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Effect of strain rate on compressive behavior of Ti-based bulk metallic glass at room temperature

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ABSTRACT

Compressive deformation behavior of the $Ti_{40}Zr_{25}Ni_8Cu_9Be_{18}$ bulk metallic glass was investigated over a wide strain rate ranging from 10^{-4} to 10^3 s^{-1} at room temperature. Fracture stress was found to increase and fracture strain decrease with increasing applied strain rate, which were due to the decrease of the density of shear bands. Serrated flow was observed at lower strain rate. The appearance of a large number of shear bands was probably associated with flow serration observed during compression. At high strain rates, the rate of shear band nucleation was not sufficient to accommodate the applied strain rate and thus caused an early fracture of the test sample. The positive strain rate dependence of compressive strength might be associated with the different microstructure on the atomic scale in the Ti-based amorphous matrix.

1. Introduction

Bulk metallic glasses (BMGs) have attracted much more attention for a potential application as structural materials. Compared to conventional engineering alloys, they show unique properties such as high strength and hardness, large elastic strains (~2%), high fracture toughness, and excellent wear resistance [1–5]. But their applicability is limited by their near-zero tensile ductility resulting from work-softening and shear localization. Although the mechanical behavior of BMGs has been extensively studied, the precise nature of the deformation mechanisms of metallic glasses remains unclear [6–8]. However, the effects of strain rate in BMGs are dependent on the loading conditions and chemical components of the material itself. BMGs with different chemical components manifest different strain rate effect. Bruck et al. [9] and Lu et al. [10] reported that the fracture strength of a Zr-based BMG was independent of the strain rate in compression. Recently, the positive and negative strain rate sensitivity was found in Zr-based [11,12] and Nd-based [13] BMGs, respectively. These results suggest that the mechanical behavior under different strain rates can be influenced significantly by many factors, such as level of amorphization, loading mode, chemical compositions of BMGs.

To date, the limited data is available for the strain rate effect on the mechanical behavior of BMGs. Therefore, more experimental data are required to fully understand the deformation mechanism of BMGs. In this paper, we investigate the effect of strain rate on the compression strength, plastic strain and fracture behavior of $Ti_{40}Zr_{25}Ni_8Cu_9Be_{18}$ BMG. No data is currently available on dynamic constitutive behavior for this class of BMGs. The experimental results can aid to better understand the deformation nature in metallic glasses over such a wide range of strain rate.

2. Experimental procedures

Ingots of $Ti_{40}Zr_{25}Ni_8Cu_9Be_{18}$ were prepared by arc-melting the constituents with a purity ranging from 99.5 to 99.99% under a Ti-gettered argon atmosphere. BMG specimens were prepared by drop casting into a Cu mold and the obtained cylindrical specimens have diameters of 3 and 1 mm. The glassy nature of as-prepared alloy rods was confirmed by X-ray diffraction (XRD). Cylindrical specimens with 1:1 and 2:1 aspect ratio were prepared for dynamic and quasi-static compression. Uniaxial quasi-static compression tests were conducted using an Instron 5567 mechanical instrument at room temperature. Dynamic compression tests were performed using the Split Hopkinson Pressure Bar (SHPB) at strain rates of 10^2–10^3 s^{-1}. In order to protect the end of the bars and limit the final strain of the specimen, some modifications such as steel inserts and lantern ring were used in dynamic compression tests. A MoS_2 lubricant was used to reduce friction between testing samples and the platen of the machine. After compression, the fracture surfaces were investigated using LEO1450 scanning electron microscope (SEM).

3. Results and discussion

Fig. 1 presents the compression stress–strain curves at different strain rates for the BMGs with different diameters at room temperature. For each sample, the stress–strain relation is linear up to about 2% elastic strain, followed by a clear yield point and macroscopic plastic strain without strain hardening prior to fracture in the tested

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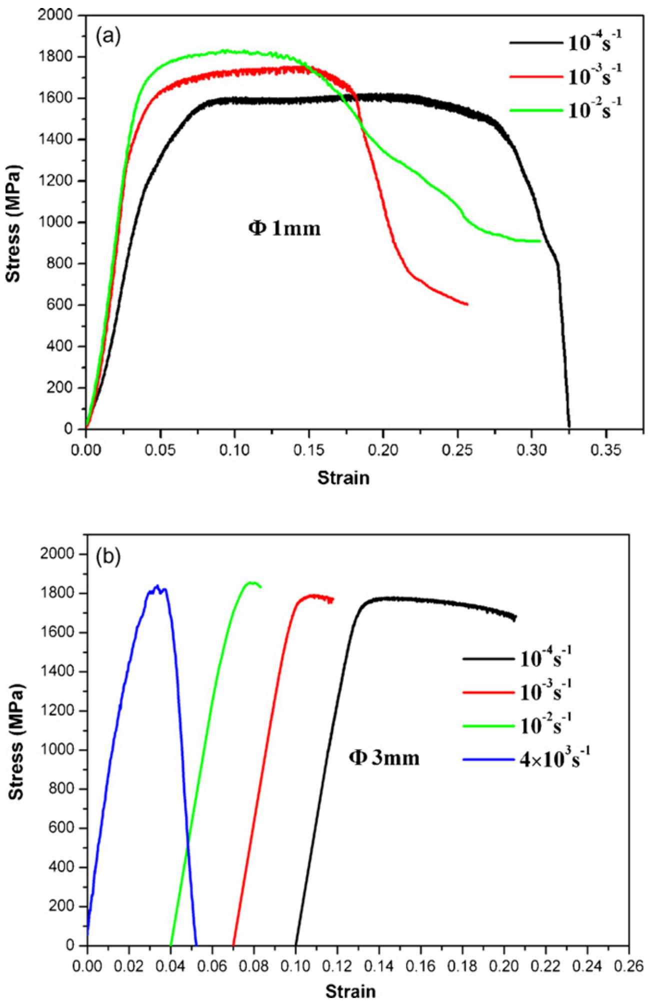

Fig. 1. Compressive stress–strain curves of $Ti_{40}Zr_{25}Ni_8Cu_9Be_{18}$ BMGs at different strain rates with diameters of 1 mm (a) and 3 mm (b).

strain rate range. However, the plastic strain is significantly different for the alloy with different strain rates. With decreasing strain rate, the plastic strain prior to failure increasing monotonically. This indicates that the stain rate plays a crucial role in achieving the plasticity of metallic glass materials.

At the same time, serrated flow phenomenon begins after yield point in the stress–strain curve. It is noted that the serrated flow at $10^{-2}\,s^{-1}$ is markedly different from those at lower strain rates. The yield strength and fracture strength distinctly increases, and the flow serration phenomenon trends vanish at $10^{-2}\,s^{-1}$. The disappearance of serrated flow at high strain rates has also been observed in nanoindentation studies by Schuh and Nieh [14] and Xing et al. [15]. The character of serrations is strongly dependent on the loading rate. The slower strain rates promote more conspicuous serrations, and rapid loading suppresses serrated flow. The phenomenon has been assumed to be associated with the initiation and propagation of individual shear bends during quasi-static loading. These results represent a transition from deformation controlled by the discrete operation of individual shear bands at low strain rate, to the simultaneous operation of multiple shear bands at higher rates. A single shear band cannot accommodate the imposed strain rapidly enough at high rates, and consequently multiple shear bands must operate simultaneously. In the present work, the decrease in serrated flow with increasing strain rate is also attributed as outlined above.

Fig. 2 shows the SEM images of shear bands on the deformed samples with diameter of 1 mm. Considering that the plastic deformation achieved by BMGs is confined at narrow region near shear bands, these specimens with different plasticities should differ in both densities and shape of the shear bands. Fig. 2(a) shows the side surface of the sample deformed at a strain rate of $10^{-4}\,s^{-1}$, dense and multiple shear bands are visible near the fracture surface. Careful observation indicates that the shear bands have a pronounced tendency to branch when they propagate through the specimen, and that some shear band paths are highly curved. In contrast, only sparse and scattered shear bands can be seen on the side surface of the sample deformed at a strain rate of $10^{-2}\,s^{-1}$. The results illustrate that the density of shear bands decreases significantly with the increasing strain rates, and the average spacing of primary shear bands increase with the increasing strain rates, thus representing the decreasing plastic strain. However, the decrease in the density of shear bands at high strain rate reported here are completely contrary to observations in previous reports. Sergueeva et al. [16] and Mukai et al. [17] found that multiple parallel shear bands and a rougher fracture surface were observed at high strain rates in tensile tests. The same experimental trends at high strain rates in compressive tests were reported by Nieh et al. [18].

Fig. 3 shows the fracture surface of the specimen with diameter of 3 mm deformed at the strain rates of 10^{-4} and $4\times10^{3}\,s^{-1}$. The fracture surface of samples tests at a strain rate of $10^{-4}\,s^{-1}$ is uneven

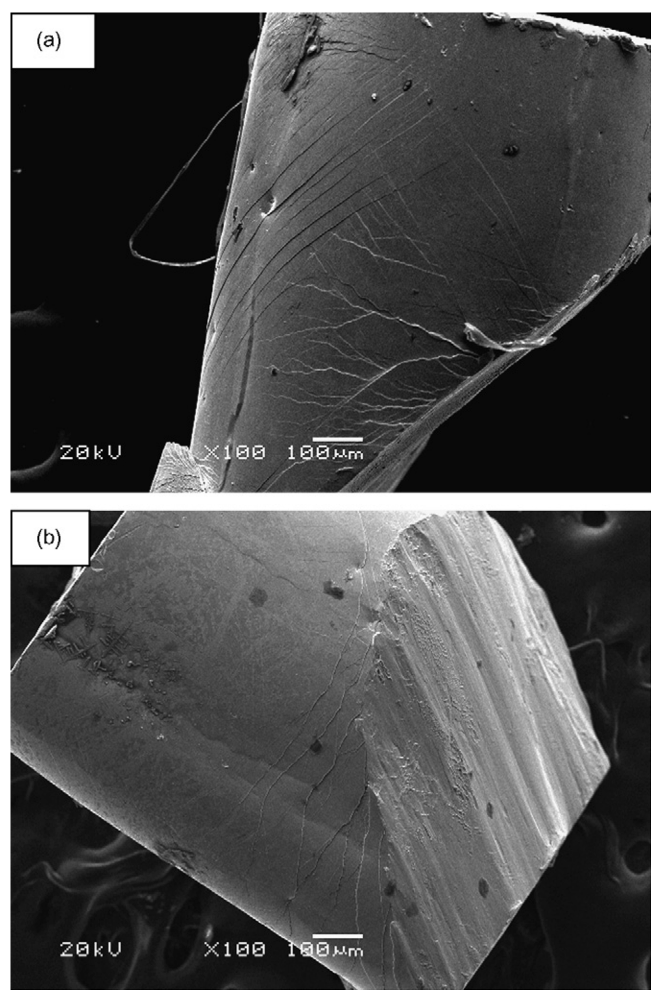

Fig. 2. SEM images showing the side view of the fractured samples with diameter of 1 mm deformed at the strain rates of $10^{-4}\,s^{-1}$ (a) and $10^{-2}\,s^{-1}$ (b).