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Deformation of Fiber Reinforced Bulk Metallic Glass Matrix Composites

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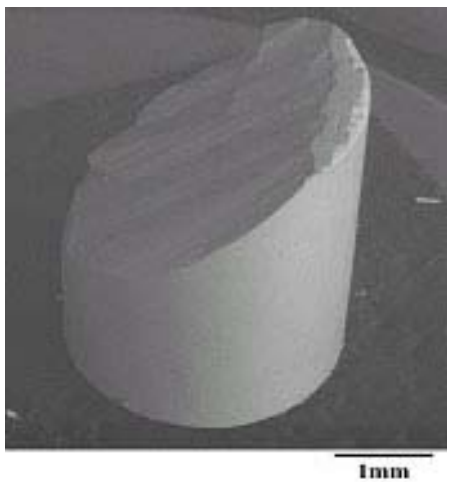
Outline

- BMG matrix fiber composites
  - Why BMG and why composites
- Neutron diffraction
  - Technique and capabilities
- Finite element modeling
  - Assumptions
- Results
- Conclusions

BMG matrix tungsten fiber composites

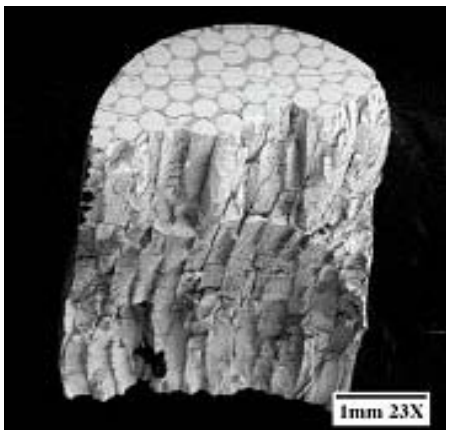
- Vitreloy 106: $Zr_{57}Nb_5Al_{10}Cu_{15.4}Ni_{12.6}$
  - Properties similar to maraging steel, except for the low ductility
    - Macroscopic shear bands cause catastrophic failure in unconstrained loading
  - Very high elastic limit (2%)
  - Good formability: BMG's can be processed thermomechanically into intricate components – like polymers – yet with much superior mechanical properties



	VascoMax C-250	Vitreloy 1
Young's Modulus	180 GPa	96 GPa
Poisson's Ratio	0.30	0.36
Compressive Yield Stress	1.93 GPa	1.9 GPa
Elongation	11%	2%
Fracture toughness (K_{IC})	98 MPa $m^{1/2}$	55 MPa $m^{1/2}$
Density	8.0 g/ccm	6.1 g/ccm

BMG matrix tungsten fiber composites

- BMG matrix fiber composites
  - Second phase interacts with shear bands and prevents formation of macroscopic shear bands that lead to catastrophic failure
  - This study: Molybdenum, Tantalum, Tungsten and Steel (SS302) fibers in Vitreloy 106 matrix ($Zr_{57}Nb_5Al_{10}Cu_{15.4}Ni_{12.6}$)
  - Large increase in ductility
    - Here shown for W and Steel Vitreloy 1 composites, Conner *et al*. Acta Mater. 1998



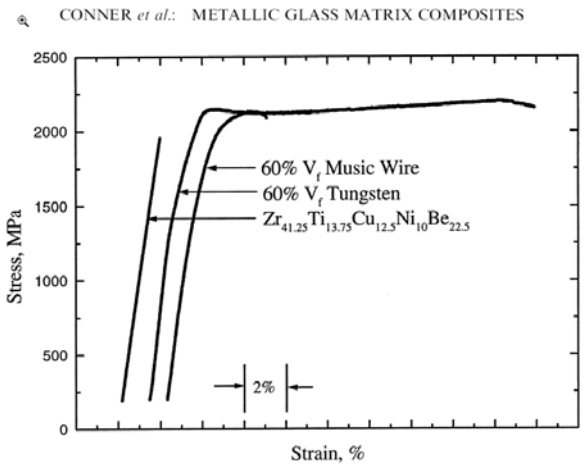
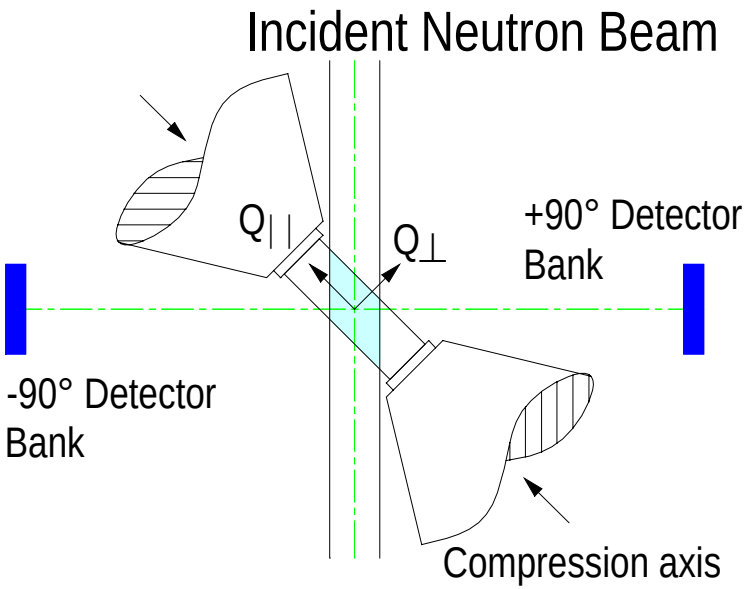


Fig. 16. Comparison of 40% V_f tungsten and steel reinforced metallic glass matrix composite compressive stress–strain properties. Ultimate strength is the same, and is not significantly different than unreinforced $Zr_{41.25}Ti_{13.75}Cu_{12.5}Ni_{10}Be_{22.5}$.

Neutron diffraction

Neutron diffraction

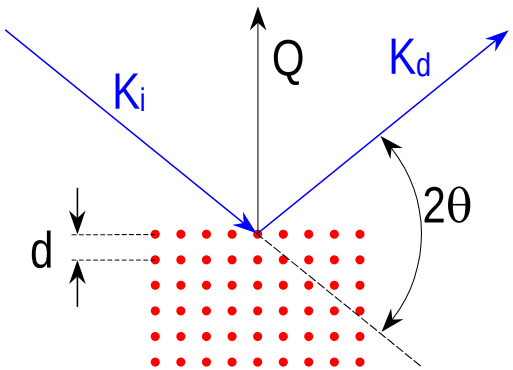


- Spectrometer for MAterials Research at Temperature and Stress (SMARTS)
- Schematic set-up for *in-situ* compression loading
  - Measurement time is about 10-20 minutes per load level
  - Measure elastic strains in two directions simultaneously

Neutron diffraction

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

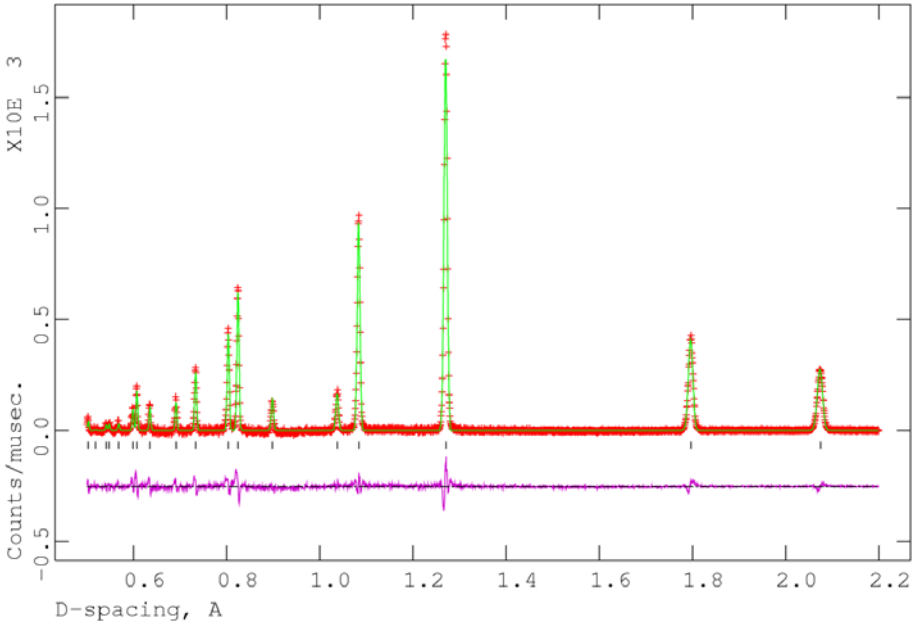
- Fixed λ; Reactor (steady state). Measure intensity as function of angle
- Fixed θ: TOF (spallation). Measure intensity as function of time-of-flight



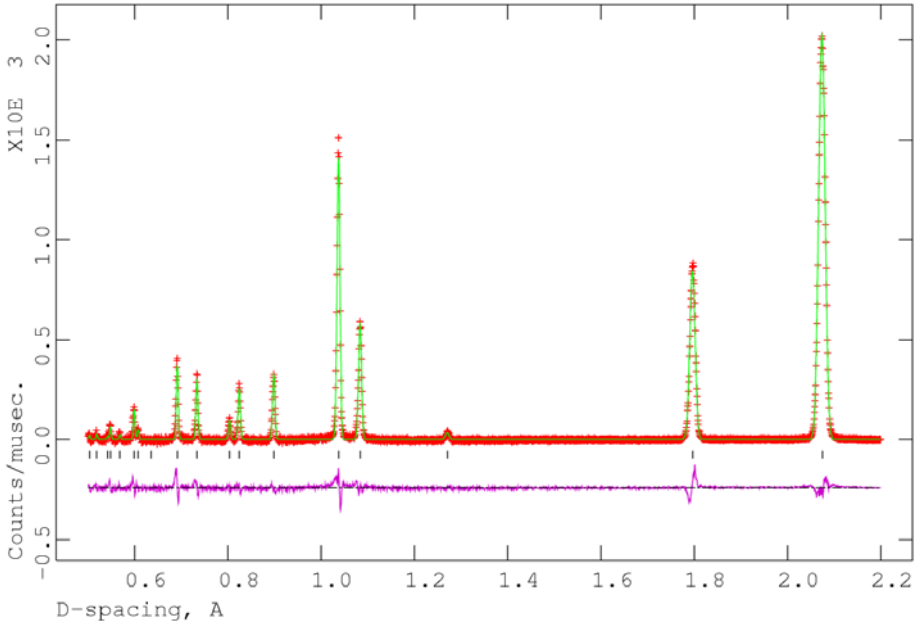
- Differences in lattice spacing $\Rightarrow$ Only Elastic Lattice Strain of Crystalline Phase

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

Neutron diffraction; Vitreloy 106/SS302



Perpendicular



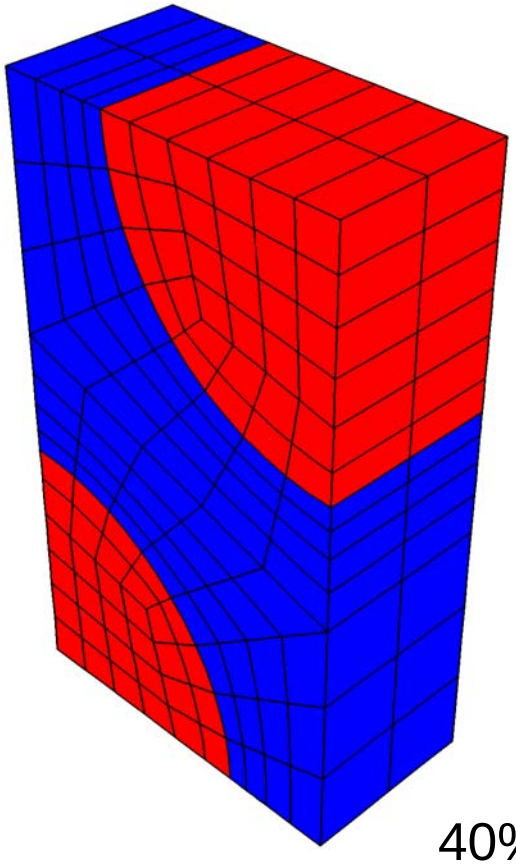
Parallel

- Diffraction pattern
  - Rietveld refinement. Lattice elastic mean phase strain.
  - Fit quality: Rwp = 6-8%, χ^2 = 2.4-3.1
  - Strong texture from wiredrawing of the fibers

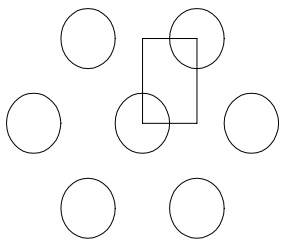
Finite element model

Finite element model

- Full 3D model due to loading along fibers
  - Unit cell model
  - Plane strain by keeping planes perpendicular to fibers plane
  - Brick 2nd order elements
- Hexagonal stacking in all models to accommodate high volume fractions
  - Same as used for high volume fractions
- Thermal cooling cycle
  - A ΔT of 380°C, i.e. from the glass transition temperature of Vitreloy 106 to room temperature, have been used in all calculations



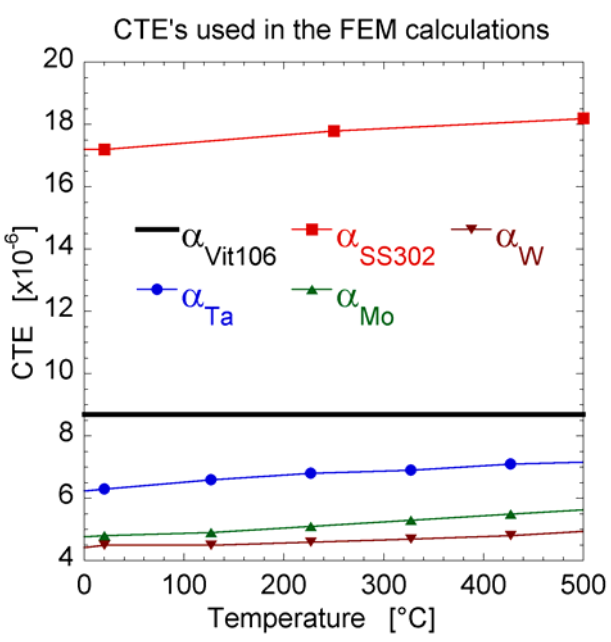
40% Mesh



Samples

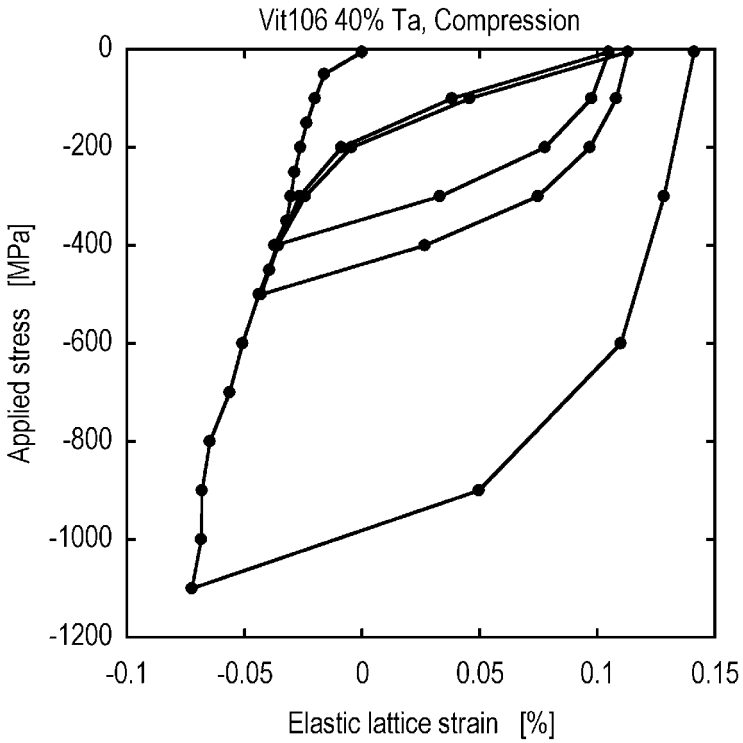
- Vitreloy 106 with 40% Tantalum fibers
  - $CTE_{Ta} < CTE_{Vit106}$
  - $E_{Ta}/E_{Vit106} = 2.2$
- Vitreloy 106 with 40% SS302 fibers
  - $CTE_{SS302} > CTE_{Vit106}$
  - $E_{SS302}/E_{Vit106} = 2.5$
- Vitreloy 106 with 40% Molybdenum fibers
  - $CTE_{Mo} < CTE_{Vit106}$
  - $E_{Mo}/E_{Vit106} = 3.9$
- Vitreloy 06 with 40% Tungsten fibers
  - $CTE_{W} < CTE_{Vit106}$
  - $E_{W}/E_{Vit106} = 4.8$

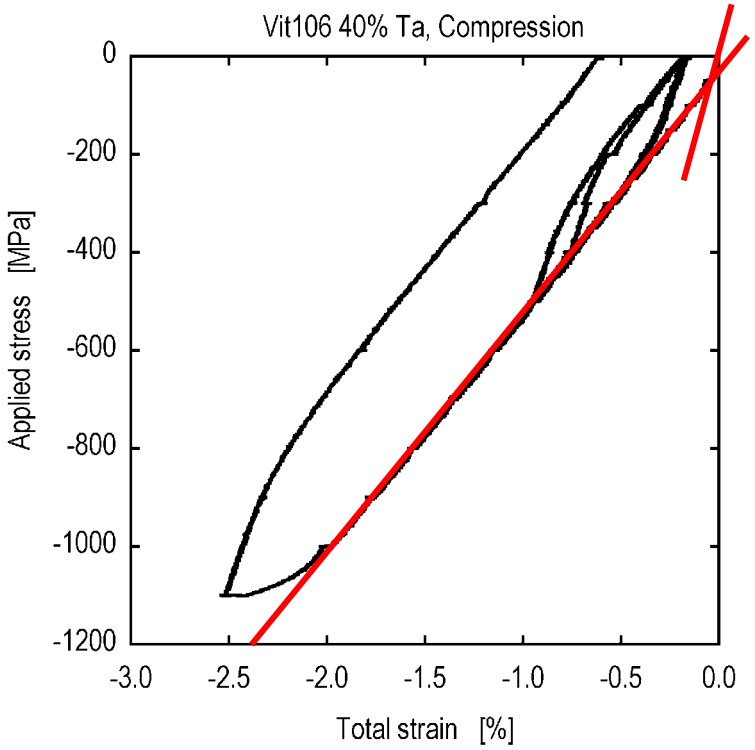
Material	E [GPa]	ν [-]	CTE [10^{-6}]
Vit106	85	0.38	8.7
Ta	186	0.34	6.3 – 7.2
SS302	211	0.29	17.2 – 18.4
Mo	329	0.31	4.8 – 5.7
W	411	0.28	4.5 – 5.0



Results; Measurements

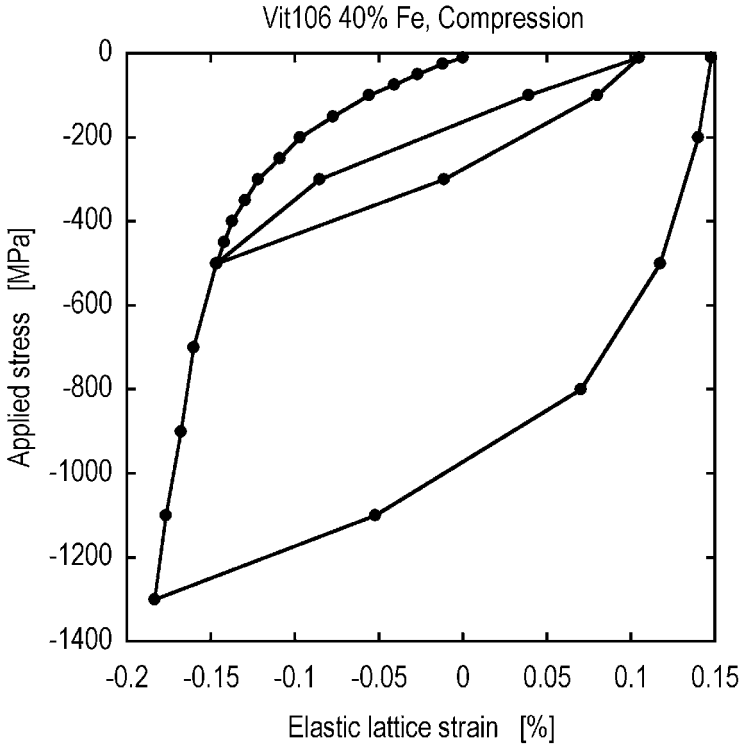
Results; Measured data. BMG/Ta

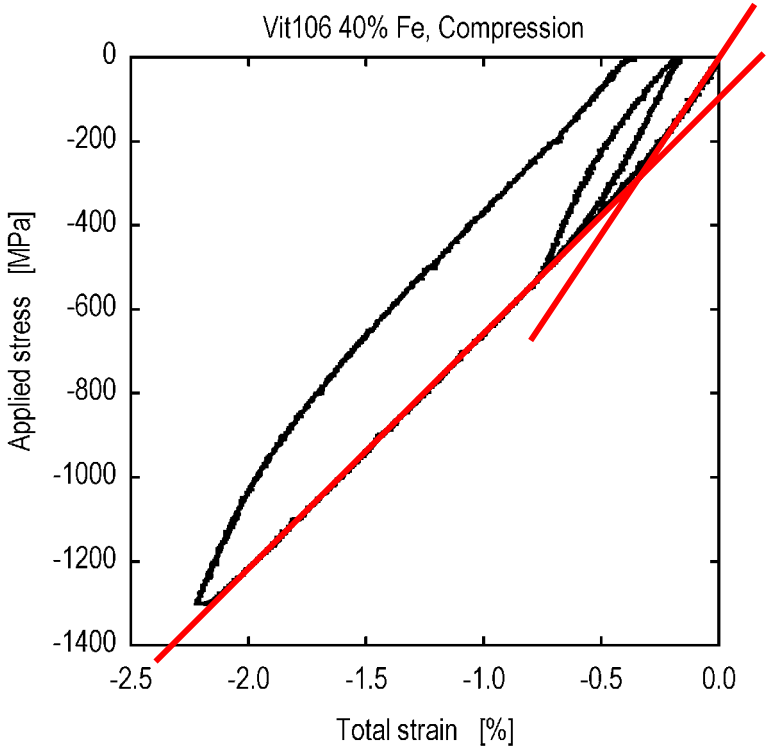




- Macro curve looks linear from the start, indicating elastic loading
- However, ND data clearly show plastic deformation in fibers from the start
- Large hysteresis loops due to reverse yielding upon unloading

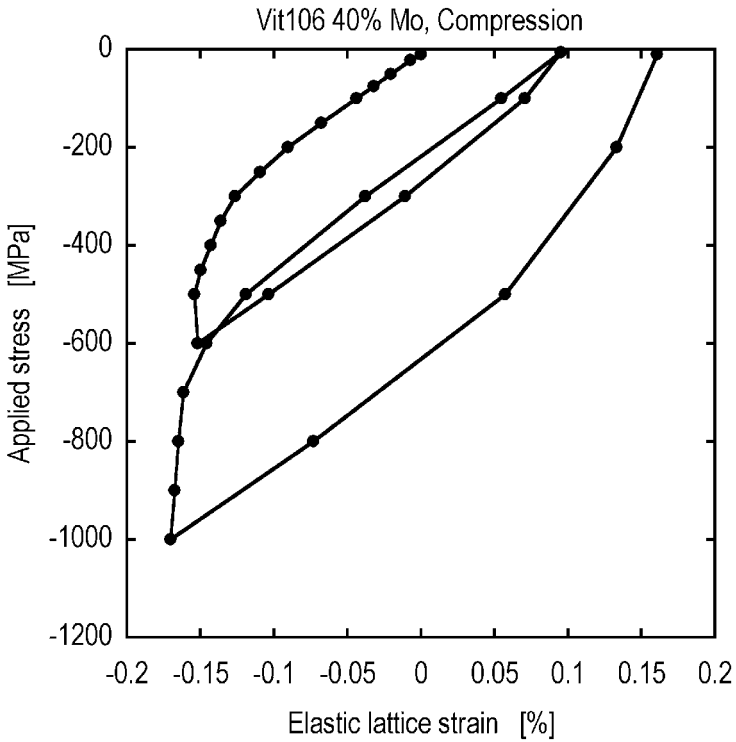
Results; Measured data. BMG/SS302

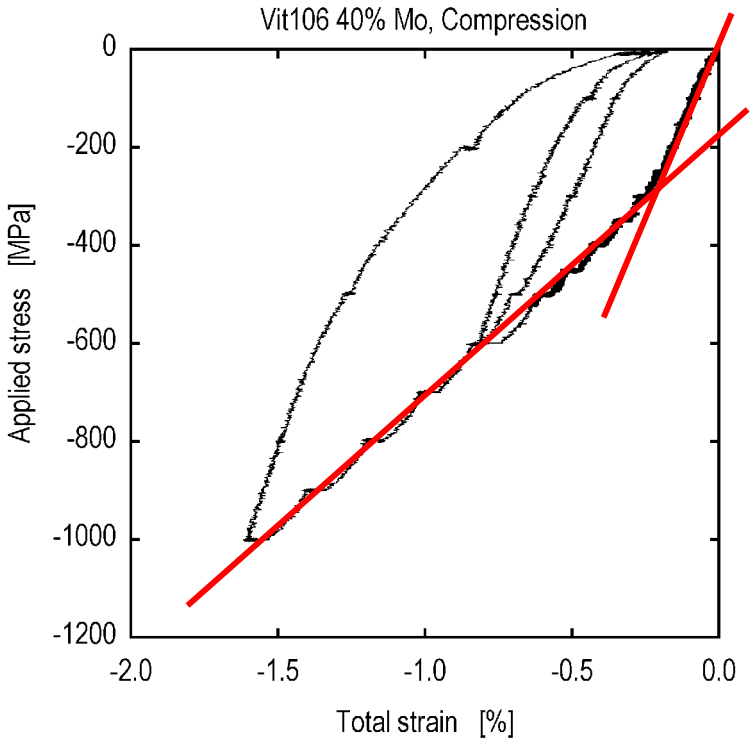




- Linear elastic region up to about 200 MPa
  - Elastic region expected to be larger due to the tensile residual stresses in fibers
- Large hysteresis loops due to reverse plasticity upon unloading

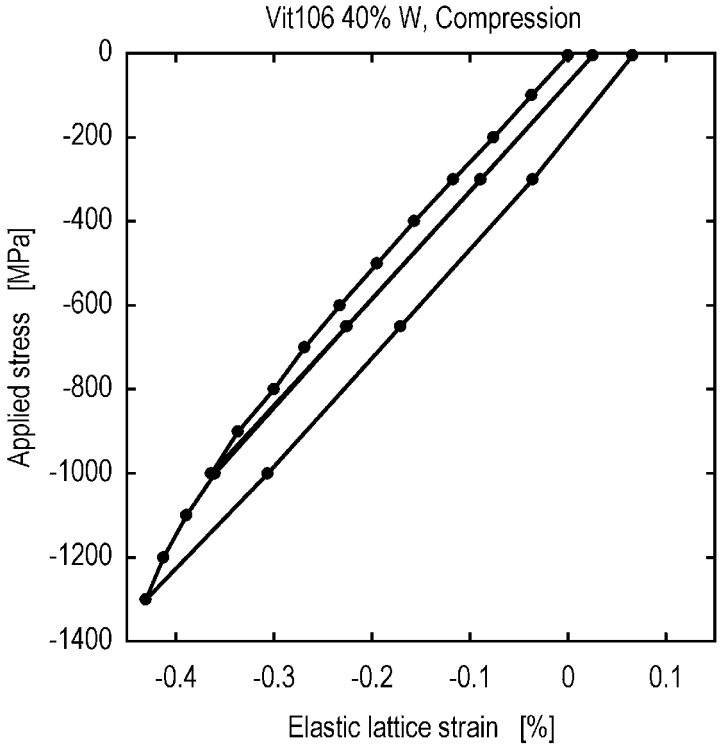
Results; Measured data. BMG/Mo

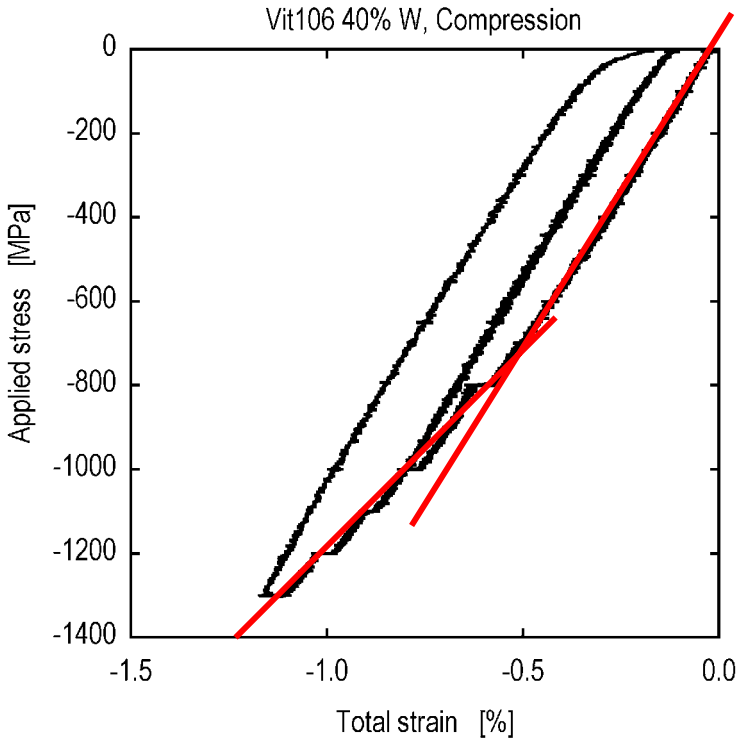




- Similar to SS302
- More pronounced time dependent relaxation during ND measurements
- Large hysteresis loops due to reverse plasticity upon unloading

Results; Measured data. BMG/W

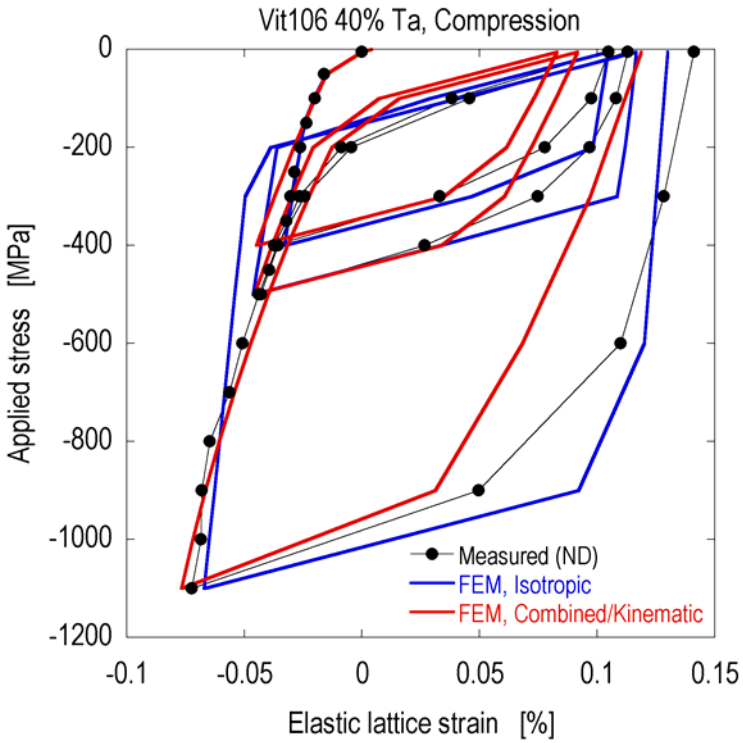


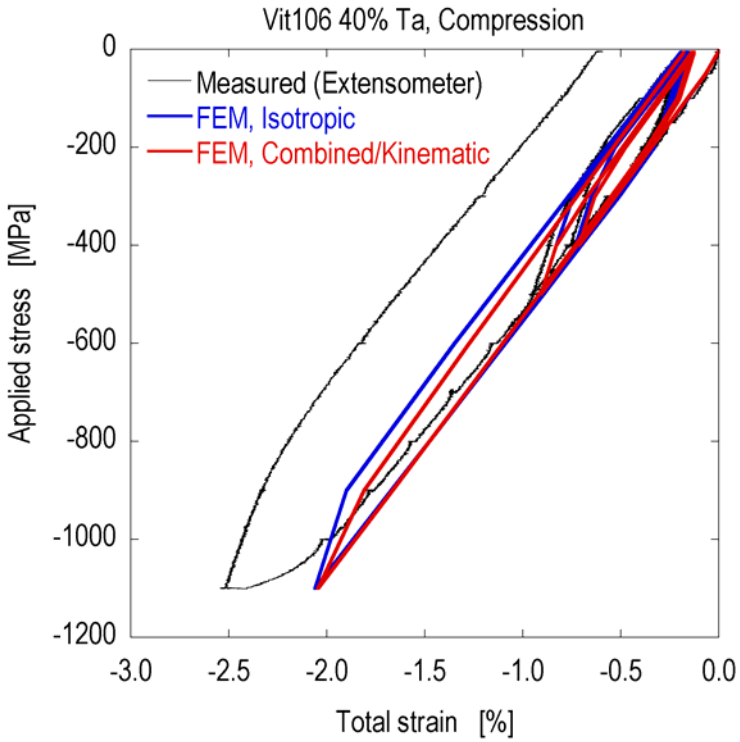


- Larger elastic region
- Visible time dependent relaxation during ND measurements from 800MPa
- Linear unloading
  - Ambiguity at 2nd unload – only a hint of nonlinearity in neutron data

Results; FEM

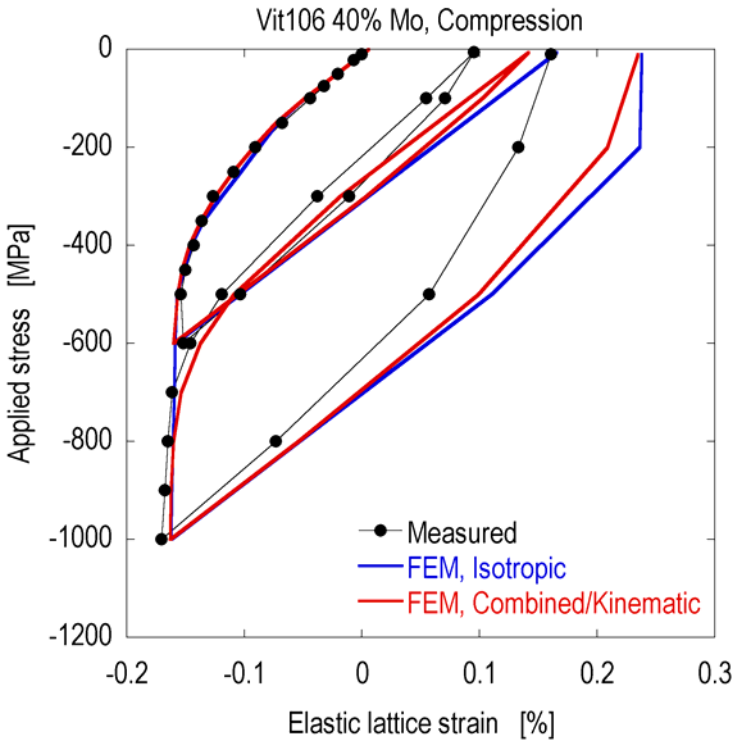
Results; FEM of 40% Ta fiber composite

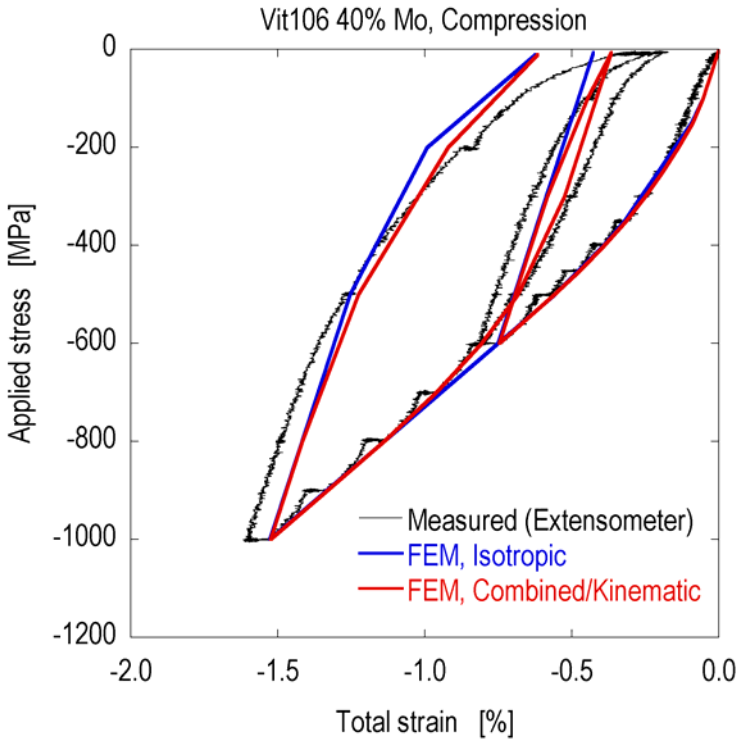




- Reasonable agreement with fiber elastic strain data (neutron diffraction data)
  - Hardening in fibers during unloading leads to step upon reloading
- The calculated macroscopic data does not show as much plasticity as measured
  - Difference in plastic slope and macroscopic yield point

Results; FEM of 40% Mo fiber composite





- Good agreement with the loading part of the elastic strain data
  - Bauschinger effect underestimated by the models, even using kinematic hardening
- Macroscopic data (extensometer) in good agreement with the loading part
  - Time dependent relaxation at high loads not included in the model

Conclusions

- Experimental
  - 10-20 minute count times gives adequate statistics
  - Very different macroscopic behavior and load sharing depending on fiber material
    - Full reverse plasticity in fibers upon unloading (Ta, SS302, Mo)
  - Time dependent relaxation during ND measurements at constant stress
    - More pronounced for the BCC fibers (Ta, Mo, W)
- Modeling
  - FEM is struggling to match measured macro and phase data
    - Much better agreement between FEM and neutron measurements was previously found for Vitreloy 1/W fiber composites
    - Neither isotropic or kinematic hardening can accurately account for the observed large reverse plasticity upon unloading.
  - No time dependent mechanisms included in model

Future work

- Including deformation mechanisms in the BMG
  - Shear band formation (Ortiz *et al.*)
- Better description of reverse plasticity in fibers
  - Possibility of geometrical effects from fiber bending/buckling
- Measurements of residual stresses
  - BMG/SS302 sample did not show large elastic region as expected from tensile residual stresses in fibers. Relaxation?
- Determine what phase is relaxing at high loads
  - Relaxation seen in all composites, but at different rates.
- PDF study to measure strains directly in BMG
  - Total scattering analysis, nearest neighbor peaks changes