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Influences of residual stresses on the serrated flow in bulk metallic glass under elastostatic four-point bending – A nanoindentation and atomic force microscopy study

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Abstract

The effects of residual stress on the deformation behavior of a Zr-based bulk metallic glass (BMG) during nanoindentation were studied by atomic force microscopy. The residual stress was introduced by elastostatically preloading a beam-shaped BMG sample by four-point bending up to tensile and compressive stress levels of ±2.0 GPa for up to 14 days. Strain-rate-controlled nanoindentations were performed on the four-point bent samples at various times during loading and after unloading to analyze the serrated flow during indentation. The hardness of the alloy, the pile-up behavior as well as the serrations strongly depend on the magnitude and sign of the applied residual stresses. Tensile stresses suppress pile-up formation, decrease the hardness but increase the jump width of the serrated flow during nanoindentation. In contrast, increased pile-up formation with increased hardness occurs along with a successive serrated flow behavior on the compression side.

The discrepancy of pile-up and serrated flow is explained by a difference in the shear banding mechanism. The results suggest that for compressive stress individual shear planes are successively activated, leading to localized shear steps on the surface. For tensile residual stresses, the plastic volume is more widely spread, leading to vanishing pile-up together with an intermittent activation of a big number of shear events, causing big serrations. Due to the widely varying pile-up behavior, a hardness correction was performed. This strongly reduced the apparent hardness variations across the beam. For this specific testing arrangement, only reversible mechanical property variations with time due to long-time prestraining at high elastostatic stresses were observed.

Keywords: Bulk metallic glass; Nanoindentation; Pile-up morphology; Residual stresses; Temporal evolution

1. Introduction

Bulk metallic glasses (BMGs) are part of an interesting class of materials which exhibit a large yield strength coupled with a large elastic limit, but often fail in a catastrophic way due to shear localization during compressive or tensile loading. Shear band formation and propagation was identified as the general deformation and failure mechanism of bulk metallic glasses. Most deformation and failure modes, as well as the mechanical properties of BMGs, have been reviewed recently [1–3].

The formation of shear bands is governed by so-called shear transformation zones (STZs), which can be regarded

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as nuclei for plastic deformation in metallic glasses. In these STZs, local diffusion-controlled rearrangements of the atomic positions and the free volume can lead to softening of the material and shear localization. In this context, compressive stress can decrease the free volume and tensile stress can lead to an increase in free volume [4]. This should not be confused with the increase in the amount of free volume that is introduced into a metallic glass upon plastic prestraining (e.g. by rolling, shot-peening), as described elsewhere [5,6].

Nanoindentation can be used to study the deformation behavior of BMGs on a local scale and at varying deformation rates. Schuh et al. observed that the load–displacement curves had staircase-like shapes at low deformation rates, which they related to the discrete activation of shear bands [7–9]. At high loading rates smooth load–displacement curves were obtained, leading to the suggestion that homogeneous yielding might occur in this regime [9]. Jiang et al. found that in the case of increasing strain rates an increased number of shear bands were permanently active [10–12]. Either multiple shear bands can be active simultaneously or only a few shear bands propagate in a stick–slip kind of way [10]. Overall, there appears to be a threshold deformation rate beyond which the spatial magnitude of a single serration is less than the instrumental resolution in space and time [12,13]. Atomic force microscopy (AFM) substantiated this assumption. Semicircular pile-ups emanating from the indent edge and containing several surface steps are frequently reported [11–19]. Shear bands have been shown to be active irrespective of the applied indentation rate, because the shear steps were always resolved on the indent faces by AFM. It seems that lower strain rates decrease the number of shear steps present at an indent but simultaneously increase the step size and spacing [12]. Moreover, the number, size and spacing of shear steps are influenced in the same way by an increase in the indentation depth [13]. Finally, the pile-up morphology is influenced by the amount of free volume in the material. It was shown that large amounts of free volume can induce stable and homogeneous flow during nanoindentation at low deformation rates [11].

Using prestraining methods, the structure and topology of a BMG can be changed, sometimes yielding increasing plastic deformation during subsequent loading. Park et al. [20–23] and Lee et al. [24,25] showed both experimentally and by using atomistic modeling that compressive loading of Zr-based amorphous alloys at 90% of their compressive strength generates free volume in the material and leads to increased plastic strain in subsequent compression tests. This behavior was furthermore experimentally confirmed by Beitelschmidt et al. [26] on the amorphous alloy $Cu_{36}Zr_{48}Ag_8Al_8$, developed in 2006 by Zhang et al. [27].

Various other prestraining methods have been published since 2006 showing that monolithic BMGs sometimes undergo structural alterations, leading to an increase in plasticity during subsequent mechanical testing. Examples for some of these methods are the bonded-interface technique with post-deformation hardness mapping by nanoindentation [28,29] or precompression [16], multiple compression experiments [6,30] and also nanoindentation on bent samples [31,32]. In these studies, the shape, number and interaction of shear bands formed during subsequent testing were specifically investigated. Conclusions were drawn about how shear bands might interact and which property changes they might cause.

Indentation screening studies across bent samples have recently been performed by several groups [17,31–34]. Therein, bulk metallic glasses showed widely varying indentation behavior, according to the residual stress present. Chen et al. [17] mapped the hardness profile of a bent BMG beam by carrying out microindentations across the stress profile induced by bending. Due to the widely varying pile-up behavior, the authors concluded that the nominal hardness profile needs to be corrected according to the actual contact area. Tensile residual stresses decreased the hardness of the BMG, whereas compressive residual stresses slightly increased it. Overall, the authors observed a linear dependency of the difference between nominal and real hardness with the applied stress. Compressive stresses caused the strongest difference between nominal and real hardness.

Closer investigation on a similar setup was carried out by Wang et al. [32]. In this case nanoindentation was performed on elastically and plastically bent beams. Finite element studies were carried out and correlated to the experimental results. The maximum hardness decreased by approximately 15% on the tension side, which was confirmed by finite element simulations. However, the authors did not study the serrated flow during nanoindentation. Furthermore, changes in the pile-up morphology according to the residual stresses were ignored and pile-up correction was not performed. Therefore the resulting hardness profiles must be considered similar to the nominal hardness profiles mentioned above.

Studies on the pile-up behavior depending on the radius of curvature in bending were carried out by Lee et al. [31,33]. The authors demonstrated that pile-up is reduced for increasing tensile stress. However, they did not investigate the influence of compressive residual stress. Moreover, no information about mechanical properties from indentation was provided. Overall, the changes in mechanical properties, load–displacement behavior and the resulting pile-up morphologies have not been comprehensively studied yet.

In the present work, elastostatic bending tests were used to analyze the influence of residual stress on the deformation resistance and the flow behavior of $Cu_{36}Zr_{48}Ag_8Al_8$ BMG. Strain-rate-controlled nanoindentation experiments were carried out in situ on elastically deformed beams at stresses ranging from -1.8 GPa compressive stress up to $+1.8$ GPa tensile stress at various time intervals. AFM was used to evaluate the pile-up morphology and the height of the pile-up formed around the residual impression. The pile-up morphology was then correlated to the serrations in