Deformation and Failure of Zr$_{57}$Nb$_5$Al$_{10}$Cu$_{15.4}$Ni$_{12.6}$/W Particle Composites Under Quasi-Static and Dynamic Compression

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We have investigated the mechanical behavior of a composite material consisting of a Zr$_{57}$Nb$_5$Al$_{10}$Cu$_{15.4}$Ni$_{12.6}$/W particle metallic glass matrix with 60 vol pct tungsten particles under uniaxial compression over a range of strain rates from $10^{-2}$ to $10^3$ s$^{-1}$. In contrast to the behavior of single-phase metallic glasses, the failure strength of the composite increases with increasing strain rate. The composite shows substantially greater plastic deformation than the unreinforced glass under both quasi-static and dynamic loading. Under quasi-static loading, the composite specimens do not fail even at nominal plastic strains in excess of 30 pct. Under dynamic loading, fracture of the composite specimens is induced by shear bands at plastic strains of approximately 20 to 30 pct. We observed evidence of shear localization in the composite on two distinct length scales. Multiple shear bands with thicknesses less than 1 μm form under both quasi-static and dynamic loading. The large plastic deformation developed in the composite specimens is due to the ability of the tungsten particles both to initiate these shear bands and to restrict their propagation. In addition, the dynamic specimens also show shear bands with thicknesses on the order of 50 μm; the tungsten particles inside these shear bands are extensively deformed. We propose that thermal softening of the tungsten particles results in a lowered constraint for shear band development, leading to earlier failure under dynamic loading.

I. INTRODUCTION

At temperatures well below the glass transition, plastic deformation in single-phase metallic glasses is localized into a relatively small number of shear bands.[1] As a result, metallic glasses typically show limited plastic strain prior to failure. If either the microstructure or the loading conditions permit the formation of multiple shear bands that cannot propagate through the material, the plastic strain to failure can be dramatically increased. Therefore, considerable effort has been devoted to the production of composite materials consisting of a metallic glass matrix reinforced by a ductile second phase.[2-8] The second phase interacts with the propagating shear bands, hindering their motion, thereby delaying the onset of fracture and increasing the plastic strain to failure.

One alloy with excellent glass-forming ability is Zr$_{57}$Nb$_5$Al$_{10}$Cu$_{15.4}$Ni$_{12.6}$, and several studies on the mechanical properties of composites of this alloy reinforced by various materials (including tungsten carbide, tungsten, and steel) have been reported.[9-14] While the single-phase glass shows only limited plastic deformation (~0.5 pct) under quasi-static (~$10^{-5}$ s$^{-1}$) compression, composites can show significant plastic strain (~16 pct) to failure.[6,10-13] Ballistic tests show that the metallic-glass-matrix composites have higher penetrating capability than a tungsten heavy alloy.[12,14]

In this work, we examine the mechanical behavior under uniaxial compression of a composite material consisting of amorphous Zr$_{57}$Nb$_5$Al$_{10}$Cu$_{15.4}$Ni$_{12.6}$/W particle reinforced with 60 vol pct tungsten particles. The strain-rate range of the experiments ($10^{-4}$ s$^{-1}$ to $10^3$ s$^{-1}$) spanned quasi-static and dynamic loading conditions. Unlike single-phase glasses, for which the failure stress decreases with increasing strain rate,[15] the failure stress of the composites increases with strain rate. Over the entire range of strain rates, the presence of the particles allows significant plastic strains to develop. Under dynamic loading, failure occurs at plastic strains of ~20 pct due to formation of adiabatic shear bands. Under quasi-static loading, adiabatic shear bands do not form, and the composite can sustain large plastic strains without failure.

II. EXPERIMENTAL PROCEDURE

The composite material used in this study was prepared by Liquidmetal Technologies, Inc. (Lake Forest, CA) using a pressure infiltration technique that we describe briefly here; additional details may be found in Reference 16. To make a cylindrical tungsten preform, tungsten powder (99.9 pct pure, −100 mesh, Alfa Aesar catalog no. 10402, Alfa Aesar, Ward Hill, MA) was cold isostatically pressed and lightly sintered in hydrogen to reduce surface oxidation and to impart some strength to the preform. The preform, together with an ingot of the glass-forming alloy, was then inserted into a stainless steel tube. The tube was sealed and heated under vacuum above the liquidus temperature of Zr$_{57}$Nb$_5$Al$_{10}$Cu$_{15.4}$Ni$_{12.6}$ (1115 K).[17] Pressurized argon gas was applied to force the liquid alloy to infiltrate the tungsten preform. After holding above the liquidus temperature to allow complete infiltration, the steel tube and its contents were withdrawn from the furnace and quenched in water. The composite was separated from the tube and a layer of surface contamination (due to interaction with the stainless steel) was removed by grinding.

The microstructure of the resulting composite is shown in Figure 1(a). There is a wide distribution of particle sizes...
In this case, fracture of the specimen will be delayed, and large plastic strains can be developed.\textsuperscript{[19]} In contrast to quasi-static testing, for dynamic testing, the optimum aspect ratio is approximately 0.5 (to minimize errors due to inertia\textsuperscript{[20]}), and we chose our specimen dimensions accordingly. Based solely on a consideration of aspect ratio, one might thus expect that the dynamic specimens would fracture later (i.e., at larger strains) than the quasi-static specimens. As we show subsequently, however, the opposite is the case; fracture occurs at smaller strains under dynamic loading. We conclude, therefore, that while the aspect ratio of the specimens is important, it is not the dominant effect.

The quasi-static tests (strain rates of $10^{-4}$ to $10^{-1}$ s$^{-1}$) were performed on a servohydraulic testing machine operating under displacement control. We inserted a pair of tungsten carbide platens between the specimen and the loading fixture, and lubricated the specimen/platen interfaces with grease to minimize friction effects. The relative displacement of the platens was measured by a linear variable differential transformer. After correction for the compliance of the system, the net displacement of the specimen ends was used to calculate the strain.

The dynamic tests (with strain rates of $10^2$ to $10^4$ s$^{-1}$) were performed on a compression Kolsky bar, the principles and details of which are described elsewhere.\textsuperscript{[20–22]} When testing materials that fail with little or no plastic deformation (such as single-phase metallic glasses), it is necessary to shape the incident pulse to increase the rise time to ensure that the stress state in the sample reaches equilibrium before failure occurs. In the present case, however, preliminary tests revealed that the composite specimens experienced significant plastic deformation, making pulse shaping unnecessary. Due to the high strength of the composite, we did use tungsten carbide platens, confined by Ti-6Al-4V collars, between the specimen and the input and output bars. The diameter of the tungsten carbide platens was chosen to provide impedance matching to the input and output bars.

### III. RESULTS

#### A. Constitutive Behavior

Stress-strain curves for the Zr$_{57}$Nb$_5$Al$_{10}$Cu$_{15.4}$Ni$_{12.6}$/60 vol pct W composite under quasi-static and dynamic loading are shown in Figure 2. (Note that true stress and true strain are obtained from engineering stress and strain using the usual expressions, which are based on an assumption of constant-volume plastic deformation.) For comparison, the figure also shows curves for the matrix (single-phase amorphous Zr$_{57}$Nb$_5$Al$_{10}$Cu$_{15.4}$Ni$_{12.6}$) and the reinforcement (nominally pure, annealed tungsten). The composite shows much larger plastic deformation than the unreinforced glass under both loading conditions. Under quasi-static loading, the single-phase glass experiences only 1 to 2 pct plastic strain to fracture, while for the composite specimens, we observed no fracture even at nominal plastic strains exceeding 30 pct. For our quasi-static compression tests, significant bending of specimens occurred at plastic strains larger than approximately 15 pct, making accurate determination of larger true strains impossible.) A similar difference is seen for dynamic loading: the single-phase glass fails after essentially zero plastic deformation, but for the composite, fracture does not