On the Serrated Behavior during Plastic Deformation of a Zr-Based Bulk Metallic Glass

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The uniaxial compression tests were conducted on an amorphous Zr-based alloy at room temperature. The results show that this alloy exhibited the typical features of metallic glasses and the stress-strain curve is extensively serrated within the plastic regime. The analysis reveals that for all the shear band events, the maximum stresses remained approximately constant during the course of plastic deformation, and the minimum stresses began to decrease when the deformation enters the late stage. This phenomenon is probably associated with the different shear-banding behaviors within various deformation stages. Calculations find that the stress accumulation sections in the stress-strain curve are parallel to each other, indicating that such reloading processes are elastic in nature. Therefore, there are elastic and plastic sections in the stress-strain curve. Further analysis discloses that the plastic strain component carried by each shear band event increases with the applied strain within the late deformation stage.

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1. Introduction

Bulk metallic glasses (BMGs) have an amorphous microstructure with the absence of long-range order and exhibit unusual properties compared to crystalline materials. As a result, studies on their mechanical behavior and deformation mechanism have received considerable interests around the world.1–7 It has been well admitted that this class of materials own an ultrahigh strength of approximately 2.0 GPa, suggesting an important potential in the structural applications. In addition to the high strength, the ductility is another key factor for structural applications. Unfortunately, BMGs usually behave in a brittle manner. Therefore, extensive efforts have been spent on improving their ductility.8–11 Recently, a significant ductility under compression has been achieved in the Zr-based BMGs via the microstructural modification.12 For crystalline materials, the ductility is carried by lattice defects, and strain hardening suppresses the catastrophic failures. In the case of amorphous alloys, the plastic deformation proceeds through the shear localization, and the permanent deformation is confined to thin shear bands. Therefore, the extent of the plastic deformation is completely determined by the shear-banding behavior. In general, a high capability to form shear bands and to retard their propagation leads to an improved ductility. Shear bands have often been observed in the fractured specimens.4,9 Because of the shear band propagation’s high speed, the shear-banding behavior was normally investigated by examining the post-deformed specimens.12,13 By now, the shear bands’ operation and development behaviors receive little attention.14,15 In the current study, the shear-banding behavior was investigated in a Zr-based BMG at room temperature.

2. Experimental Procedure

The Zr-based alloy (Zr_{57.4}Ni_{13.4}Cu_{17.9}Al_{10.3}Nb_1, atomic percent) was synthesized using an arc-melting and drop-casting system. The X-ray diffraction results verified its amorphous structure. Uniaxial compression tests were conducted at a strain rate of 2 × 10^{-4} s^{-1} at room temperature. The strain was measured using a clip-on extensometer. The cylindrical compression specimens have a length/diameter ratio of 2 : 1. The fractured samples were examined using the scanning electron microscopy (SEM). For the purpose of comparison, the same compression tests were also performed on a nanocrystalline Ni-20%Fe (mass percent) alloy under the similar condition (strain rate, load level, specimen dimension, and temperature).

3. Results and Discussion

Figure 1(a) presents the stress-strain curve of the Zr_{57.4}Ni_{13.4}Cu_{17.9}Al_{10.3}Nb_1 alloy. The yield strength is about 1795 MPa, elastic limit 2.25%, Young’s modulus 78.5 GPa, and global plastic strain 1.5%. Also, no strong strain hardening was observed. A combination of these properties represents a typical characteristic of amorphous alloys.1) In addition, similar to other BMGs, shear bands were detected near the fracture surface, as shown in Fig. 1(b). This observation contends that the plastic deformation is inhomogeneous and extremely localized within shear bands.

Figure 2(a) shows the plastic part of the stress-strain curve. It is obvious that the stress-strain curve becomes greatly serrated after the specimen deformed plastically. As a comparison, the compression testing was also accomplished on a nanocrystalline Ni-20%Fe alloy with an average grain size of about 22 nm, whose mechanical property has been well characterized elsewhere.15 Its partial stress-strain curve within the plastic range is given in Fig. 2(b). The major difference between Fig. 2(a) and (b) is that for crystalline specimens, the flow stress increases smoothly, and no load drop was observed. This representative phenomenon in crystalline materials is attributed to the dislocation-controlled deformation and strong strain hardening, which prevents the load drops. The importance of this comparison is to ensure that the load drops for the Zr-based amorphous samples are...
not artifacts caused by the testing system. That is, the repeated load drops are a unique phenomenon in BMGs and has been found in different amorphous alloys. Generally, such serrated behavior is closely correlated to the shear band development. Approximately, one discernible serration could be considered as a shear band event, which includes one or multiple shear bands.

For convenience, several terms used later are defined in Fig. 3. The $A_i$ and $A_{i+1}$ denote the minimum stress points, and $B_i$ and $B_{i+1}$ the maximum stress points. $\sigma^{A_i} - \sigma^{A_{i+1}}$ and $\sigma^{B_i} - \sigma^{B_{i+1}}$ are defined as the stress drop and accumulation amplitudes, respectively. $\varepsilon^{A_i} - \varepsilon^{B_i}$ and $\varepsilon^{A_{i+1}} - \varepsilon^{B_{i+1}}$ are the plastic strain differences between two adjacent minimum and maximum stress points, respectively.

Figure 4 plots the maximum and minimum stress points at individual shear band events. Please note that the shear band events were counted from left to right in the stress-strain curve. It is observed that the maximum stresses did not change dramatically throughout the plastic deformation process. Interestingly, the minimum stresses start to decrease when the deformation proceeded to some extent. We call the deformation processes prior to and beyond this point the early and late stages, respectively. Therefore, it could be deduced that within the late stage, the stress drop/accumulation amplitudes would increase with increasing the applied strain. These findings are probably associated with the different shear-band behaviors at different deformation stages.

Fig. 1 (a) Compressive stress-strain curve of the Zr$_{57}$Ni$_{13.4}$Cu$_{17.5}$Al$_{10.3}$Nb$_1$ alloy; (b) shear band morphology near the fracture surface.

Fig. 2 The plastic part of stress-strain curves. (a) amorphous Zr$_{57}$Ni$_{13.4}$Cu$_{17.5}$Al$_{10.3}$Nb$_1$ alloy; (b) nanocrystalline Ni-20%Fe alloy.

Fig. 3 Schematic of the stress-strain curve for the Zr-Based metallic glass.
Literature results suggest that within the early stage, one shear band event maybe involves multiple shear bands; while at large strains, a single shear band is responsible for one serrated behavior. Further discussions will be addressed later.

Figure 5(a) displays the plastic strain differences between every two near shear band events at maximum and minimum stress points, i.e. $\varepsilon_{\text{Bi+1}}^{\text{Hi}} - \varepsilon_{\text{Bi}}^{\text{Hi}}$ and $\varepsilon_{\text{Ai+1}}^{\text{Hi}} - \varepsilon_{\text{Ai}}^{\text{Hi}}$ defined in Figure 3. It is of interest that the plastic strain changes between two adjoining maximum stress and two corresponding minimum stress points are nearly overlapped. Furthermore, careful examinations reveal that in the stress-strain curve, the segment during reloading is nearly straight, as seen in Fig. 2(a). Therefore, it could be derived from Fig. 5(a) that the stress accumulation rates (slopes of the reloading segments) are approximately the same, implying that all the segments are roughly parallel to each other. Furthermore, the calculation found that the average slope of those segments is $78.1 \pm 5.3$ GPa, which is in good agreement with the Young’s modulus of 78.5 GPa. This finding strongly suggests that the stress accumulation/reloading process is an elastic behavior even within the plastic regime. Thereby, the strain $\varepsilon_{\text{Bi}}^{\text{Hi}} - \varepsilon_{\text{Bi}}^{\text{Hi}}$ in Fig. 3 gained during reloading should be the elastic component. Although these reloading processes occurred within the plastic regime, they do not contribute to the plastic strain. The plastic strain only comes from the displacement acquired during the load drop (the shear band propagation) and could be measured using the equation of $\varepsilon_{\text{Bi+1}}^{\text{Hi}} - \varepsilon_{\text{Bi}}^{\text{Hi}}$. A close analysis discloses that the plastic strain component gained during one single shear band event increases when the deformation advances into the late stage, as shown in Fig. 5(b). Recent studies have shown that the shear band propagation is a thermally activated process. Accordingly, it could be expected that the strain rate could affect the plastic behavior. With increasing the strain rate, the serration could be inhibited and, consequently, the plastic strain may decrease at high strain rates.

For BMGs, the plastic deformation starts with the onset of the shear localization, and the emission/formation of shear bands is associated with the free volume concentration. At low temperatures, it is believed that the free volume creation is realized mainly by the external load. Once the free volume reaches one certain value at one site, the shear band will nucleate preferentially at this position. The subsequent shear band evolution results in the load drop. In the view of the energy, simulation results propose that the load drop is a result of the cascade in the potential energy. Due to the ultrafast propagation speed, this shear band becomes stable shortly after its nucleation, and, then, the load drop stops. To deform further, because the existing shear bands are not movable, new shear bands are required. For new shear bands to nucleate, the stress should be brought back to the yield point due to the stress drop. The new shear band event leads to the load drop again. The repeat of this process generates the serrated stress-strain curve. Since the required stress level, i.e. the required free volume size, for shear band’s nucleation is approximately a constant for one BMG, the maximum stresses are comparable for different shear band events, as shown in Fig. 4. Although all the plastic strains are accommodated at shear bands, the strain amount carried by each shear band is different and depends on its
Within the early course of the deformation, each shear band event may consist of several shear bands, while at the late stage of deformation, one single shear band bears the load drop. As a result, the minimum stress decreases with applied strains. Finally, it is worth pointing out that one shear band event consists of the stress accumulation, shear band nucleation/emission, and shear band propagation, but only the shear band propagation contributes to the plasticity.

4. Conclusion

In the current study, a Zr-based metallic glass was successfully produced using an arc-melting system. The compression testing was carried out at room temperature at a strain rate of \( 2 \times 10^{-4} \, \text{s}^{-1} \). The compression results demonstrate that this amorphous alloy owns a high strength, large elastic limit, lack of strain hardening, and low global ductility. After yielding, the stress-strain curve became highly serrated. In contrast, the serration was not observed in the crystalline Ni-Fe alloy, which excludes the possibility of artifacts regarding the serration behavior in the case of the Zr-based metallic glass. Furthermore, based on the computed Young’s modulus, it is found that the reloading process is an elastic behavior, and only the displacements resulted from the load drops contribute to the plastic strain. Detailed analysis shows that the maximum stresses corresponding to the onset of shear bands at individual shear band events did not varied significantly during the plastic deformation. The decrease in the minimum stresses with the applied strain within the late deformation stage is suggested to be due to the different shear-banding behaviors at different deformation stages. Furthermore, it is found that within the late stage of deformation, the plastic strain contributed by one shear band event increases with continuing loading.

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REFERENCES