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Deformation and fracture behaviors of Ti-based metallic glass under multiaxial stress state

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Abstract

The deformation and fracture behaviors of a Ti-based metallic glass (MG) under a multiaxial stress state were investigated using a small punch test. It was found that controlling both the initiation and propagation of a shear crack can significantly stabilize the plastic deformation of Ti-based MG by forming multiple shear bands and delaying the shear crack from reaching the critical crack length. Radial, circumferential and spiral shear band patterns and corresponding fracture modes were observed. The relationship between the shear band pattern and the stress state was established. This finding implies that a MG could be stabilized and become ductile in nature under suitable stress conditions.

Keywords: Metallic glass; Plastic deformation; Fracture; Multiaxial stress

1. Introduction

The shear deformation and fracture of metallic glass (MG) is still a hot topic, though it has been extensively investigated for decades [1–4]. Under ordinary compression, there are few shear bands, and the sample fails fast by the propagation of individual shear bands, just displaying limited plasticity (usually < 2%) [5,6]. Under uniaxial tension, because there is nothing like grain or phase boundaries to stop the fast propagation of shear bands, once the shear band initiates, it propagates quickly, leading to the catastrophic failure of MG and nearly zero macroscopic plasticity, though the shear band itself has high microscopic plasticity up to 10^2–10^4% [7,8]. Although a bending test is considered to be an inherently stable deformation method, since the stress to drive shear bands decreases gradually as the shear band approaches the neutral axis [9,10], the ductility under a bending test can be achieved only if the sample's dimension is below a critical value, suggesting a strong size effect on the bending ductility [11,12]. In addition, indentation, especially instrumented nanoindentation, has been extensively used to study the evolution of shear bands and plastic deformation instability, i.e., serrated flow behavior, in MG [13–15]. It was found that dense and regular shear bands were often formed in the region beneath the indenter [16,17], which is very intuitive for understanding the shear band morphology and is useful for investigating the plastic deformation behavior of MG. However, one of the disadvantages of indentation is that it reveals the deformation behavior of a very localized region, which cannot fully embody the macroscopic properties of MG. In contrast to the catastrophic shear failure under uniaxial compression, an MG can display a large plastic deformation of >10% with more shear bands due to the confined loading, demonstrating a ductile nature [18]. It was reported that cladding the surface can also significantly improve the plastic deformation capability of MG [19].

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A recently developed small punch (SP) test for MG can create regularly arrayed fine multiple shear bands in the MG samples, indicating that MG essentially have good plastic deformation stability and thus high ductility under suitable loading conditions [8,20]. Under SP loading, there are three failure modes, i.e., radial normal fracture, corresponding to intrinsic brittle MG, such as most Fe-, Co- and Mg-based MG with low fracture toughness; radial shear fracture; and circumferential shear fracture, corresponding to intrinsic ductile MG, such as most Zr-, Cu- and Ti-based MG with high fracture toughness [20,21]. The deformation capability of an MG with radial shear fracture is very limited, though it still shows shear deformation behavior of the intrinsic ductile MG. Therefore, the question is: can this radial shear fracture be controlled, or can the shear deformation stability be improved by tuning the stress state? Here, using the SP test, the shear deformation and fracture behaviors, and the effective plastic strain of a Ti-based MG under biaxial tension are evaluated and analyzed. It is confirmed that, under multiaxial constraint, the shear deformation stability of an MG can be greatly improved, and even the failure modes can be changed. Meanwhile, the relationship between the shear band pattern and the stress state is established.

2. Experimental

Ti-based MG with nominal chemical composition $Ti_{40}Zr_{25}Ni_3Cu_{12}Be_{20}$ was prepared by arc-melting and cast into a copper mold [22,23]. The final ingots had a rectangular shape with dimensions $60 \times 30 \times 3\ mm^3$. The microstructure was characterized by X-ray diffractometry (XRD) using a Rigaku instrument with $Cu\,K_\alpha$ radiation. XRD patterns showed that the as-cast alloy had a fully glassy structure. The mechanical properties of the MG were characterized using uniaxial compression and the SP test method [8,20,21], as illustrated in the insets in Fig. 2a. The disk MG specimen was clipped in the upper (3.0 mm diameter) and lower (5.0 mm diameter) dies. The steel ball was made of bearing steel with diameter 3.0 mm, and the die material was medium carbon steel. The nominal dimension of the rectangular samples for uniaxial compression was $3.0 \times 3.0 \times 6.0\ mm^3$. The SP samples, 0.7 mm thick and 10 mm in diameter, were cut from the Ti-based MG ingot by an electric spark cutting machine, then ground and polished to a thickness of 0.3–0.5 mm with 2.5 μm diamond abrasive paste. The constraint discs were made of a cold-rolled Cu–11.6 at.% Al alloy with a yield strength of 575 MPa and a total elongation >10%. The disc size was equal to that of the Ti-based metallic samples for the SP test. Samples S1 with a free lower surface, samples S2 with a strongly constrained lower surface and samples S3 with a weakly constrained lower surface were all tested for observation of their differences in plastic deformation and fracture behavior. The constraint level was controlled by the pressure-pad force exerted on the upper die, i.e., the pressure-pad force for strongly constrained samples S2 is larger than that of the weakly constrained samples S3. The pressure-pad force was applied to the upper die using the torque spanner. The torques were 2 Nm and 5 Nm for the weak and strong constraint, respectively. According to mechanical design principle and engineering mechanics [24], the pressure-pad force per unit area can be approximately calculated by

$$P = \frac{T}{1.25\mu DA} = \frac{T}{1.25\mu D\pi(R^2 - r^2)} \quad (1)$$

where P is the pressure-pad force per unit area, T is the torque existing on the upper die, μ is the friction coefficient between the upper and the lower dies, D is the diameter of the upper die, A is the effective contact area between the sample and the upper die, R is the diameter of the sample, and r is the diameter of the lower die. Inserting the experimental parameters ($T = 2$ Nm for S2 and 5 Nm for S3, $D = 0.015$ m, $R = 0.005$ mm, $r = 0.0025$ mm, $\mu = 0.2$) into Eq. (1), one gets the pressure-pad force per unit area for samples S2 and S3 as $9.05 \times 10^4\ N\,m^{-2}$ and $2.26 \times 10^5\ N\,m^{-2}$. All mechanical tests were performed using an MTS810 testing machine at room temperature. The strain rate for uniaxial compression was $1.0 \times 10^{-4}\ s^{-1}$, and the punching rate was $0.001\ mm\,s^{-1}$. All tests were repeated at least three times. After the tests, all the samples were observed by scanning electron microscopy (SEM) under an FEI Quanta 600 instrument to reveal the deformation and fracture features.

3. Results

3.1. Deformation and fractural morphology of the Ti-based MG under uniaxial compression

The typical engineering stress–strain curve of the Ti-based MG, as shown in Fig. 1, indicates that the sample began yielding at 1.8 ± 0.2 GPa and fractured with a compressive plasticity of $0.1 \pm 0.05\%$. However, from the deformation and fracture morphology, it still failed in a shear fracture mode with a shear angle of $\sim 41 \pm 1°$, and

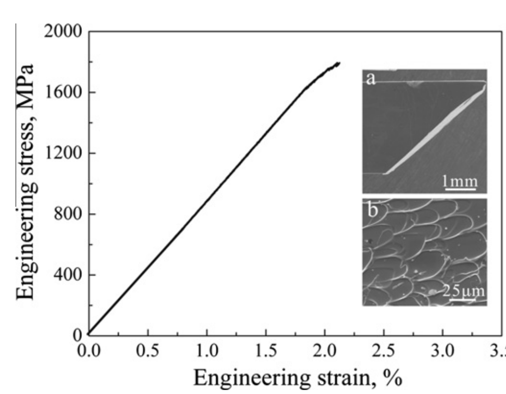

Fig. 1. Typical engineering compressive stress–strain curve for Ti-based MG. Insets (a) and (b) are SEM images showing the shear fracture angle and the vein patterns, respectively.