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Achieving high uniformity of the elastic strain energy accumulation rate during the serrated plastic flows of bulk metallic glasses

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ABSTRACT

The shear-band formation and propagation mechanisms of bulk metallic glasses (BMGs) have been studied extensively, however, the interpreting of the mechanisms of the serrated plastic flows is still challenging. In this work, the variation of the elastic strain energy accumulation rates of the serrations during the plastic flows of BMGs was examined using a statistical analysis. High uniformity of elastic strain energy accumulation rates was achieved in the serrated plastic flows under complex stress fields with three-parameter Weibull modulus reaching to 14.29, which is much larger than the value of 4.06 under conventional compression tests. The variations of the elastic strain energy accumulation rates are related to the formation and propagation of shear bands under varying loading conditions, and the high uniformity under complex stress fields is due to that the formation and propagation of shear bands can be confined to certain shearing path. The present findings are of significance for giving more insight into the mechanisms of the serrated plastic flows of BMGs.

1. Introduction

Stemming from the stochastic atomic arrangements, bulk metallic glasses (BMGs) are known to have attractive properties, such as the high strength approaching the theoretical values, a relatively large elastic limit of about 2%, high corrosion resistance, good biocompatibility, and excellent processing capability at high temperature (supercooled liquid region) [1–4]. With non-ordered atomic structures, the plastic deformation in BMGs is localized thin layers of shear bands at room temperature, displaying serrated plastic flows [5–7]. Research findings have shown that the bursts of the flow serrations are related to the formation of shear bands [6,8]. Each serration consists of a stress arising process to accumulate the elastic energy, and a stress drop process to dissipate the energy through plastic deformation, i.e., the formation and propagation of shear bands [6,9]. Many studies have been devoted to uncover the plastic deformation mechanisms of BMGs, such as the nucleation of shear bands [5,10–13], the criticality of the plastic-flow dynamics [9,14–18] and the transition of the plastic deformation modes [7,19–21]. Zhang et al. have summarized the serrated plastic flows of BMGs under varying strain rates, temperature and sample dimensions [22]. However, the understanding of the underlying mechanisms of the serrated plastic flows of BMGs is still challenging and hinders the understandings of the plastic deformation mechanisms of BMGs. For example, the constitutive laws of BMGs which can accurately describe the serrated flows are still under debate [5,19,23–25].

Due to the meta-stable atomic structures, BMGs have scattered properties, such as the fracture toughness [26,27], strength [28–30] and nominal plasticity [31]. The scattering of the properties may hinder the understanding of the underlying physical mechanisms. For example, the burst of shear bands in a specimen is affected by the structural inhomogeneities [5,32], pre-existing shear bands [33–35] and the evolution of surrounding stress [13,36], resulting in varying magnitudes in the flow serrations. How to achieve reliable properties of BMGs is important for the characterization of the relating deformation mechanisms. Regarding that the formation of shear bands dependents on the surrounding stress fields, the plastic deformation behavior of BMGs can be tuned by tailoring the distribution of complex stress states [36–38]. Under gradient stress distributions, more reliable plasticity of BMGs was also observed [31]. The complex stress fields can even drive the plastic-flow dynamics of BMGs to evolve to a criticality to delay the catastrophic failures, which are also independent on the change of the loading rates [39]. Therefore, it might be possible to obtain flow serrations with reliable properties by tailoring the distributions of complex stress fields. In this work, the variations of the elastic strain energy accumulation rates of the serrated plastic flows of BMGs under complex stress fields as well as conventional compression tests were examined using statistical analysis. Relatively-higher uniformity of the elastic

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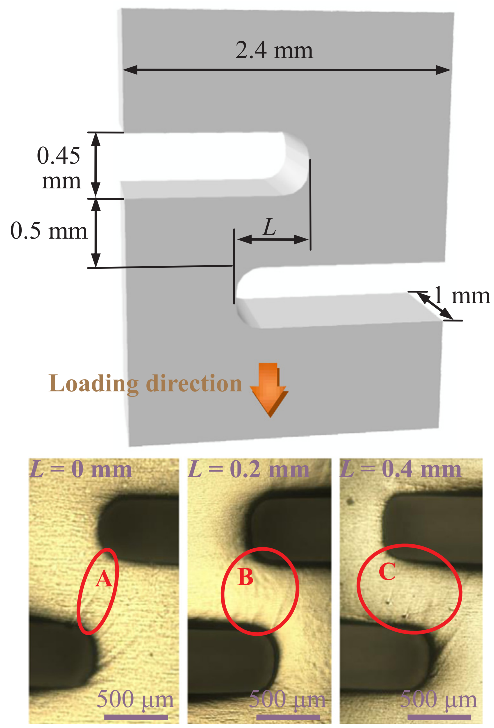

Fig. 1. The schematic diagram of the notched specimens, where the specimens with $L = 0$ mm, 0.2 mm and 0.4 mm are labeled as L00, L20 and L40, respectively. The optical images show the examples of the prepared specimens.

strain energy accumulation rates under complex stress fields was achieved and discussed.

2. Experimental

Master alloy ingots with a nominal composition of $Zr_{57}Cu_{20}Al_{10}Ni_8Ti_5$ (*at.*%) were prepared from the pure elements by arc melting under an argon atmosphere. Cylindrical BMG samples of 3 mm diameters were then fabricated by suction-casting the melted alloys into water-cooled copper molds, and the amorphous atomic structures were confirmed using standard X-ray diffraction (XRD) analysis. The distribution of the complex stress fields was achieved by tailoring double-side notches, as shown in the schematic diagram in Fig. 1 [39]. The cuts were fabricated using a diamond saw. The mechanical tests of the notched specimens were performed on an Instron 5565 electro-mechanical materials testing machine at loading rates of 0.3, 0.06 and 0.012 mm/min., respectively. The serration data were collected at 100 points per second. For comparison, rod samples with an aspect ratio of 2 were tested on an 810 Materials Testing System (MTS) at a strain rate of 1×10^{-4} s^{-1}. After mechanical testing, the surfaces of the specimens were examined using scanning electron microscopy (SEM).

3. Result and discussion

With double side notches, the notched specimens deform and fracture under a mixed mode (I/II) loading condition. The increase of the notch bottom distance (L in Fig. 1) leads to the increase of the mode-I component, resulting in the presence of more complex stress fields in the regions between two notches (regions A-C in Fig. 1) [39]. With tailored complex stress fields, the notched BMG specimens have plastic-flow-plateau stages with serrated flows, where the typical load-axial displacement curves at a loading rate of 0.6 mm/min. are given in Fig. 2a. Since the notched specimens have plastic flows independent on the applied loading rates, the loading curves of the specimens tested at other loading rates are similar to the L00 specimens (as shown in Fig.

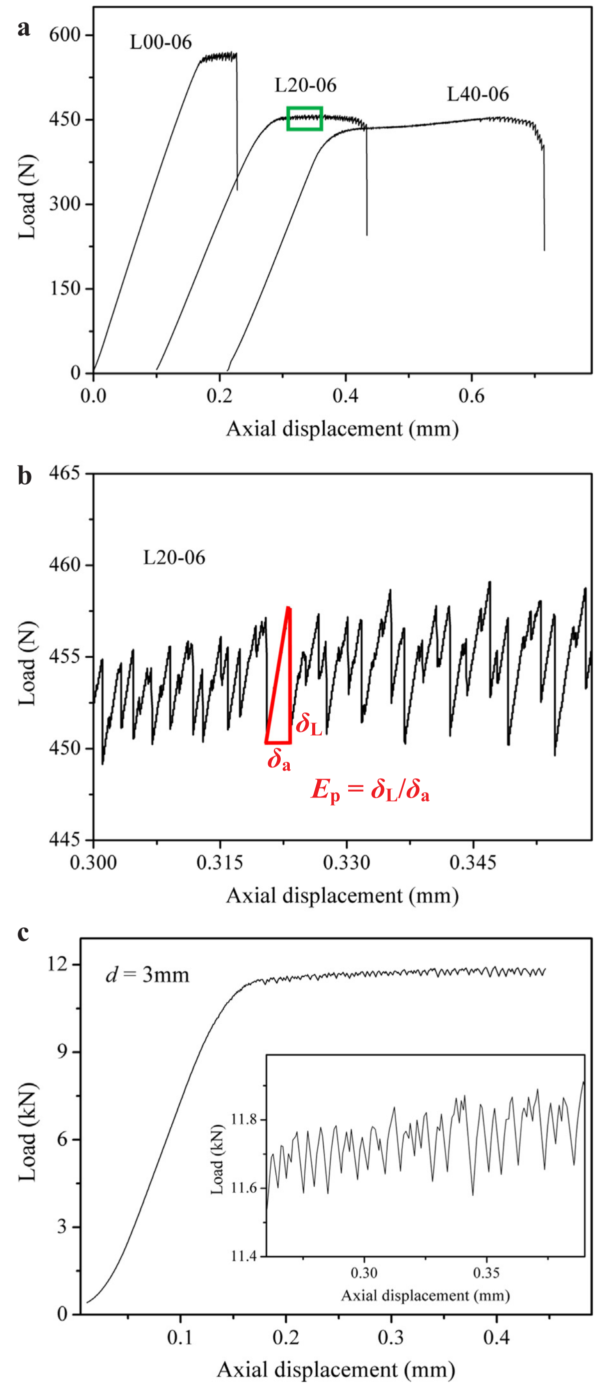

Fig. 2. (a) The load-axial displacement curves of the notched specimens at a loading rate of 0.06 mm/min., where (b) shows the serrated flows of the L20 specimen (the green rectangular in (a)) at a higher magnification. (c) Compressive load-axial displacement curve of a BMG specimen with 3 mm in diameter, where the inset shows the magnified flow serrations.

SI1 in the supplementary materials) [39]. Previous findings have shown that the load-drop magnitudes are different at different plastic-flow-plateau stages [39], however, the serrations have variations on the elastic strain energy accumulation rates from serration to serration at all plastic-flow-plateau stages. The elastic strain energy accumulation rate of the serrations is correlated to the capability of BMGs to store the elastic strain energy before the initiation of shear bands, which can manifest the underlying physical properties of the material, for example, the relatively-larger elastic limit of BMGs. To characterize the variations of the elastic strain energy accumulation rate of the serrated