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Effect of stress gradient on the deformation behavior of a bulk metallic glass under uniaxial tension

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ABSTRACT

In the present study, the stress gradient is shown to significantly affect the deformation behavior of a monolithic bulk metallic glass (BMG) at room temperature under tensile loading. It is demonstrated that the stress concentration areas of the BMG specimens facilitate the formation of shear bands, and the presence of “soft” and “hard” regions due to the stress gradient confines the propagation. With these stress gradients, brittle monolithic BMGs exhibit plastic deformation at the stress concentration areas under tensile loading, and higher orders of stress gradient result in larger confinement for the propagation of shear bands. The findings are significant in controlling the plastic deformation behavior of BMGs and in understanding the deformation mechanisms of monolithic BMGs under complex stress states, which is important for potential engineering applications.

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1. Introduction

In view of the fact that vanished crystalline defects enable bulk metallic glasses (BMGs) to possess superior mechanical, chemical and physical properties, a large amount of research has been undertaken to investigate this new class of material in the last few decades [1,2]. One key issue in BMGs which hinders their engineering applications is their limited plastic deformation especially under tension [3,4]. Nevertheless, most of the reported results of poor plastic deformation behavior are reflections of the behavior under uniform stress distributions [5], whereas in a vast number of structural applications, the material always deforms under complex stress states [6,7]. Even in structures with uniform stress distributions, the micro-inhomogeneity of the material may cause unevenly distributed stresses. Therefore, understanding of the mechanical behavior of BMGs under complex stress states is of high significance. Under stress gradients, BMGs have demonstrated some enhanced plastic deformation before fracture when compressed [8–13]. However, due to the “work-softening” phenomenon of BMGs and the different stress evolution processes [14], most BMGs are known to exhibit different mechanical behaviors under compressive and tensile stress states. It is of significance to further study the deformation behavior of BMGs with stress gradients under tensile loading, which may lead to a better understanding of the deformation behavior of BMGs in complex states under tension. In this study, Z-shaped specimens are used to examine the effect of stress gradient on the deformation behavior of BMGs under uniaxial tension tests. The results of this study lay down a good foundation for further analysis of the deformation mechanisms of BMGs under complex stress states, either in BMG structures or micro inhomogeneous BMGs.

2. Experimental details

As-cast rods of $Zr_{57}Cu_{20}Al_{10}Ni_8Ti_5$ BMGs [15], 3 mm in diameter and 90 mm in length, were produced by suction casting of a melted mixture of pure elements into water-cooled copper molds, purified by a Ti getter. The glassy state of the As-cast rods was confirmed by standard X-ray diffraction analysis with Cu-K_α radiation. To investigate the effect of stress gradient on the tensile deformation behavior of monolithic BMGs, three different kinds of tensile specimens were fabricated using wire-cut electrical discharge machining, according to the schematic diagram shown in Fig. 1. The specimen with $\alpha = 0^\circ$ is a conventional uniaxial specimen which usually exhibits very limited plastic deformation under tension tests. After electrical discharge machining, the machined surface layers of all the specimens were removed by abrasive paper with grits from 150 to 2000 in order to minimize the heat effect. The final dimensions of the reduced sections of the specimens were about 0.7 mm × 0.7 mm. The prepared specimens are shown in the inset in Fig. 1. Uniaxial tension tests were performed at room temperature on a servo-hydraulic 810 Material Testing System (MTS mechanical testing machine) at a constant crosshead displacement rate of 0.06 mm/min. The elongations along the loading direction were measured using an extensometer. At least

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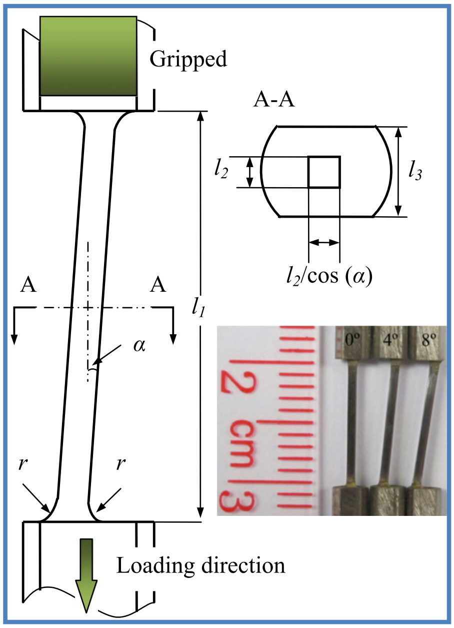

Fig. 1. Schematic illustration of the reduced sections of tensile specimens, where $l_1=10.6$ mm, $l_2=0.8$ mm, $l_3=2.4$ mm, $r=0.3$ mm, and $\alpha=0°$, 4°, 8° respectively. The inset optical image shows the prepared specimens.

four specimens were tested for each condition. A Jeol JSM-6490 scanning electron microscope was utilized to image the formation and propagation of the shear bands on the fractured specimens.

3. Results and discussion

Fig. 2 illustrates the load–axial elongation curves of the specimens. The average total elongations of the specimens with $\alpha=0°$, 4° and 8° were 2.25% ± 0.13%, 2.83% ± 0.18% and 3.66% ± 0.34% respectively, illustrating that the elongation increases with increasing α values. When compared to the conventional specimen ($\alpha=0°$) with a constant slope of the load–axial elongation curve, both of the curves of the Z-shaped specimens have demonstrated a constant initial slope followed by a non-linear slope. The initial slope of the load–axial elongation curve was found to decrease with increasing α values. This phenomenon is due to the decrease in the inclination angle of the reduced section of the Z-shaped specimen during deformation, leading to the larger axial elongation under the same axial loading. For the Z-shaped specimens, the non-linear and decreasing slopes were also observed when the axial elongation reached about 2%, which is related to the plastic deformation behavior of the specimens. Fig. 3 shows the photos of the fractured specimens, and their corresponding scanning electron microscopy (SEM) micrographs. The enhanced plastic deformation behavior of Z-shaped specimens has been found to be due to the formation of shear bands in localized areas. It can be seen that there are no shear bands on the conventional uniaxial specimens, only a few shear bands on the specimens with $\alpha=4°$, and many more shear bands on the specimens with $\alpha=8°$ (Fig. 3(b–d)). This is consistent with the results of other researchers who found that more plastic deformation is accompanied with a denser shear band distribution.

Differing from the conventional uniaxial specimens which experience relatively uniform stress distributions under tensile loading, Z-shaped specimens have two stress concentration areas with gradient stress distribution. In order to study the gradient stress distribution of the Z-shaped specimens under uniaxial tension, finite element modeling (FEM) analysis was conducted

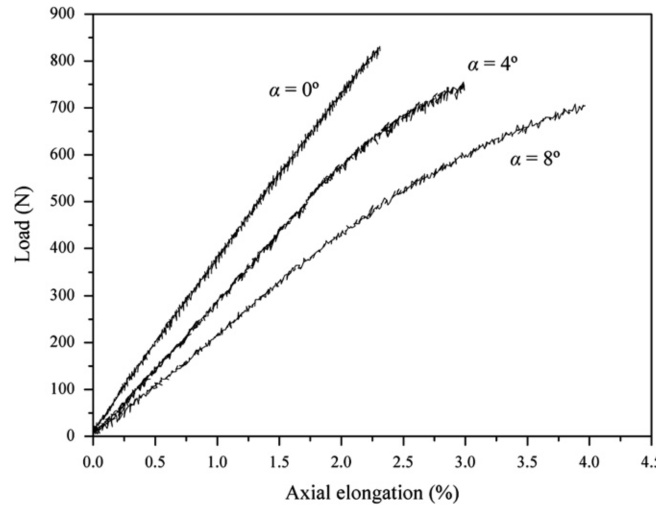

Fig. 2. Load–axial elongation curves of specimens with $\alpha=0°$, 4° and 8°.

using the commercial ABAQUS software. For simplicity, simulation of the von Mises stress distribution in the specimen with $\alpha=8°$ before yielding was carried out. The average Young's modulus of the BMG of 64.7 GPa (based on the experimental tensile test results of conventional uniaxial specimens) and Poisson's ratio of 0.375 [16] were employed in the simulation. Due to the symmetry of the specimen, only one stress-concentrated section of the specimen is presented in this paper. In the elastic region, the simulation result (Fig. 4) reveals a stress concentration at the corner, and that the stress decreases from region B to region C. If the applied loading further increases, it is most likely that region B will yield first and start to initiate shear bands to alleviate the load. The shear bands will then propagate toward the unyielded region C. In fact, this reasoning is supported by the SEM image illustrating the shear band patterns in regions B and C, as shown in Fig. 3(d). A similar distribution of shear bands on the other end of the specimen is also observed due to the symmetry of the specimens. Based on both the experimental and theoretical results of the present work, the mechanisms for the formation and propagation of shear bands in the Z-shaped specimen under uniaxial tension can be described as follows. Firstly, region B will yield with some shear bands activated. Owing to the small volume of the yielded region, the propagation of the shear bands is arrested by the unyielded BMGs located outside region B. As the loading proceeds, more regions outside region B begin to yield, resulting in the initiation of more shear bands. In the mean time, due to the "work-softening" effect, confinement of the propagation of the shear bands in region B is alleviated leading to further propagation. By continuous loading, more and more shear bands are activated until there is a shear band that propagates to the other side of the specimen, leading to fracture. It is expected that a higher order of the stress gradient distribution can result in stronger confinement of the shear band propagation, which leads to more plastic deformation.

In Fig. 3(d), deflected shear bands are observed on the specimens with $\alpha=8°$, similar to the results of the compression tests [8]. The propagation directions of the shear bands change toward region C, which agrees well with the simulated stress distribution shown in Fig. 4. The deflection of the shear bands can be attributed to the stress gradient in which the propagation of the shear bands is restricted. Thereby, the deflection of shear bands can be found only in the specimens with the larger α values associated with a higher stress gradient, rather than in the conventional uniaxial specimens. In the specimens with small α values, the stress gradient may not be strong enough to force the shear bands to

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