Materials Science & Engineering A 735 (2018) 441–447

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

# Distinct compressive and tensile behavior of a metallic glassy composite at elevated temperature

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ARTICLE INFO

*Keywords:*
Metallic glass
Composite
Mechanical property
Titanium alloys

ABSTRACT

The mechanical properties and deformation behaviors of a Ti-based metallic glassy composite consisting of a dendrite phase with a body-centered-cubic structure and a glassy matrix were examined under the compression and tension at elevated temperature. The composite was characterized by the work-hardening behavior and high plasticity of over 50% under compression loading but the strain-softening behavior with strain of 25% under tension loading in supercooled liquid region temperatures. The difference was discussed according to the local uniformity and instability between the multiplied dislocations in the dendrite phase and the homogenous viscous flow of the glassy matrix.

## 1. Introduction

Bulk metallic glasses (BMGs) exhibit outstanding mechanical properties, such as remarkable yielding strength, hardness, and elastic properties, because of their unique atomic structures [1–3]. Thus, these alloys have stimulated widespread interest. However, the deformation of BMGs through highly localized shear bands at low temperatures (even at room temperature) results in limited plasticity during compression and catastrophic failure under tension [1–3]. This characteristic restricts the promising applications of BMGs as structural materials. Metallic glassy composites (MGCs) consisting of an *in situ* dendrite phase and a metal glassy matrix is an effective approach to overcome this problem [4–7]. These composites have high strength and hardness similar to metallic glasses combined with the good plasticity and ductility of crystalline alloys [8–12]. The motion of dislocations within dendrites induces the yielding of the composite and prohibits the rapid propagation of the major shear bands through the plastic deformation of dendrites. These processes increase the number of shear bands through the dendrite/glass interface such that excellent plasticity and ductility are obtained at room temperature [4–12]. Monolithic BMGs display excellent homogeneous and uniform deformation, that is, superplasticity, in the supercooled liquid region (SLR, $0.6T_g < T < T_x$, where $T$ is the applied temperature, $T_g$ is the glass transition temperature, and $T_x$ is onset of crystallization temperature). This characteristic offers superior shaping and forming capabilities [2,3] and has been considered in semi-solid processing to directly form components [13–15]. However, a fatal brittle failure still hinders the applications of BMGs at room temperature. Thus, the deformation of MGCs at elevated temperature has been extensively investigated.

The deformation behavior of these composites is often complex and susceptible to many factors, such as composition, microstructure, strain rate, temperature, and loading pattern [16–23]. For monolithic BMGs, the majority of previous findings refers to a homogenous flow behavior in the SLR [2,3,13–15,18]. However, Fu et al. [16] found that the viscosity of $Zr_{51}Cu_{28}Al_{21}$ MGCs (crystalline phase volume fraction, $V < 20\%$) increased by introducing a low volume fraction of *in-situ* particles. Moreover, the MGCs were further strengthened with increasing $V$ in a homogenous flow [17]. Liu et al. [19] reported that when the $V$ of a Cu-based MGC is over a threshold, the yield strength is dominated by the dendrite at room temperature. Singh et al. [20] believed that when $T_g < T < T_x$, the $Zr_{39.6}Ti_{33.9}Nb_{7.6}Cu_{6.4}Be_{12.5}$ ($V \sim 67\%$) MGCs exhibit homogeneous and even superplastic deformation at lower strain rates under compression loading (*e.g.,* $10^{-4}$/s) but inhomogeneous deformation at higher strain rates (*e.g.* $10^{-2}$/s). However, Qiao et al. [21] showed that $Ti_{46}Zr_{20}V_{12}Cu_5Be_{17}$ MGC ($V = 43\%$) do not exhibit superplastic elongation under tension because of the evidently increased viscosity in the presence of dendrites within the glass matrix. Cui et al. [22,23] observed a strong work-hardening behavior in $Ti_{50}Zr_{20}Nb_{12}Cu_5Be_{13}$ MGC ($V = 51\%$) because of the dislocation motion in a dendritic phase under compression in the

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https://doi.org/10.1016/j.msea.2018.08.062
Received 20 May 2018; Received in revised form 17 August 2018; Accepted 20 August 2018

SLR, but the strain is over 80% under tensile loading.

The plastic deformation in monolithic BMGs results from the competition between the creation and annihilation of free volume induced by a shear-stress-driven atomic diffusion and rearrangement [1–3]. The localized unstable deformation region, as localized shear bands, is in narrow disk-shaped shear transformation regions at low temperature but in roughly spherical regions at high temperature [2,3,13–15]. By contrast, the plastic deformation of crystalline alloys is related to the production and annihilation of dislocations [26,27]. Hardening results from the increasing continuous immobilization of mobile dislocation as strain increases, but the softening behavior is associated with the generation or recovery of mobile dislocations [28,29]. The local deformation of the crystalline, such as the local strain-hardening in a cross-section of a specimen, refers to the evolution of the coupled effects of the mobile and immobile dislocations. The local mechanical properties can be estimated from the bulk properties by measuring the overall strain-hardening in the macroscopic bulk specimen [28–30]. Considering the constituents of MGCs, the crystalline dendrites and amorphous matrix are fundamentally different in terms of initiation and continuation of plastic deformation because of the dislocation mechanism of dendrites and the shear transformation zones of a glassy matrix phase. Hence, understanding the local nonuniformity and instability of the hot deformation behavior of MGCs has become significant.

In this paper, *in situ* ductile dendrite-phase reinforced Ti-based MGCs were chosen to investigate the deformation at high temperature under compression and tension loading. The local uniformity and plastic instabilities at elevated temperatures were discussed to obtain a fundamental understanding of the deformation of MGCs and offer a meaningful strategy for the hot processing of MGCs.

## 2. Materials and experiments

Master ingots, with the base composition of $Ti_{47}Zr_{19}Be_{15}V_{12}Cu_7$ (at %), were fabricated by arc melting at least 4 times a mixture of high-purity Ti (99.99%), Zr (99.90%), Be (97.00%), V (99.99%), and Cu (99.99%) under a Ti-gettered argon atmosphere, followed by Cu mold suction casting to obtain rod-like MGC specimens with diameter of 3 mm. The $T_g$ and $T_x$ of the composite were 613 K and 680 K, respectively, according to a previous report [31]. The microstructure and phases of the MGCs were examined by X-ray diffraction (XRD, PHILIPS APD-10, Cu Kα) and scanning electron microscopy (SEM, SUPRA-55).

Cylindrical specimens with an aspect ratio of 1:2 were cut from the rod-like specimens using a diamond saw for the uniaxial compression tests. Before the compression tests, both compressive ends were polished carefully to be parallel and perpendicular to the loading axis. The tensile specimens with a dimension of 50 mm (length) × 2 mm (width) × 1.5 mm (thickness) were cut from the plate specimens by a wire electric discharge machine. All surfaces were carefully dry ground using #2500 abrasive paper. Uniaxial tensile and compressive tests were conducted on a MTS testing machine (SANS, CMT5000) at a given temperature. The applied temperature was maintained within ± 1 K and measured by a thermocouple (WRPK- 131). All specimens were heated from room temperature to the given temperature at a rate of 10 K/min and maintained at the given temperature for 10 min.

## 3. Results

Fig. 1 shows the representative microstructure of Ti-based MGCs. The dendrites (darker regions) with an average size of 4 μm are distributed homogenously in an amorphous matrix (lighter regions). The volume fraction of the dendrite phase is calculated as 45% using a photoshop software. The β-Ti crystal and an amorphous matrix are identified by the sharp characteristic diffraction peaks of the dendrite and the broad diffuse scattering maxima of the glassy matrix in the XRD pattern.

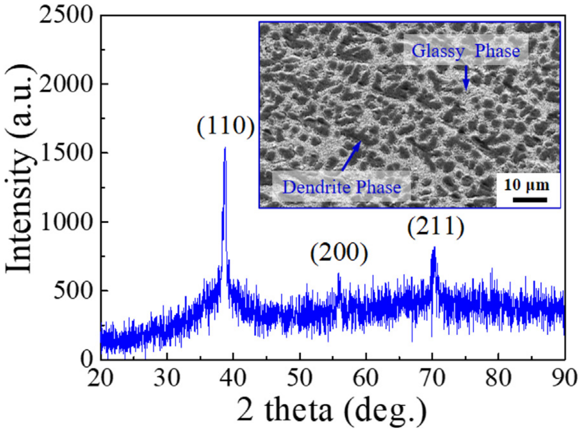

**Fig. 1.** Representative microstructure of a Ti-based MGC (inset) and corresponding XRD spectrum.

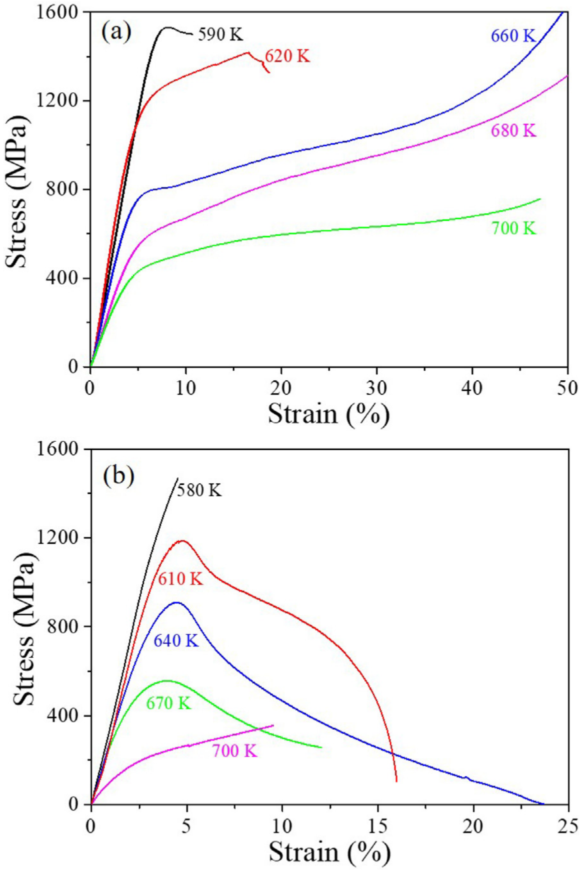

**Fig. 2.** Stress-strain curves of the Ti-based MGC at evaluated temperatures. (a) compression loading results, (b) tension loading results.

The compressive and tensile stress-strain curves at different temperatures are shown in Fig. 2(a) and (b), respectively. Both curves showed a decrease in the yielding strength with increase in *T*. When $T < T_g$, the composites exhibit an initial elastic deformation and then yield and fracture (fracture strain of 5%) under compressive loading but a brittle fracture under tension loading. When $T_x > T > T_g$, the composites show a work-hardening behavior and enhanced plasticity with increase in temperature under compressive loading because of the homogenous flow deformation of the glassy phase. The specimens were interrupted before failure for tests at 660 K and 680 K. Nevertheless, similar to the monolithic BMGs, the samples display a strain softening behavior under tension tests [14,18]. When $T_x < T$, compared with the