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Serrated flow and stick–slip deformation dynamics in the presence of shear-band interactions for a Zr-based metallic glass

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Abstract

In this paper, shear-band interactions (SBIs) were introduced by a simple method and their effect on the dynamics of shear bands and serrated flow was studied for a Zr-based metallic glass. Statistical analysis on serrations shows that the stick–slip dynamics of interacting shear bands is a complex, scale-free process, in which shear bands are highly correlated. Both the stress drop magnitude and the incubation time for serrations follow a power-law distribution, presenting a sharp contrast to the randomly generated, uncorrelated serrated flow events in the absence of SBIs. Observations on the fracture morphologies provide further evidence and insights into the deformation dynamics dominated by SBIs. A stick–slip model for multiple shear bands with interactions is also proposed and numerically calculated. The results, in good agreement with the experimental results, quantitatively show how multiple shear bands operate and correlate, especially for those with large serrated flow events. Our studies suggest that one serration in the stress–strain curve may correspond to collective stick–slip motions of multiple shear bands for those ductile bulk metallic glasses where a large number of shear bands are observed during deformation.

Keywords: Metallic glass; Serrated flow; Stick–slip; Shear band

1. Introduction

At temperatures well below the glass transition, metallic glasses typically deform inhomogeneously with plastic strain highly localized into thin shear bands [1–3], which is completely different from the dislocation-mediated plasticity in crystalline alloys. Characterizing the shear banding process [4–10] in parallel with theoretical efforts to describe the underlying physical origin [11–16] has been the subject of extensive research in the past decades, and still attracts considerable interest [17], particularly for the case of bulk metallic glasses (BMGs) which have attractive properties such as high strength and large elastic limit, and wide potential applications [18–22]. Focused topics include the structure of shear bands [23–25], the temperature rise of shear bands during deformation, the free volume accumulation or volume dilation within shear bands [4,10,26] and the velocity of propagating shear bands [5,27–29], features which are all indispensable for a full description and understanding of shear band dynamics.

Broadly speaking, a shear band is usually initiated at a local region by some softening mechanism, which has been attributed to the influence of local heating [30–32] or shear dilation (free volume generation) [11–13], or a combination of both [33]. Once triggered, such a shear band will propagate rapidly due to the reduced viscosity or resistance to deformation in its vicinity, leading to catastrophic failure of the glass along the primary shear plane. The macroscopic outcome is almost the zero plastic deformability in tension testing [31], thus limiting the wider application of BMGs. The shear banding process in compression, how-

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ever, does not always have catastrophic consequences. Some BMGs can undergo shear banding in a stable and intermittent manner, which manifests as serrated flow behavior in the plastic regime of stress–strain curves [4]. Similar behaviors are also widely observed in other load-constrained modes such as pop-ins during nanoindentation [34]. The serration process is characterized by repeated cycles of a sudden stress drop followed by reloading elastically. In addition, serrated flow also shows a strong dependence on the strain rate and the temperature [6,9,35]. For example, serrations tend to be suppressed at high strain rates or low temperatures, and disappear at certain critical values [34]. Despite extensive studies, the physical origin of serrated flow as well as its connection to the shear banding process in metallic glasses is still elusive.

In an early study of the compressive behavior of Zr-based BMGs, Wright et al. [4] assumed that each serration was associated with the emission of an individual shear band, and subsequently offered a detailed analysis of the shear-band dynamics. Although the location from which a shear band was emitted was not identified, the assumption of individual shear-band emission has since been widely accepted for interpreting the deformation behavior of BMGs under different loading modes. Based on this viewpoint, Schuh et al. [34] attributed the disappearance of serrations at high strain rates in nanoindentation to the kinetic limitation for shear bands, where a single shear band cannot accommodate the imposed strain rapidly enough at high strain rates, and consequently, multiple shear bands operate simultaneously. Some authors [36] also correlated each serration with the shear-band activity on the surface of deformed specimens based on the observation of rate-dependent shear-band patterns. Recently, the serrated flow in compression was recognized to arise from the stick–slip operation of a single shear band [7–9]. Song et al. [8] found that the regularly spaced striations on the shear surface match well with the serration spacing recorded in the load–displacement curve, and further *in situ* compression experiments also revealed a one-to-one correspondence between the intermittent slidings of the primary shear band and the serrated events. By carefully correcting the experimentally determined displacement jump magnitude during a serration, Maaß et al. have shown that the disappearance of serrations on lowering the temperature was directly linked to the shear-band propagation velocity, and the transition occurred at the temperature for which the shear-band velocity equals the applied cross-head velocity, giving underpinning evidence that flow serrations are caused by intermittent shear-band slidings in BMGs [9].

The stick–slip process of shear banding indicates that the mechanical properties of BMGs (especially plasticity) are not only affected by intrinsic properties such as the glassy structure [37,38] and free volume contents [39], but also by the extrinsic materials properties [15,40] and experimental factors [41,42]. Indeed, Han et al. [40] have shown that the plasticity of monolithic BMGs strongly depends on the sample size and the stiffness of the testing machine. Based on the observations, they proposed a single parameter, called the “shear-band instability index”, that governs the critical transition from unstable to stable shear banding as a function of sample size and machine stiffness. In addition, enhanced plasticity may also be a consequence of geometrical constraints during mechanical testing. For instance, after a carefully conducted series of compression tests, Wu et al. [42] found that any deviation from a perfect coaxial alignment of the sample with respect to the compression axis results in a large apparent plasticity. Recently, Cheng et al. [15] also proposed a stick–slip model for the operation of a single shear band, which quantitatively showed that the experimental factors (such as sample size and machine stiffness) can greatly affect the temperature rise in the shear band as well as its sliding speed, thus causing either cold and stable or hot and runway shear banding in BMGs.

Usually, most BMGs fail along a single dominant shear band. Most analyses so far have focused on the instability process of such a single shear band. However, for some ductile BMGs or their composites [43], the deformation proceeds via the simultaneous operation of multiple shear bands, with each band contributing to the plasticity and none of them carrying enough strain to cause catastrophic failure, thus leading to the large plasticity. In such cases, shear bands inevitably interact with each other and thus affect their formation and propagation. A few studies [44–46] have shown that SBIs play an important role in the dynamics of multiple shear bands. However, it is difficult to characterize SBIs due to the fact that shear bands are spatially and temporally generated, and also have a short propagation time. In this study, we introduce SBIs by a simple method and study their effects on the deformation dynamics and serrated flow in a Zr-based metallic glass. A stick–slip model considering SBI is also proposed and calculated, showing how multiple shear bands operate and correlate during a single serration event.

2. Experimental procedures

Alloy ingots with a nominal composition of $Zr_{65}Cu_{15}Ni_{10}Al_{10}$ were produced by arc melting a mixture of pure metals (purity $\geqslant$ 99.5%) in a Ti-gettered argon atmosphere. To ensure compositional homogeneity, each ingot was remelted at least three times. Rod-shaped samples with a diameter of 1.5 mm and a length of about 50 mm were obtained by suction casting into a copper mold. The amorphous nature of the as-cast specimens was examined by X-ray diffraction (XRD, PANalytical X'Pert PRO) with Co K_α radiation and differential scanning calorimetry (DSC, Perkin Elmer DSC7). Specimens about 4 mm long were cut from BMG rods by means of a diamond saw, and then carefully ground into compression specimens with an aspect ratio of 2:1 to an accuracy of ± 5 μm. Uniaxial compression tests were performed with an Instron 5869 electromechanical test system at a constant strain rate of $2 \times 10^{-4}\ s^{-1}$ at room temperature. The strain was mea-