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Interactions of Shear Bands in a Ductile Metallic Glass

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Abstract: Shear bands play a key role in the plastic deformation of metallic glasses (MGs). Even though there are extensive studies on the initiation and propagation of shear bands, the interactions among them have not been systematically studied yet. The interactions between the primary shear bands (PSBs) and secondary shear bands (SSBs) in a ductile Zr-based MG were studied. The residual stress near PSBs can deflect the propagation direction and reduce the propagation velocity of SSBs, which contributes to the plasticity and toughness of the MG. It was demonstrated that the probability and strength of the interactions between PSBs and SSBs would become stronger for MGs with larger Young's modulus and smaller shear modulus, i. e. , larger Poisson's ratio. These results are valuable in understanding the plastic deformation of MGs and may be helpful in designing new MGs with desirable mechanical properties.

Key words: bulk metallic glass; shear band; interaction; plasticity; serration

Bulk metallic glasses (BMGs) have promising applications as the structural materials due to their superior mechanical properties, e. g. , excellent elasticity, high strength and high hardness. However, the limited ductility has always been an inherent obstacle for their applications, and extensive efforts have been devoted to developing the ductile BMGs[1-3]. It has been widely recognized that their plastic deformations at temperatures far below the glass transition temperature usually occur via the formation of shear bands (SBs). The nucleation[4-8], propagation[9-14] and interaction[15,16] are three key processes for the SB operation. The nucleation of SBs derives from the activation and percolation of the flow units, also called as shear transformation zones[17,18]. The activation of flow units is a thermally activated phenomenon, whose activation energy is quite close to that of the secondary relaxations in BMGs[19]. The propagation speed of SBs can be as high as the sound velocity[20,21], which is much faster than the slip velocity of the sample on the two sides of a SB[10]. The propagation of SBs is a stress-controlled behavior. For an as-cast BMG sample, the SB propagation is usually about 45° to the uniaxial compression direction[22]. When introducing stress with directions different from that of the natural SB propagation, they will change their propagation directions, along the new maximum shear stress orientation. Various methods have been tried to introduce the residual stress to change the propagation direction of SBs, and have proved to be effective in improving the apparent plasticity of BMGs[11,13,14,23-25]. Even though there are many researches on the initiation and propagation of SBs, few is known about how they interact with each other and contribute to the plasticity during deformation[12].

In this study, the interactions of SBs in a ductile Zr-based BMG with a 17% compressive plasticity were investigated. During the plastic deformation, plenty of SBs were formed, which correspond to the

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serrations (stress drops) in the stress-strain curve. The ones formed with large stress drops can be defined as primary shear bands (PSBs), while the ones causing only small stress drops can be defined as secondary shear bands (SSBs). It was shown that SSBs usually initiated from a PSB and that their sliding directions usually got deflected when propagating in the vicinity of a PSB. A qualitative model was proposed to demonstrate the interactions among the SBs and their relations with the properties of BMGs.

1 Experimental

The master alloy with nominal composition of $Zr_{52}Cu_{18}Ni_{15}Al_{10}Ti_5$ (at. %) was prepared by melting high purity elements (>99.9 mass%) using the arc melting furnace under the protection of Ar atmosphere. Then, the master alloy was remelted in a quartz tube using an induction furnace and subsequently injected into a copper mold to form the BMG rods with 2 mm in diameter. The amorphous nature of the rods was confirmed by X-ray diffraction and differential scanning calorimetry (data not shown here). Samples in the dimension of $\phi 2$ mm × 4 mm were used for quasi-static compression tests with a strain rate of 10^{-4} s^{-1}. The surface morphologies of the sample and SB distributions were studied using the scanning electron microscope (SEM).

2 Results and Discussion

2.1 Serration behaviors of the BMG

Fig. 1 shows the nominal compressive stress-strain curve of the BMG. After 2.1% elastic deformation, the sample exhibits 17% plasticity before fracture. The plastic strain curve at two deformation stages is magnified and shown in the insets. During the steady plastic deformation, multiple stress drops (see the left inset in Fig. 1) exist, which are attributed to the formation of multiple new SBs[7]. In this steady serration, the maximum stress drop (approximately 0.03 GPa) is about 1.6% of the yield stress ($R_e = 1.9$ GPa). When approaching the fracture, the stress drops increase to as high as 3.4% of the yield stress, which are not stable and attributed to the stick-slip sliding movement of PSBs[26,27].

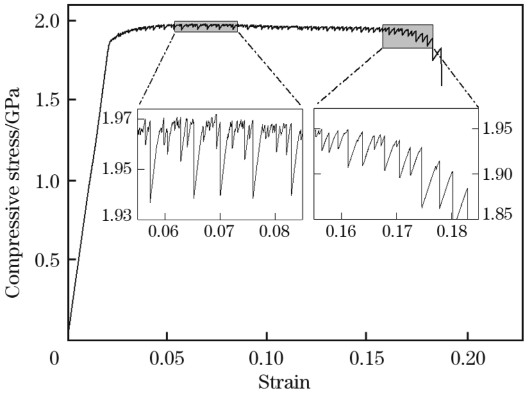

Fig. 1 Compressive stress-strain curve of BMG at strain rate of 10^{-4} s^{-1}

Then, the stress drops during the plastic deformation are studied statistically, as shown in Fig. 2. The stress drop versus the corresponding frequency count is plotted in Fig. 2(a), which can be well fitted by a power law relation, $y = 0.0149x^{-1.41}$. This demonstrates that the plastic deformation in this alloy is a self-organized critical (SOC) state, which is quite consistent with the previously reported results in other ductile BMGs[7,28]. The emergence of the SOC state also indicates that the effect of shear band interaction on the dynamic behaviors during the deformation of MGs must be considered[7]. The normalized cumulative count versus stress drop is shown in Fig. 2(b). It can be seen that

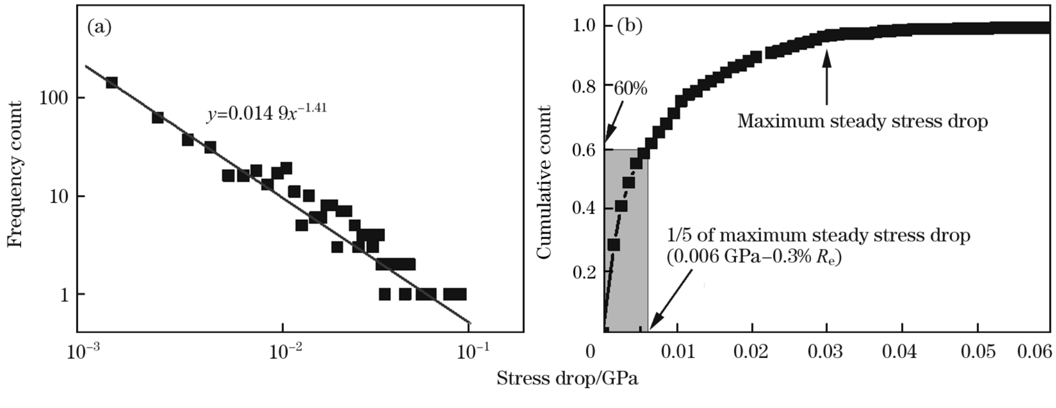

Fig. 2 Double logarithmic plot of statistical analysis of stress drop distribution at serration plastic deformation range (a) and cumulative count of stress drops during serration plastic deformation (b)