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Anisotropic dynamic mechanical response of tungsten fiber/Zr-based bulk metallic glass composites

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ABSTRACT

The anisotropic dynamic mechanical behavior of the W fiber/Zr-based bulk metallic glass composites (W_f/BMGCs) with different W fiber orientations (θ_f) were investigated by split Hopkinson pressure bar (SHPB) and finite element method (FEM). The composites exhibited the most excellent mechanical properties at θ_f of 0° while the poorest at θ_f of 45°. The composites failed by longitudinal splitting at θ_f of 0°, shearing at θ_f of 45°, a mixture of shearing and splitting during 0° < θ_f < 45° or 45° < θ_f < 90°, and a mixture of shearing and transverse splitting at θ_f of 90°. Strain rate sensitivity of the composites also varied with θ_f, exhibiting positive strain rate sensitivity at θ_f of 0°, 15°, 60°, and 75° ranging from the strain rate of 10^{-3} to 2.1×10^3 s^{-1}, positive strain rate sensitivity with the strain rate ranging from 10^{-3} to 10^{-2} s^{-1} but negative strain rate sensitivity from 10^{-2} to 2.1×10^3 s^{-1} at θ_f of 30° and 90°, and even strain rate insensitivity at θ_f of 45°.

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, BMGs usually exhibit nearly no macroscopic plasticity during room temperature deformation due to that the deformation is highly localized in shear bands [4–6]. Thus, to improve the plasticity of BMGs, considerable efforts were proposed to develop BMG based composites (BMGCs) [7–10].

The 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 [11–12]. The bonding characteristics and interfacial status between the two phases are the key factors to determine whether the W_f/BMGCs fail by shearing or splitting [13–16]. The failure mode varied from shearing to longitudinal splitting with the increase of W fiber volume fraction (V_f) [17–20]. The W_f/BMGCs also exhibited obvious anisotropic mechanical behavior, possessing the most excellent compressive properties when the angle (θ_f) between the W fiber and loading axis is 0°, while relatively the poorest at θ_f of 45° or 90° under quasi-static compression [21–22].

However, limited data is currently available on the dynamic anisotropic mechanical behavior of the W_f/BMGCs, while which is very important for the W_f/BMGCs to be used as a kind of effective penetrator material in anti-armor application. BMGs exhibited inconsistent strain rate sensitivities, all of the positive strain rate sensitivity, negative strain rate sensitivity, and even strain rate insensitivity have been reported [23–29], while polycrystalline W usually exhibited positive strain rate sensitivity [30]. Thus, the mechanical response of the W_f/BMGCs containing metallic glass phase and W fiber may be greatly affected by strain rate. The W_f/BMGCs with high V_f (≥75%) exhibited higher stress while lower fracture strain under dynamic compression compared to that under quasi-static compression [20,31–32]. Similarly, the anisotropic mechanical behavior may also exhibit different characteristics under quasi-static and dynamic compressions, and understanding the dynamic anisotropic mechanical behaviors is very important to further evaluate the deformation and fracture mechanisms of the W_f/BMGCs under impact service environment. Thus, in the present paper, the dynamic mechanical properties and failure behavior of the W_f/BMGCs with different θ_f were investigated and discussed in detail.

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 elemental metals (purity ≥ 99.9%) in a Ti-gettered argon atmosphere. The W fiber with diameter of 300 μm was selected as the

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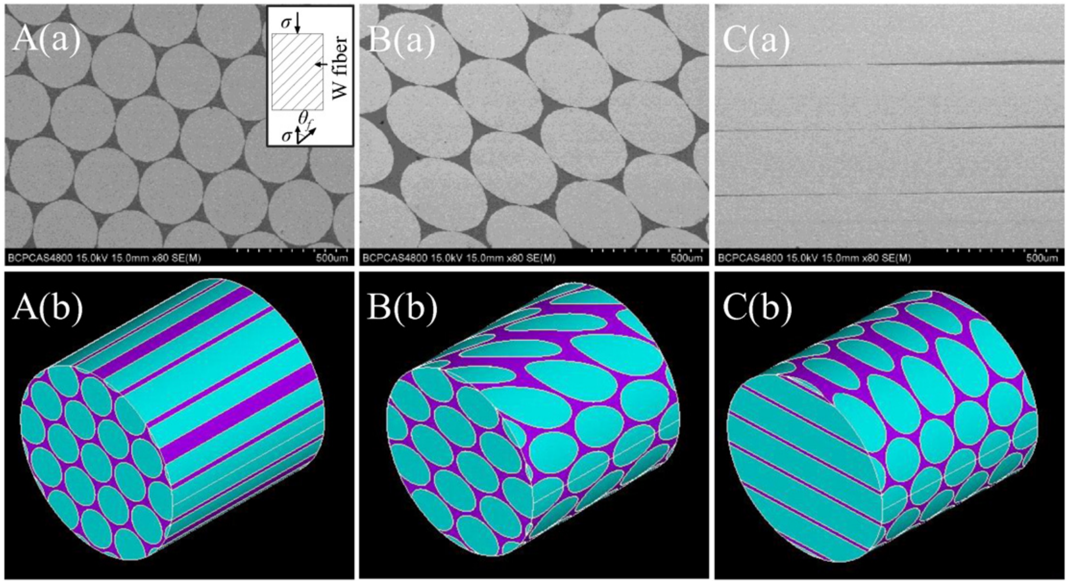

Fig. 1. SEM images of the composites (a) and the corresponding FEM models (b): (A) $\theta_f = 0°$; (B) $\theta_f = 45°$; (C) $\theta_f = 90°$ (inset: schematic diagram of uniaxial compression).

Table 1
Parameters of the W fiber and the metallic glass phase.

Properties	Tungsten	Metallic glass
Young's modulus (GPa)	410	96
Density (kg/m^3)	17,600	6680
Poisson's ratio	0.28	0.36
Yield strength (MPa)	1700	1900

reinforcement phase. The W_f/BMGCs with V_f of 83% were prepared successfully by pressure infiltration [21,33–34]. In order to investigate the effect of W fiber orientation on the mechanical behavior of the W_f/BMGCs, θ_f of 0°, 15°, 30°, 45°, 60°, 75°, and 90° were selected, respectively. Fig. 1a shows the typical microstructure of the composites with θ_f of 0°, 45°, and 90° on the transverse section by scanning electron microscope (SEM), respectively. The gray W fibers distribute homogeneously within the continuous dark metallic glass phase. No other crystalline phases except W were detected within the sensitivity limit of X-ray diffraction (XRD).

Quasi-static (strain rate from 10^{-3} to 10^{-2} s^{-1}) and dynamic (strain rate ~ 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 [35]. The specimens are 5 mm in diameter and 7.5 mm in length for the quasi-static compression, while 5 mm in diameter and 5 mm in length for the dynamic compression. Three tests were performed for a set of specimens. To reflect the work hardening/softening behaviors of the W_f/BMGCs accurately, 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, respectively.

The specimens were polished to ensure parallelism and perpendicular to the axial direction before compression. Vaseline was used to

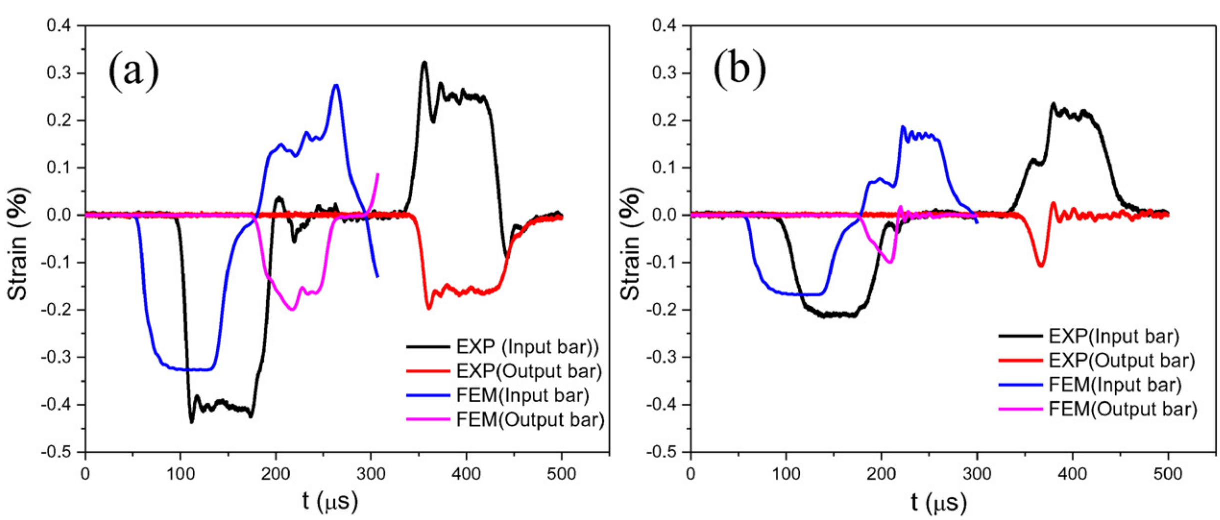

Fig. 2. Typical experimental pulse waveform and the corresponding FEM waveform under dynamic compression by SHPB: (a) $\theta_f = 0°$; (b) $\theta_f = 45°$.