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Effect of strain rate and temperature on the plastic deformation behaviour of a bulk metallic glass composite

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ABSTRACT

The composites consisting of amorphous matrix reinforced with crystalline dendrites offer extraordinary combinations of strength, stiffness, and toughness and can be processed in bulk. Hence, they have been receiving intense research interest, with a primary focus to study their mechanical properties. In this paper, the temperature and strain rate effects on the uniaxial compression response of a tailored bulk metallic glass (BMG) composite has been investigated. Experimental results show that at temperatures ranging between ambient to 500 K and at all strain rates; the onset of plastic deformation in the composite is controlled by that in the dendrites. As the temperature is increased to the glass transition temperature of the matrix and beyond, flow in the amorphous matrix occurs readily and hence it dictates the composite's response. The role of the constituent phases in controlling the deformation mechanism of the composite has been verified by assessing the strain rate sensitivity and the activation volume for deformation. The composite is rate sensitive at room temperature with values of strain rate sensitivity and activation volume being similar to that of the dendrites. At test temperatures near to the glass transition temperature, the composite however becomes rate-insensitive corresponding to that of the matrix phase. At low strain rates, serrated flow akin to that of dynamic strain ageing in crystalline alloys was observed and the serration magnitude decreases with increasing temperature. Initiation of the shear bands at the dendrite/matrix interface and propagation of them through the matrix ligaments until their arrest at another interface is the responsible mechanism for this.

1. Introduction

Bulk metallic glasses (BMGs) exhibit extraordinary strengths (typically of the order of 2 GPa) and modulus that ranges between crystalline aluminium and titanium alloys (about 100 GPa) [1]. However, they suffer from low or negligible tensile ductility, no intrinsic resistance to crack growth, and relatively poor fatigue performance [1–4]. One of the possible ways to circumvent these problems is by using BMG matrix composites and several processing routes to fabricate such materials have been demonstrated [5–9]. Recently, it has been shown that composites with tailored microstructures of crystalline dendrite phase in the amorphous matrix yield a combination of higher ductility, strength and toughness [10–12]. Consequently, there has been considerable research activity on processing and understanding of the mechanical properties of these composites [13–16].

The constituents of BMG composites; crystalline dendrites and amorphous matrix, differ fundamentally in terms of the sources for initiation and continuation of plastic flow in them. While the dendrites deform by virtue of dislocation motion, plasticity in the amorphous alloys is mediated by shear transformation zones (STZs) and inhomogeneous flow in terms of shear bands [1]. Additionally, plasticity in metallic glasses tends to be pressure sensitive and flow localization occurs readily when the temperature of testing is relatively low [17,18]. These differences get reflected in mechanical properties of the composite in a number of ways. In the context of the present study, the following are the key contrasting aspects. (a) At temperatures well below their glass transition temperature, T_g, metallic glasses tend to be strain rate insensitive. In contrast, crystalline metals and alloys tend to be fairly to highly rate sensitive. (b) The temperatures of relevance for metallic glass and dendrites are T_g and T_m (the melting point), respectively. Typically, T_m is much larger than T_g. Thus, as the temperature of testing, T, is increased from room temperature (which would be $\sim 0.5 \times T_g$ but only about $0.2 \times T_m$) to higher temperatures, significant transitions in the mechanisms of plasticity can be expected. For example, when $T = 600$ K, which is the T_g of the composite examined in this work, the matrix becomes relatively soft and highly rate sensitive whereas the dendrite would still be strong. The BMG composite's response as a function of temperature and strain rate, therefore

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becomes an important issue to address. Additionally, the use of BMG matrix composites in commercial applications requires an understanding of how they behave at elevated temperatures, and specifically, what the maximum operating temperature can be. Such a study will also enable us to understand the operative micro-mechanisms of plastic deformation for various temperature–strain rate combinations. These are the primary objectives of the current study.

2. Materials and experiments

A BMG composite with the chemical composition of $Zr_{39.6}Ti_{33.9}Nb_{7.6}Cu_{6.4}Be_{12.5}$ (at.%) was used in the present work. The composite was produced by arc melting. In a separate step, the ingot was heated to the semi-solid region to obtain uniform microstructure. It was further hand-forged between two water-cooled brass plates in the semi-solid state and quenched via conduction. Further details of processing can be found in reference [19]. Scanning electron microscopy (SEM) was performed on polished samples of composite to obtain the microstructure of it as well as to quantify the volume fractions of the dendrite and the amorphous matrix. An electron probe micro analyzer equipped with a field emission gun was used to determine the chemical compositions of matrix and dendrite. The body centred cubic (bcc) [6] crystalline dendrite phase composition was found to be $Zr_{41.3}Ti_{43.9}Nb_{13.1}Cu_{1.7}$ whereas the glassy matrix phase has the composition of $Zr_{32.5}Ti_{23.1}Nb_{2.9}Cu_{10.5}Be_{31}$. Differential scanning calorimetry was utilized to estimate T_g of the composite to be ~600 K whereas the liquidus temperature of the composite is around ~1300 K.

Cylindrical specimens of 5 mm diameter and 7.5 mm height were used for conducting uniaxial compression tests. Although these composites exhibit ductility in tension, compression testing was used to conserve the material. Independent tensile tests confirm that there is no tension-compression asymmetry in these composites. Concentric circular grooves of 0.5 mm were made on the top and bottom surfaces of these specimens. Graphite lubricant was applied on the grooves to reduce the frictional stresses that arise during the deformation between the platens and the specimen. Chromel/Alumel thermocouple was put on to the specimen surface for measuring the specimen temperature directly. The tests had been performed in a servo-hydraulic testing machine with split furnace attached to it. Temperature control of the furnace was accurate up to ±2 °C. Compression tests were performed at temperatures, T = 300, 400, 500, 550, 600, and 650 K and strain rates, $\dot{\varepsilon} = 10^{-4}$, 10^{-2}, 10^{-1}, and 10^{1} s^{-1}. For monitoring the deformation mechanisms, uniaxial compression tests were conducted on specimens of square cross section (5 mm × 5 mm) and height of 7.5 mm. Specimens are polished up to 1 μm grit size prior to testing. For imaging the transition from serrated to non serrated flow during deformation, these samples are compressed progressively at 300, 400, 500, 550, and 600 K and strain rates of 10^{-3} and 10^{-1} s^{-1}. The samples were compressed up to yield point before unloading and examination using SEM. The samples were further compressed by 3% and the procedure was repeated.

3. Results

3.1. Microstructure

The microstructure of the composite is shown in Fig. 1. The dendrites appear to be bimodal in size, with the coarse dendrites being 23.1 ± 4.4 μm in size whereas the fine dendrites are 4.9 ± 1.2 μm. The bimodal microstructure is a result of the casting process. To make the composite fluid enough to forge into a thin plate, the temperature must be increased in the semi-solid region closer to the liquidus of the alloy. Upon quenching, the dendrites that were not in solution grow and coarsen while smaller dendrites re-precipitate from the supersaturated matrix during the rapid cooling. This causes two distinct dendrite morphologies.

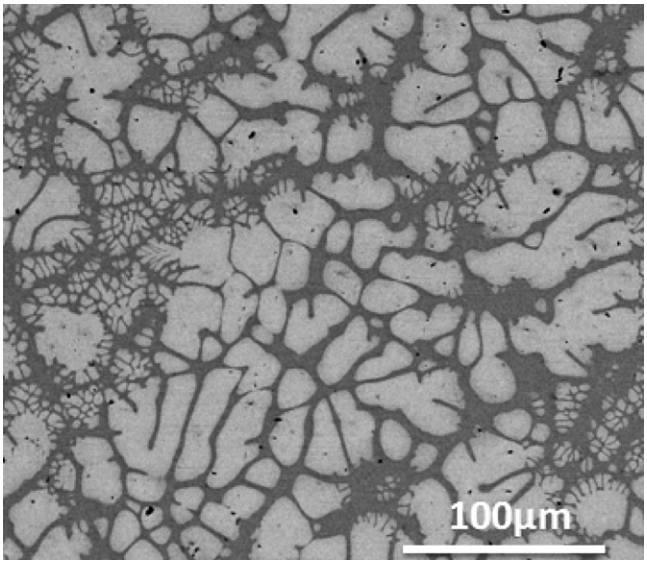

Fig. 1. Representative microstructure of the BMG composite examined in this paper.

Estimates based on area analysis of the SEM images reveal that the total volume fraction of dendrites is approximately 67%. The average inter-dendritic spacing, taken as the average minimum distance of a dendrite to its neighbouring dendrite, is 3.1 ± 0.75 μm for the coarser dendrites and 0.80 ± 0.07 μm for the finer dendrites.

3.2. Stress–strain responses

Representative engineering stress, σ, vs. engineering strain, ε, plots, which are obtained at a fixed temperature, T, and different strain rates, $\dot{\varepsilon}$, are shown in Fig. 2 whereas Fig. 3 compares σ–ε responses at fixed $\dot{\varepsilon}$ basis but at different T. These plots suggest that σ–ε responses that one obtains on the BMG composites depend strongly on T and $\dot{\varepsilon}$ combinations. For example, Fig. 3c indicates that the flow response of the composite is nearly temperature insensitive at $\dot{\varepsilon} = 10^{-2}$ s^{-1}. The ductility of the composite is also a strong function of the testing conditions imposed. (Admittedly, the tests reported in this paper are all conducted in compression and hence the strain at which the composite fails does not truly reflect the ductility of the material. Also, not all the samples were compressed until failure, but to a maximum strain of 15–20%, if they have not failed already. Nevertheless, the data presented does indicate to considerable variations in the strain at which the composite fails.) Several noteworthy features in from Figs. 2 and 3 are listed below.

- When the composite is deformed at 650 K, i.e., $T > T_g$, the stress–strain response is highly strain rate sensitive, with the sample tested at 10^{-4} s^{-1} exhibiting low yield strength, σ_y (156 MPa). When $\dot{\varepsilon}$ is increased to 10^{-1} s^{-1}, composite's σ_y increases significantly to 915 MPa. Further increase in strain rate appears to have no influence on σ_y, but flow softening beyond yield and low ductility are noteworthy in the sample tested at 10^{+1} s^{-1}. The following important difference between these responses of the composite and those of a monolithic BMG, both in their respective super-cooled liquid regimes, is noteworthy. In the latter, deformation at high strain rates generally leads to flow softening beyond yield and attainment of steady-state flow after some strain. As the strain rate is lowered, the 'broad peak'