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Effect of W volume fraction on dynamic mechanical behaviors of W fiber/Zr-based bulk metallic glass composites

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ABSTRACT

The effect of W volume fraction (V_f) on dynamic mechanical behavior of W fiber/Zr-based bulk metallic glass composites (W_f/BMGCs) was investigated by split Hopkinson pressure bar (SHPB) and finite element method (FEM). The yield strength increased with the increase of V_f under both quasi-static and dynamic compression, and the dynamic flow stress is obviously greater than that under quasi-static compression. The fracture strain also increased with the increase of V_f under dynamic compression, which is different from that the composite with ~70 vol% W exhibited the highest fracture strain under quasi-static compression. With the increase of V_f under both quasi-static and dynamic compression, the failure mode of the composites changed from shearing to a mixture of shearing and splitting, and lastly only splitting. High strain rate suppressed macro-shearing but promoted micro-shearing and splitting compared to that under low strain rate, which is suggested to be the reason why the composites exhibited different rules of strain rate-related fracture strain under quasi-static and dynamic compression.

1. Introduction

Bulk metallic glasses (BMGs) have many excellent mechanical properties, such as high yield strength, high hardness, and low Young's modulus [1–3]. However, the fracture of BMGs is highly localized by shear band during deformation, leading to nearly no macroscopic plasticity [4–6]. Thus, to improve the plasticity of BMGs, considerable efforts were taken to develop BMG based composites (BMGCs) [7–10].

W fiber/Zr-based bulk metallic glass composite (W_f/BMGC), as one kind of the earliest BMGCs, has been investigated widely due to the excellent mechanical properties and potential armor application [11,12]. Pressure infiltration [13,14] and liquid pressing process [15] were employed to prepare the W_f/BMGCs. Zhang et al. [14] reported that no reactive layer is the key to prepare the W_f/BMGCs with excellent properties. Thermal residual stress in the W fiber was established to be under compressive stress state in the three-dimensional (3D) directions, which is beneficial to the performance improvement of the W_f/BMGCs [16,17]. It was found that the W fibers yielded firstly and then transferred load to the metallic glass phase during deformation, the bonding characteristics and the interfacial status between the two phases are the key factors to determine whether the W_f/BMGCs shear or split [18–21]. In addition, the failure mode of the W_f/BMGCs is influenced seriously by W fiber volume fraction (V_f), the failure mode varied from shearing to longitudinal splitting with the increase of V_f [22–24]. Zhang et al. reported that the W fiber orientation also had a great influence on the properties of the W_f/BMGCs, exhibiting obvious anisotropic mechanical behaviors [25,26].

Although the W_f/BMGCs have been investigated and discussed widely, those works so far mainly focus on the synthesis and deformation under quasi-static compression. The mechanical behaviors of the W_f/BMGCs under dynamic compression are still unclear. Understanding the dynamic mechanical behavior is not only beneficial to the structural design for the W_f/BMGCs, but also the key to evaluate whether the W_f/BMGCs are suitable for use in the impact service environment. Thus, in the present paper, the dynamic mechanical properties and failure mode of the W_f/BMGCs with different V_f were investigated and discussed in detail.

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2. Experimental procedures

Ingots of $Zr_{41.2}Ti_{13.8}Ni_{10.0}Cu_{12.5}Be_{22.5}$ alloy were prepared by arc melting the mixture of those elements with purity of 99.8% or higher in a Ti-gettered Argon atmosphere. The W fiber with diameter of 300 μm was selected as the reinforcement. The V_f was determined to be 40%, 65%, 70%, 75%, and, 83%. The W_f/BMGCs were prepared successfully by infiltration and rapid solidification [13]. The specific procedure for preparing the composites was described in Refs. [14,25]. Fig. 1a shows the microstructure of the composite with V_f of 83% on the transverse section by SEM. The W fibers distribute homogeneously within the continuous metallic glass phase. No other crystalline phases except W were detected within the sensitivity limit of XRD.

Quasi-static (strain rate from 10^{-4} to $10^{-2}\,s^{-1}$) and dynamic (strain rate$\sim 10^3\,s^{-1}$) compression tests were performed on CMT4305 instrument and split Hopkinson pressure bar (SHPB) at room temperature, respectively. The details of SHPB can be found elsewhere [27]. The specimens are 5 mm in diameter and 10 mm long for the quasi-static compression and 5 mm in diameter and 5 mm long for the dynamic compression. Three tests were performed for a set of specimens. To reflect the work hardening/softening behaviors of the composites accurately, the true stress–true strain curves were given in the present paper. The true stress and true strain are defined by the laws:

$$s = \sigma(1-\varepsilon) \tag{1}$$

$$e = -\ln(1-\varepsilon) \tag{2}$$

where s is the true stress, e is the true strain, σ is the engineering stress, and ε is the engineering strain.

It is difficult to determine the yield stress under dynamic compression. Thus, to facilitate the comparison of the flow stress under quasi-static and dynamic compression, the stress corresponding to strain of 5% was selected. The specimens were polished to ensure parallelism and perpendicular to the axial direction before compression. Vaseline was used to reduce the friction effects between the specimens and the pressure heads under both quasi-static and dynamic compression. Fracture morphologies of the composites were examined by SEM.

To study the formation and propagation of micro-cracks in the composites accurately during dynamic compression, a maraging stop ring was fixed to constrain the deformation of the specimens. The details of the set up could be found in Ref. [28]. A plane with width of 3 mm at the side surface of the specimen was ground out and polished before compression for observing the deformation characteristics.

The relationship between the V_f and strain rate-related flow stress was established by empirical mathematical models based on response surface methodology (RSM). Finite element model (FEM) was also employed to better elucidate the deformation and failure behavior of the composites under dynamic compression by commercial software Ansys/LS-DYNA. The 3D FEM models for the specimens, the input bar, and the output bar of the SHPB were meshed in SOLID164 10 nodes mode. The 3D FEM model was built by a mesh-generated program. Fig. 1b shows the mode of the composite with V_f of 83%. The size of the mode is the same as the specimen subjected to quasi-static and dynamic compression.

The W fiber and the metallic glass phase were defined as a plastic kinematic model which is relevant to stain rate. The stain rate was introduced by the Cowper–Symonds model expressed as Eq. (3):

$$\sigma_Y = \left[1 + \left(\frac{\dot{\varepsilon}}{c}\right)^{1/P}\right]\left(\sigma_0 + \beta E_p \varepsilon_p{}^{\mathrm{eff}}\right) \tag{3}$$

where σ_Y is the yield stress, σ_0 is the initial yield stress, $\dot{\varepsilon}$ is the strain rate, c and p are the strain rate-related parameters, β is the hardening parameter, $\varepsilon_p{}^{\mathrm{eff}}$ is the effective plastic strain, and E_p is the plastic hardening modulus that is defined by Eq. (4).

$$E_p = \frac{E_{\tan}\cdot E}{E - E_{\tan}} \tag{4}$$

where $E_{\tan}$ is the tangent modulus and E is Young's modulus.

The parameters of the two phases for the constitutive model are shown in Table 1. Due to the uncertainty in the accuracy of the stress at the initial stain under dynamic compression, the stress at strain of 5% was chosen for comparison.

3. Results

Fig. 2 shows the typical true stress–true strain curves of the composites with different V_f under compression at strain rate of $10^{-3}\,s^{-1}$ (a) and $3\times10^3\,s^{-1}$ (b), respectively. As seen in Fig. 2a, the stress–strain curves of the composites clearly exhibit a yield drop response at strain rate of $10^{-3}\,s^{-1}$, which is common to bcc metals. Different from the traditional metals/alloys exhibiting work-hardening behavior, the present composites show work-softening behavior, which is related to the brittle metallic glass phase. By contrast, the typical true stress–true strain curves of the

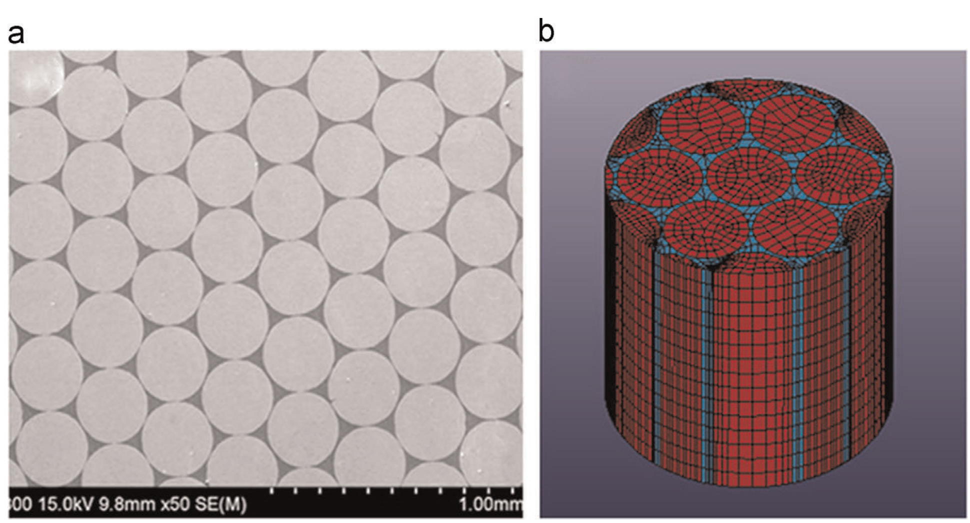

Fig. 1. SEM image of the composite with V_f of 83% (a) and the corresponding FEM model (b).