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: $\text{Zr}_{56.2} \text{Ti}_{13.8} \text{Nb}_{5.0} \text{Cu}_{6.9} \text{Ni}_{5.6} \text{Be}_{12.5}$
  - Matrix: $\text{Zr}_{47} \text{Ti}_{12.9} \text{Nb}_{2.8} \text{Cu}_{11} \text{Ni}_{9.6} \text{Be}_{16.7}$
  - $\beta$ Phase: $\text{Zr}_{71} \text{Ti}_{16.3} \text{Nb}_{10} \text{Cu}_{1.8} \text{Ni}_{0.9}$
- About 25% volume fraction $\beta$ phase

Mechanical properties of the BMG composites

- Monolithic BMG fails catastrophic due to formation of macroscopic shear bands
- Monolithic $\beta$ 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

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

\[ \lambda = 2dsin\theta \]

- Fixed \( \lambda \); Reactor (steady state). Measure intensity as function of angle
- Fixed \( \theta \); TOF (spallation). Measure intensity as function of time-of-flight

Differences in lattice spacing \( \Rightarrow \) Only Elastic Lattice Strain of Crystalline Phase

\[ \varepsilon_{hkl}^{el} = \frac{d_{hkl} - d_{hkl}^0}{d_{hkl}^0} = \frac{d_{hkl}}{d_{hkl}^0} - 1 \]
Monolithic $\beta$-phase sample

- Diffraction patterns from monolithic $\beta$-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

- 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 $\beta$ phase sample

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

The $\beta$ 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 $\nu$ assuming isotropy as initial guess

\[
\begin{align*}
C_{11} &= 92 \pm 2 \\
C_{12} &= 70 \pm 2 \\
C_{44} &= 33 \pm 1
\end{align*}
\]

Anisotropy factor = 3.0
Young’s modulus = 59±3 GPa (63.3)
Poisson’s ratio = 0.37±0.02 (0.401)

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

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 $\beta$ phase is 670 MPa compared to 600 MPa for the monolith
- Yielding initially in the $\beta$ phase
  - Initiates multiple shear bands in glass that penetrates $\beta$ phase
  - Improved ductility over the monolithic BMG
- No evidence of phase transformation in $\beta$ phase
- Single crystal stiffnesses from diffraction data using SCM
  - Relatively strong elastic anisotropy in the $\beta$ phase