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Discontinuities of Plastic Deformation in Metallic Glasses with Different Glass Forming Ability

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Abstract

The metallic ribbons $Fe_{40}Ni_{40}B_{20}$, $Cu_{47}Ti_{35}Zr_{11}Ni_6Si_1$ and $Zr_{65}Cu_{17.5}Ni_{10}Al_{7.5}$ with different microhardness and glass forming ability were studied at different loading rates from 0.05 to 100 mN/s. We describe in details the differences in elemental discontinuities on the loading curves for the studied alloys. It was found that the discontinuities began at a certain local deformation independently on the macroscopic mechanical properties of a ribbon. More developed discontinuities at higher deformations are created for the materials with lower microhardness and so lower strength.

Keywords: metallic glasses, indentation, pop-ins, shear bands

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1 Introduction

Metallic glasses exhibit unique properties and their combination, including the high strength, and the excellent soft magnetic properties (low coercive force and high permeability), which makes them attractive for practical applications. Many of these properties can be modified by deformation treating (Csach et al., 1994). For examples the magnetic properties (especially the coercivity) of amorphous alloys depend strongly on the residual strain (Schwarz et al., 2004).

Recently, the Fe and Co rich composition with the high glass forming ability was found out. Wright et al. (Wright et al., 2001) and Golovin et al. (Golovin et al., 2001) found that during

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nanoindentation of Zr-based bulk metallic glasses the onset of the plasticity occurred at a discrete displacement burst (“pop-in”). Serrated flow is characterized by repeating cycles of a sudden stress drop during displacement rate-controlled experiments followed by the elastic reloading (Chen et al., 1973). Discontinuities in the load-displacement (*P-h*) curves are correlated with the discrete shear banding events (Schuh, Nieh, 2004). It is generally accepted that the development of shear transformation zones leads to localized deformation, to shear bands and therefore to inhomogeneous flow in metallic glasses (Argon et al., 1985). The inhomogeneous nature of the deformation in metallic glasses is reflected in the serrated plastic flow with complex topology (Brandt et al., 2008). It has been found that the presence of pop-in events at nanoindentation is observed preferably near the glass transition temperature (Li et al., 2007). The origin of serrated flow in metallic glasses is still unclear but, it is generally accepted its role at the formation of shear bands.

In this work we concentrate on the plastic deformation and the differences in elemental discontinuities on the loading curves during indentation for FeNiB, CuTiZrNiSi and ZrCuNiAl types of metallic glasses with different glass forming ability over a wide range of loading rates.

2 Experimental Materials and Methods

The samples of the amorphous metallic ribbons with the nominal compositions of $Fe_{40}Ni_{40}B_{20}$, $Cu_{47}Ti_{35}Zr_{11}Ni_{6}Si_{1}$ and $Zr_{65}Cu_{17.5}Ni_{10}Al_{7.5}$ (at. %) were used for the nanoindentation experiments. The ribbons with the cross-sections of 10 mm × 0.018 mm ($Fe_{40}Ni_{40}B_{20}$), 1.72 mm × 0.02 mm ($Cu_{47}Ti_{35}Zr_{11}Ni_{6}Si_{1}$) and 1.13 mm × 0.01 mm ($Zr_{65}Cu_{17.5}Ni_{10}Al_{7.5}$) were prepared by rapid melt quenching on a spinning metallic disc.

The specimens were mechanically polished to mirror finish and tested using nanoindentation equipment MTS NanoIndenter® XP with a cube corner diamond tip. For tip calibration procedure the fused silica was used. The indentation measurements were performed at room temperature in load rate-control mode up to the maximal load of 250 mN using five loading rates from 0.05 to 100 mN/s. The high data acquisition rate up to the 100 Hz was chosen for resolving rapid dynamic events. For each measurement up to twenty-five indents were carried out. After nanoindentation, the morphology of indents and shear bands of the ribbons was observed by XL30 ESEM-FEG scanning electron microscope (SEM).

3 Results and discussion

Load-displacement (*P-h*) curves of three studied alloys during indentation with loading rates *dP/dt* ranging from 0.05 to 100 mN/s are presented in Figure 1 (left column). It is clear visible that Fe- and Cu-based metallic glass ribbons have similar shapes of indentation curves for all loading rates. The shape of indentation curves for Zr-based metallic glass ribbon varies with the using loading rate. With increasing of load the smooth line becomes zig-zag one with the increase of displacement without load increasing. The details of the final parts of loading sequence on the *P-h* nanoindentation curves for all loading rates and all studied alloys are shown in Figure 2 (right column). It is evident that at lower loading rates (0.05, 0.1 and 1) the pop-in events are more pronounced and gradually disappear with the increasing loading rate.

For description these discontinuities on loading curves the individual pop-ins were analyzed. The concept of discrete plasticity ratio (Schuh, Nieh, 2003), (Schuh, Nieh, 2004), (Greer et al., 2004), (Jang et al., 2007) based on the separation of contribution of the elastic, homogeneous plastic and inhomogeneous plastic deformation was chosen. The concept of this ratio is illustrated schematically in Figure 3.

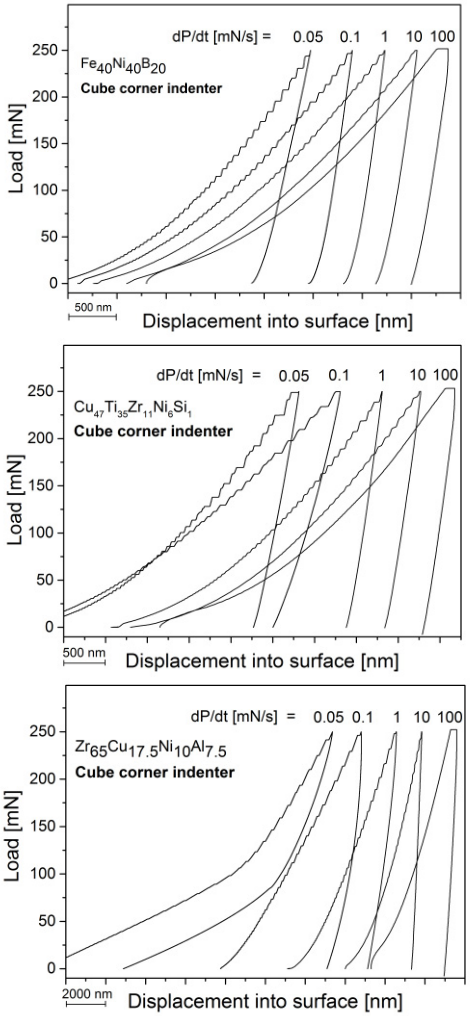

Figure 1: *P-h* curves during indentation for all observed alloys

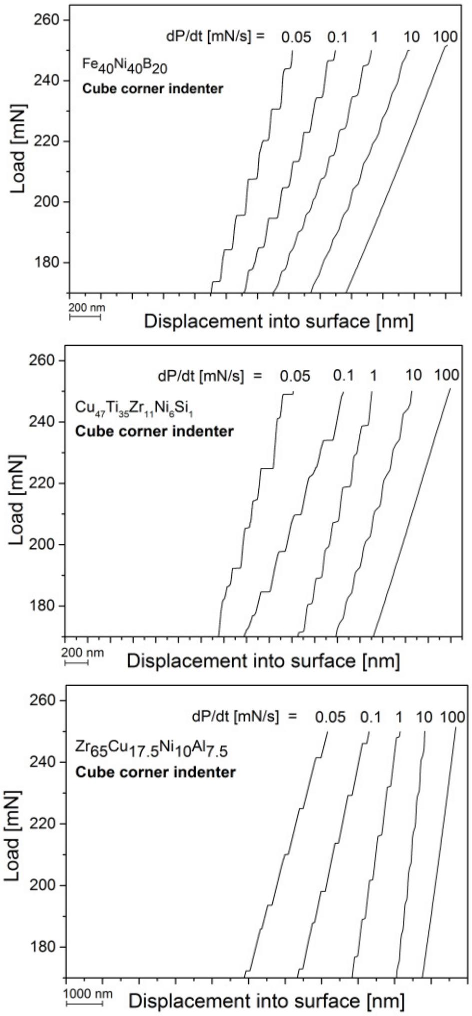

Figure 2: Details of final loading part of *P-h* curves for all observed alloys

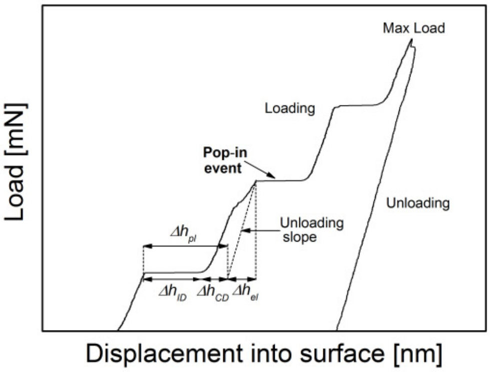

Figure 3: Estimating of the elastic and the plastic component of individual stepwise deformation events (pop-ins) (Huráková et al., 2015)

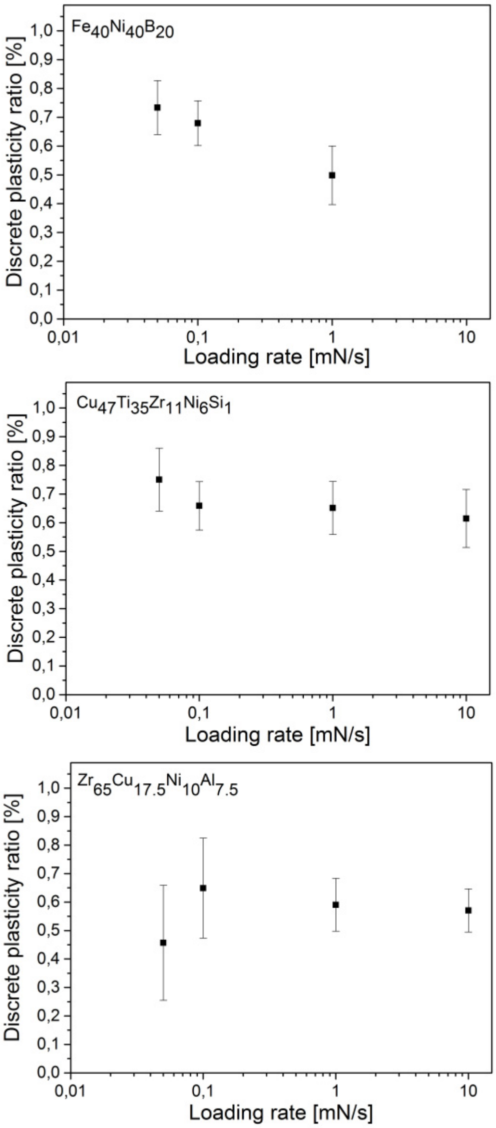

Figure 4: The discrete plasticity ratio as a function of the loading rate at indentation for different metallic glasses

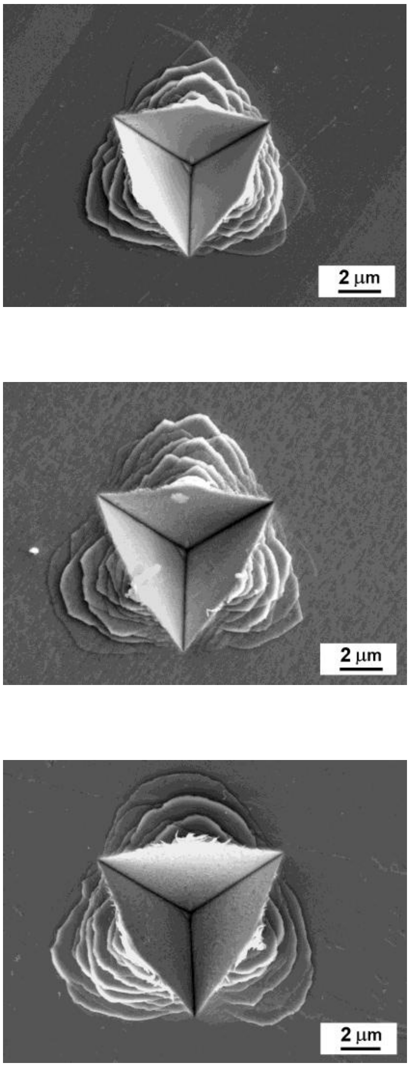

Figure 5: Morphology of the indents after indentation with the loading rate of 0.1 mN/s

The total displacement recorded during nanoindentation is a superposition of three components: an inhomogeneous part of the plastic deformation ($\boldsymbol{\Delta h_{ID}}$), a continuous part of the plastic deformation ($\boldsymbol{\Delta h_{CD}}$) and an elastic part of the deformation ($\boldsymbol{\Delta h_{el}}$). It is expected that the elastic deformation will be fully recovered during unloading. Then the plastic portion of deformation ($\boldsymbol{\Delta h_{pl}}$) is simply given as the sum of $\Delta h_{ID} + \Delta h_{CD}$. Thus, the contribution of discrete plasticity to the total plasticity (called "discrete plasticity ratio") given as $\Delta h_{ID} / \Delta h_{pl}$ indicates the fraction of plastic deformation that can be attributed to the discrete pop-in events for a given indentation. In the case of ideal homogeneous flow the discrete plasticity ratio is equal to 0 and it reaches the value of one in the case of the absence homogeneous deformation when only localized shear is present (Schuh, Nieh, 2004).

In Figure 4 (left column) the discrete plasticity ratio $\Delta h_{ID} / \Delta h_{pl}$ is plotted as a function of the indentation rate at loading rates from 0.05 to 10 mN/s and for all examined alloys. For each loading rate up to 25 indents were analyzed. The measured values for about 150-180 individual pop-ins were averaged for each loading rate and the alloy composition. For loading rates of 10 mN/s (only for Fe-based amorphous alloy) and 100 mN/s the pop-ins were not developed to the form suitable for regular quantification of individual pop-ins. For all studied alloy composition the discrete plasticity ratio parameter reaches the values from 0.4 to 0.8. For Fe-based alloy the tendency to the decrease of this parameter with the increase of loading rate can be suggested. For Cu- and Zr-based alloys the conclusions about the deformation rate influence on the discrete plasticity ratio cannot be made. For Zr-based alloy the investigated parameter seems to be lower than in the Cu-based alloy.

Localized plastic flow of the deformation in the indent area was observed by scanning electron microscopy. Figure 5 (right column) represents the plastic flow around cube corner indents on the surface of all alloys for the loading rate of 0.1 mN/s. Due to the cube corner indenter tip form and the maximum used load of 250 mN the indent and the deformed volume with shear bands are relatively large. The size of the indent and the form of plastic deformed area seem to be preserved for all applied loading rates. For the whole interval of the loading rates, no principal differences in the shear band density or shear band pattern were found. We conclude that the disappearance of pop-ins with increasing loading rate is not directly connected with the changes in shear band morphology in the plastic zone around the indent.

4 Conclusions

Instrumented nanoindentation experiments on three types of amorphous alloys in wide range of deformation rates have revealed the presence of the deformation discontinuities for all ($Fe_{40}Ni_{40}B_{20}$, $Cu_{47}Ti_{35}Zr_{11}Ni_{6}Si_{1}$ and $Zr_{65}Cu_{17.5}Ni_{10}Al_{7.5}$) amorphous alloys at loading rates up to 10 mN/s. These discontinuities start at the load up to 50 mN. As the indent penetrates deeper, the discontinuities are more pronounced. For loading rates above the 10 mN/s these discontinuities vanish. More developed discontinuities are created for the materials with lower microhardness and so lower strength (Cu- and Fe-based). The deformation discontinuities were analyzed using discrete plasticity ratio concept. This ratio reaches comparable values for all examined alloy compositions. The observation of indent region morphology does not show the simple connection between the presence of pop-ins and the shear bands morphology.

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