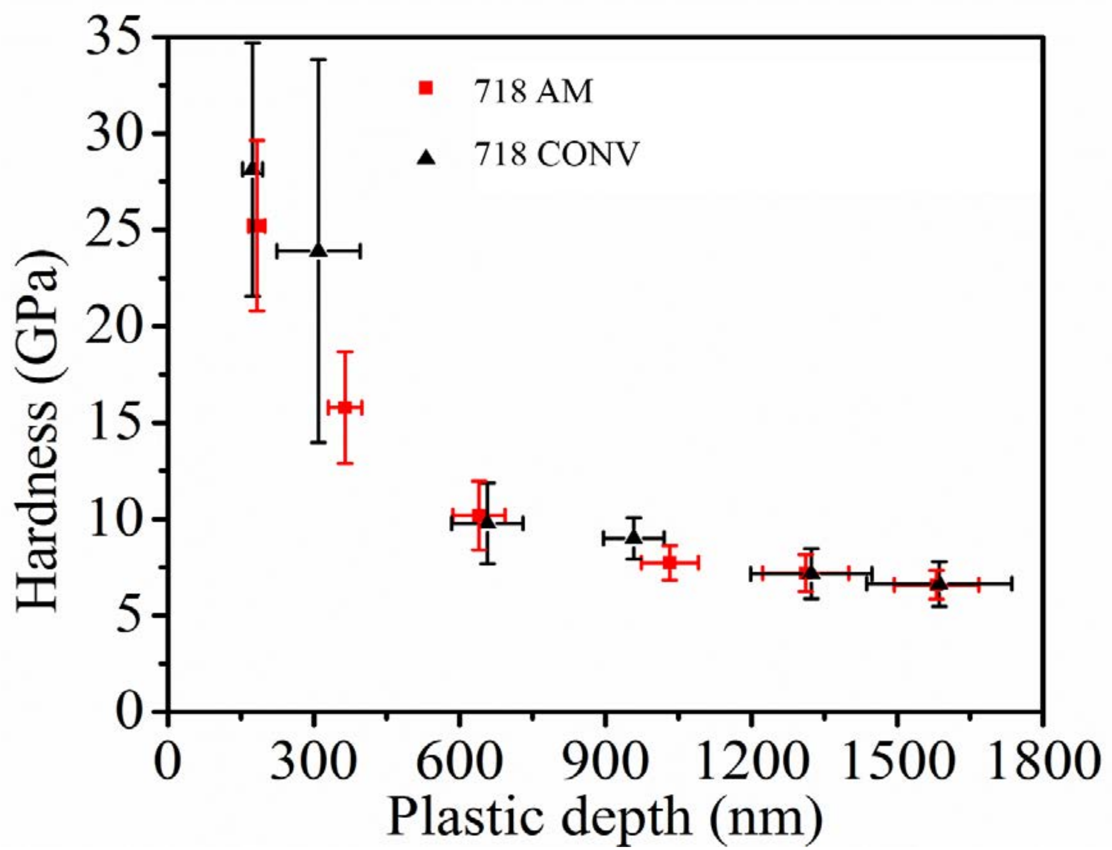
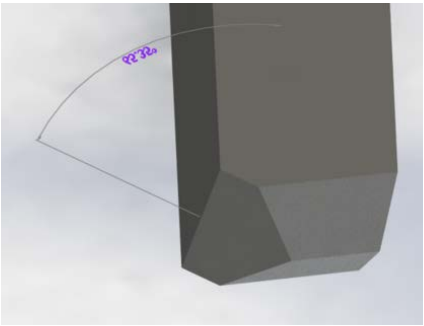
Hardness is Load Dependent

This is a key finding which confirms a key hypothesis: Plastic deformation at high temperatures is size dependent



Smaller





Berkovich Indenter
C-BN

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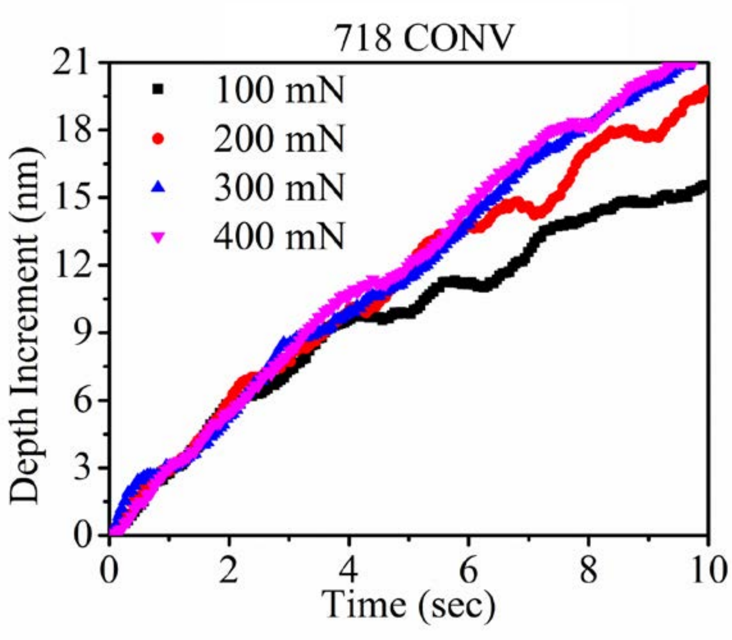
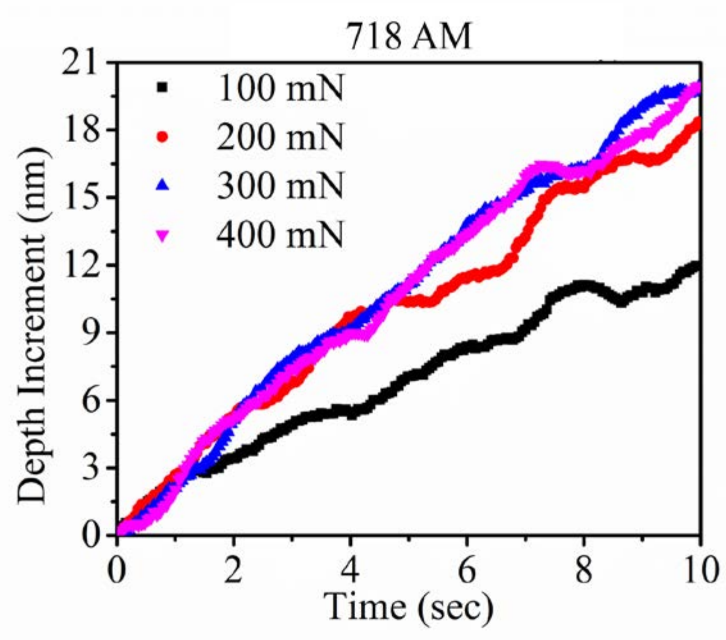
Creep (short term) is Load Dependent

This is a key finding which confirms a key hypothesis: Creep deformation at high temperatures is size dependent





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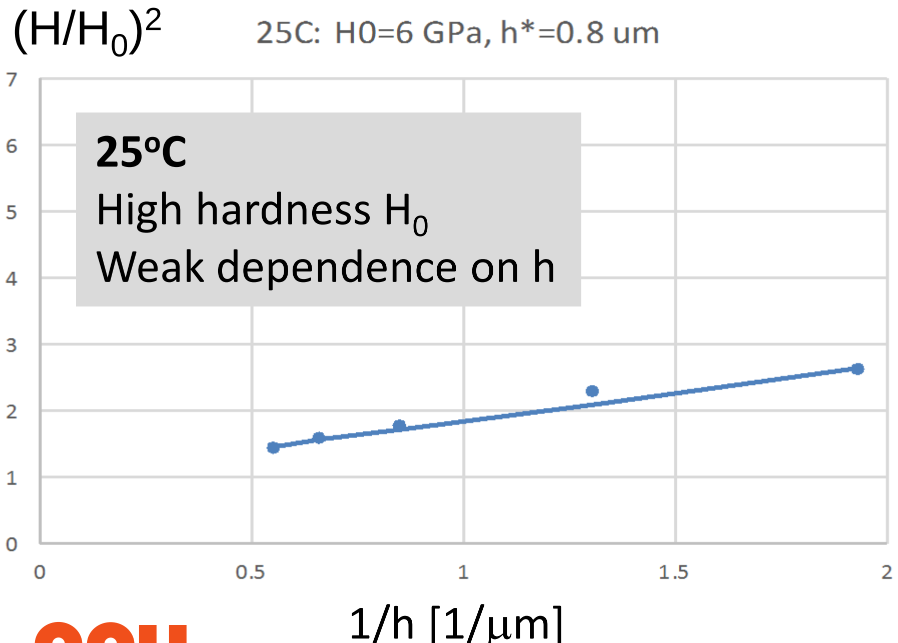
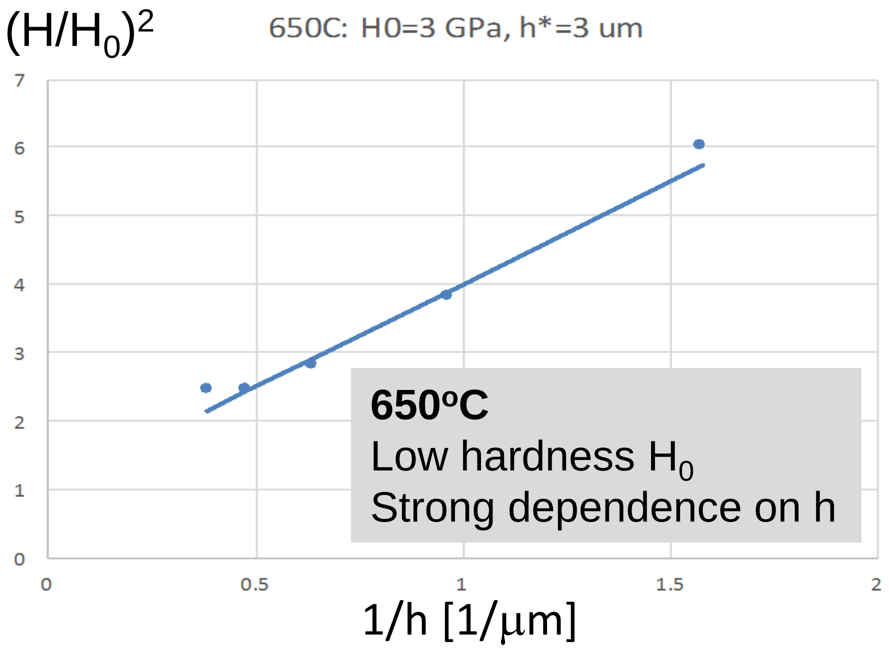
Strain Gradient Plasticity Theory:

Hardness (H) is indentation depth (h) dependent:

$$\left(\frac{H}{H_0}\right) = 1 + \frac{h^*}{h}$$

	H_0	h*
25°C	6 GPa	0.8 μm
650°C	3 GPa	3.0 μm





Smaller

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Plasticity at Small Scales

- IN718 exhibits a dependence of hardness of indentation depth at 650^{o}C confirming a key hypothesis
- IN718 exhibits a dependence of creep on indentation load at 650^{o}C confirming a key hypothesis

- Hardness and its size dependence was similar for the CONV and AM version of IN718

- Hardness follows a model strain gradient plasticity
- While hardness is lower at 650^{o}C than at 25^{o}C, the dependence of hardness of indentation depth is stronger at 650^{o}C

Computational Mechanics

Constitutive Models:

- Strain Gradient Viscoplastic Theory as justified by indentation experiments
- Tension-compression asymmetric yield theory

Crack Growth Models:

- Micromechanical models combining material separation and plastic deformation as justified by crack growth experiments
- Cohesive Zone Model

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Unified Viscoplastic Constitutive Models With Strain Gradients

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

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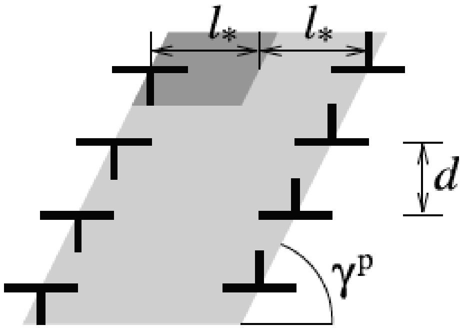
Dislocations: Carriers of Plastic Deformation

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

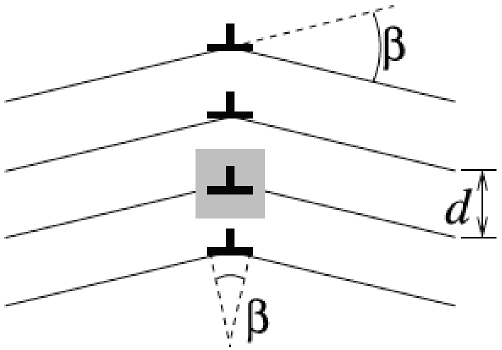
- Statistically stored dislocation:

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



- Geometrically necessary dislocation:

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



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

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

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Dislocation Density based Constitutive Model

Total strain rate	$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{e} + \dot{\boldsymbol{\varepsilon}}^{vp}$
Elastic strain rate: $\dot{\boldsymbol{\sigma}} = \mathbf{D}\dot{\boldsymbol{\varepsilon}}^{e}$ *Elasticity tensor* $D_{ijkl} = \mu\left(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}\right) + \lambda\delta_{ij}\delta_{kl}$ *Lamé's coefficients:* $\lambda,\ \mu$	*Viscoplastic strain rate:* $\dot{\boldsymbol{\varepsilon}}^{vp} = \frac{\partial\phi}{\partial\boldsymbol{\sigma}}$ *Isotropic material* $\bar{\sigma} = f(\boldsymbol{\sigma}) = \sqrt{\frac{3}{2}\mathbf{s}:\mathbf{s}}$ $\dot{W}^{vp} = \bar{\sigma}\dot{\bar{\varepsilon}}^{vp} = \boldsymbol{\sigma}:\dot{\boldsymbol{\varepsilon}}^{vp}$

Kinetic equation	$\frac{\bar{\sigma}}{\sigma_{\text{ref}}} = \left(\frac{\dot{\bar{\varepsilon}}^{vp}}{\dot{\varepsilon}_0}\right)^{1/m}$
Taylor equation	$\sigma_{\text{ref}} = \sigma_0 + M\alpha\mu b\sqrt{\rho}$
Dislocation density:	$\rho = \rho_S + \rho_G$
Statistically stored dislocation $\rho_S = \rho_S^{+} + \rho_S^{-}$ - *Accumulation:* $\frac{d\rho_S^{+}}{d\bar{\varepsilon}^{vp}} = Mk_1\sqrt{\rho_S + \rho_G}$ - *Dynamic recovery:* $\frac{d\rho_S^{-}}{d\bar{\varepsilon}^{vp}} = Mk_2\rho_S$ *Strain rate sensitivity* $k_2 = k_{20}\left(\frac{\dot{\bar{\varepsilon}}^{vp}}{\dot{\varepsilon}_0}\right)^{-1/n}$	*Geometrically necessary dislocation* $\rho_G = \bar{r}\frac{\bar{\eta}^{vp}}{b}$ *Effective strain gradient* $\bar{\eta}^{vp} = \sqrt{\frac{1}{4}\eta_{ijk}^{vp}\eta_{ijk}^{vp}}$ $\eta_{ijk}^{vp} = \varepsilon_{ik,j}^{vp} + \varepsilon_{jk,i}^{vp} - \varepsilon_{ij,k}^{vp}$

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FE Implementation (UMAT for ABAQUS)

At the time step $[t_n, t_{n+1}]$, quantities $\left(\boldsymbol{\sigma}, \boldsymbol{\varepsilon}, \bar{\varepsilon}^{vp}, \rho_S, \rho_G, \sigma_{\mathrm{ref}}, \Delta t\right)_n$ are given.

Step 1. Loop

1.1 *Calculate viscoplastic strain increment (explicit Euler method):* $\Delta\bar{\varepsilon}^{vp} = \dot{\bar{\varepsilon}}_n^{vp}\Delta t$

1.2 *Update state variables*

SSD density:

$$\left(\rho_S\right)_{n+1} = \left(\rho_S^+\right)_{n+1} + \left(\rho_S^-\right)_{n+1} \qquad \begin{aligned} \left(\rho_S^+\right)_{n+1} &= \left(\rho_S^+\right)_n + \Delta\rho_S^+ \\ \left(\rho_S^-\right)_{n+1} &= \left(\rho_S^-\right)_n + \Delta\rho_S^- \end{aligned} \qquad \begin{aligned} \Delta\rho_S^+ &= \Delta\bar{\varepsilon}^{vp} M k_1 \sqrt{\left(\rho_S\right)_n + \left(\rho_G\right)_n} \\ \Delta\rho_S^- &= \Delta\bar{\varepsilon}^{vp} M k_2 \left(\rho_S\right)_n \end{aligned}$$

GND density:

$$\left(\rho_S\right)_{n+1} = \bar{r}\frac{\left(\bar{\eta}^{vp}\right)_n}{b} \qquad \left(\bar{\eta}^{vp}\right)_{n+1} = \left(\bar{\eta}^{vp}\right)_n + \Delta\bar{\eta}^{vp} \qquad \Delta\bar{\eta}^{vp} = \sqrt{\frac{1}{4}\left(\Delta\eta_{ijk}^{vp}\right)_n\left(\Delta\eta_{ijk}^{vp}\right)_n}$$

$$\left(\Delta\eta_{ijk}^{vp}\right)_n = \left(\frac{\partial N_I}{\partial X_j}\left(\Delta\varepsilon_{ik}^{vp}\right)_I + \frac{\partial N_I}{\partial X_i}\left(\Delta\varepsilon_{jk}^{vp}\right)_I - \frac{\partial N_I}{\partial X_k}\left(\Delta\varepsilon_{ij}^{vp}\right)_I\right)_n$$

Reference stress:

$$\left(\sigma_{\mathrm{ref}}\right)_{n+1} = \sigma_0 + M\alpha\mu b\sqrt{\left(\rho_S\right)_{n+1} + \left(\rho_G\right)_{n+1}}$$

1.3 *Solve a nonlinear equation for stress using a Newton-Raphson scheme*

$$f\left(\Delta\bar{\sigma}\right) = 3\mu\left(\tilde{e} - \Delta\bar{\varepsilon}^{vp}\right) - \left(\bar{\sigma}_n + \Delta\bar{\sigma}\right) = 0$$

1.4 *Check convergence criterion for the* k*-th iteration:* $\left|\dfrac{\Delta\bar{\sigma}_{(k+1)} - \Delta\bar{\sigma}_{(k)}}{\Delta\bar{\sigma}_{(k+1)}}\right| \le \mathrm{TOL}$

if satisfied go to **Step 2** *otherwise go to* **1.1**.

Step 2. *Update stress tensor and viscoplastic strain*

Stress tensor $s_{ij} = \dfrac{2\mu}{1 + \dfrac{3\mu}{\left(\bar{\sigma}_n + \Delta\bar{\sigma}\right)}\Delta\bar{\varepsilon}^{vp}}\hat{e}_{ij}$ *Viscoplastic strain* $\bar{\varepsilon}_{n+1}^{vp} = \bar{\varepsilon}_n^{vp} + \Delta\bar{\varepsilon}^{vp}$

Step 3. *Compute the material Jacobian* $\mathbf{C} = \partial\Delta\boldsymbol{\sigma} / \partial\Delta\boldsymbol{\varepsilon}$

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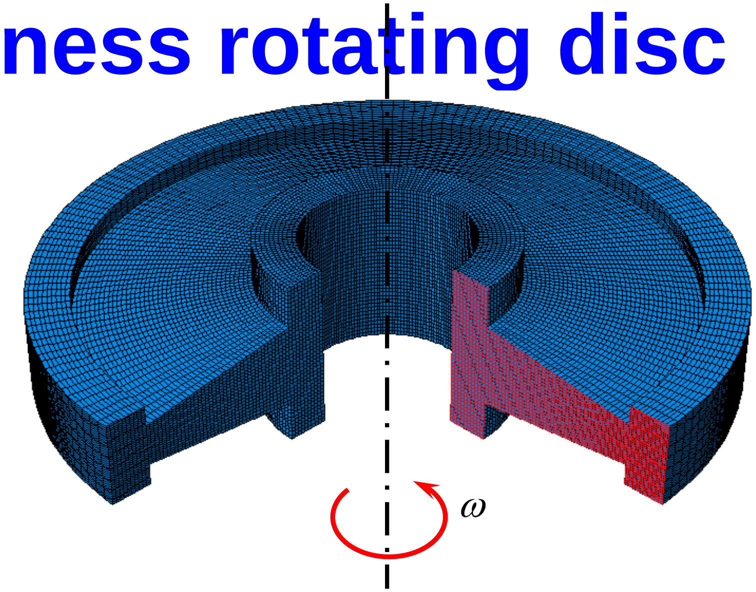
Annular non-uniform thickness rotating disc

- **FE model**
  - Axisymmetric conditions
  - Mass density $\delta = 8.220 \cdot 10^{-3}\ g/mm^3$
  - Loading: centrifugal loading (body force)

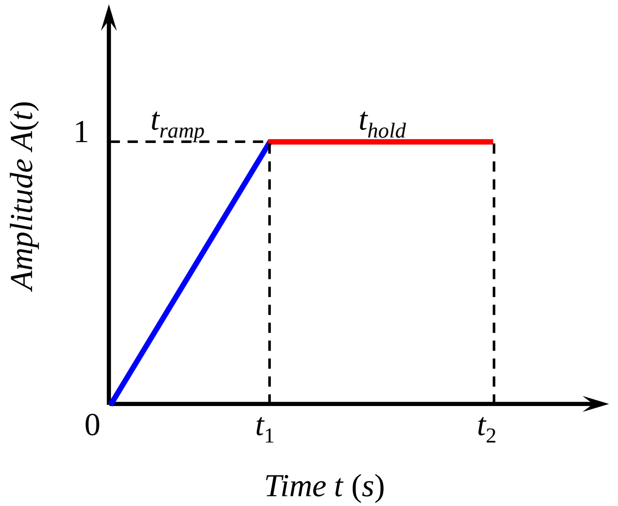
    Angular velocity: $\omega(t) = A(t)\omega_0$

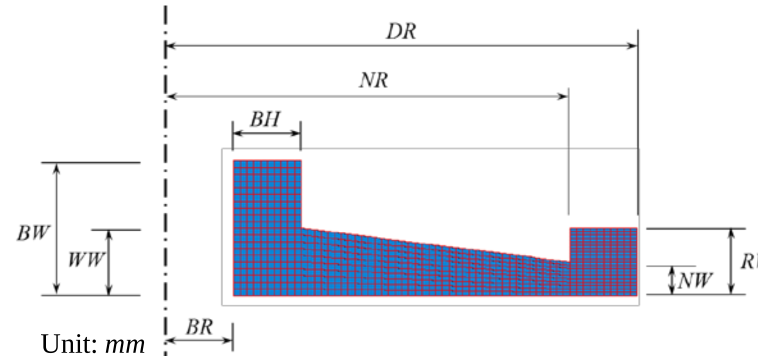
    with $\omega_0 = 26179.9\ rad/s$ (250,000 RPM)

    $t_{ramp} = 600\ s$, $t_{hold} = 10^5\ s$



Non-uniform annular rotating disc





NW	WW	RW	BW	BR	BH	NR	DR
1	2	2	4	4	2	12	14

2D axisymmetric model

  - Generic material data for SG-KM model

E (GPa)	ν	σ_0 (MPa)	m	n	k_1 (mm^{-1})	k_{20}	M	α	b (nm)	$\dot{\varepsilon}_0$ (s^{-1})
165	0.3	779	25	5	8e5	28.29	1.73	0.3	0.25	1e-3

NUMERICAL EXAMPLES

Annular uniform thickness rotating disc

- **Elastic solution**
  - Radial stress as a function of distance r from the central axis:

$$\sigma_r(r)=\frac{3+\nu}{8}\delta\omega^2\left(R^2+R_0^2-\frac{R^2R_0^2}{r^2}-r^2\right)$$

  - Hoop stress as a function of distance r from the central axis:

$$\sigma_t(r)=\frac{1}{8}\delta\omega^2\left[(3+\nu)\left(R^2+R_0^2-\frac{R^2R_0^2}{r^2}\right)-(1+3\nu)r^2\right]$$

  - Maximum radial stress occurs at $r=\sqrt{RR_0}$

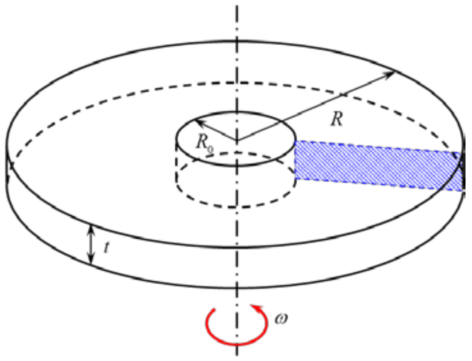
$$\sigma_{r,\max}=\frac{3+\nu}{8}\delta\omega^2\left(R-R_0\right)^2$$

  - Maximum radial stress occurs at the perimeter of the hole

$$\sigma_{t,\max}=\frac{1}{4}\delta\omega^2\left[(3+\nu)R^2+(1-\nu)R_0^2\right]$$

  - Radial displacement

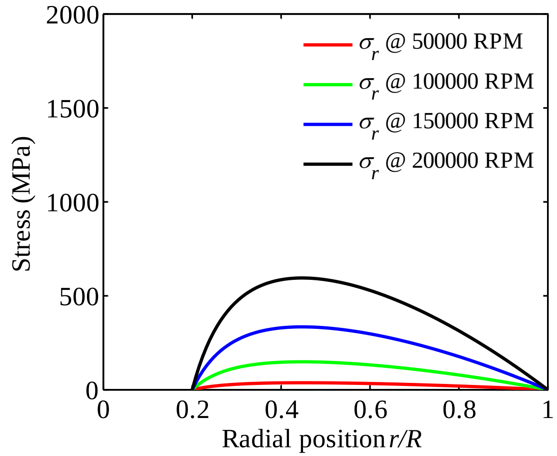
$$u_r=\frac{1}{8}r\delta\omega^2\frac{(3+\nu)(1-\nu)}{E}\left[R^2+R_0^2+\frac{1+\nu}{1-\nu}\frac{R^2R_0^2}{r^2}-\frac{1+\nu}{3+\nu}r^2\right]$$

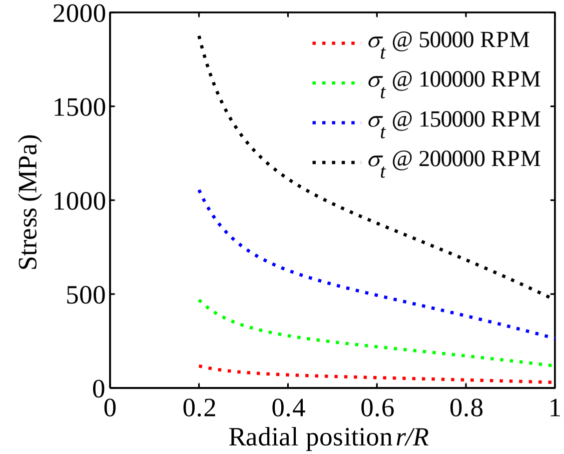


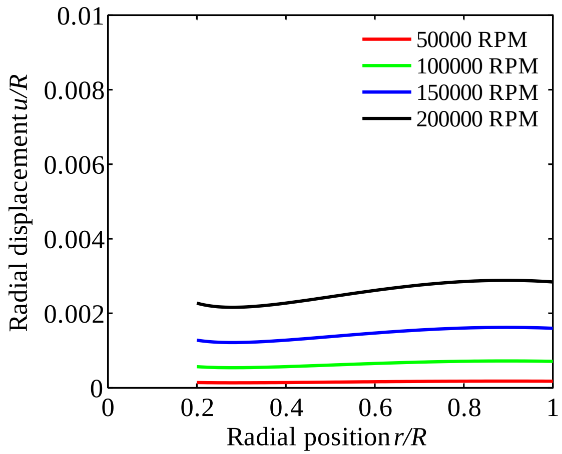
δ density
E Young's modulus
ν Poisson's ratio

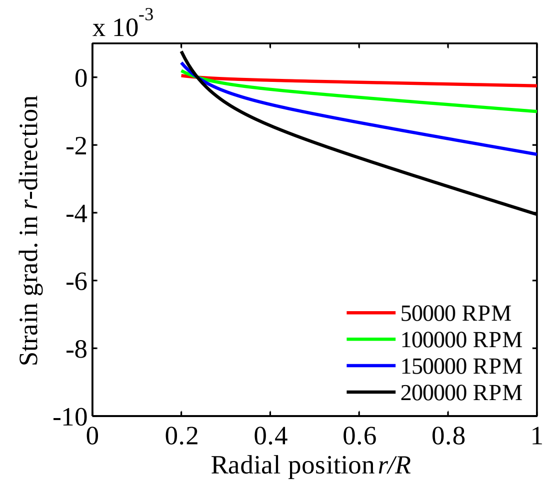
NUMERICAL EXAMPLES

Annular uniform thickness rotating disc









Strain Gradients from centrifugal forces:
Does this matter?

Inputs:
Inner radius: R_0 = 5 *mm*, outer radius R = 25 *mm*.
Young's modulus: E = 165 *MPa*, Poisson's ratio: ν = 0.3, mass density δ = 8.220e-3 g/mm^3

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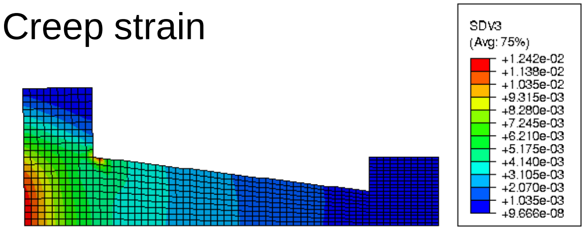
After a hold time of $t_{hold} = 10^5$ s

Norton	Kocks-Mecking (KM)	SG-KM

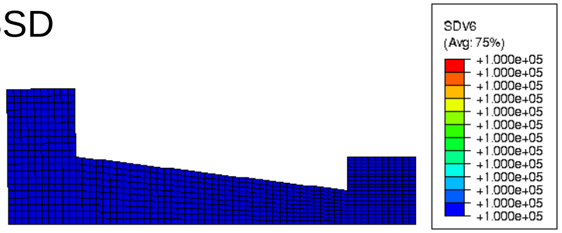
Norton

Von Mises stress

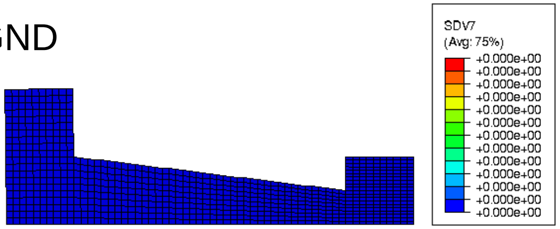
Creep strain



SSD

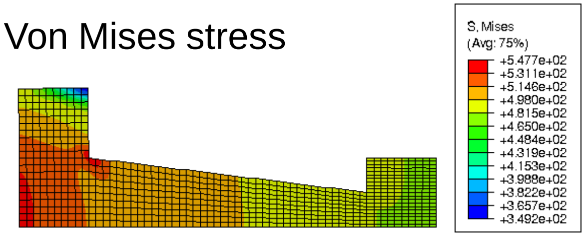


GND

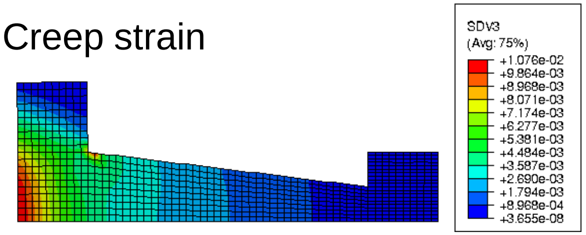


Kocks-Mecking (KM)

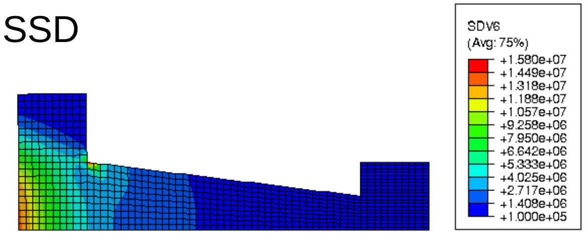
Von Mises stress



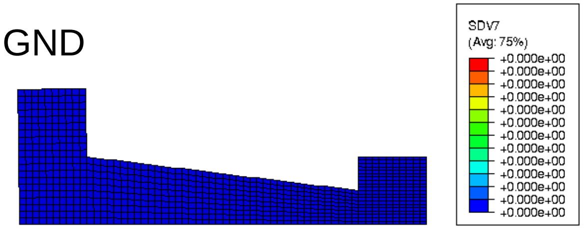
Creep strain



SSD

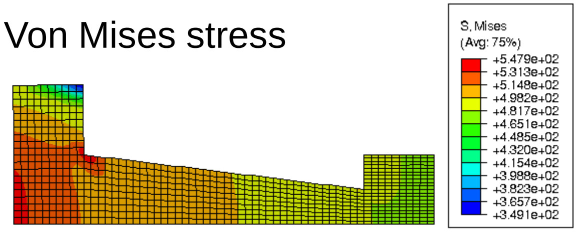


GND

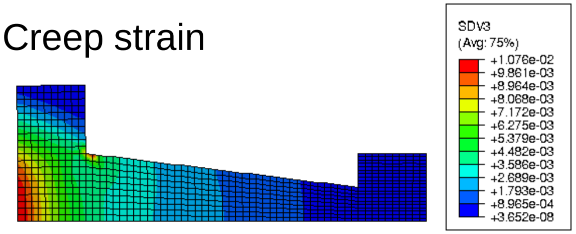


SG-KM

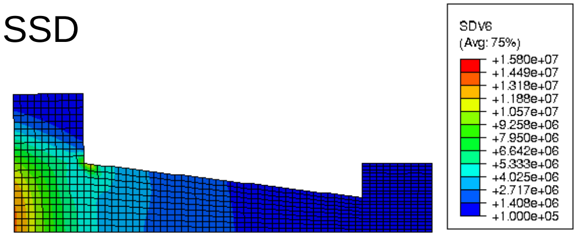
Von Mises stress



Creep strain



SSD



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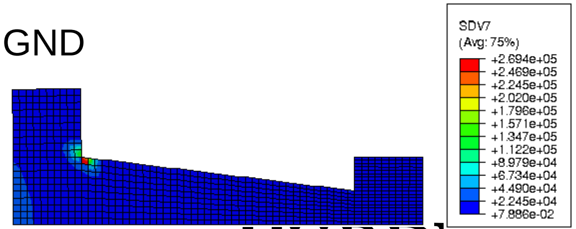

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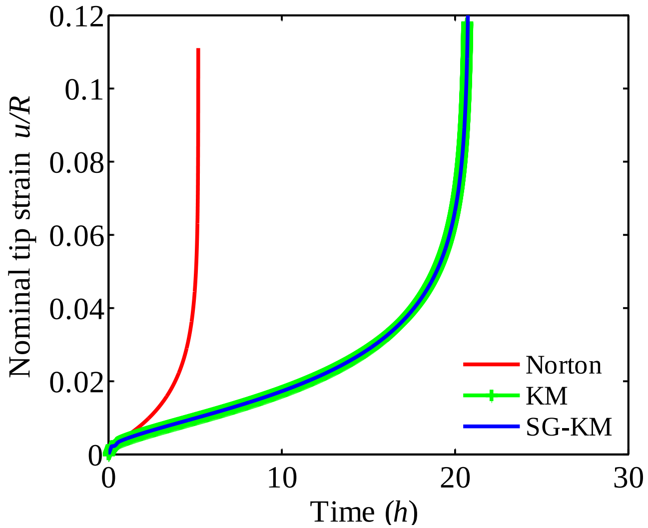
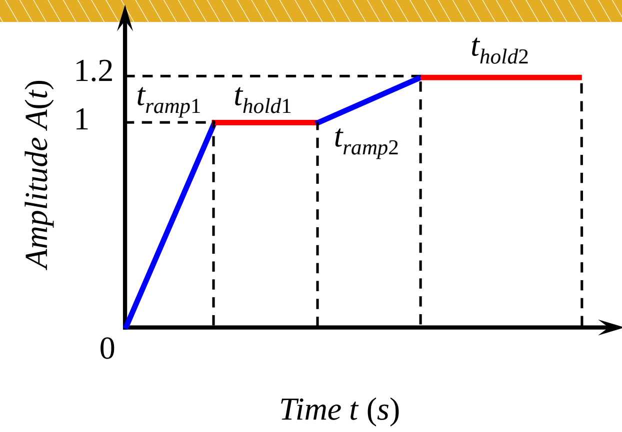
Tip displacement





Inputs:

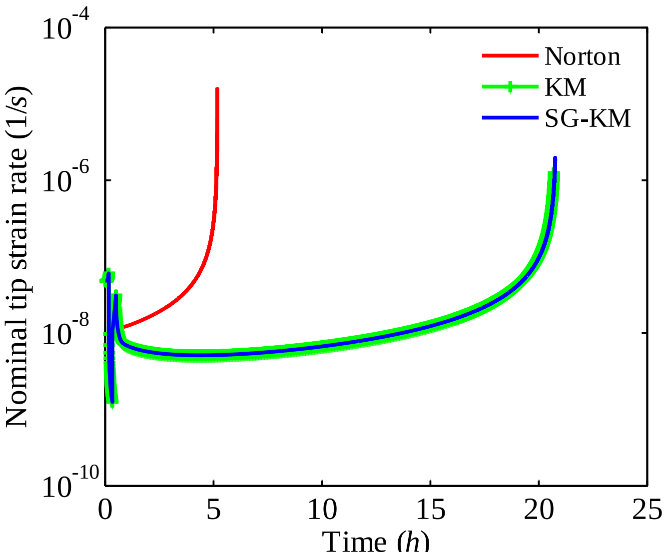
$t_{ramp1} = t_{hold1} = t_{ramp2} = 600\ s$

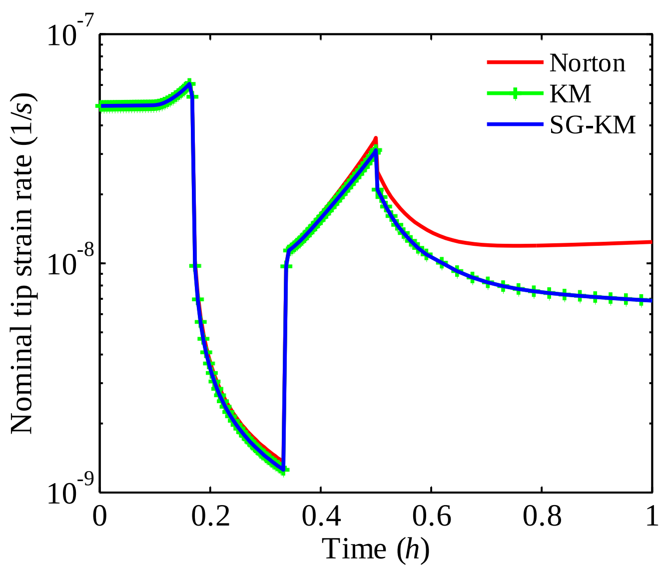
Ramp 1: from 0 to 250,000 RPM in 600 s

Hold 1: 600 s

Ramp 2: from 250,000 RPM to 300,000 RPM in 600 s

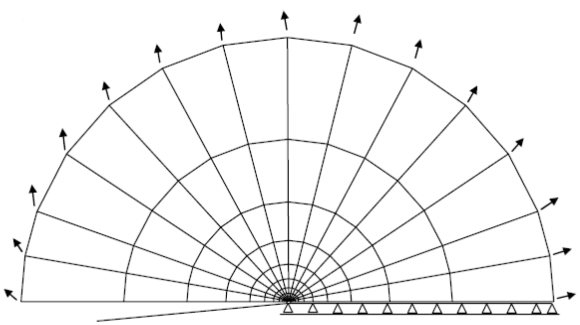
Hold 2: until failure





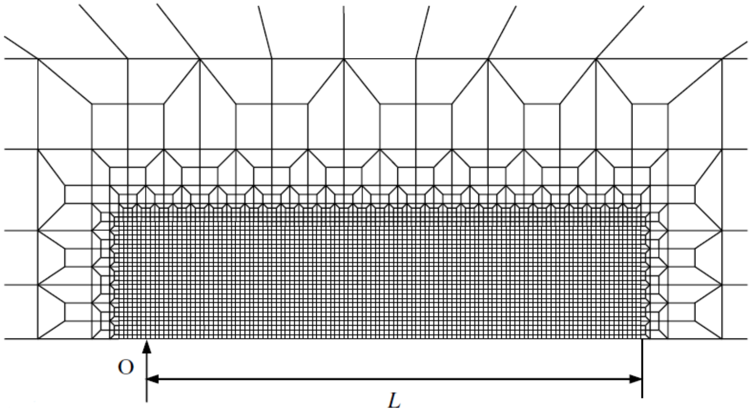
NUMERICAL EXAMPLES

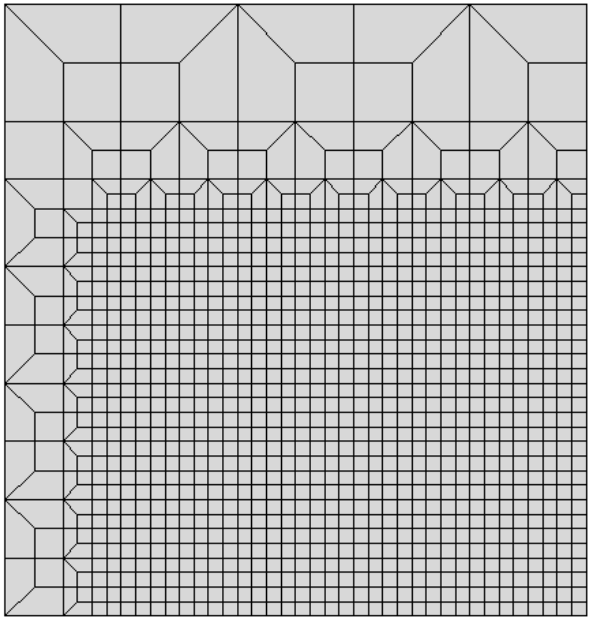
Crack tip fields under creep condition



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

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

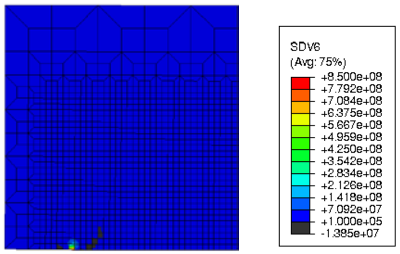




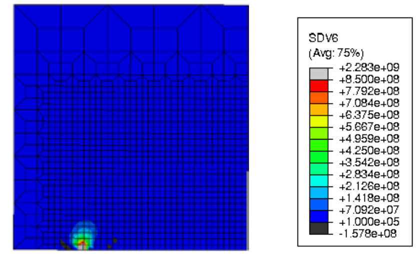
NUMERICAL EXAMPLES

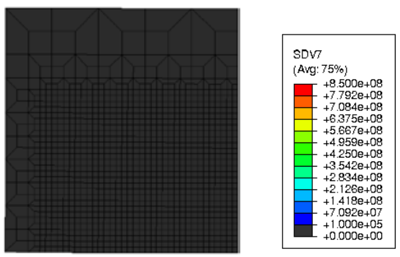
At a ramp time (t_{ramp} = 1 s)

Kocks-Mecking | **SG-KM**

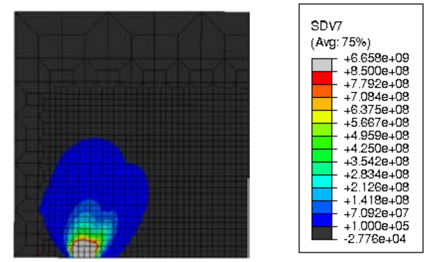


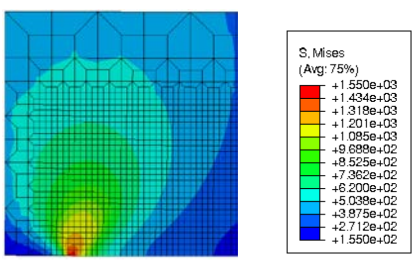
SSD



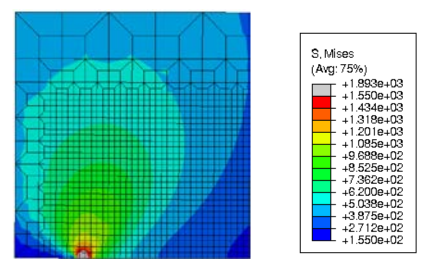


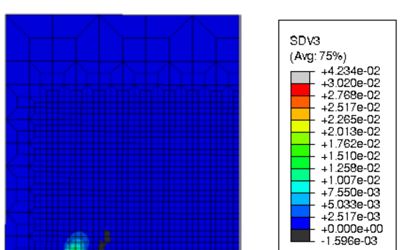
GND



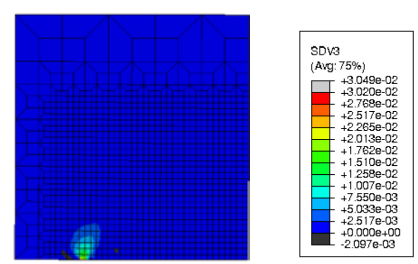


Von Mises stress





Plastic strain



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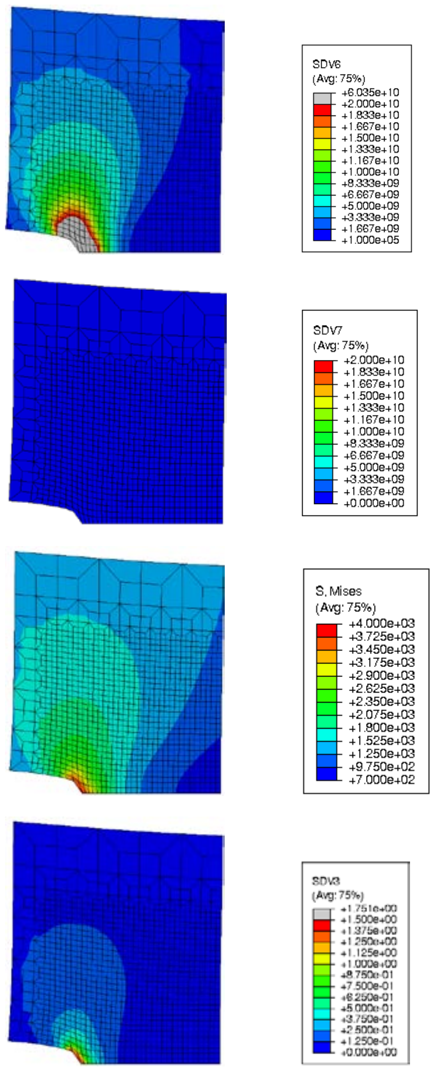
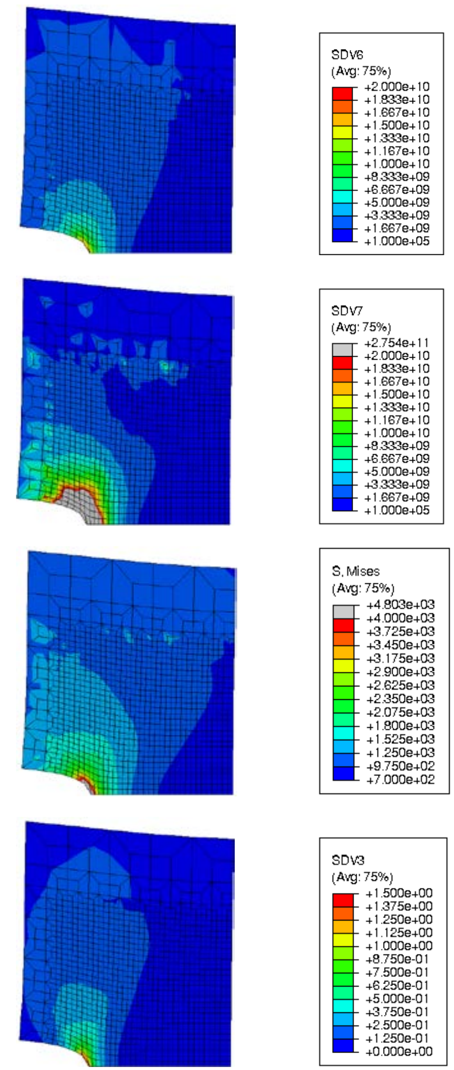
NUMERICAL EXAMPLES

After a hold time of t_{hold} = 40 s

Kocks-Mecking		SG-KM
	SSD GND Von Mises stress Plastic strain	

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Creep-Fatigue Crack Growth

- **Fatigue damage and creep damage evolve independently and act additively**

- **Embedded in FEM as a Cohesive Zone Model**
  - **Cyclic damage law (Roe-Siegmund)**
  - **Time damage law (Kachanov-Robotnov)**

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Creep-Fatigue Crack Growth Model Equations

Damage-free traction-separation law:

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

Damage-free cohesive energy $\phi_0 = \sigma_{\max,0} \delta_0 e$

Fatigue damage increment	*Time-related damage increment*
$\Delta D_F = \max\left\{ 0, \frac{\lvert\dot{\Delta}_n\rvert}{\delta_\Sigma} \left[\frac{T_n}{\sigma_{\max}} - \frac{\sigma_f}{\sigma_{\max,0}} \right] \left\langle \Delta_{n,acc} - \delta_0 \right\rangle \right\}$	$\dot{D}_{KR} = (1-D)^{-p} \left\langle \frac{\bar{T} - T_C}{C} \right\rangle^q$
Accumulated fatigue damage	*Accumulated time-related damage*
${}^{n}D_F = {}^{n-1}D_F + \Delta D_F$	${}^{n}D_{KR} = {}^{n-1}D_{KR} + \dot{D}_{KR} \Delta t$

Total damage $D = D_F + D_{KR}$

Material fracture takes place when $D = 1$.

Current cohesive strength

$$\sigma_{\max} = \sigma_{\max,0} (1 - D)$$

Unloading/reloading condition:

$$T_n = T_{n,\max} + \left[\frac{T_{n,\max}}{\Delta_{n,\max}} \right] (\Delta_n - \Delta_{n,\max})$$

Traction-overclosure treatment:

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

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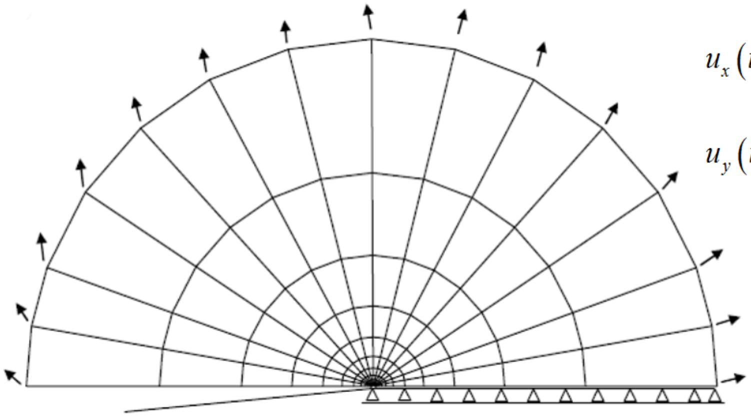
Creep-Fatigue Crack Growth Simulation Model



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

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

$$r = \sqrt{x^2+y^2},\ \theta = \tan^{-1}(y/x)$$

MBL	ICZM	Material IN718
$r_b/l_e = 10{,}000$ $L/l_e = 110$ $\Delta G/\phi_0 = 0.4$	$\delta_0 = 0.4\times\min l_e$ $\sigma_{\max,0} = 4\sigma_Y$ $\sigma_f/\sigma_{\max,0} = 0.25$ $\delta_\Sigma/\delta_0 = 4$ $p = 6,\ q = 3$ $C = 6000$ MPa s$^{(1/3)}$ $T_C = 200$ MPa	$E = 165\ GPa$ $\nu = 0.297$ $\sigma_0 = 779\ MPa$ $\phi_0 = 62\ kJ/m^2$ $b = 0.25\ nm$ $\Lambda = 5000b$ $m = 7$ $\bar{\varepsilon}_0 = 0.005\ s^{-1}$

Computations are consider a simplified strain gradient continuum model (no transient effects)

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Creep-Fatigue Crack Growth Simulation Result

Creep-fatigue crack growth emerges as a complex interaction of creep & stress relaxation in the bulk together with cyclic & time dependent damage

Fatigue Damage dominates: high freq. case

Time Damage dominates: low frequency case

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Computational Mechanics

Implemented a strain gradient, unified viscoplastic constitutive theory needed for the description of the deformation response of IN718

Demonstrate the model in structures (disk) and for cracks

Creep-fatigue crack growth emerges from the competition of viscoplasticity (augmented by strain gradients), cycle-dependent and time-dependent damage

CONCLUSION

Creep-fatigue crack growth interaction emerges as the interaction and competition from multiple sources:

→ Viscoplasticity and the gradient dependence of plasticity
→ Cycle dependent damage accumulation
→ Time dependent damage accumulation

At high frequency or slow time-dependent damage (vacuum), cyclic damage dominates leading to transgranular failure

At low frequency or fast time-dependent damage (oxygen), time damage dominates leading to intergranular failure

Strain gradients play a significant role

Computational models available for predictions

CONV and AM both appear to exhibit similar deformation characteristic but the crack growth rate in the AM case is higher and the threshold is lower

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CONTRIBUTION

Fundamentals

Creep-fatigue crack growth predictions accounting for fundamental mechanics

Turbines

NDE finds cracks → Diagnostics

Mechanics predicts how crack growth → Intelligence

Reduce maintenance intervals

Realize digital twin with physics based engines

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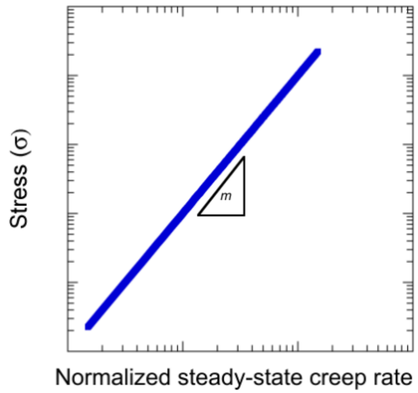
Purdue University

BACKUP SLIDES

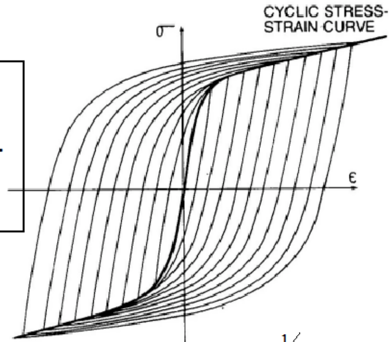
OVERVIEW: ORIGINAL PLAN

Research on Constitutive Parameters



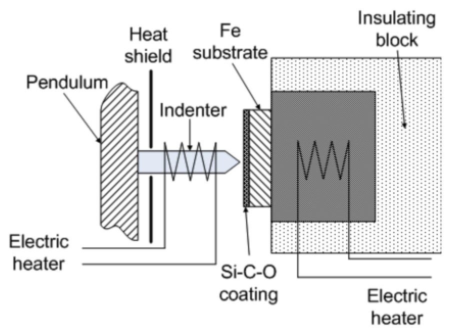
Uniaxial Creep at 650°C
@ multiple stress levels

Tensile cyclic stress-strain at 650°C

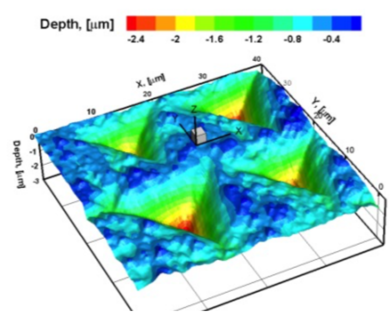


$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2A'}\right)^{1/n}$$

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	l	Nanoindentation
Dislocation-strain softening	ρ_i	Nanoindentation post creep



Nano-indentation at 650°C



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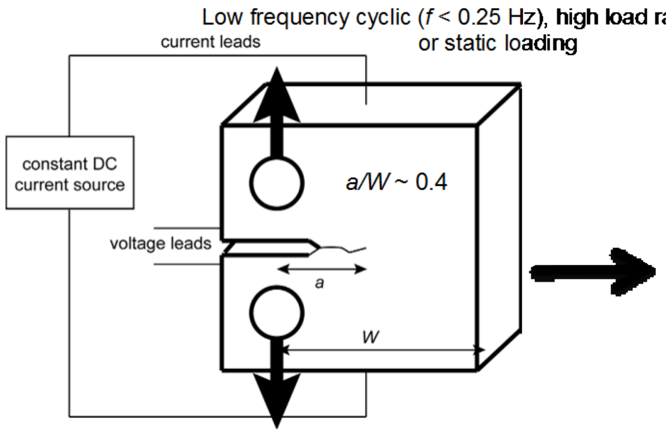
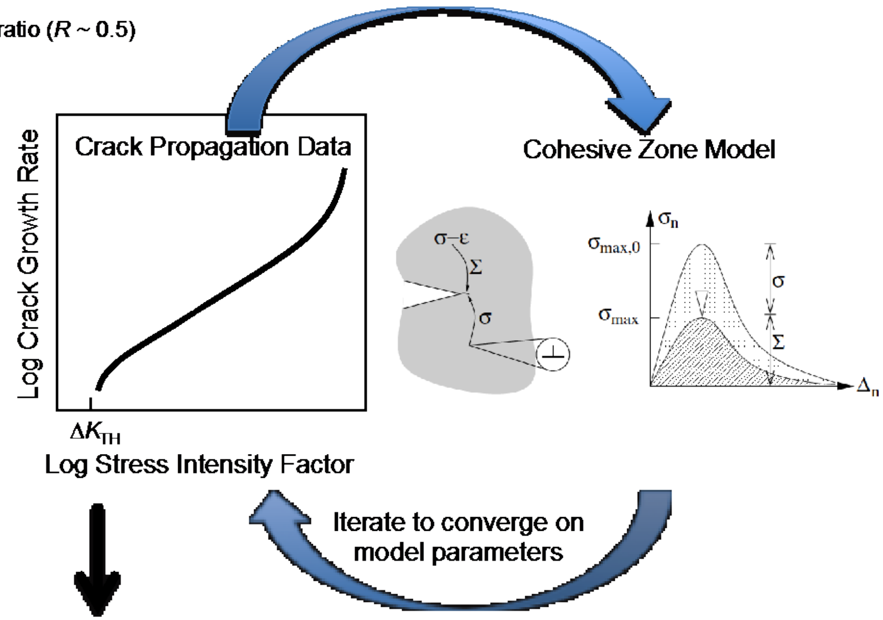
OVERVIEW: ORIGINAL PLAN

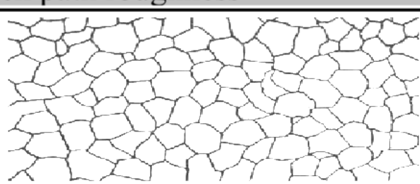
Research on Crack Propagation Models



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



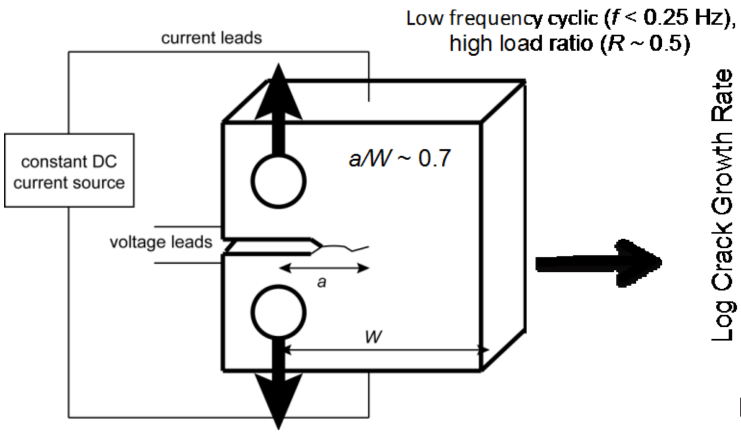
Experimentally determined parameter	Symbol	Experiment
Cohesive zone threshold	σ_f	Long crack fatigue threshold
Cohesive zone strength and length	$\sigma_{max,0}, \delta_\Sigma$	Long crack fatigue – Paris law Overload retardation
Creep damage parameters	Ω , p	Creep crack growth
Crack path roughness	R_A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

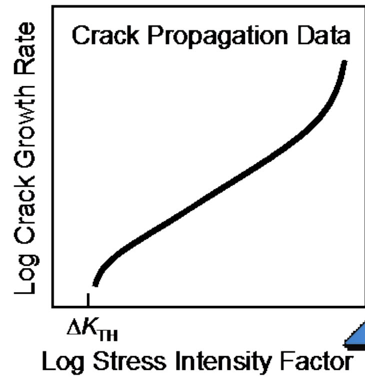


Grain size to estimate crack path

OVERVIEW: ORIGINAL PLAN

Initial Validation & Model Refinement

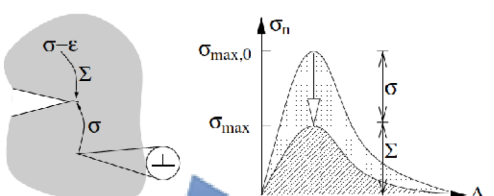


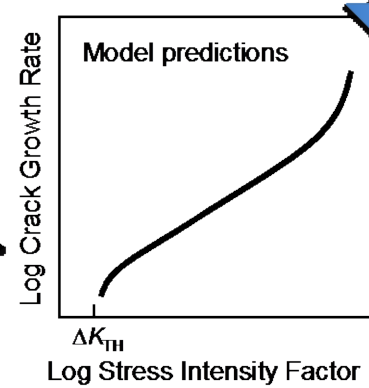


Model must achieve transferability across ***changing crack tip constraint conditions***

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

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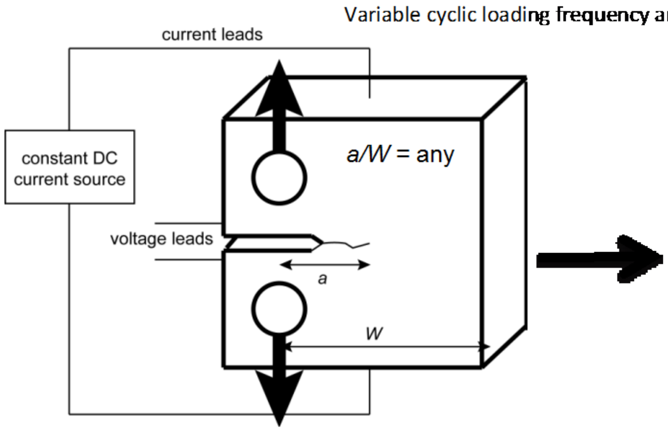
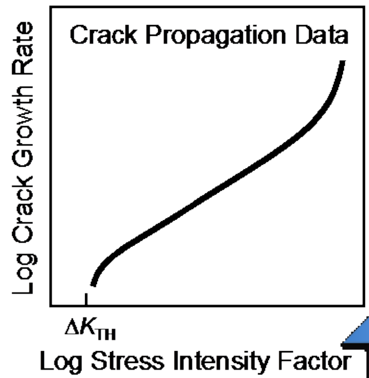
OVERVIEW: ORIGINAL PLAN

Final Validation & Model Refinement

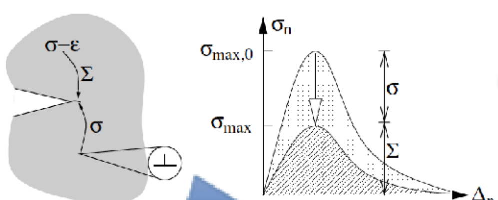


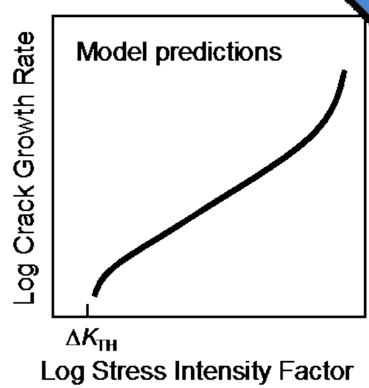


Model must achieve transferability across ***changing cyclic loading frequencies and dwell times***

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

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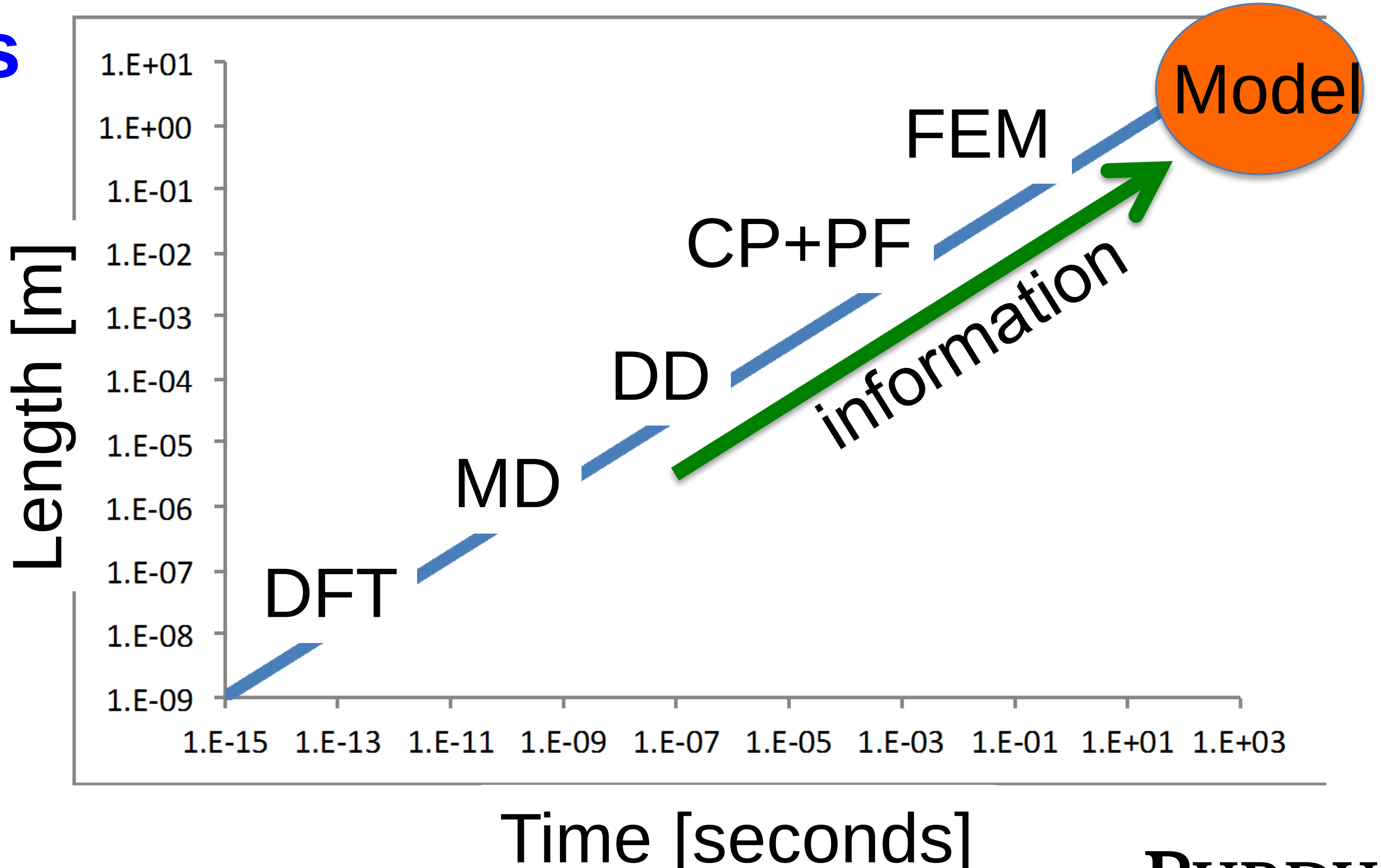
OVERVIEW: LENGTH AND TIME

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



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2015: 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 621ºC and held for 10 hrs, then air cooled.

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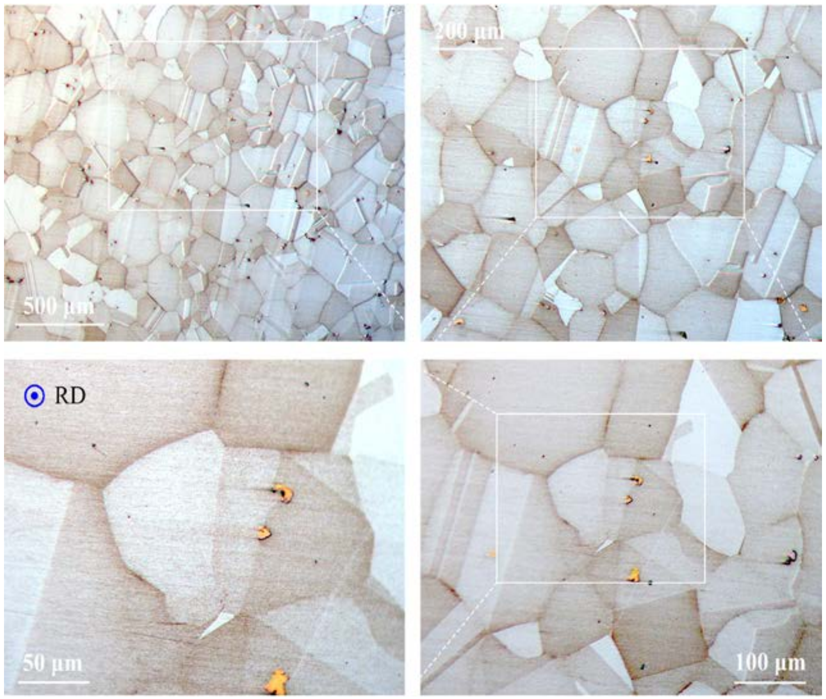
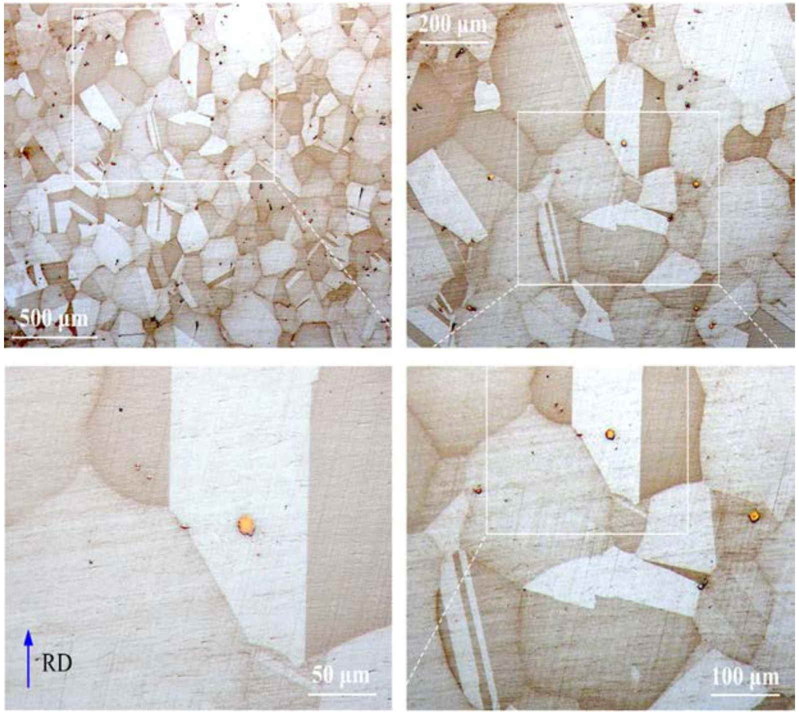
Optical Microstructure Characterization





Uniform and equiaxed microstructure

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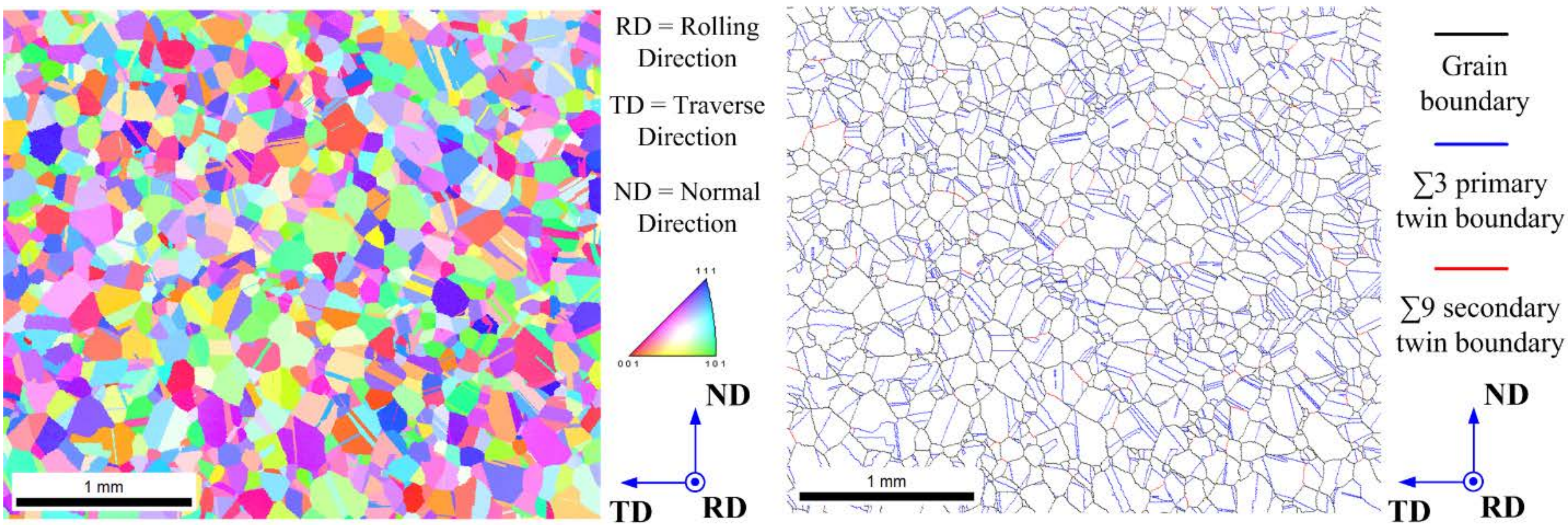
EBSD on Transverse Section



(a) Crystal orientation map

(b) Grain/twin boundary map

Highly twinned

Most twins as ∑3 (from recrystallization)

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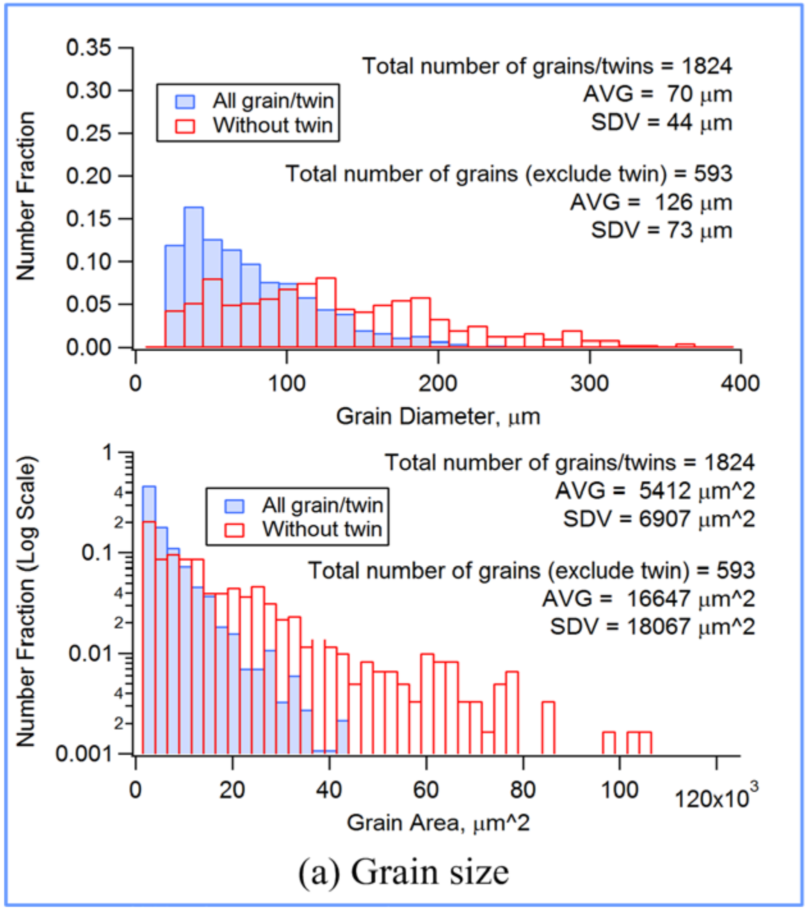
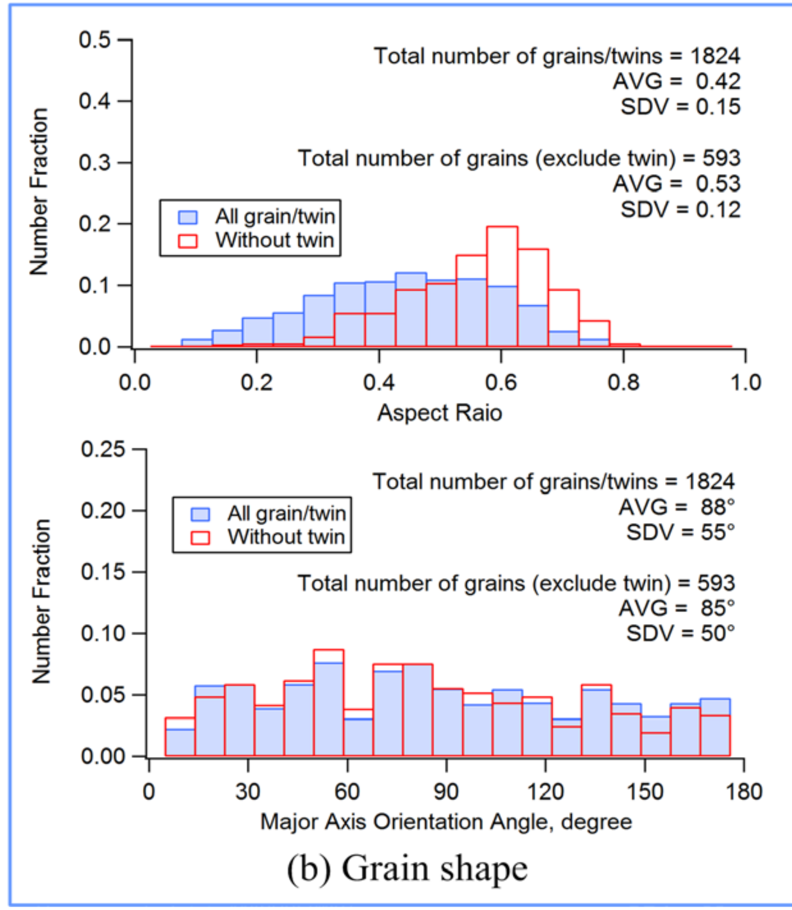
Grains & Twins: Grain Size and Orientation



(a) Grain size



(b) Grain shape

Analysis with and without twins

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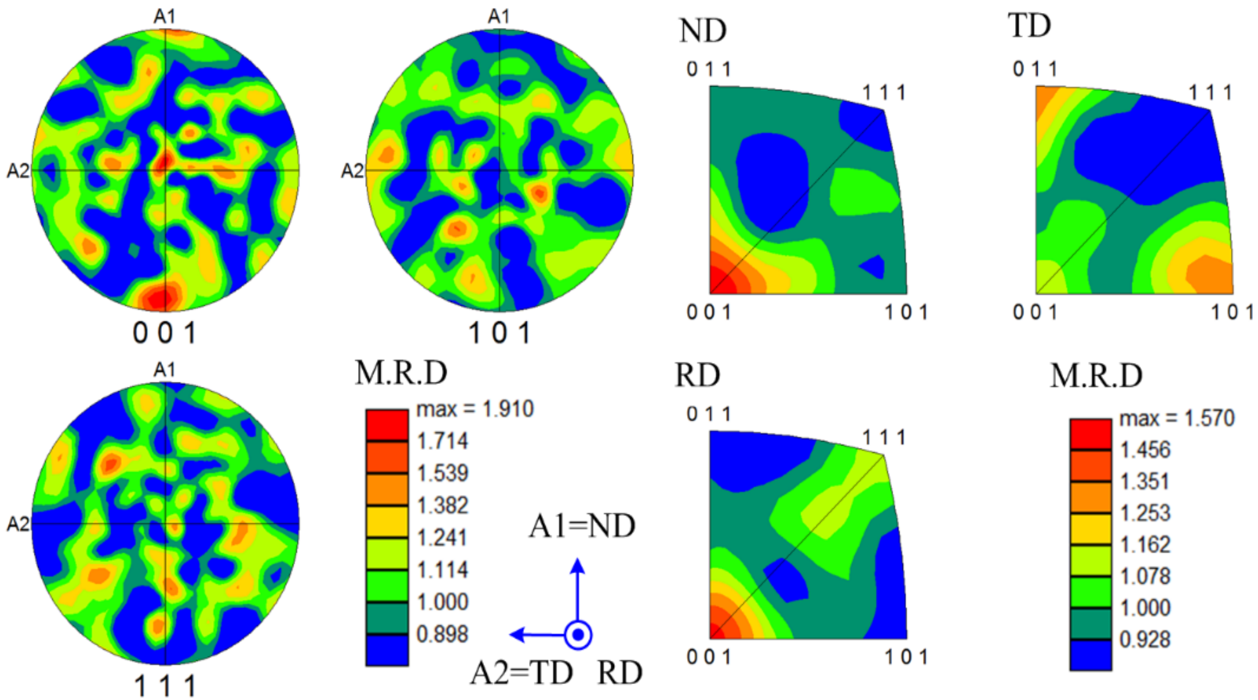
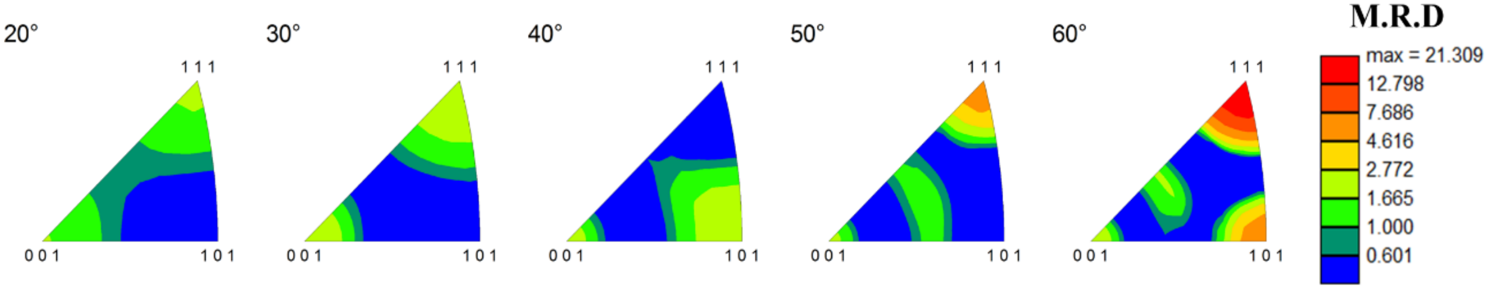
Texture



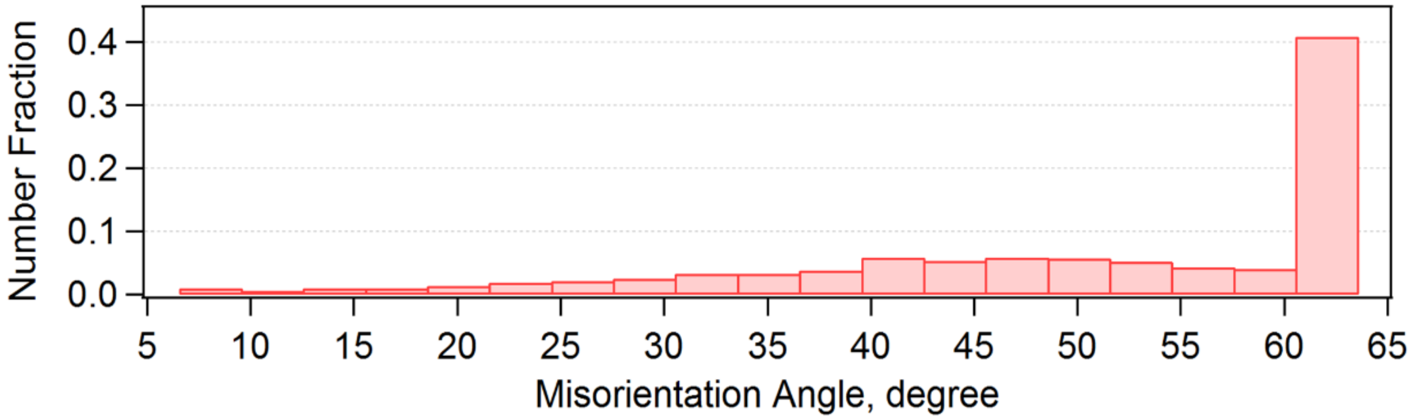
(a) Pole figure (b) Inverse pole figure

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

Grain and Twin Boundaries



(a) Misorientation axis distribution



(b) Misorientation angle distribution

Strongly influenced by S3 twins

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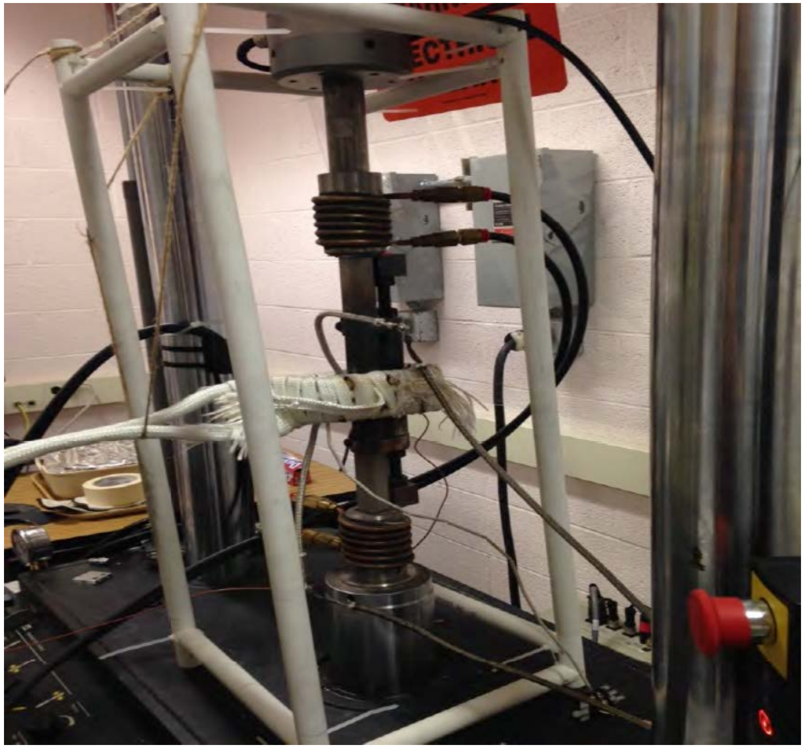
Crack Growth: Experimental Set Up



HT Experiments on CT specimens with potential drop measurements

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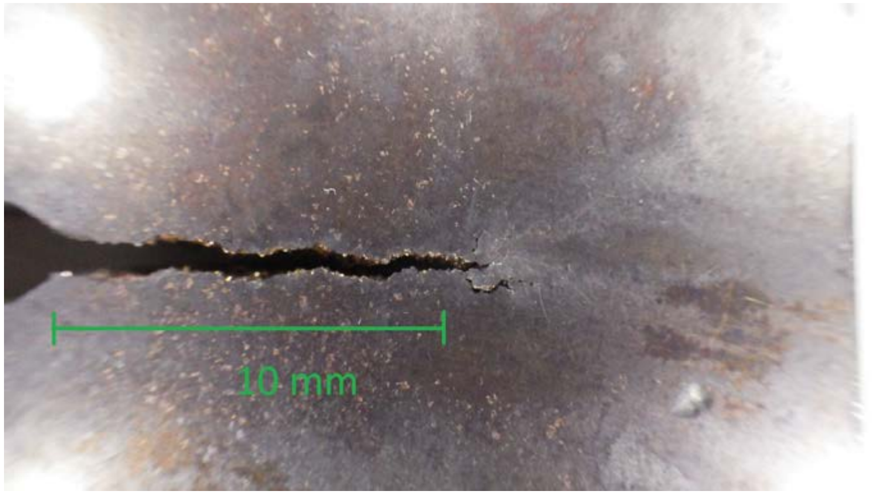
Crack Growth: Initial Experiments

Test parameters:

- **Compact tension C(T) sample**
- **Constant force range, *ΔP***
- **Load ratio, $P_{min}/P_{max} = R = 0.5$**
- **0.1 Hz triangle waveform**
- **T = 650°C in air**
- **Crack was grown from *a* = 6.5 – 16.7 mm**



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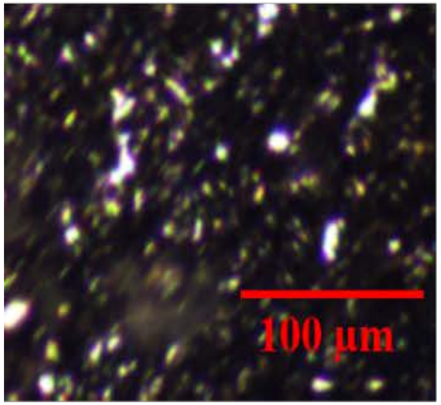
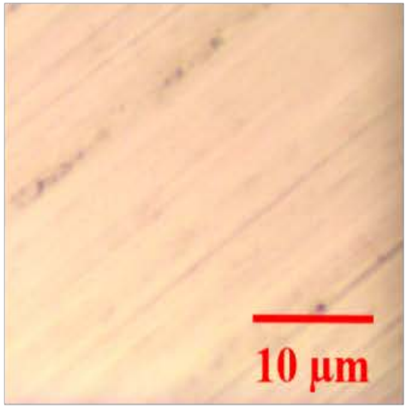
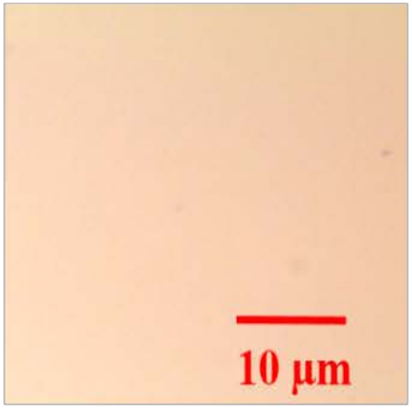
HT Nanoindentation: Specimen preparation

320 grating → 400 grating → 600 grating → Diamond powder 6 µm → Diamond powder 3 µm → Alumina powder → Vibro-polishing 10 hours





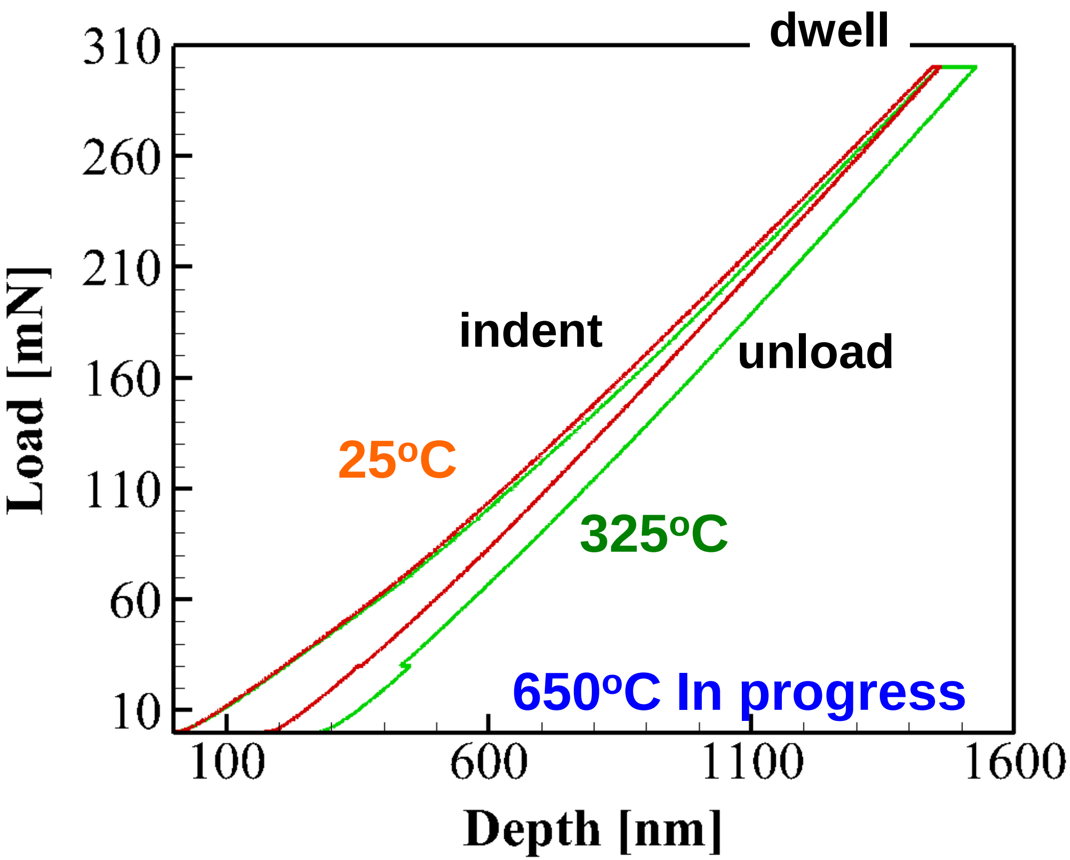


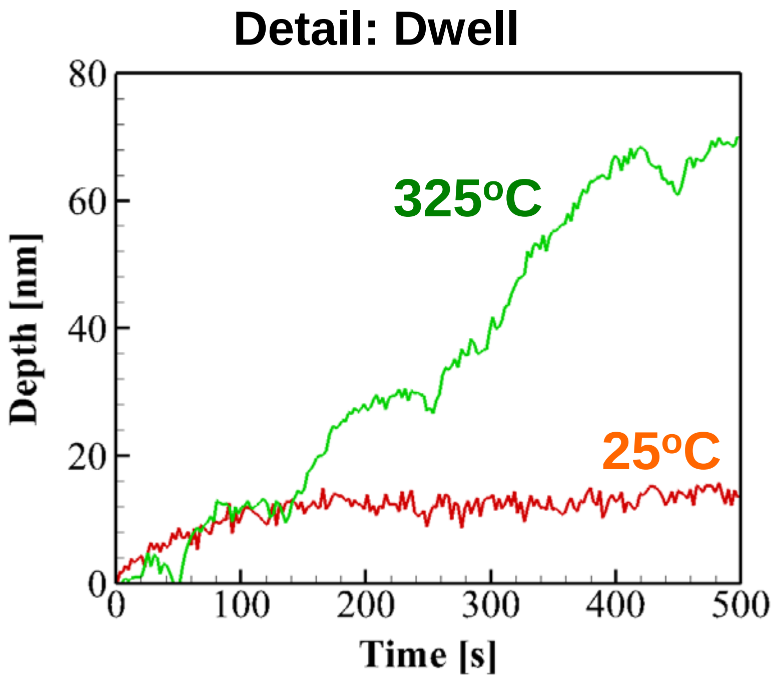
HT Nanoindentation: Experimental plan

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

HT Nanoindentation: 1st data on IN 718





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Current Status

- Calibrate indentation system to account for machine compliance at high temperature (ceramic)
- Currently, waiting for indenter tip to be provided by manufacturer. Delayed due to end of year closures and budget allocations
- Expect indenter tip back at Purdue with a short time

Constitutive Models: Flow Stress

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

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

q: state variable vector

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

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

Computational Implementation

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

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

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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

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

Computational Implementation

- Iteration

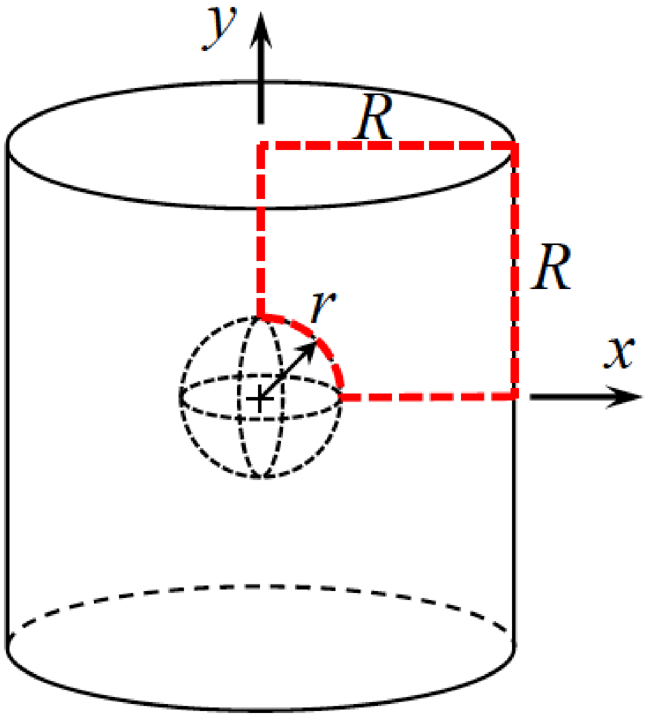
$$\begin{Bmatrix} \Delta\bar{\varepsilon}^{vp} \\ \bar{\sigma} \end{Bmatrix}_{n+1} = \begin{Bmatrix} \Delta\bar{\varepsilon}^{vp} \\ \bar{\sigma} \end{Bmatrix}_{n} - \mathbf{J}_n^{-1} \begin{Bmatrix} f_1\left(\Delta\bar{\varepsilon}^{vp}, \bar{\sigma}\right) \\ f_2\left(\Delta\bar{\varepsilon}^{vp},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

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

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

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

Results: Creep Rupture



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

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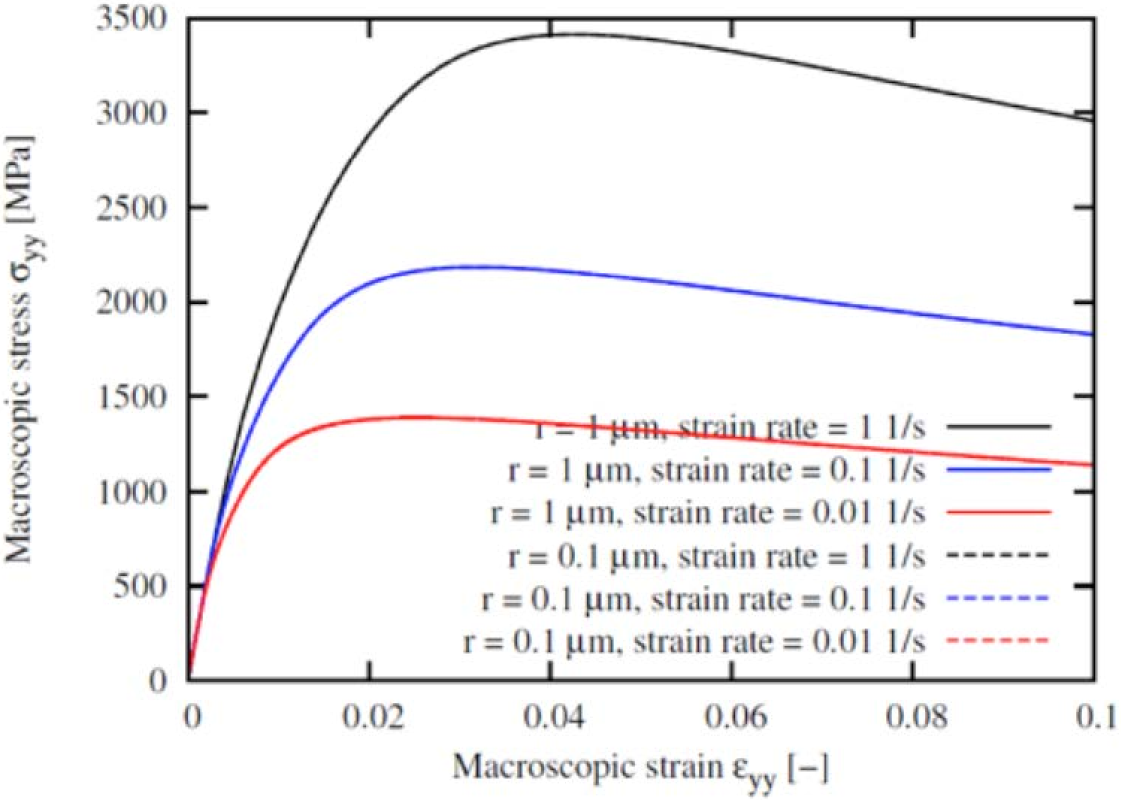
Void Growth conventional plasticity

No size effect only rate effect



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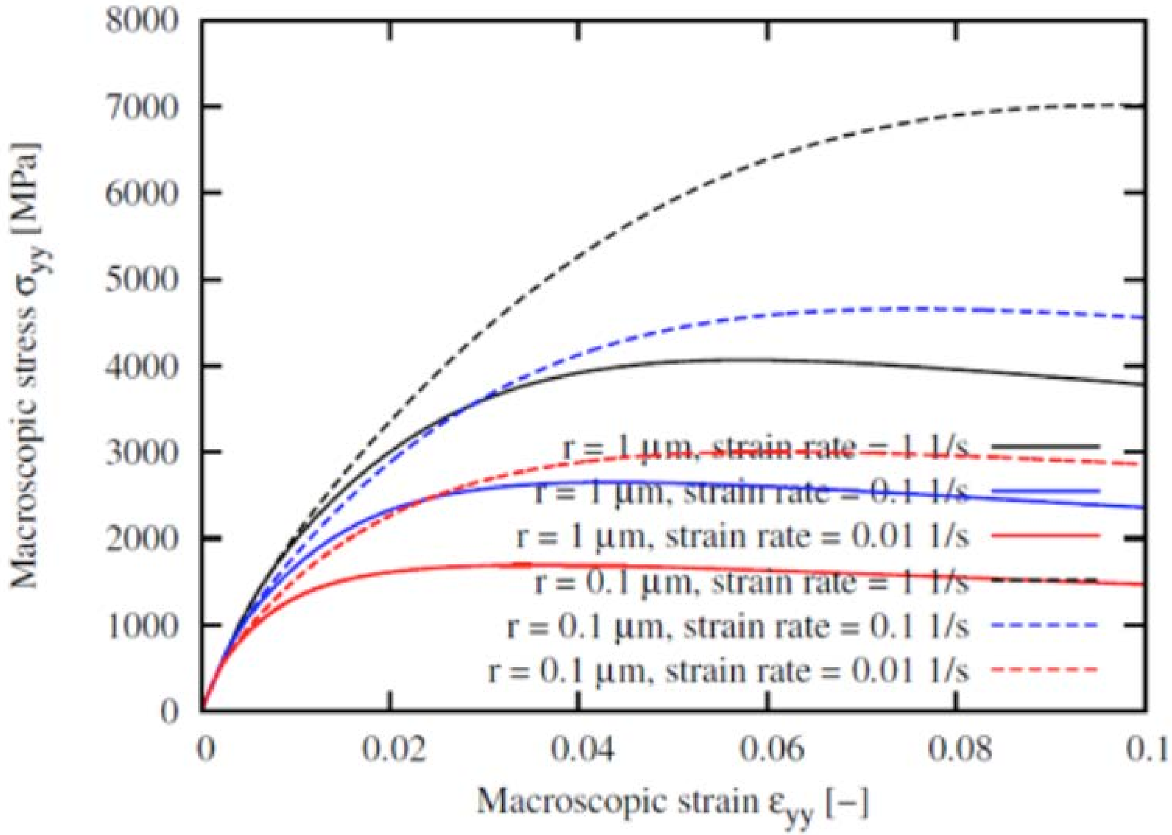
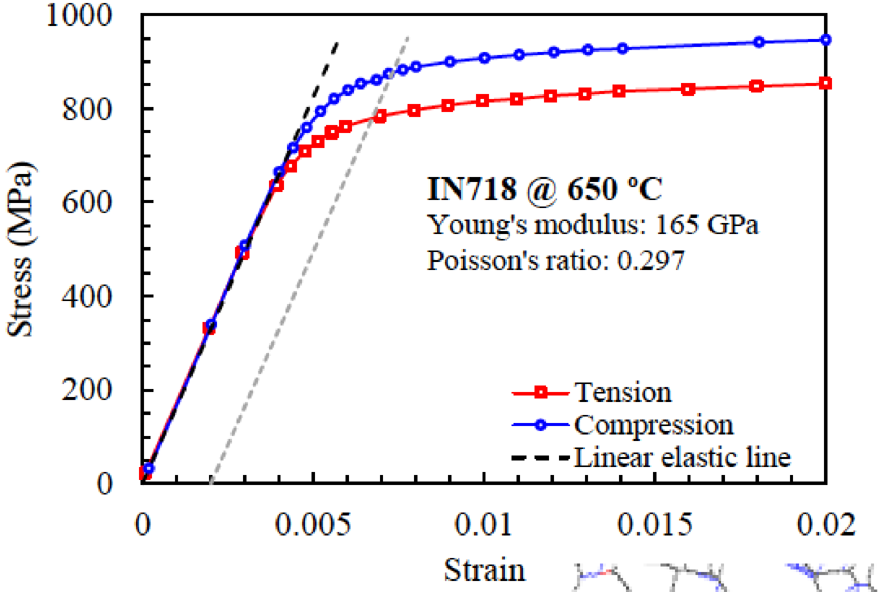
Void Growth with SGP:
Void Size Effect combined with a rate effect



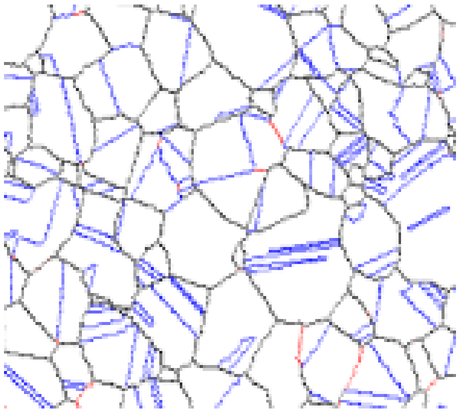
- Smaller voids lead to higher stresses
- Smaller voids are more sensitive to rate

Strength Differential Effect (Data by Lissenden et al)



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

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



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Strength Differential Effect: Yield Function

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

m, k

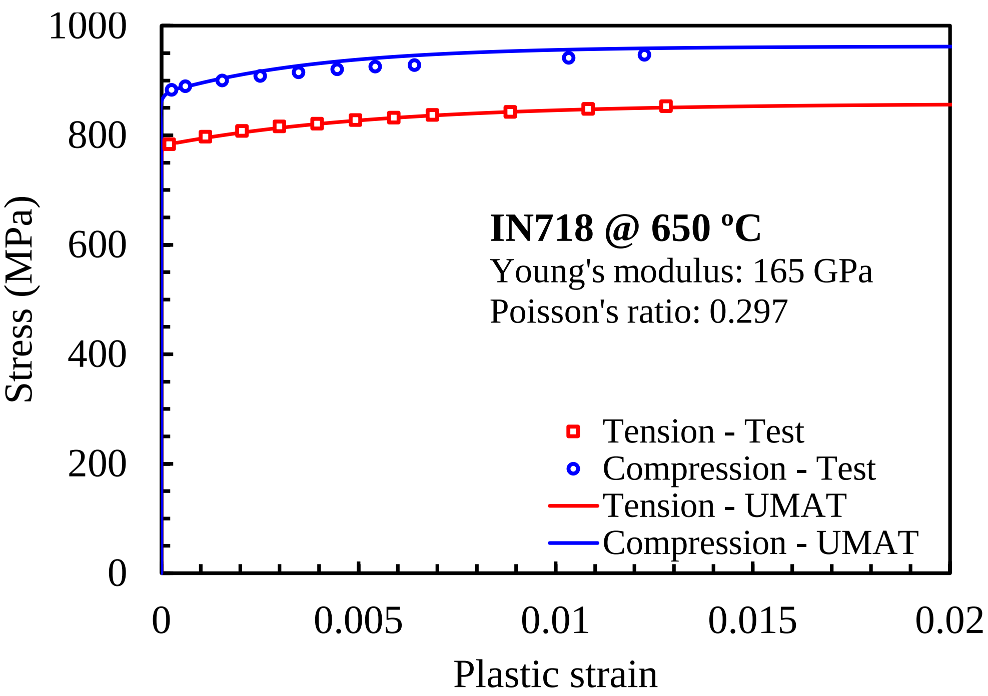
$m = 2, k = 0 \ldots \text{von Mises}$

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

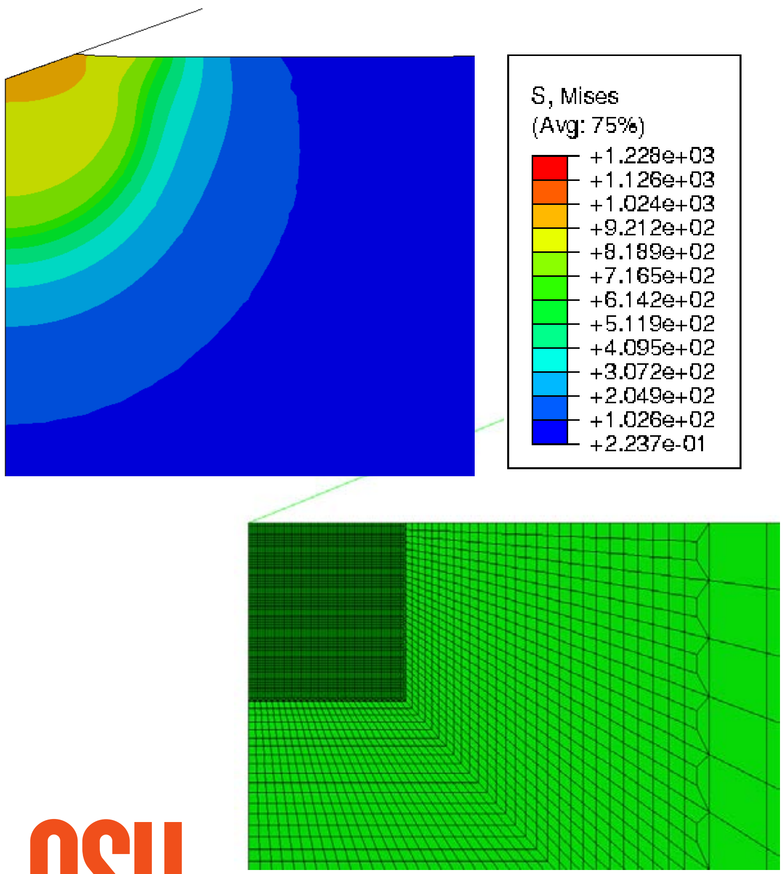
Strength Differential Effect: UMAT

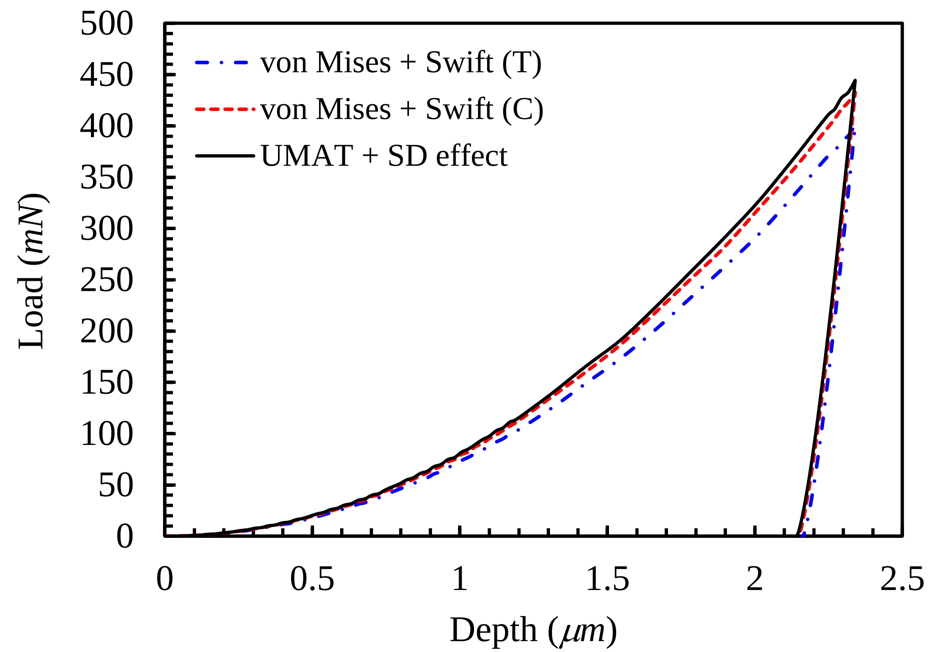
E (GPa)	ν	σ_T (MPa)	σ_C (MPa)	K (MPa)	ε_0	n
165	0.297	779	876	1003	0.0013	0.038

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



Strength Differential & Indentation





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

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Crack Growth: Cohesive Zone Models

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

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

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

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

$$D_C = D_C + \Delta D_C$$

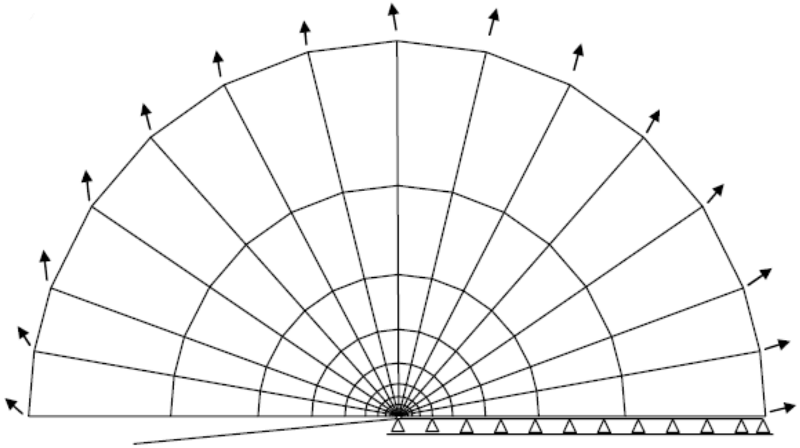
$$\boxed{\left(\frac{J}{2\sigma_0} / \Lambda \right), \left(b / \Lambda \right), \left(\frac{\dot{J}}{2\sigma_y} / \dot{\varepsilon}_0 \Lambda \right), \left(\delta / \Lambda \right)}$$

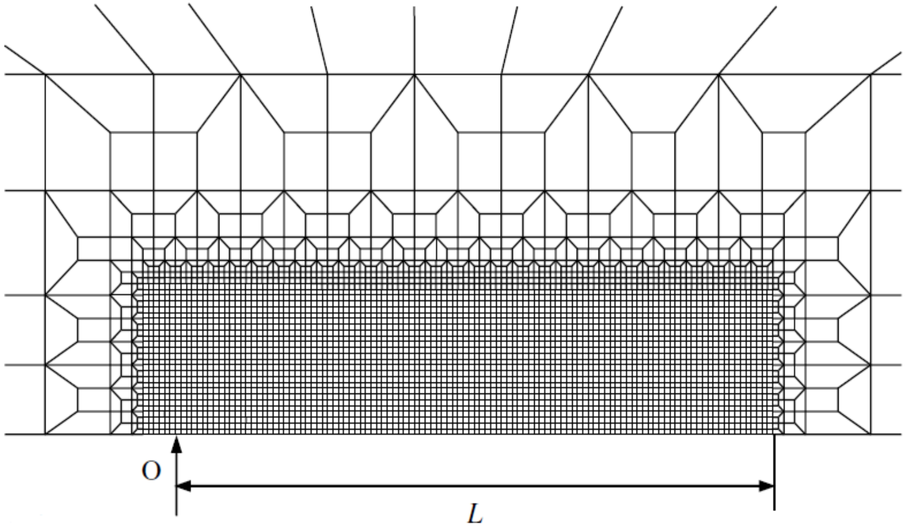
Modified Boundary Layer Model

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

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

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





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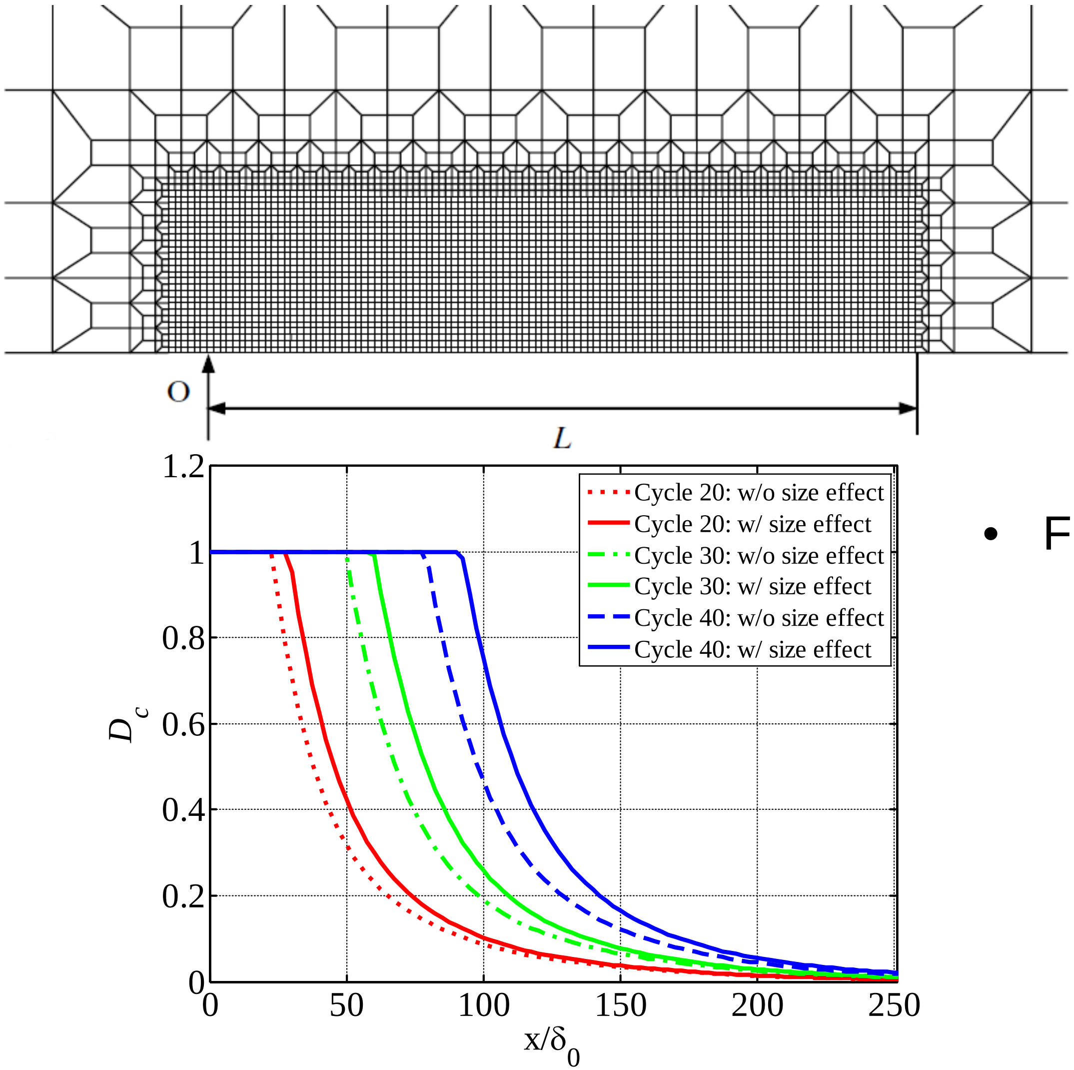
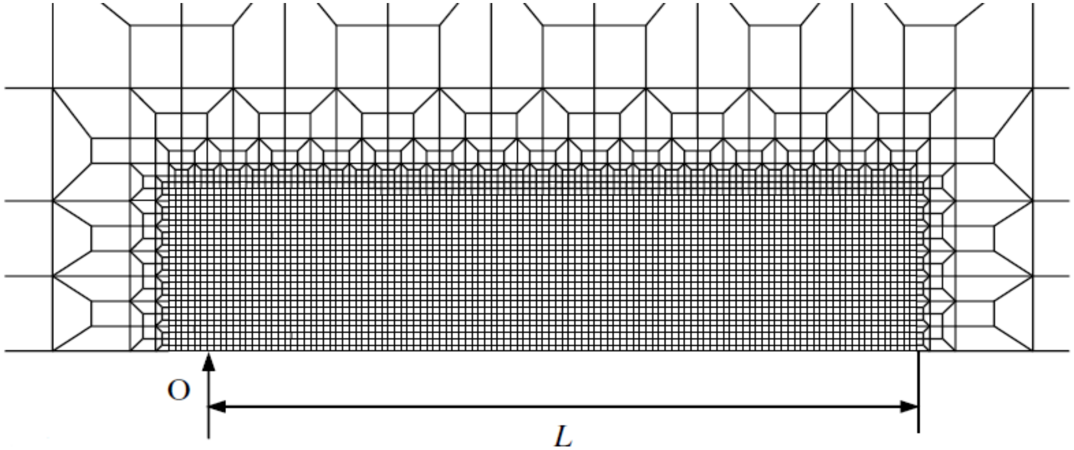
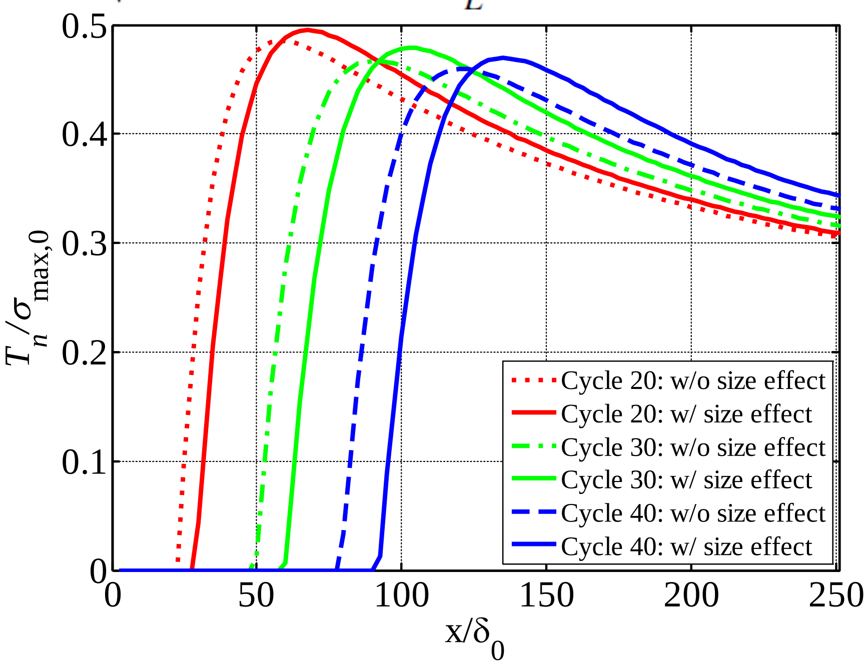
Strain Gradients and FCG



- FCG Rates with SGP are larger than without

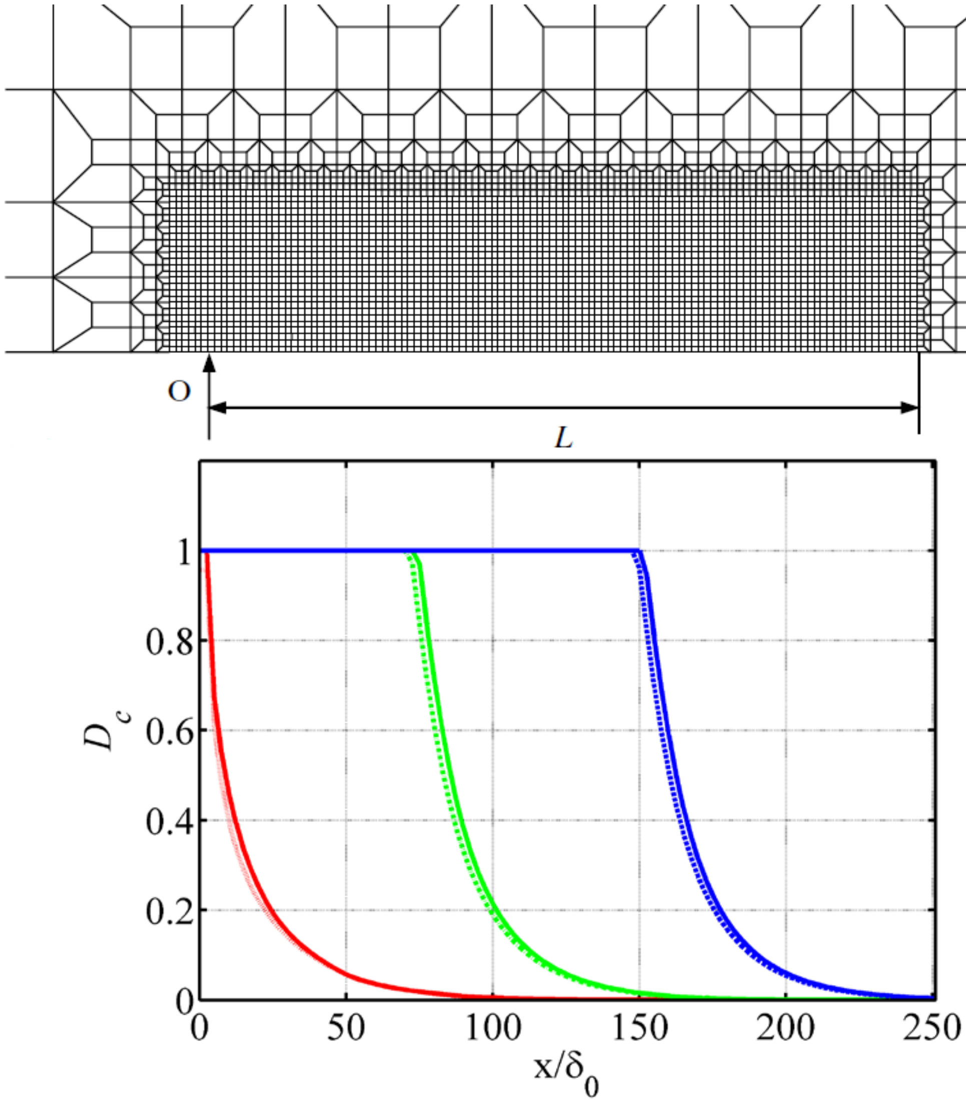
Strain Gradients and FCG





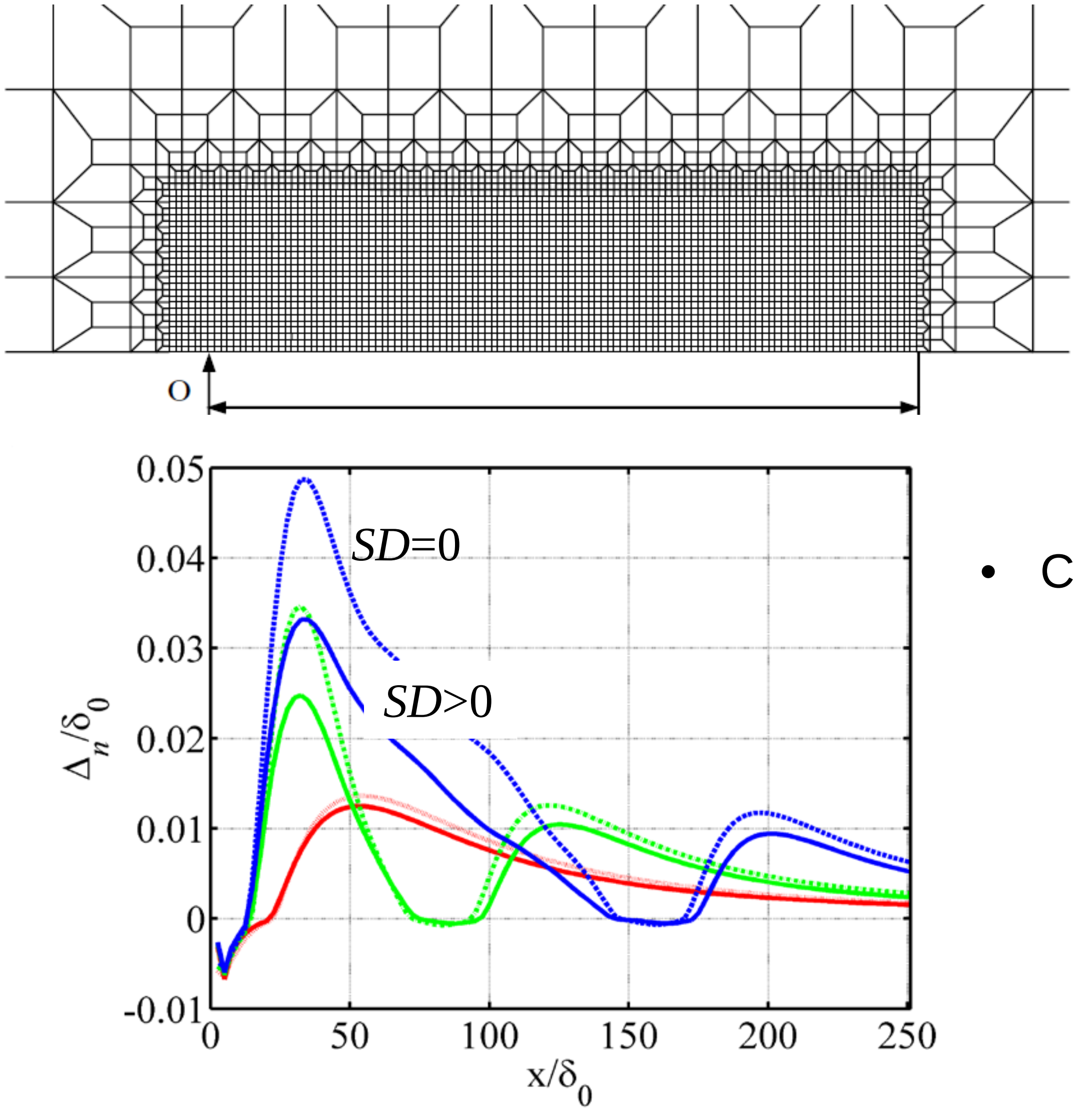
- Opening stresses with SGP are larger than without

Strength Differential and FCG



- FCG Rates appear as little affected by SD alone

Strength Differential and FCG



- Crack closure appear as affected by SD alone

2015 CONCLUSION

- **Procured and characterized materials (NETL Albany)**
- **Property measurements ongoing**
- **Computational mechanics: Advanced model implementation on several fronts**

- **Additional Potential Actions:**
  - **Establish a tentative collaboration to explore AM manufactured materials**
  - **Follow up with industry showed interest but no concrete action**
  - **Explore the use of methods in structural part (blisk)**

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