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

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TEAM AND COLLABORATION

Purdue University

- Thomas Siegmund
- Vikas Tomar

Oregon State University

- Jay Kruzic (now University New South Wales)

NETL Collaboration

- Jeff Hawk, Albany OR: Material and creep experiments

Industry

- i3D MFG, Bend OR: EOS AM Material

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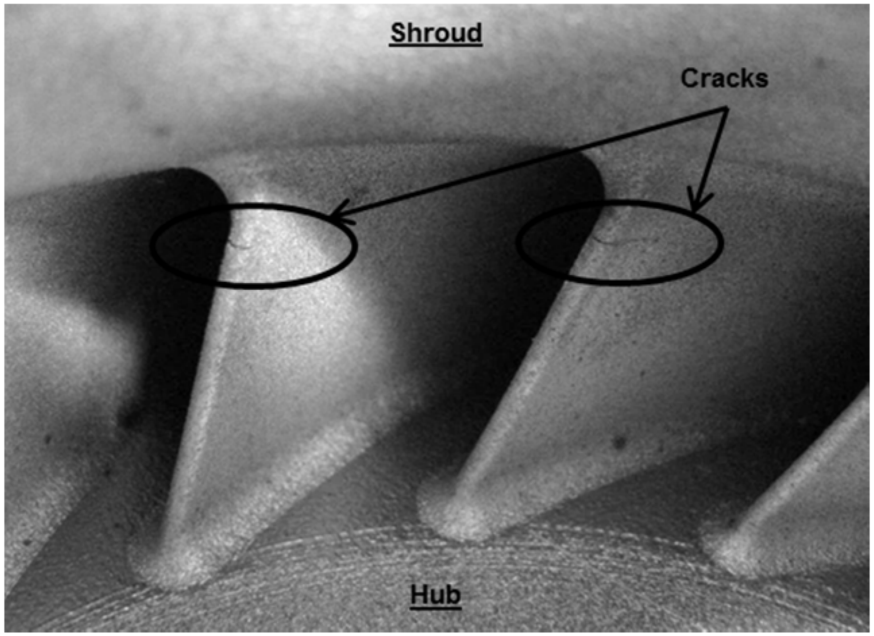
MOTIVATION

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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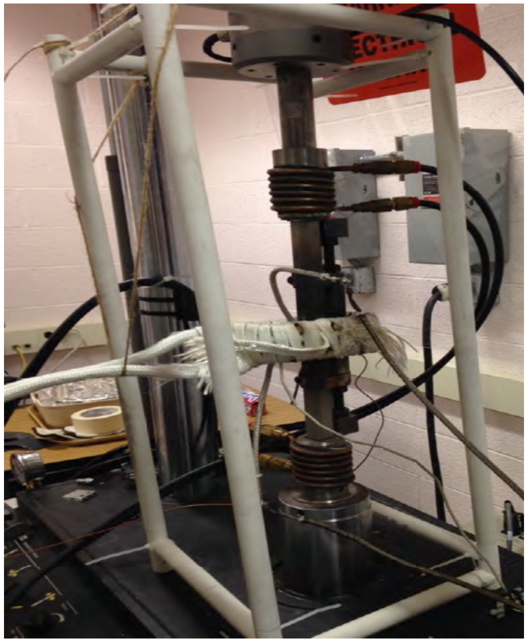
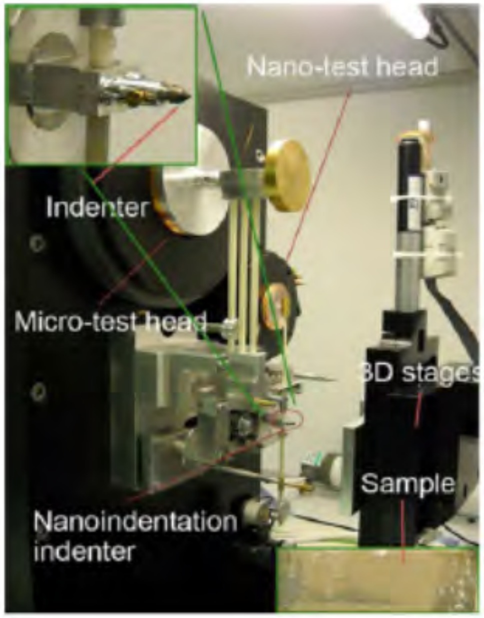
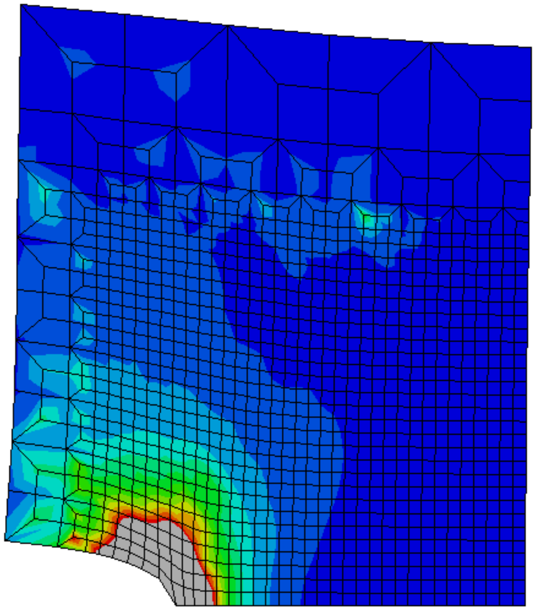
MATERIALS & METHODS

- IN 718 CONV (NETL, J. Hawks)
- IN 718 AM (i3D MFG)
- Microstructure Characterization (Kruzic)
- High Temperature Nanoindentation (Tomar)
- High Temperature Fatigue Crack Growth (Kruzic)
- Computational Mechanics (Siegmund)







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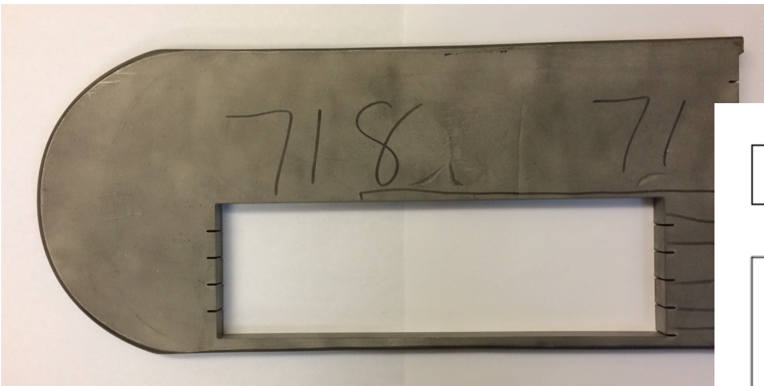
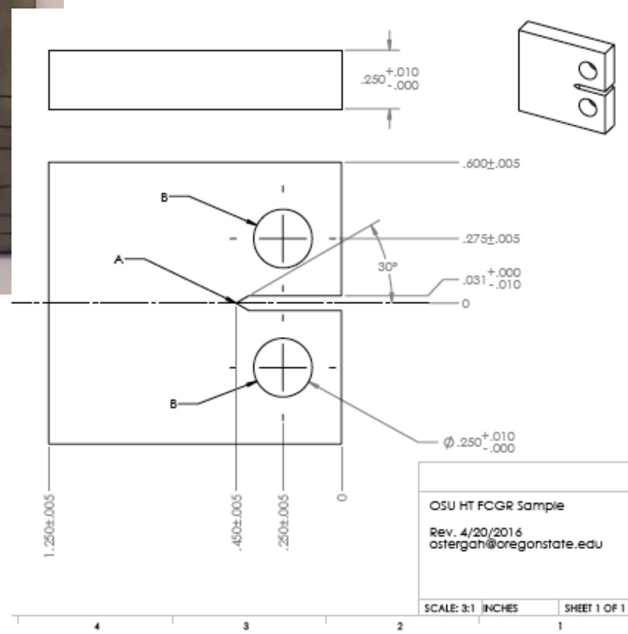
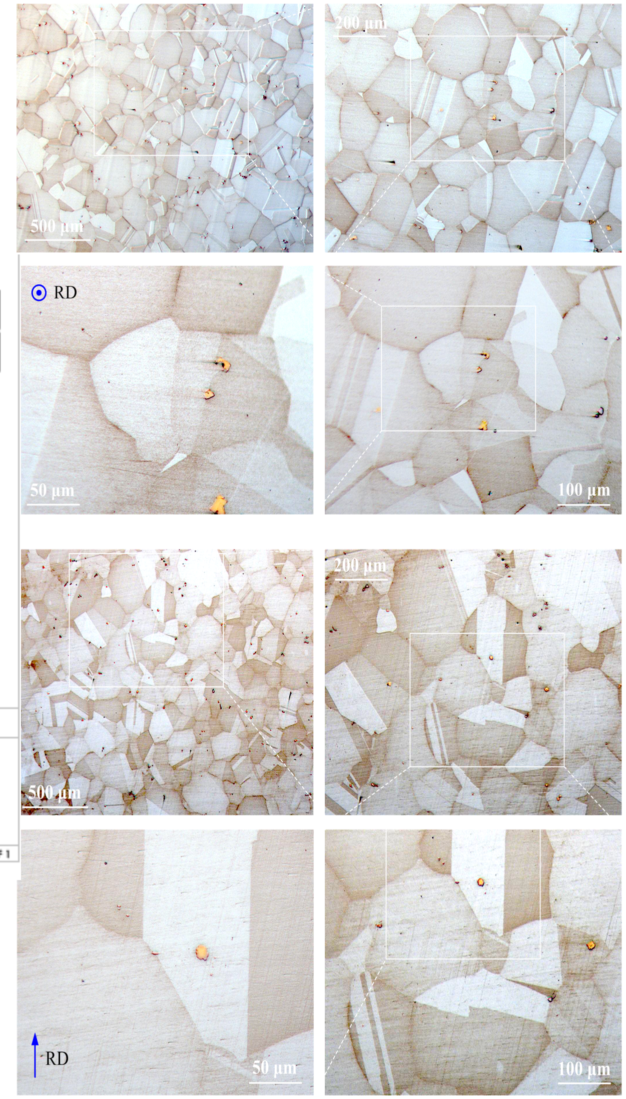
MICROSTR. AND FCG (KRUZIC)

IN 718 CONV



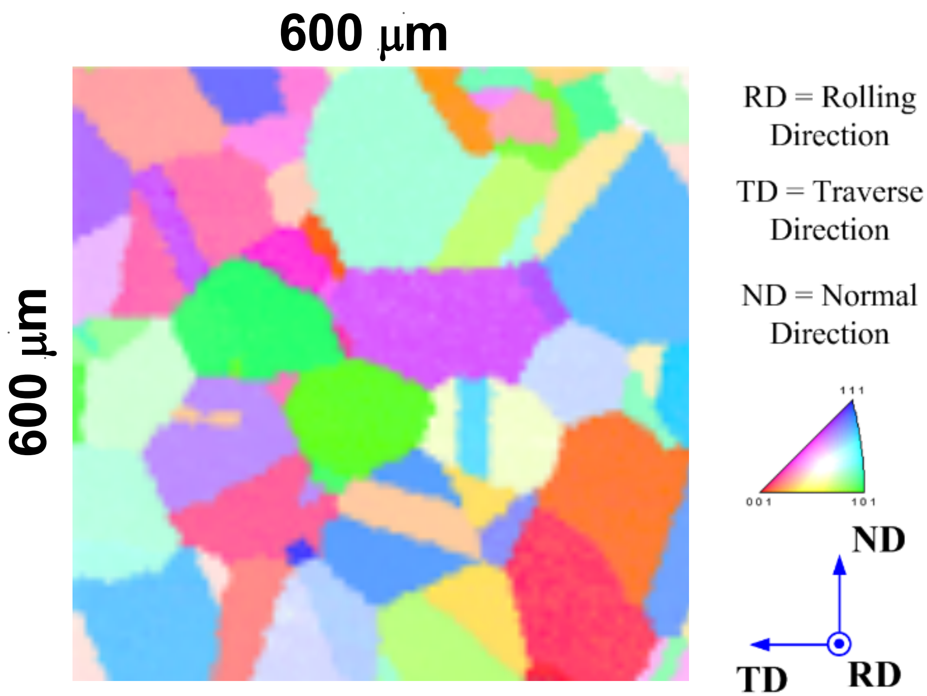


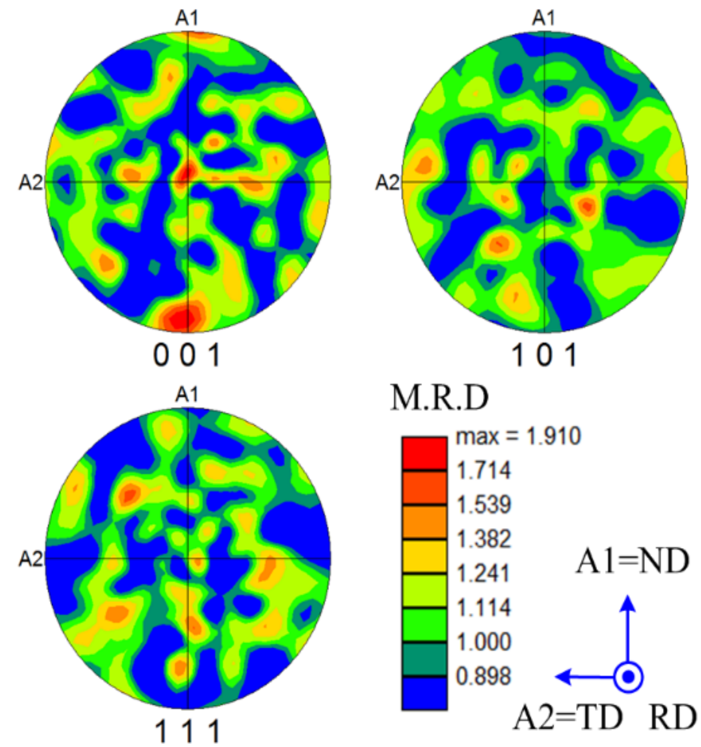


718 samples:

- Rolled, NETL Albany, Jeff Hawk
- Heat treatment steps follow AMS 5662
- Samples: 0.25 in thick, 1.25 in x1.25 in

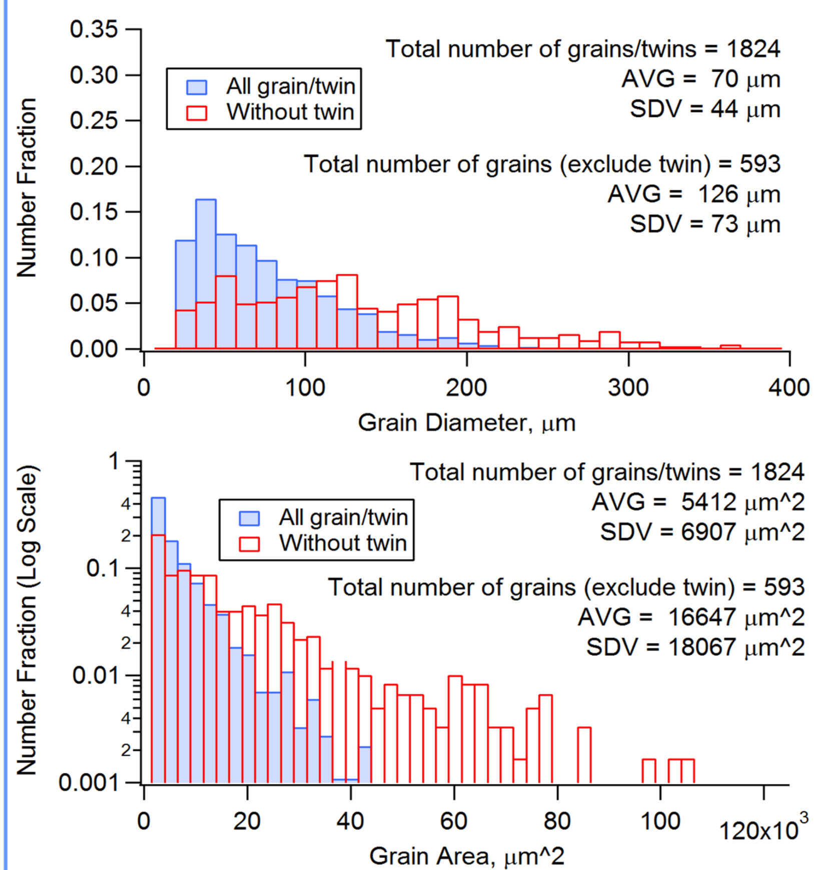
IN 718 CONV



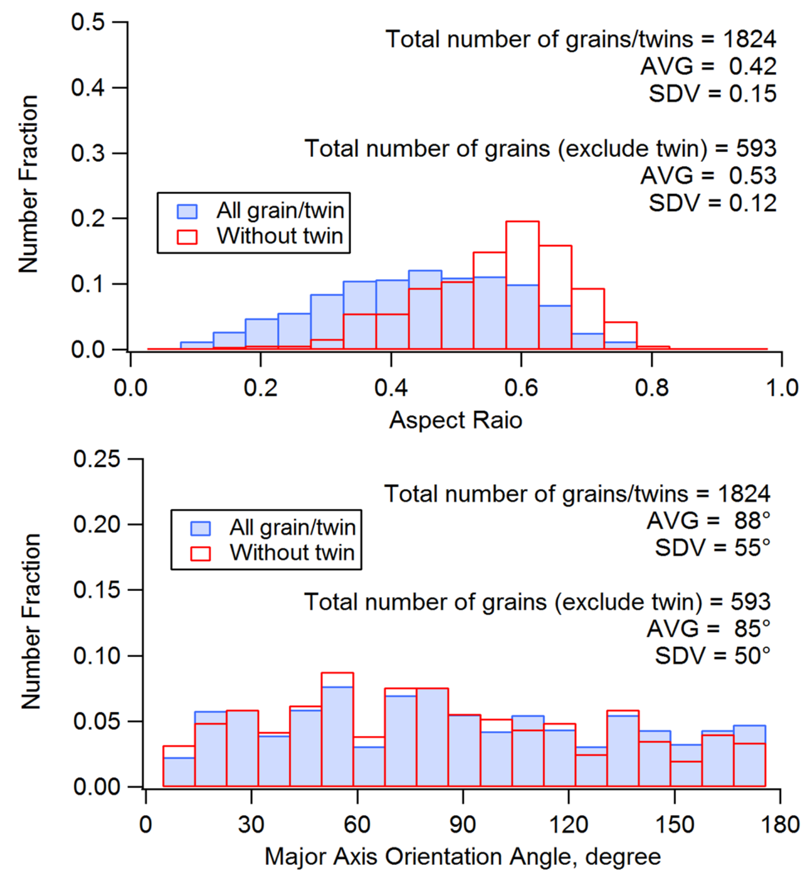


- Equiaxed grains
- Only little texture

IN 718 CONV



(a) Grain size



(b) Grain shape

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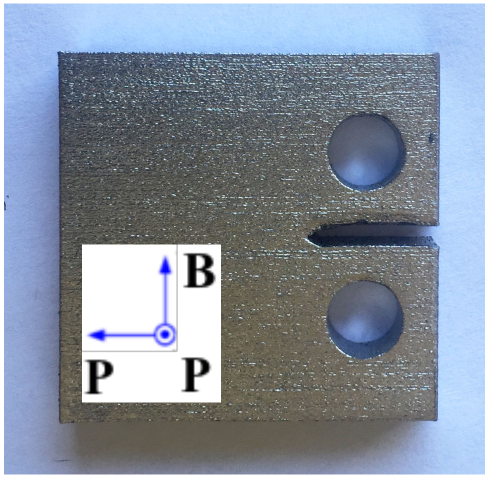
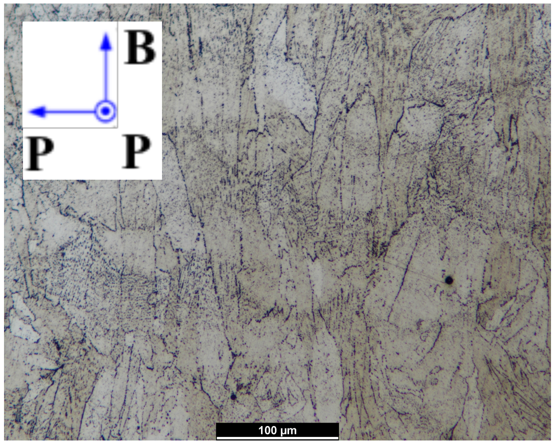
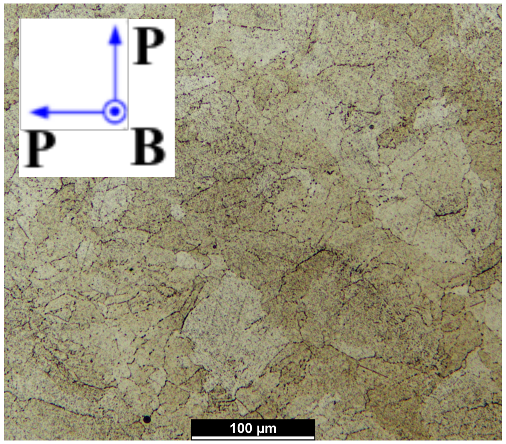
IN 718 AM







Direct metal laser sintered (DMLS) alloy 718 samples:

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

- heat treatment AMS 5662

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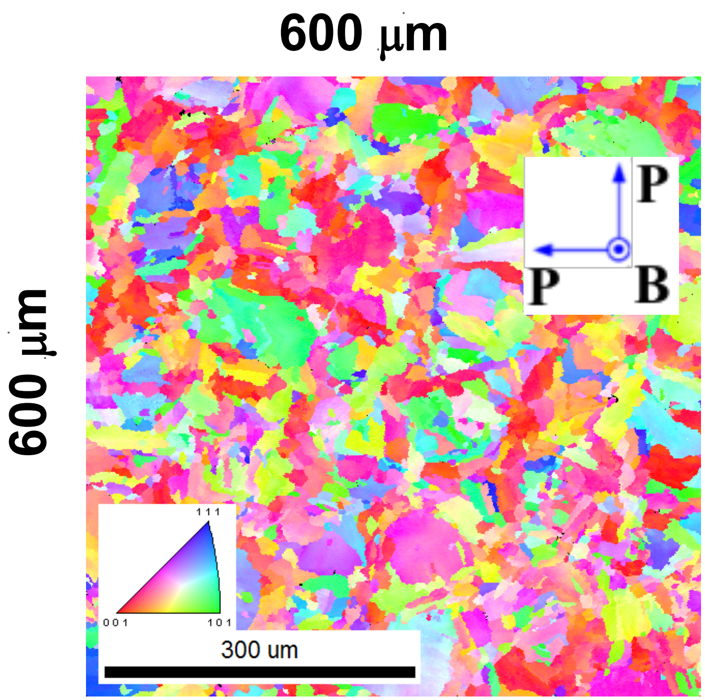
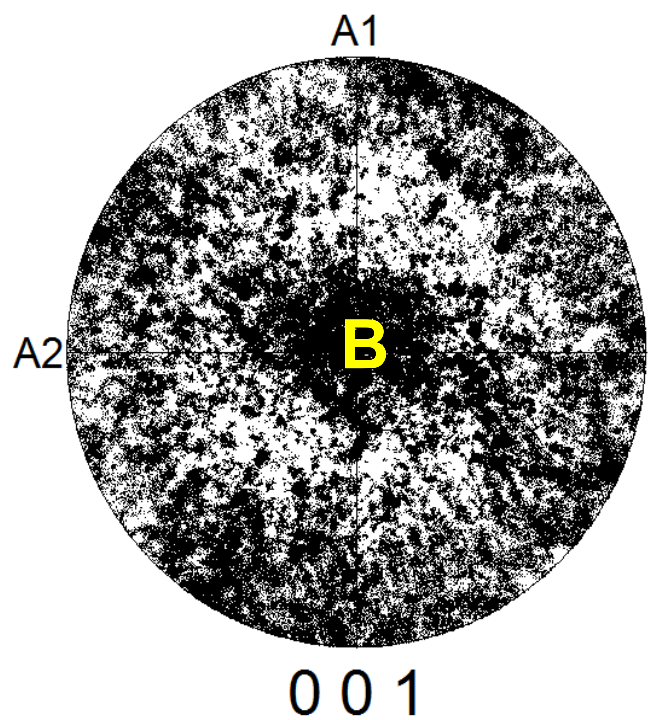
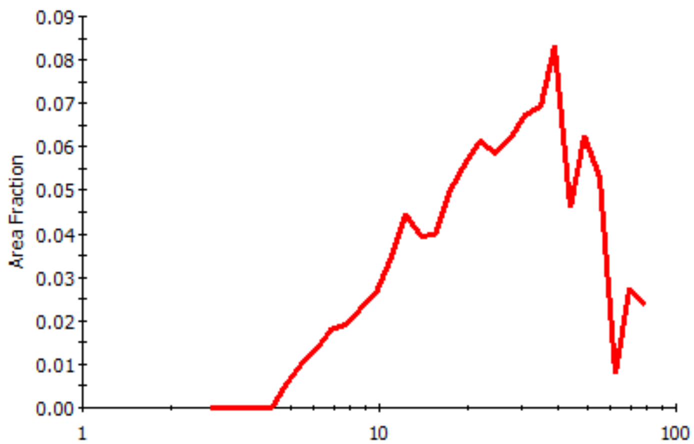
IN 718 AM; Print Plane



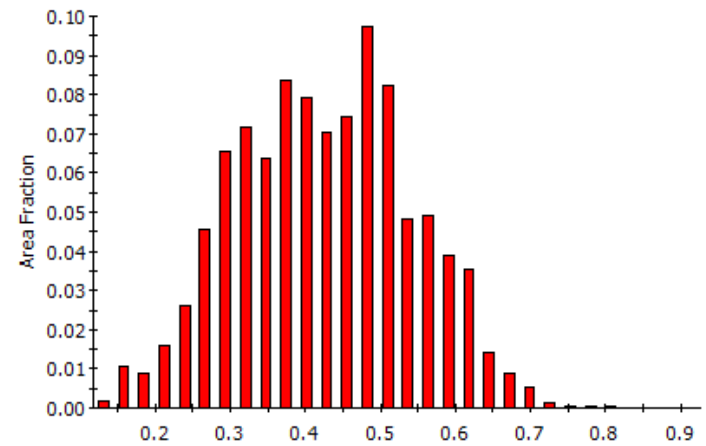


- Finer grains than the CONV
- Rather equiaxed grains in P-P
- Significant texture with 001 aligned in P
  - Transversely isotropic

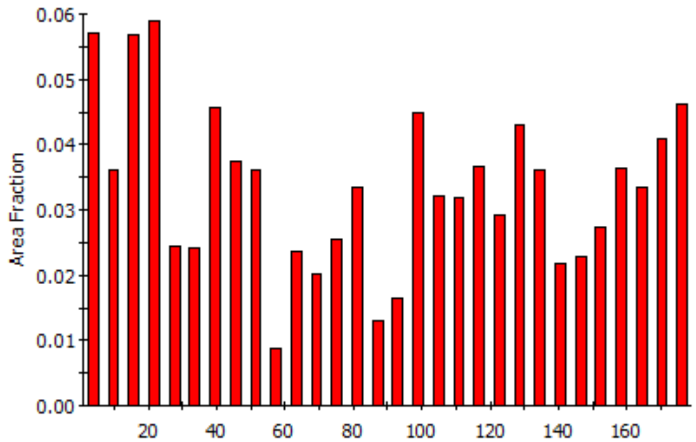
IN 718 AM: Print Plane



Grain Size [micron]



Grain Aspect Ratio



Major Axis Orientation

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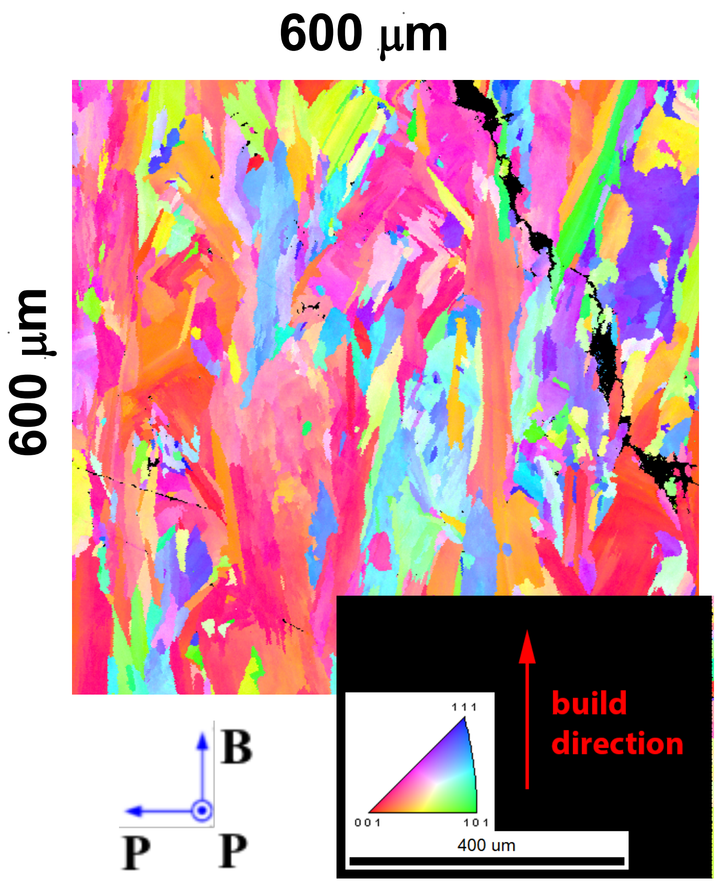
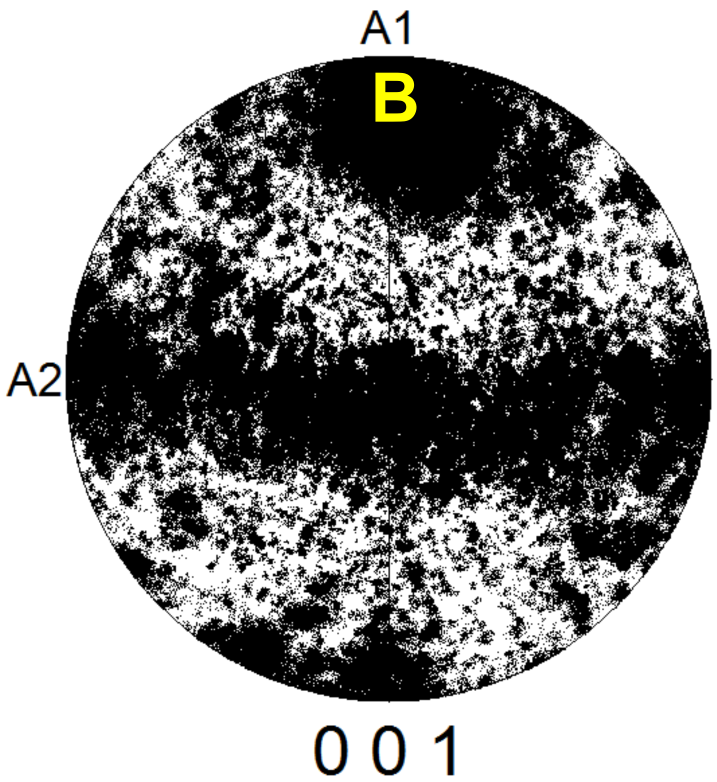
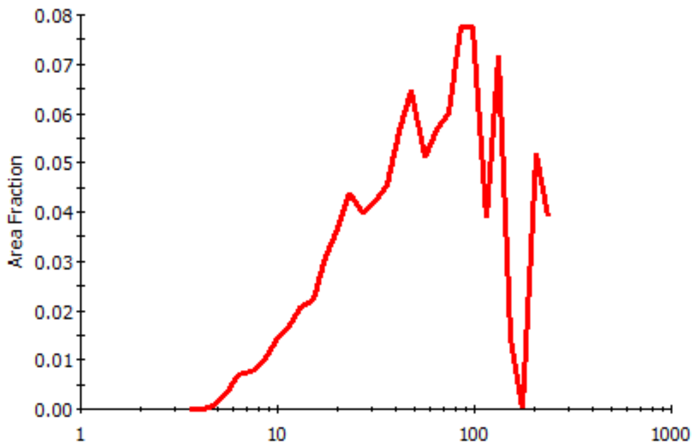
IN 718 AM: Build Plane



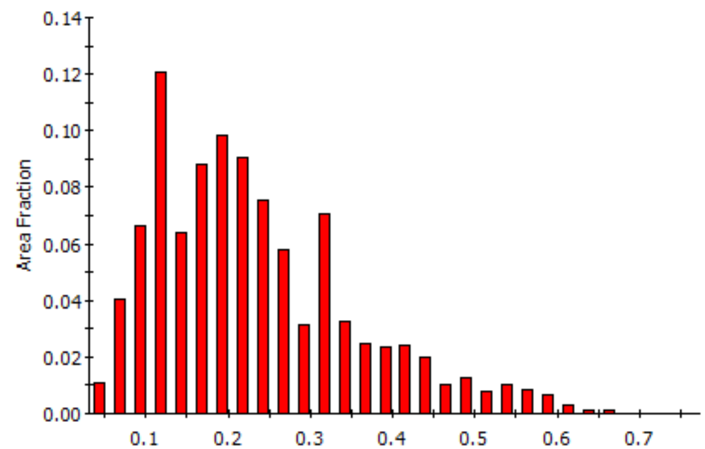


- Highly elongated grains
- Untextured in P-P and Textured in B
  - Transversely isotropic

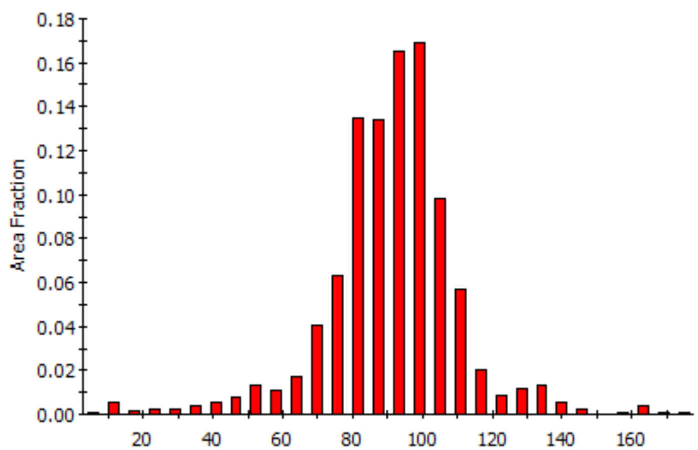
IN 718 AM: Build Plane



Grain Size [micron]



Grain Aspect Ratio



Major Axis Orientation

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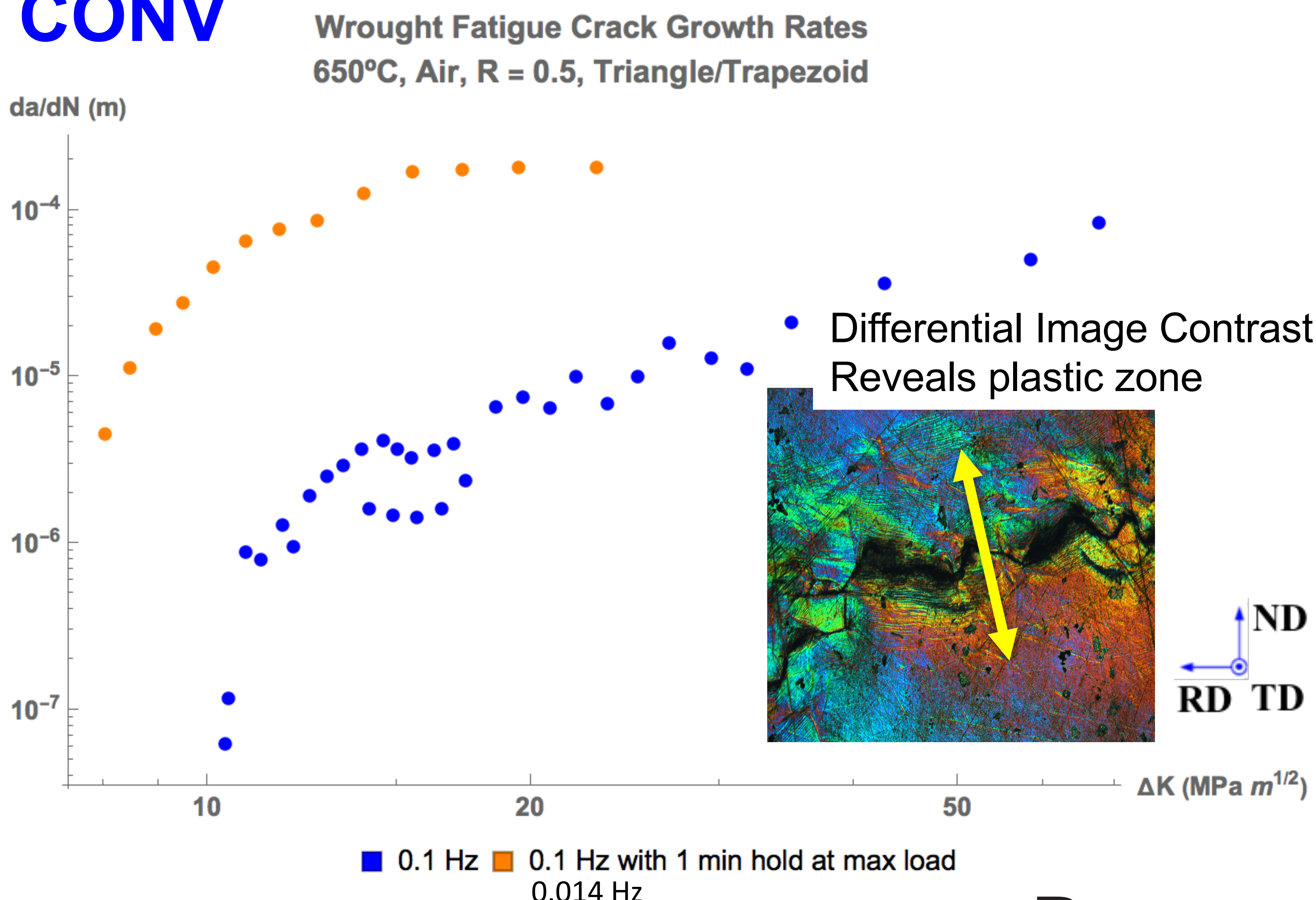
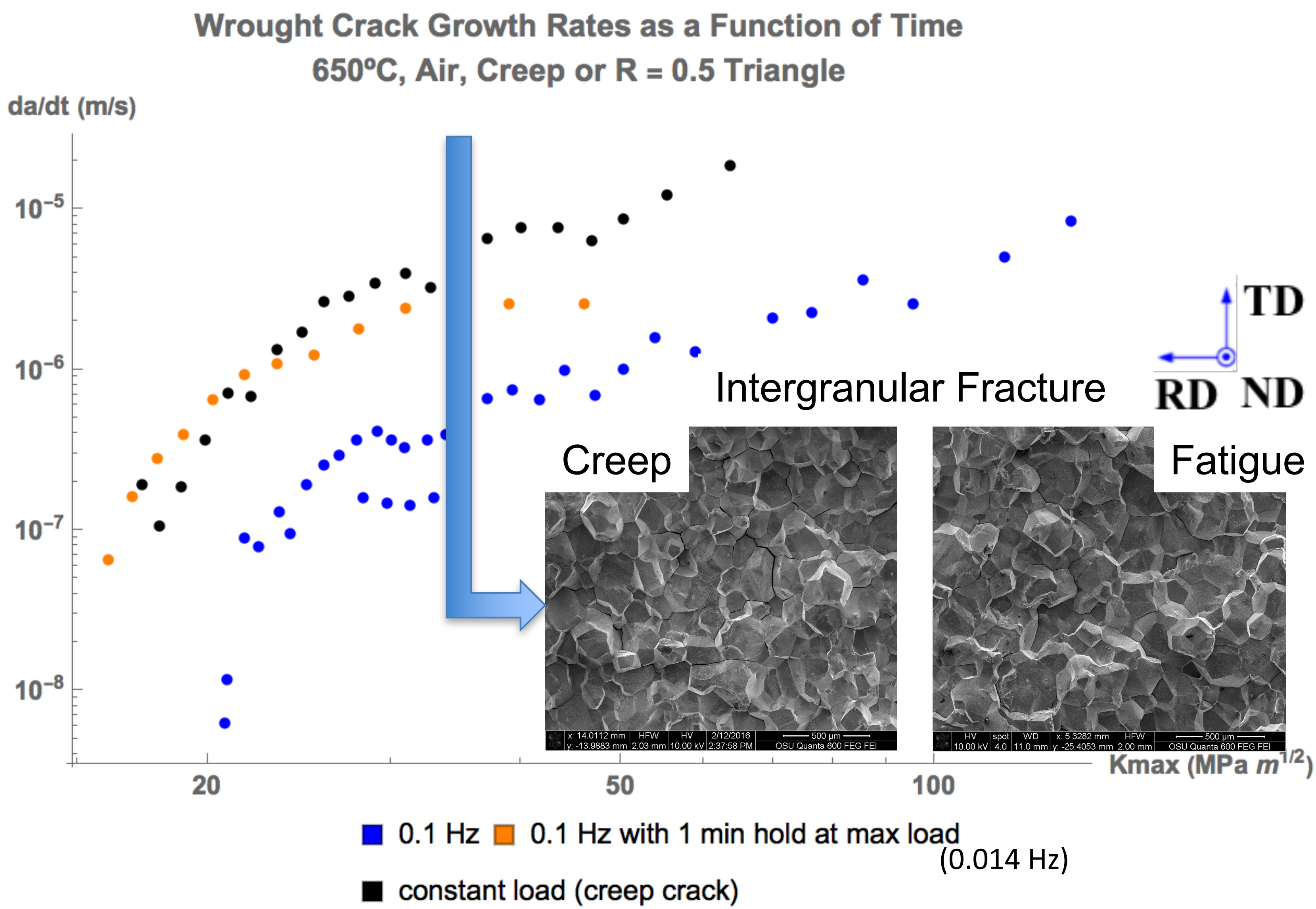
IN 718 CONV

da/dN



IN 718 CONV

da/dt



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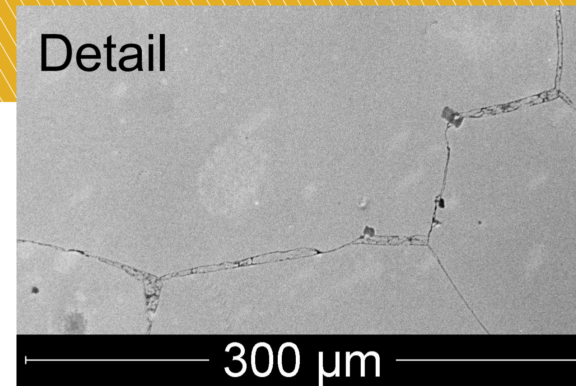
IN 718 CONV
Crack growth mechanism

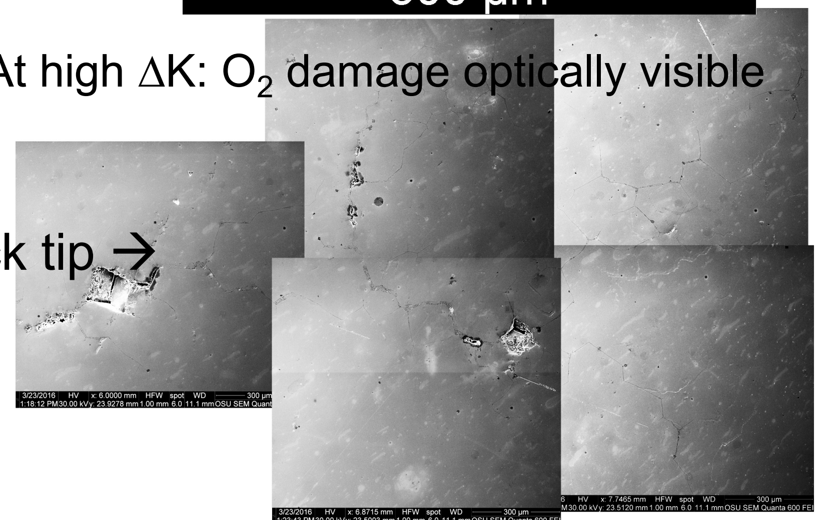
(for CREEP AND LOW FREQ.)

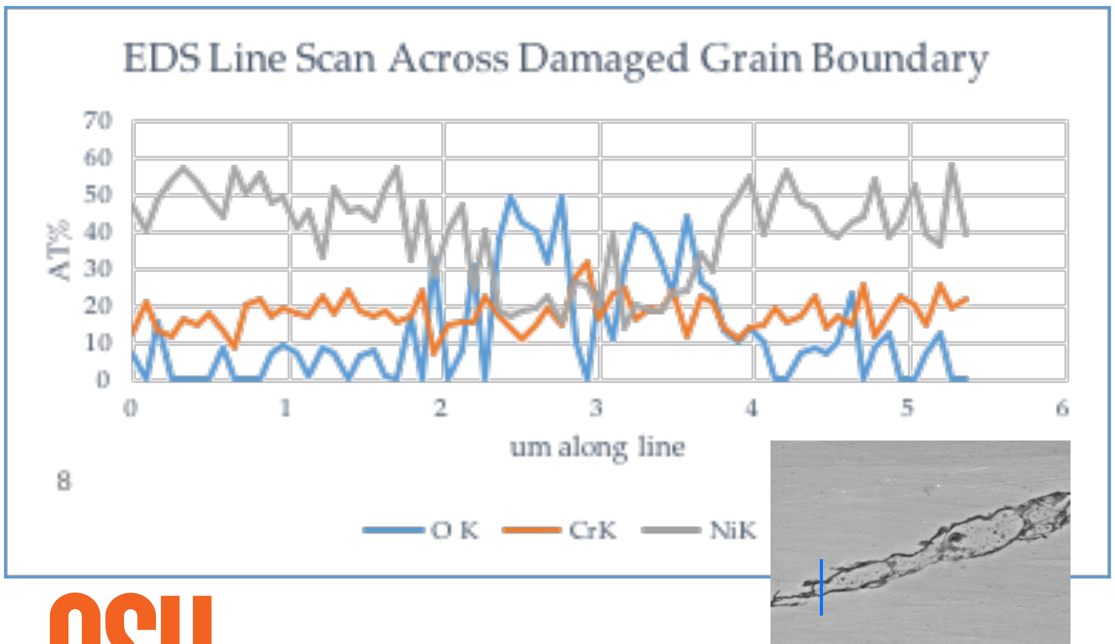
- stress assisted grain boundary oxidation (**SAGBO**)
- Coupled with plastic deformation

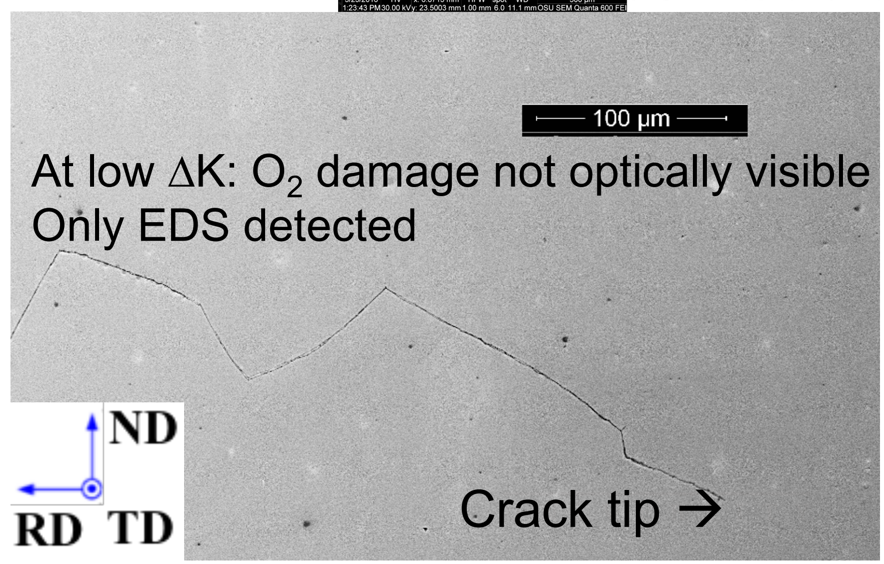


At high ΔK: O_2 damage optically visible

Crack tip →







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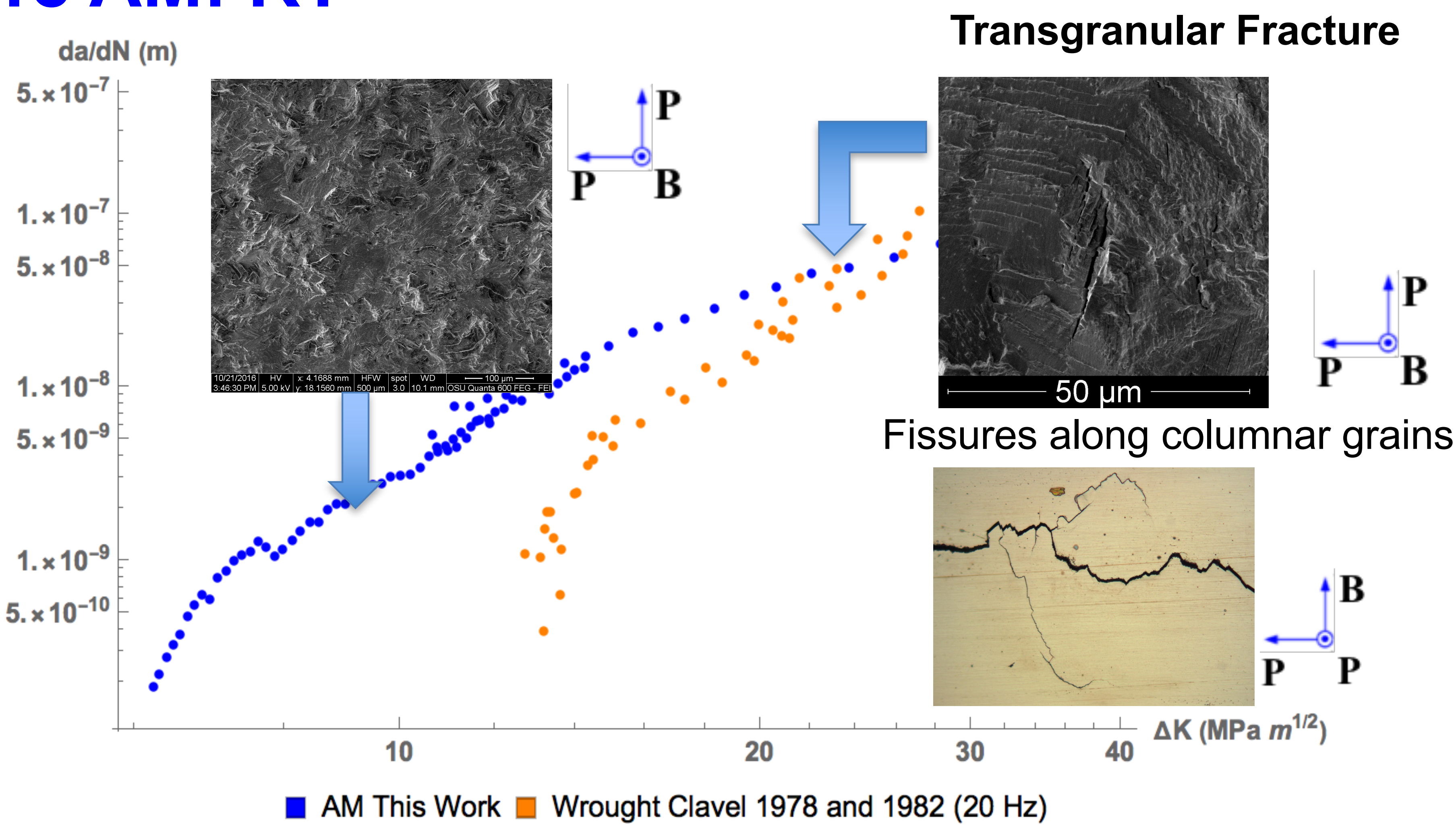
IN 718 CONV: Crack Growth Experiments

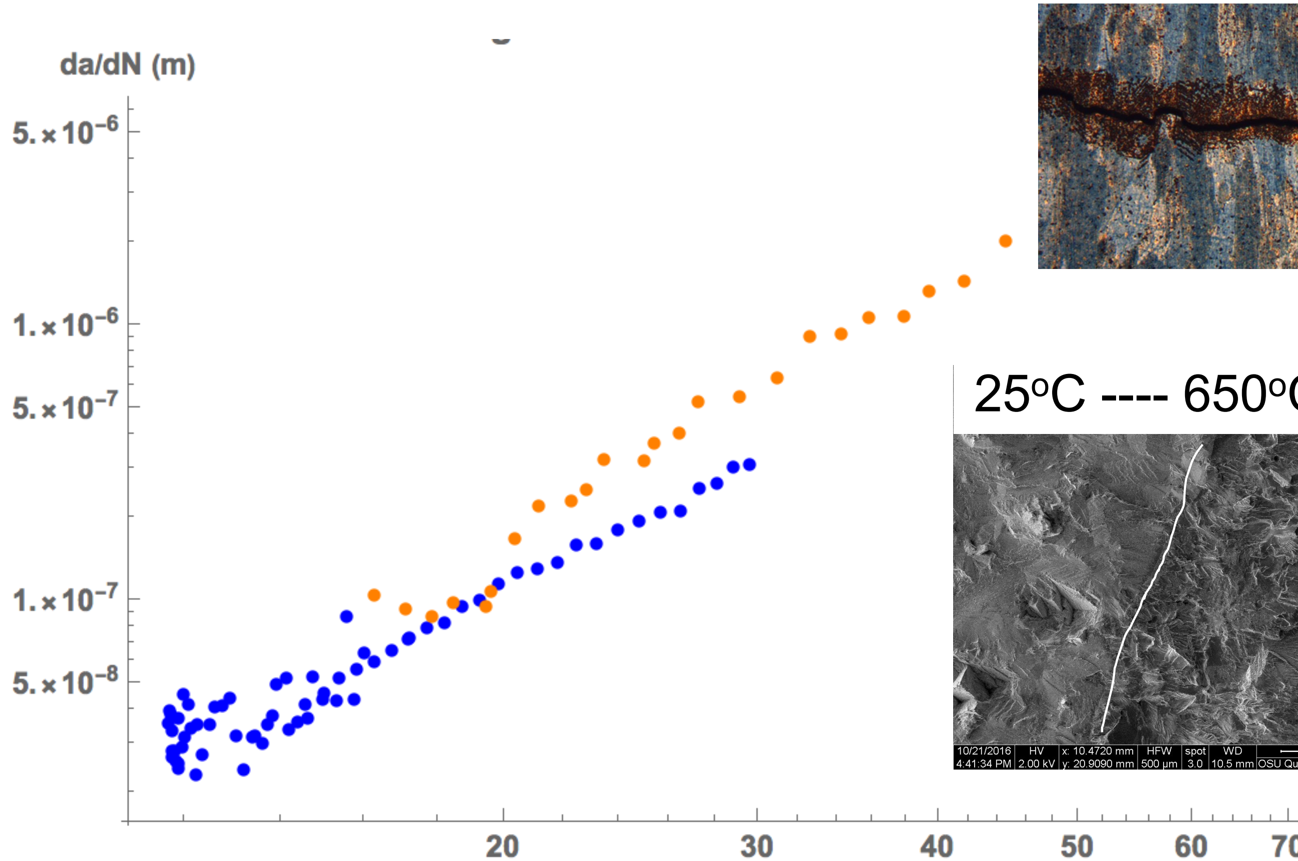
- IN 718 CONV: At low frequency and 650^{o}C
- Intergranular fracture together with plasticity
- SABO effect
- Time dominates

IN 718 AM: RT



AM Fatigue Crack Growth Rates at 20°C
30 Hz, R = 0.1, Sine

IN 718 AM: 650°C



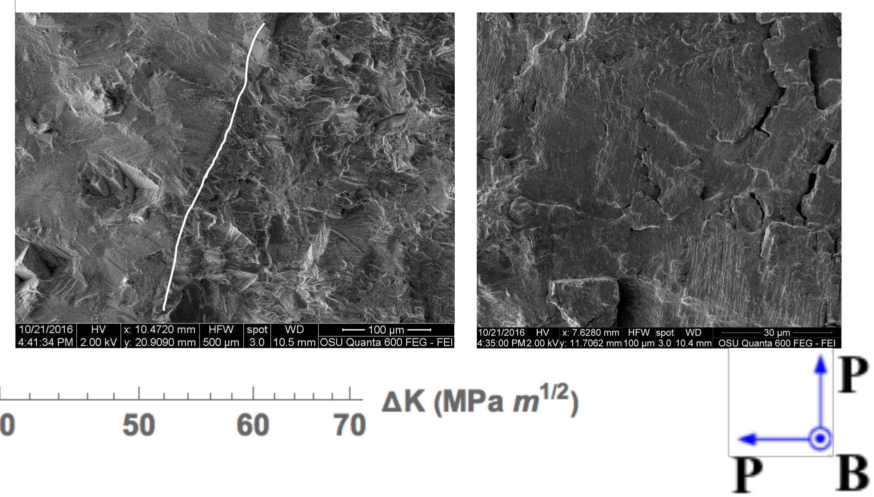
AM This Work
30 Hz, R = 0.1, Sine

Wrought James 1975 Hanford
0.67 Hz, R = 0.05, Sine

Plasticity Revealed

25°C ---- 650°C

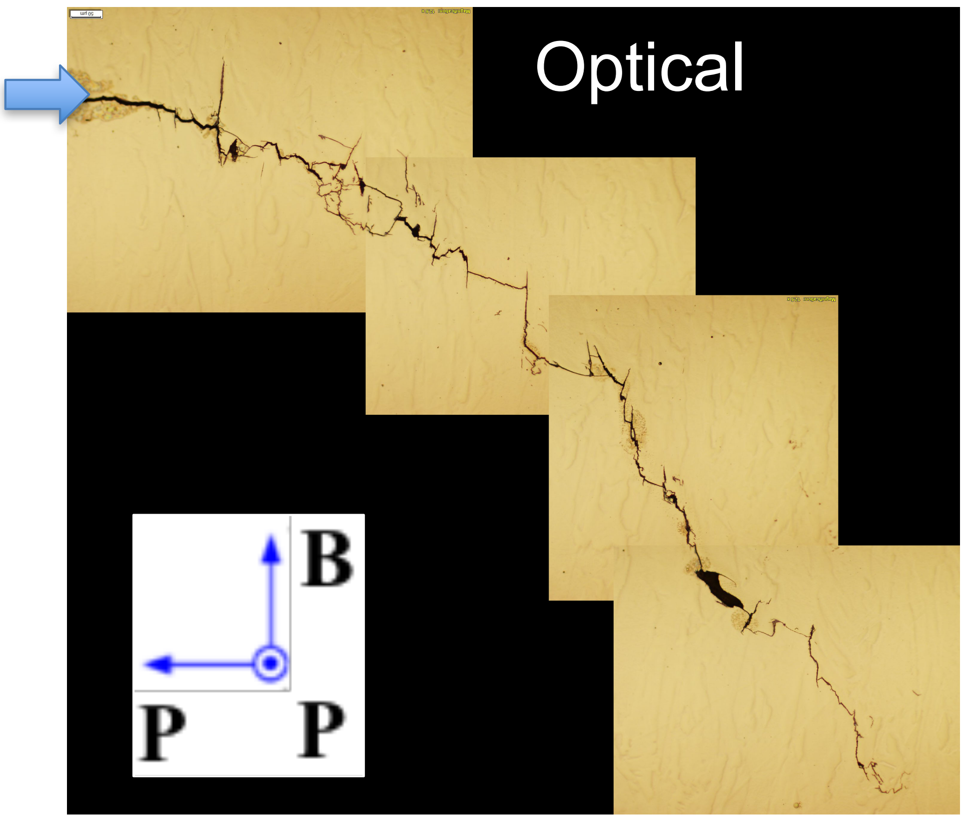
More fissures

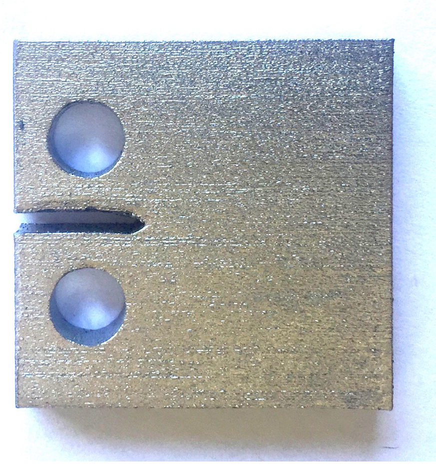


IN 718 AM:

650^{o}C, R=0.5, 0.1 Hz

No growth below ΔK=28 MPa.m$^{1/2}$





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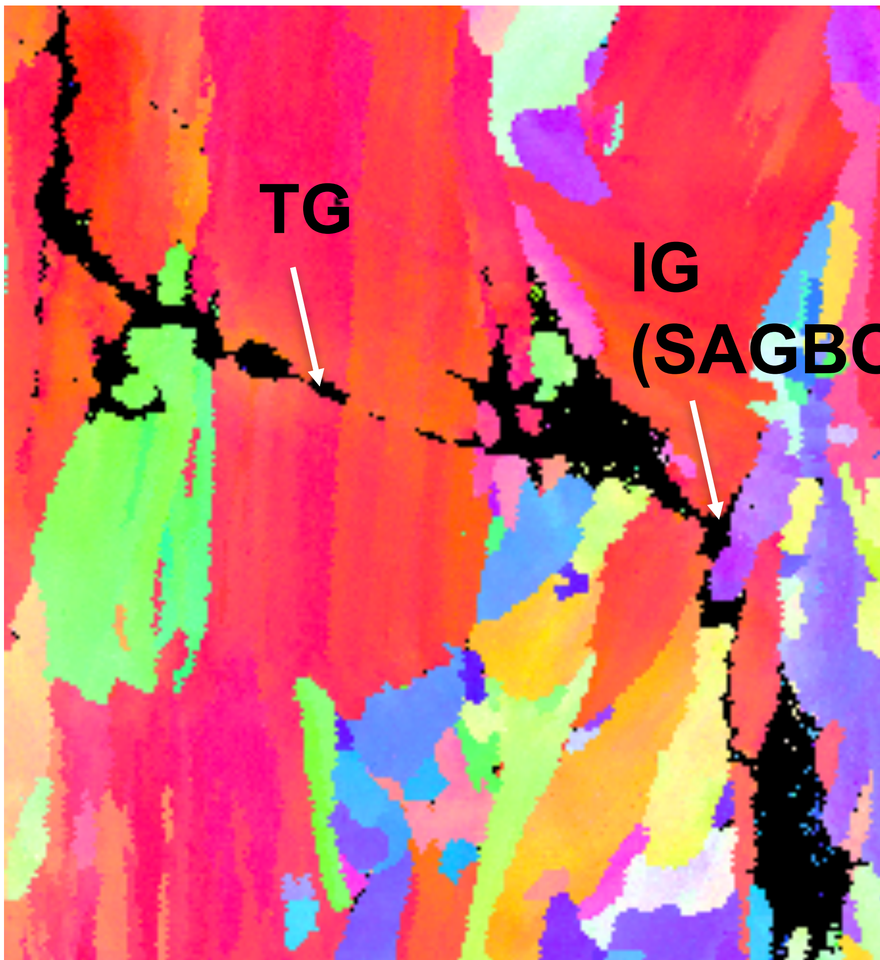
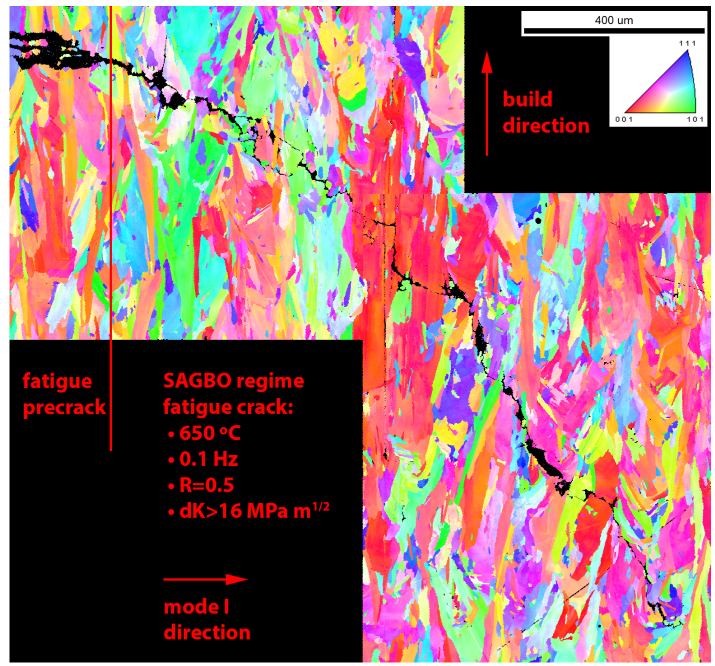
IN 718 AM: EBSD

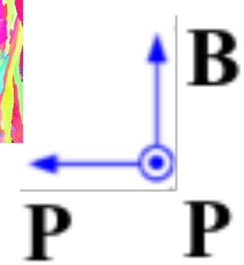
650^{o}C, R=0.5, 0.1 Hz, ΔK>16 MPa.m$^{1/2}$

Detail



Overview





IN 718 AM Crack Growth Experiments

- **IN 718 AM: At RT**
- **High da/dN and low threshold**

- **IN 718: At high frequency and 650°C**
- **Transgranular fracture with fissures, plasticity**
- **Cycling dominates**

- **IN 718: At low frequency and 650°C**
- **Intergranular fracture along Build-plane GB**
- **Transgranular fracture across Print-plane grains**
- **Strong crack deflection**

IN 718 CONV vs. IN 718 AM

At RT

- AM exhibits higher da/dN than CONV and
- Lower threshold value

At 650 °C and low rates

- CONV fails intergranular, GB are SAGBO effected,

At 650 °C and low rates

- CONV fails intergranular, GB are SAGBO effected,
- FCG is time dominant
- AM crack growth is a mix of transgranular and intergranular
- SAGBO affects built-plane GB
- Strong crack path deflection

NANOINDENTATION (TOMAR)

High Temperature Nanoindentation

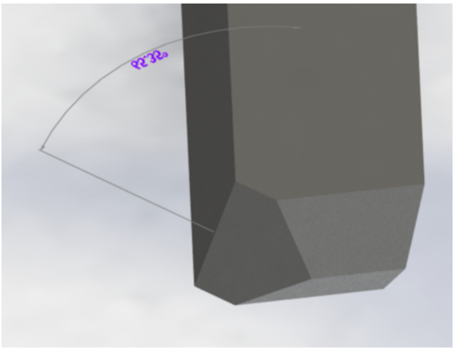
An efficient method for the determination of viscoplastic and creep properties of metallic solids

$$H = \frac{P}{A},\ A = 3\sqrt{3}(h - \frac{1}{4}P \cdot c)^2 \tan^2 65.3^\circ$$

$$H \approx 3\sigma_Y(h)$$

$$\dot{\varepsilon} = \frac{\dot{h}}{h},\ \sigma \propto \frac{P}{h^2}$$

$$\dot{\varepsilon} = K\sigma^n,\ n = \frac{\log(\dot{\varepsilon})}{\log(\sigma)}$$



Berkovich Indenter
C-BN

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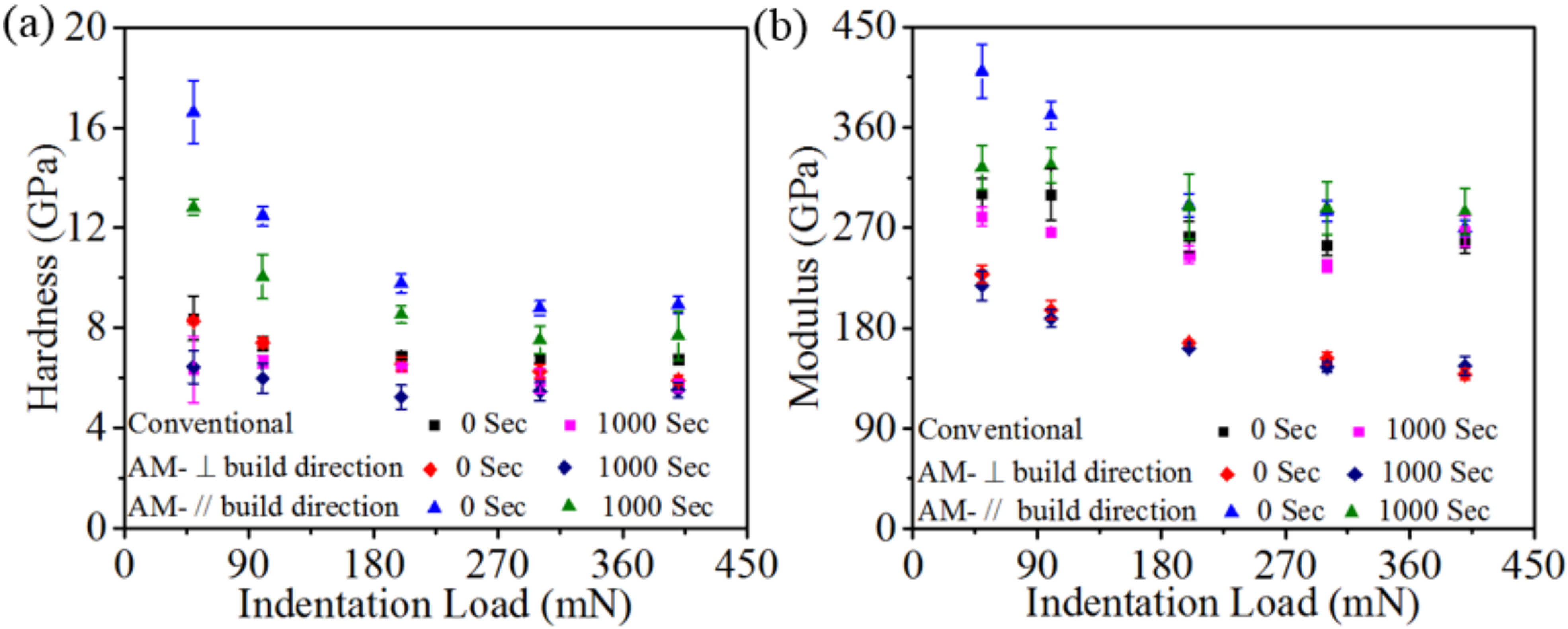
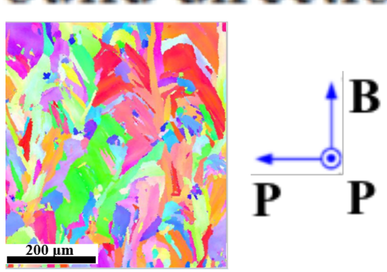
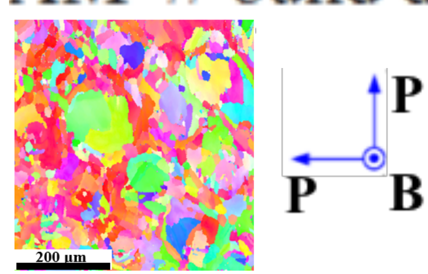
Hardness at Room Temperature



AM- ⊥ build direction



AM- // build direction



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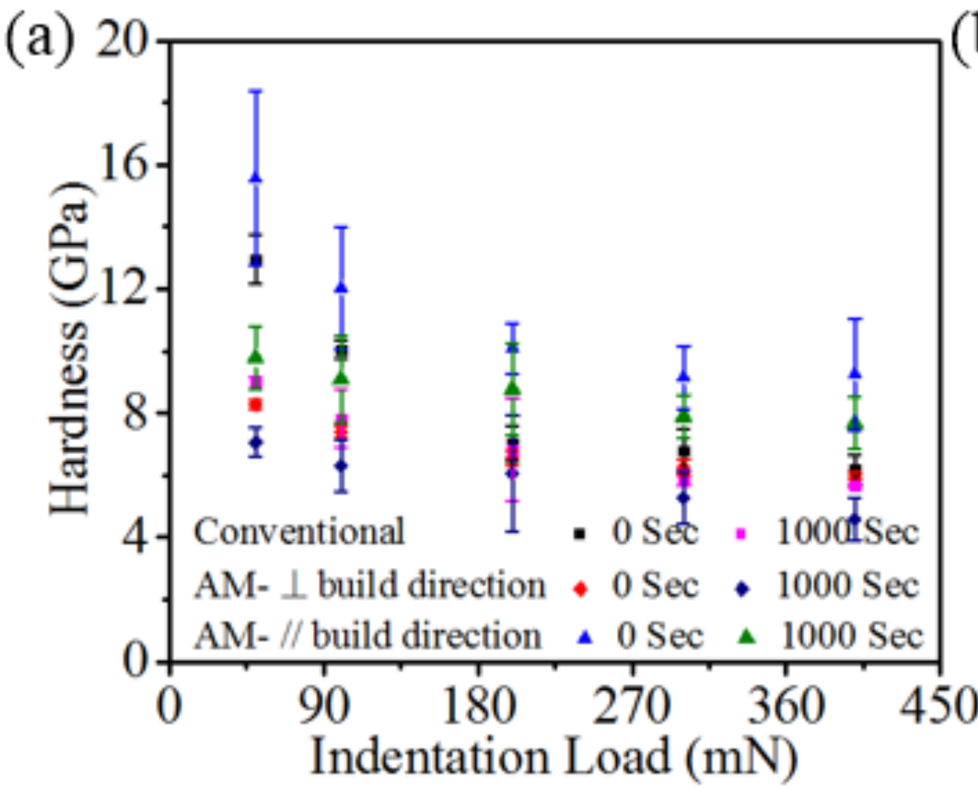
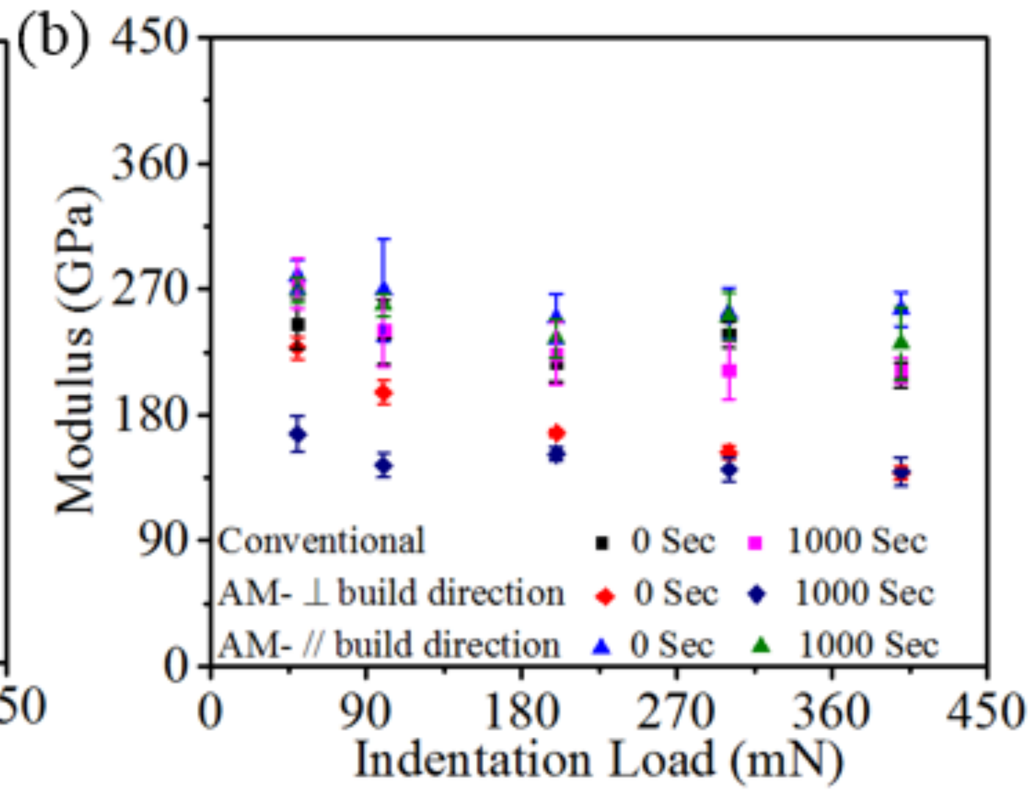
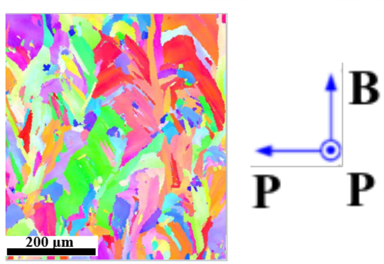
Hardness at 650°C

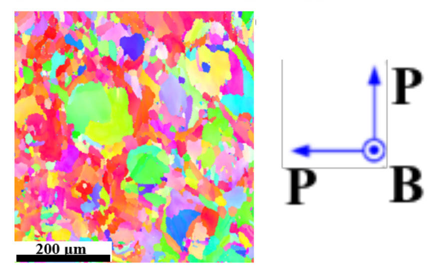




AM- ⊥ build direction



AM- // build direction



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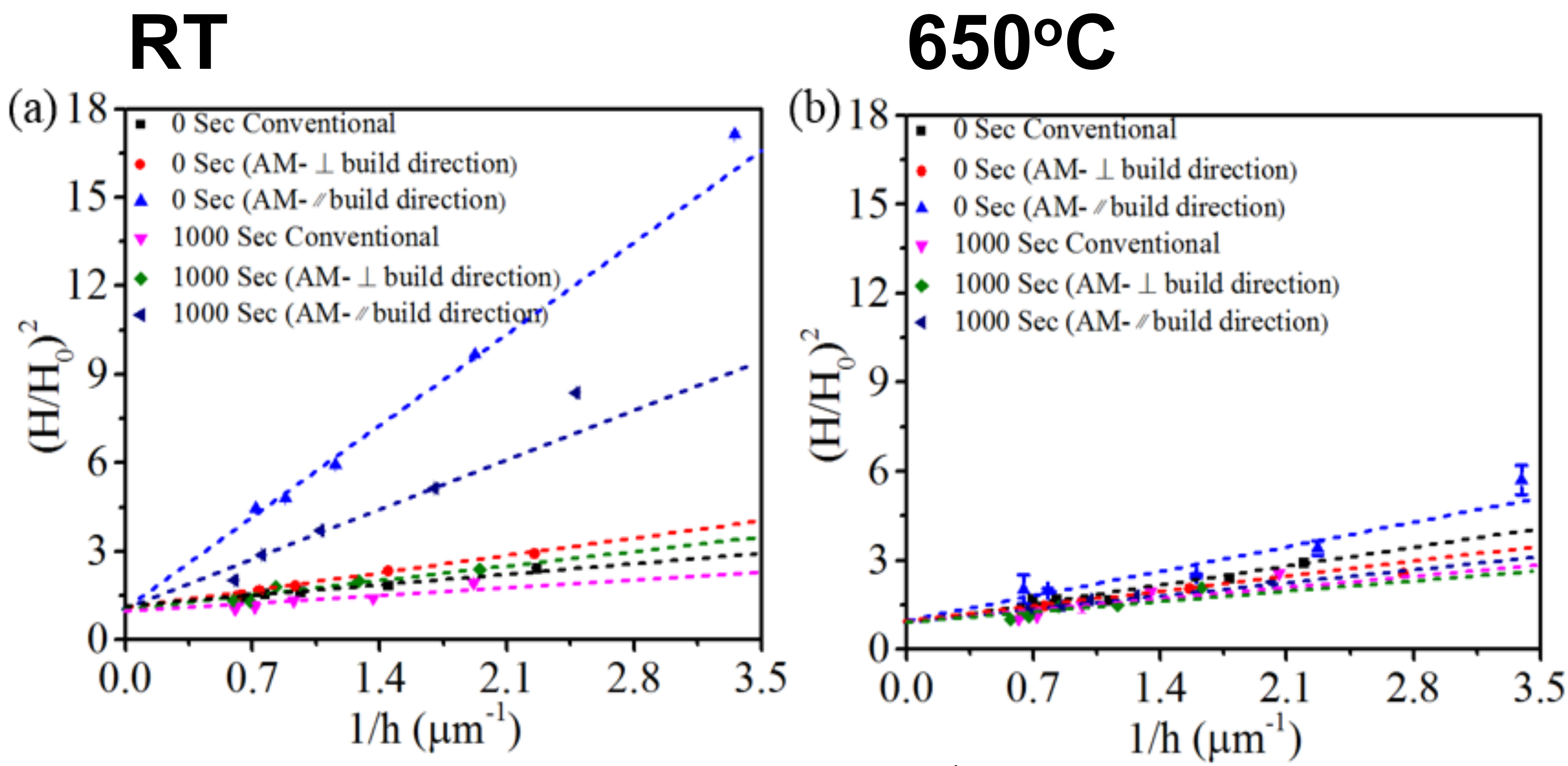
Indentation Size Effect



$$\frac{H^2}{H_0^2} = 1 + \frac{h^*}{h}$$

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Indentation Size Effect - Summary

	no dwelling			1000 sec dwelling period		
	CONV	AM (normal to build direction)	AM (parallel to build direction)	CONV	AM (normal to build direction)	AM (parallel to build direction)
Room Temperature						
h^* (nm)	472.64	878.38	4666.06	201.89	404.51	2722.94
H_0(GPa)	5.78	4.84	4.61	5.60	4.80	4.43
650^0 C Temperature						
h^* (nm)	817.04	596.78	1217.31	2155.62	2758.44	672.07
H_0(GPa)	4.74	4.17	6.51	3.32	3.07	6.295

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Size Effects in Plasticity of IN 718

- **In IN 718 AM, hardness is anisotropic. Hardness is highest when indenting in the build direction.**

- **In both IN 718 AM and IN 718 CONV a size effect of hardness was found at RT and 650°C.**

- **The size effect is stronger at 650°C than at RT for two IN 718 CONV and IN 718 AM (↴ to print plane) but less in IN 718 AM (↴ to build plane)**

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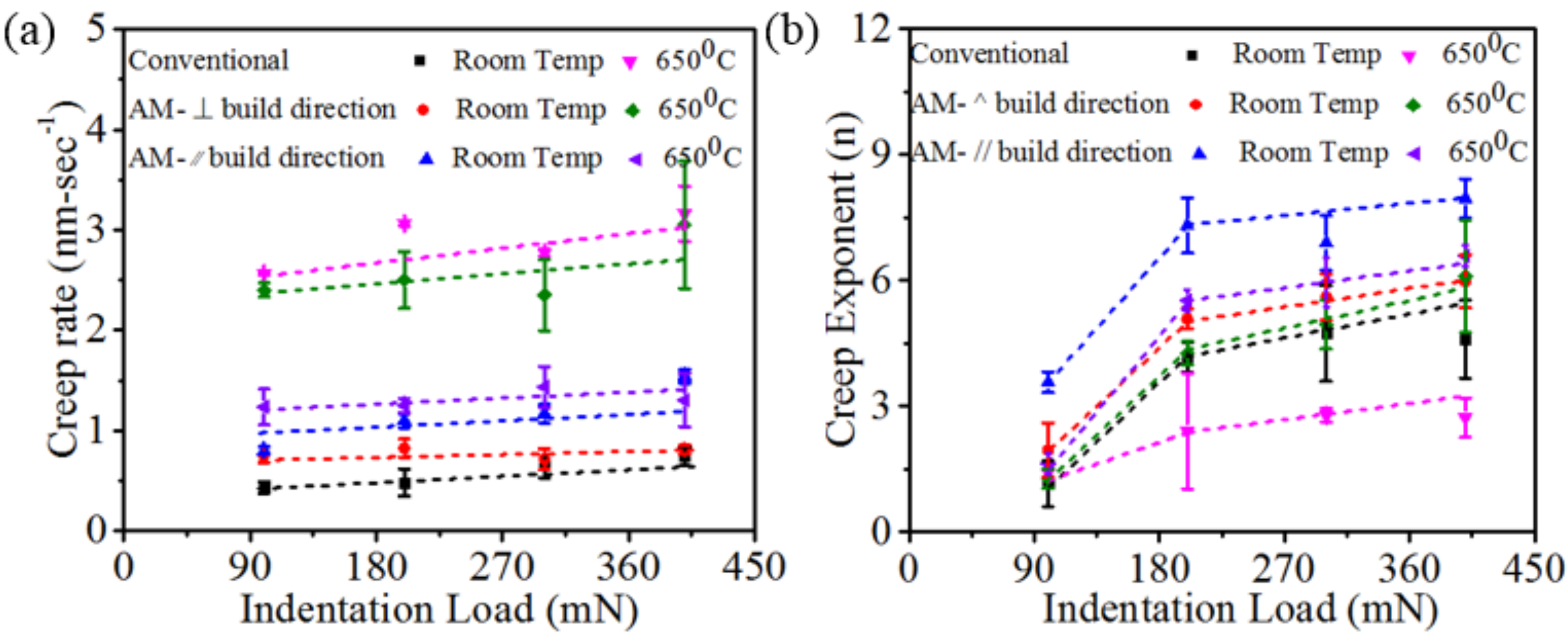
Creep at RT and 650oC



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Indentation Creep of IN 718

- **Indentation appears as a viable low-cost approach to the determination of creep exponents**
- **Creep rates decline with low loads and low indention depth. This also indicates a size effect.**
- **Creep response of IN 716 AM was found to be anisotropic**

COMPUTATIONS (SIEGMUND)

Computational Mechanics

Constitutive Models:

- Strain Gradient Viscoplastic Theory, justified by indentation experiments
- Tension-compression asymmetric yield theory, justified by IN 718 literature data

Crack Growth Models:

- Cohesive Zone Model
- Time independent (transgranular)
- Time dependent (SAGBOE)

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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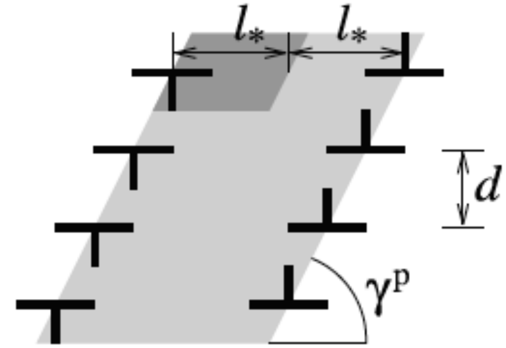
Dislocations: Carriers of Plastic Deformation

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

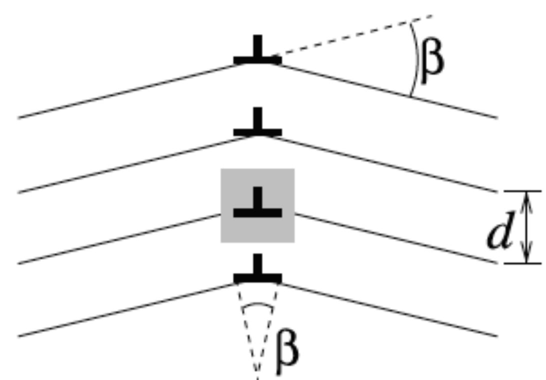
- Statistically stored dislocation:

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



- 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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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: λ, μ

Viscoplastic strain rate: $\dot{\boldsymbol{\varepsilon}}^{vp}$

$$\overline{\sigma}\dot{\overline{\varepsilon}}^{vp} = \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}^{vp}$$

Isotropic material:

$$\overline{\sigma} = \sqrt{\frac{3}{2}\mathbf{s}:\mathbf{s}}\ ;\ s_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{ii}$$

Kinetic equation:

$$\frac{\overline{\sigma}}{\sigma_{\text{flow}}} = \left(\frac{\dot{\overline{\varepsilon}}^{vp}}{\dot{\varepsilon}_0}\right)^{1/m}$$

Taylor equation:

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

Dislocation density:

$$\rho = \rho_S + \rho_G$$

Statistically stored dislocation

$$\rho_S = \rho_S^{+} + \rho_S^{-}$$

- *Initial density:* ρ_0
- *Accumulation:*

$$\frac{d\rho_S^{+}}{d\overline{\varepsilon}^{vp}} = Mk_1\sqrt{\rho_S + \rho_G}$$

- *Dynamic recovery:*

$$\frac{d\rho_S^{-}}{d\overline{\varepsilon}^{vp}} = Mk_2\rho_S$$

- *Strain rate sensitivity:*

$$k_2 = k_{20}\left(\frac{\dot{\overline{\varepsilon}}^{vp}}{\dot{\varepsilon}_0}\right)^{-1/n}$$

Geometrically necessary dislocation

$$\rho_G = \overline{r}\frac{\overline{\eta}^{vp}}{b}\ ;\ \overline{r} = 1.9$$

Effective strain gradient:

$$\overline{\eta}^{vp} = \sqrt{\frac{1}{4}\eta_{ijk}^{vp}\eta_{ijk}^{vp}}$$

where

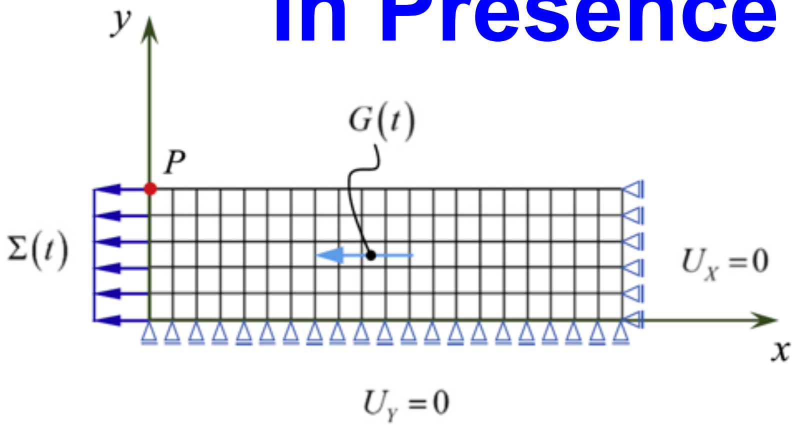
$$\eta_{ijk}^{vp} = \varepsilon_{ik,j}^{vp} + \varepsilon_{jk,i}^{vp} - \varepsilon_{ij,k}^{vp}$$

Constraint:

$$\rho_G \le \rho_G^{\max}$$

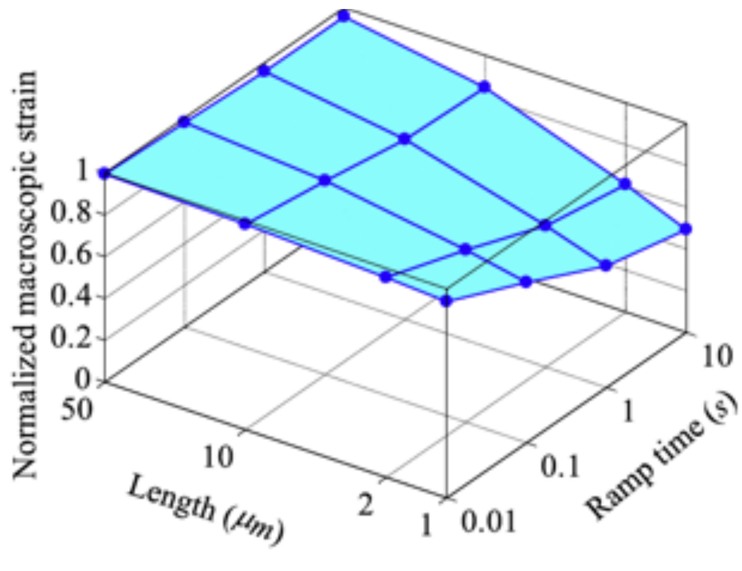
UMAT-ABAQUS

Example: Viscoplasticity to Creep Response in Presence of a Gradient



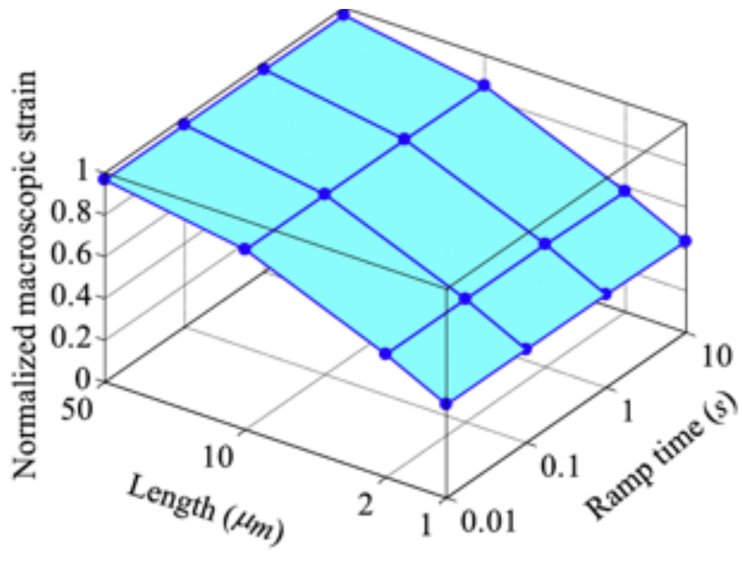
- Unify plastic deformation and Creep (indent-hold)
- Size effects increase with time in agreement with results from indentation

End of Ramp



(a)

During Hold



(b)

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Creep-Fatigue Crack Growth

- Fatigue damage and time dependent damage evolve independently and act additively

- Embedded in FEM as a Cohesive Zone Model
  - Cyclic damage law for transgranular crack growth
  - Time damage law SAGBO intergranular crack growth

TG-CG

IG-CG

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 $$\Delta D_F = \max\left\{0, \frac{\lvert\dot{\Delta}_n\rvert}{\delta_\Sigma}\left[\frac{T_n}{\sigma_{\max}} - \frac{\sigma_f}{\sigma_{\max,0}}\right]\langle \Delta_{n,acc} - \delta_0 \rangle\right\}$$	*Time dependent damage increment* $$\dot{D}_C = (1-D)^{-p}\left\langle \frac{\overline{T} - T_C}{C} \right\rangle^q$$
Accumulated fatigue damage $${}^nD_F = {}^{n-1}D_F + \Delta D_F$$	*Accum. time dependent damage* $${}^nD_C = {}^{n-1}D_C + \dot{D}_C \Delta t$$
Total damage $$D = D_F + D_C$$ 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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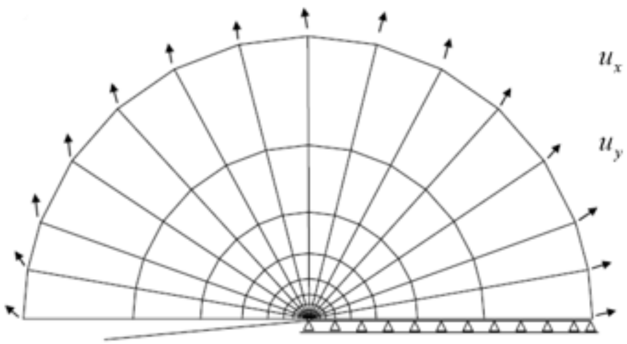
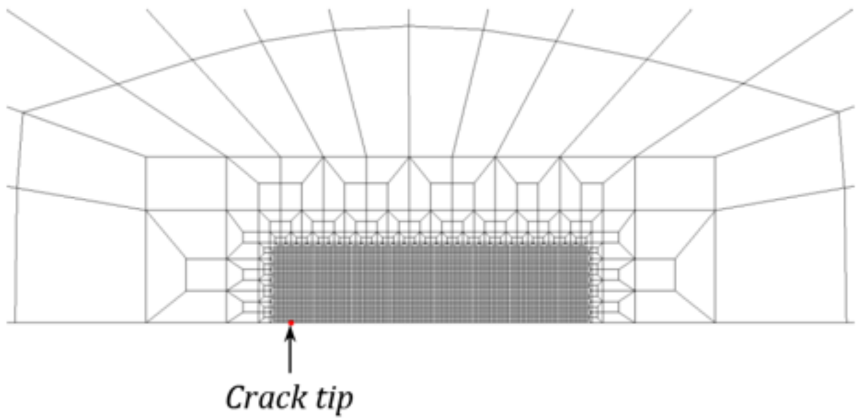


$$u_x(t) = K_{I,\max} A(t) \sqrt{\frac{r}{2\pi}} \frac{1+\nu}{E} (3 - 4\nu - \cos\theta) \cos\frac{\theta}{2}$$

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

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

(a)



E (GPa)	ν	σ_0 (MPa)	m	n	k_1 (mm^{-1})	k_{20}	M	α	b (nm)	$\dot{\varepsilon}_0$ (s^{-1})	ρ_0 (mm^{-2})	$\rho_G^{\max}$ (mm^{-2})
165	0.3	779	25	5	$8 \cdot 10^5$	28.29	1.73	0.3	0.25	10^{-3}	10^5	10^{10}

MBL	ICZM	Time Dep. damage
$r_b/l_e = 10{,}000$	$\delta_0 = 0.4 \times \min l_e \left(7.36\times10^{-6}\ m\right)$	$p = 6$
$L/l_e = 110$	$\sigma_{\max,0} = 4\sigma_Y$	$q = 5$
$\Delta G/\phi_0 = 0.2$	$\sigma_f/\sigma_{\max,0} = 0.25$	$C = 2000\,MPa$
$\phi_0 = 62\ kJ/m^2$	$\delta_\Sigma/\delta_0 = 4$	$T_C = 600\ MPa$
$f = 5\ Hz$	$k_{penalty} = 30$	
$\min l_e = 1.84\times10^{-5}\ m$		

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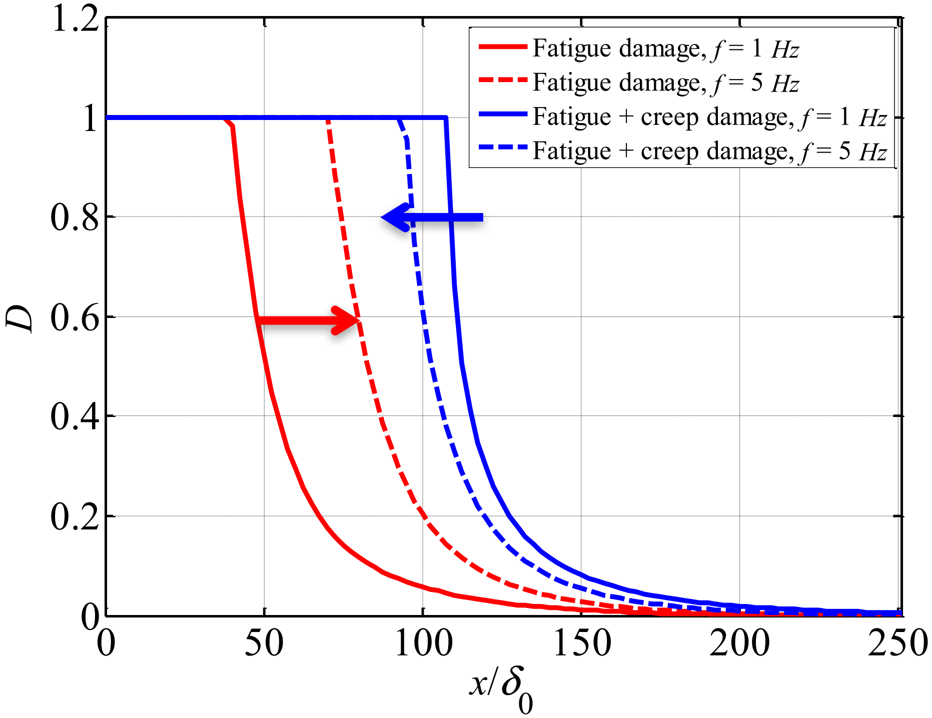
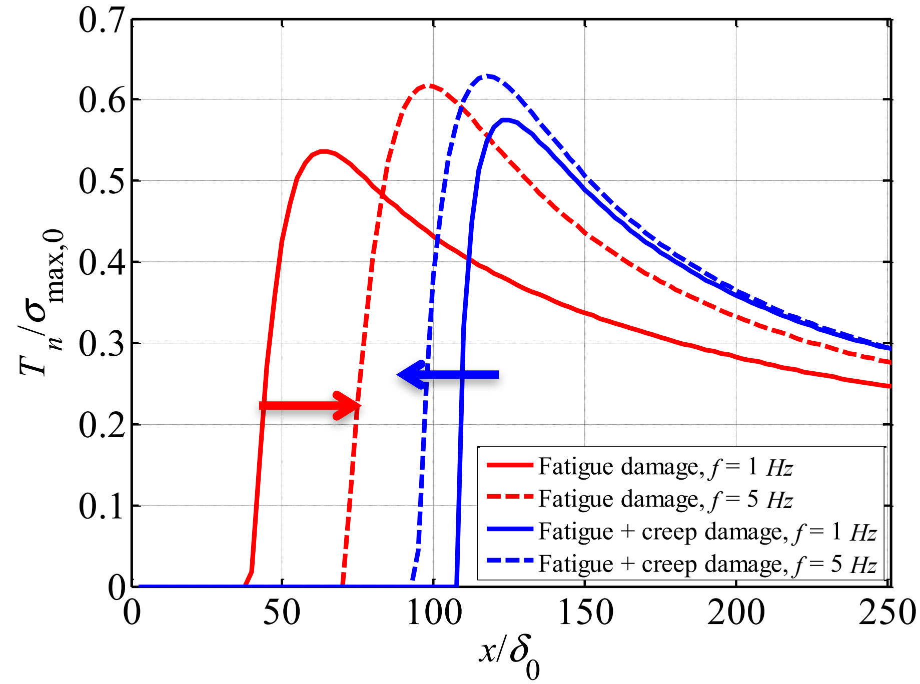
Creep-Fatigue Crack Growth Simulations





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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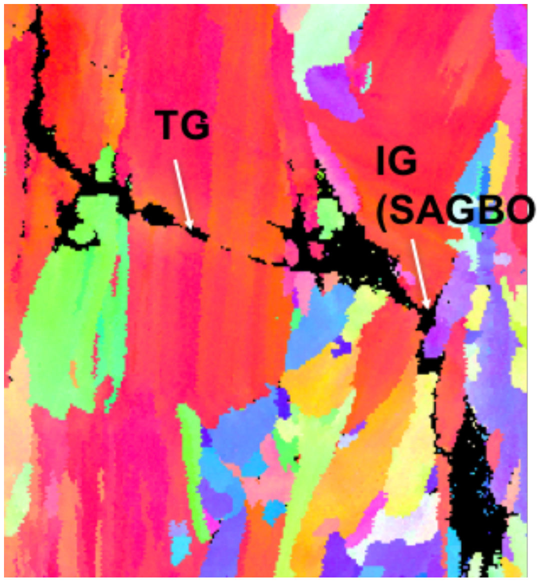
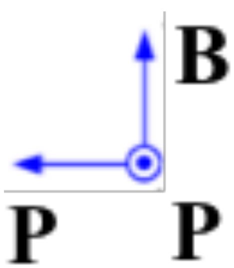
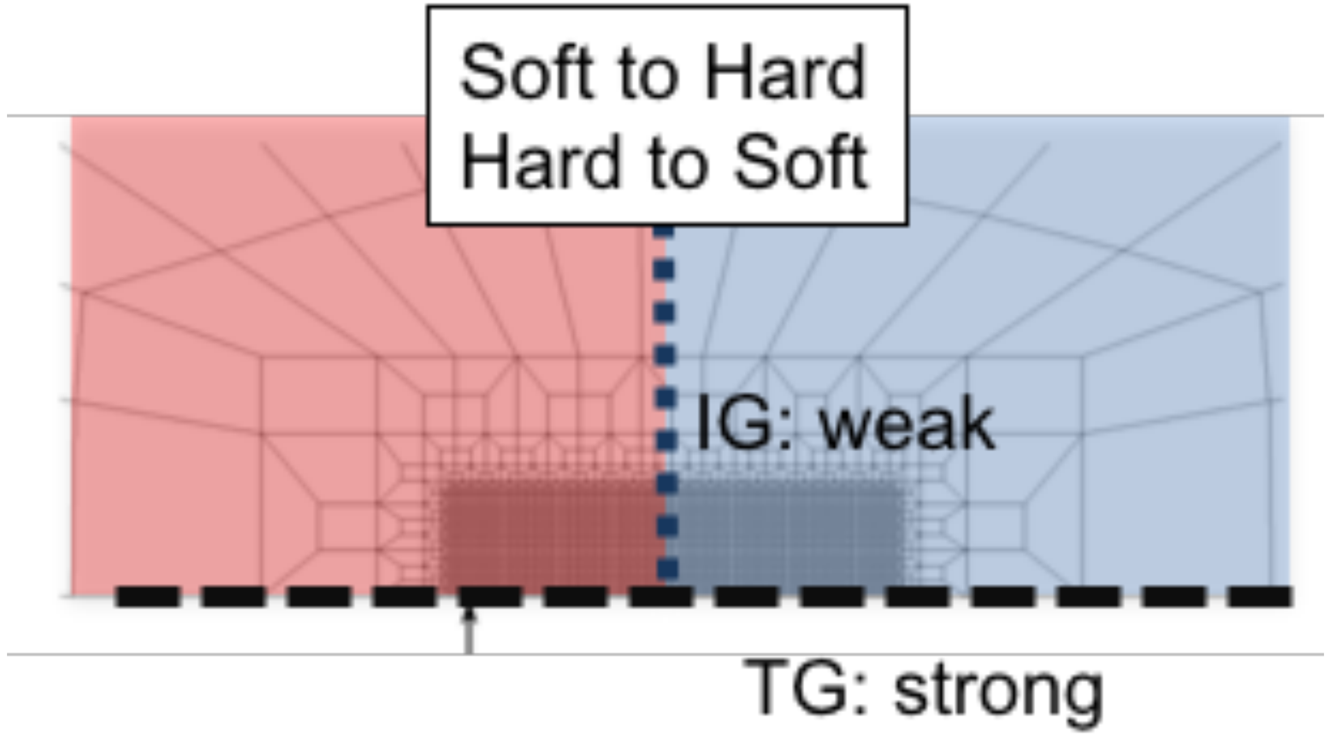
Creep-Fatigue Crack Growth Simulations







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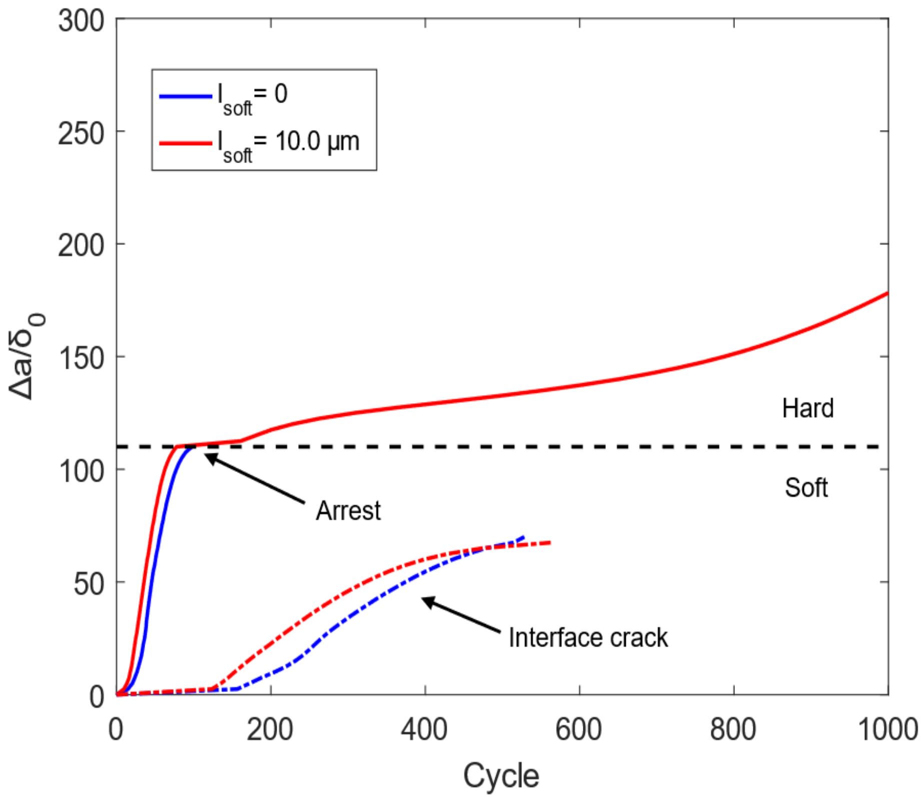
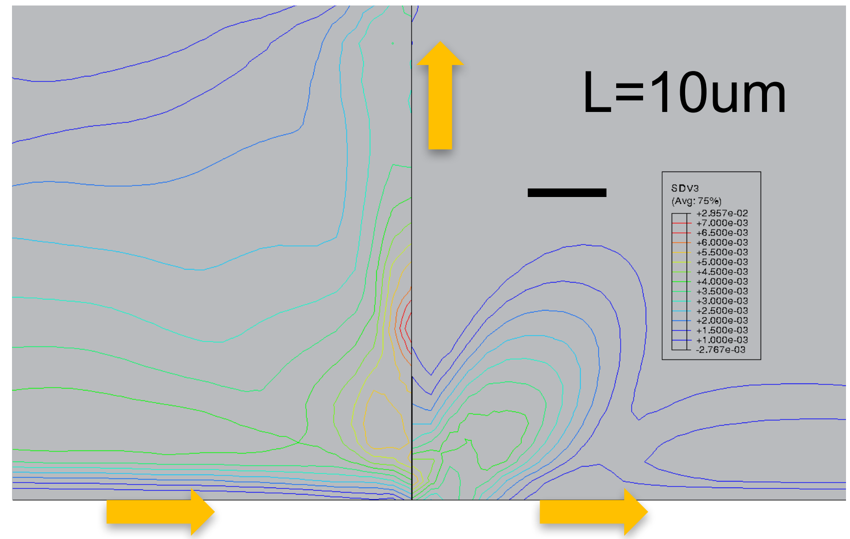
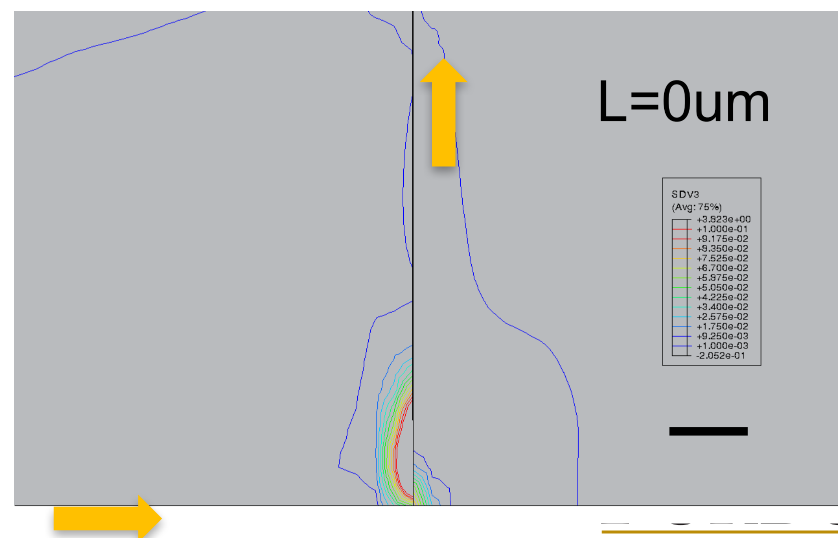
Crack Growth Simulations: Soft→ Hard



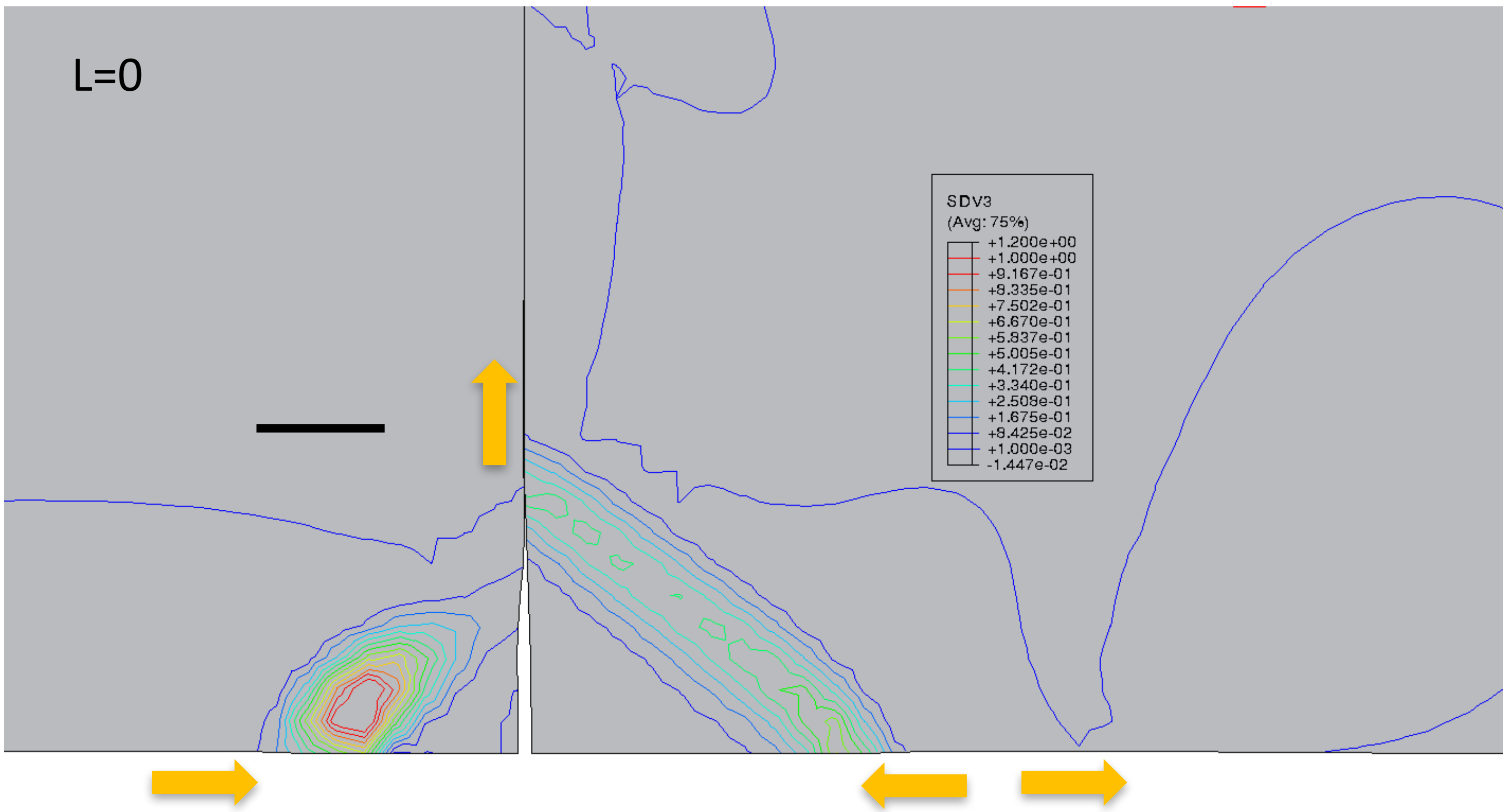




Accounting for plastic strain gradients alters how a crack interacts with a weak interface

For L=0 the deflection into the interface is overpredicted

Crack Growth Simulations: Hard → Soft



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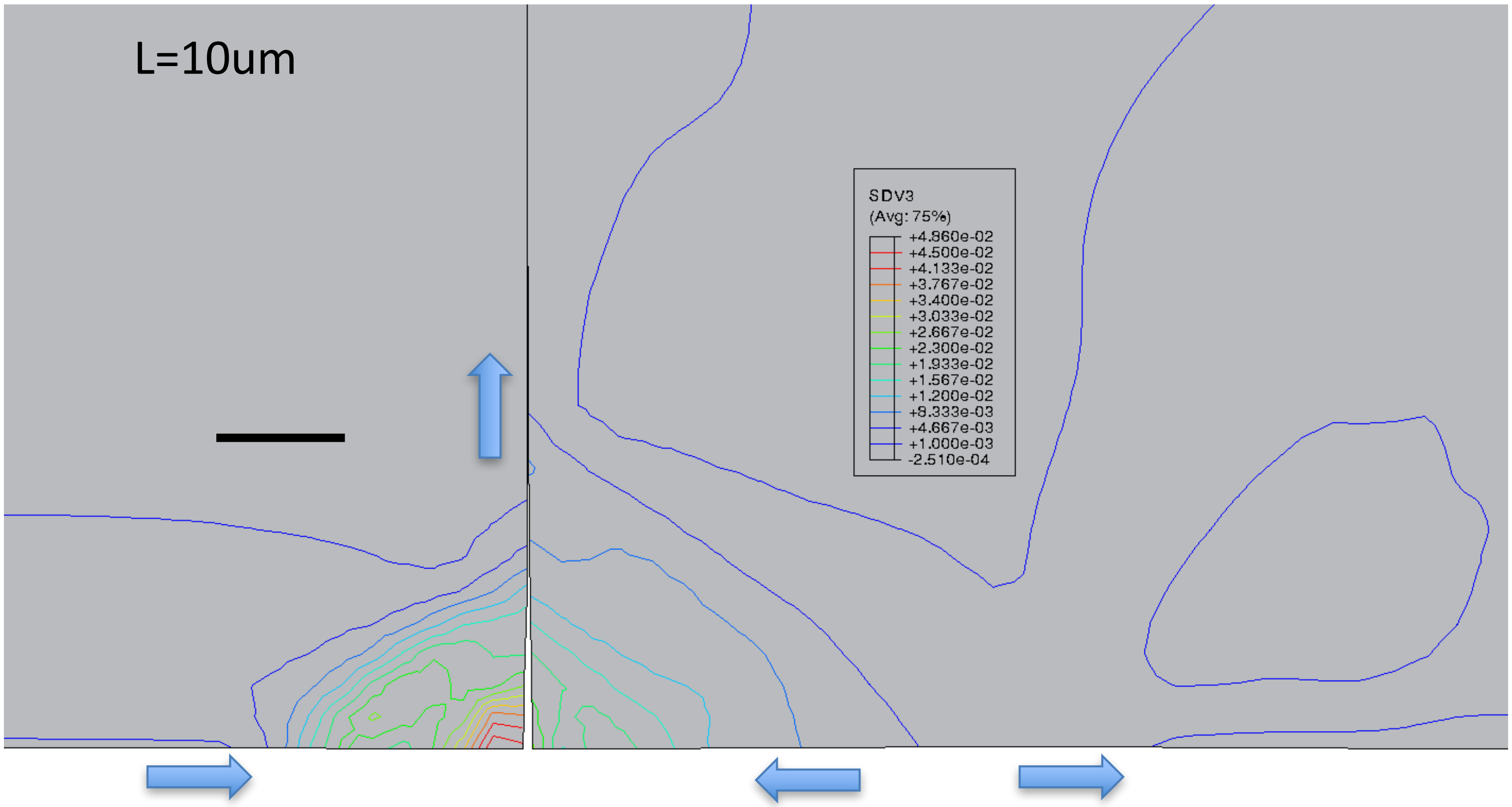
Crack Growth Simulations: Hard → Soft



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Computational Mechanics

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

The unified viscoplastic strain gradient model explains the increase of strain gradient effect with hold times

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

What constitutes a weak interface depends on plasticity

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CONCLUSION

Creep-fatigue crack growth in IN 718 AM and IN 718 CONV differs substantially

Microstructure differences: grain size and shape, texture

Viscoplastic properties of IN 718 AM are anisotropic, grain size appears to contribute to differences between AM and CONV. In both AM and CONV a size effect in the viscoplastic response has been documented

Time dependent crack growth emerges from the interaction of viscoplasticity in the bulk and the rate dependence of the material separation process

Crack growth response appears as strongly directional in IN 718 AM as a mix of growth along weak intergranular build-direction GBs and across strong transgranular grains.

What constitutes a weak interface depends on understanding of plasticity in the adjacent grains

CONCLUSION

Creep-fatigue crack growth in IN 718 AM and IN 718 CONV differs substantially

Microstructure differences: grain size and shape, texture
In IN 718 AM EOS the weak plane is not P-P but P-B

Viscoplastic properties of IN 718 AM are anisotropic, grain size appears to contribute to differences between AM and CONV. In both AM and CONV a size effect in the viscoplastic response has been documented

Time dependent crack growth emerges from the interaction of viscoplasticity in the bulk and the rate dependence of the material separation process

Crack growth response appears as strongly directional in IN 718 AM as a mix of growth along weak intergranular build-direction GBs and across strong transgranular grains.

What constitutes a weak interface depends on understanding of plasticity in the adjacent grains

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CONTRIBUTION

Fundamentals

Differences in CONV and AM materials
Fracture mechanics of complex microstructures
Size effects in viscoplasticity
Unified viscoplasticity
Crack growth simulation models for AM

Turbines

Advance AM material implementation
Advanced stress and deformation analysis
Increased systems reliability

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