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# Spall damage of a Ta particle-reinforced metallic glass matrix composite under high strain rate loading

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## ABSTRACT

We investigate deformation and damage of a Zr-based bulk metallic glass (BMG) and its Ta particle-reinforced composite (MGMC) under impact loading, as well as quasi-static tension for comparison. Yield strength, spall strength, and damage accumulation rate are obtained from free-surface velocity histories, and MGMC appears to be more damage-resistant. Scanning electron microscopy, electron back scattering diffraction and x-ray computed tomography, are utilized for characterizing microstructures, which show features consistent with macroscopic measurements. Different damage and fracture modes are observed for BMG and MGMC. Multiple well-defined spall planes are observed in BMG, while isolated and scattered cracking around reinforced particles dominates fracture of MGMC. Particle–matrix interface serves as the source and barrier to crack nucleation and propagation under both quasi-static and impact loading. Deformation twinning and grain refinement play a key role in plastic deformation during shock loading but not in quasi-static loading. In addition, 3D cup-cone structures are resolved in BMG, but not in MGMC due to its heterogeneous stress field.

## 1. Introduction

Bulk metallic glasses (BMG) generally sustain little plastic deformation before catastrophic failure, despite its high yield and fracture strengths [1]. Extensive studies have been carried out to improve the toughness of BMG without significantly compromising its strength [2], and one of the promising solutions is metallic glass matrix composites (MGMC), which offer certain excellent properties and flexibility in design [3]. However, deformation and damage of MGMC under high strain-rate loading, as well as underlying mechanisms, are still poorly understood, although they are of great interest to impact dynamics and engineering applications (e.g, tank armor, satellite shield).

MGMCs exhibit considerable plastic deformation and apparent strain hardening under quasi-static [4] and split Hopkinson bar [5] compression. The physical origin is stress concentration caused by the mismatch in elasticity and plasticity between particles and matrix, which plays an important role in initiation and propagation of multiple shear bands [6]. Spallation studies were carried out on several kinds of metallic glasses [7–10] and their composites [7] through planar impact experiments, and BMGs and MGMCs display different spall damage modes. However, microstructural characterizations were focused on BMG matrix, and detailed deformation of embedded particles was essentially untouched. For instance, serrated cracks were found on the cross-section of recovered BMG, indicating brittle shear fracture of BMG while debonding fracture was characteristic of MGMCs [11]. In addition, cup-cone structures have been widely observed in the spall region of BMG via scanning electron microscopy (SEM) [11–13]. However, 3D configurations of cup-cone structures have not been clearly demonstrated. Cup-cone structure in MGMC, if it exists, is another subject of interest.

Extensive experimental and simulation studies have been devoted to the effects of microstructural factors on mechanical performance of MGMCs, including volume fraction [14], shape [15,16], length scale [17] and yield strength [18,19] of reinforcing particles. However, the role of particles in microscopic deformation of MGMC has not been fully understood, including particle-crack interactions, and plastic deformation of particles. Deformation and fracture mechanisms of reinforcing particles, such as deformation twinning, inter- and transgranular

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fracture, are of significance bulk properties of MGMCs [20] and thus materials design. Electron back scattering diffraction (EBSD) is a useful tool in characterizing plastic deformation of metals. However, EBSD characterizations on reinforcing particles in metallic glasses matrix are extremely rare.

In this work, we investigate deformation and damage of a Zr-based bulk metallic glass (simply referred to as BMG) and its Ta particulate-reinforced composite (MGMC) during quasi-static tension and shock-induced spallation. Macroscopic measurements including tensile loading curves and free-surface velocity histories are obtained, from which such parameters as tensile strength, spall strength, reacceleration due to pullback, are derived. Multiple characterization tools, including SEM, EBSD and x-ray computed tomography (CT) are applied to recovered BMG and MGMC specimens. SEM micrographs of fracture under quasi-static tension and spallation show quite different damage and fracture modes for BMG and MGMC. EBSD analyses indicate that Ta particles are subjected to pronounced plastic deformation, especially under spallation. In addition, we report the first CT characterization of cup-cone structures in BMG during shock-induced spallation, but such a structure feature is absent in MGMC.

## 2. Materials and experiments

A bulk metallic glass, $Zr_{55}Cu_{30}Ni_{5}Al_{10}$, and a metallic glass matrix composite, $(Zr_{70}Cu_{20}Ni_{10})_{82}Ta_{8}Al_{10}$, are examined in this work. The MGMC specimens are prepared by a two-step process. Ta crystals are firstly precipitated from a Zr-Ta solid solution, and then melted below the melting point of Ta together with three other elements. The resulting mixture is finally cast into a copper mold [2,6]. The composition of MGMC is 92 at% $Zr_{63}Cu_{17}Ni_{9}Al_{11}$, and 8 at% Ta. The densities of BMG and MGMC are measured with the Archimedean method, and their longitudinal and transverse sound speeds, via ultrasonic testing. The data of Cu and Ta are measured for high-purity bulk plates. The relevant material parameters are listed in Table 1.

Fig. 1(a) displays a schematic configuration of MGMC, with Ta particles uniformly distributed in the BMG matrix. We utilize x-ray computed tomography (CT), conducted at the beamline 2-BM of the Advanced Photon Source, to reconstruct its 3D microstructures. Further details on CT characterization can be found elsewhere [21,22]. CT measurements illustrate numerous Ta particles homogeneously dispersed in the BMG matrix. The particle size distribution of Ta, in terms of particle number vs. single-particle volume, follows a power decay law with a power of 1.01 (Fig. 1(d)). The number percentage of particles smaller than the average size ($10^5$ μm$^3$) is 84%, which occupy only 6% of the total volume. Fig. 1(e) is the x-ray diffraction patterns of BMG and MGMC specimens. Diffraction peaks of Ta particles can be seen clearly in diffraction patterns of MGMC.

To reveal the microstructure of embedded Ta particles, electron backscattered diffraction (EBSD) characterization is performed in a FEI Quanta 250 FEG-SEM equipped with Oxford EBSD detector and *HKL* channel 5 OIM software, at a 30 kV voltage, 15 mm working distance, and 70° tilt. The misorientation map in Fig. 1(c) shows that a Ta particle is polycrystalline, consisting of tens of grains with sizes ranging from 1 μm to 50 μm or larger. Grains exhibit many irregular brachial shapes, due to aggregation during the precipitation and morphology evolution process, different from equal-axis grains in conventional bulk tantalum [23], or another Ti-based MGMC reinforced with Nb-Ta dendrites [20].

**Table 1**
Material parameters. $\rho_0$: initial density; $C_L$: longitudinal sound speed; $C_T$: transverse sound speed; $C_0$: bulk sound speed; $\nu$: Possion's ratio.

| Material | $\rho_0$ (g/cm$^3$) | $C_L$ (m/s) | $C_T$ (m/s) | $C_0$ (m/s) | $\nu$ |
|---|---|---|---|---|---|
| BMG: $Zr_{55}Cu_{30}Ni_{5}Al_{10}$ | 6.64 | 4677 | 2179 | 3943 | 0.361 |
| MGMC: $(Zr_{70}Cu_{20}Ni_{10})_{82}Ta_{8}Al_{10}$ | 7.04 | 4649 | 2118 | 3954 | 0.369 |
| Cu | 8.50 | 4576 | 2171 | 3828 | 0.355 |
| Ta | 16.65 | 4130 | 2040 | 3392 | 0.339 |

Planar impact experiments are conducted on a 14-mm bore single-stage gas gun. The schematic setup for impact loading, time-resolved optical measurements, and soft recovery of samples, is shown in Fig. 2. When the solenoid valve is opened, high pressure nitrogen gas is injected into the gun barrel (1), accelerating a Cu flyer (4) attached to a PMMA sabot (3). Upon impact, the sabot is blocked by a holder (6) and separated from the flyer plate, while shock wave propagates into the specimen (7), and the accelerated specimen passes through a membrane mirror (8) and is caught by soft materials (11). Time-resolved optical signals are relayed by the mirror and a lens system (9) into recording oscilloscopes. Impact loading is performed within a vacuum chamber (12).

The flyer velocity ($u_f$) is measured with an optical beam block system (5), and the free surface velocity histories of the specimen, with a Doppler pin system (DPS), which is essentially a displacement interferometer. The DPS signals are converted into velocity histories via sliding window Fourier transformation. The impact velocity and free surface velocity are measured within 1–2%.

Both the flyer plate and specimen are cut into disks with diameters of 13.5 mm and 8 mm, respectively. Their flat surfaces are polished to mirror finish for impact loading. Some material parameters of the Cu flyer plates, and BMG and MGMC targets are listed in Table 1. For comparison, we also perform quasi-static tensile tests at a low strain rate ($5 \times 10^{-4}$ s$^{-1}$) utilizing an INSTRON universal testing machine with a maximum load capacity of 2 kN. The gauge length, width and thickness of the flat dog bone-shaped specimens are 2.16 mm, 1.08 mm and 0.39 mm for BMG, and are 2.16 mm, 1.00 mm and 0.49 mm for MGMC.

Specimens are recovered from planar impact and quasi-static tensile experiments for scanning electron microscopy (SEM), EBSD and x-ray CT characterizations. Specimens recovered from planar impact experiments are bisected along the impact direction and polished with SiC sand papers. For EBSD analysis, further electrochemical polishing is necessary. Satisfactory results are obtained with a 1:7 sulphuric acid methanol solution at 20 V and $-10-0$ °C.

## 3. Results and discussion

### *3.1. Analysis of quasi-static tensile tests and planar impact experiments*

Fig. 3(a) shows stress-displacement curves for BMG and MGMC under quasi-static tension up to failure. The curves for both materials are linear before yield, and followed by catastrophic failure, without obvious plastic deformation. The yield stage in BMG is negligible, and much shorter than that in MGMC. Compared to previous MGMC experiments [2], plastic deformation of MGMC in this study is less pronounced, probably due to much smaller gauge dimensions (cross-section in particular) in our tests. The enlarged views of the stress–displacement curves before the catastrophic failure (Fig. 3(a) inset) show a clear serrated flow pattern, with repeating cycles of elastic loading and abrupt stress drop, due to partial release of elastic energy [24–26]. Such serrated flow starts much later in MGMC (mainly after yield) than that in BMG (during elastic loading). The amplitude of serrations and interval between neighboring serrations are both smaller in MGMC than in BMG.

The impact experiment parameters are listed in Table 2. Free surface velocity curves for BMG and MGMC subjected to impact loading, display drastic differences in yield and damage (Fig. 3(b)). Overall, the MGMC curves are much less smooth since individual Ta particles distort wave front in both time and space, due to impedance and wave speed differences between the matrix and the Ta particles. Shock-compression induced yield is characterized with the Hugoniot elastic limit (HEL, at point A). Single elastic shock and elastic-plastic two-wave structure are