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Crossover from free propagation to cooperative motions of shear bands and its effect on serrated flow in metallic glass

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ABSTRACT

The serrated flow dynamics and shear band motions can be controlled by changing aspect ratio (AR) and deformation degree. With decreasing ARs, the serration pattern transforms from a sharp-peak type with uniform size into a complex type with various sizes, the ratio of stress drop time t_D to rising time t_R for serrated flow increases, the time intervals t_n between adjacent serrations decreases. The serrated flow exhibits a crossover from Gaussian-type distribution to power-law-type distribution with decreasing ARs. This crossover is mainly governed by a transition from single-shear-band dominated deformation to cooperative motions of multiple shear bands dominated deformation. Additionally, such crossover can also be governed by deformation degree.

1. Introduction

Metallic glasses exhibit poor ductility at room temperature because their plastic deformation is highly localized into shear bands [1]. Previous works suggested that bulk metallic glasses (BMGs) can endure remarkable plastic deformation under geometric constraints such as low aspect ratios (ARs) [2]. Besides, AR has been found to be correlated with the shear band stability. For example, shear bands propagate more stably in samples with lower ARs [3]. Obviously, ARs act as both external and intrinsic factors affecting plastic deformation of BMGs.

Serrated flow in stress-strain curve, which displays repeated cycles of a stress rising followed by a stress drop, is a typical feature of the plastic deformation in metallic glasses [4]. Serrated flow weakens or even disappears when the test temperature or strain rate increases [5,6]. This implies that the serrated flow has the dynamic characteristics. Such stress fluctuations in stress-strain curve are also observed in crystalline alloy, which is known as Portevin-Le Chatelier (PLC) effect [7]. The origin of PLC effect is the interactions between dislocations and solute atoms. However, for BMGs, their plastic deformation is carried by shear bands. According to previous research works, the serrated flow can be well understood by intermittent sliding of shear bands so far, i.e. shear band motion follows the repeated propagation-and-arrest cycles [8,9]. By analogy, the intermittent sliding of shear bands can be regarded as a stick-slip process [10]. Based on the stick-slip model, Cheng et al. found that the intermittent sliding size of shear band corresponds well to the stress drop magnitude [8]. Sun et al. interpreted the intermittent sliding of shear band from atomic-scale using the cooperative shearing model of shear transformation zones (STZs) [11]. Therefore, serrated flow behaviors are closely related to shear band motions.

When BMGs with low ARs deform or BMG samples endure a large plastic deformation, multiple shear bands will form and shear band interactions can be greatly enhanced [2,12,13]. Shear bands interactions can hinder the propagation of shear band [14]. Therefore the serrated flow may be influenced by strong shear band interactions. Previous studies have shown that strong shear band interactions can induce hardening in metallic glasses [13–15]. However, considering from the aspect of deformation mechanism, the effect of shear-band-interaction evolution with the ARs and deformation degree on the serration dynamics remains to be further studied.

In addition, the plastic deformation process of metallic materials is often treated as a complex system, which was analyzed by mathematical and statistical methods [7,16]. Such as in crystalline Cu-Al alloy, a crossover in plastic deformation mechanism from chaotic state to self-organized critical (SOC) state happened as the strain rate increases [7]. The plastic deformation of brittle and ductile BMGs could evolve into chaotic state and SOC state, respectively [16]. However, “how the BMG deformation systems essentially evolve with the developing of the shear band interactions?” is an urgent and meaningful question. In this work, we have introduced strong shear band interactions into deforming BMG by controlling ARs and deformation degree, and the effect of shear band interactions on serrated flow was investigated. It was found that the stress drop amplitudes of serration exhibit a crossover from Gaussian-type to power-law-type distributions with ARs decreasing or

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deformation degree increasing. The physical origin of this crossover was investigated by analyzing shear band behaviors. The present work may shed light on toughening BMGs.

2. Experimental

$Zr_{64.13}Cu_{15.75}Ni_{10.12}Al_{10}$ BMG rods with a square cross section of $2 \times 2\ mm^2$ were prepared by suction casting method. The compression tests were performed on a universal testing machine (Shijin WDW-100D, China). Before compression tests, two ends of all compression specimens were polished to be parallel. The strain rate of compression tests is $1 \times 10^{-3}\ s^{-1}$. The aspect ratios of compression specimens are 3.0, 2.0, 1.0 and 0.5, respectively. The amorphous structure of the as-cast sample was examined by X-ray diffraction (XRD) on a Rigaku D/max-2400 X-ray diffractometer (Cu K_α radiation). The thermal response was analyzed by differential scanning calorimetry (DSC) on a Perkin-Elmer Pyris Diamond thermal analyzer at a heating rate of 20 K/min. The shear band patterns were analyzed by scanning electron microscopy (SEM) using a Hitachi S-4800 field emission scanning electron microscope (acceleration voltage is 5 kV).

The normalization method for stress drop magnitude ($\Delta\sigma_{SD}$) is as follows [16,17]. A linear fitting $\overline{\Delta\sigma_{SD}} = f(t)$ was performed on the plot of $\Delta\sigma_{SD}$ versus time (Figs. S1a and S2a, in the Supplementary material). Then the normalized stress drop magnitude (Figs. S1b and S2b)

$$s = \frac{\Delta\sigma_{SD}}{f(t)/f(t_0)} \tag{1}$$

was obtained, where $f(t_0)$ is the fitted value at the starting time t_0 (marked with arrow in Figs. S1a and S2a).

3. Results and discussion

3.1. Structure of the as-cast BMGs

To identify the amorphous nature of the as-cast $Zr_{64.13}Cu_{15.75}Ni_{10.12}Al_{10}$ sample, XRD and DSC were performed. The XRD pattern of the as-cast sample exhibits only a broad diffuse halo around $2\theta = 36.8^\circ$ (Fig. 1a.). No detectable sharp diffraction peak corresponding to any crystalline phases was observed. The DSC trace exhibits a broad endothermic event due to the glass transition (Fig. 1b.). The enthalpy of crystallization event is about 58 J/g, which is agreement with that of completed amorphous $Zr_{64.13}Cu_{15.75}Ni_{10.12}Al_{10}$ BMG [13]. Hence, the XRD and DSC results indicate that the structure of as-cast $Zr_{64.13}Cu_{15.75}Ni_{10.12}Al_{10}$ sample is amorphous. So the interfering influences of crystallization on serrated flow can be excluded [18].

3.2. Effects of aspect ratios on the dynamics of serrated flow

To investigate the effects of aspect ratios on serrated flow dynamics, the samples with ARs of 3.0, 2.0, 1.0, and 0.5 were compressed at a strain rate of $1 \times 10^{-3}\ s^{-1}$. The room-temperature compression stress-strain curves of the samples with different ARs are shown in Fig. 1c. The sample with an AR of 3.0 fractured after undergoing about 15% plastic deformation. For the samples with ARs of 2.0, 1.0 and 0.5, large plastic deformations without fracturing were achieved. Fig. 2 shows partial stress-time curves of the $Zr_{64.13}Cu_{15.75}Ni_{10.12}Al_{10}$ BMG samples with different ARs. All samples exhibit obviously serration behaviors, i.e. the repeated cycles of a stress drop followed by elastic reloading. For the samples with ARs of 0.5 and 1.0, their serrations display a complex pattern with various sizes (Fig. 2a and b). However, the serrations of the samples with ARs of 2.0 and 3.0 exhibit a sharp-peak pattern with relatively uniform sizes (Fig. 2c and d). The average stress drop amplitudes in Fig. 2 were further determined as 2.9, 5.8, 21.5, and 23.8 MPa for the samples with ARs of 0.5, 1.0, 2.0, and 3.0, respectively. Apparently, the average stress drop amplitudes increase with ARs increasing. Sun et al. found that the serrated flow dynamics were closely related to shear band motions [16]. The long BMG samples are inclined to deform via single dominant shear band due to the absence of geometric constraints. But the short BMG samples deform via multiple shear bands with strong interactions [2]. Therefore, shear bands interactions, which can hinder the propagation of shear band [14], will gradually play powerful roles in deformation with decreasing ARs. So the serrated flow may be influenced by ARs.

To quantitatively study the serrated flow, statistical works were performed on the stress drop magnitude. Before the statistics, a normalization of stress drop magnitude should be done [17,19]. As shown in Fig. S1a, the stress drop magnitude of serrations ($\Delta\sigma_{SD}$) increases with time for the sample with an AR of 3.0. This systematic shift, which does not reflect the nature of plastic deformation, results from a geometric effect induced by expanding cross-section during plastic deformation [16,17]. Accordingly, this shift should be subtracted. After the normalization, the baseline for the plot of $\Delta\sigma_{SD}$ versus time is flattened (Fig. S1b). Fig. 3a shows the frequency distribution histogram of normalized stress drop magnitude s for the sample with an AR of 3.0. As can be seen, the s tends to focus on larger values, indicating larger shear band avalanche sizes. And the histogram exhibits a peak shape, which follows Gaussian distribution. This suggests that the plastic deformation is closely related to thicker and fewer shear bands. Based on the previous reports, the Gaussian-type serrated flows can be attributed to the stick-slip behavior of single shear band [16]. Actually, here the regular serration pattern is very similar to the serrations caused by only single shear band [9]. Hence, for the BMGs with large ARs, the plastic deformation is dominated by one or several separated shear bands.

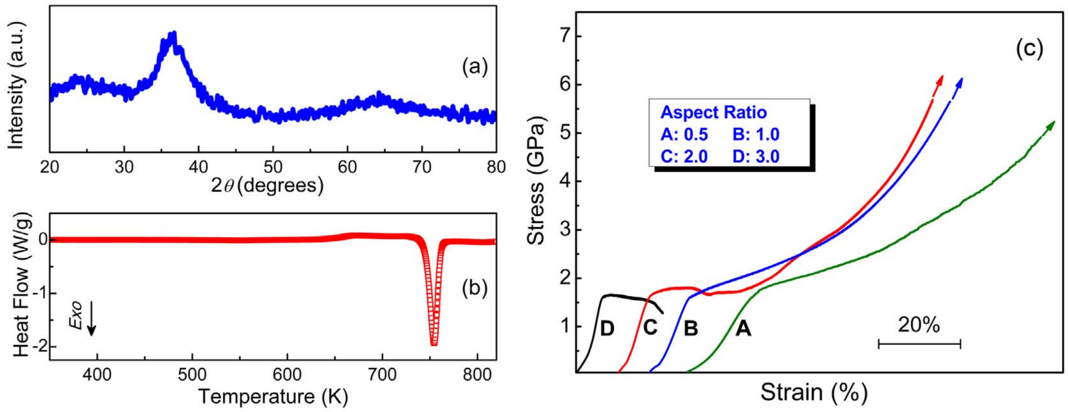

Fig. 1. The XRD pattern (a) and DSC trace (b) of the as-cast $Zr_{64.13}Cu_{15.75}Ni_{10.12}Al_{10}$ BMG sample. (c) The room-temperature compressive engineering stress-strain curves of the as-cast samples with different aspect ratios, and the arrows indicate that the samples can endure plastic strains larger than 80%.