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Plasticity improvement for dendrite/metallic glass matrix composites by pre-deformation

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ABSTRACT

The mechanical properties of in-situ metallic glass matrix composites (MGMCs) are investigated by tensile pre-deformation, followed by compression. The pre-deformation is utilized to exploit notable increases in plasticity, accompanied by slight increases in the compressive strength, and the deformation mechanisms are explored. The increased free volumes in the glass matrix after tensile pre-deformation contribute to the decrease of the Young's modulus of the glass matrix and lead to the increase in the stress concentration, promoting multiplication of shear bands. When the Young's modulus of the glass matrix matches that of the dendrites, the plasticity of in-situ dendrite-reinforced MGMCs is the optimized. Matching Young's modulus opens a door to design the MGMCs with excellent plasticity and remarkable work-hardening capability.

1. Introduction

Plastic deformation in bulk metallic glasses (BMGs) manifests through the strain localization shearing into narrow bands, which are often referred to as shear bands [1,2]. The shear bands, which have an unhindered propagation in monolithic BMGs, yield negligible tensile ductility. Recently, great interest arises in BMGs as structural materials, since they exhibit superior mechanical properties, such as high strength, large elastic limits, and high corrosion resistance [3]. However, a widespread acceptance of monolithic BMGs in engineering applications is limited by their poor ductility under loading at room temperature. One way to alleviate this problem is that the crystalline phases are in-situ introduced to effectively generate multiple shear bands and impede the rapid propagation of shear bands [4,5]. To date, the dimension for lightweight in-situ dendrite-reinforced metallic glass matrix composites has reached a centimeter scale and even larger for systems such as Ti–Zr–V–Cu–Be [6], Ti–Zr–Ni–Cu–Be [7], and Ti–Zr–Cu–Ni–Al [8]. These ingots are large enough to be used as potential structural materials in various application fields. It should be noted that the improvement of plasticity and the enhancement of work-hardening capacity are badly needed for dendrite-reinforced metallic glass matrix composites (MGMCs).

For in-situ MGMCs, the deformation mechanisms should be fully understood before actual service. After introducing the secondary phases in the glass matrix, both phases in the composites are under the multi-axial stress state during the deformation. The concentrated stress, induced by the secondary phases, can interact with the stress field, originated from propagating shear bands, leading to the multiplication, branching, and deflection of shear bands. As a result, shear bands in these MGMCs are characterized to be dense, short, and wavy [9]. The profuse shear bands could accommodate more strain energy, resulting in effective toughening.

For monolithic BMGs, introducing structural inhomogeneity can produce residual stress, and then, the pre-existed shear bands and free volumes improve the plasticity [10–12]. Zhang et al. [10] have pointed out that the plasticity of Vitreloy 1 BMGs was improved by introducing compressive residual stress on the sample surface by shot-peening. Cao et al. [11] have reported that pre-existed properly-spaced soft inhomogeneities can stabilize shear bands and lead to tensile ductility, and the effective intersection of shear bands in conjugated directions resulted in obvious work hardening. Haruyama et al. [12] put forward that cold-rolled BMGs exhibited volume dilatation, caused by the generation of free volumes. Generally, the heterogeneities can manipulate nucleation and propagation of shear bands, which is responsible for the enhanced plasticity of BMGs [13]. Hofmann et al. [14] have reported that the shear bands generated during rolling provided nucleation sites for the new shear bands generated during tension. The deformation mechanisms of β-Ti solid solution (dendrites) are based on the dislocation

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multiplication and slip [15–18]. The work-hardening capacity, associated with homogeneous deformation, is highly dependent on the large plastic deformation of both the dendrites and the metallic glass matrix [19]. Based on the above micromechanisms, multiplication, branching, and deflection of the shear bands are crucial to improve the plasticity. The pre-deformation not only increases the free volumes in the glass matrix [12,20–25], but also the dislocation density within the crystalline dendrites increases [15–18]. Recently, Ke et al. reported [26] that the $Zr_{46.75}Ti_{8.25}Cu_{7.5}Ni_{10}Be_{27.5}$ BMG exhibited volume dilatation of up to 0.2% after compressive creep of the as-cast sample at a yield stress of 80%, and this phenomenon is attributed to the generation of a great amount of free volumes. The increased free volumes make the Young's modulus of the glass matrix decrease [20,24,25], resulting in the Young's modulus of the glass matrix and dendrites being approaching, since the crystalline dendrites have a lower Young's modulus than the glass matrix. The aim of this study is to investigate the contribution of matching the Young's modulus between the glass and dendrite phases to the plasticity of in-situ dendrite-reinforced MGMCs.

2. Experimental procedures

Ingots of a nominal composition: $Ti_{48}Zr_{18}V_{12}Cu_5Be_{17}$ (at.%) were prepared by arc-melting a mixture of the elements Ti, Zr, V, Cu, and Be with high purity (>99.9%) under a Ti-gettered argon atmosphere. Two cylindrical rods with a diameter of 2 mm and 6 mm were prepared via suction casting into a copper mold, respectively. The phases of the samples were checked by X-ray diffraction (XRD) in a Philips APD-10 diffractometer with Cu Ka radiation. The pre-deformation experimental procedures were schematically shown in Fig. 1. The dog-bone-like tensile samples with a nominal diameter of 2 mm and a length of 15 mm were machined from the as-cast rods with 6-mm diameter. Sample A with an aspect ratio of 2:1 was cut from the gage section of as-cast samples, and their ends were prepared and polished to ensure the parallelism. The tensile samples were drawn to the stage of work hardening and the failure at room temperature at a constant strain rate of $5 \times 10^{-4}\ s^{-1}$, respectively. And then, samples B and C with an aspect ratio of 2:1 were cut from the deformed samples within the gage section, respectively, as shown in Fig. 1. Sample D with an aspect ratio of 2:1 was directly cut from as-cast bars with a diameter of 2 mm. The compressive tests were carried out on samples A, B, C, and D at a strain rate of $5 \times 10^{-4}\ s^{-1}$. The microstructures of as cast samples and the fracture surfaces after compression were investigated by scanning electron microscopy (SEM).

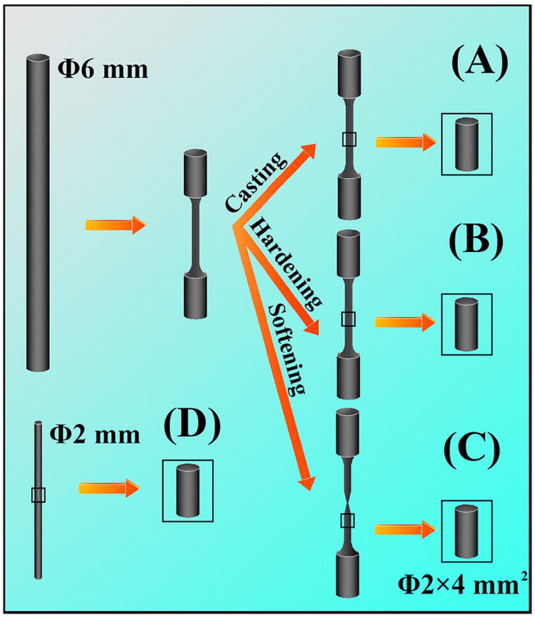

Fig. 1. The experimental procedure schematic diagram.

3. Results

3.1. Microstructures

The microstructures of samples D and A are illustrated in Fig. 2(a) and (b), respectively. The SEM images of the cross-sections for samples B and C are very similar to that of sample A (not shown). The dense small dendrites are homogeneously embedded in the glass matrix, as shown in Fig. 2(a). From the magnified image in the inset of Fig. 2(a), the average diameter of the dendritic arms of sample D is less than 1 μm. However, that of samples A, B, and C are the same with a value of ~2 μm, as shown in Fig. 2(b). The size of the dendritic arm can be controlled by the cooling rate during casting [27]. The dendrite's volume fractions in samples A, B, C, and D are all ~46% by analyzing the contrast of the SEM image, and similar results have been observed by Jeon et al. [28]. X-ray diffraction patterns of the composites (not shown here) indicate that the dendritic phase is a β-Ti solid solution with a body-centered cubic crystal structure.

3.2. Mechanical behavior

3.2.1. Tensile behavior

Fig. 3 displays the tensile stress–strain curve of the present composites. After yielding, the MGMCs exhibit not only high tensile strength of 1422 MPa, but also remarkable work-hardening capacity. The following softening dominates until the final fracture at a fracture strain of ~5.9%.

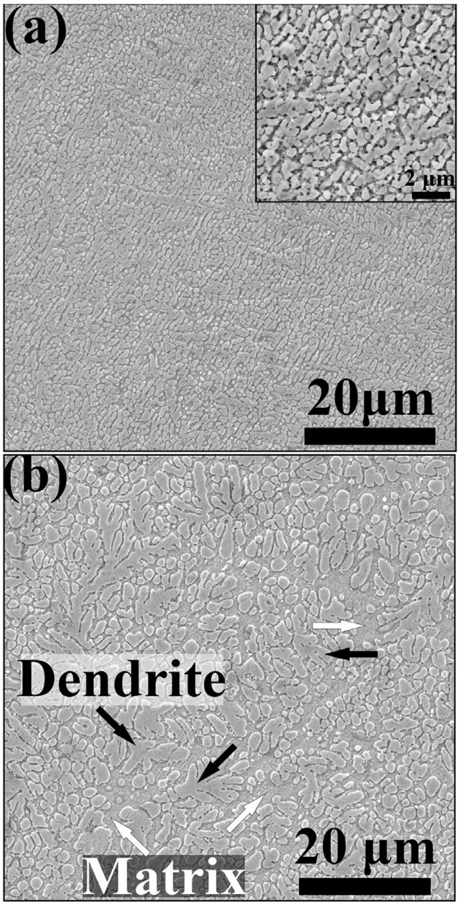

Fig. 2. The SEM micrographs of the as-cast composites with a diameter of 2 mm and 6 mm in (a) and (b), respectively. The inset of (a) being magnified micrograph of as-cast composite with a diameter of 2 mm.