



Stable shear of $\text{Cu}_{46}\text{Zr}_{47}\text{Al}_7$ bulk metallic glass alloy by controlling temperature rise

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ABSTRACT

$\text{Cu}_{46}\text{Zr}_{47}\text{Al}_7$ bulk metallic glass (BMG) alloys with different microstructure were fabricated by adjusting the casting size. For the monolithic BMG with different diameters, the measured plasticity decreased with the increase of sample size and was mainly due to the sliding of two undeveloped parts along main shear band. Excellent compression plastic strain ($\sim 13.2\%$) was obtained for the marginal BMG containing *in situ* nanocrystals with sample size up to 3.5 mm in diameter where multiple shear bands formed. It is suggested that failure of BMG samples will occur when the temperature rise in shear layer reaches a critical value. The temperature rise is closely related to the sample size and stress drop, moreover, it can be controlled through adjusting final stress drop (via sample size) and increment rate of stress drop (via microstructure), resulting in enhanced plasticity.

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1. Introduction

Bulk metallic glasses (BMGs) have been regarded as potential functional and structural materials since their first emergence several decades ago due to their unique physical and mechanical properties [1–3]. Recently, substantial improvements on plasticity have been achieved in some Zr- [4], Pd- [5], and Pt- [6] based BMGs. In particular, due to their excellent mechanical properties and cheap and environmentally friendly raw materials used, CuZr-based BMGs such as $\text{Cu}_{50}\text{Zr}_{50}$ [7,8], $\text{Cu}_{47.5}\text{Zr}_{47.5}\text{Al}_5$ (or $\text{Zr}_{47.5}\text{Cu}_{47.5}\text{Al}_5$) [9,10], $\text{Zr}_{65}\text{Al}_{17.5}\text{Cu}_{17.5}$ [11], $\text{Cu}_{50}\text{Zr}_{43}\text{Al}_7$ [12], which are free of poisonous (Be, Ni, etc.) and noble elements (Pd, Pt, etc.), exhibited large compressive plastic strain. The presence of small nanocrystals [7–11] and the deformation induced nanocrystallization [12,13] have been given for factors contributing to the intrinsic ductility of these CuZr-based BMGs. Moreover, the free volume effect [14–16], geometrical size effect [16–19] have also been put forward recently. As is known, the large plasticity of these CuZr-based BMGs [7–13] is usually found in samples with a diameter of 2 mm or less. Therefore, the large compressive plasticity obtained from these CuZr-based alloys might be related with complicated factors such as free volume [14–16], sample size [16–19], small nanocrystals [7–13,20,21], and the origin of their enhanced plasticity is still not fully understood. In this study, fully bulk metallic glass and marginal BMG of $\text{Cu}_{46}\text{Zr}_{47}\text{Al}_7$ alloy with different size

were prepared. The plastic deformation behavior related with sample size and microstructure was systematically investigated. It is suggested that catastrophic failure will occur when temperature rise in shear layer reaches a critical value. Temperature rise can be tailored through adjusting sample size and microstructure, which exhibits a useful guideline to obtain enhanced plasticity of BMGs.

2. Experiments

An ingot with the nominal composition of $\text{Cu}_{46}\text{Zr}_{47}\text{Al}_7$ was prepared by arc-melting of 99.9% (at.%) pure Zr, Cu and Al under Ti-gettered argon atmosphere. The ingot was re-melted at least four times to ensure the chemical homogeneity. The rods of 1, 2, 3 and 3.5 mm in diameter were prepared by copper mould suction casting in an argon atmosphere. The alloys were characterized by X-ray diffraction (Rigaku D/MAX-RB, Cu K_α radiation) and transmission electron microscope (JEOL Ltd., JEM2100F). Compression samples with the aspect ratio of 2:1 were prepared. Room temperature compression tests were conducted on a screw-driven Instron 1195(5500R) testing machine at an initial strain rate about $2.0 \times 10^{-4} \text{ s}^{-1}$. After the compression tests, the fracture morphology of the rod samples were observed by a scanning electron microscope (SEM).

3. Results

XRD results confirmed glassy nature of these samples (not shown). HRTEM observations were further performed on the 3 and 3.5 mm rod samples. The HRTEM images as well as the selected

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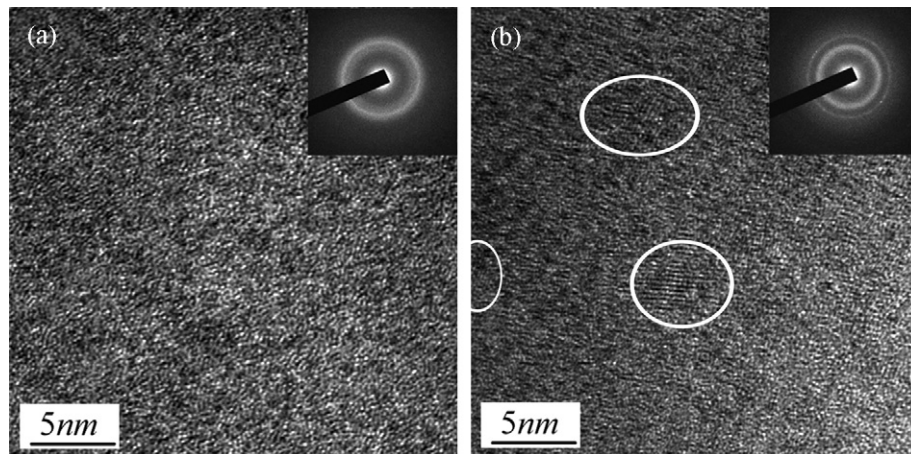


Fig. 1. HRTEM images and the corresponding SAED patterns of $\text{Cu}_{46}\text{Zr}_{47}\text{Al}_7$ BMG alloy with the diameters of (a) 3 and (b) 3.5 mm.

area electron diffraction (SAED) patterns (insets) were given in Fig. 1. The 3 mm sample displays mazelike clusters without any visible nanocrystals and heterogeneity as shown in Fig. 1(a), which is the typical feature of metallic glasses, as widely observed before. Meanwhile, the samples with the size less than 3 mm are all fully amorphous (not shown here). Comparing with the 3 mm sample, the HRTEM image of 3.5 mm samples (marginal BMG), as shown in Fig. 1(b), indicates that small nanocrystals are formed and embedded in the glassy matrix with the size of 3–5 nm. The corresponding SAED patterns [Fig. 1(b) inset] show distinct lattice fringes, also confirming the existence of nanocrystals, which is consistent with our previous results [22]. Above results demonstrate that the glass formation ability of this $\text{Cu}_{46}\text{Zr}_{47}\text{Al}_7$ bulk metallic glass is 3 mm in diameter, as is in accordance with Xu et al. [23].

Different sized samples were compression tested at room temperature for mechanical behaviors. Fig. 2(a) presents the representative compressive engineering stress–strain curves for the alloys investigated. As it can be seen, the plastic strain of the monolithic BMG alloys is obviously dependent on the casting size, consisting with the results of other BMGs [14,16–19], where the smaller sample shows larger plastic strain. The yield strength of the samples increases with the sample size, which is consistent with the other report that “smaller is softer” [14]. It is interesting that the 3.5 mm sample (marginal BMG) presents excellent plastic strain of 13.2%. As is known, the CuZr-based BMGs with enhanced plasticity usually have a small size of 2 mm or less in diameter [7–13], there has no other larger sized CuZr-based BMG showing so high a plastic strain (>10%) except our present marginal BMG sample. The overall plastic deformation was accompanied by the serration flow. In general, the stress drops ($\Delta\sigma$) gradually increase from the onset of plastic deformation to the final fracture for all samples as shown in Fig. 2(b). We measured every stress drop values during plastic flow and calculated the slope of stress drops, *i.e.* increment rate of stress drop, K [24] as shown in Fig. 2(c). The values of K for 1, 2, 3 and 3.5 mm samples are 5.1, 7.3, 20.3 and 0.2 MPa, respectively. A relatively smaller K value of the marginal BMG than expected is obtained.

Fig. 3 shows the SEM morphology of lateral surface of the fractured BMG samples. Few shear bands were visible on 1, 2 and 3 mm samples [Fig. 3(a)–(c)]. The three monolithic BMG samples all failed along a single shear band and in the almost same fractured angel of 42° . In contrast, a large amount of shear bands developed on the 3.5 mm fractured sample as shown in Fig. 3(d). Most of the shear bands were interconnected and intersected each other. At the end, the marginal sample still failed along a shear band. The multiple

shear banding was beneficial to the observed global plasticity of the marginal BMG in compression.

4. Discussion

It is well known that the room temperature plastic strain of metallic glass is produced by the shear sliding of two undeveloped parts separated by the localized shear band in the compression tests [25]. The shear band consists of a layer of material with viscosity lower than that of the rest in the sample, which weakens the plane against fracture by the Taylor instability mechanism. Once the viscous layer formed in the shear bands, the shear modulus will dramatically decrease, leading to lower resistance of applied stress and shear softening as is observed in the stress drop. In turn, the released elastic energy ΔE due to the stress drop can be transformed into heat δ_h to increase the temperature of shear layer and further decrease the viscosity of shear layer. At the same time, the material on either side of the shear band must migrate perpendicularly to the loading direction with additional shear occurring on the pushrod/material interface in the form of friction as shown in Fig. 4(a) [26]. This frictional force not only breaks the sample off the initial pure normal loading condition, but also provides a driving force against further slip along the shear band. Since the slip along this band is effectively slowed, the local temperature at the shear band is given time to decrease, whereupon the viscosity of shear layer increases that introduces the re-freezing of the melt accompanying the stop of shear sliding [26]. If the shear band propagation can be stopped, there will be competition between initiating new shear bands and reactivating the formed shear band to provide strain or displacement to meet the requirement of test machine loading.

For the monolithic BMG, once the shear band nucleates and propagates, it becomes the weak site of the sample [27]. Furthermore, the shear-induced structural changes can lead to a situation where reactivation of the existing shear band is more favorable than initiation of new shear band [28]. Therefore, the stable sliding along the formed shear band will continue due to the repeated melting and re-freezing, *i.e.* viscosity decreases with local melting, then increases as the material cools. While for the marginal BMG, the presence of small nanocrystals in the shear bands may effectively raise the flow stress [11,21] and help the re-freezing of the melt. Moreover, the stress concentration producing by the difference in elastic properties between the nanocrystals and the matrix can easily initiate new shear bands. When reloading on the sample, shear band will initiate in other sites rather than the preformed shear band. Once the second shear band was also

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