Mechanical Behavior of *In-Situ*-Formed Bulk Metallic Glass Matrix Composites

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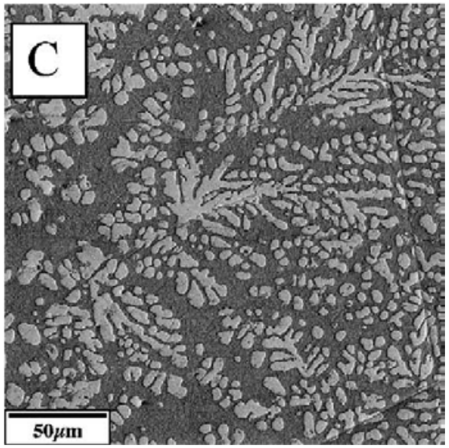
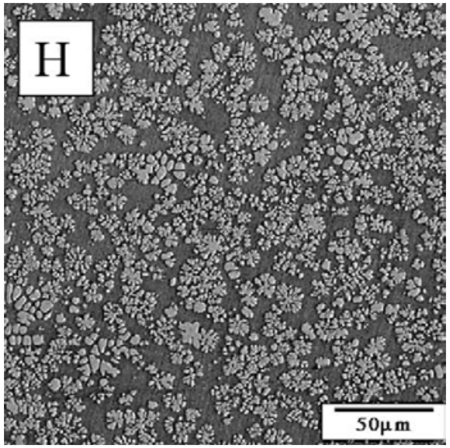
Outline

- *In-situ*-formed BMG matrix composites
- Neutron diffraction
- Self-consistent modeling
- Results
- Conclusion

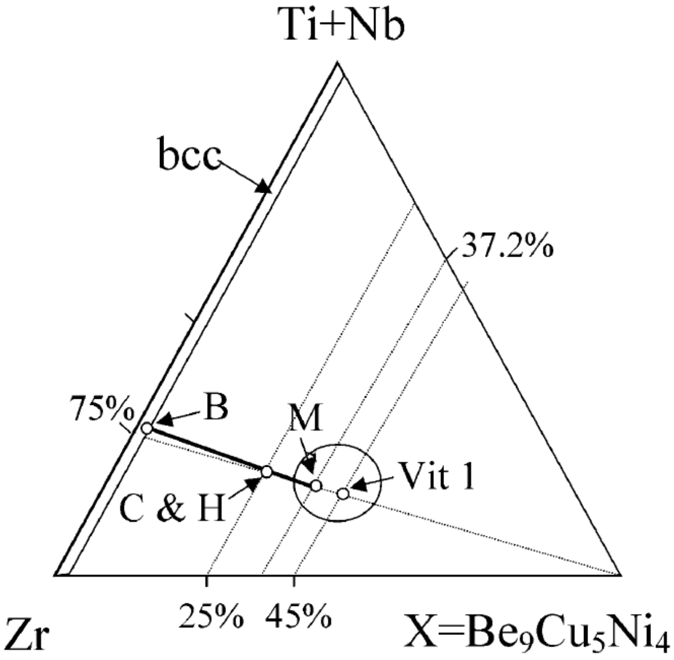
In-situ-formed BMG matrix composites



Caltech



Howmet Corp.

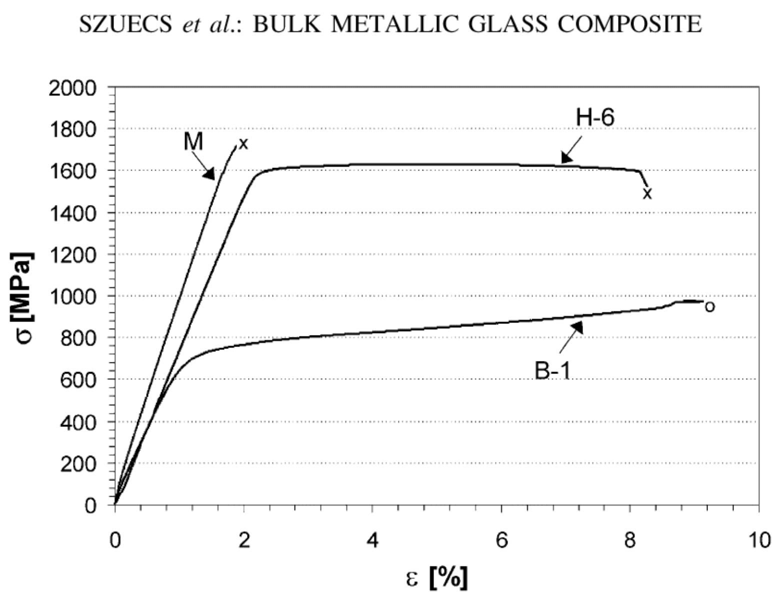


- Total: $Zr_{56.2}\,Ti_{13.8}\,Nb_{5.0}\,Cu_{6.9}\,Ni_{5.6}\,Be_{12.5}$
  - Matrix: $Zr_{47}\,Ti_{12.9}\,Nb_{2.8}\,Cu_{11}\,Ni_{9.6}\,Be_{16.7}$
  - β Phase: $Zr_{71}\,Ti_{16.3}\,Nb_{10}\,Cu_{1.8}\,Ni_{0.9}$
  - About 25% volume fraction β phase

F. Szuecs, C. P. Kim and W. L. Johnson, Acta Mater. Vol. 49, 1507-1513, 2001

Mechanical properties of the BMG composites

- Monolithic BMG fails catastrophic due to formation of macroscopic shear bands
- Monolithic β phase is very ductile but has a lower yield strength
- The in-situ composite show almost the same yield strength as the monolithic BMG, but it is ductile
- Load sharing and transfer in composite
  - Origin of increased ductility?
  - Phase transformation from BCC to HCP



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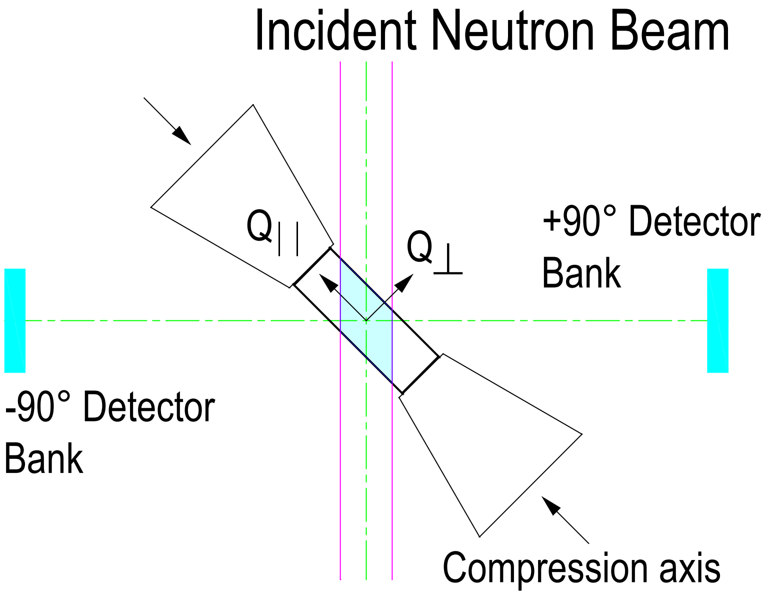
Neutron diffraction

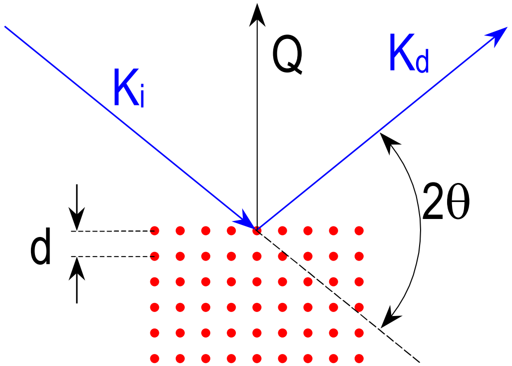


- Neutron Powder Diffractometer (NPD) at LANSCE
- Schematic set-up for *in-situ* compression loading measurements
- Measurement time is about 2 hours per load level
- Measure elastic strains in two directions simultaneously
- Bulk measurements contrary to conventional X-ray measurements

Neutron diffraction

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

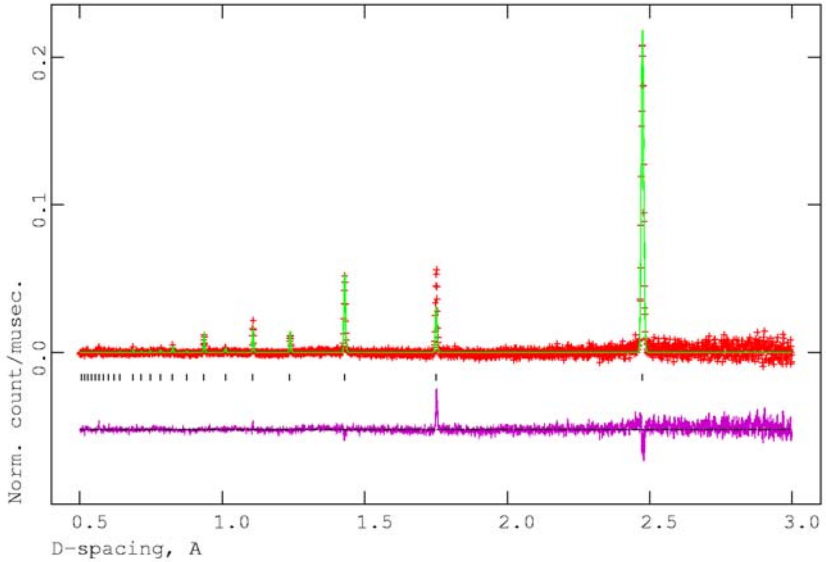
- Fixed λ; Reactor (steady state). Measure intensity as function of angle
- Fixed θ: TOF (spallation). Measure intensity as function of time-of-flight



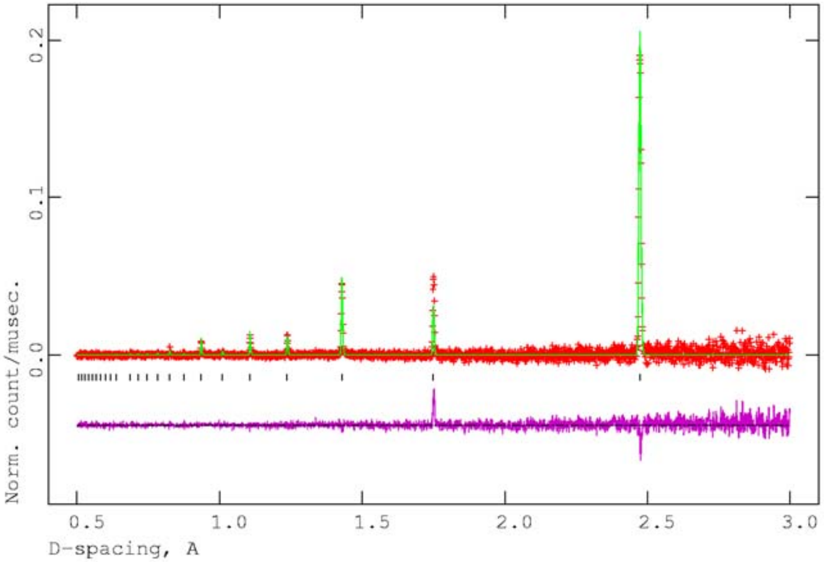
- Differences in lattice spacing => Only Elastic Lattice Strain of Crystalline Phase

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

Monolithic β-phase sample



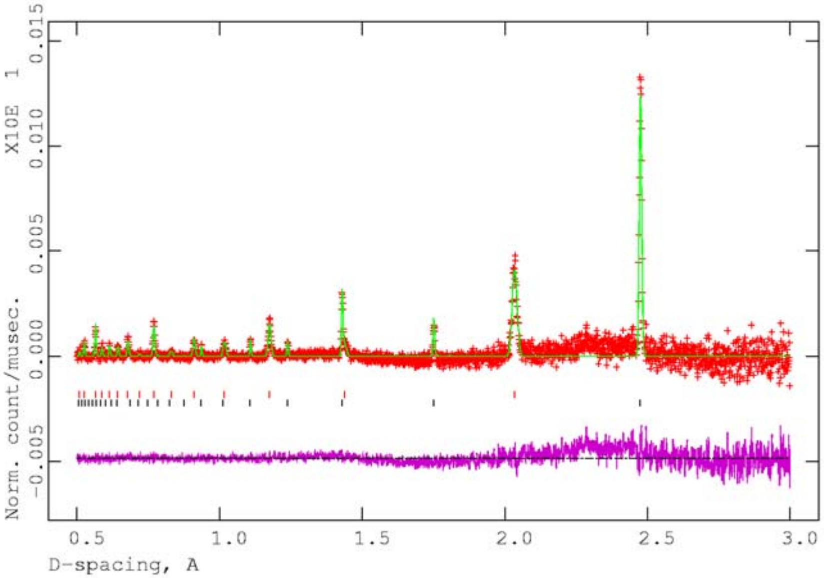
Parallel



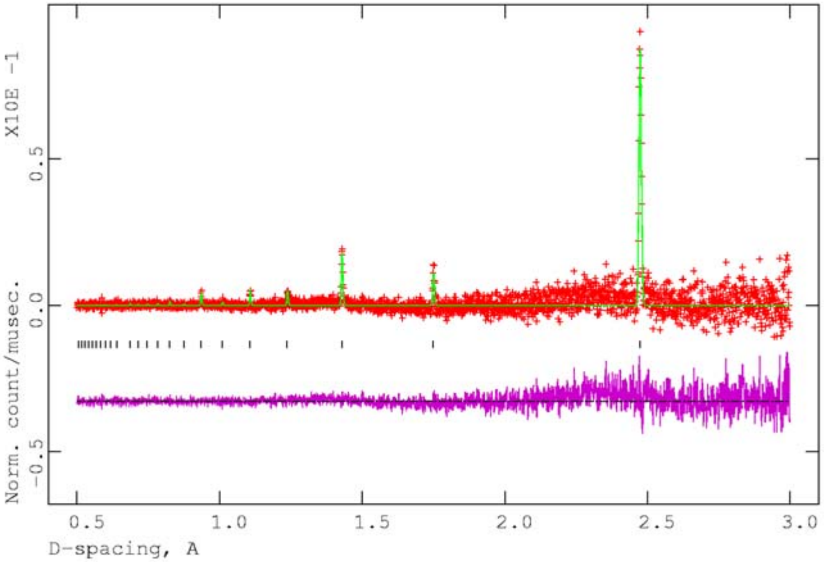
Perpendicular

- Diffraction patterns from monolithic β-phase sample (BCC)
  - Negligible texture
- $R_{wp} \approx 8$ - 9%, strain error bar $\approx 20\ \mu\varepsilon$ (40 - 85 $\mu\varepsilon$ for single peak fits)

BMG/β-phase sample



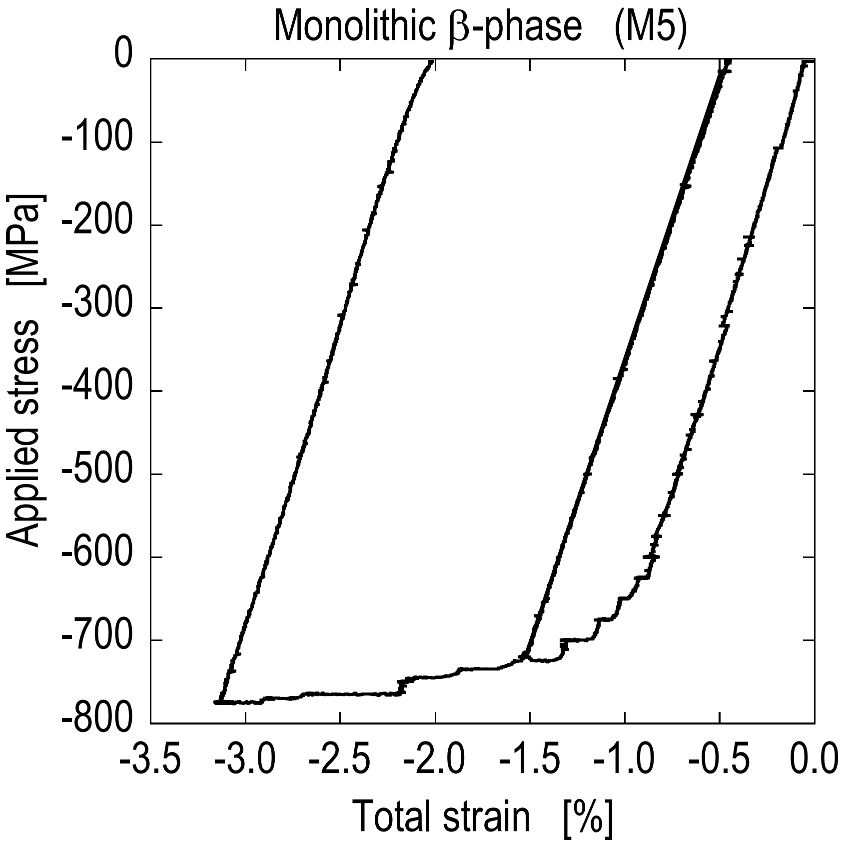
Parallel

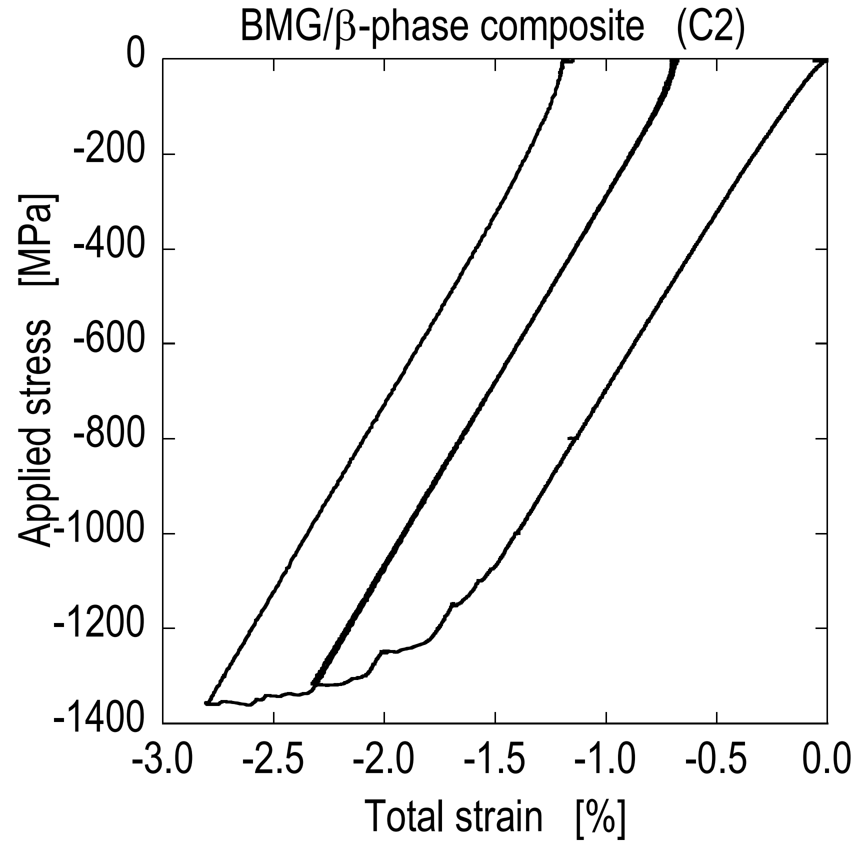


Perpendicular

- Diffraction patterns from BMG/β-phase composite sample
  - Negligible texture
- Steel peaks due to short sample - only in the parallel data (red tick marks)
- $R_{wp} \approx 7$ - 10%, strain error bar $\approx 30\ \mu\varepsilon$ (50 - 200 $\mu\varepsilon$ for single peak fits)

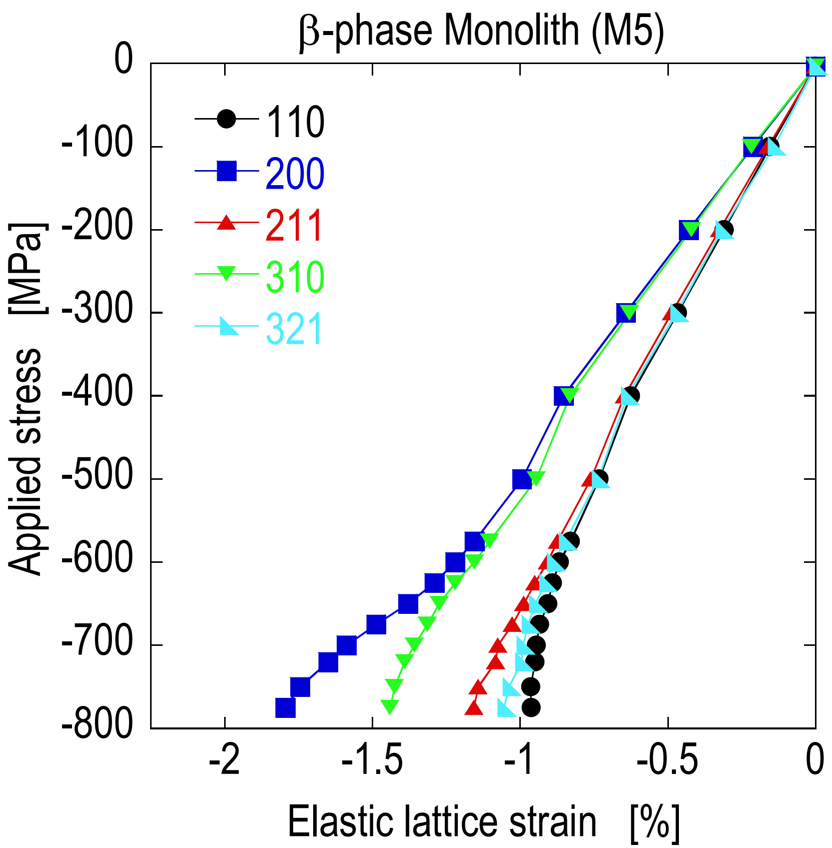
In-situ loading measurements

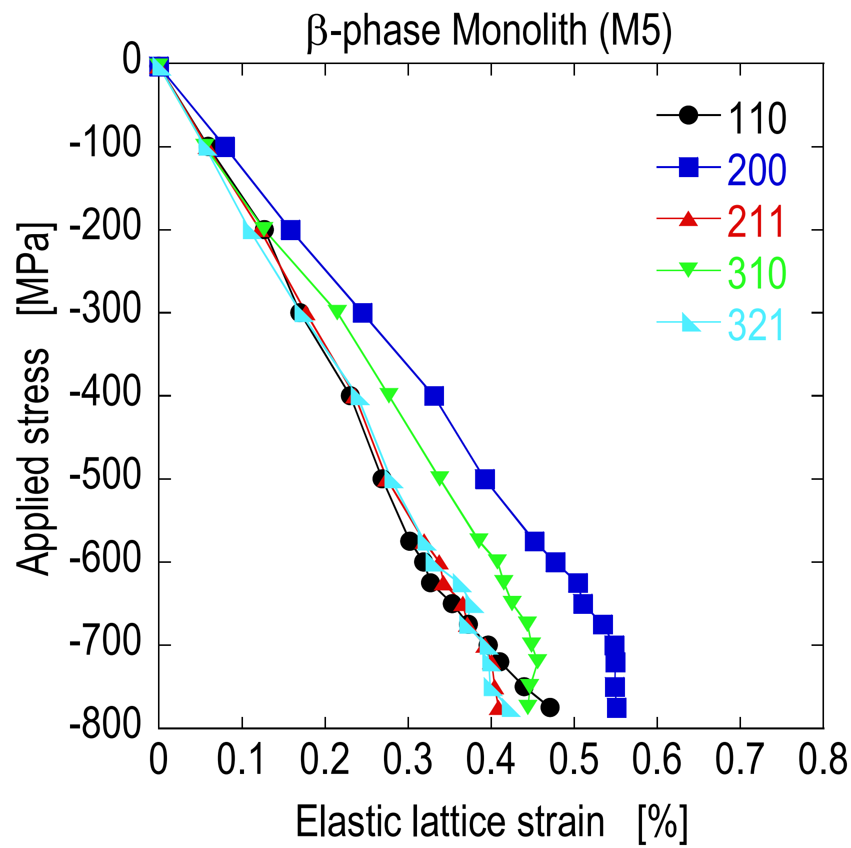




- 2 unloads per sample
- “Flat spots” where stress kept constant for neutron measurement

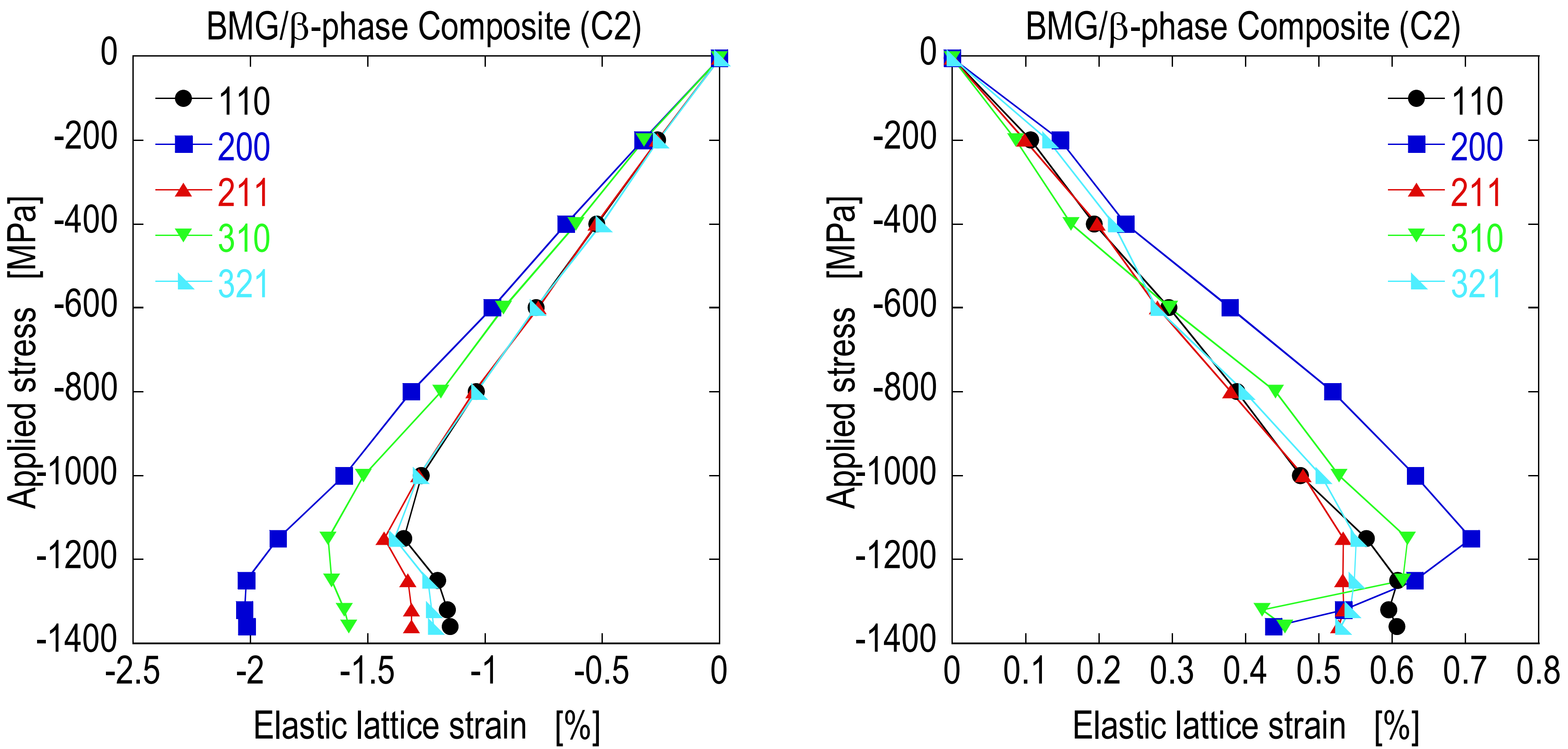
Measured lattice strains, monolithic β phase sample





- Large elastic anisotropy
- 110, 211 and 321 are elastically identical, but after yield they split up due to the plastic anisotropy

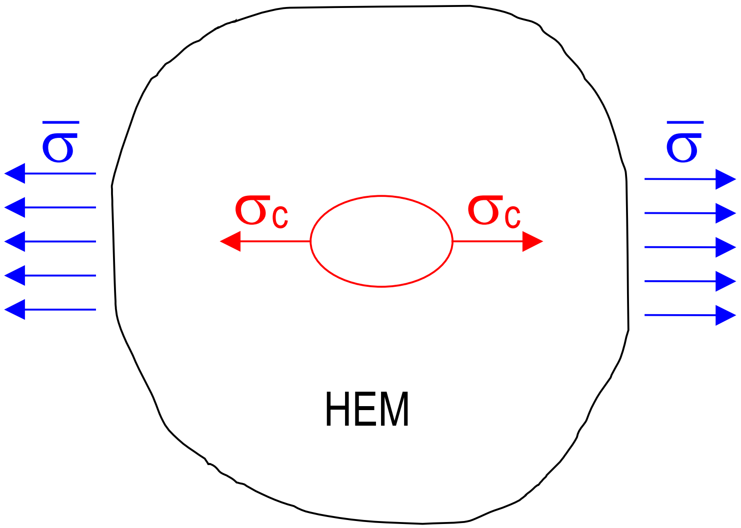
Measured lattice strains, composite sample



- Large elastic anisotropy
- The β phase behaves perfectly plastic in the composite
  - Vertical after yield in the glass

Self-consistent model (Eshelby)

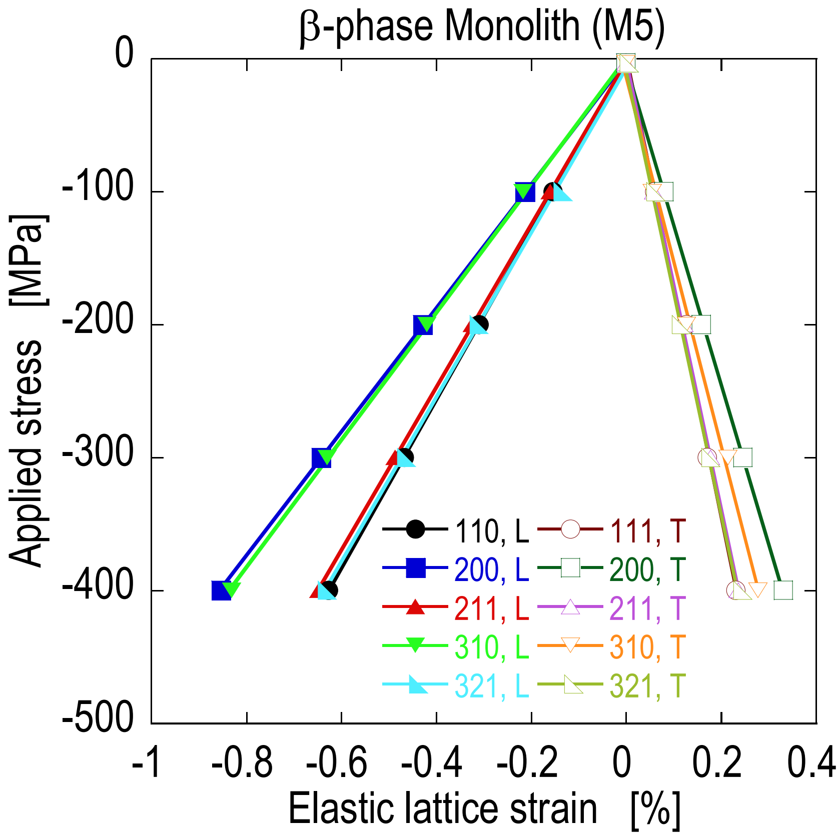
- Model Assumptions
  - Eshelby inclusion theory
  - Homogeneous equivalent medium (HEM) with properties equal to the appropriate weighted average of all the grains (inclusions)



- Input
  - Single crystal stiffnesses and hardening behavior
- Output
  - Direct comparison with neutron diffraction measurements
  - Averages over grains sets representing reflections
  - Information about material behavior on a microscopic scale

Self-consistent model (Eshelby)

- Determine single crystal stiffnesses from diffraction data
- Call SCM from least squares refinement routine
- Use values calculated from E and ν assuming isotropy as initial guess



C_{11} = 92±2

C_{12} = 70±2

C_{44} = 33±1

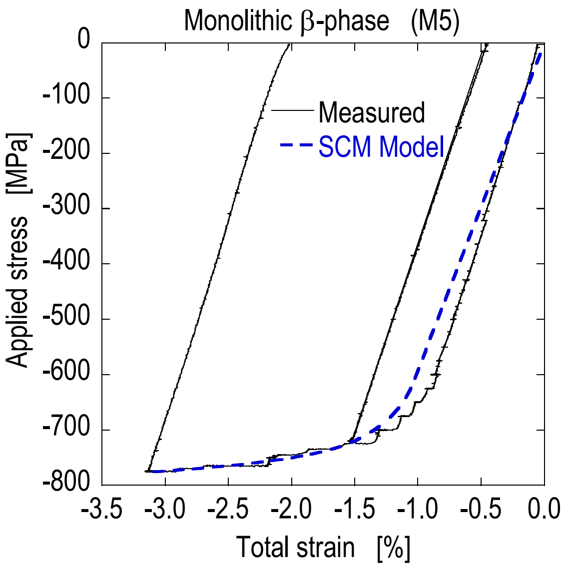
Anisotropy factor = 3.0

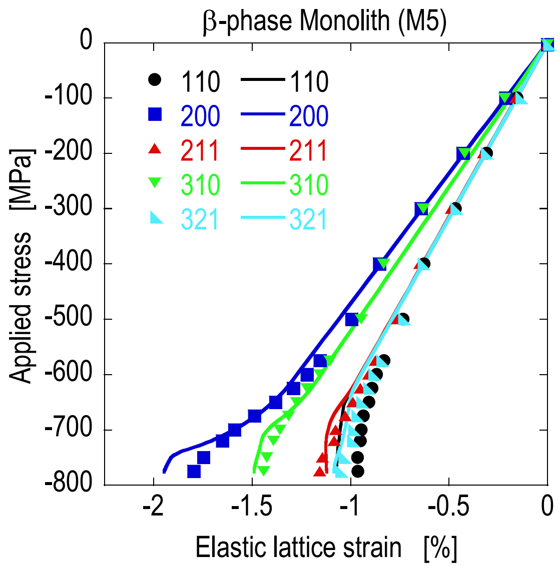
Young's modulus = 59±3 GPa (63.3)

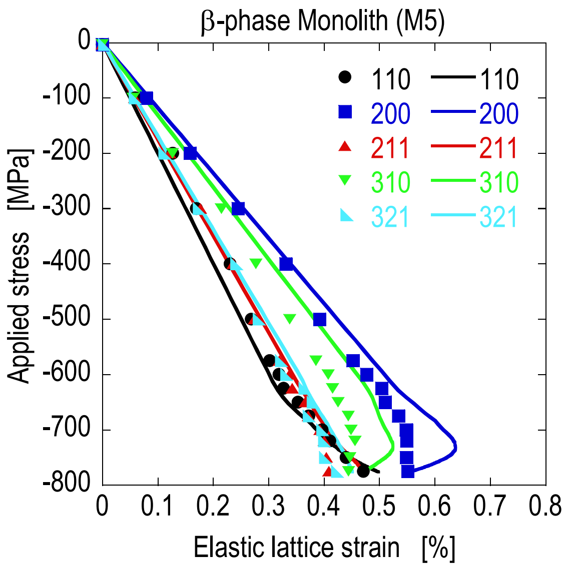
Poisson's ratio = 0.37±0.02 (0.401)

F. Szuecs, C. P. Kim and W. L. Johnson, Acta Mater. Vol. 49, 1507-1513, 2001

Model comparison, β phase monolith

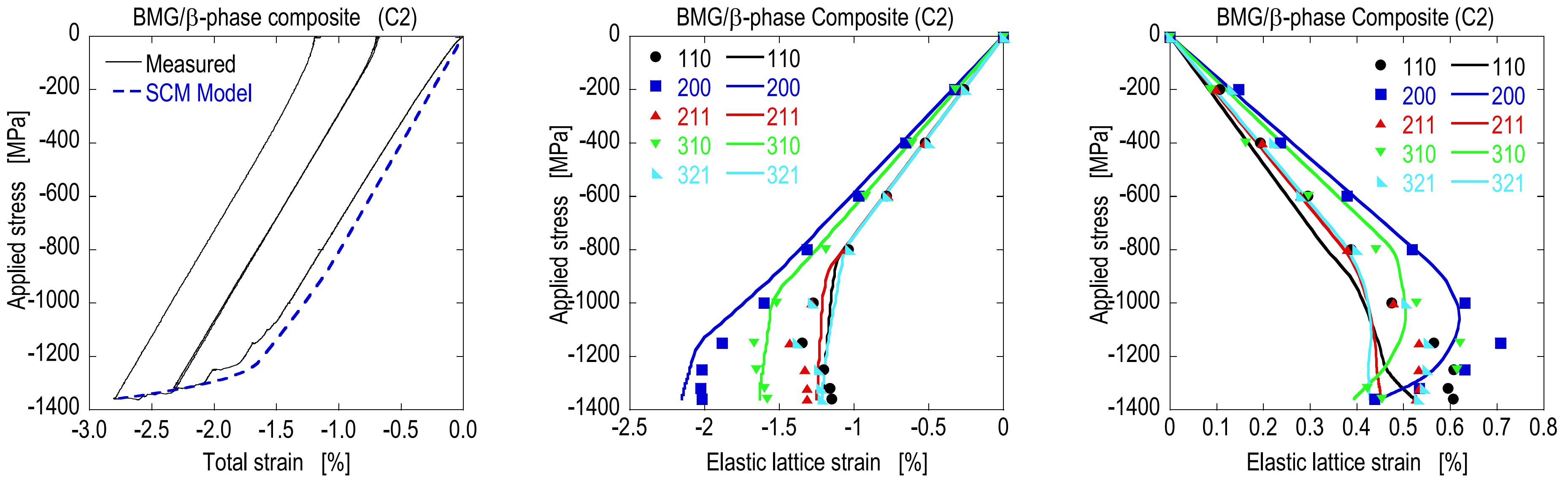






- Ensure good agreement macroscopically
  - Choose yield stress. Hardening set to zero
- Also good agreement for lattice strains
  - Elastic stiffnesses show accurate determination of single crystal stiffnesses

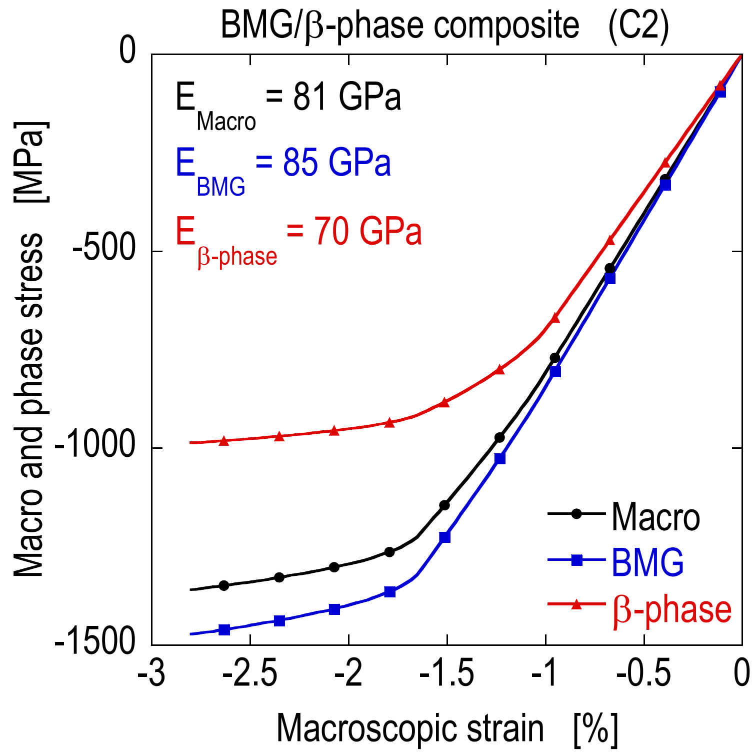
Model comparison, BMG/β phase composite



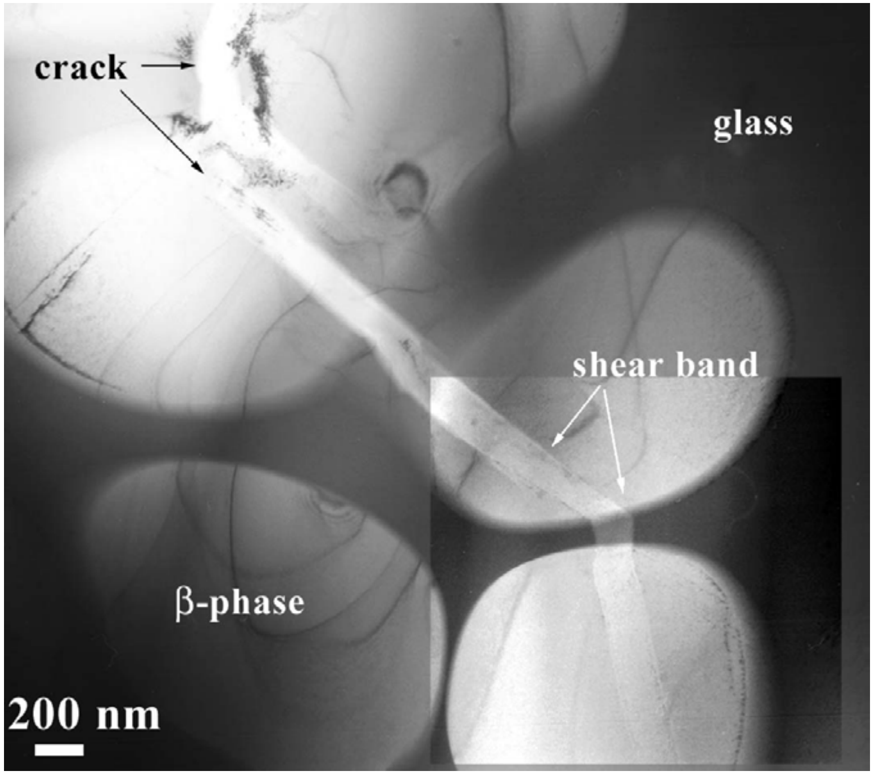
- Ensure good agreement macroscopically
  - Choose yield stress for BMG. Hardening set to zero for both phases
- Model captures the “perfectly plastic” behavior of the β phase after yield in the BMG parallel to the loading direction

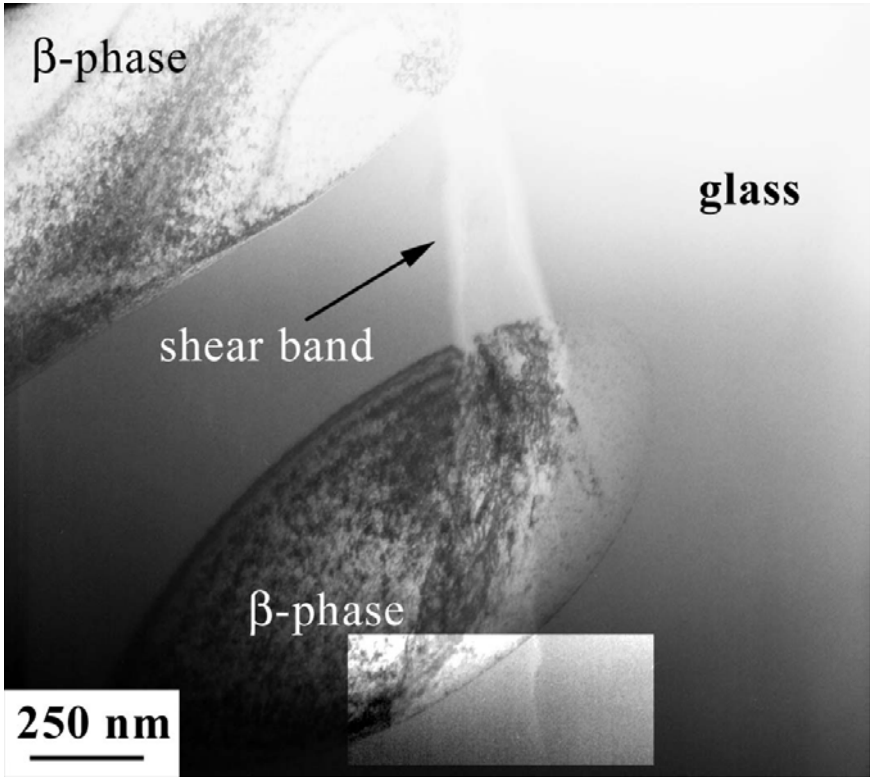
BMG/β phase composite

- Calculated in-situ yield strength (Von Mises phase stress at yield)
  - Matrix: 1340 MPa
  - β phase: 670 MPa
- Measured monolithic yield strength
  - Matrix: 1700 MPa
  - β phase: 600 MPa



TEM of BMG/β phase composite





- Multiple shear bands
- Shear bands penetrate β phase

E. Pekarskaya, C. P. Kim, and W. L. Johnson, J. Mater. Res., vol. 16(9), pp. 2513-2518, 2001

Conclusions

- Indirectly determine the mechanical behavior of the BMG matrix
  - The in-situ yield stress of the matrix is lowered to 1340 MPa compared to the monolithic yield stress of 1700 MPa
  - In-situ yield stress of the β phase is 670 MPa compared to 600 MPa for the monolith
- Yielding initially in the β phase
  - Initiates multiple shear bands in glass that penetrates β phase
  - Improved ductility over the monolithic BMG
- No evidence of phase transformation in β phase
- Single crystal stiffnesses from diffraction data using SCM
  - Relatively strong elastic anisotropy in the β phase