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Enhanced plasticity of bulk metallic glass in different aspect ratios via laser shock peening with multiple impacts

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ABSTRACT

In this study laser shock peening (LSP) with multiple laser impacts was used to improve the mechanical properties especially the plasticity of $Zr_{35}Ti_{30}Cu_{8.25}Be_{26.75}$ bulk metallic glass (BMG) pillars in two aspect ratios (1:1 and 2:1). It was found that, with increasing laser impacts up to 5, the compression plastic strain of BMG pillar with aspect ratio of 1:1 increased from 0 to 1.48% and the compression strength increased significantly from 1569 MPa to 1721 MPa. With further laser impacts beyond 5, the changes in the plasticity and the compression strength were observed to be insignificant. Considering the effect of sample geometry at the same laser impacts, it could be concluded that the BMG pillars with smaller aspect ratio of 1:1 had better mechanical properties than that of the lager BMG pillars with aspect ratio of 2:1. Besides, the elastic strain limit of BMG pillars with LSP was not only independent of the laser impacts, but also irrelevant to the aspect ratio. At last, we discussed the reason for the increase of plasticity in view of the creation of excess free volume during LSP.

1. Introduction

Laser shock peening (LSP) is an innovation surface modification technique and has been shown to be effective in improving the mechanical properties of a number of materials such as fatigue life and plasticity by introducing residual compressive stress to the surface of the components [1,2]. The study of LSP process was originally carried out by Fairand at the Battelle Columbus Laboratory in the 1970s [3] in which they studied the effect of laser induced shock wave on mechanical property changes of 7075 aluminum alloy. Since then considerable researches have been applied to potential applications of LSP in the aerospace and machinery manufacturing [4,5]. Comparing to other conventional surface treatment methods such as deep rolling (DR) and shot peening (SP), LSP introduces deeper residual stress, more uniform stress distribution and less microstructure modifications to the surface of the material [6,7].

In LSP process, the laser pulses with high power density (GW/m^2) and short pulse width (ns) cause vaporization of the substrate's surface into high pressure plasma. The rapid expansion of the plasma generates a high pressure shock wave which propagates into the substrate. When the peak pressure of the shock wave exceeds yield stress, the material is plastically deformed, thereby generating compressive residual stress on the surface of the substrate. For efficient utilization of laser shock wave to introduce compressive surface stress, a suitable laser-transparent layer (usually water or quartz glass) is used to confine laser-generated plasma resulting in significant increase in the peak pressure [8]. For avoiding thermal effect to substrate's surface, a suitable thermo-absorptive layer (usually black paint) covers on the substrates surface [9].

Bulk metallic glasses (BMGs) have many unique properties such as superior strength, lower Young's modulus, high elastic strain limit and excellent corrosion resistance, which lead to outstanding potential applications as structural materials [10,11]. However, the high strength of BMGs is often accompanied by remarkably little plasticity at room temperature[12,13] which restricts the use of BMGs as engineering materials. Generally, due to the lack of grain structure and dislocation mechanism, the plastic deformation of metallic glasses is localized in single shear band, followed by sudden fracture. Therefore, improving the plasticity of BMGs is a matter of generating of multiple shear bands instead of single shear band throughout plastic deformation. The formation of shear bands is associated with excess free volume which can be generated under various stress states subjected to BMG. Thus, free volume formed by the application of stress is assumed to control the plastic flow, suggesting that mechanical treatment can be a potential technique to enhance the plasticity of BMGs [14,15]. In recent decades, great efforts have been made to enhance the room

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temperature plastic deformation of BMGs [16–18]. For example, Conner et al. [19] found that the bending ductility of metallic glassy ribbons would increase with the increase of the thickness. In addition, Bruck et al. [20] investigated the compressive properties of metallic glassy bars in two aspect ratios (1:1 and 2:1) and found an obvious increase in the compressive plasticity. Also, Liaw [21] studied the dependence of the mechanical behavior of metallic glasses on the specimen geometry and concluded that the specimen-geometry effects on the mechanical behavior of metallic glasses were closely related to the constraint of shear-band processes. Other research found that applying confining pressure to the BMG samples could also promote the formation of multiple shear bands. Greer et al. found that exerting SP on the surface of BMG can generate a high level of compressive surface stress and promote the initiation of new shear bands, thus improving the plasticity. Davis et al. [22] and Yu [23] have investigated the effect of hydrostatic pressure on the ductility and fracture behavior of Zr-based metallic glasses. They found that BMGs exhibit a significant increase of plasticity owing to the induced shear bands and excess free volume. Besides, several studies had been done on improving the mechanical behavior of BMG by using the laser-surface treatment. Cao et al. [24] studied the effect of LSP on the plasticity of BMGs through the experimental and modeling results and provided an effective way to extend the ductility of intrinsically-brittle BMGs. Song and Huang et al. [25] investigated the deformation feature on the BMG surface under LSP and found that numerous arc plastic steps induced by LSP would be benefit for improving the plastic deformation of BMG. These researches indicate that the observed ductility of BMGs depends not only on the sample geometry, but also the applied loading modes.

In the present work, the effects of LSP with different laser impacts on compressive behavior of Zr-based bulk metallic glass in two aspect ratios (1:1 and 2:1) were studied in detail. In order to discuss the influence rule of LSP impact, the BMG pillars were processed with different LSP impacts. The mechanical properties were studied by the methods of uniaxial compression test. After compression, the fracture surfaces were investigated using scanning electron microscopy (SEM). The thermal analysis was performed using differential scanning calorimetry (DSC).

2. Materials and experimental procedures

The metallic glass used in this study was $Zr_{35}Ti_{30}Cu_{8.25}Be_{26.75}$ (atomic ratio) BMG which possessed excellent glass forming ability, high thermal stability against crystallization, a wide supercooled liquid region and superior mechanical properties [26]. The master ingot with composition $Zr_{35}Ti_{30}Cu_{8.25}Be_{26.75}$ was fabricated by arc-melting pure Zr, Ti, Cu and Be metals (purity >99.5%) in Ti-gettered argon atmosphere. The BMG rod was produced by suck casting into cooper mold of 5 mm in diameter. Before compression test, the BMG rod was cut into small pillars with different heights of 5 and 10 mm. The aspect ratio H/D of height (H) to diameter (D), i.e. 1 and 2 referred to as pillars A and pillars B, respectively. The two ends of all the pillars were carefully polished to ensure parallelism.

The LSP process in this study is shown in Fig. 1, the laser peened pillars are covered by two different layers, a black paint layer (0.1 mm thick) used as thermo-absorptive layer and a quartz glass layer (1–2 mm thick) used as transparent confining layer. Firstly laser pulse passes through the transparent confining layer and strikes on the thermo-absorptive layer. Then the laser pulse is absorbed to form plasma with high pressure. The expanding plasma leads to the formation of shock wave which propagates into BMG pillar with an intensity of several GPa. The laser peened pillars are mounted on electric rotating platform which is controlled by uniaxial motion stage in the vertical direction to implement the designed laser beam paths, shown in Fig. 1. And the quartz glass clamped tightly against the samples by artificial control. In order to avoid energy absorption by the damaged quartz glass, the relative position between the quartz glass and the sample was alternately relocated manually after several laser impacts. The horizontal laser beam is set to 1 mm spot size using a convex lens with 100 mm focal length and the distance between two successive laser spots is 0.5 mm controlled by vertical and rotary motions of the electric platform. The laser pulse with a wavelength of 1064 nm and a duration of 8 ns is generated by a frequency doubled Nd-doped yttrium aluminum garet (Nd:YAG, type: Nimma-600) operating at 1 Hz pulse frequency. The laser power energy is 700 mJ/pulse which is measured by an optical power meter (Coherent, type: Field MaxII). The processing parameters used in LSP are shown in detail in Table 1.

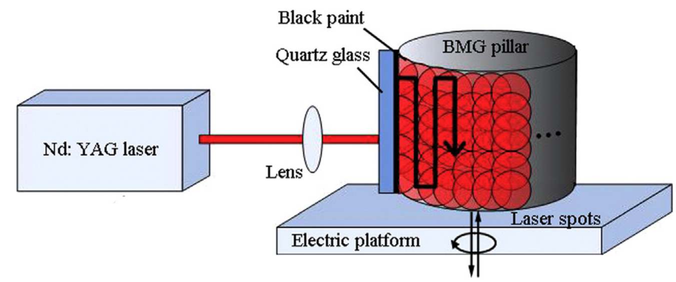

Fig. 1. Schematic illustration of the process setup and laser beam path of the laser shock peening experiment.

In order to discuss the influence rule of LSP impacts, the BMG pillars were treated with different impacts (0/1/3/5/7/10) on the same laser spot(three BMG pillars used for each condition). The fully amorphous structure of the Zr-based BMG was checked by X-Ray diffraction (XRD) operating at 40 kV and 40 mA with Cu Kα radiation. Fig. 2 shows the XRD patterns for BMG pillars in as-cast state and laser peened state. In the XRD pattern, there were only broad diffraction maxima and no peaks of crystalline phase could be observed. It was indicated that no crystallization of any kind was formed for these pillars. After LSP, all BMG pillars were tested under compression at room temperature at a strain rate of $10^{-4}s^{-1}$. After compression, the fractured pillars were investigated with scanning electron microscope (SEM) (Hitachi, type: SU-70) to reveal the fracture surface morphology and the fracture features. The changes in the excess free volume associated with LSP were measured using DSC at a heating rate of 20 K/min in a flow of purified argon gas.

3. Results and discussion

Fig. 3 shows the engineering stress-strain curves of BMG pillars A (A_1–A_7) and BMG pillars B (B_1–B_7) with different laser impacts, showing how the mechanical properties vary with the increasing laser impacts. For better visibility, the curves are shifted along the

Table 1
The processing parameters used in LSP.

Parameter	Value
Spot diameter (mm)	1
Pulse energy (mJ)	700
Pulse width (ns)	8
Repetition rate (Hz)	1
Laser wavelength (nm)	1064
Overlapping ratio	50%