Simulation Research in the McMeeking Group

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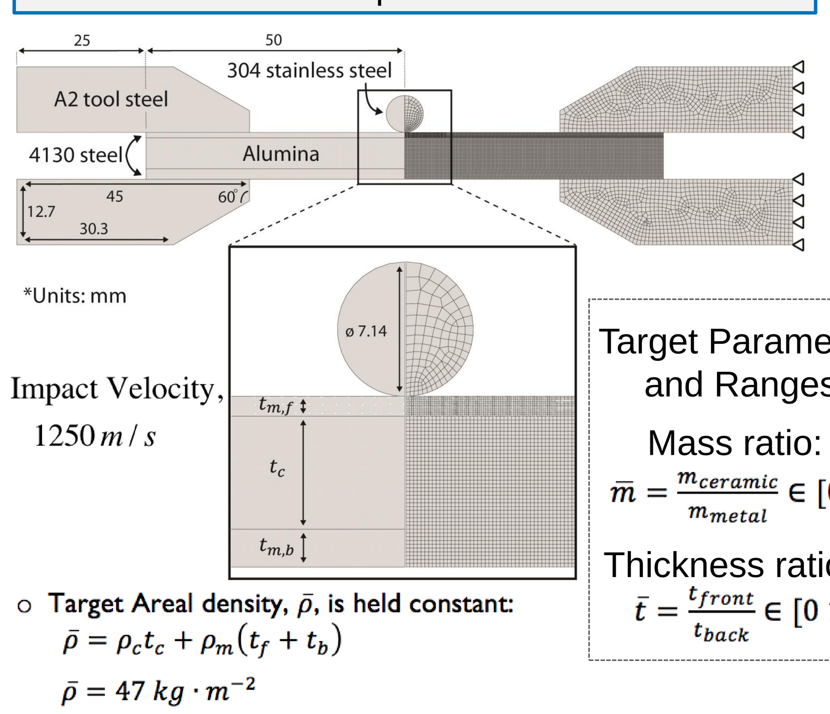
The Effect of Design on the Ballistic Resistance of Ceramic-Metal Multilayers

Significance: Ceramic-metal composites are recognized for their resistance to ballistic penetration but their performance is sensitive to design. The objective of the study is to identify design principles that impart high ballistic resistance to the target.

Details of the Impact Test Simulations



- Target Areal density, $\bar{\rho}$, is held constant:

$\bar{\rho} = \rho_c t_c + \rho_m (t_f + t_b)$

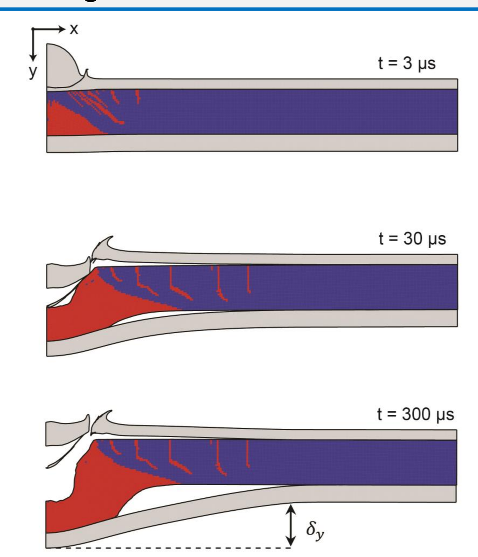
$\bar{\rho} = 47\ kg \cdot m^{-2}$

Target Parameters and Ranges:

Mass ratio: $\bar{m} = \frac{m_{ceramic}}{m_{metal}} \in [0\ 2]$

Thickness ratio: $\bar{t} = \frac{t_{front}}{t_{back}} \in [0\ 1]$

Target Performance Metrics



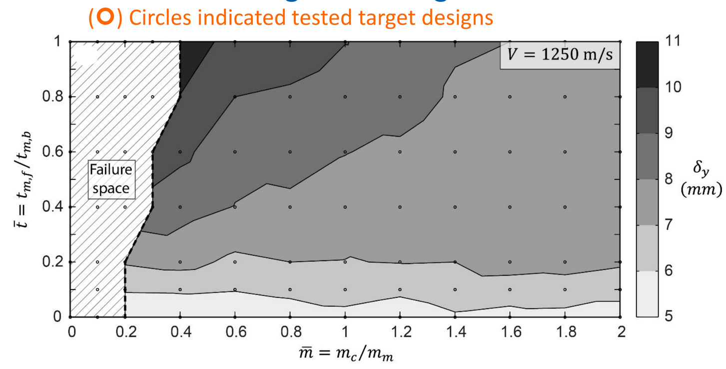
End of simulation measurements:

1. Max permanent deflection
2. Target energy dissipation

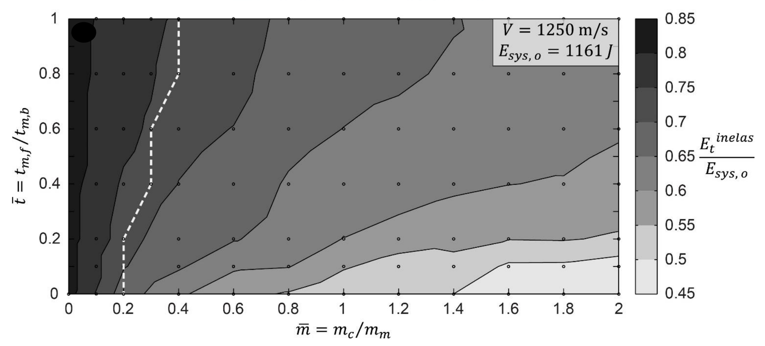
Results from the Parametric Study

Effect of Design on Target Deflection

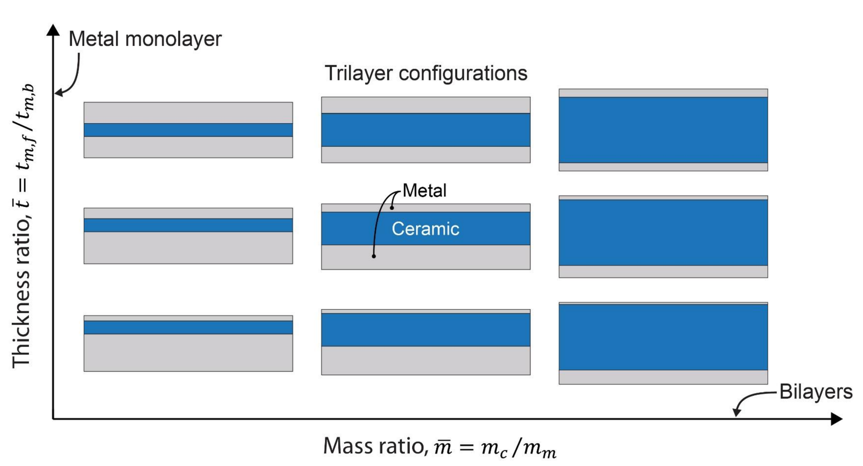
(O) Circles indicated tested target designs



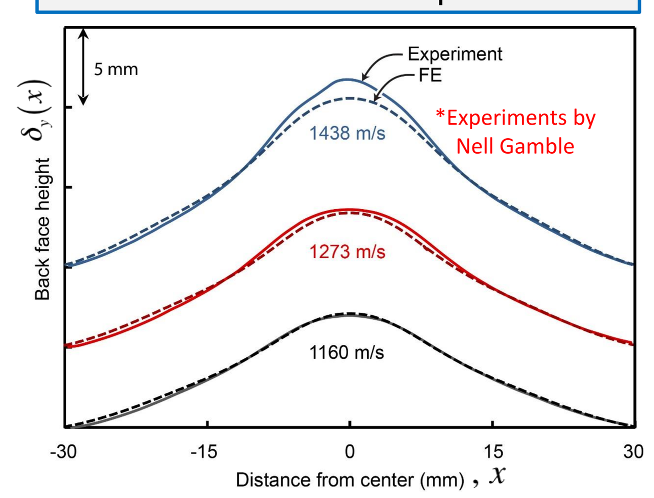
Target Energy Dissipation and its Effect on Failure



Design Space of Equal-Weight C-M Systems



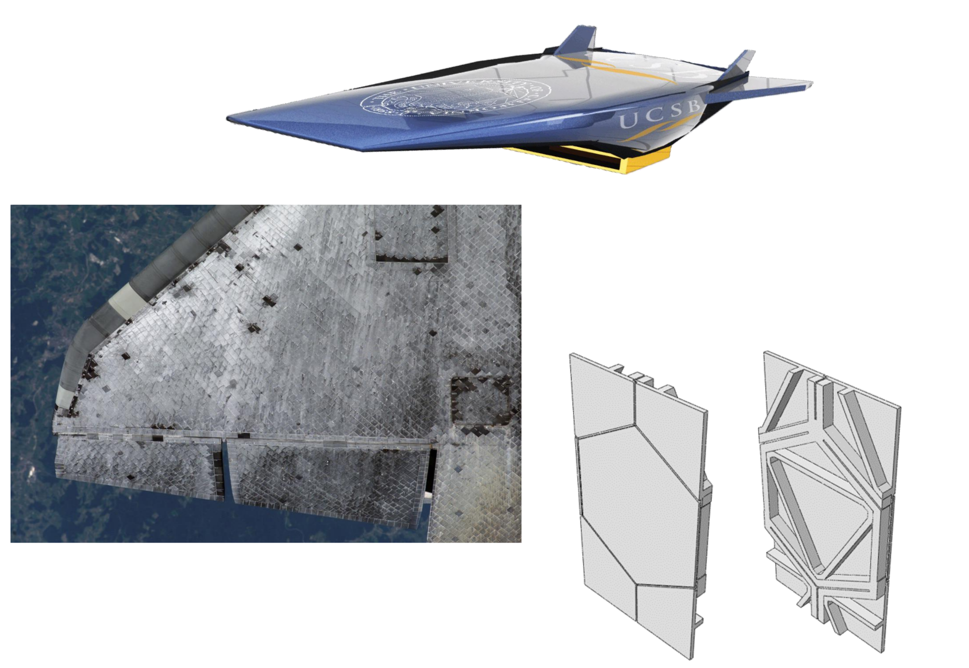
Model Validation to Experiments



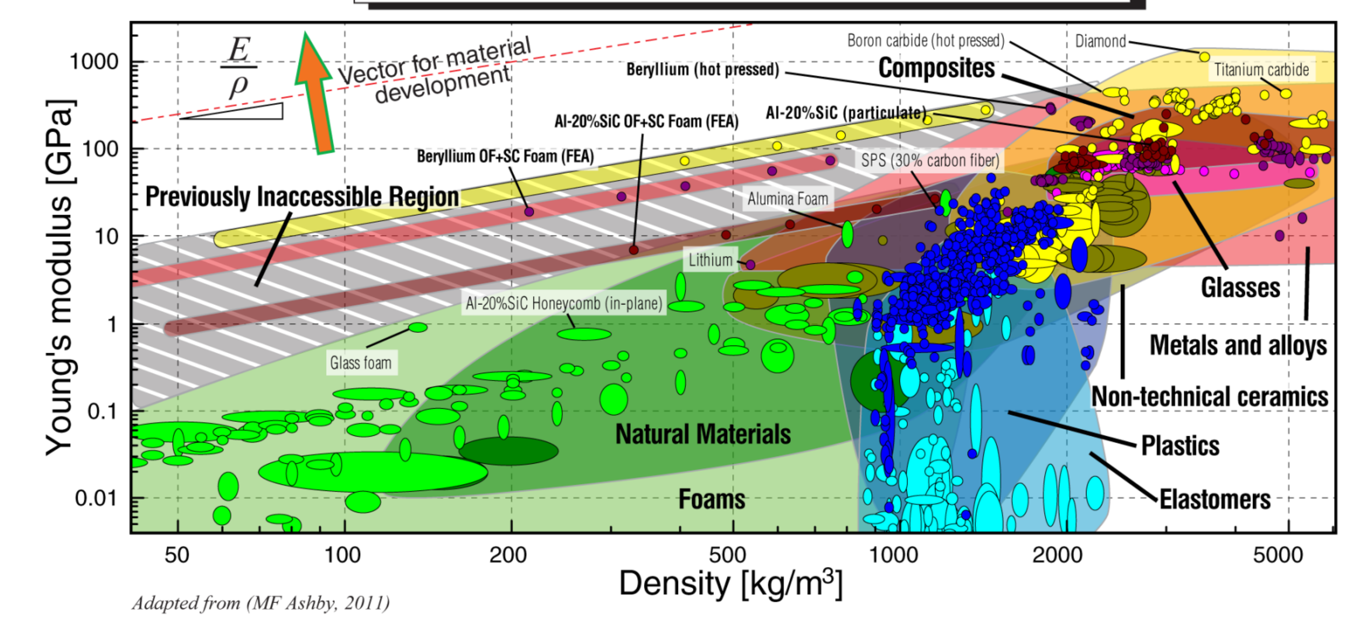
Conclusions

1. For fixed areal density, systems that combine ceramic and metal have improved ballistic resistance, relative to monolithic systems.
2. The design with the greatest ballistic resistant is the bilayer with the ceramic layer on the impact face and the metal layer at the rear.
3. Failure resistant designs are found to have large ratios of ceramic-to-metal mass.

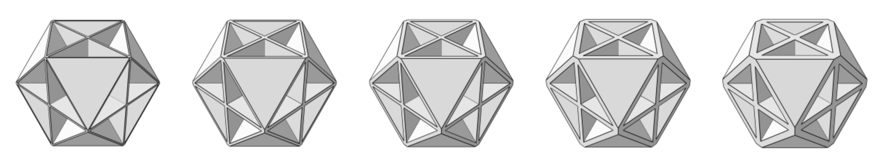
Modeling of Periodic Materials with Novel Properties



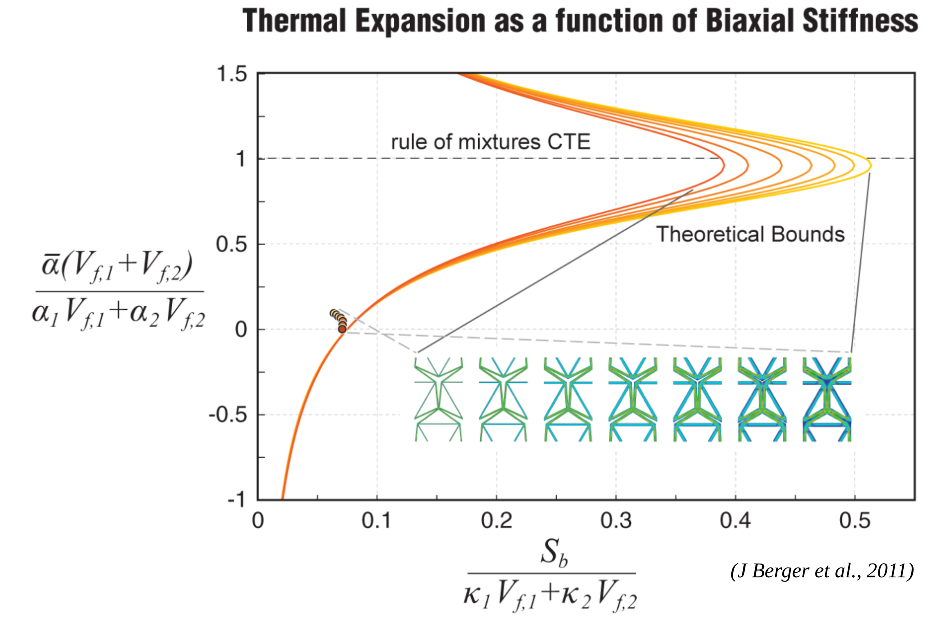
Young's Modulus of Isotropic and Nearly Isotropic Materials



Adapted from (MF Ashby, 2011)



Thermal Expansion as a function of Biaxial Stiffness



(J Berger et al., 2011)

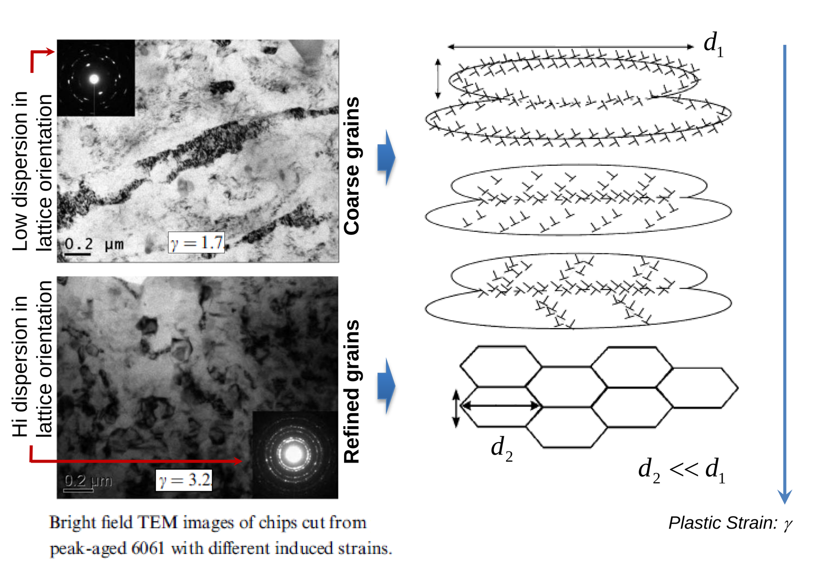
Low coefficient of thermal expansion (CTE) lattices can achieve a large portion of theoretical bounds for stiffness (left-bottom). By combining two materials with appreciably different and potentially large CTEs material systems can be designed that have zero or even negative thermal expansion. While there are potentially many applications, this particular material was developed for use on hypersonic aircraft (left-top) as an acreage material to replace brittle thermal barriers such as those used on the space shuttle (left-center).

A cellular material has recently been identified that achieves theoretical bounds for isotropic stiffness (above). When constructed of diamond its properties define the boundary of property space (right-top). Its stiffness exceeds those of stochastic foams by more than an order of magnitude.

Microstructural Evolution under Severe Plastic Deformation

Severe Plastic Deformation (SPD) can create an evolution in the Microstructure: Dislocation Density ρ and Grain Size *d*

Recrystallization (RX) occurring during SPD, caused by saturation of dislocations, gives Grain Refinement



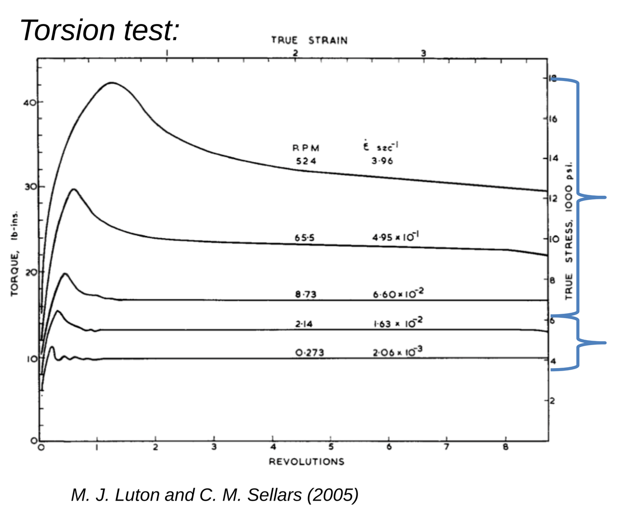
Bright field TEM images of chips cut from peak-aged 6061 with different induced strains.

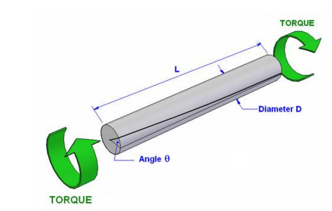
M. Ravi Shankar et al. (2005) *A. Mishra et al. (2005)*

The mechanical properties of a metal are given by its Microstructure: ρ and *d*

Evolution of the Yield Strength

Torsion test:



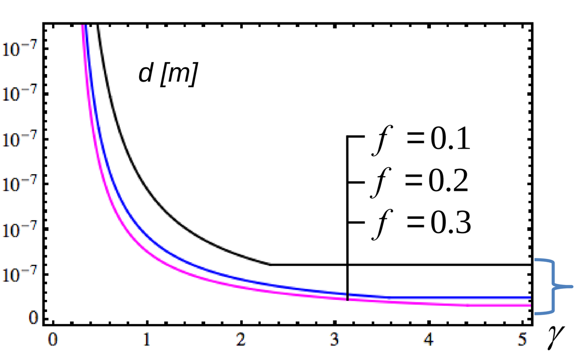


CDRX shows monotonic behavior

DDRX (discontinuous RX) shows multiple peaks: multiple RX cycles

M. J. Luton and C. M. Sellars (2005)

Grain Refinement prediction for Continuous Dynamic Recrystallization (CDRX), for various Strain Rates and Temperatures



$f = (\dot{g}/\dot{g}_0)^{kT/A}$

$\dot{g}$ - Strain Rate

T - Temperatures

$\dot{g}_0, k, A$ - Constants

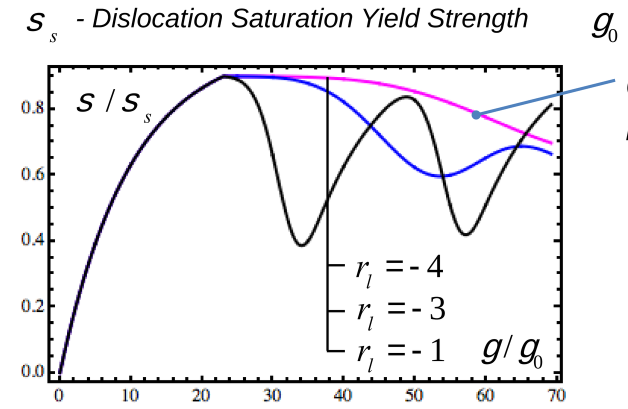
Nanostructure

Prediction of the evolution of the Yield Strengh, from DDRX to CDRX

s - Yield Strength

s_s - Dislocation Saturation Yield Strength

g_0 - Constant



***CDRX,** Hi dislocation evolution rate: Hi Strain Rate*

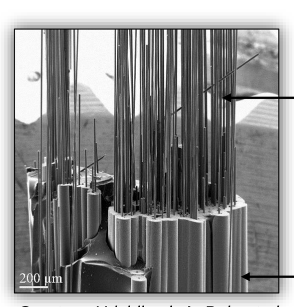
$r_l = \log(k_n / k_r)$

k_n - RX rate

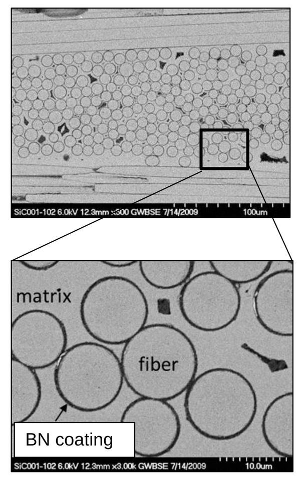
k_r - Dislocation evolution rate

Modeling the Oxidation Embrittlement of SiC/SiC Composites

SiC/SiC composites consist of SiC matrix reinforced with BN-coated SiC fibers.



Courtesy Hrishikesh A. Bale et al.



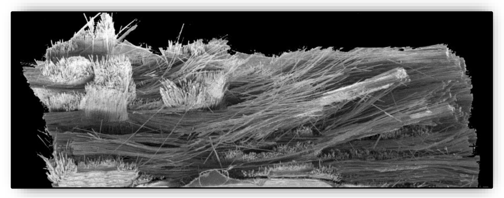
Courtesy Opila et al.

The first use of SiC/SiC composites in commercial engines

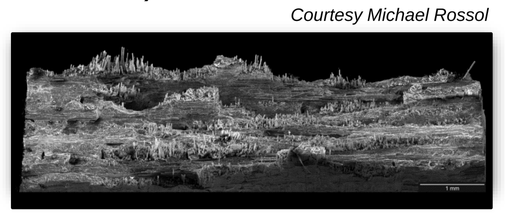
- 10% improvement in thrust
- 15% reduction in fuel consumption
- 15% reduction in CO_2 emissions
- Over 20,000 hours of testing

SiC/SiC composites are susceptible to oxidation embrittlement at intermediate temperatures (700°~900°C).

Courtesy Michael Rossol

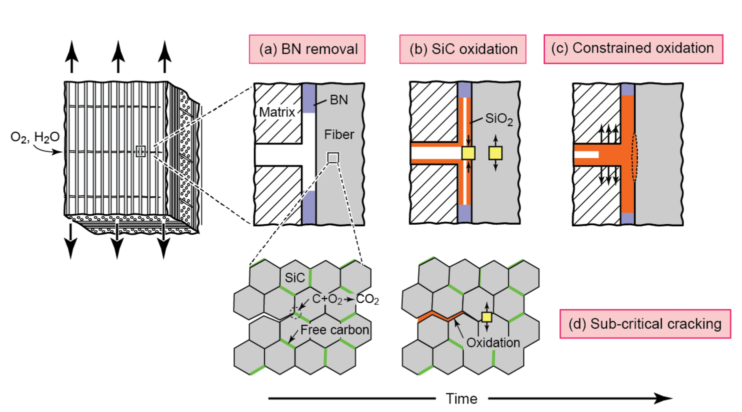


Stress rupture in pristine state

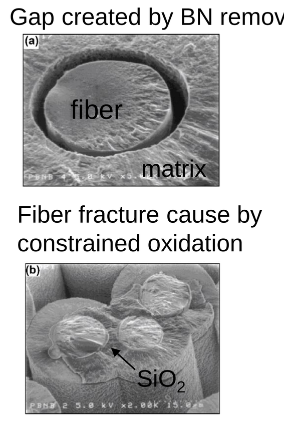


After oxidation in H_2O/O_2

Embrittlement mechanism



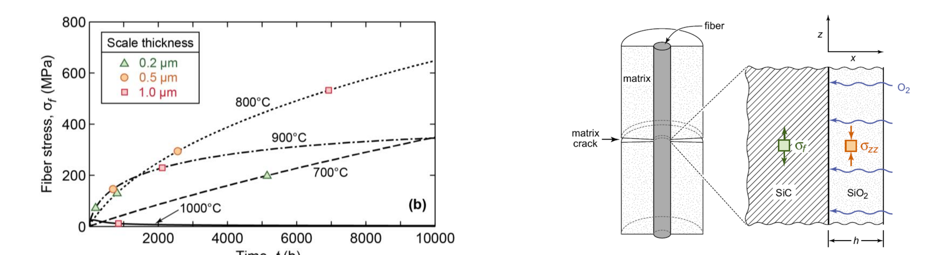
Gap created by BN removal



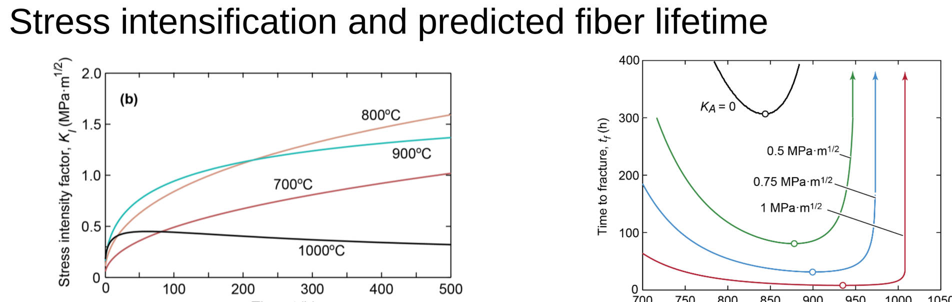
Fiber fracture cause by constrained oxidation

Morscher et al.

Oxidation induced stress evolution within SiC fibers



Stress intensification and predicted fiber lifetime



1. Growth stress depends on the growth kinetics and viscous flow of SiO_2 scales.
2. Fiber core stress and stress intensify factor are not monotonic with temperature.
3. Fiber lifetime reaches minimum at intermediate temperatures (840°~940°C).
4. Above a threshold temperature, fiber fracture can not occur.