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Cooling rate effect of nanomechanical response for a Ti-based bulk metallic glass

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ABSTRACT

The effect of cooling rate on the mechanical behaviors of a Ti-based bulk metallic glass has been studied using nanoindentation technique. It is found that the hardness increases, while the plastic deformation capacity gradually decreases from the edge to the center of the sample. The variation of the structural uniformity within the as-cast glassy sample may account for the cooling rate dependence of mechanical performance.

1. Introduction

Bulk metallic glasses (BMGs) exhibit unique properties, such as excellent mechanical properties and corrosion resistance. They thus offer great potential for various structural applications [1–3]. However, the limited macroscopic plastic strain before fracture of metallic glasses seriously constrains their applications [4]. At high stresses and temperatures far below the glass transition temperature, plastic deformation of BMGs is localized within relatively thin regions called shear bands, resulting in a very low macroscopic plastic flow limit (usually less than 2% under uniaxial tension/compressive tests) [4].

It has been observed that the cooling rate during glass formation exerts a crucial influence on the deformation behaviors of metallic glasses [5–9]. For instance, Jiang et al. [5] found that the as-cast bulk Cu-based glassy alloy possesses less free volume, leading to its higher hardness than the as-spun ribbon alloy of the same composition but formed at a much higher cooling rate. Chen et al. [6] observed that decreasing the cooling rate of glass forming promoted the formation of denser atomic configuration in the resultant alloy. Furthermore, it has also been shown that the microhardness of bulk Pd–Si glassy alloy is higher than that of a rapidly solidified glassy ribbon. More recently, Chen et al. [7] suggested that the plasticity for amorphous alloys can be tailored by applying different cooling rates during solidification. These results indicate that controlling the applied cooling rate may be a promising way of tailoring the mechanical deformation response of metallic glasses. In the present work, nanoindentation is utilized to investigate the mechanical response of different parts of a Ti-based BMG sample, i.e. from the edge to the center of an alloy where a cooling rate gradient exists during the glass forming process. It is expected that this work can provide some insights into the effect of cooling rates on the mechanical behaviors of metallic glasses.

2. Experimental procedure

The $Ti_{40}Zr_{25}Ni_3Cu_{12}Be_{20}$ (at.%) alloy ingot used in this work was prepared by arc melting of pure elements of Ti, Zr, Ni, Cu and Be on a water cooled copper plate in a Ti-gettered argon atmosphere. The ingot was melted three times in order to achieve composition homogeneity. No noticeable chemical composition segregation has been observed using energy dispersive X-ray spectroscopy. A rod-shaped sample with a diameter of 5 mm was formed by drop-casting into a copper mold. The amorphous nature of the as-cast sample was confirmed by X-ray diffraction (XRD) using copper K_α radiation. The BMG alloy rod thus formed was cut into disks of 1 mm thick and polished to a mirror-like finishing. Nanoindentation tests were performed on the polished cross-section at room temperature on an MTS Nano indenter® XP system using a Berkovich diamond indenter. Fused silica was used as the reference sample for the initial tip calibration. The indentation tests were conducted in a depth-control mode to the prescribed maximum depths of 200, 500, and 800 nm, respectively, under a constant

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strain rate of 0.05 s^{-1}. The nanoindentation measurements were performed from the edge to the center of the sample (i.e. about 2.5 mm from the edge), at an interval of 50 μm. The hardness values were calculated following the Oliver and Pharr method [10]. After the test, the resultant indentation mark was scanned immediately using a NanoVision Nanomechanical microscope equipped on the MTS Nano indenter® XP system.

3. Results

The XRD pattern obtained from the 5 mm diameter BMG alloy rod is shown in Fig. 1. Except for the broad diffraction peak, no detectable sharp Bragg diffraction peaks typical of a crystalline structure can be observed. This confirms that the alloy is amorphous.

Fig. 2 shows the hardness of the as-cast Ti-based glassy sample when measured at different distance from the edge, at three different maximum indentation depths of 200, 500, and 800 nm. As can be seen in Fig. 2, at the maximum indentation depth of 200 nm, the

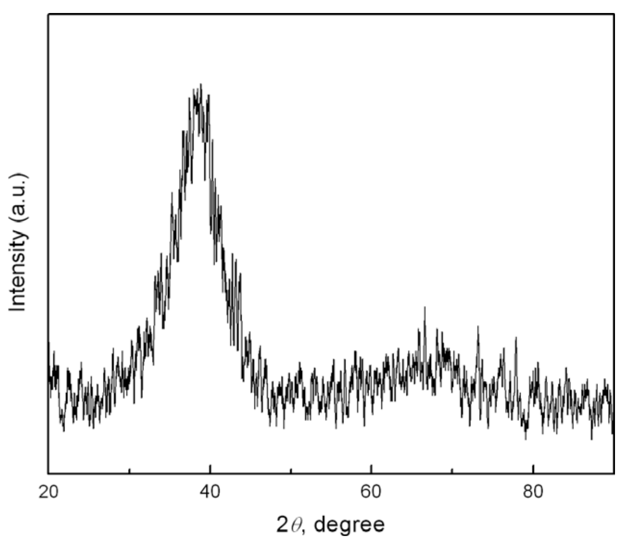

Fig. 1. XRD pattern for the as-cast $Ti_{40}Zr_{25}Ni_3Cu_{12}Be_{20}$ bulk sample with a diameter of 5 mm.

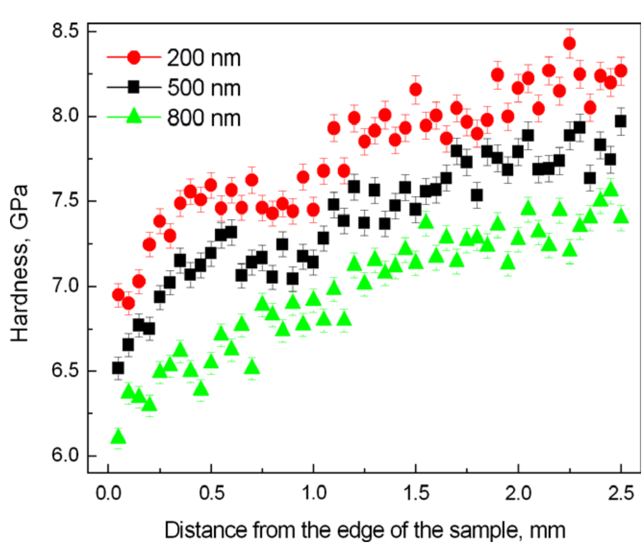

Fig. 2. Hardness of the as-cast $Ti_{40}Zr_{25}Ni_3Cu_{12}Be_{20}$ bulk glassy alloy measured by nanoindentation.

hardness value measured is lower near the edge and increases steadily towards the center of the sample. At the maximum indentation depths of 500 and 800 nm, the overall hardness position profiles obtained show lower values but a similar trend when compared to that of obtained at the maximum indentation depth of 200 nm in that the hardness value increases gradually from the edge of the sample towards the center of the sample. When drop-cast into a copper mold, the cooling rate that the alloy was subjected to changes with the distance from the sample's edge that has been directly in contact with the mold. The edge of the alloy sample has experienced a faster cooling rate than the center. In other words, the hardness measured shows a cooling rate dependence.

Fig. 3 shows the load–displacement (P–h) curves recorded from the indentation tests at three different distances into the sample

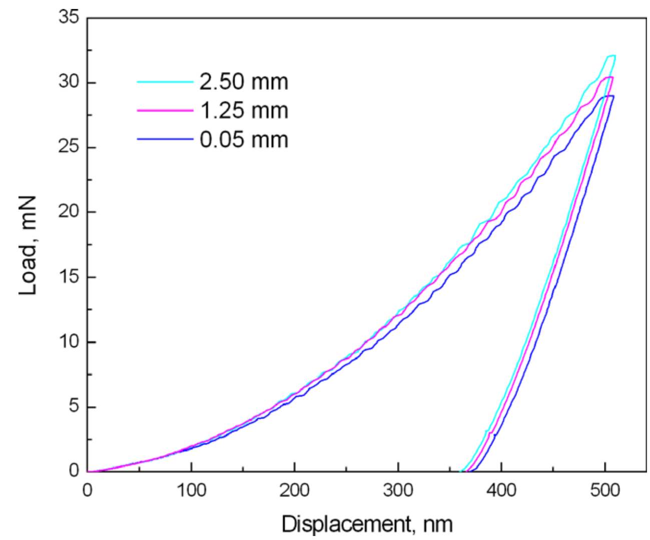

Fig. 3. Load–displacement curves of three indents located at 0.05, 1.25, and 2.5 mm from the edge of the as-cast $Ti_{40}Zr_{25}Ni_3Cu_{12}Be_{20}$ glassy sample for a depth of 500 nm.

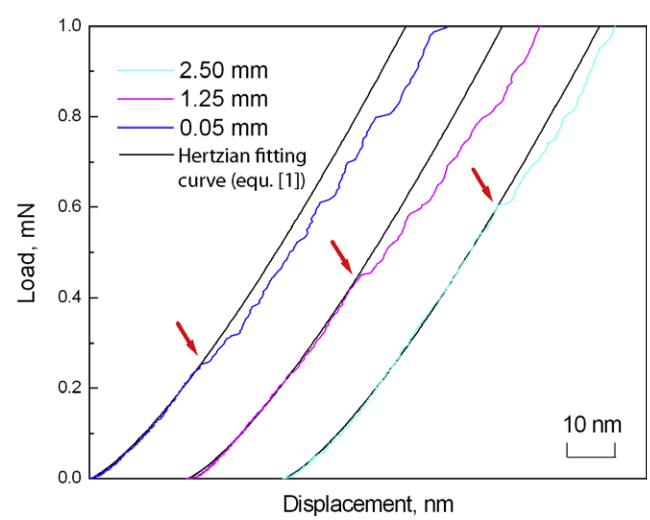

Fig. 4. Initial nanoindentation response of three indents located 0.05, 1.25, and 2.5 mm from the edge of the as-cast $Ti_{40}Zr_{25}Ni_3Cu_{12}Be_{20}$ glassy sample for a depth of 500 nm. In each case, the first portion of the experimental data can be well described by the Hertzian elastic contact law (solid black lines), but the departure from ideal elasticity occurs earlier for samples at smaller loading rates or with smaller sizes.