Physics of Failure

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ISHEM 2005

NAPA Valley, CA

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Concept

material scientist

Failure modes

Microstructural factors and dependence

designer

Identify relevant failure modes for component of interest

NDE/ISHEM engineer

Measure Relevant Microstructural and Damage Features "Diagnostics"

Predict remaining life "Prognosis"

This talk
'Physics of Failure'

material scientist

Failure modes

Microstructural factors and dependence

designer

Identify relevant failure modes for component of interest

NDE engineer

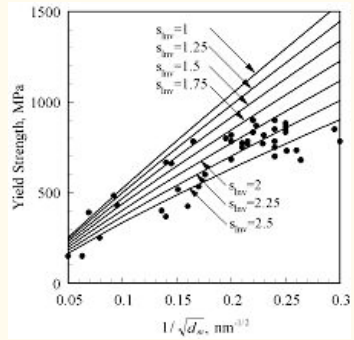
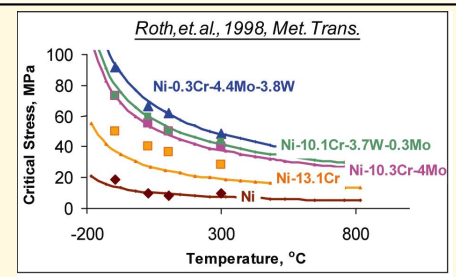
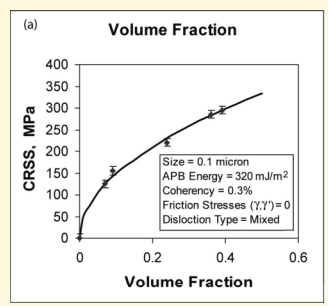
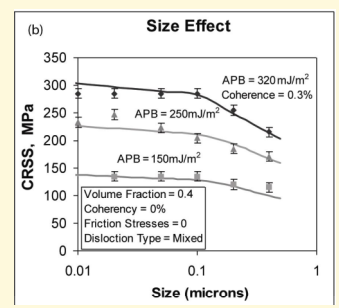
Measure relevant microstructural features

Predict remaining life

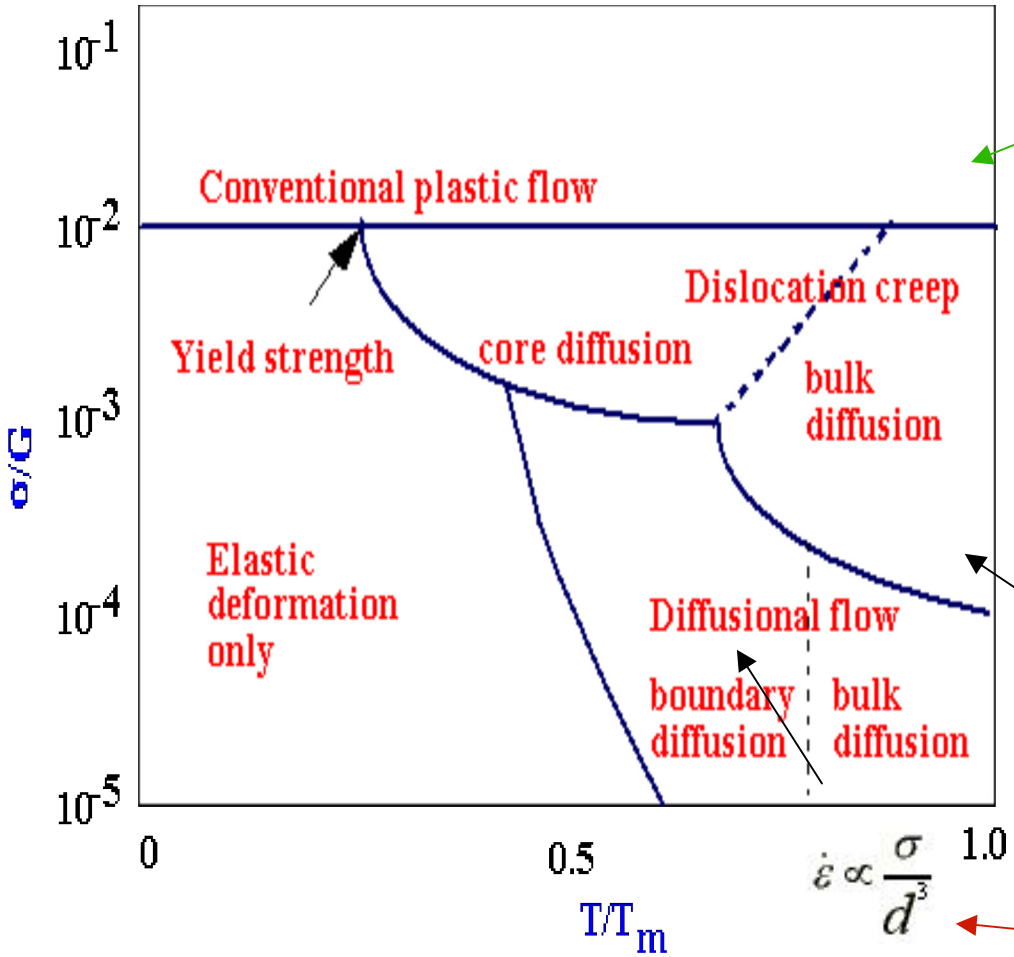
Failure Modes - Metals

Deformation	Yield	athermal plasticity	f (stress)
	Creep	thermally activated plasticity	f (temp, time, stress)
Fracture	Static	athermal / acyclic fracture	f (stress)
	Creep rupture	thermally activated cavitation leading to fracture	f (temp, time, stress)
	Dynamic fatigue	Cyclic plasticity leading to nucleation/growth of cracks	f (cyclic stress, cycle#)
Material Loss	Corrosion	athermal loss of material	f (time, environment)
	Oxidation	thermally activated	f (time, temp, O_2 pres)

Metal Yield - factors

grain size	$\sigma = \sigma_0 + \frac{k}{\sqrt{d}}$	 *nano-copper, Morita*
grain chemistry	$\tau(\gamma) = \tau_o(\gamma) + (k1/T)^{k2}[\sum_{allsolutes}(\delta\tau/\partial C^{0.5}_{solute,\gamma})C^{0.5}_{solute,\gamma}]$	
deformation history	$\sigma = k\varepsilon^m$	
second phase size, morphology & distribution	$\sigma \sim V_f^{1/2}, (1/a^n)$	 

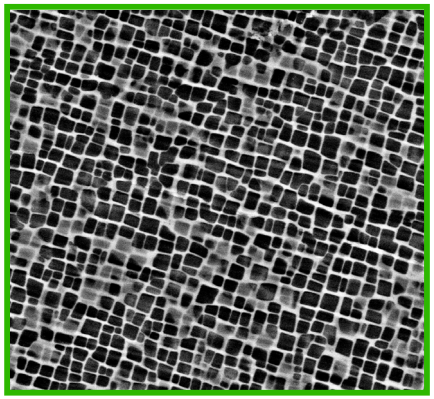
Metal Creep - factors



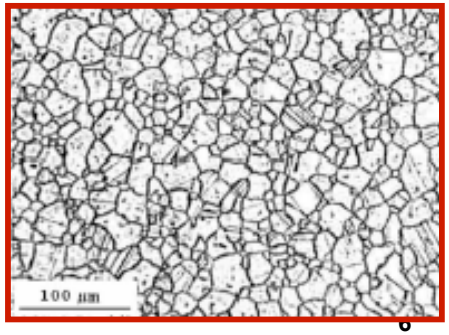
$$\dot{\varepsilon} \propto \frac{\sigma}{d^3}$$

$$\dot{\varepsilon} \propto \frac{\sigma}{d^2}$$

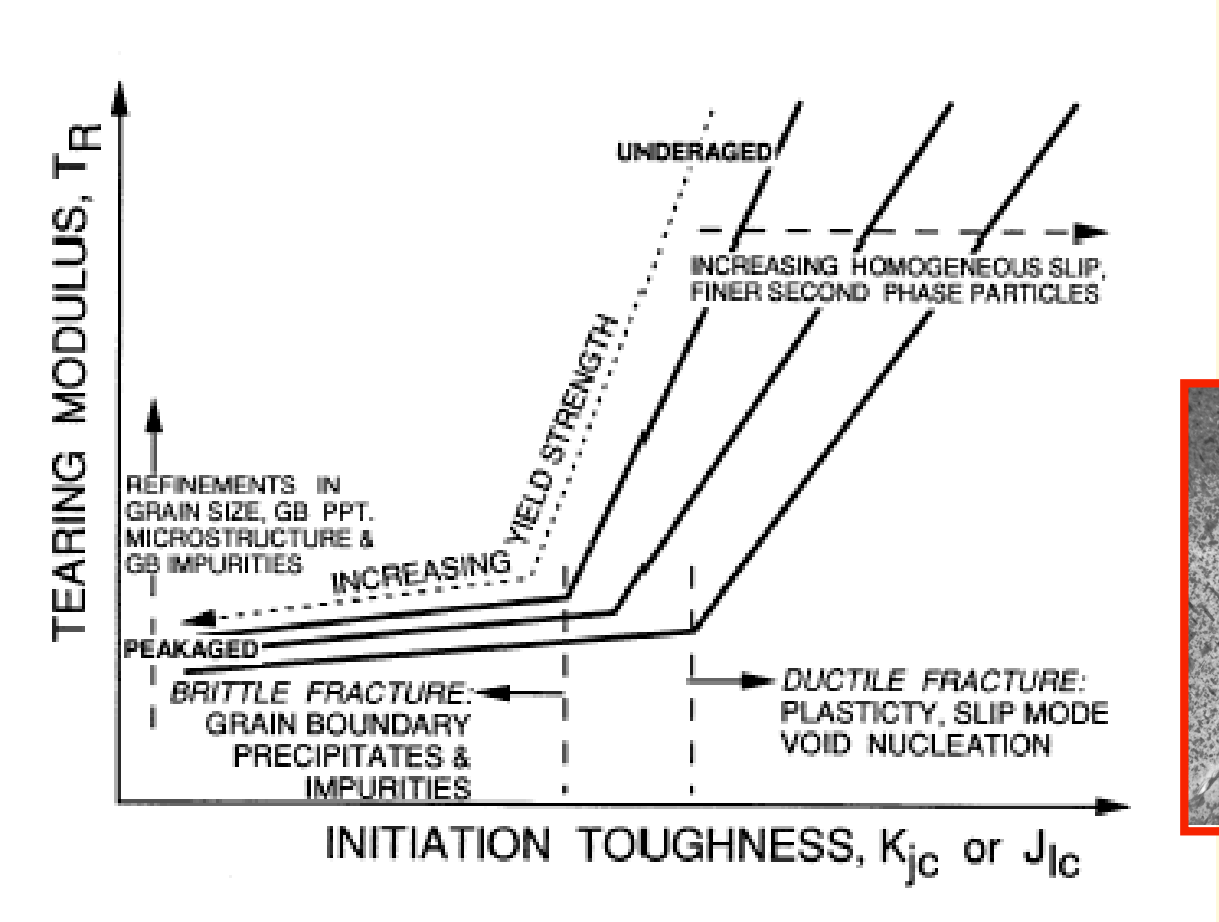
second phase size, morphology & distribution



grain size

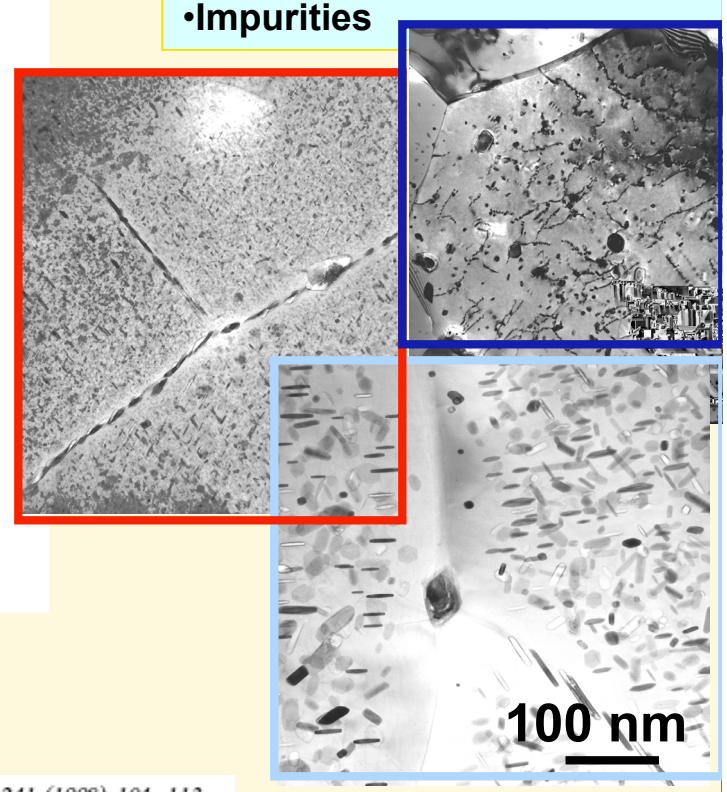


Metal Static Fracture-Factors



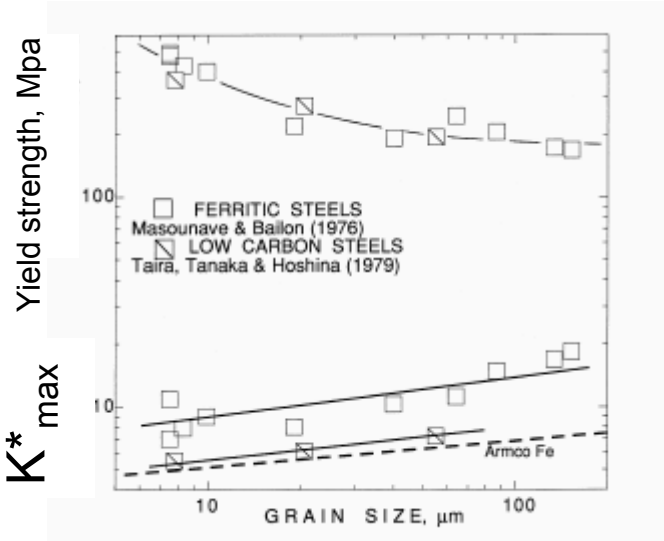
- Strengthening phases
  - Coherent
  - Incoherent
- Grain boundary precipitates
- Second phase particles
- Grain size

- Impurities

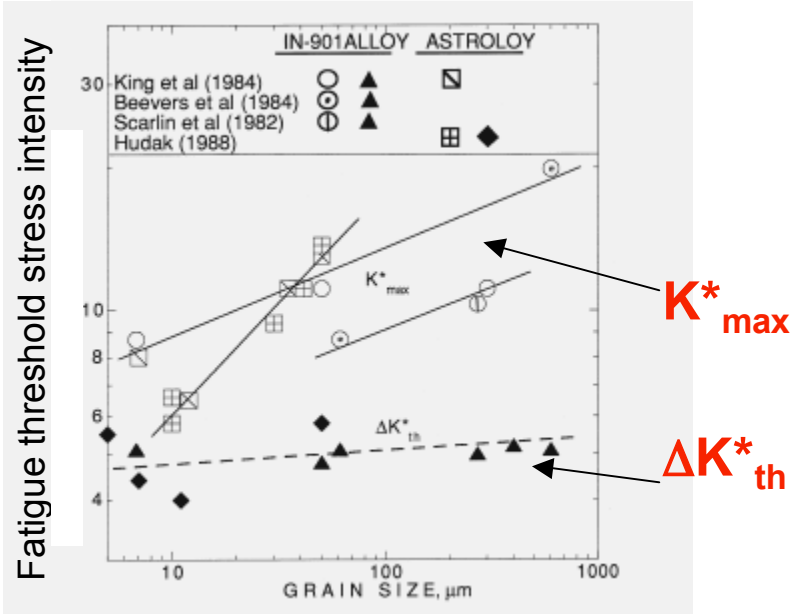


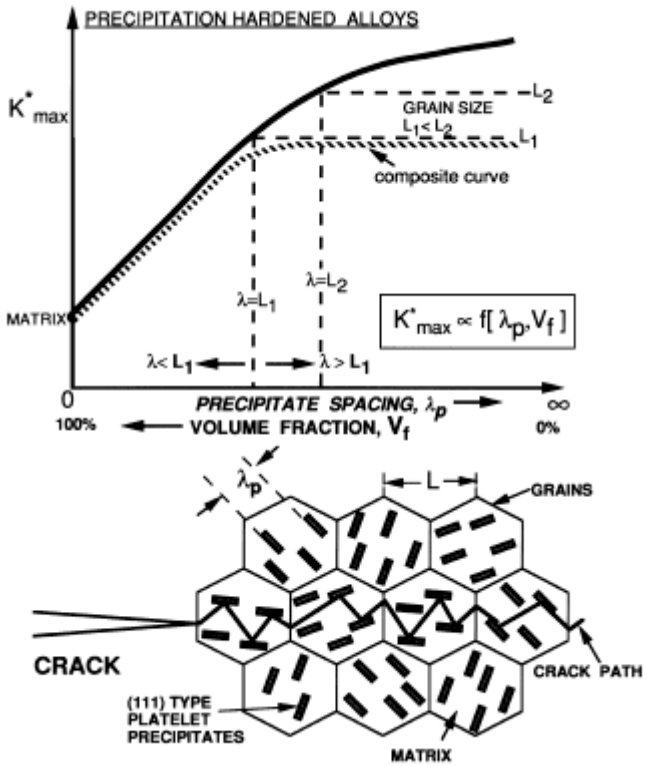
K.V. Jata, A.K. Vasudevan / Materials Science and Engineering A241 (1998) 104–113

Metal Fatigue - factors



Increase in grain size and particle spacing leads to increase in fatigue threshold stress intensity



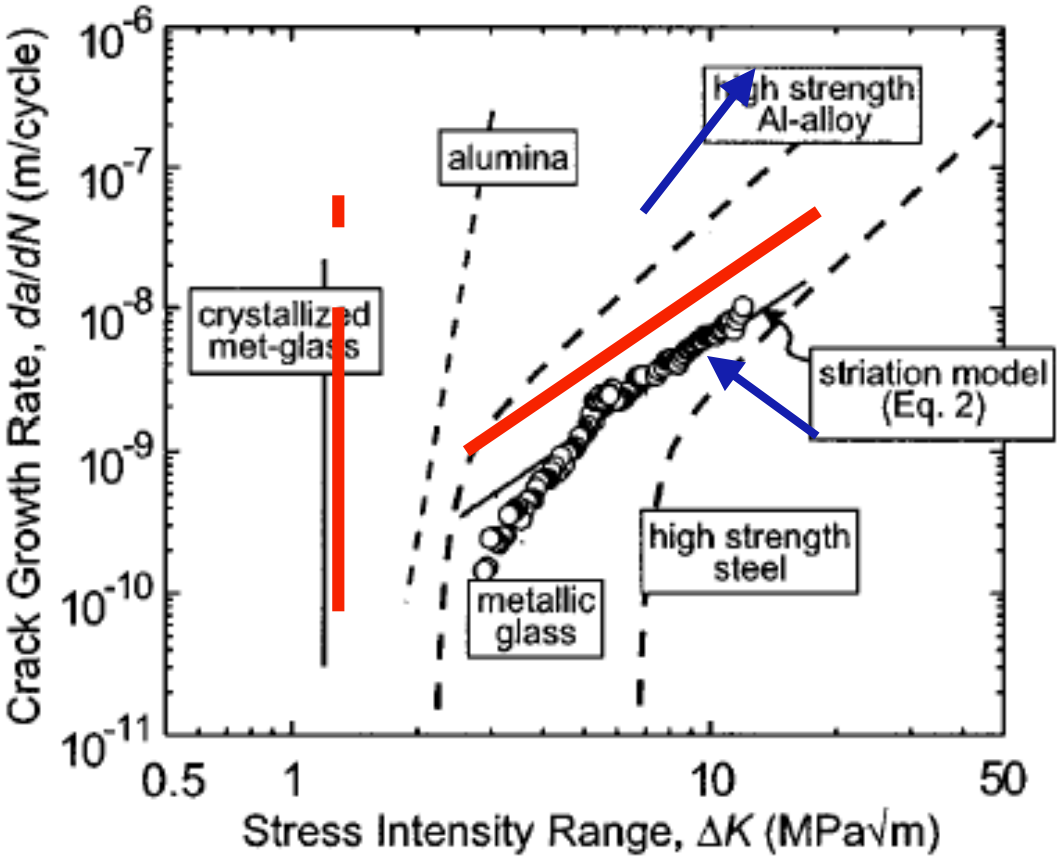


Vasudevan & Sadananda

Metal Fatigue - factors

Aluminum, steel, amorphous and crystallized glass

Growth rates scale range of crack tip opening displacements



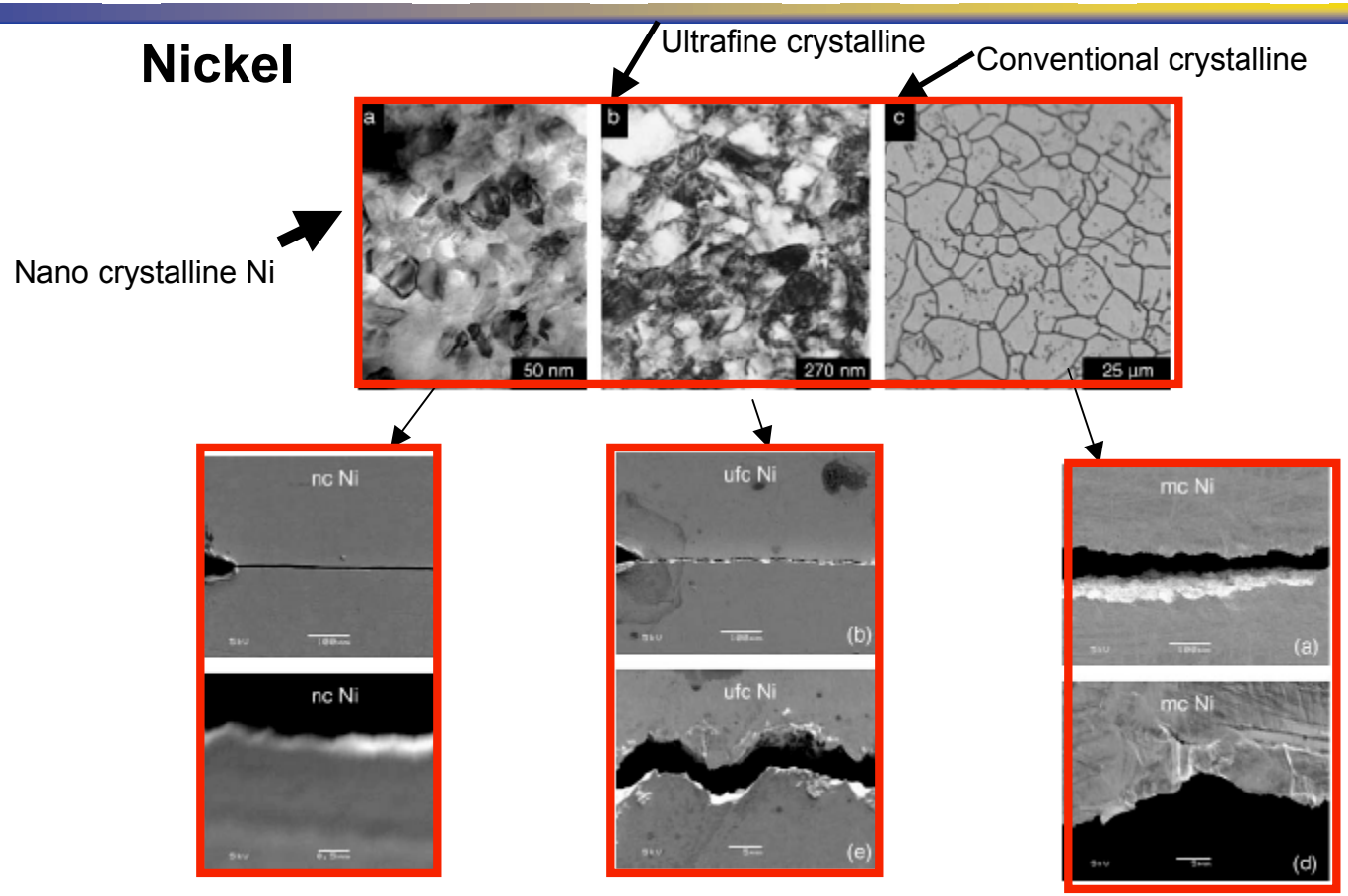
$$da/dN = \Delta K^m \text{ ----(1)}$$

$$\Delta\delta = \beta(\Delta K^2/\sigma_y * E) \text{----(2)}$$

R.O. Ritchie et.al

Metal Fatigue - factors

Nickel

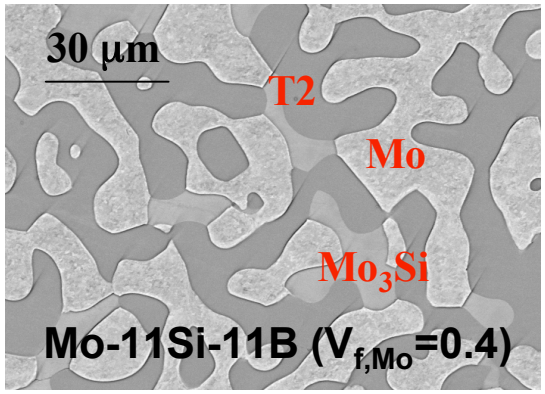


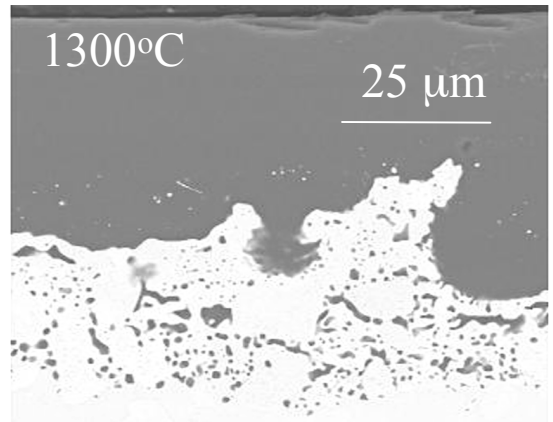
Crack deflections increase with increase in grain size leading to better fatigue crack growth resistance.

Nan crystalline nickel has poor or faster fatigue crack growth rates

Hanlon et.al., Materials Science and Engineering, 2005

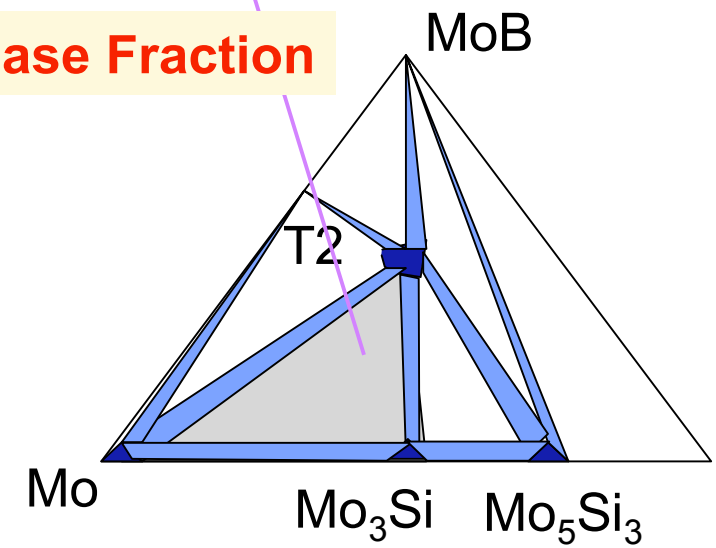
Metal oxidation - factors

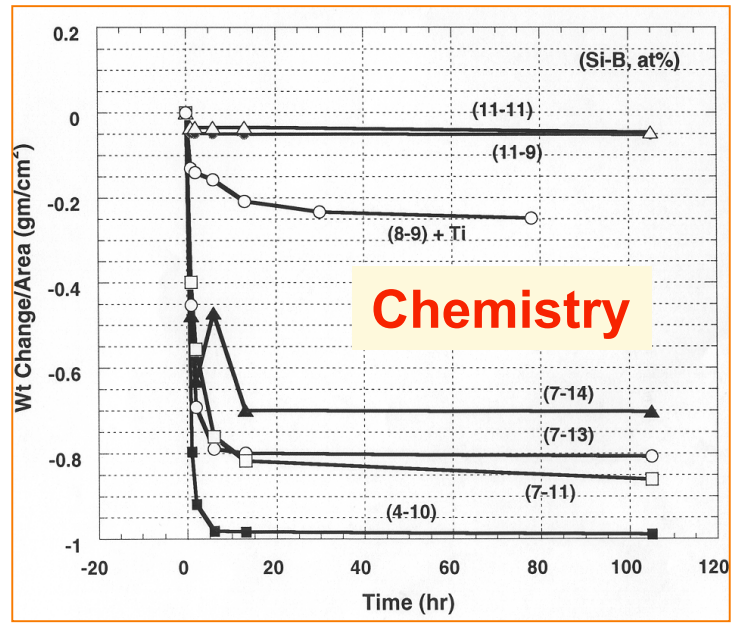




P_{oxygen} of environment

Phase Fraction

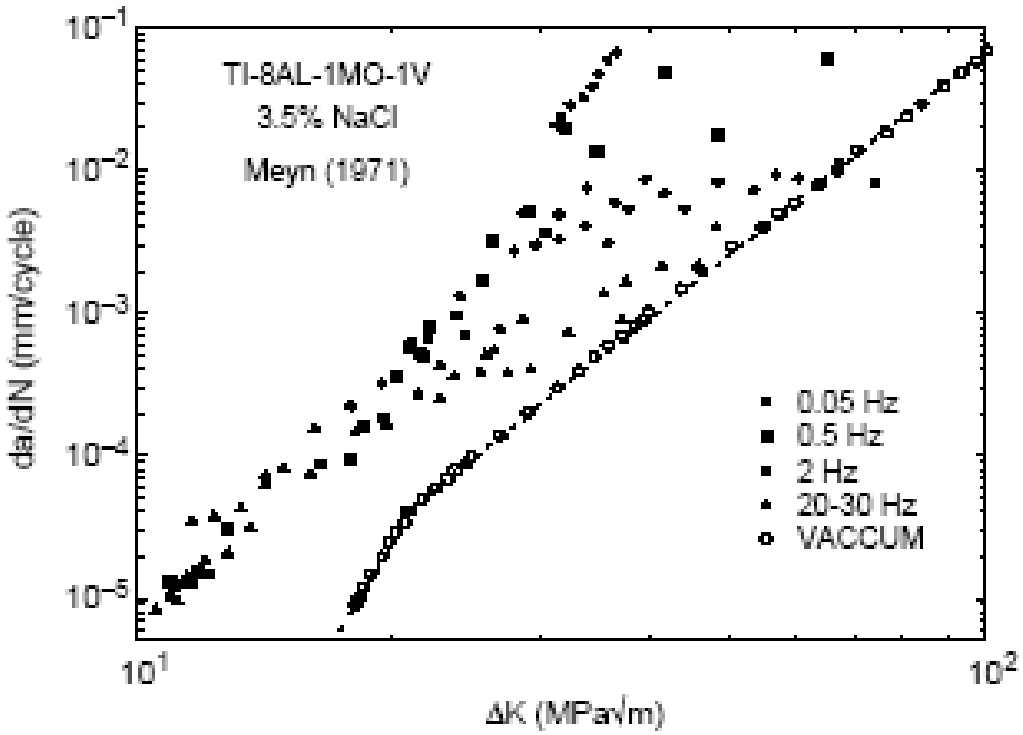


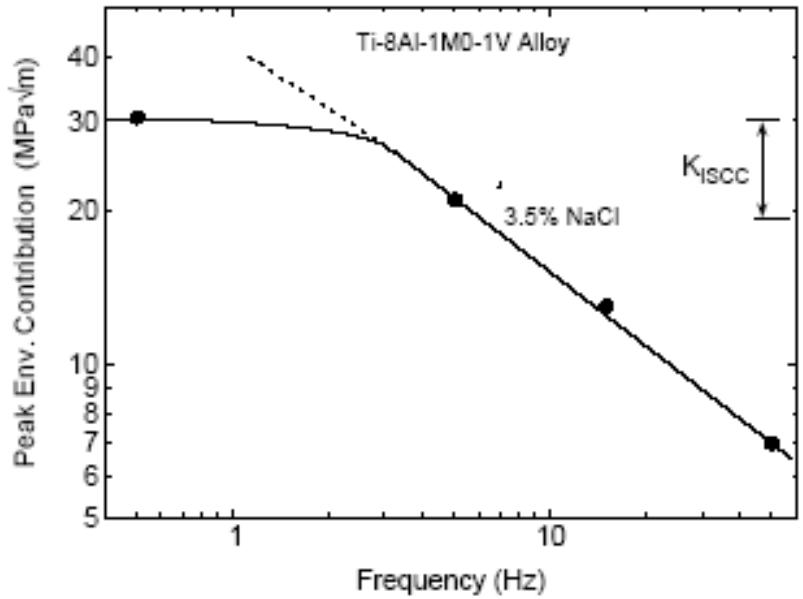


Chemistry

Metal Corrosion - factors

Corrosion Fatigue

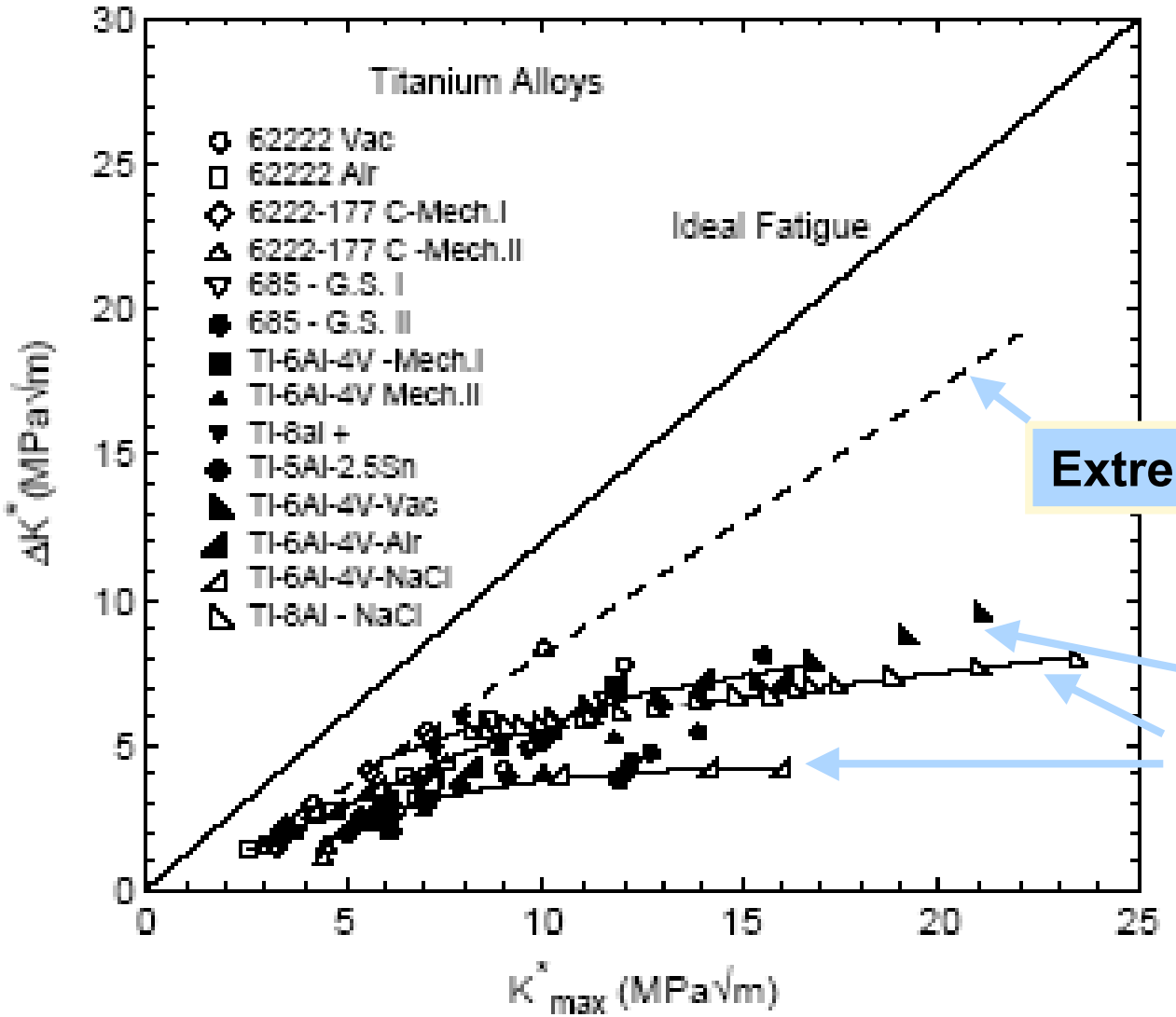




Frequency effects/ time to exposure

Grain size, microstructure, K_{1scc}

Corrosion Fatigue



Extremely Good Vacuum

Alloy Chemistry

Mode of failure - CMCs

Deformation	Yield	NONE	
	Creep	thermally activated plasticity (same as in metals)	f (temp, time, stress)
Fracture	Static	damage progression	f (stress)
	Creep rupture	fiber dominated	f (temp, time, stress)
	Dynamic fatigue	interface degradation	f (cycles, stress)
Material Loss	Corrosion	NONE	
	Oxidation	in non-oxides (same as in metals)	f (time, temp, O_2 pres, H_2O)

Modes of failure - CMCs

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Material Loss	Corrosion	NONE	
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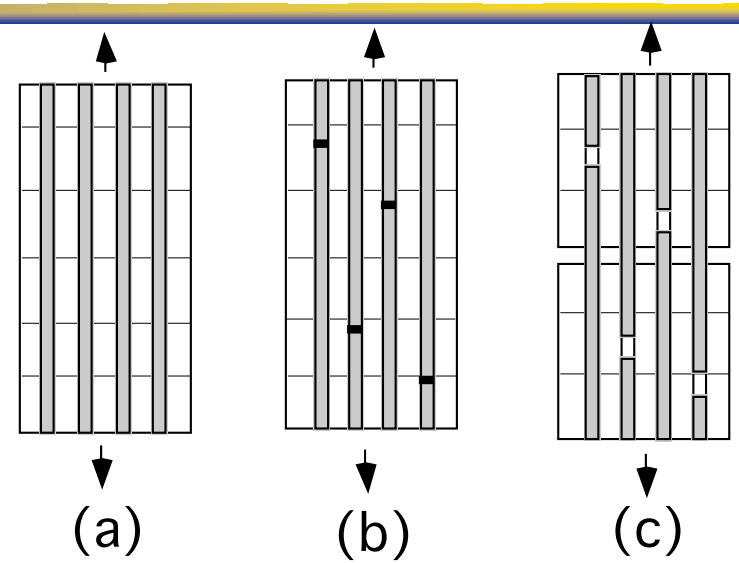
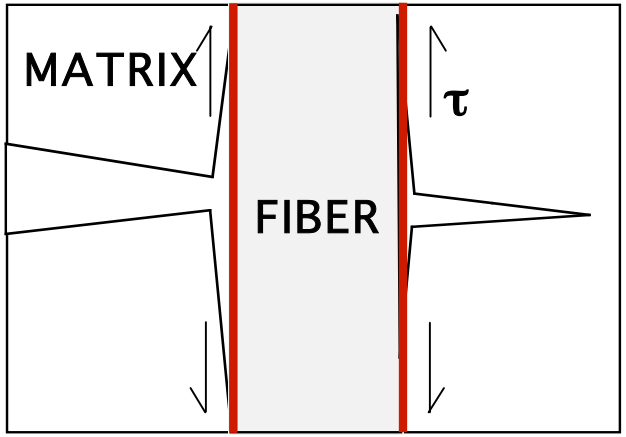
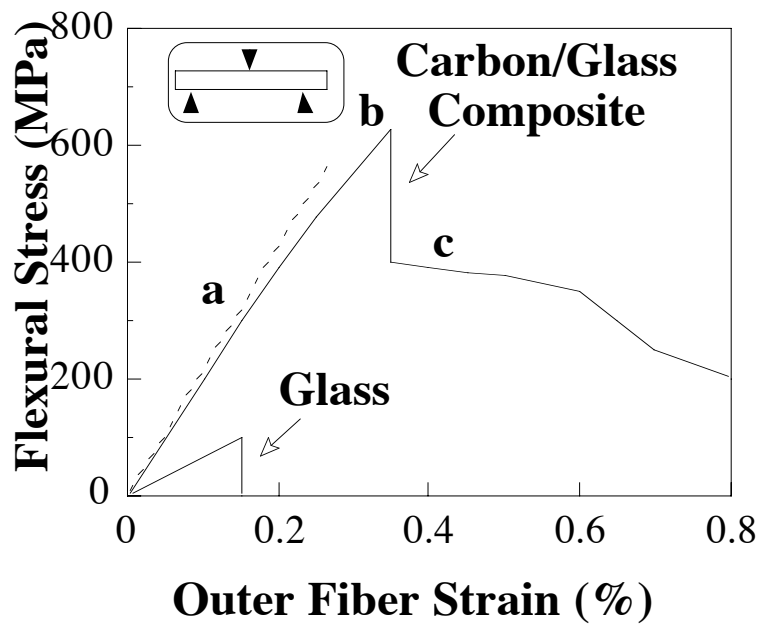
Idealized Composite Behavior

Optimum composite properties require uncorrelated fiber fracture and decoupling from matrix during loading



Engineer fiber/matrix "interface" to promote debonding and sliding of fibers ⇒ fiber coatings

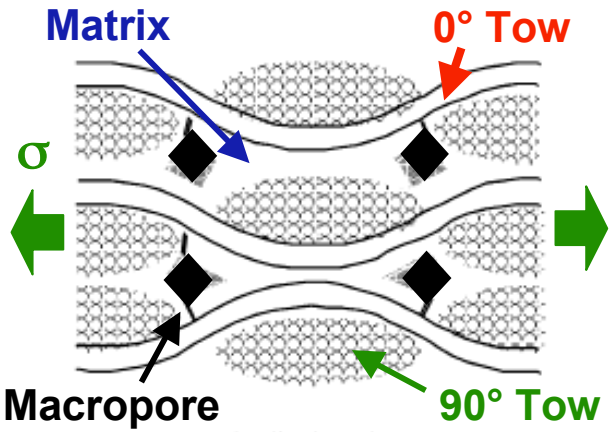




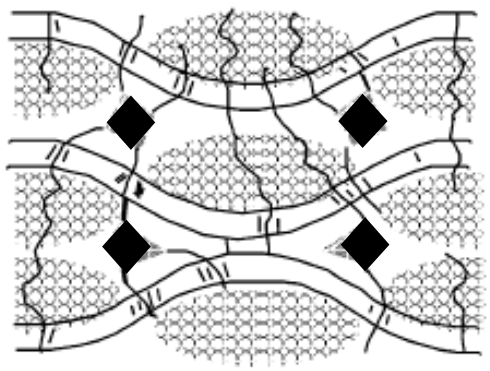
Parthasarathy, Kerans, CSI Handbook, 2, 2003

Dense Matrix Composites: RT Mechanical Behavior

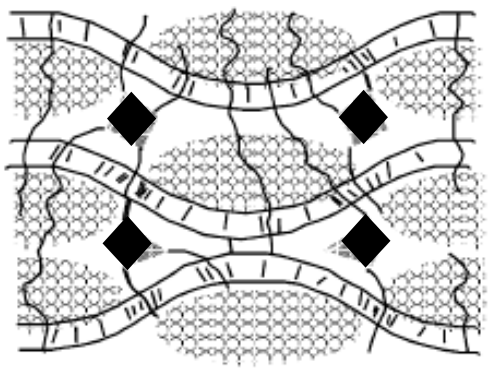
Damage Progression in Tension - 2D SiC/CVI SiC Composites:



Longitudinal strain = 0.06 %

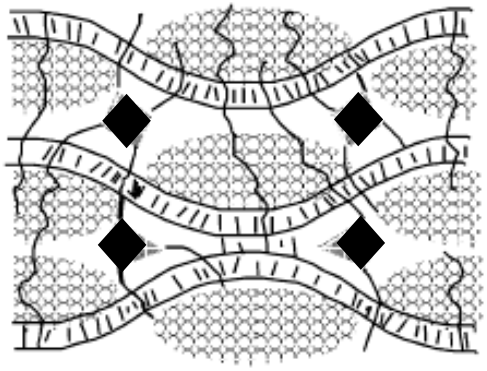


Longitudinal strain = 0.2 %

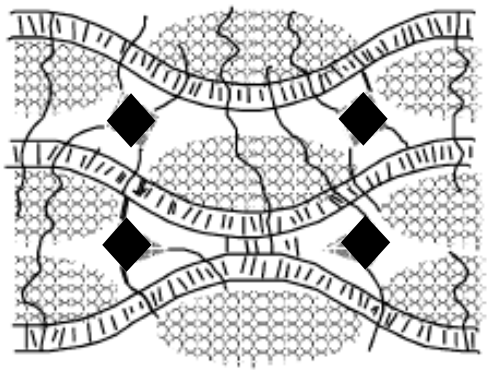


Longitudinal strain = 0.4 %

1. Initiate at macropores **2. Cracking of 90° tows** **3. Microcracking of . . .**



Longitudinal strain = 0.6 %



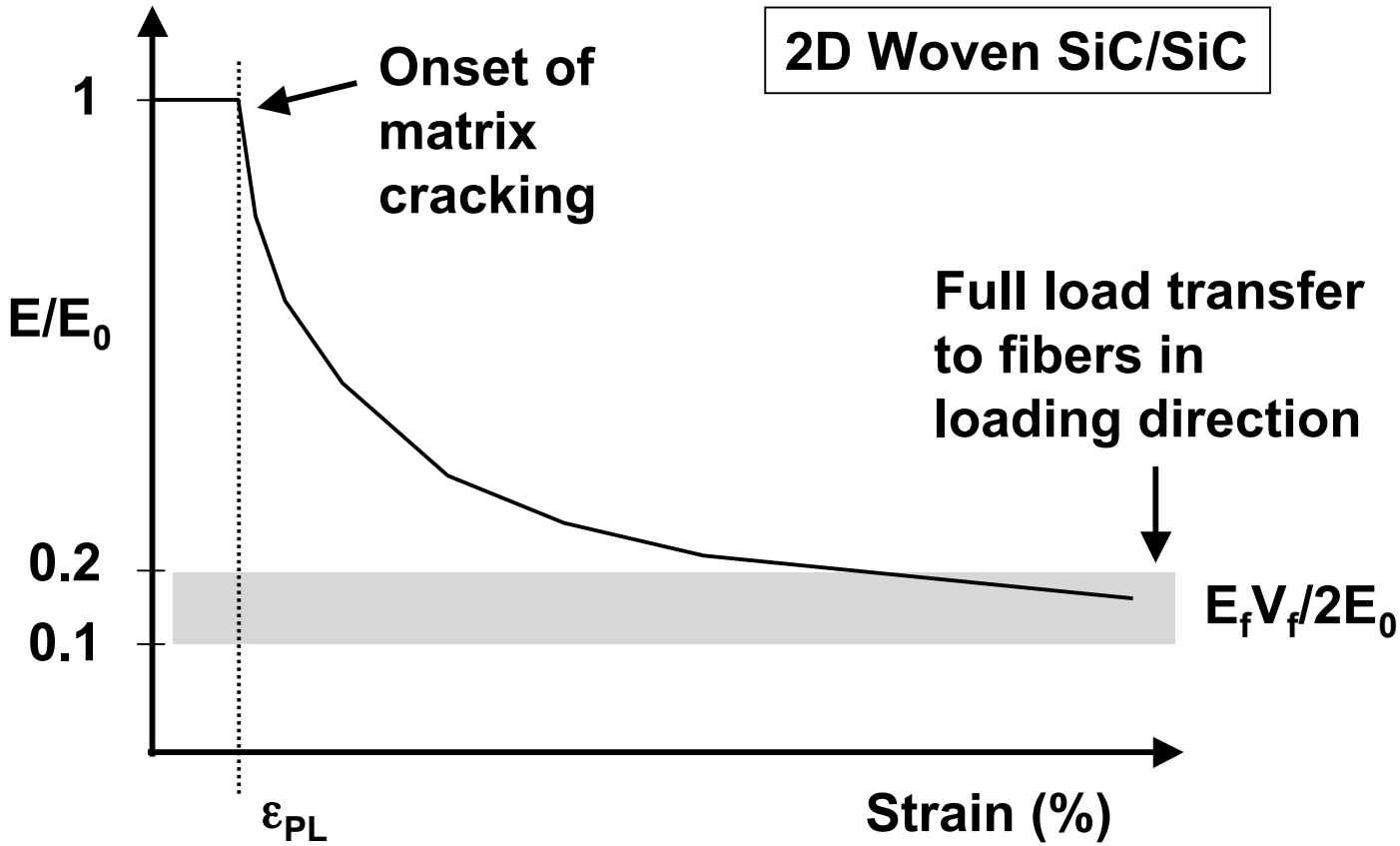
Longitudinal strain = 0.8 %

3. . . . 0° tows with progressive load transfer to fibers

J. Lamon, *Compos. Sci. Tech.*, 61, 2259 (2001)

Dense Matrix Composites: RT Mechanical Behavior

Modulus decreases with matrix damage:

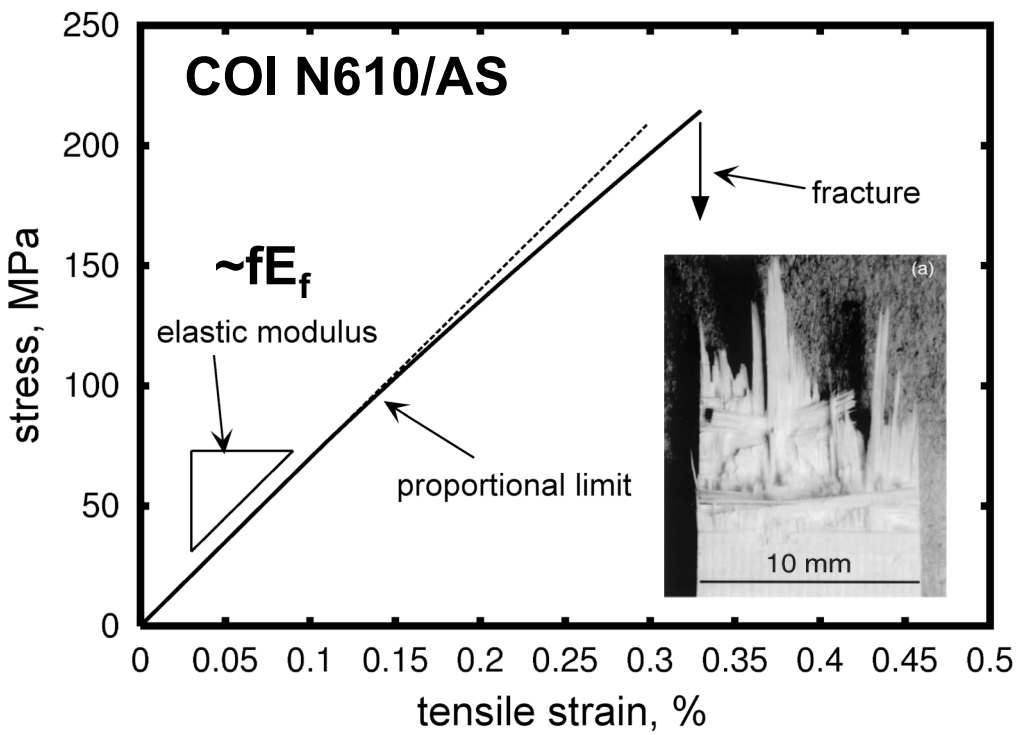


After J. Lamon, *Compos. Sci. Tech.*, 61, 2259 (2001)

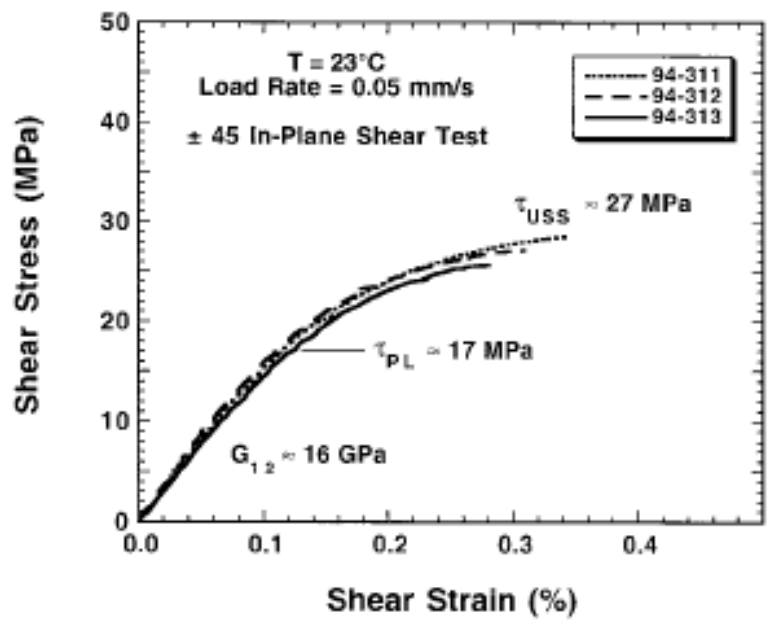
Porous Matrix Composites: RT Mechanical Behavior

RT Tensile Behavior of Model Porous Matrix Composite:

0°/90°: Fiber-dominated behavior up to failure



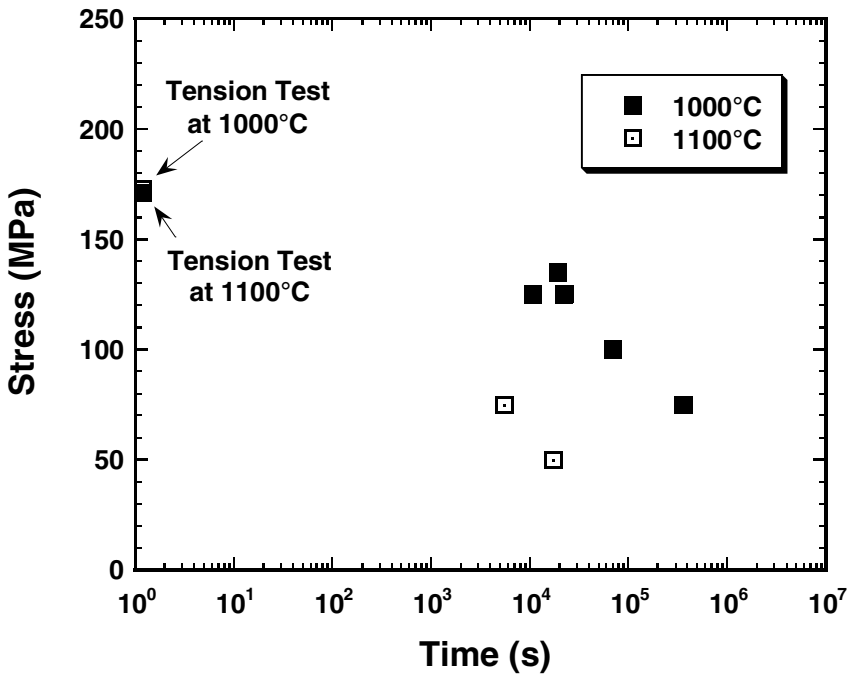
±45°: Matrix-dominated behavior up to failure

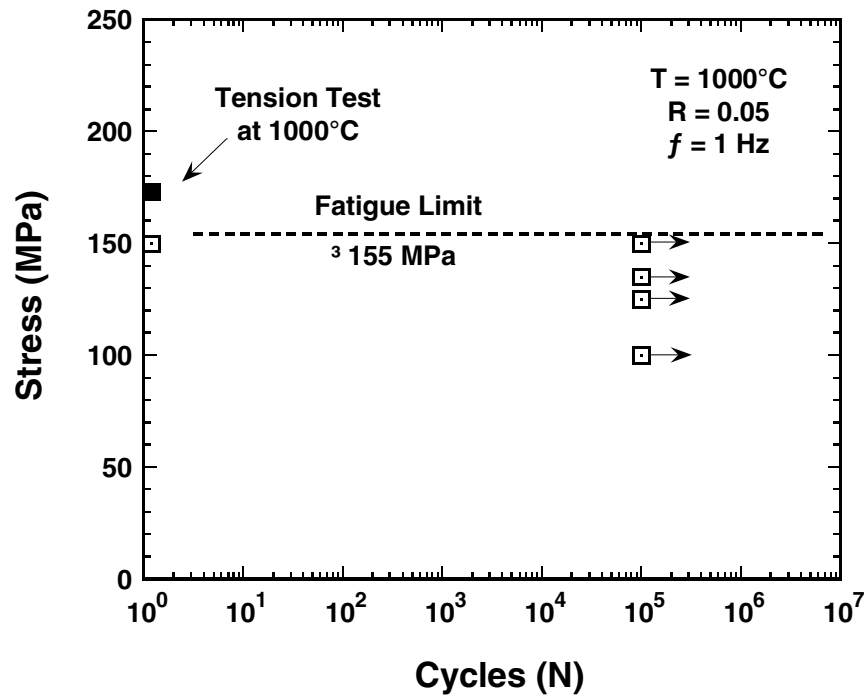


L. Zawada et al, *J. Am. Ceram. Soc.*, 86, 981 (2003)

Porous Matrix Composites: HT Mechanical Behavior (cont'd)

Creep rupture and HT fatigue of COI N610/AS:





Creep rupture dictated by creep rate of N610 fibers

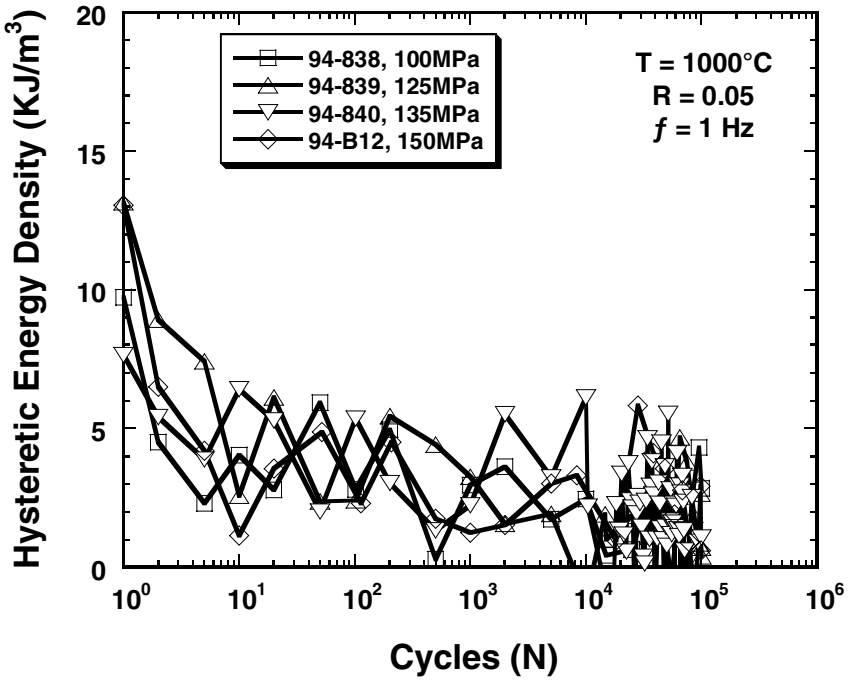
(poor behavior highlights need for improved oxide fibers!)

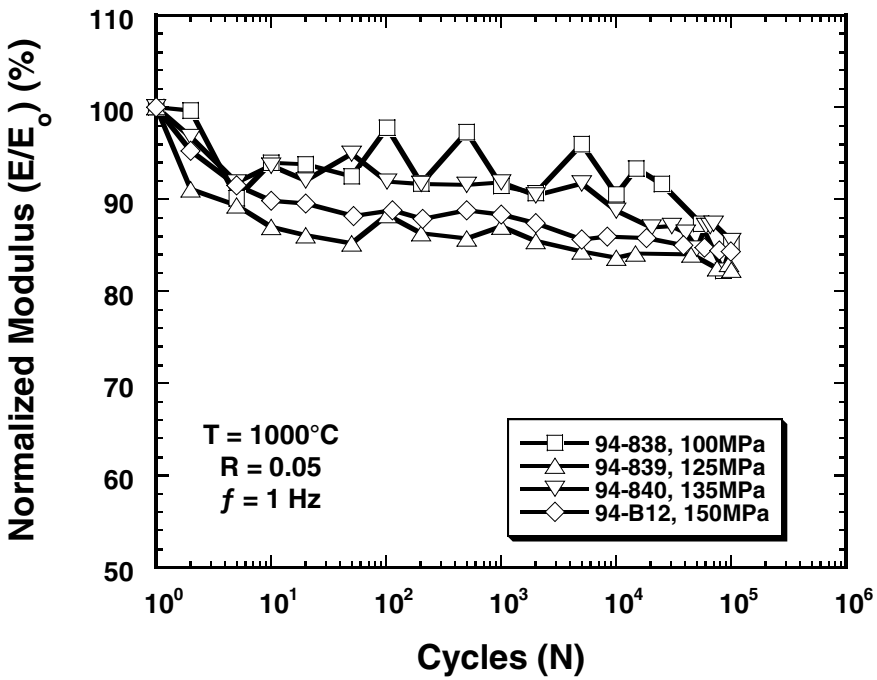
High fatigue limit due to absence of environmentally sensitive "interface"

Zawada et al, *J. Am. Ceram. Soc.*, 86, 981 (2003)

Porous Matrix Composites: Fatigue Behavior

COI N610/AS:





Stress-strain hysteresis provides measure of fiber debonding/sliding

Modulus change provides measure of matrix microcracking

Interface Degradation a measure of remaining life ?

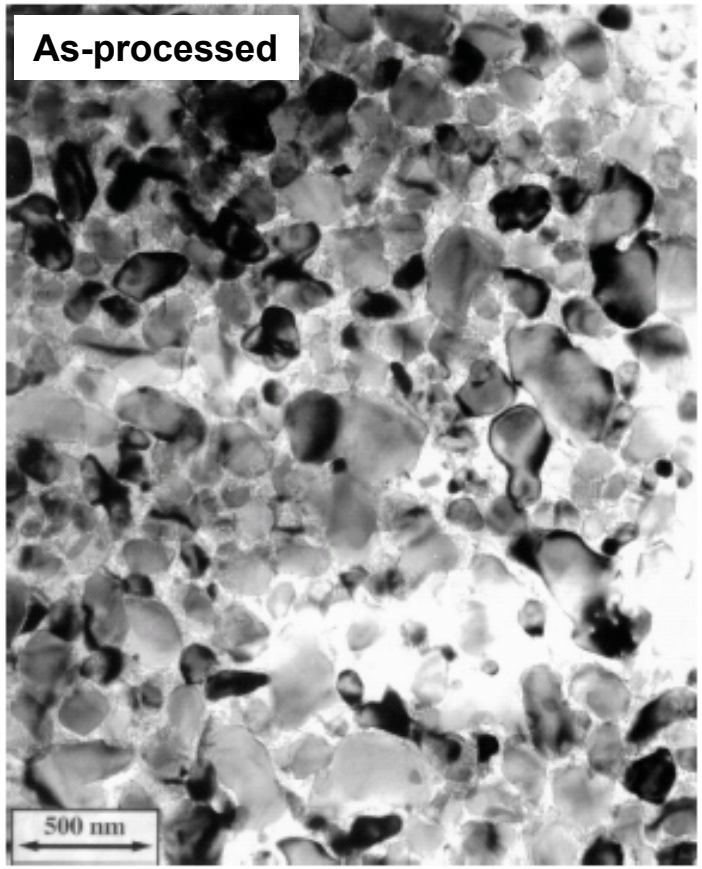
Modulus is a measure of remaining life ?

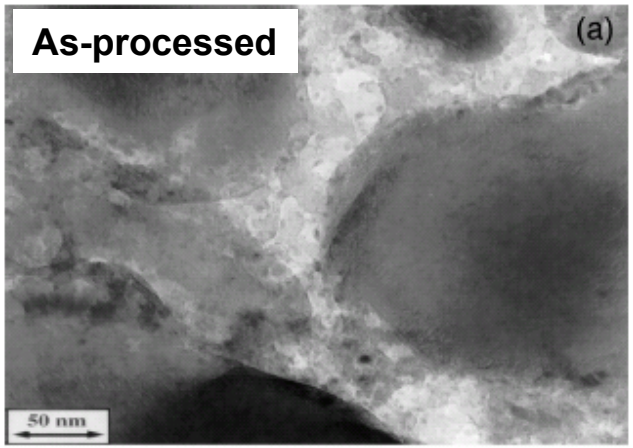
Zawada et al, *J. Am. Ceram. Soc.*, 86, 981 (2003)

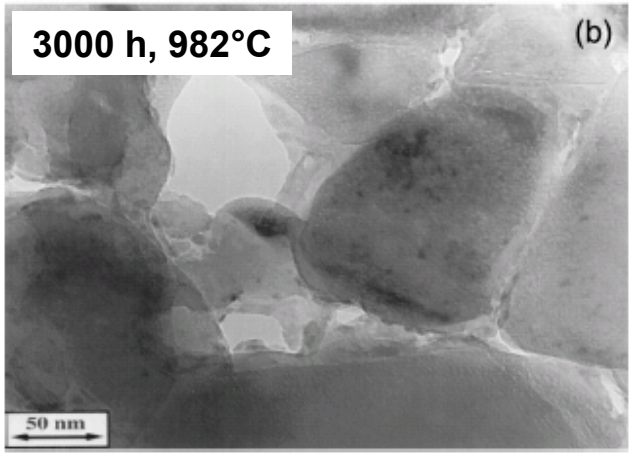
Porous Matrix Composites: Damage Progression in Service

Sintering of porous matrix during extended thermal exposure:

COI N610/AS





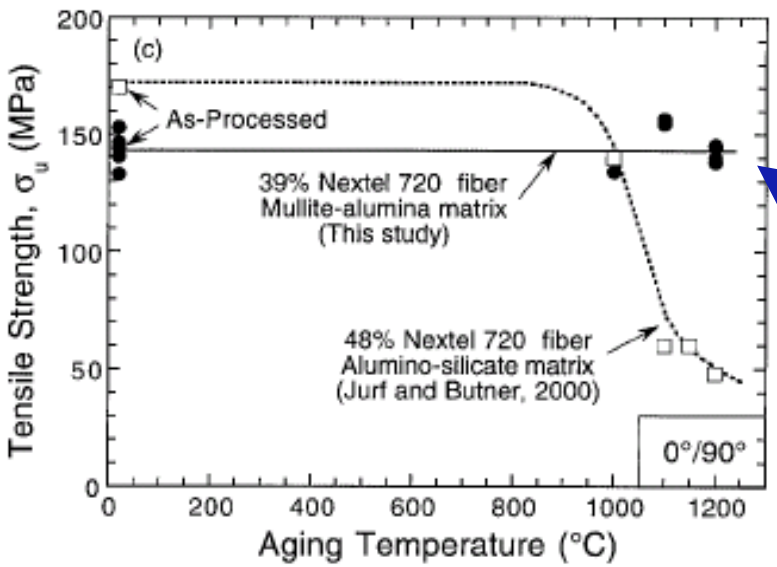


Matrix becomes stronger, bonds strongly to fiber

Zawada et al, *J. Am. Ceram. Soc.*, 86, 981 (2003)

Porous Matrix Composites: Damage Progression in Service

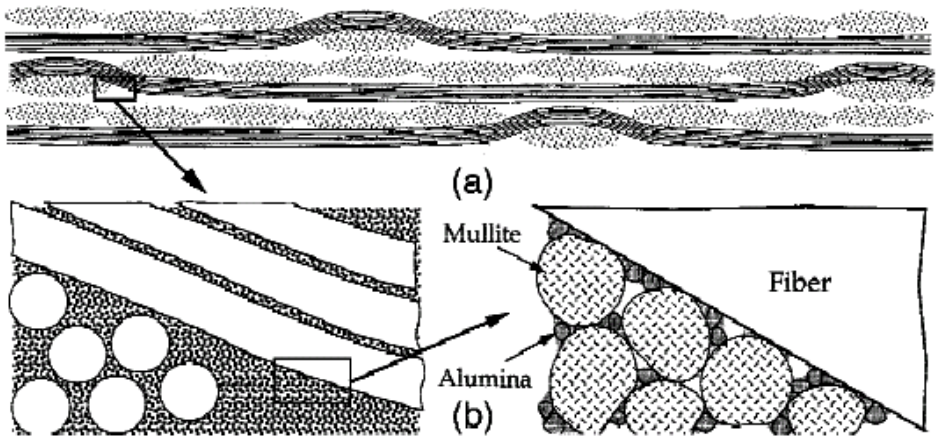
Sintering of porous matrix during extended thermal exposure:



Retained tensile strength following HT aging (1000 h)

"Non-sintering" matrix:

Refractory mullite bonded with small sintering particles (alumina)



E. Carelli et al, *J. Am. Ceram. Soc.*, 85, 595 (2002)

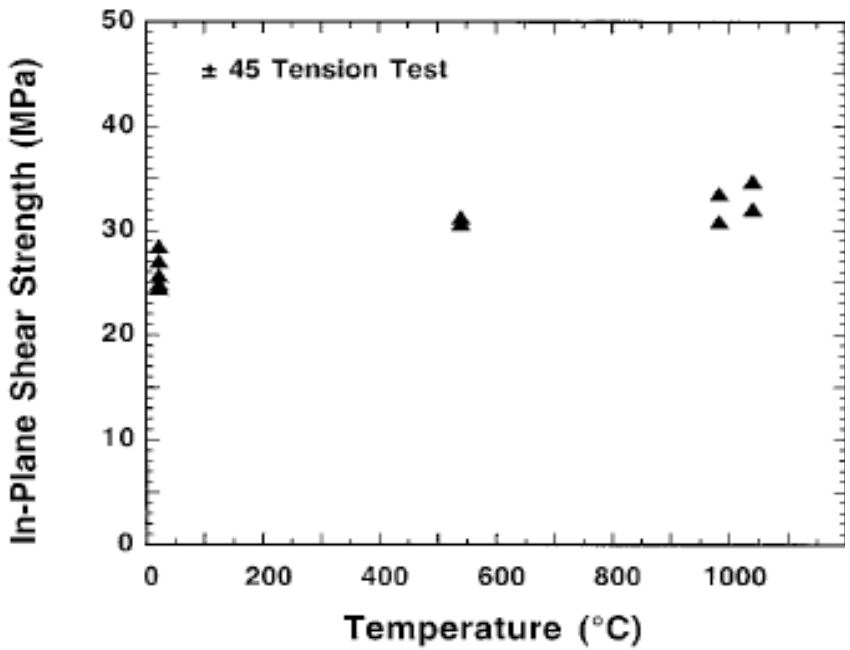
C. Levi et al, *J. Am. Ceram. Soc.*, 81, 2077 (1998)

Pervasive CMC Behavior: Anisotropy of mechanical properties

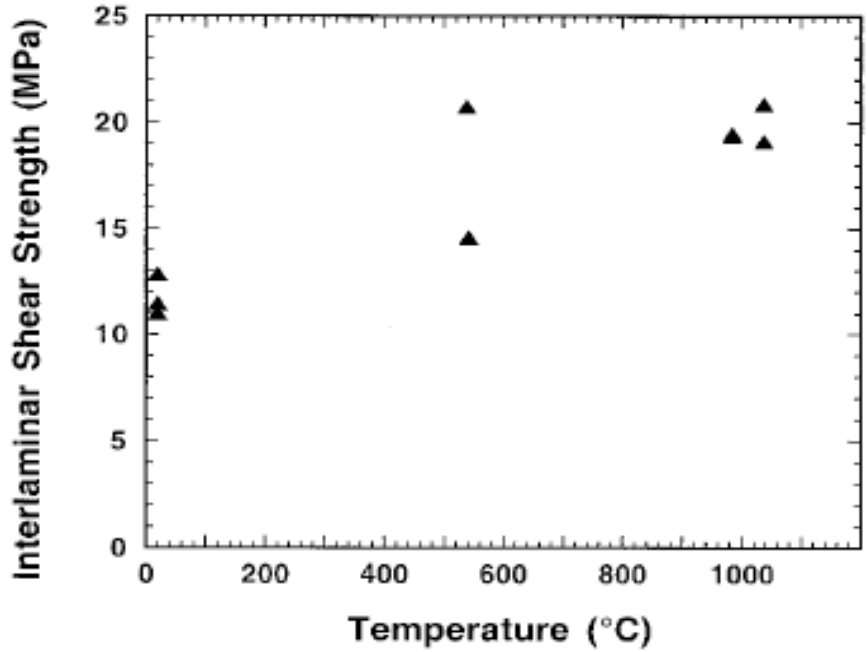
Plagues all CMC's, worse for porous matrices:

COI N610/AS:

off-axis strength



interlaminar shear strength



CMC failures dominated by anisotropy:

Transverse thermal gradients cause delaminations

Accelerated creep in off-axis directions

Zawada et al, *J. Am. Ceram. Soc.*, 86, 981 (2003)

SUMMARY

Challenge: Connection of Physics of Failure to Damage sensing at Material Level

(1) How do you take into consideration material factors that control physics of failure to devise new sensors?

(2) What scale of defect detection is important ?

(3) How does one handle when components become geometrically more complex and multi-materials are used?

- Constituent volume fractions, properties, processing defects expected to vary within component

(4) Meaningful damage must be detected against background of processing defects, etc.

(5) Physics of failure in operational-extreme environments not well documented !!