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Dynamic compressive response of a dendrite-reinforced Ti-based bulk metallic glass composite

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ABSTRACT

Dynamic compressive response of a dendrite-reinforced Ti-based bulk metallic glass composite is investigated. Strain rate dependencies of the max strength and strain energy density are illustrated. The inherent mechanisms are revealed by studying the dynamic deformation behaviors at lower and higher strain rates. Under high-rate loading, the deformation and fracture of the soft crystalline dendrites and the hard amorphous matrix are characterized, respectively. Then, their contributions to the failure of the composite material are discussed. Finally, the dynamic damage efficiency of the composite material is addressed.

1. Introduction

Bulk metallic glasses (BMGs), as the advanced structure materials, have attracted a tremendous research interest due to their superior mechanical data such as large elastic limit, high strength and considerable fracture toughness, compared with the conventional crystalline metals and alloys with comparable composition [1–3]. These advantages in mechanical performance give BMGs a high potential of engineering application in impact events, which creates a new research community: dynamic mechanical response of bulk metallic glass materials [2–10]. Negative strain rate effect of the mechanical properties has been widely reported, i.e. decrease of yield stress with the increase of strain rate [9–11]. Meanwhile, catastrophic failure with very little plastic deformation is accompanied. Temperature rise and local tensile stress inside a single shear band are clarified to result in the softening behavior under high-rate loading [12]. Thus, the effort to improve the impact-resistant performance of BMGs is highly necessary.

Dendrite, as a ductile crystalline phase, has been applied towards effectively enhancing the plasticity of BMGs under static loading, which enables the multiplication, branching and restriction of shear bands [13–15]. Recently, a ductile dendrite reinforced Ti-based BMGs composite was developed, which shows a large plastic deformation after yielding and strong necking before fracture under static tensile loading [16]. In Ti-based BMG composite, the ductile dendrites can affect the initiation and propagation of deformation bands, shear bands and/or twins as well as the final cracking to fracture, which contributes to the excellent tensile properties of about 1.3 GPa yield strength and 9% elongation under static loading [16]. Therefore, we can conclude that the ductile dendritic phase is an effective additive for improving the ductility of BMGs and overcoming the strength-ductility trade off at a static loading rate. Then, a technological question is raised: how about the effects of this toughening technique under dynamic loading?

In this paper, a β dendrite reinforced Ti-based bulk metallic glass composite (β-BMGC) is investigated for revealing the dynamic compressive mechanical response. The differences in mechanical behaviors are illustrated and the distinct inherent mechanisms are clarified.

2. Experimental procedure

The β dendrite reinforced Ti-based bulk metallic glass composite (β-BMGC) with chemical composition of $Ti_{43}Zr_{27}Mo_5Cu_{10}Be_{15}$ was prepared by arc melting under a Ti-gettered argon atmosphere, followed by the cast in a water-cooled copper mold [16]. The β dendrite phase of the BMGC were characterized by X-ray diffraction (XRD) using a diffractometer equipped with a Cu-Ka radiation. The microstructure and chemical composition were examined by a field-emission scanning electron microscopy (SEM) equipped with energy disperse spectrometer (EDS). The microstructure was also observed using a Carl Zeiss optical microscope (OM).

Split-Hopkinson pressure bar (SHPB) is a most commonly used setup for experimentally testing the dynamic mechanical behavior of various materials at different strain rates [10–12,17–19]. In this work, we

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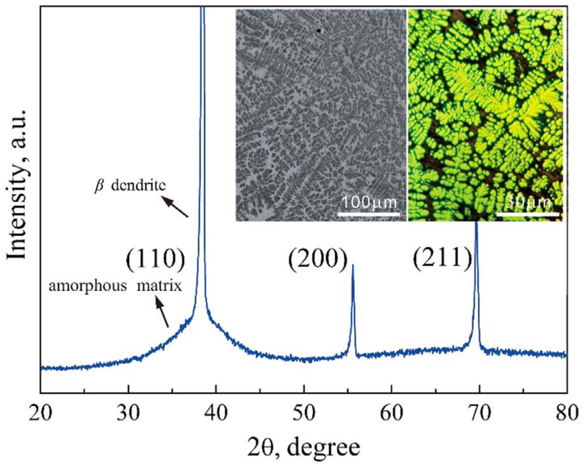

Fig. 1. XRD analysis revealing the as-cast β-BMGC material structure consisted of β-dendrites and amorphous matrix. As insets, the optical microscopic image and inverse pole figure (IPF) color image show the corresponding structure of the β-dendrites homogeneously embedded in the amorphous matrix, the ratio of which in volume fraction is about 1:1.

employed the SHPB technology to investigate the strain rate effect on mechanical behavior of the β-BMGC. The 18Ni-steel with a yield strength of 2 GPa is used to make the bars of SHPB setup, which have a uniform diameter of 37 mm. The specimens of SHPB test are cylindrical rods with the uniform dimension of 6 mm in diameter and 6 mm in height. Each test at a strain rate was repeated for duplicating the mechanical data. Afterwards, field-emission scanning electron microscopy (SEM) is applied to explore the dynamic deformation and fracture behaviors and the inherent physical mechanisms are analyzed.

3. Results and discussions

The XRD pattern of the prepared β-BMGC material shows that the β dendrites have a body-centred cubic (bcc) lattice structure with a background of the amorphous matrix (see Fig. 1). The secondary arm of the dendrites has an average size of about 3 μm. Besides, by distinguishing the color difference of the dendrites and matrix in the OM and SEM images (see the insets of Fig. 1), the volume fraction of the dendrites can be measured operating by a professional software. Multiple measurements are conducted in the selected areas with different sizes at some representative locations. The average date of the volume fraction of the β dendrites is achieved as 50%, and the error bar is ± 6%, which are in line with the report in [16]. Thus, the β-BMGC material with a micro structure of soft crystalline dendrites embedded in hard amorphous skeleton is prepared. The nanohardness and Young's modulus are evaluated as 3.12 GPa and 90.91 GPa for the soft crystalline dendrites and 7.12 GPa and 117.77 GPa for the hard amorphous skeleton, respectively [20].

Dynamic mechanical response of the β-BMGC material is characterized by a SHPB apparatus. Stress-strain plots at different strain rates are shown in Fig. 2. At each strain rate, two nearly-coincident plots are achieved for proving the repeatability of the dynamic mechanical data. At a lower strain rate of around 800/s, the max strength of 1740 MPa is arrived within a limited total strain of 3.8%. At a medium strain rate of around 1600/s, the max strength of 1620 MPa is arrived within an increased total strain of 4.7%. At a higher strain rate of around 2800/s, the max strength of 1120 MPa is arrived within a further increased total strain of 6.8%.

Strain rate dependencies of the max strength and energy density are shown in Fig. 3. Negative rate dependency of the max strength is obviously found, i.e. the max strength decreases with the increase of strain rate. However, positive rate dependency of the energy density is found, i.e. the energy density increases with the increase of strain rate. The related deformation mechanisms are revealed.

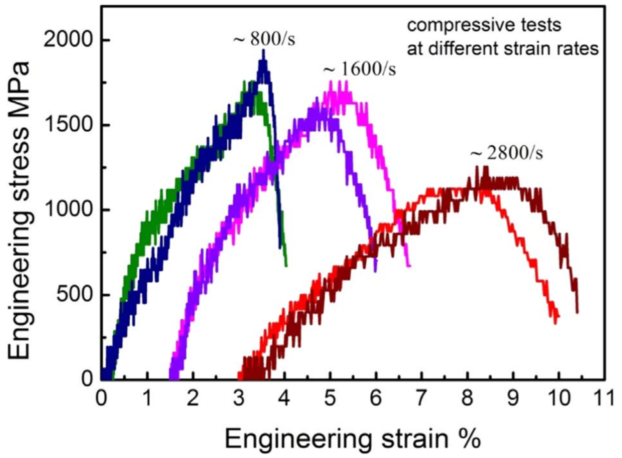

Fig. 2. Dynamic compressive stress-strain plots of the β-BMGC material at different strain rates.

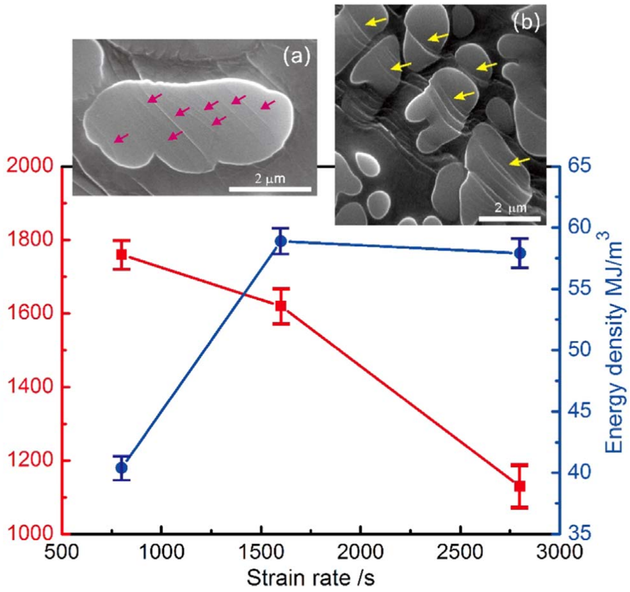

Fig. 3. Strain rate dependencies of the max strength and energy density as well as the related deformation mechanisms revealed in the insets: (a) deformation bands initiating and propagating inside the soft dendrites at lower strain rates; (b) shear bands going through the soft crystalline dendrites and hard amorphous skeleton at higher strain rates.

At lower strain rate, the deformation of soft dendrites and hard amorphous skeleton is step-by-step. A representative dendrite was observed (see Fig. 3(a)), surrounding which a few shear bands are formed in the amorphous matrix and inside which numerous deformation bands are found as pointed by arrows. In addition, these bands do not connect with each other. Thus, we can deduce that the deformation bands firstly initiate and propagate inside the soft dendrites, and then shear bandings occur in the hard amorphous skeleton. Afterwards, the applied stress goes up to a high level and the material failure at a fast speed is caused. Thus, the resultant strain energy density is lower (see Fig. 3). This deformation mechanism results in the curved characteristic of the stress-strain plots at the strain rates of around 800/s and 1600/s (see Fig. 2). This phenomenon is similar but not the same with the deformation characteristics of BMGC under a static loading reported in Ref. [21].

At higher strain rate, the deformation of soft crystalline dendrites and hard amorphous skeleton is synchronous. The deformation bands go through the soft crystalline dendrites and hard amorphous skeleton