Effect of Shot Peening on Mechanical Behavior of Zr-Based Bulk Metallic Glasses under Monotonic and Cyclic Loading Mode

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The mechanical behavior of as-cast and peened (Zr₅₅Cu₃₀Ni₅Al₁₀)₉₉Y₁ bulk metallic glass (BMG) under monotonic loading and cyclic loading mode was investigated. Abundant pre-existing shear bands were observed on the surface of the BMG after shot peening. It is suggested that shot peening can significantly enhance the compressive plasticity of the BMG. Interestingly, compared with the as-cast specimen, the peened specimen exhibits the similar yield stress of about 1850 MPa and fatigue limit of about 1095 MPa in stress range, but shorter fatigue life at high stress level. That is to say, shot peening has a great influence on the fatigue properties of BMG in high stress range, and has little influence on the fatigue properties of BMG in low stress range near fatigue limit. This is attributed to mutually competition between the positive effect and negative effect on the mechanical behaviors of BMG induced by shot peening, and which one of the two effects plays the dominant role depends mainly on the loading mode. The present study will give suggestion for the safe service of Zr-based BMG.

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1. Introduction

Bulk metallic glasses (BMGs) have been considered as potential structural materials due to their superior strength, high elastic limit and excellent corrosion resistance^{1–4}. However, the poor fatigue behavior and plasticity of BMGs limit their engineering application, which remains a great challenge to the materials^{5–7}. The fatigue performance of conventional structural alloys can be enhanced by shot peening⁸, which is of a reference significance to improve mechanical properties of BMGs. For quasi-static monotonic compression, Greer *et al.*⁵ found that the plasticity of BMGs can be enhanced by compressive residual stress through shot peening treatment. Raghavan *et al.*⁹ reported that the shot peening does not cause significant enhancement of the fatigue performance of the BMGs in the four-point bending loading mode. It is worth noting that the fatigue performance of Zr-based BMGs depend strongly on the loading mode¹⁰. For example, fatigue limit of Zr-based BMGs in stress range terms under cyclic tensile load was almost three times higher than that under the three-point bending condition¹⁰. Up to now, few literatures have simultaneously revealed the effect of shot peening on the plasticity and fatigue behavior of Zr-based BMGs. In this paper, uniaxial monotonic compressive and cyclic compression-compression experiments were conducted on Zr-based BMGs with as-cast and peened state respectively, and the possible micro-mechanism accounting for the research results were discussed.

2. Experimental Procedure

(Zr₅₅Cu₃₀Ni₅Al₁₀)₉₉Y₁ alloy was chosen for the current investigation because of its high glass forming ability¹¹. Alloy rods with 3 mm in diameter (Φ) and 50 mm in length (L) were produced by copper mold casting in a high-purity argon

atmosphere. The amorphous structure of the rods was identified by X-ray diffraction (XRD). The as-cast rods were shot peened with 4 MPa air pressure and 0.6 mm diameter steel balls. Peening time of 2 min was chosen for the treatment. Although all the samples were prepared at the same time by the same condition, there still appeared little different peened surface morphology. In order to ensure comparability and reliability, we further selected those samples with the same peening intensity and homogeneity to be used in the experiments, which means the surface was completely peened. The specimens in shape of rod with the size of $\Phi 3 \text{ mm} \times L 6 \text{ mm}$ were well prepared for uniaxial monotonic compressive and cyclic compression-compression tests. The monotonic compressive tests were conducted at strain rates of $10^{-5}/\text{s}$. Cyclic compression-compression were conducted at various stress ranges with an R ratio ($R = \sigma_{\min}/\sigma_{\max}$, where $\sigma_{\min}$ and $\sigma_{\max}$ are the applied minimum and maximum stresses, respectively) of 0.1 at 100 Hz under a load-control mode. The cyclic loading was terminated in cases the number of cycles reached 1×10^7 where failure did not occurred. At least five samples were tested at fatigue limit stress, due to the fatigue results may depend on the specimen. The fracture morphology of the specimens was observed by scanning electronic microscope (SEM).

3. Results and Discussions

Figure 1(a) shows typical stress-strain curves of the as-cast and peened BMG samples. One can see that all samples exhibit nearly an equal yield stress σ_y (about 1850 MPa). However, the plasticity of the as-cast samples is significantly enhanced through shot peening treatment, as evidenced by the increased plastic strain from only 0.5% to 2.5%. Smaller stress drop amplitude of the peened samples indicates more stable shear deformation. Figure 1(b) and (c) show the fracture lateral surface of as-cast and the peened samples respectively. There are more shear bands in the peened sample than

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that in the as-cast sample, which is consistent with the stress-strain curves in Fig. 1(a).

Mukai *et al.*¹²⁾ reported that the localized shear band initiation stress (σ_e) is much lower than the σ_y of the BMG samples. In order to clearly present σ_e of the BMG samples, the inset in Fig. 1(a) exhibits their enlarged portions below its σ_y . For the as-cast BMG samples, it can be seen that σ_e is much lower than its σ_y , which is in agreement with earlier reports¹²⁾. In as-cast BMGs, shear bands readily nucleate from stress concentration sites (e.g. rough surface in the process of loading), which induces the low σ_e . However, for peened BMG samples, it can be seen that shear serrations obviously multiply from σ_e to σ_y , while the corresponding σ_e only slightly decreases compared to the as-cast BMG samples. Therefore, the rough surface and pre-existing shear bands created by shot peening on the sample surface are beneficial to shear bands nucleation⁵⁾. Evidently, shot peening could boost shear band nucleation. The compressive residual stress (CRS) induced by shot peening could inhibit the prop-

agation of shear bands in quasi-static compression⁵⁾, implying that shot peening could promote the proliferation of shear bands under monotonic compression.

The stress range ($\sigma_r = \sigma_{\max} - \sigma_{\min}$) is plotted as a function of fatigue cycles to failures (N_f) for the as-cast and peened samples in Fig. 2(a). The maximum stress range (the material subjected for 10^7 cycles without failure) is defined as the fatigue limit. The peened and as-cast samples exhibit the similar fatigue limit (about 1095 MPa). However, the fatigue life of the peened samples at high stress level is shorter than that of the as-cast samples. This is contrary to that shot peening could enhance the fatigue performance of crystalline alloys⁸⁾, which is possibly due to the different fatigue mechanisms between BMGs and crystalline alloys.

The fatigue fracture surface of as-cast and peened samples under σ_r of about 1197 MPa are shown in Fig. 2(b) and (c). Compared to the samples under monotonic compression (Fig. 1 (b) and (c)), there are many shear bands and some

Fig. 1 Monotonic compression stress-strain curves of the as-cast and peened samples. Insets are the enlarged portions of the curves near their σ_e (a). Fracture surface of as-cast (b) and peened (c) samples.

Fig. 2 Stress-life data for the as-cast and peened samples tested at a frequency of 100 Hz and a load ratio of $R = 0.1$ (a). Fatigue fracture surfaces of as-cast (b) and peened (c) samples under σ_r of about 1197 MPa.

cracks on the fatigued specimens, indicating that shear band may be easier to initiate under cyclic loading condition than that under monotonic loading, i.e., σ_e might be much lower under cyclic loading. This is consistent with the reports in Ref. 2). It is possibly that the decreasing in temperature of the shear zone during unloading process of cyclic loading increases its viscosity, and then accelerates the formation of shear bands in some new sites. In addition, it was obviously that the surface roughness of peened samples (Fig. 1 (c)) was significantly larger than that of the as-cast samples (Fig. 1 (b)).

Figure 3 shows the fatigue fracture morphologies of as-cast and peened samples at high stress level. Figure 3 (a) and (d) show overall fatigue fracture morphologies of as-cast and peened samples respectively, which mainly consists of two regions, crack propagation (P) region and fast fracture (F) region. It is obviously seen that the area ratio of P region in the as-cast sample is larger than that in the peened sample, implying the good fatigue performance of the as-cast sample¹³. The P region of both as-cast (Fig. 3(b)) and peened (Fig. 3(e)) samples is composed of cracks, striation-like and smooth-like region. In addition, the P region of the as-cast sample also possesses staircase-like fracture feature, which is a common characteristics of BMGs with excellent fatigue performance^{3,6}. As shown in Fig. 3(c) and (f), the boundary between F region and P region is obviously separated by macroscopic crack (as indicated by the arrows), indicating cleavage fracture has occurred before fast fracture. Relatively speaking, striation-like feature occupies most of the area in the P region for as-cast sample (Fig. 3(c)), whereas the corresponding region in peened sample (Fig. 3 (f)) exhibits smooth-like feature. In short, fatigue fracture morphologies show that the

as-cast specimens have better fatigue performance at high stress level.

In general, the mutually competing between the positive effect and negative effect could be induced by shot peening. In monotonic compression, the positive effect such as CRS and pre-existing shear bands could outweigh the negative effect (rough surface), i.e. playing dominant role. Consequently, the plasticity of BMG could be enhanced by shot peening. As well known, the enhanced fatigue performance of conventional alloys is due to that the positive effect (CRS and strain hardening) could exceed the negative effect (rough surface)⁹. However, the peened layer of the BMGs is softer than the bulk^{1,5}. As mentioned above, the rough surface and pre-existing shear bands could promote shear bands nucleation under cyclic compression. These multiple shear bands could promote fatigue crack nucleate below the surface⁹ and then propagate along the shear bands^{2,14}. That is to say, pre-existing shear bands are negative effect under cyclic compression. In addition, the internal stress at the interface between the peened layer and the bulk might even promote the fatigue crack propagation. Thus, these negative effects would outweigh the positive effect (CRS) in BMGs after shot peening at high stress level. Nevertheless, the CRS could balance the negative effects caused by shot peening at low stress range near fatigue limit, which makes the BMGs exhibit the similar fatigue limit. These micro-mechanisms, however, need further investigation. So, the method of surface shot peening could not enhance fatigue life of BMGs at high stress level. It is suggested that improving the intrinsic toughness of BMGs, such as enhance its Poisson's ratio, could be an effective method to improve its fatigue limit^{3,15}.

4. Conclusion

In summary, this study indicates that shot peening could enhance the compressive plasticity of BMGs by promoting the proliferation of shear bands. However, the rough surface and pre-existing shear bands created by shot peening could degrade the fatigue life of BMGs at high stress level, but has little influences on the fatigue properties of BMG in low stress range near fatigue limit due to the compressive residual stress (CRS). This is the result of mutually competition between positive effect (CRS) and negative effect (rough surface and pre-existing shear bands) under cyclic compression condition. The present study suggests that whether or not conducting shot peening treatment on BMGs depends on its application environment.

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Fig. 3 Fatigue fracture morphologies of as-cast (a)-(c) and peened (d)-(f) samples at σ_T of about 1197 MPa, the (a) and (d) image showing the overall fatigue fracture surface, (d) and (e) image showing the crack propagation region, and (c) and (f) showing boundary between fast fracture region and crack propagation region.

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