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Influence of loading rate on the mechanical performance of metallic glass

Mária Huráková[a,*], Kornel Csach[a], Alena Juríková[a], Jozef Miškuf[a], Štefan Demčák[b], Václav Ocelík[c], Jeff Th.M. De Hosson[c]

[a] Institute of Experimental Physics, Slovak Academy of Sciences, Watsonova 47, 040 01 Košice, Slovakia
[b] Department of Environmental Engineering, Faculty of Civil Engineering, Technical University of Košice, Vysokoškolská 4, 040 01 Košice, Slovakia
[c] Department of Applied Physics, Zernike Institute for Advanced Materials, Faculty of Science and Engineering, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

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ABSTRACT

Amorphous metallic glass $Cu_{47}Ti_{35}Zr_{11}Ni_6Si_1$ was investigated by load-control nanoindentation experiments using the cube corner indenter tip over a wide range of loading rates. The indentation hardness was calculated using different methods either from the loading curves or indent area. Pop-in events were observed on the loading part of the indentation curves mainly at lower rates of loading. Instantaneous plastic deformation decreases with increasing loading rate according to a power law. At high loading rate the instantaneous deformation is suppressed by continuous plastic deformation and no well-developed pop-ins are observed. The morphology of shear bands in the pile-up area of indents showed no correlation with the pop-in event population of the nanoindentation curves and the loading rate.

1. Introduction

Metallic glasses having an amorphous structure show a completely different deformation mechanism in comparison with conventional crystalline materials due to their absence of grain boundaries and lattice dislocations. The conventional theory of lattice dislocations cannot be used for an explanation of plastic deformation of metallic glasses and at the ambient temperature deformation occurs by the formation and localization of shear bands [1–3].

In recent years, the method of nanoindentation has been commonly used to investigate the phenomenon of plastic deformation of metallic glass ribbons at room temperature because of this technique allows to obtain a high resolution in recording load-displacement data [2,4–6].

Spatially and temporally inhomogeneous plastic deformation of metallic glasses is characterized by the creation and propagation of individual shear bands. It turned out that the work softening is closely related to the localization of shear bands but the stress of shear band propagation is less than the stress needed to the initiation of shear bands [7]. Therefore it is possible to observe the serrated flow in metallic glasses which manifests itself as small displacement bursts or load drops during plastic deformation with nanoindentation or in compression experiments [7–9]. In load-displacement indentation curves (*P-h* curves) during load-control nanoindentation experiment discontinuities (pop-ins) can be observed. Discontinuous plastic flow is characterized by repeating the cycles of a sudden stress drop during the nanoindentation experiment with a controlled movement of the indenter into the surface of the material [10]. Wright et al. [11] and Golovin et al. [12] found that the onset of plasticity during nanoindentation of bulk metallic glasses occurs at discrete serrated displacement at the beginning of the *P-h* curve. It has been shown that the nature of pop-ins in *P-h* curve during nanoindentation depends on the composition and the structure of metallic glasses, on the loading rate and the temperature [13–15]. Shear bands in the pile-up area of the indent have been observed in Mg-, Pt-, Pd-, Cu-, Ni- and Fe-based metallic glasses. After nanoindentation of Fe- and Ni-based metallic glasses the relatively small number of shear bands around of indent after nanoindentation was observed. However, the shear bands in the indent area clearly indicate that plastic deformation of metallic glasses is highly localized and inhomogeneous, regardless of the occurrence of pop-ins in *P-h* curve [14,16].

Schuh et al. [2,17–19] described the dependence of deformation of metallic glasses on the loading rate during the nanoindentation experiment. They found that a low loading rate supports the occurrence of pop-in events in *P-h* curves, while high loading rates can partly or completely suppress the formation of pop-ins. The pop-in events in *P-h* curve are magnified with the increasing load or the displacement into surface of material what can be caused by geometry of the indenter tip. Greer et al. [20] noted that the absence of pop-ins at higher loading

* Corresponding author.
E-mail addresses: hurakova@saske.sk (M. Huráková), csach@saske.sk (K. Csach), akasard@saske.sk (A. Juríková), miskuf@saske.sk (J. Miškuf), stefan.demcak@tuke.sk (Š. Demčák), v.ocelik@rug.nl (V. Ocelík).

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rates is only due to a lack of resolution of nanoindentation equipment at low penetration depth. Bei et al. [21] observed that the first pop-in occurred at a load of about 1.2 mN and corresponded to a transition from perfectly elastic to plastic deformation, which is considered as the onset of plastic flow in investigated metallic glasses.

Several indentation studies have pointed out that there is a correlation between the number of slip markers and the number of strain serrations on the *P-h* curve: the higher is the number of shear bands the higher is the number of pop-ins. This might mean that strain serrations can be directly determined by formation of localized macroscopic shearing and each pop-in event that occurs during nanoindentation of metallic glasses corresponds to a single shear event [4,5,11,12,18,22–24].

The understanding the deformation behaviour of metallic glasses can be enhanced through the nanoindentation technique. Remaining questions are how the serrated flow is formed and where the origin of a shear band is, even though it is widely accepted that the flow serration is strongly associated with the shear band creation. In this work we concentrated on the deformation behaviour of Cu-based metallic glass ribbon using nanoindentation over a wide range of loading rates. We focused on the detailed in-depth statistical analysis of the contributions of the instantaneous and continuous displacements at individual pop-in events. Common features of plastic deformation and morphologies of pile-up area of indents occurring at different loading rates were also investigated.

2. Experimental

An amorphous metallic ribbon with the nominal composition of $Cu_{47}Ti_{35}Zr_{11}Ni_6Si_1$ (at%) and with the cross-section of 1.72 mm × 0.02 mm was prepared by rapid melt quenching on a spinning metallic disc. The structure of the ribbon was investigated by X-ray diffraction (XRD) using the Philips X'Pert Pro diffractometer equipped with Cu cathode at operating parameters of 40 kV and 50 mA. Thermal behaviour was examined using of a differential scanning calorimeter, applying the heating rate of 10 °C/min under a nitrogen flow using DSC Q2000-TA Instruments apparatus.

The metallic glass ribbon was studied by means of the nanoindentation technique using the equipment MTS NanoIndenter® XP with cube corner indenter tip. Before nanoindentation test the specimens were mechanically polished to mirror finish and for calibration procedure the fused silica was used. Nanoindentation measurements were performed at room temperature (around 20 °C) in the load rate-control mode up to the maximal load P_{max} = 250 mN. Five loading rates of 0.05, 0.1, 1, 10 and 100 mN·s^{-1} followed by holding for 1 s and then unloading were used and for each measurement up to twenty-five indents were made. High data acquisition rate up to the 25 Hz was chosen for resolving rapid dynamic events. After nanoindentation the morphologies of indent area and shear bands were observed by scanning electron microscope XL30S SEM-FEG.

3. Results and discussion

XRD and DSC analyses confirmed that as-cast amorphous metallic ribbon $Cu_{47}Ti_{35}Zr_{11}Ni_6Si_1$ has an amorphous structure. As Fig. 1a shows XRD pattern of the sample reveals no distinct (crystalline) peaks but only characteristic an amorphous broad maximum centred approximately at 2θ = 42°. DSC scan in Fig. 1b performed at the heating rate of 10 °C/min reveals the midpoint of glass transition at the temperature around of 442.5 °C and the onset temperature of crystallization T_{on} at 452.2 °C.

The load-displacement (*P-h*) curves of the studied alloy during indentation with loading rates d*P*/d*t* ranging from 0.05 to 100 mN·s^{-1} are shown in Fig. 2. The curves were shifted along the displacement axis for a better presentation. The shape of indentation curves is similar for all loading rates applied. Individual pop-ins are more developed at the lower loading rates (0.05 and 0.1 mN·s^{-1}) and gradually diminish with increasing the loading rate. In *P-h* curves at loading rate of 100 mN·s^{-1} no visible serrated flow was observed.

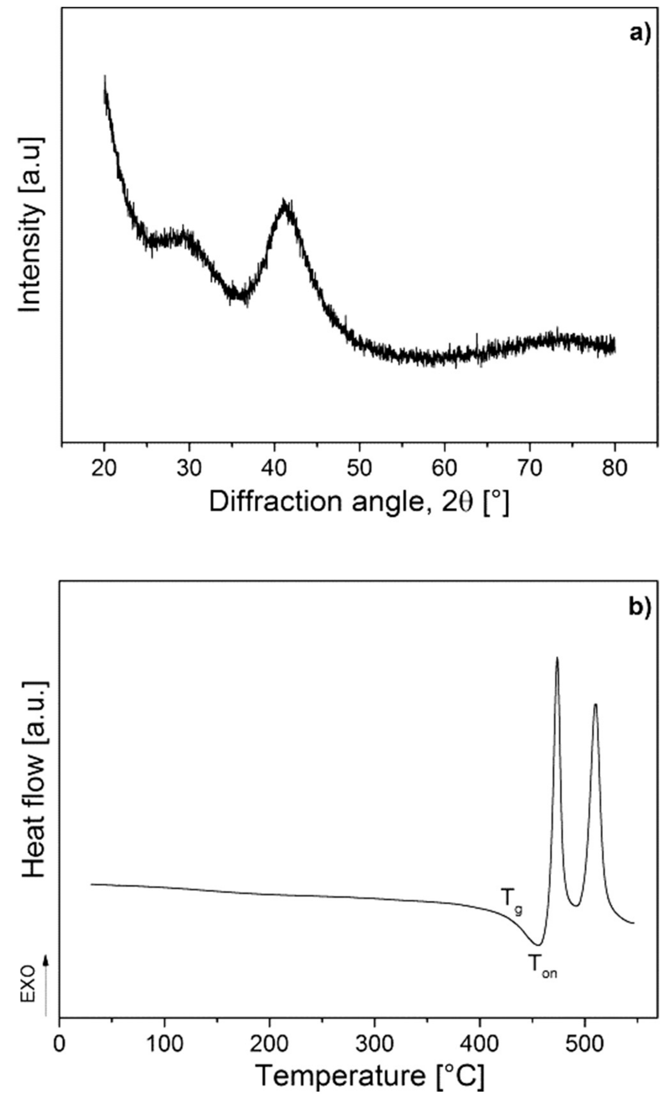

Fig. 1. Typical a) XRD and b) DSC scan of the metallic glass ribbon $Cu_{47}Ti_{35}Zr_{11}Ni_6Si_1$.

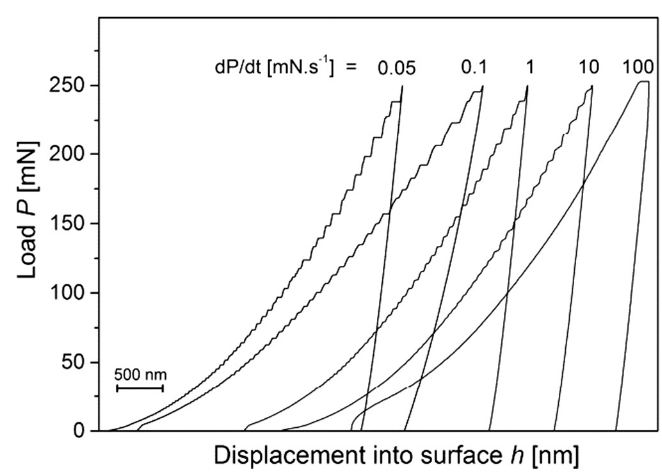

Fig. 2. *P-h* indentation curves for all used loading rates.

The hardness of Cu-based amorphous ribbon was estimated by different methods using the measurements of indent area on SEM