Tribological behaviors of Zr-Cu-Al-Ni bulk metallic glass

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1. Introduction

Progresses in developing advanced and functional materials for everyday engineering applications are extremely increased to match with current high-tech requirements. Bulk metallic glass (BMG) have been listed one of the functional materials having excellent physical and mechanical properties such as high hardness, strength and good wear and corrosion resistance. However, it is important to understand the mechanical and tribological behaviors of newly developed BMGs (amorphous alloys) as the deformation mechanism of BMGs is completely different from the counterpart crystalline alloys. It demands potential mechanical testing methods for evaluating the reliability and quality of engineering products.

BMGs are used as wear resisting coatings and hard facing alloys in sensor and medical implants, and dry bearings for outer space applications, surface of BMGs experiences sliding contact condition [1]. Although, the scratch studies on understating the tribological and wear behaviors of BMGs are limited in the literature, it was revealed that the tribological behaviors of certain BMG are mostly different from another BMG [1]. Therefore, it is inappropriate to derive the similar techniques for different BMGs.

In this study, the tribological behaviors of $Zr_{65}Cu_{15}Al_{10}Ni_{10}$ (Zr-BMG) are investigated through the nanoscratch tests. The nanoindentations are employed to assess the nanomechanical properties of Zr-BMG. By performing nanoscratch tests under progressive and constant loading modes, the lateral force and COF variations are studied. Proposed study provides remarkable understating of the surface failure mechanism in Zr-BMG.

2. Experiments

Nanoindentation and scratch experiments were conducted with $Zr_{65}Cu_{15}Al_{10}Ni_{10}$ (at. %) specimens, which were fabricated by hot-press method. To determine the nanomechanical properties of Zr-BMG, nanoindentations with Berkovich tip were mainly employed. In quasi-static indentation, hardness *H* and elastic modulus *E* were calculated by using the Oliver-Pharr (OP) method [2]. Nano-indentation tests were conducted with maximum indentation load of P_{max} = 50 mN and constant loading rate of 40 mN/min to reduce the effect of serration flows. Finite element (FE) simulations with the linear Drucker-Prager (DP) model were also performed. The mechanical properties (*E*, zero pressure yield strength σ_o, and friction angle β) of $Zr_{65}Cu_{15}Al_{10}Ni_{10}$ were obtained based on *trial and error* method by matching FE load-depth curves with experimental curves and then compared with literature.

For nanoscratch studies, Nano Scratch Tester (NST) with sphero-conical tip with radius of 2 μm was employed for making scratch on the surface of Zr-BMG. The scratches were made by applying progressively increasing and constant normal load (maximum normal load P_{max} = 20, 50, 100 mN, normal loading rate in progressive loading = 40, 100, 200 mN/min) on the indenter. The lateral force and scratch depths were continuously monitored for a scratch length of 0.5 mm with lateral displacement rate of 1 mm/min in all the cases. Before and after (residual profile) scratch process, surface profiles were obtained from the pre-scan and post-scan process, respectively, with a lower normal load of *P* = 0.1 mN. A panoramic optical image of the whole scratch profile was taken immediately after the post-scan process.

3. Results and discussion

Under nanoindentation, load-displacement (*P*-*h*) response of $Zr_{65}Cu_{15}Al_{10}Ni_{10}$ is plotted as shown in Fig. 1. According to the OP method [2], *H* and *E* are calculated as 7.88 ± 0.2 GPa and 155 ± 3.1 GPa, respectively; while, Poisson's ratio of the specimen is taken as ν = 0.367.

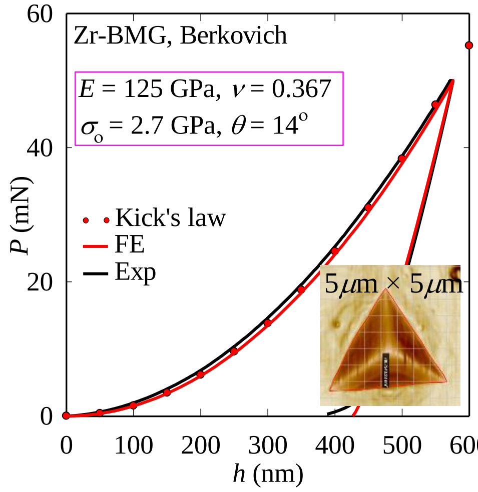

Fig.1 Nanoindentation *P*-*h* curves; inset- residual imprint obtained in AFM

However, occurrence of significant pile-up around the residual indent questions the application of OP method to Zr-BMG. It was also reported that indentation size effect (ISE) in nanoindentation of BMG is attributed to the pile-up. Therefore, the values obtained using OP method are corrected with AFM measured projected contact area A_{res}. By using the corrected values of H = 6.56 GPa and E = 125 GPa, the nanoindentation response of $Zr_{65}Cu_{15}Al_{10}Ni_{10}$ is numerically optimized based on *trial and error* method. We obtain a best match of FE *P-h* curve for DP model parameters σ_o = 2.7 GPa, and β = 14° as compared in Fig. 1. In addition, the loading part of the *P-h* curve is also approximated by using the Kick's law ($P = Ch^2$ for sharp indenter) with coefficient C = 153 GPa.

Panoramic image of each scratch profile was taken by using in-built optical microscope. For various applied normal loads, the scratch profiles are compared between constant and progressive loading conditions (Fig. 2). When compared to smaller P_{max} = 20 mN, fracture and chipping were observed with higher P_{max} = 50, 100 mN; in the case of constant load applications, fracture and chipping occurred throughout the scratch.

With the constant load, the variation of lateral force and COF are expected to be constant throughout the scratch length; however, the fluctuations (increase and decrease in plot) are attributed to the roughness created by the fracture and chipping as well as the shear band formation alongside of the scratch groove. Unlike with higher P_{max} = 50, 100 mN, the lateral force and COF tend to decrease with scratch distance for lower P_{max} = 20 mN as the plastic deformation dominates rather than fracture and chipping. The amount of COF increases as 0.18, 0.47, 0.56 with applied constant normal load P_{max} = 20, 50, 100 mN, respectively. With the progressively increasing load, the lateral force and COF increase with load and scratch length. At the end of scratch profile, the values of lateral force almost match with that recorded with constant loading conditions (Fig. 3); however, the variation is not linear with the normal load. Formation of fracture and chipping with higher P_{max} = 50, 100 mN causes the sudden increase and drop in lateral force and COF variations.

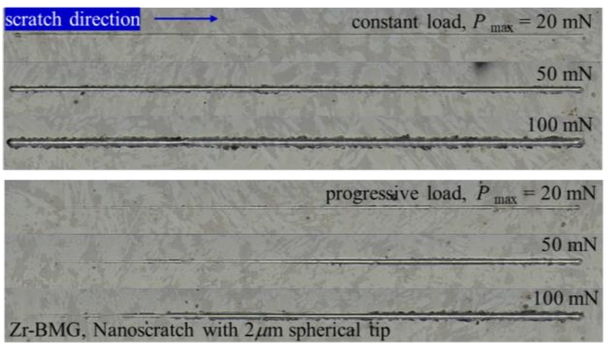

Fig.2 Panoramic optical images of scratch profiles for applied constant and progressive loads

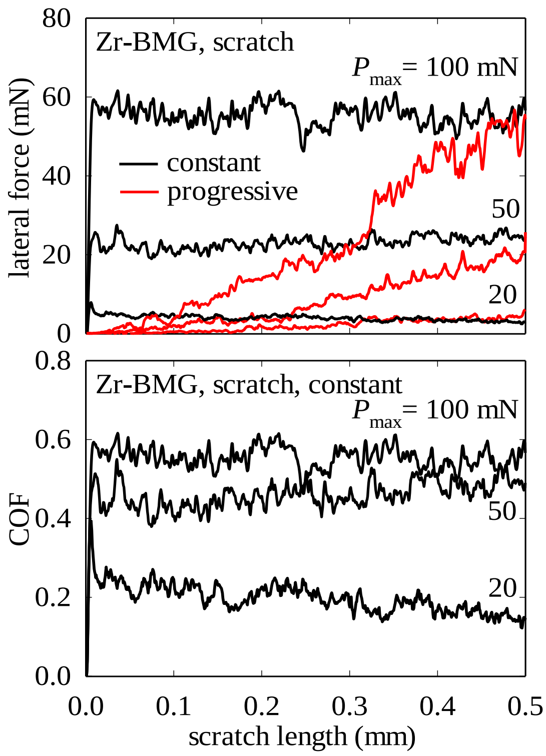

Fig. 3 Variation of lateral force and COF *vs.* scratch length under different loading conditions

4. Summary and conclusion

Tribological behaviors of $Zr_{65}Cu_{15}Al_{10}Ni_{10}$ were investigated based on the nanoindentation / scratch methods. Lateral force and COF variations were plotted along with scratch length. As the applied normal load increases, COF increases in both progressive and constant load modes due to the roughness created by the fracture and chipping. Further analyses of surface failure mechanism with various scratch velocities can lead to accurate prediction of tribological behaviors of Zr-BMG.

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