Stress Measurements in Bulk Metallic Glass Matrix Composites

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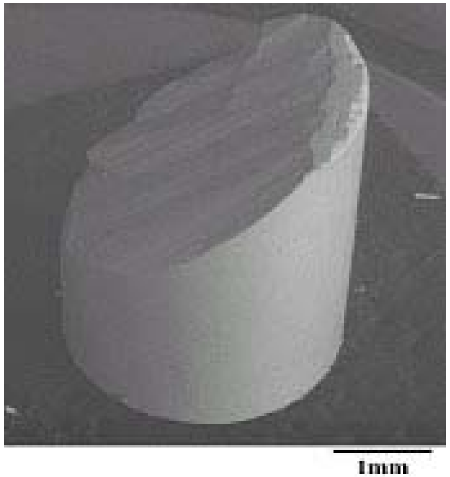
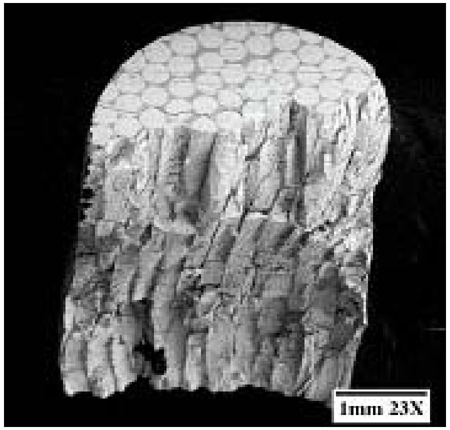
Demonstration of the elastic limit of BMG

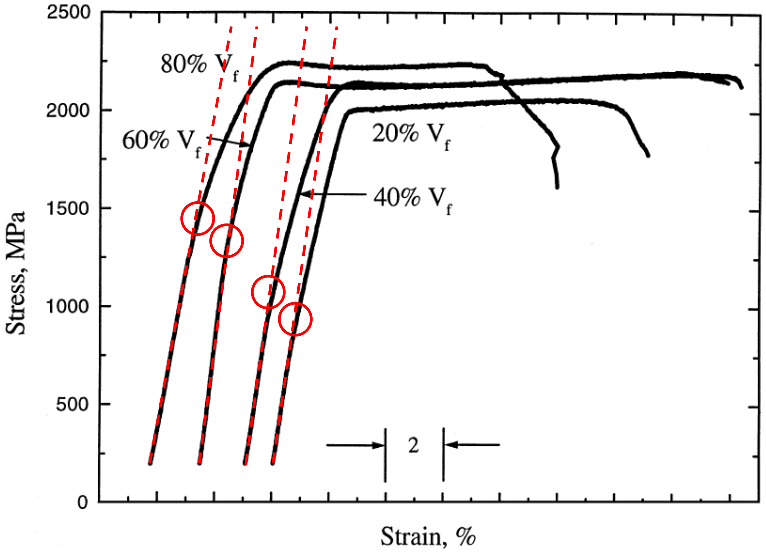
Bulk Metallic Glasses

- Vitreloy1 (Vit1) Developed at Caltech in early 90's
  - Composition: $Zr_{41.2}\ Ti_{13.8}\ Cu_{12.5}\ Ni_{10}\ Be_{22.5}$
  - Critical cooling rate about 1°C per second
  - Glass transition temperature: 350°C
  - Maximum size approaching 100 mm in thickness
- Mechanical properties
  - Yield strength: 1.9 GPa, Young's modulus: 96 GPa
  - Elastic strain limit: 2%
  - No ductility. Due to formation of macroscopic shear bands
  - Fracture toughness: up to 55 MPa $m^{1/2}$ (similar to maraging steel)

Why BMG matrix tungsten fiber composites?



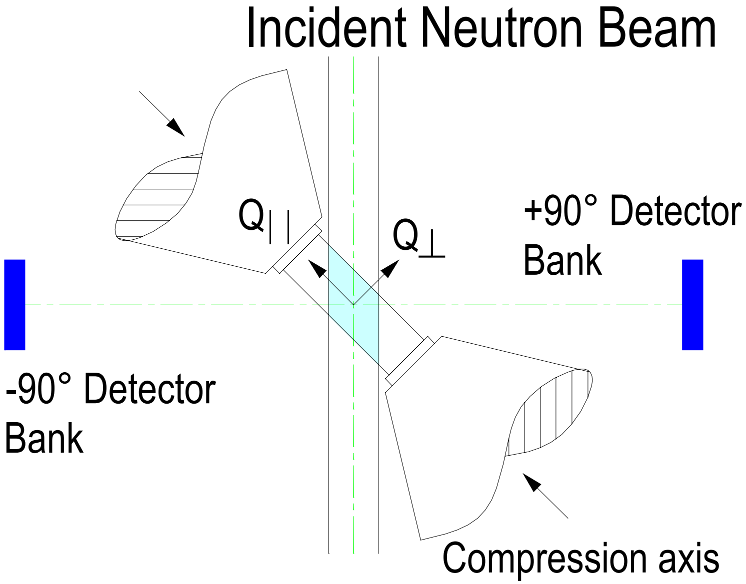




- BMG/Tungsten fiber composites
  - Same ultimate stress as monolithic Vit1
  - Large increase in ductility
  - Knee in stress strain curve: Yielding in tungsten?

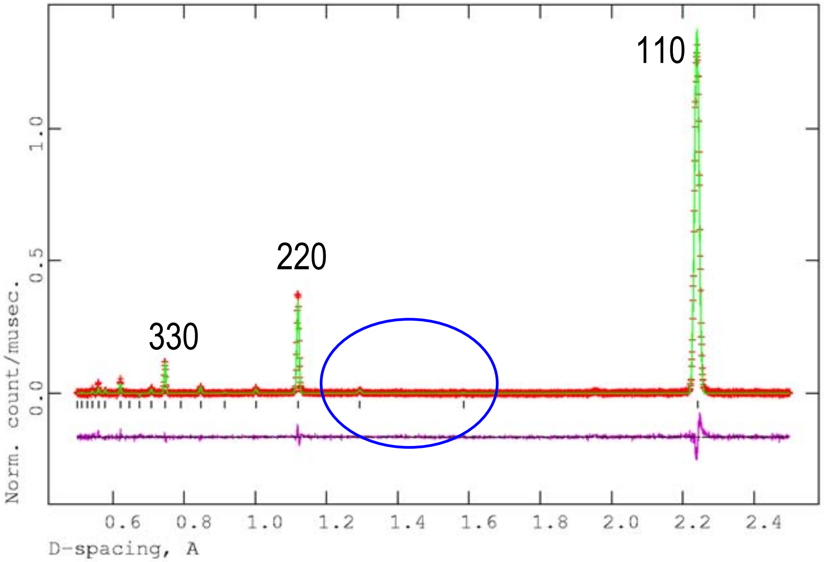
R. D. Conner, R. B. Dandliker and W. L. Johnson, Acta Mater., vol. 46(17), pp. 6089-6102, 1998

Neutron diffraction equipment

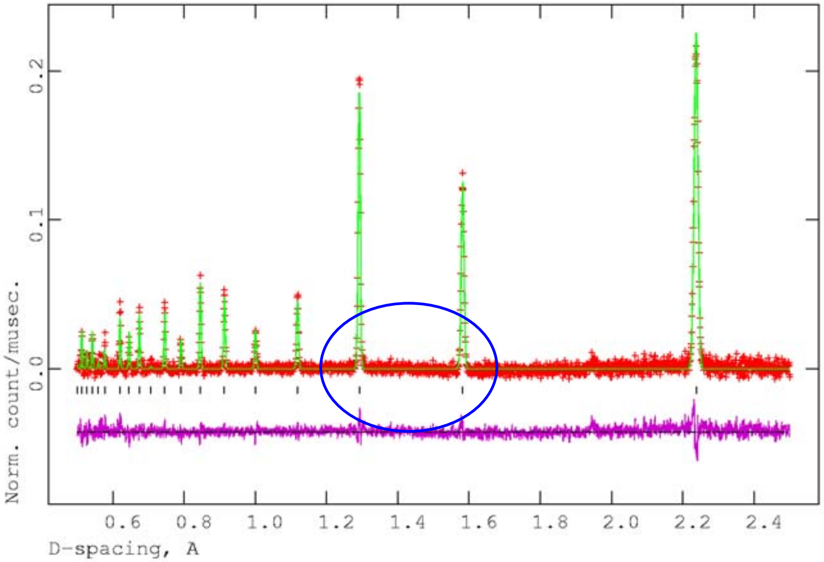


- Spectrometer for MAterials Research at Temperature and Stress (SMARTS)
- Schematic set-up for *in-situ* compression loading
- Measurement time is about 10-20 minutes per load level
- Measure elastic strains in two directions simultaneously
- Bulk measurement contrary to conventional X-ray measurements

Neutron diffraction measurements



Parallel

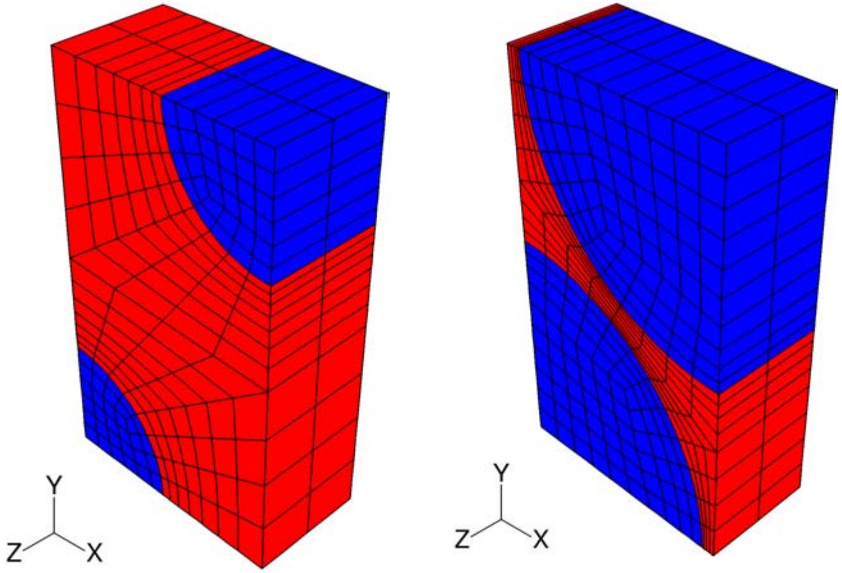


Perpendicular

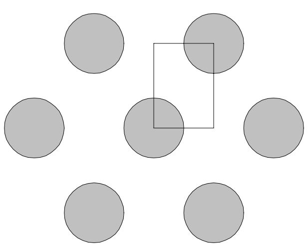
- Diffraction patterns from BMG tungsten fiber composite sample (80%)
- Highly textured fibers; hh0 texture for wire drawn bcc metals
- Good statistics from short count times
  - $R_{wp} \approx$ 6-8%, strain error bar $\approx$ 15 $\mu\varepsilon$

Finite element model: inputs

- BMG
  - Young's modulus: 96 GPa
  - Poisson's ratio: 0.36
  - Yield stress (Mohr-Coulomb):
    $\tau_c = 946 - 0.04\sigma_n$ [MPa]
  - No hardening
- Tungsten
  - Young's modulus: 410 GPa
  - Poisson's ratio: 0.28
  - Yield stress (Von Mises):
    $\sigma_y = 1305$ [MPa]
  - Hardening deduced from the neutron data



20% Mesh   80% Mesh



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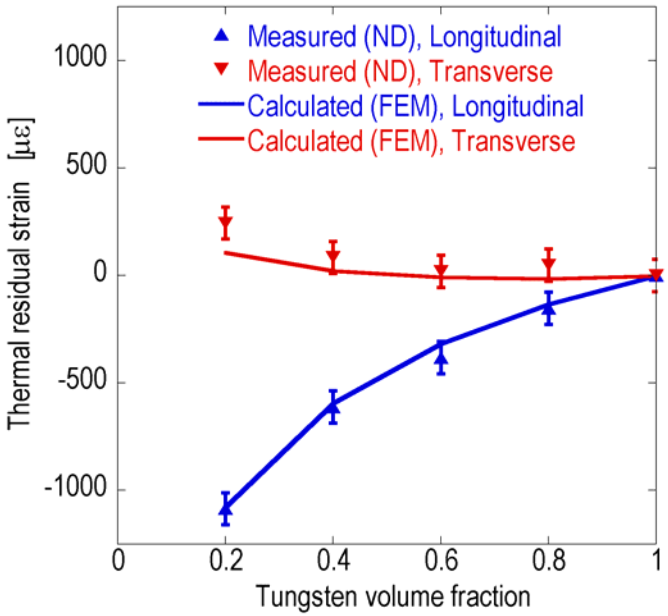
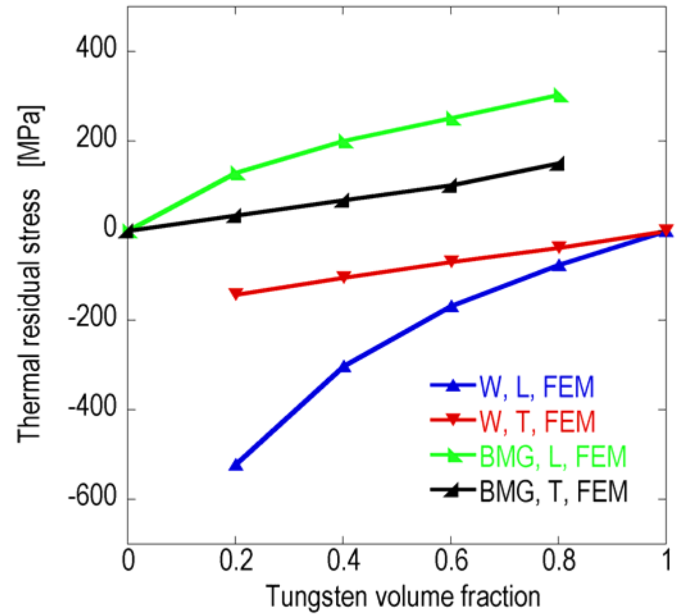
Lewandowski J. J. and Lowhaphandu P., Phil. Mag. A., in print
A. Saigal and G.G. Leisk, Mat. Sci & Eng. A, vol. 237, pp. 65-71, 1997
Y. He, R. B. Schwarz and D. G. Mandrus, J. Mater. Res., vol. 11, p. 1836, 1996

Validation of FEM using measured thermal residual strains

ND and FEM for W fiber $\Rightarrow$ FEM, Thermal residual ***STRESSES***



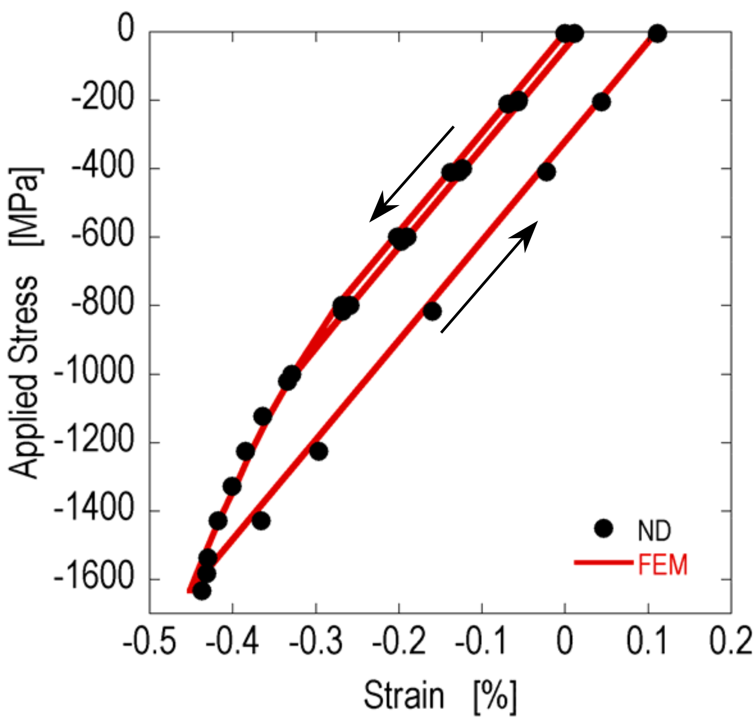


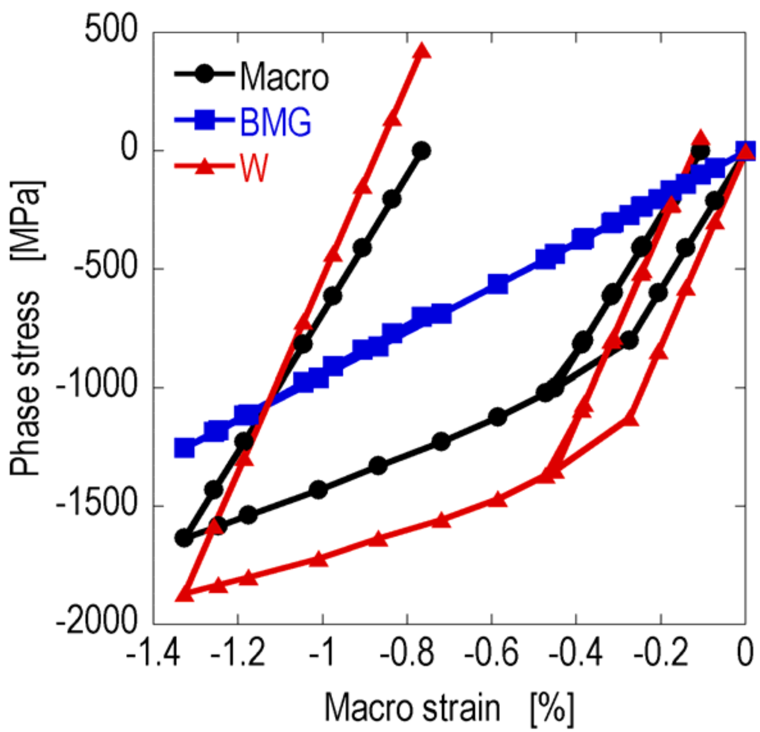
- Measured and calculated thermal residual stresses
  - No plasticity observed in either phase during the cooling cycle
  - Good agreement for the tungsten fibers
- Determine the thermal residual ***stresses*** in both phases from the validated FEM calculations

D. Dragoi, E. Üstündag, B. Clausen and M. A. M. Bourke, Scripta Mater., vol. 45, pp. 245-252, 2001

In situ loading measurements

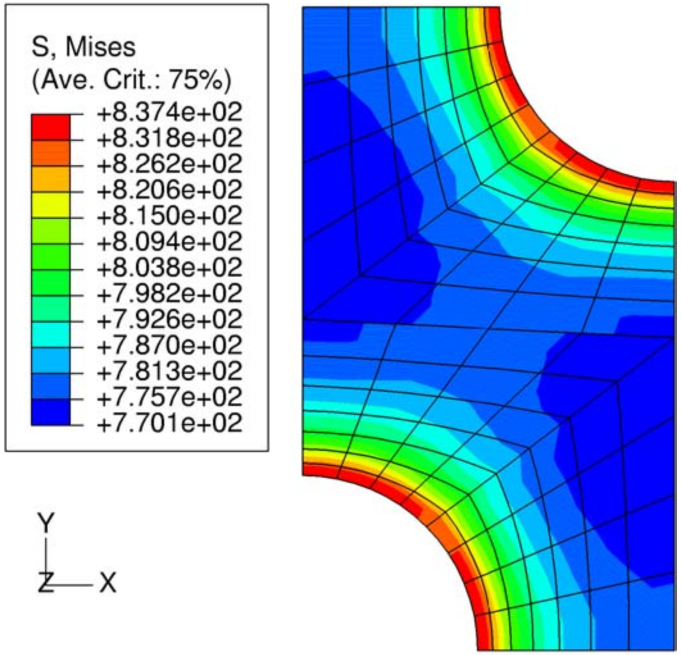
ND and FEM for W fiber ⇒ FEM, Load partitioning



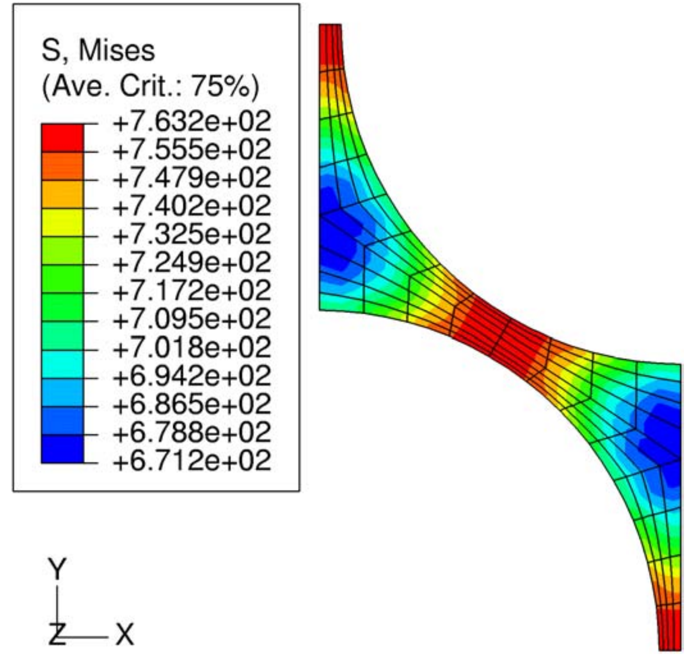


- Good agreement with measured data ⇒ Use the FEM to obtain information not measurable by neutron diffraction

Finite element model: Additional insights



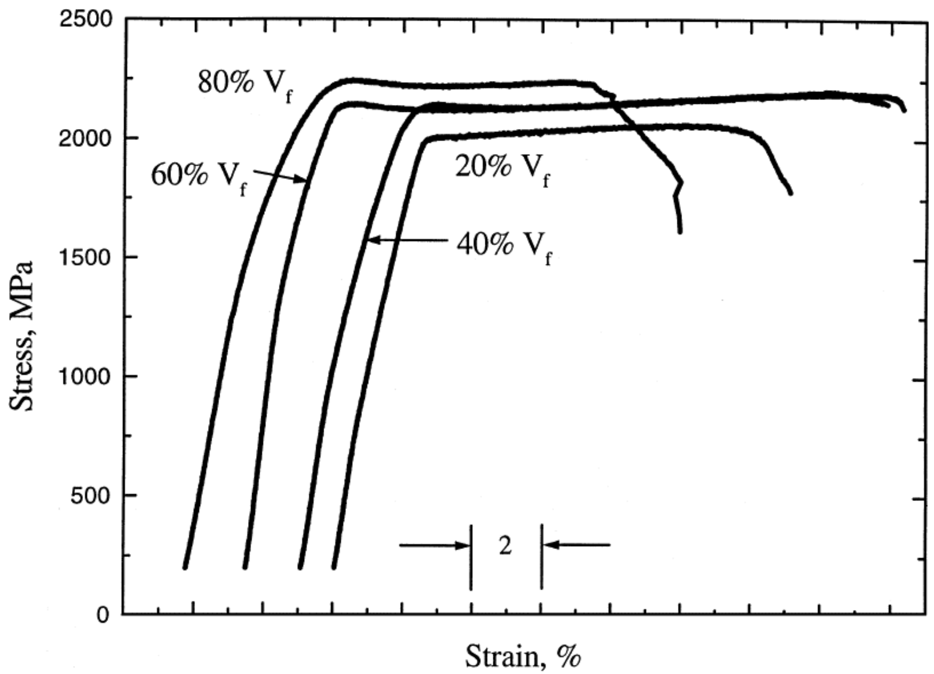
20% sample:
Von Mises stress, Matrix only



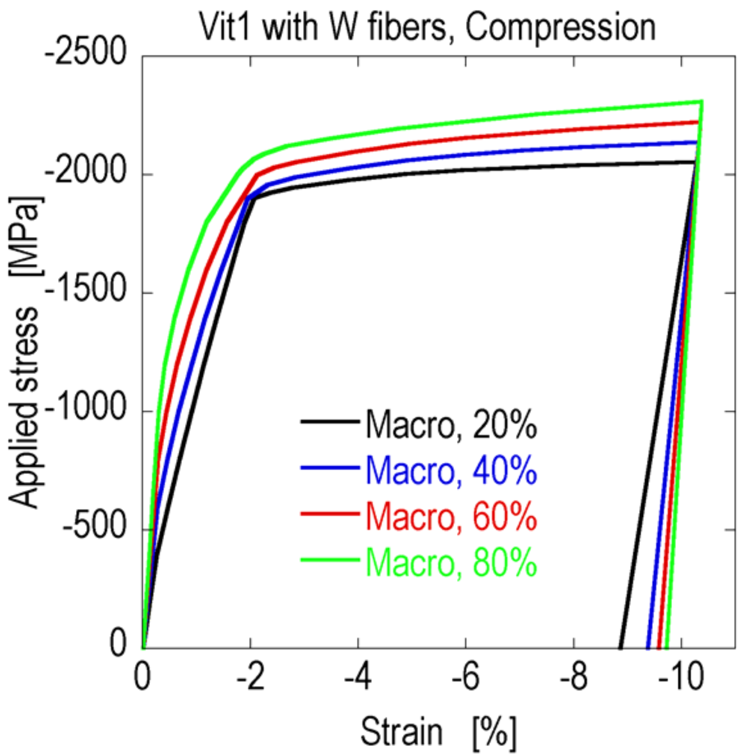
80% sample
Von Mises stress, Matrix only

- Von Mises stresses at highest load level (1000MPa for 20%, 1600MPa for 80%)
  - Stress concentration for the 80% - precursor for shear band formation
  - No appreciable variation of Von Mises stress in fibers (not shown)

Finite element model: Macroscopic yielding



Measured



Calculated (FEM)

- Calculated and measured macroscopic yielding
  - Capture the increase in yield point (knee) with increasing fiber volume fraction
  - Does not capture the perfect plastic behavior at high strains

R. D. Conner, R. B. Dandliker and W. L. Johnson, Acta Mater., vol. 46(17), pp. 6089-6102, 1998

Conclusions

- Combination of diffraction measurements and modeling (e.g. FEM) allows for the determination of internal and residual **stresses**
  - Even for the BMG, whereas neutron diffraction alone does does not provide any data for the glass

- Load sharing during uniaxial compression
  - Knee in macroscopic loading curves: Decrease in elastic strain development in the tungsten fibers clearly shows that the fibers are yielding

Future Work

- The ductility of the composites are linked to formation of multiple shear bands caused by the obstruction of the shear bands by the tungsten fibers
  - Planned studies of formation of multiple shear bands *in situ* in composites using synchrotron x-ray tomography

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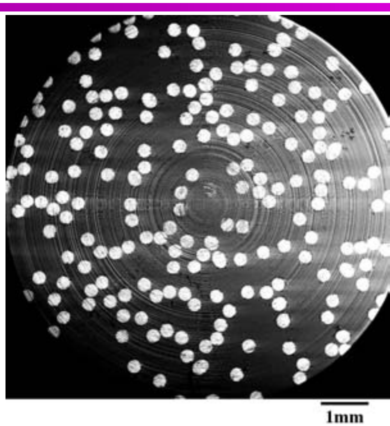
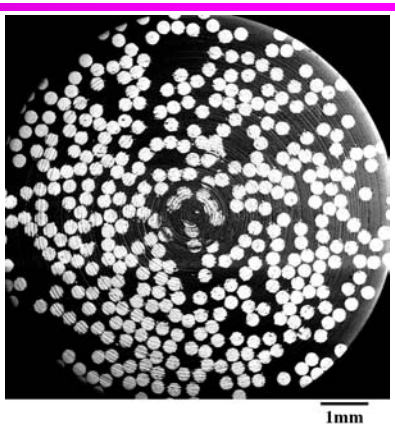
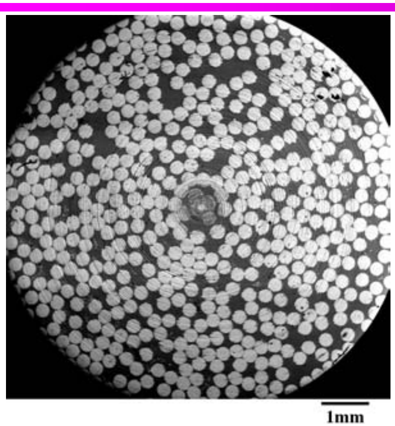
BMG matrix tungsten fiber composites



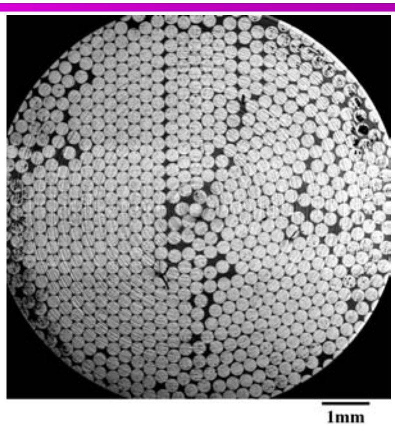
20% (21.0%)



40% (42.4%)



60% (61.9%)



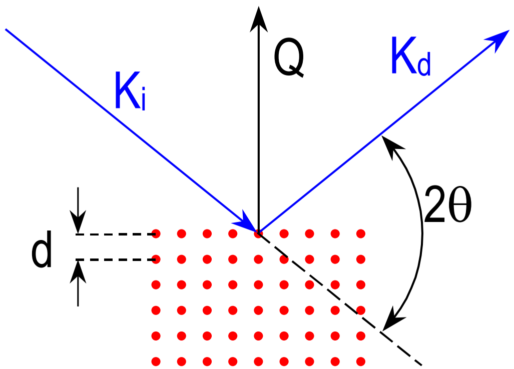
80% (84.2%)

- Measured volume fractions deviates slightly compared to nominal volume fractions
- “Agglomeration” seen for all volume fractions
- “Stacking faults” seen for the 80% sample

Neutron diffraction: Basics

$$\lambda = 2d\sin\theta$$

- Fixed λ; Reactor (steady state). Measure intensity as function of angle
- Fixed θ: TOF (spallation). Measure intensity as function of time-of-flight



- Differences in lattice spacing => Only Elastic Lattice Strain of Crystalline Phase

$$\varepsilon_{hkl}^{el} = \frac{d_{hkl} - d_{hkl}^{0}}{d_{hkl}^{0}} = \frac{d_{hkl}}{d_{hkl}^{0}} - 1$$

Finite element model input

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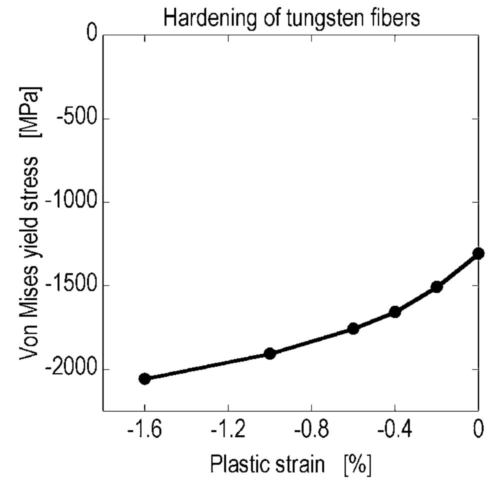

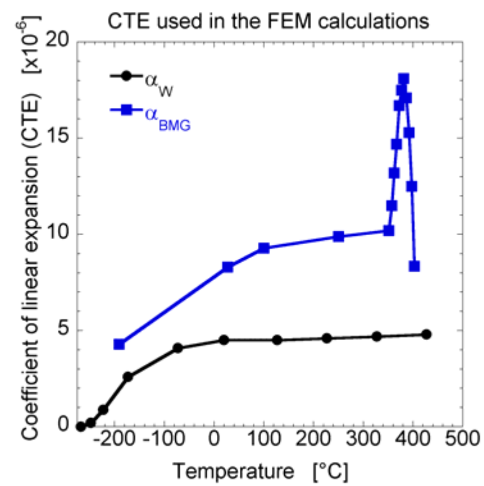

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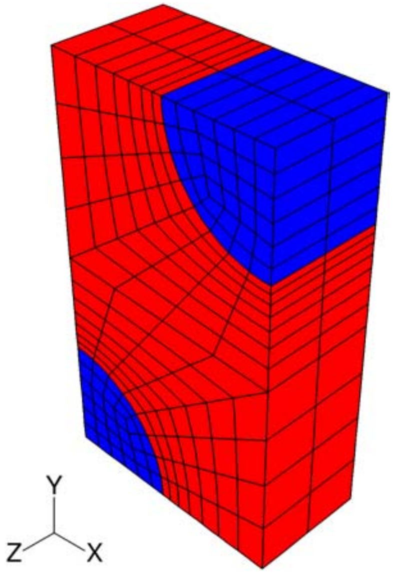
Finite element model

- Full 3D model due to loading along fibers
  - Plane strain by keeping planes perpendicular to fibers plane
  - Unit cell model
  - Brick 2nd order elements
- Hexagonal stacking in all models to accommodate high volume fractions
- Thermal cooling cycle
  - Choose ΔT (335°C) to give good comparison with measured thermal residual stresses
  - Same ΔT for all volume fractions
  - Close to T_g (350°C)



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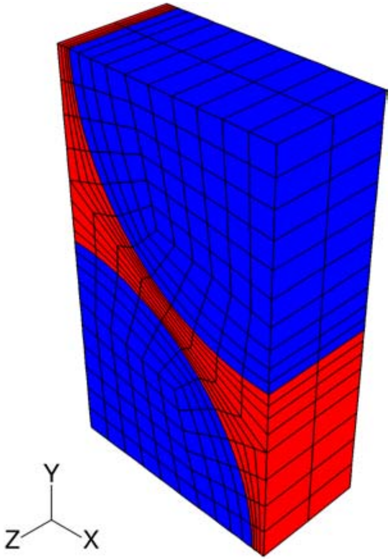

80% Mesh