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A strategy for designing bulk metallic glass composites with excellent work-hardening and large tensile ductility

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ABSTRACT

Bulk metallic glass (BMG) composites have demonstrated enormous potential for improved ductility and toughness over the traditional BMGs by in-situ formed crystalline phase in glass-matrix, which brings about delocalized strain and can inhibit shear bands rapid propagation in glass-matrix. However, an early onset of necking after yielding arises upon tension loading process. Enhancing work-hardening of bulk metallic glass (BMG) composites is therefore vitally important for practical applications. By tailoring the intrinsic properties of a $Ti_{47}Zr_{25}Nb_6Cu_5Be_{17}$ BMG composite with an addition of Sn to reduce the shear and the elastic modulus of dendrite-phase, the current work gives full play to strain-induced work-hardening of dendrite phase and makes it succeed the completion with strain-induced work-softening of glass-matrix. Because of the significant enhancement of work-hardening by dislocation deformation in dendrite-phase, and the stabilized plastic flow in glass-matrix, large tensile ductility (tensile strain till necking $\varepsilon_u \approx 10\%$) and high tensile strength ($\sigma_u \approx 1.5$ GPa) are attained simultaneously by the Sn2 BMG composite.

1. Introduction

Bulk metallic glasses (BMGs) are currently taken to be candidate of structural materials ascribing to their outstanding properties such as high strength, excellent wear resistance and good hot plasticity forming ability [1–4]. A major problem for their potential applications is the rapid development of localized shear bands and subsequent catastrophic failure upon loading which lead to a negligible plasticity especially in uniaxial tension [5,6]. By in-situ introducing a ductile crystal-phase into the glass-matrix to hinder propagation of and initiate multiplication of shear banding [7,8], the BMG composites solve the problem and can even overcome the conflict of attaining simultaneously high strength and high toughness [9]. This kind of composites has been manufactured widely in the Zr- [7], Cu- [8], Ti- [10–12] based BMG composite et al. Moreover, the quasi-static and dynamic loading compressions have been detailed performed under different strain rates to understand the deformation behavior of in-situ BMG composites and extend their applications [10–12]. Nevertheless, because of a macroscopic strain-softening phenomenon with an early onset of necking always appears upon the loading process, the tensile deformation mechanism of BMG composites has not been investigated in detail [13,14]. This strain-softening behavior is generally attributed to the existence of strain-softening in glass-matrix and the low work-hardening capability in crystalline phase under tension, which has restrained the application potential of such materials [13–20].

Plastic deformation of BMG composites is controlled by the competition between strain-induced work-hardening of crystal-phase and strain-induced work-softening of glass-matrix; after yielding, a work-hardening stage is usually followed by a work-softening stage [18]. By modulating the competition relation, two strategies were proposed to enhance work-hardening of BMG composites. (1) Introduction of B2 phase with strain-induced phase transformation. Several groups successively prepared the CuZr-based BMG composites [21–30], upon loading of which strain-induced martensitic transformation of B2 to B19′ phase happens. The BMG composites [25–30] have excellent work-hardening and large tensile ductility, however their unique deformation mechanism was only found in few alloy systems [31–34]. (2) Reducing the size of glass-matrix to nanometre-scale. Metallic glasses are not intrinsically brittle [35], e.g. when their size is reduced to a critical value (30–100 nm for Zr-based BMG [35]), localization of shear

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bands is inhibited and transformed to homogeneous deformation, thus leading to a transition from brittleness to toughness [35,36]. Accordingly, a new compositional design of Mg-based BMG composite with micrometre-scale dendrite-phase and nanometre-scale glass-matrix was proposed to obtain high toughness and excellent work-hardening [37]. However, because the existence of high volume fraction dendrite-phase in these Mg-based BMG composites, the yielding strength has been significantly reduced.

The mechanical properties of materials are highly related to their intrinsic properties [1,38]. For example, superplasticity can be obtained by tailor the alloy composition of BMGs according to the Poisson's ratio ν [39–41]. Hence, we speculate that the mechanical properties of BMG composites could also be modulated by tailoring the intrinsic properties. Our recipe is to reduce the Young's modulus and shear modulus of dendrite-phase to make it yield and deform easily, thus giving full play to its strain-induced work-hardening by the common dislocation deformation mechanism. The dendrite-phase in this case can become strong enough to make its work-hardening succeed in the competition with work-softening of glass-matrix. The current strategy should be of general meaning because it is able to enhance remarkably work-hardening of BMG composites without strain-induced phase transformation.

To test our proposal, a $Ti_{47}Zr_{25}Nb_6Cu_5Be_{17}$ (Sn0) BMG composite which exhibits an ultimate tensile strength $\sigma_u \approx 1.36$ GPa and a total strain to failure $\varepsilon_{tot} \approx 3.17\%$ is chosen. Because the Sn element not only has very small Young's modulus ($E = 50$ GPa) and shear modulus ($G = 18$ GPa) but also can improve the glass forming ability (GFA) of Ti-based BMGs [42], thus it is chosen here to tailor the intrinsic properties, i.e. $Ti_{47\text{-}x}Zr_{25}Nb_6Cu_5Be_{17}Sn_x$ (Snx, x = 1, 2, 3, 4 at.%). For the Sn2 BMG composite in which the dendrite-phase has the smallest Young's modulus ($E \approx 75$ GPa) and shear modulus ($G \approx 28$ GPa), large tensile ductility (strain $\varepsilon_u \approx 10.12\%$) is attained without strain-induced phase transformation. After yielding at $\sigma_y \approx 0.9$ GPa, the work-hardening stage dominates until to an ultimate tensile strength of $\sigma_u \approx 1.5$ GPa. The microscopic deformation mechanism shows that tailoring the intrinsic properties is a useful strategy for designing BMG composites with high strength, excellent work-hardening and large tensile ductility.

2. Experimental

Alloy ingots with nominal composition of $Ti_{47-x}Zr_{25}Nb_6Cu_5Be_{17}Sn_x$ (x = 0, 1, 2, 3, 4 at.%) are prepared by arc-melting the mixture of Ti, Zr, Cu, Nb, Sn and Be metals (purity better than 99.9 wt%) under a Ti-gettered high purity argon atmosphere. Plate samples (5 × 20 × 60, mm) are prepared by casting into a water-cooled copper mold. Tensile samples with a gauge dimension of 1 × 2 × 10 (mm) are machined from the as-cast rods and then carefully polished. The samples are characterized by X-ray diffraction (XRD: Bruker D8 with Co Kα radiation), scanning electron microscopy (SEM: TESCAN VEGA 3 LMU) with an energy-dispersive spectrometer (EDS), and high-resolution transmission electron microscopy (HRTEM: Tecnai G2 F30, 300 kV). The transmission electron microscopy (TEM) samples are prepared by mechanically grinding and ion milling within the liquid nitrogen. Tensile tests are performed by an AGS-X (Shimadzu, 5 kN) test machine. The initial tensile engineering strain rate is 1×10^{-4} s^{-1}. Nanoindentation tests (Agilent, G200) are conducted in the continuous stiffness mode to measure the hardness of dendrite-phase and glass-matrix by nano indenter with a depth of 300 nm and a loading rate of 0.1 nms^{-1}. Intrinsic properties (E, G, B, υ) of the samples (2 × 3 × 4, mm) are measured by the resonant ultrasound spectroscopy (RUS). Sample density was measured by the archimedean technique. In order to measure intrinsic properties of dendrite-phase, the average composition of dendrite-phase in BMG composite is measured by the EDS, and then the pure dendrite-phase samples are prepared individually by arc-melting.

3. Results

3.1. Microstructure

Fig. 1a shows the XRD patterns of as-cast $Ti_{47-x}Zr_{25}Nb_6Cu_5Be_{17}Sn_x$ samples. For the Sn0-Sn3 BMG composites, a typical diffraction pattern of body-centered cubic (bcc) β-Ti phase is superimposed on a broad halo of glass-matrix [10,18]. For the Sn4 BMG composite, several other crystalline peaks that correspond to the Zr_5Sn_3 intermetallics are found. Fig. 2 shows the SEM images of the as-cast $Ti_{47-x}Zr_{25}Nb_6Cu_5Be_{17}Sn_x$ samples. The dendritic structures (bright regions) distribute homogeneously within a featureless glass-matrix (gray regions). Besides the bright and the gray regions, another white regions that correspond to the Zr_5Sn_3 intermetallic are available in the Sn4 BMG composite (Fig. 2e). Because an extra Zr_5Sn_3 intermetallic precipitation that could damage the ductility is detected in the Sn4 BMG composite, the

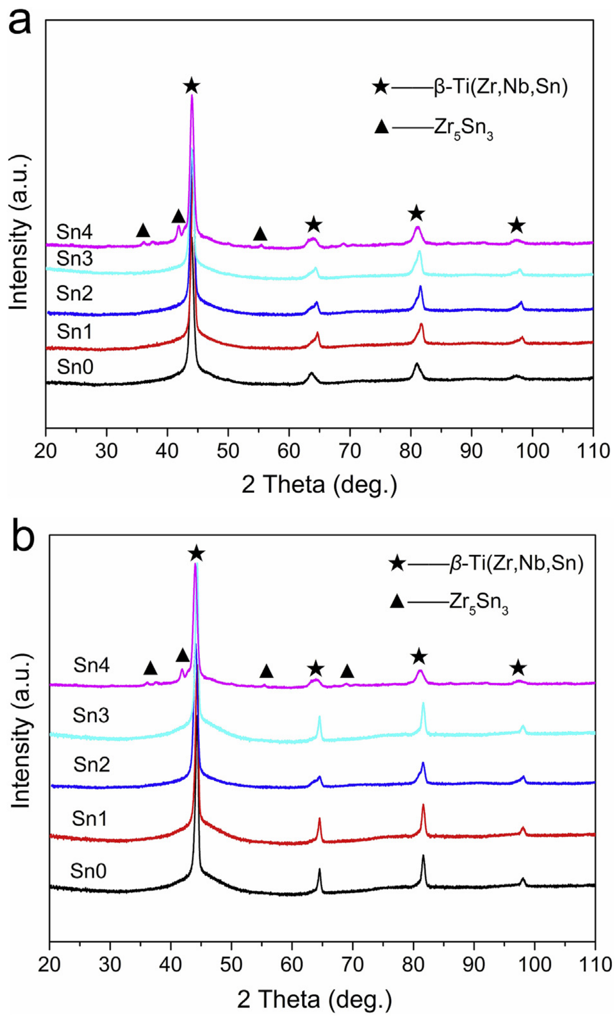

Fig. 1. XRD patterns of (a) the as-cast and (b) the fractured $Ti_{47-x}Zr_{25}Nb_6Cu_5Be_{17}Sn_x$ (x = 0, 1, 2, 3, 4) BMG composites. For both the as-cast and fractured samples, the peaks of crystal phases (β-Ti for Sn0-Sn4 and Zr_5Sn_3 for Sn4) are superimposed on the amorphous hump. Because there is no appearance of new phase after fracture, strain-induced phase transformation is not relevant to the current work.