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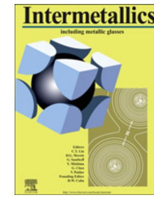

Effects of residual stress in elastic regime on the surface formability of a Zr-based metallic glass

Y.-H. Lee*, U. Baek, H.M. Lee, S.H. Nahm

Division of Industrial Metrology, Korea Research Institute of Standards and Science, Daejeon 305-340, South Korea

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In order to study elastic stress effects on the surface deformability of BMGs, indentations with a Berkovich diamond pyramid were done on an artificially bent Zr-based metallic glass stripe (Vitreloy-1). Residual indentation marks formed with a peak load of 500 mN were observed with an atomic force microscope for 7 artificial stress steps. Significant pile-ups (or surface upheavals around indents) and shear bands were observed at low stress levels less than 244 MPa and disappeared with an increase of the tensile stress. From a 3D morphological viewpoint, the tensile stress in elastic regime is understood to be beneficial to the surface formability of the Zr-based BMG, because the tensile stress invokes deeper indentations with slight elastic recovery and reduces the irregular pile-ups with shear bands.

1. Introduction

Bulk metallic glasses (BMGs) have attracted an increasing attention in various industries due to their superior mechanical properties, including high strength, relatively low Young's modulus, and excellent elastic behavior [1,2]. However, since the BMGs in amorphous state have no feasible deformation mechanism such as the dislocation slip, inelastic deformation is limited in few inhomogeneous shear bands. Brittle fracture occurs directly after the shear band propagation along the maximum shear stress plane in uniaxial tensile test [3]. While multiple shear bands frequently occur in inelastically constrained conditions such as compression, bending, and indentation [4,5]. With increasing a shear band density, the accommodation of applied strain increases and finally the amount of inelastic deformation or ductility of the BMGs is enhanced.

Also a thermoplastic deformation is possible in a supercooled liquid region of the BMGs [6,7]. In this temperature region, the BMGs shows a viscous flow behavior and can accommodate more than 100% of elongation strain by selecting a proper strain rate condition. Recently, this thermoplastic deformation technique in the BMGs is applied to the surface nanomachining researches, because the good formability and durability of the BMGs surpass the advantages of conventional nanoimprinting materials such as silicon, nickel and other hard metals. Especially, the BMGs in amorphous state can be a breakthrough solution of the grain size limitations in metallic nanomachining. Kumar et al. [8] made surface nanopatterns as small as 13 nm onto metallic glass by advancing the thermoplastic forming method.

However, the thermoplastic process needs complex heat control and can accompany property degradations due to partial crystallization. Also, detailed studies on the effects of loading rate and direction, stress confinement, and pre-deformation are still insufficient in driving the inelastic surface nanomachining of the BMGs. Thus, we try to investigate the mechanical loading effects on the surface micromachining with an indentation technique at the ambient temperature. Especially, the variations in indent morphology are studied with an application of external stresses in elastic regime; 3D morphological changes are quantitatively analyzed and discussed with a viewpoint of the BMG's surface formability.

2. Experiments

A 7 × 40 × 0.5 mm stripe specimen was sampled from an as-cast Zr-based metallic glass with a composition of $Zr_{41}Ti_{14}Ni_{10}Cu_{12.5}Be_{22.5}$ (Vitreloy-1). The stripe was mechanically polished and then bent with a home-made 4-point bending jig in Fig. 1; a 10 mm-wide inner span shows uniform tensile stress and the stress level can be controlled with the attached micrometer. A curvature of each bending level was measured by scanning the specimen surface with a laser displacement sensor (LJ-G015

* Corresponding author. Tel.: +82 42 868 5385; fax: +82 42 868 5635.
E-mail address: uni44@kriss.re.kr (Y.-H. Lee).

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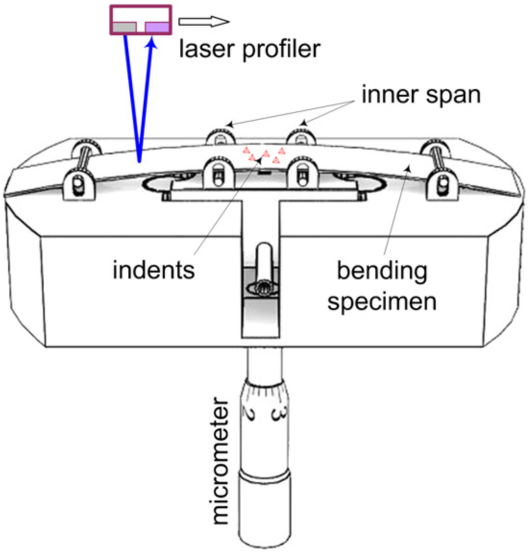

Fig. 1. A 4-point bending apparatus for stressing stripe specimens.

reflective model, Keyence Co., Japan). The applied stress (or residual stress) on the specimen surface was calculated from the curvature geometry based on the elastic bending theory.

Indentation tests were performed with a MZT 512 system (Mitutoyo Co., Japan) combined with a Berkovich diamond pyramid. 5 indentations with a peak indentation load of 500 mN were done at each stress level and resulting deformation morphologies were observed using an atomic force microscope (XE-100 model, Park's Systems, South Korea). A scanning speed of the AFM head was controlled less than 0.2 Hz for the scanning area of 30 μm × 30 μm including the remnant indent as its center. The obtained 3D morphological information was analyzed quantitatively using the Matlab image analyzing software (Mathworks Inc., US).

3. Results and discussion

Fig. 2 shows curvature radii determined from circumscribing circles of the bent specimen profile data. From Eq. (1) related to the elastic bending theory [9], the curvature radii are converted to applied surface stresses.

$$\sigma_{app} = \frac{Et}{2R}. \tag{1}$$

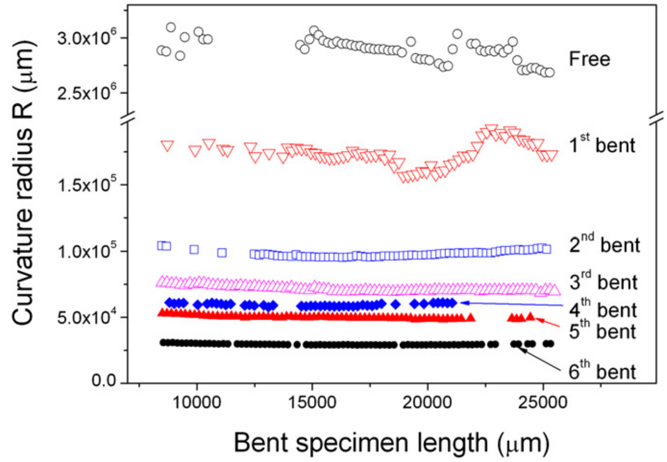

Fig. 2. Curvature radii measured from the 4-point bent specimens.

Here, σ_{app}, R are the applied surface stress in elastic regime and the curvature radius, respectively. The specimen thickness t is 0.5 mm and the Young's modulus E of the Zr-based metallic glass is given to 95 GPa [10]. The calculated tensile stresses were 8, 137, 244, 332, 398, 475 and 818 MPa corresponding to 7 bending steps. Hereafter, testing results from the lowest stress level of 8 MPa is regarded as the behaviors of stress-free surface.

Fig. 3 shows AFM morphologies of remnant indents on the nearly stress-free (8 MPa) and tensily stressed (818 MPa) surfaces. Significant differences in two morphologies are shear bands and pile-ups around the impressions; while discrete and non-continuous shear bands were formed at the stress-free or slightly tensioned surfaces, the surface upheavals (or materials pile-ups) and shear bands disappeared with an increase of the tensile stress. In this study, the shear bands could be observed on the tensily stressed surface less than 244 MPa.

In order to characterize the stress effects on the inelastic contact deformations, three-dimensional morphologies of remnant indents were analyzed. First, a contact boundary was determined by adopting the radial differentiation method [11], which is powerful to extract the pile-up peak points surrounding an impression. The hardness is measured by dividing the indentation load with the contact area inside of the contact boundary (see Fig. 4). The hardness decreased about 6.3% corresponding to an increment of the tensile stress until 818 MPa. This means that the contact area between the Berkovich indenter and the metallic glass surface is nearly constant regardless of the significant morphological changes in the pile-up (see Fig. 3).

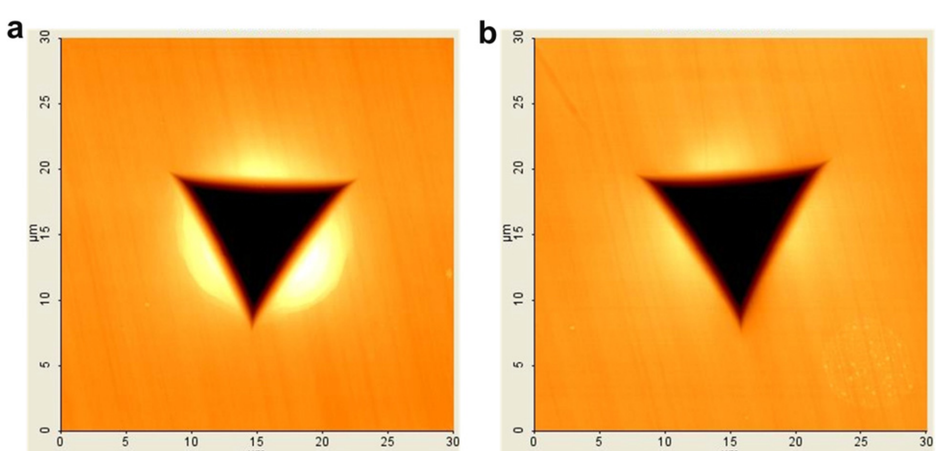

Fig. 3. Remnant indents observed from (a) the nearly stress-free and (b) tensily stressed surfaces.