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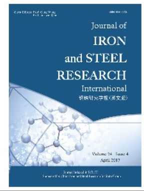

Effect of pre-existing shear bands on mechanical properties and serration behaviors in bulk metallic glasses

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ABSTRACT

Pre-existing (multiple) shear bands were introduced into the ductile $Zr_{56}Co_{28}Al_{16}$ and $Zr_{65}Ni_{10}Cu_{15}Al_{10}$ bulk metallic glasses (BMGs) through the lateral-deformation, respectively. It was found that the pre-existing shear bands can further enhance the compressive plasticity of ductile BMGs. According to the serration analysis on the plastic deformation of the as-cast and the pre-deformed samples, the serration events in the stress-strain curves during deformation display a self-organized critical (SOC) behavior. Compared with the as-cast BMGs, a larger power-law scaling exponent calculated based on serrated flow behaviors becomes larger for the pre-deformed BMGs, implying that the shear banding stability of BMGs is effectively enhanced. This should be caused by the pronounced interactions of shear bands during plastic deformation for the pre-deformed BMGs. However, by introducing a large amount of multiple shear bands into the glassy matrix, it also becomes easier for shear bands to propagate along the pre-existing shear bands, leading to a lower cut-off elastic energy density for the pre-deformed BMGs. More multiple shear bands with stronger interactions for the pre-deformed BMGs could provide a larger chance to activate the shear-band cracking but less local elastic energies are remained for the subsequent crack-linking.

1. Introduction

Recently, the fabrication and deformation of bulk metallic glasses (BMGs) have attracted much attention due to their excellent mechanical properties such as high hardness, high strength, and large elastic limit[1-5]. Different from the dislocation-mediated plasticity in metallic crystalline alloys, BMGs typically deform inhomogeneously with a limited plastic strain highly localized within shear bands[4,5], resulting in their intrinsic brittleness at room temperature. Therefore, it is a long-term topic to study the deformation behaviors of BMGs in order to enhance their room-temperature plasticity, which strongly depends on how to induce the formation of multiple shear band and inhibit the rapid propagation of shear bands[6]. During deformation, once the shear banding process is triggered due to the local heating[7], shear dilation[8-10], or a combination of both[11], a fierce catastrophic consequence would be induced[12,13]. However, it was also found that the shear banding process of some BMGs during compression is usually carried out in a stable and intermittent manner, which is reflected to be a serrated flow behavior in the plastic regime of compressive stress-strain curves[12,13]. Until now, it has been demonstrated that the serrated flow behaviors of BMGs during deformation depend on not only the material itself[14,15] but also the loading conditions (e.g. compression, tension, or bending)[4,6,16], temperature[17,18], loading rate[19,20], sample size[21,22], testing machine stiffness[23], and external constraint[24].

Early studies[25-27] have shown that the serrated flow in the plastic regime of compressive stress-strain curves is attributed to the stick-slip operation of a single dominant shear band. By correlating the regularly spaced striations on the shear surface and the serration spacing recorded in the load-displacement curves, the serrated flow behaviors during compression can be treated as a one-to-one correspondence between the intermittent sliding of the single dominant shear band and the serrated events[25-27]. In the recent years, it has been found that the plastic deformation during compression for some ductile

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BMGs proceeds via a simultaneous operation of multiple shear bands[28,29]. Based on the statistical analysis on serrations in the plastic regime of compressive stress-strain curves, the stick-slip plastic dynamics of BMGs exhibits a chaotic behavior when one single dominant shear band governs the plastic deformation, leading to a low shear banding stability[30-37]. When shear bands are highly correlated and interacted in a complex and scale-free process, the plastic dynamics of BMGs exhibits a self-organized critical (SOC) behavior, resulting in a large compressive plasticity[30-37].

Therefore, the formation and propagation of multiple shear bands should be very vital for the enhancement of the shear banding stability during deformation. Recently, by introducing pre-existing shear bands into the glassy matrix using cold rolling, imprinting, shot peening methods and so on, the room-temperature compressive plasticity of BMGs can be effectively enhanced and even a little tensile plasticity can be reached[38-41], which should be attributed to the increase of the shear banding stability of BMGs during deformation. However, statistical studies of serrations for the BMGs with the pre-existing shear bands in the glassy matrix during deformation are still rare. In this work, two types of ductile BMGs, i. e. $Zr_{56}Co_{28}Al_{16}$ and $Zr_{65}Ni_{10}Cu_{15}Al_{10}$, were chosen to investigate the effect of pre-existing shear bands, which were introduced by lateral-deformation on their both sides, on the serrated flow behaviors of BMGs during plastic deformation. The present studies could provide a complemental understanding of how to improve the shear banding stability of BMGs during deformation.

2. Experimental

$Zr_{56}Co_{28}Al_{16}$ and $Zr_{65}Ni_{10}Cu_{15}Al_{10}$ (at. %) master alloys were prepared by arc melting appropriate amounts of the constituting elements (>99.9% purity) under a Ti-gettered argon atmosphere. The master alloys were remelted at least three times in order to achieve chemical homogeneity before casting into rods with a diameter of about 2 mm and a length of (40±35) mm using a custom-made suction casting device under an argon atmosphere. Differential scanning calorimetry (DSC) measurements were carried out using a METTLER TOLEDO TGA/DSC 1 calorimeter under a flow of purified argon at a heating rate of 20 K/min to measure the glass transition and the crystallization temperatures of the investigated samples. In order to introduce the pre-existing shear bands in the glassy matrix, the as-cast rods were pre-deformed on their both sides using an electronic universal testing machine (New SANS, MTS) at an initial strain rate of 5×10^{-4} s^{-1}. During pre-deformation, the loading displacement was set up as about 0.10 mm. The phase analysis of the as-cast BMGs and the pre-deformed BMGs was carried out by X-ray diffraction (XRD, Rigaku D/max-rB) in reflection geometry and scanning electron microscopy (SEM, Gemini 1530). The mechanical properties of the samples were determined using a nanoindenter (Anton Paar CSM-NHT2) and a universal mechanical testing machine (MTS CMT5305). The maximum applied force in the nanoindentation tests was 50 mN, the loading rate was 100 mN/min, and the holding time at the maximum applied force was 10 s. For the compression tests, the initial strain rate was 2.5×10^{-4} s^{-1}, and the geometric size of the compression samples was about $\phi2$ mm×4 mm. The surface and fracture morphologies of the samples after deformation were investigated by SEM.

3. Results and Discussion

Fig. 1(a,b) shows the room-temperature compressive strain-stress curves for the as-cast $Zr_{56}Co_{28}Al_{16}$ and $Zr_{65}Ni_{10}Cu_{15}Al_{10}$ BMGs. All the investigated BMG rods show a high yield strength together with an obvious plasticity. As listed in Table 1, the average yield strength and average plastic strain of the as-cast $Zr_{56}Co_{28}Al_{16}$ BMGs are (2060±75) MPa and (5.3±1.2) %, respectively. The as-cast $Zr_{65}Ni_{10}Cu_{15}Al_{10}$ BMGs show a lower average yield strength of (1730±22) MPa and a larger average plastic strain of (9.1±2.5) %. It has been demonstrated that the yield strength (σ_y) should be linked with the glass transition temperature (T_g) of BMGs, which can be described by a universal scaling law[42]:

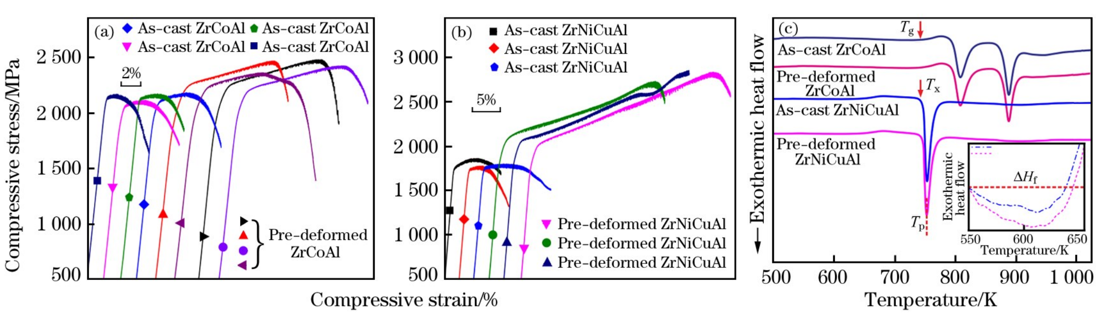

Fig. 1. Compressive strain-stress curves of as-cast and pre-deformed $Zr_{56}Co_{28}Al_{16}$ (a) and $Zr_{65}Ni_{10}Cu_{15}Al_{10}$ (b) BMGs, and DSC curves of as-cast and pre-deformed BMGs (c).