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Different deformation behaviors of two *in-situ* Ti-based metallic glass matrix composites upon quasi-static and dynamic compressions

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ABSTRACT

Two kinds of *in-situ* Ti-based metallic glass matrix composites, Ti40:$Ti_{40}Zr_{24}V_{12}Cu_5Be_{19}$ (at%) and Ti48:$Ti_{48}Zr_{18}V_{12}Cu_5Be_{17}$ (at%), containing ductile dendrites are fabricated. Quasi-static and dynamic compression behaviors of the composites are investigated. Upon quasi-static compression, the Ti40 composite exhibits brittle fracture because the fine dendrites cannot retard the propagation of shear bands. In contrast, macroscopic plasticity is available for the Ti48 composite due to plastic deformation of the coarse dendrites and effective obstruction to the propagation of shear bands. Upon dynamic compression, the fracture strain of the Ti48 composite decreases due to the insufficient time for multiplication of shear bands. The strain-rate sensitivity exponent of the Ti40 composite is calculated. The Johnson–Cook (J–C) plasticity model is employed to model the flow stress behavior of the Ti48 composite.

1. Introduction

Bulk metallic glasses (BMGs) are ranked as potential engineering materials, since they exhibit a series of excellent mechanical properties at room temperature, such as ultrahigh fracture strength, large elastic limit (~2%), superior wear and corrosion resistance [1], *etc.* However, the poor room-temperature ductility, as a consequence of the prompt propagation of highly-localized shear bands [2], has extremely restricted wide applications of BMGs in engineering fields. In order to deal with the fatal problem, the crystalline phases with macroscopic ductility are introduced into the glass matrix to obtain metallic glass matrix composites (MGMCs) [3–10]. The ductile secondary phases are homogeneously dispersed in the glass matrix, which retard the prompt propagation of shear bands and facilitate their multiplication, avoiding an early failure of the composites upon loading [3–9]. Consequently, an improved plasticity is available for MGMCs. At present, three methods are usually adopted to produce MGMCs: precipitation of a dendritic crystalline phase from the glass matrix (*in-situ* composites) [3–6]; casting of the mixture of a glass-forming alloy and reinforcements such as crystalline particles and fibers (*ex-situ* composites) [7,8]; and production of a nanocrystalline phase in amorphous alloys [9,10]. Among these composites, the most commonly investigated are the *in-situ* composites developed by copper-mold-suction casting, due to the easy and convenient fabrication.

The mechanical properties of the *in-situ* MGMCs upon quasi-static loadings have been extensively investigated [3–6]. The combination of ultrahigh strength and large plasticity is available for these composites. However, to better render them the potential as structural materials, many extreme conditions, such as high speed dynamic loading, should be carefully taken into account. Up to now, although several investigations on the dynamic compression behavior of *in-situ* MGMCs have been conducted [11–18], agreements are rarely reached. Qiao et al. [11] have reported that *in-situ* Zr-based MGMCs exhibited ultrahigh strength and large macroscopic plasticity upon quasi-static compression, but failed abruptly with brittleness upon dynamic compression owing to the absence of multiple shear bands. Similar results of a Zr-based MGMC were found by Chen et al. [12]. However, Jeon et al. [13] have reported that the maximum fracture strain of Zr-based MGMCs upon dynamic compressions could be as high as 10%. Recently, an *in-situ* Ti-based MGMC exhibiting plasticity of about 2% upon dynamic loading was reported [14]. Wang et al. [15,16] have found that the total strain of *in-situ* Ti-based MGMCs upon

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dynamic loading amounted to 7%. Additionally, distinguished work-hardening capability and considerable plasticity were found when *in-situ* Ti-based MGMCs were subjected to the dynamic compression [17,18]. These contradictory results indicate that the dynamic deformation behavior of the *in-situ* MGMCs can be affected by many factors like the composition and microstructure, which motivates more investigations on the dynamic compression behavior of this kind of composites to contribute to get a better understanding of deformation and fracture mechanisms.

Conventional Ti alloys have gained broad applications in the aerospace field, due to their unique combination of physical and mechanical properties, such as low density and high specific stiffness and strength [19]. Two kinds of lightweight *in-situ* Ti-based metallic glass matrix composites with different microstructures are fabricated by copper-mold-suction casting in this study. Quasi-static and dynamic compression experiments are carried out to explore the deformation and fracture mechanisms. Dependences of the mechanical properties on microstructures and loading rates are investigated.

2. Experimental

The nominal compositions of the present *in-situ* Ti-based metallic glass matrix composites were $Ti_{40}Zr_{24}V_{12}Cu_5Be_{19}$ (at%) and $Ti_{48}Zr_{18}V_{12}Cu_5Be_{17}$ (at.%) (labeled as Ti40 and Ti48, respectively). Ingots were prepared by arc-melting the mixture of Ti, Zr, V, Cu, and Be with purity higher than 99.9% (wt%) under a Ti-gettered argon atmosphere. In order to ensure chemical homogeneity, the master alloy ingots were re-melted at least four times. Then, the rod-like samples were fabricated by suctioning the liquid alloys into a cylindrical copper mold with a diameter of 3 mm and a length of 80 mm. The cross sections of the samples were polished, and etched by a solution of 40 mL HF, 20 mL HNO_3, 40 mL HCl, and 200 mL H_2O. The microstructure was investigated by the scanning-electron microscopy (SEM). Longitudinal sections of the rods were examined by the X-ray diffraction (XRD) to identify the phases of the samples. Cylindrical samples with a length of 3 mm were prepared for the uniaxial quasi-static compressions, which were performed under a strain rate of $1\times10^{-3}\,s^{-1}$ at room temperature. The dynamic compressive loadings were conducted at ambient temperature on samples with an aspect ratio of 1:1 using a split Hopkinson pressure bar (SHPB) apparatus. An SHPB apparatus is displayed in Fig. 1 [14], which consisted of input and output bars that were made of the high strength steels. The sample was located between the input and output bars. The striker bar was launched from a gas gun towards the input bar. A compressive stress pulse was generated when the input bar was impacted by the striker bar, which would travel along the input bar towards the sample and subject it to the required stress levels. A portion of the pulse was reflected back into the input bar, while the remaining pulse was transmitted into the output bar. The input and output bars were both mounted with strain gages at midway points along the length of the bars to capture the strain signals associated with the waves when they passed by. Therefore, the compressive strain rate, $\dot{\varepsilon}$, and the strain, ε, both expressed as a function of time, t, could be obtained from the reflected wave, $\varepsilon_r(t)$, and the stress, σ, also expressed as a function of time, t, could be obtained from the transmitted wave, $\varepsilon_t(t)$. The formulas are expressed as follows:

$$\dot{\varepsilon} = -\frac{2C_b}{L_s}\varepsilon_t(t) \tag{1}$$

$$\varepsilon = -\frac{2C_b}{L_s}\int_0^t \varepsilon_r(t)dt \tag{2}$$

$$\sigma = \frac{A_bE_b}{A_s}\varepsilon_t(t) \tag{3}$$

where A, L, E, and C were the cross section area, length, elastic modulus, and elastic wave velocity, respectively. s and b represented the sample and pressure bar, respectively. Therefore, the stress–strain curves upon dynamic compressions could be obtained by eliminating the time parameter, t. More descriptions of the dynamic compression process could be found elsewhere [11,14,20]. After the quasi-static and dynamic compressions, lateral surfaces and fracture surfaces of the deformed samples were investigated by SEM to identify the deformation and fracture mechanisms.

3. Results

Fig. 2(a) and (b) shows the typical SEM images of the microstructure for the composites Ti40 and Ti48, respectively. From the two composites, it can be seen that dendrites are homogeneously distributed within the featureless and continuous glass matrix. During cooling of the melt from the high temperature, the embedded dendrites are formed by nucleation and dendritic growth, followed by the solidification of the remaining liquid alloy. For the Ti40 composite, the volume fraction of the dendrites is approximately 60%, and the average diameter of dendritic arms is about 0.3 μm. In comparison, the dendrite volume fraction of the Ti48 composite is about 65%, and the average diameter of dendritic arms is about 1 μm. In this study, it is assumed that the dendrite volume fractions of the two composites are approximately identical. The XRD patterns of two composites, shown in Fig. 2(c), indicate that only the β-Ti crystalline phase with a body-centered-cubic (bcc) structure can be detected. The sharp diffraction peaks of the β-Ti phase are superimposed on the broad diffuse scattering amorphous maxima, which is in agreement with the SEM results, further identifying the dual-phase structure of the composites.

Fig. 3 displays the engineering stress–strain curves of the two composites upon quasi-static compressions. The Ti40 composite exhibits no plasticity upon quasi-static compression. Once the maximum strength is approached, which is about 1750 MPa, the composite fails abruptly with a brittleness. It should be noted that even if the volume fraction of dendrites is higher than 70%, the strength of *in-situ* MGMCs is mainly dominated by the metallic glass matrix [3], since dendrites have much lower strength compared with the glass matrix [21]. As for the Ti48 composite, the result is completely different. It can be seen that the yielding strength is about 1630 MPa, and the ultimate strength is about

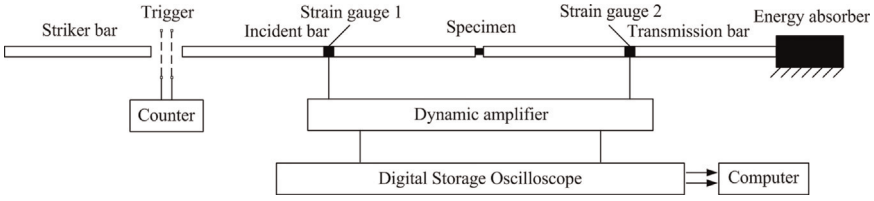

Fig. 1. A schematic diagram of the Split Hopkinson Pressure Bar (SHPB) and recording system [14].