Materials Science & Engineering A 677 (2016) 376–383

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

# Excellent plasticity of a new Ti-based metallic glass matrix composite upon dynamic loading

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ARTICLE INFO

*Article history:*
Received 8 May 2016
Received in revised form
13 September 2016
Accepted 15 September 2016
Available online 16 September 2016

*Keywords:*
Bulk metallic glass
Dynamic loading
J-C model
Adiabatic temperature rise

ABSTRACT

Quasi-static and dynamic compressive properties of *in-situ* $Ti_{60}Zr_{14}V_{12}Cu_4Be_{10}$ bulk metallic glass matrix composites containing ductile dendrites were investigated. Upon quasi-static compressive loading, the composite exhibits a high fracture strength of ~2,600 MPa, combined with a considerable plasticity of ~40% at room temperature. However, upon dynamic loading, an excellent plasticity of ~16% can be obtained due to the abundant dislocations and severe lattice distortions within dendrites and multiplication of shear bands within the glass matrix analyzed by transmission-electron microscopy. A constitutive relationship is obtained by Johnson-Cook plasticity model, which is employed to model the dynamic flow stress behavior. In addition, under dynamic compression, the adiabatic temperature rise increases with increasing strain rates, resulting in that the softening effect within the glass matrix is obviously enhanced during deformation.



## 1. . Introduction

Since firstly fabricated by rapid cooling from the melts by Duwez et al. [1], the bulk metallic glasses (BMGs) were developed quickly and attracted significant technological and scientific studies all over the world on account of a series of superior mechanical properties at ambient temperature, such as ultrahigh strength, high hardness, large elastic limits, and excellent wear and corrosion resistance [2–6]. BMGs are esteemed as potential engineering structural materials [7]. However, owing to highly localized shear deformation upon loading, BMGs exhibit limited plasticity at room temperature and have subsequent catastrophic failure without apparent macroscopic plasticity by shear softening in one band [5,8]. In order to circumvent the poor plasticity, *in-situ* formed ductile secondary phases can be introduced into the glass matrix to form the metallic glasses matrix composites (MGMCs) [9,10]. To date, compared with monolithic BMGs, the existence of dendrites within the glass matrix contributes to obvious macroscopic compressive plasticity and tensile ductility, together with the improved toughness upon quasi-static loading for *in-situ* MGMCs. The dendrites hinder the prompt propagation of shear bands and lead to multiplication of shear bands [11].

Nevertheless, actual structural engineering materials are always performed superb ductility even upon dynamic compression. Therefore, many researches focus on the dynamic loading of MGMCs to meet the engineering applications in recent years, which can be efficaciously applied to strategic fields, such as defense, aerospace, and precision optical machinery [12]. Wang et al. [13] have demonstrated that the dynamic compressive yielding strength and the maximum strain value in Zr-based MGMCs are ~2,700 MPa and ~4%, respectively. Jeon et al. [14] have investigated the dynamic compressive behavior of Ti-based MGMCs modified from Ti-6Al-4V alloy and the dendrites inside have great impact on the plasticity of alloys. According to previous study by Qiao et al. [15], the multiple shear bands have been discovered for the *in-situ* Zr-based MGMCs under quasi-static compression, leading to large plasticity, whereas expeditious failure under the dynamic case is due to insufficient time to form profuse shear bands. Previously, researchers have found that brittle fracture or little plasticity occurred for *in-situ* MGMCs upon dynamic loading [16–18]. However, during quasi-static and dynamic loading, only limited information of the influence of temperature rise on the mechanisms of the deformation from the microstructure is available.

In the current study, a new Ti-based MGMC was developed and investigated at quasi-static and dynamic loadings so as to further understand the deformation mechanisms.

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http://dx.doi.org/10.1016/j.msea.2016.09.057

## 2. . Experimental

### 2.1. . Sample preparation and characterization

The ingot with a nominal atomic percent composition of $Ti_{60}Zr_{14}V_{12}Cu_4Be_{10}$ (Ti60) was prepared by arc melting the mixture of Ti, Zr, V, Cu, and Be with purity higher than 99.99 wt% in a Ti-getted high purity argon atmosphere. In order to ensure the chemical homogeneity, the pre-alloyed ingots were re-melted at least four times. The rod like samples with 3 mm in diameter and about 85 mm in length were obtained by suctioning the melt into the copper mould in an argon atmosphere. The structure of phases was checked by X-ray diffraction (XRD) with a monochromatic Cu-Kα radiation. The microstructures of the as-cast samples, and the lateral and fracture surfaces of the deformed samples after quasi-static and dynamic compression tests were investigated using scanning-electron microscopy (SEM). The cross sections of the as-cast samples were polished, and etched by a solution of 40 mL HF, 20 mL $HNO_3$, 40 mL HCL, and 200 mL $H_2O$ for SEM observation. The structural characteristics of the samples before and after compression were investigated using transmission-electron microscopy (TEM) and high-resolution transmission electron microscopy (HRTEM) (JEOL-2010). The TEM specimens were obtained by ion thinning with liquid nitrogen cooling.

### 2.2. . Mechanical tests

The uniaxial compressive tests under quasi-static loading were preformed on a 3-mm cylinders at ambient temperature at a strain rate of $5 \times 10^{-4}\ s^{-1}$. The dynamic compressions were carried out by a split Hopkinson pressure bar (SHPB) [12] on samples with an aspect ratio of 1:1 at room temperature. It is made of a compressed gas-gun, a striker bar, a incident bar, specimen, a transmission bar, strain gauges, and an oscilloscope. The stress-strain curves of the tested specimen were obtained by inputting the recorded strain pulses into computing software. According to the one-dimensional stress wave theory [19], the stress and strain as well as strain rate could be obtained finally. Furthermore, in order to ensure the stability of results, the quasi-static compression tests were repeated at least three times and five times for dynamic compression tests. The detailed process was described elsewhere [20,21].

## 3. . Results

### 3.1. . Microstructures of MGMCs

The microstructure and the dual-phase structure of the Ti60 are tested by the SEM and the XRD pattern, respectively. Fig. 1 (a) shows the back scattered SEM image of the cross-section of the as-cast composites. It can be seen that the dendrites are homogeneously embedded in the continuous glass matrix. By estimating the contrast in SEM images, the volume fraction of the dendrites is approximately 67%. This means that the secondary phase takes most part of the composites. It has been demonstrated that the size of the dendritic arms in the composites are 3–5 μm. The XRD exhibited in Fig. 1(b) reveals that the body-centered-cubic (bcc) crystalline peaks are overlapped on the broad diffuse scattering amorphous maxima, which means that the matrix has amorphous structure, and the dendrites are β-Ti solid solution. It is certified by the microstructure characterization mentioned above.

To further examine the dual-phase structure, TEM and HRTEM analyses are employed on the as-cast composites. It is obviously observed that the bright-field image of the dendrites and the matrix with a low magnification is shown in Fig. 2(a), which is similar to the SEM in Fig. 1(a). The edge of the dendrites is very smooth, indicating the absence of deformation [22]. Fig. 2 (b) displays the HRTEM image of the matrix, and no crystallization can be detected. Only diffuse halos, typical characterization of an amorphous structure, can be found from the selected area electron diffraction (SAED) pattern in the inset of Fig. 2(b). On the contrary, the crystal lattice is presented in Fig. 2(c), and the SAED pattern is identified as the $[\bar{1}11]$ zone axis of bcc β-Ti, as presented in the inset of Fig. 2(c). Fig. 2(d) shows the inverse fast-Fourier transform (IFFT) pattern of the area of the dendrites. Lacking of the stress, no lattice distortion and dislocations can be found. Similar results can be observed in other Ti-based MGMCs [22].

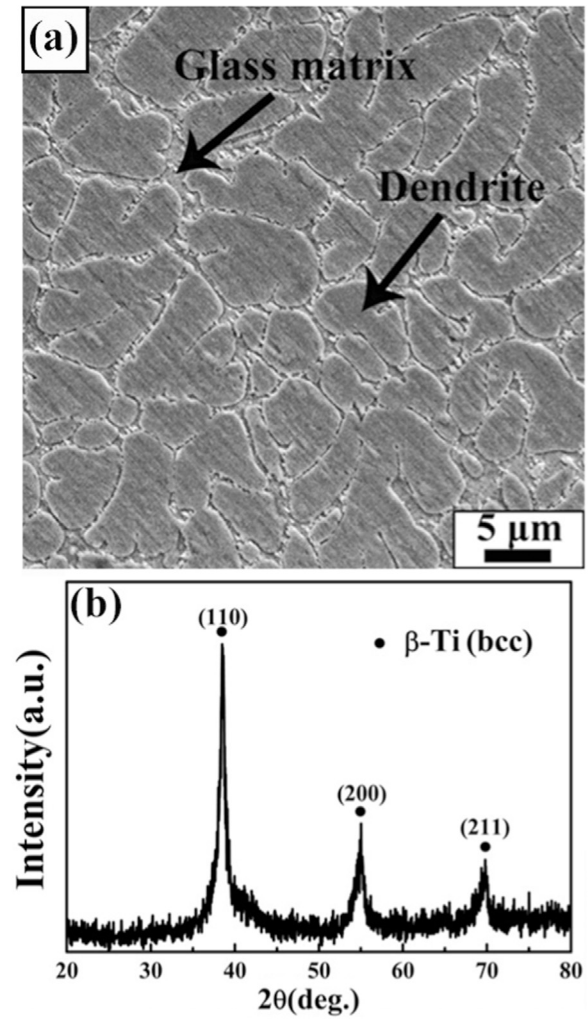


**Fig. 1.** (a) SEM image of the microstructure for Ti60 composite. (b) XRD pattern of the composite.

### 3.2. . Mechanical properties

The typical engineering stress-strain curves under quasi-static and dynamic compressions of the present MGMCs are shown in Fig. 3. Fig. 3(a) displays the engineering stress-strain curve of the present composite upon quasi-static compressive loading at room temperature at a strain rate of $5 \times 10^{-4}\ s^{-1}$. It can be clearly seen that for the present composites, the yielding strength and the plasticity are about 1120 MPa and 43%, respectively.

Compared with the typical monolithic BMGs with little plasticity [23,24], the plasticity of present MGMCs has been greatly improved. After obvious linear work-hardening, the MGMCs finally