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Effect of residual stresses on the onset of yielding in a Zr-based metallic glass

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Abstract

Indentation experiments were performed on as-cast and elastically-bent-and-constrained Zr-based metallic glass samples to investigate the effect of strain rate and residual stresses on the onset of yielding in the material. The critical shear stress for the onset of yielding in the as-cast sample was found to be insensitive to the applied strain rate. By contrast, in the elastically-stressed sample, the maximum contact pressure from the Hertzian stress field at the onset of yielding was found to largely decrease under tensile residual stress, but only slightly increase under compressive residual stress. Despite the different residual stresses, the effective shear stress, i.e. the superimposition of residual and Hertzian stress fields, for the onset of yielding in the Zr-based metallic glass was essentially a constant. The constancy of the effective stress for the onset of yielding was discussed in light of a critical excess volume associated with the atomic structure upon loading.

Keywords: Residual stresses; Onset of yielding; Metallic glasses; Nanoindentation; Glass transition

1. Introduction

Bulk metallic glasses (BMGs) have recently attracted extensive research attention. Among their superior properties, their mechanical behavior is probably of most interest [1–4]. Although they have high yield strength, high hardness and large elastic limit [2,3], metallic glasses are plastically brittle and suffer from shear localization at ambient temperature. When a metallic glass is under loading, shear bands are formed to accommodate the applied shear strain [5–7], and their formation has been widely studied in recent years, including the nucleation [8,9] and propagation processes [10,11]. Large efforts have been made to prevent catastrophic failure and enhance the plastic strain in BMGs by introducing second phases to block shear band propagation [12–16]. It is now clear that, kinetically, shear band nucleation controls the plastic deformation in metallic glasses [8,17–20]. It is widely accepted that shear banding initiates from local atomic shuffling, i.e. formation and clustering of shear transformation zones (STZs) [6,8,21]. Attempts have been made using molecular dynamics (MD) simulation to uncover the details of the shear localization process at the atomic level [22–27]. However, it is difficult to experimentally observe the atomic-scale processes underlying the shear localization, owing to the extremely short time and fine length scales involved.

Nanoindentation has been demonstrated to be an effective technique for identifying the onset of yielding and the ideal shear strength of crystalline materials [28–30]. The onset of yielding during nanoindentation is usually marked by the first pop-in, and the pop-in stress corresponds to the "ideal" or "theoretical" strength of the material, which is

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on the order of $\mu/30$–$\mu/5$, where μ is the shear modulus [31,32]. However, the study of onset of yielding of metallic glasses using nanoindentation is limited [33,34]. The onset of yielding represents the completion of shear band nucleation, after which shear band rapidly propagates. Recently, it was found that residual stresses could affect the flow stress in metallic glasses, and the effect resulted from the change in initial structure, in particular the density or excess volume in the materials [35].

This paper reports on nanoindentation tests using a spherical indenter tip to study the effects of residual stresses (in both tension and compression) on the onset of yielding in metallic glasses, i.e. the first pop-in. It is demonstrated that the presence of residual stresses can affect the onset of yielding, which is determined by excess volume in the metallic glass.

2. Experimental procedure

A small $Zr_{52.5}Al_{10}Ti_5Cu_{17.9}Ni_{14.6}$ (BAM-11) disk with dimensions $3 \times 4 \times 2$ mm was cut by electric discharge machining (EDM) from a 7 mm diameter rod fabricated by arc melting, and this specimen was denoted as the as-case sample. To study the residual stress effect, a thin sheet with dimensions $0.6 \times 3 \times 15.3$ mm was cut from the same rod. The specimen was then elastically bent and constrained in a steel ring 15 mm in internal diameter, and was denoted as the stressed sample. The cross section of the stressed sample was immediately imaged using scanning electron microscopy (SEM), and the radii of curvature of both compressive and tensile surfaces were measured, as shown in Fig. 1. No shear band is observed, indicating that the bending is in the elastic region. The bent curvature was calculated as $\kappa_C = 1/R_C = 0.046\ \text{mm}^{-1}$ on the compressive side and $\kappa_T = 1/R_T = 0.047\ \text{mm}^{-1}$ on the tensile side, with the subscripts C and T representing compression and tension, respectively. The thickness of the sheet is 0.6 mm. The stress is estimated to be 1.17 GPa, taking the average value of κ_C and κ_T as the curvature of the neutral plane. Details of sample preparation can be found elsewhere [35]. Both specimens (as-cast and stressed samples) were then mounted with epoxy and polished to a mirror finish prior to further testing.

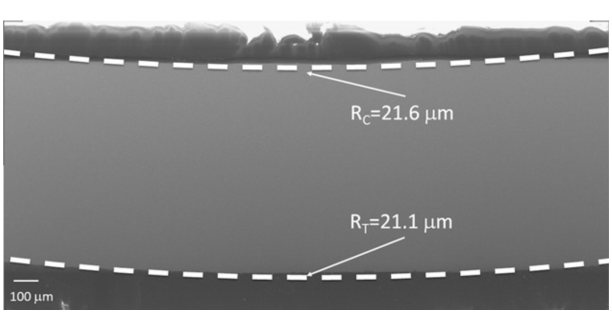

Fig. 1. Secondary electron image shows the curvature of elastically bent sample.

Nanoindentation tests were performed on specimens using a commercially available TriboIndenter model (Hysitron, MN). A blunt spherical tip was used to capture the first pop-in in BAM-11, and the tip radius which was carefully calibrated with a tungsten single crystal [36,37] is 780 nm. Load control mode with a constant loading rate was applied during nanoindentation, and the maximum load was pre-set at 1 mN. For the as-cast sample, different loading rates, ranging from $0.1\ \text{mN s}^{-1}$ to $1\ \text{mN s}^{-1}$, were applied. To eliminate the statistical error, 100 indents were performed at each loading rate. For the stressed sample, only one loading rate ($0.1\ \text{mN s}^{-1}$) was used. The indentation locations were carefully selected along the central axis of the sheet, as schematically illustrated in Fig. 1 in Ref. [35]. At least 30 indents were performed at each horizontal location with respect to the central axis.

3. Onset of yielding in BAM-11

3.1. First pop-in in the as-cast sample

The nanoindentation load–displacement curve with a loading rate of $0.1\ \text{mN s}^{-1}$ is plotted in Fig. 2. The first pop-in is clearly identified, as marked by a discontinuity at a relatively shallow indentation, $\sim$20 nm. The first pop-in is normally attributed to the onset of plasticity [33], thus the completion of shear band nucleation, and the shear stress at the first pop-in is regarded as the theoretical strength of a material. Prior to the first pop-in, the load–displacement relationship can be fitted to the Hertzian contact solution [38]:

$$P = \frac{4}{3} E^* \sqrt{Rh^3} \tag{1}$$

where E^* is the effective modulus of the pair of contacting solids, and can be derived from $E^* = [(1 - \upsilon_s^2)/E_s + (1 - \upsilon_i^2)/E_i]^{-1}$ [38]. Here, E_s and υ_s and E_i and υ_i are the Young's modulus and Poisson's ratio of the BMG sample and diamond indenter, respectively. Fitting the

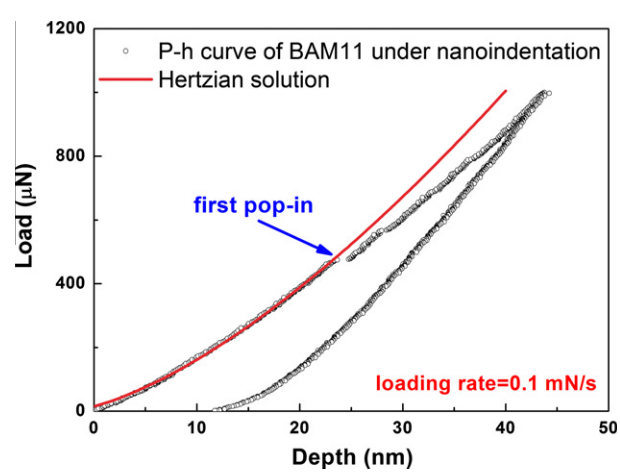

Fig. 2. Load–depth curve of the as-cast BAM-11 under nanoindentation. The first pop-in is indicated.