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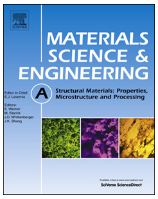

On the stress-state dependent plasticity of brittle metallic glasses: Experiment, theory and simulation

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ABSTRACT

In this work, the stress-state dependent plasticity of brittle Ti-based metallic glass was investigated by experiment, mechanics theory and simulation systematically. With different settings of arc-shaped edges, various stress gradients could be generated artificially. The systematical work showed that the global plastic deformability of a metallic glass depended strongly on the stress states under compressive loadings. By introducing the Mohr–Coulomb yielding criterion and the associated flow rule, we proposed an elastic–plastic model to analyze the deformation behaviors of all specimens. Combined with the experimental results and the numerical results by finite element method (FEM), it was demonstrated that the present simulation model could suitably describe the plastic deformation process of the specimens, and the different stress states might have a vital significance on the global plastic deformation behavior. The current results and analytical model could provide an approach to understand the further plastic deformation mechanism of brittle metallic glasses with different stress states.

1. Introduction

Bulk metallic glasses (BMGs) are of interest due to several properties attractive in structural materials, such as high strength, high hardness as well as high fracture toughness [1–7]. Different from the crystalline materials, under tension and compression loading, metallic glasses often fracture along one shear band (SB) instantaneously owing to its isotropy and shear localization [8]. Therefore, for the monolithic metallic glasses, few approaches reported the large tensile plasticity and many researchers tried diverse ways to improve the plasticity of metallic glasses [9–14]. For example, by adding secondary-phase particles or high-strength fibers into the amorphous alloys [9,10] or preparing the metallic glassy composites containing the in-situ formed ductile dendrites [11], scholars found that the rapid propagation and extension directions of SBs could be limited and changed largely, leading to a large plasticity. Additionally, by changing the aspect ratio or the size of the compressive specimens, researchers showed that the plastic deformation behaviors could also be enhanced to a large extent [12–14]. In brief, the major pathway for improving the plasticity of metallic glasses is to confine the initiation and propagation of SBs, and then try to have the intersection of multiple SBs. In a further way, the plastic deformation of metallic glasses under different loadings has attracted much attention.

From a microscopic point of view, plastic deformation of metallic glasses is highly localized in very thin shear bands which may extend rapidly once yielding occurs. The approach of the mechanisms of inelastic deformation is therefore precluded using uniaxial testing. This is because fracture often occurs in a quasi-brittle way when the predominant shear band reaches the free surfaces of the sample under uniaxial loadings. Therefore, for understanding the plastic deformation ability, scholars had to exploit several mechanical approaches under multiaxial loadings to reveal the plastic flow mechanism. Typically, the indentation test is an easy way to study the plastic flow mechanism of materials [15–21]. For example, by using the different shapes of indentation, Keryvin [15] investigated the plastic deformation process by means of experiment, analytical model and finite element method. The results showed that determining the true hardness of a particular amorphous alloy depends on the correct choice of indenter, unlike the crystalline alloys. Besides, by changing the loading directions, Chen et al. [22] reported that the local stress gradient could lead to severe intersection of SBs and improve the macroscopic deformation abilities. Furthermore, by employing some arrangements on the specimen shapes, Wu et al. [23] proposed a "stress gradient enhanced plasticity" concept to describe the improved plastic deformation mechanism induced by stress gradients.

Although these researches mainly focused on the plastic flow mechanisms via different mechanical loadings, there is still a lack of an established mechanism in revealing the plastic deformation behaviors induced by large stress gradient [22,23], since the plastic flow characters under complex stress states might be varying and

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difficult to capture. Therefore, it is necessary for us to investigate the stress-state dependent plastic deformation behaviors systematically. Then, based on the above concerns, the present work investigated the stress-state dependent plasticity of Ti-based metallic glasses by means of experiment, theory and simulation. On one hand, in order to clarify the plasticity differences caused by the diverse stress states, we selected the brittle Ti-based metallic glasses [24] for study since this kind of metallic glass displays near zero plasticity even under compressive loadings. On the other hand, for obtaining the continuous stress variation, we installed different arc-shaped edges in specimens, which was a simple and valid way to generate different stress gradients. Finally, the major purpose of this work is to provide a systematic pathway to understand the plastic deformation mechanism of brittle metallic glasses under different stress states, which could be doubtlessly regarded as one fundamental mechanism of metallic glasses.

2. Experimental procedures

A Ti-based metallic glass alloy, with nominal chemical compositions of $Ti_{40}Zr_{25}Ni_3Cu_{12}Be_{20}$, was prepared by the arc-melting method. The final plate had a rectangular shape, with the dimension of $60\times30\times3\ mm^3$. As illustrated in Fig. 1, the metallic glass plate was cut into five kinds of specimens which were designated as A, B, C, D and E. The height and width of all the specimens were 3.0 mm uniformly. For specimens B and C, two symmetrical concave edges were installed, and the corresponding dimensions were marked in Fig. 1; specimen B had a larger arc-shaped edge. In the same way, the convex edges were processed in specimens D and E. Then, conventional compression tests were applied in order to measure the mechanical properties of the metallic glass specimens with the INSTRON 8862 testing machine at room temperature in air. All the tests were conducted at a strain rate of about $10^{-4}\ s^{-1}$. After the tests, the specimens were observed with a LEO Supra 35 scanning electron microscope (SEM) to reveal the deformation and fracture morphologies. In addition, a finite-element method (FEM) with the commercial software ANSYS was adopted to simulate the stress distributions of the specimens. It could display the numerical results of the nodes by dispersing the whole model into many finite elements.

3. Experimental results

3.1. Compressive stress–strain responses

Fig. 2 displays the engineering compressive stress–strain curves of specimens A, B, C, D and E. Here, we apply an engineering stress, i.e. the ratio of the applied force to the minimum bearing area of the specimen, to represent the global stress since the stress distributions in the specimens with arc-shaped edges are non-uniform [24–27]. As shown in Fig. 2, specimen A shows nearly zero compressive plasticity with the yielding strength of ~1.75 GPa [24]. However, samples B–E which had different curved edges, exhibited various compressive plasticity, unlike the straight sample A [24]. For instance, the plasticity of specimen B was 2.2%, which was slightly larger than the value of specimen A. Besides, the corresponding strength was 1.95 GPa, suggesting that the changing of specimen edges could result in the enhancement of global strength and plasticity. Interestingly, for

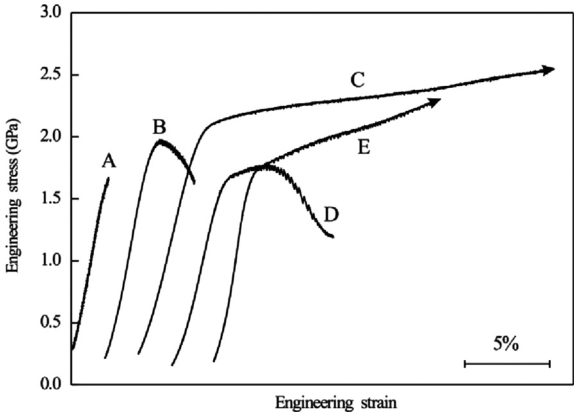

Fig. 2. Compressive engineering stress–strain curves for five specimens (A–E).

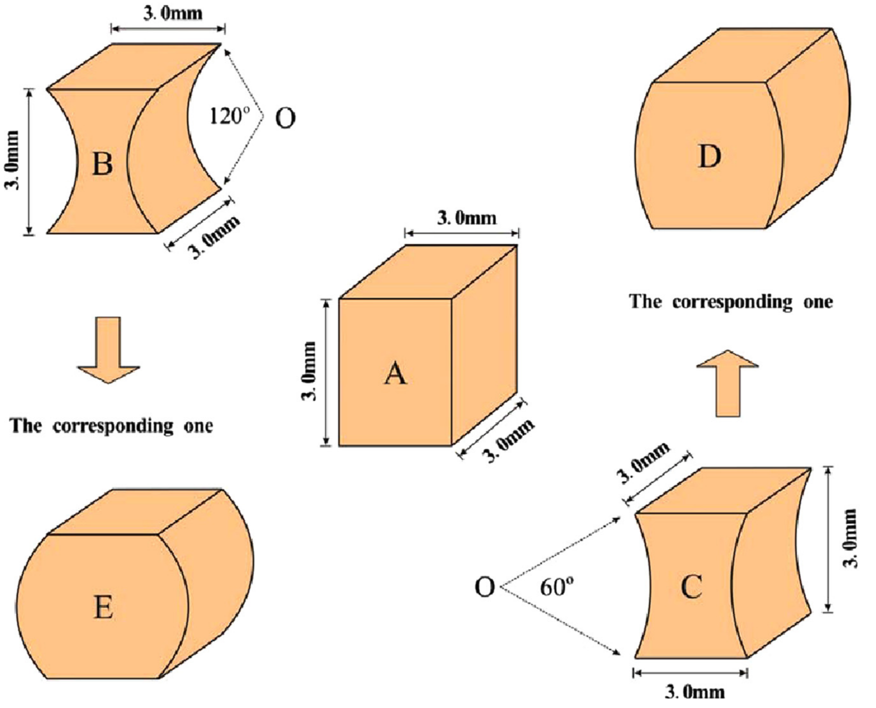

Fig. 1. Illustration of five kinds of Ti-based specimens (A–E) with arc-shaped edges, as well as the corresponding dimensions.