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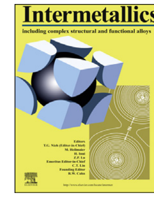

Quasi-static and dynamic compression behaviors of metallic glass matrix composites

Y.S. Wang [a, b], G.J. Hao [a], R. Ma [a], Y. Zhang [a], J.P. Lin [a, *], Z.H. Wang [c], J.W. Qiao [b, **]

[a] State Key Laboratory for Advanced Metals and Materials, University of Science and Technology Beijing, Beijing 100083, PR China
[b] Laboratory of Applied Physics and Mechanics of Advanced Materials, College of Materials Science and Engineering, Taiyuan University of Technology, Taiyuan 030024, PR China
[c] Institute of Applied Mechanics and Biomedical Engineering, Taiyuan University of Technology, Taiyuan 030024, PR China

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ABSTRACT

Compressive tests were conducted on metallic glass matrix composites at a series loading rates. It was found that mechanical properties of the composite, e.g. yielding stress and plasticity, have a week dependence on strain rates of 4.0×10^{-4} s^{-1}–4.0×10^{-1} s^{-1}. Four composites were tested at a constant strain rate of 2.3×10 s^{-1} to uncover the dynamic deformation behaviors. Compared with the quasi-static case, the yielding strength increased under dynamic loading rate, but the plasticity decreased significantly. On the other hand, the dynamic compressive has closely relation with the dendrite size and volume fraction. The decreasing of the dendrite size and volume fraction leaded to the dynamic yielding strength increased but the plasticity decreased. For a same composite, e.g. T1 alloy, the yielding strengths increased slightly but fracture strain decreased with increasing of dynamic strain rates.

1. Introduction

Bulk metallic glasses (BMGs) have been explored extensively for the excellent mechanical properties [1–4]. Most monolithic BMGs, however, fail in a catastrophic way owing to the unconstrained propagation of the highly local shear-bands at low temperature (e.g. the room temperature), hampering their engineering applications [2–7]. Fortunately, *in-situ* metallic glass matrix (MGM) composites, as one of efficient ways to alleviate this problem have been developed by introducing the crystal phase into the glass matrix [8–10]. The contributions of crystalline phase to ductility are to deform plastically by dislocations, to prohibit the rapid extension of single shear bands and to promote the formation of multiple shear bands. As a result, compared with crystalline alloys and monolithic BMGs, MGM composites offer extraordinary combinations of strength, stiffness, plasticity and toughness. Hence, these alloys have attracted extensive interests.

On the other hand, unlike the positive strain rate dependence of fracture strength in polycrystalline metallic materials [11–15], both the strain rate independent and dependent, e.g. the positive as well as negative strain rate sensitivity, have been established in monolithic BMGs. For MGM composites, although the strain rate effects have been investigated extensively, no agreement has been reached on the rate sensitivity of their mechanical response. Qiao et al. [16] found that the $Zr_{60.0}Ti_{14.7}Nb_{5.3}Cu_{5.6}Ni_{4.4}Be_{10}$ MGM composite had large plastic strain under quasi-static compression, but failed in a brittle pattern at the dynamic loading. Chen et al. [17] also reported the similar result in $Zr_{39.6}Ti_{33.9}Nb_{7.6}Cu_{6.4}Be_{12.5}$ MGM composite. On the contrary, Jeon et al. [18] found that the dynamic plasticity of $Zr_{56.2}Ti_{13.8}Nb_{5.0}Cu_{6.9}Ni_{5.6}Be_{12.5}$ MGM composites was connected with the dendrite size, and the maximum dynamic fracture strain was up to 10% in a composite with coarsening size of dendrites (9.1 μm). Very recently, MGM composites with distinguished work hardening (the fracture strain ~10%) have been found in the composition of $Ti_{62}Zr_{12}V_{13}Cu_4Be_9$ and $Ti_{48}Zr_{20}V_{12}Cu_5Be_{15}$ [19,20]. These conflicting results indicate that the mechanical behaviors of MGM composites under dynamic loading are influenced by many factors like the composition, and microstructure of these alloys, which motivates further investigation to reveal the correlation between the mechanical behaviors and strain rates.

In the current work, Ti-based MGM composites were tested at a wide range of loading rates varying from 10^{-4} s^{-1} to 10^3 s^{-1}. The dependences of the strength and plasticity on strain rates were

* Corresponding author. Tel.: +86 10 62332192; fax: +86 10 82375390.
** Corresponding author.
E-mail address: linjunpin@ustb.edu.cn (J.P. Lin).

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explored, which may increase the understanding of the rate effect on these alloys.

2. Experimental procedures

2.1. Sample preparation and characterization

The nominal composition of $Ti_{47}Zr_{19}Be_{15}V_{12}Cu_7$ (atomic percentage) ingots were prepared by arc-melting a mixture high purity elements (purity > 99.9 wt%) under a Ti-guttered argon atmosphere. Ti-base MGM composites with a diameter of 7 mm and a length of 60 mm were fabricated by the Bridgman solidification apparatus under a fixed heating temperature and a constant holding time, but the different withdrawal velocities of 0.5, 1.0, 1.6, and 2.0 mm/s, named as T1, T2, T3 and T4 composites [21]. The X-ray diffraction (XRD) in a PHILIPS APD-10 diffractometer with Cu Kα radiation was employed to analyze the microstructure characteristic of the composite. The scanning electron microscopy (SEM, SUPRA-55) was used to investigate the microstructure and fracture. Thermal properties were measured by a Perkin–Elmer DSC 7 differential scanning calorimeter under argon atmosphere at a heating rate of 20 K/min.

2.2. Mechanical tests

The quasi-static compression with a cylindrical sample (3 mm × 6 mm) was performed at various strain rates (from $4.0 \times 10^{-4}\ s^{-1}$ to $4.0 \times 10^{-1}\ s^{-1}$) by an Instron 5969 testing machine. Dynamic compression with a cylindrical sample (3 mm × 3 mm) was carried out by a split Hopkinson pressure bar (SHPB) apparatus. All samples for compression tests were cut from Ti-based MGM composites by a wire cut electric discharge machine, and were carefully prepared to ensure the parallels of their ends. Moreover, compression tests were repeated at least five times for dynamic strain rates and three times for quasi-static rates to ensure the stability of results. More descriptions of the dynamic compressive process can be found elsewhere [18,22].

Table 1
Dendrite volume fraction, size and results of DSC analysis for Ti-based MGM composites.

Composite	ν (μm/s)	V_f (%)	λ (μm)	T_g (K)	T_{x1} (K)	ΔT (K)
T1	500	62 ± 1.7	11.2 ± 1.1	597.9	658.6	60.7
T2	1000	65 ± 2.5	7.3 ± 0.8	605.6	664.8	59.2
T3	1600	61 ± 0.9	4.8 ± 1.2	609.5	671.0	61.5
T4	2000	58 ± 1.1	2.6 ± 1.0	613.1	675.1	62.0

ν – Withdrawal velocity of the Bridgman solidification V_f – Volume fraction of the dendrite λ – Dendrite size T_g – Glass transition temperature T_g – The onset crystallization temperature T_{x1} – The supercooled liquid region.

3. Results

3.1. Materials characterization

3.1.1. Microstructure

Representative SEM images of T1, T2, T3 and T4 composites are shown in Fig. 1. Basically, the crystalline phase is homogenously distributed in the amorphous matrix. Similar results can been found in Refs. [9,10,21,23]. With increasing of withdrawal velocities, though the volume fraction of dendrites decreased slightly, the average dendrite size decreased from 11.2 μm of T1 to 2.6 μm of T4, as provided in Table 1. Here, the percentages of dendrites were attained by analyzing the contrast of the two phases from SEM images using Photoshop software [8]. Based on the theory of the nucleation/growth of the liquid/crystal reaction during solidification [24], a large withdrawal velocity (corresponds to a high cooling rate) leads to a large super-cooling temperature for the Bridgman solidification. The growth of the crystalline phase is depressed, but nuclei are promoted under a large super-cooling temperature. Comparing Fig. 1(a) to (d), the dendrite size decreased because

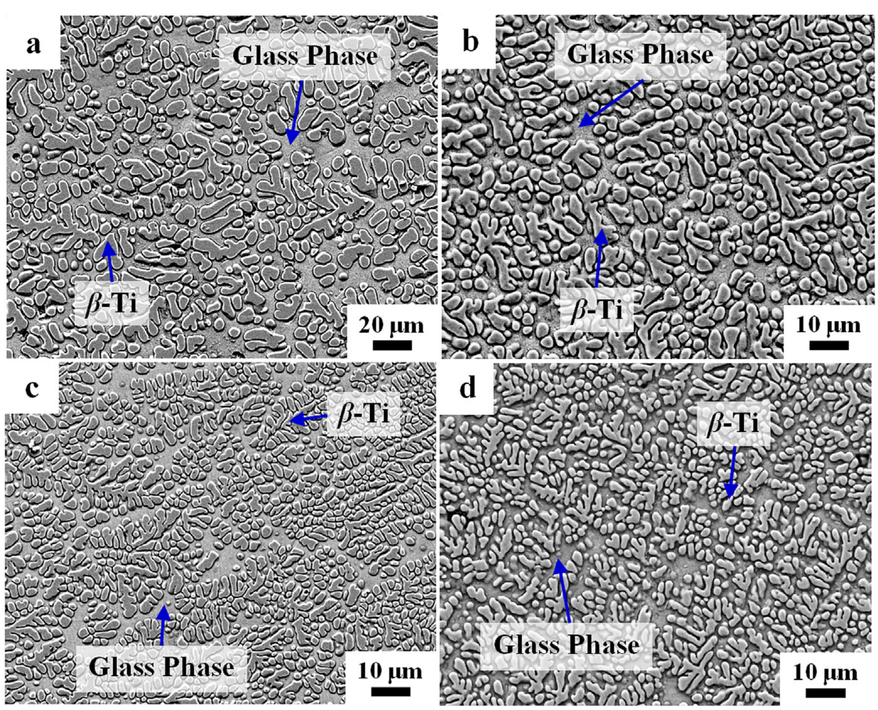

Fig. 1. SEM micrographs of Ti-based MGM composites: (a) T1, (b) T2, (c) T3 and (d) T4.