Intermetallics 96 (2018) 94–103

Contents lists available at ScienceDirect

Intermetallics

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

A comparative study of the rate effect on deformation mode in ductile and brittle bulk metallic glasses

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ARTICLE INFO

Keywords:
Metallic glass
Rate effect
Deformation mode
Ductile
Brittle

ABSTRACT

The rate effect on the deformation mode of bulk metallic glasses (BMGs) is investigated by a comparative study between ductile and brittle compositions via real-time photographing. The strain-rate controls the deformation mode transition from shear-dominated sliding under quasi-static compression to cracking-dominated fracture under dynamic compression. In ductile BMGs, progressive sliding occurs at lower strain rate and contributes to a stable deformation manner. In brittle BMGs, however, unstable deformation occurs through rapid sliding even under quasi-static compression. Both ductile and brittle BMGs undergo unstable deformation under dynamic compression. The rate-dependent and composition-dependent tendency of stable or unstable deformation is well characterized by a model based on the ratio of the applied strain energy to the critical dissipation energy at the local shear banding region.

1. Introduction

The coexistence of macroscopically brittle failure and being capable of considerable plastic shear flow at microscale in metallic glasses leads to complicated deformation modes under various loading conditions. It is well accepted that the plastic deformation of bulk metallic glasses (BMGs) is accommodated by shear banding [1–6]. The multiplication and intersection of shear bands contribute to a stable deformation manner [7,8]. However, the catastrophic failure also originates from shear instability within shear bands [9–13]. Thus, the various deformation modes in BMGs are determined by different shear banding behaviors. Extensive reports have shown that the shear banding behaviors and hereby deformation modes are influenced by various factors, including material compositions [14–16], loading rate [17–24] and temperature [25–28]. In addition, sample size [29–31] and stress state during loading [32,33] also affect deformation mode.

Among these factors, loading rate is considered as one of the most significant since metallic glasses are applied to areas over a wide range of strain rate. Zeng et al. [23] reported a shear-dominated failure under quasi-static compression, while a fragmental fracture under dynamic compression. The flow serrations during plastic flow was suggested to be related to shear stability [34], and the serrations gradually disappeared with increasing strain rate [35,36]. Mukai et al. [17] proposed BMGs occurred progressive sliding at lower loading rate, while rapid sliding at higher rate. These findings indicate a transition from stable deformation to unstable deformation with increasing loading rate. However, some compositions exhibit unstable failure even at a low strain rate [4,20]. Thus, a systematic study of how rate-effect controls the deformation mode in different compositions is needed.

In the present study, we have investigated the strain-rate effect on the deformation mode in ductile and brittle BMGs under quasi-static and dynamic compression. $Zr_{65}Cu_{18}Ni_{7}Al_{10}$ (short for Zr65-BMGs) and $Zr_{50}Cu_{40}Al_{10}$ (short for Zr50-BMGs) bulk metallic glasses were selected as model materials for ductile and brittle BMGs, respectively. Real-time photographing and scan electronic microscope (SEM) observation were utilized to relate the mechanical responses to specific shear banding or cracking behaviors. The results showed the tendency of stable deformation or unstable deformation originates from different shear banding and cracking behaviors during softening process. Such tendency showed both rate dependence and composition dependence. A model from the energy-dissipation perspective was introduced to reveal how rate-effect controlled deformation mode in ductile and brittle BMGs.

2. Materials and methods

Monolithic $Zr_{65}Cu_{18}Ni_{7}Al_{10}$ and $Zr_{50}Cu_{40}Al_{10}$ (at %) BMGs were prepared by arc-melting a mixture of corresponding pure compositions

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https://doi.org/10.1016/j.intermet.2018.01.020
Received 26 December 2017; Received in revised form 24 January 2018; Accepted 28 January 2018
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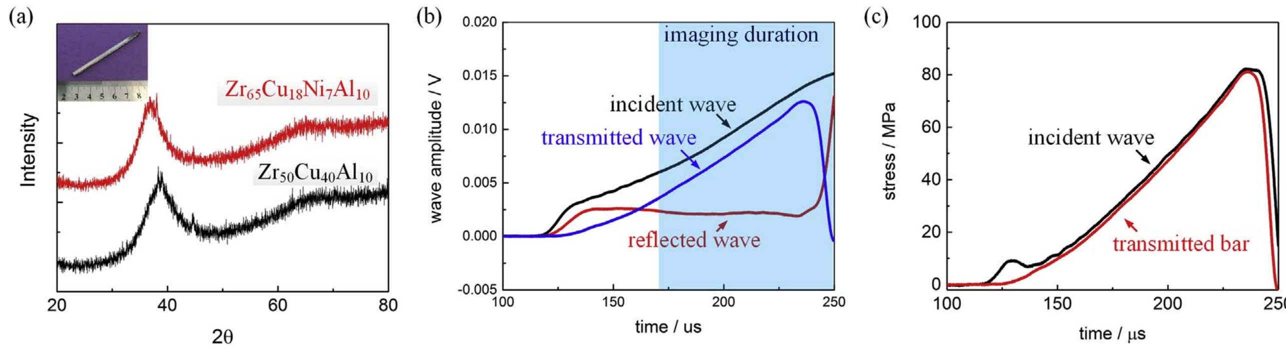

Fig. 1. (a) XRD patterns of Zr65-BMG and Zr50-BMG. Inset is the alloy ingot. (b) Typical incident, reflected and transmitted wave under dynamic loading. The image duration (the blue area) is set to cover the first impulse during loading. (c) The stresses on the incident and transmitted bar during the first impulse, indicating the stress equilibrium is guaranteed in the specimen. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(99.9%) in a Ti-gettered argon atmosphere. The master alloy ingots were re-melted six times to ensure homogeneity, which was then injected into a water-cooled copper mold to fabricate rectangle ingots (see the inset of Fig. 1a). The amorphous nature of the ingots was confirmed by X-ray diffraction (XRD) (Fig. 1a). Rectangle samples with a cross section of 3×3 mm were cut from the ingots. The aspect ratio of the specimens is 2:1 under quasi-static compression, and 1:1 under dynamic compression. Both ends of the samples were polished to ensure surface parallelism.

Quasi-static compressive tests were performed by a CRIMS DNS-100 hydraulic testing machine. The loading rates were set at 5×10^{-4} s^{-1} and 5×10^{-3} s^{-1}. Dynamic compressive tests were performed by split Hopkinson pressure bar (SHPB) with loading rates of 300 s^{-1} and 1000 s^{-1}. Typical wave signals under dynamic loading were shown in Fig. 1b. The stress equilibrium in the specimen was guaranteed during the first impulse (Fig. 1c). Real-time deformation processes under quasi-static and dynamic loading were captured by high-speed cameras. Under dynamic loading, the high-speed camera was triggered by the first rising edge of the incident wave, ensuring the capture of deformation process during the first impulse (see the imaging duration in Fig. 1b). For each testing sample, its one surface was polished to be a mirror surface in order to capture shear banding and cracking behaviors. At least six samples were tested for each condition to exclude occasional cases. The fracture samples were observed by a scan electronic microscopy (SEM, ZEISS SUPRA 55).

3. Results

3.1. Stress-strain curves under quasi-static and dynamic compression

The stress-strain curves of Zr65-BMGs under quasi-static and dynamic compression are shown in Fig. 2a. The Zr65-BMGs show considerable plasticity with serrated flow under quasi-static compression, which corresponds to a stable deformation manner. It is worthy to mention that the sample of 5×10^{-4} s^{-1} is unloaded before catastrophic fracture, but it is obvious that Zr65-BMGs can keep stable deformation at a much larger strain under lower loading rate. However, the stress-strain curves under dynamic loading show merely approximate elastic loading and sudden stress-drop without serrated flow. This indicates a brittle failure under dynamic loading, and a transition from stable deformation to unstable deformation with increasing strain rate. Different from Zr65-BMGs, Zr50-BMGs show limited plasticity under both quasi-static and dynamic loading (Fig. 2b). This implies the rate effect on the deformation mode might not be obvious in Zr50-BMGs. To further investigate the deformation modes of both ductile and brittle BMGs under various loading conditions, the real-time deformation images are synchronized with the corresponding mechanical responses.

3.2. Shear banding and cracking behaviors in ductile BMGs

Fig. 3 shows the stress-strain curves and characteristic shear banding behaviors of Zr65-BMGs under quasi-static compression. The stress-strain curves can be divided into three stage, i.e., elastic deformation, work-hardening stage and softening stage (Fig. 3a1 and a2). At the end of the work-hardening stages, a number of shear bands are observed on the imaging surface of the Zr65-BMG samples (Fig. 3b1 and b2). This indicates the formation of multiple shear bands occurs during work-hardening. Fig. 3c1 and c2 shows preferential slip planes originate from existed shear bands during the softening stage under 5×10^{-4} s^{-1} and 5×10^{-3} s^{-1}, respectively. Comparing Fig. 3c1 and d1 (or c2 and d2), one can see progressive sliding occurs along the slip planes in a stable manner. The stick-slip motion was suggested to

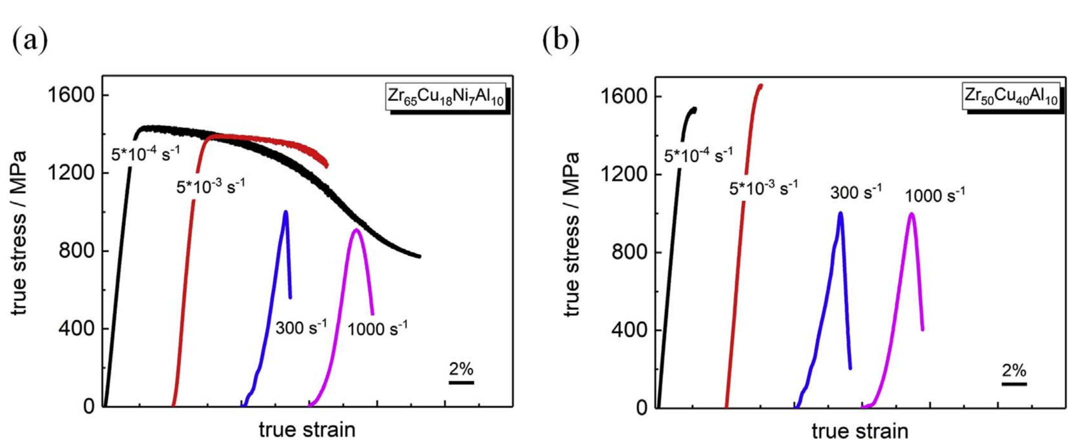

Fig. 2. Stress-strain curves of (a) ductile (Zr65-BMGs) and (b) brittle (Zr50-BMGs) under quasi-static and dynamic compression.