Optics & Laser Technology 86 (2016) 54–60

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Structural and mechanical modifications induced on Zr-based bulk metallic glass by laser shock peening

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ARTICLE INFO

Article history:
Received 30 March 2016
Received in revised form
18 May 2016
Accepted 5 July 2016
Available online 19 July 2016

Keywords:
Zr-based metallic glass
Laser shock peeing
Free volume
Micro-hardness

ABSTRACT

In this study, surface modification of a $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ (vit1) bulk metallic glass (BMG) has been studied in an effort to improve the mechanical properties by laser shock peening (LSP) treatment. The phase structure, mechanical properties, and microstructural evolution of the as-cast and LSP treated specimens were systematically investigated. It was found that the vit1 BMG still consisted of fully amorphous structure after LSP treatment. Measurements of the heat relaxation indicate that a large amount of free volume is introduced into vit1 BMG during LSP process. LSP treatment causes a decrease of hardness attributable to generation of free volume. The plastic deformation ability of vit1 BMG was investigated under three-point bending conditions. The results demonstrate that the plastic strain of LSP treated specimen is 1.83 times as large as that of the as-cast specimen. The effect of LSP technology on the hardness and plastic deformation ability of vit1 BMG is discussed on the basis of free volume theory. The high dense shear bands on the side surface, the increase of striations and critical shear displacement on the tensile fracture region, and more uniform dimples structure on the compressive fracture region also demonstrate that the plasticity of vit1 BMG can be enhanced by LSP.

1. Introduction

Metallic glasses, which are also known as amorphous alloys, have been continually synthesized and investigated since the first fabrication of Au–Si binary amorphous alloy system in 1960 [1]. More recently, the field of metallic glasses has received much attention to the fabrication of specimen in excess of 1 mm in thickness dimension [2]. As compared to conventional engineering metals, bulk metallic glasses (BMGs) generally have the same order of elastic moduli, while the strength and elastic limits are significantly higher than polycrystals as a result of the microstructure of BMGs with short-range order, long-range disorder [3,4]. Due to the several excellent mechanical properties, such as high hardness, high elastic limit and strength, BMGs are quite attractive for many potential structural and functional applications [5–8]. However, the practical applications of bulk metallic glasses as structure materials is strictly restricted by their limited plastic strain in compression or uniaxial tension where the materials fail catastrophically by the formation of highly localized shear banding [9,10]. Great efforts have been devoted to circumventing the above-mentioned shortcomings [11–13]. To overcome brittle fracture of bulk metallic glass, laser shock peening (LSP) as a new surface modifications technology has been introduced.

LSP is considered as one of the most innovative surface modification technologies that can significantly improve the fatigue performance of polycrystalline metallic materials by introducing a layer of beneficial compressive residual stress to the surface of the components [14–16]. As a result, LSP technology also can enhance wear resistance [17], corrosion resistance [18–20], and tensile properties [21] in polycrystalline metallic components. LSP uses high intensity pulsed laser beam (power density of several GW/cm^2) with duration of nanoseconds on metallic specimens producing a high temperature and high density plasma [22]. The rapid expanding ionized plasma induces a high surface pressure (several GPa) which propagates into material as a shock wave. Comparing to conventional shot peening, LSP introduces a much greater depth of compressive residual stress and less risk of microstructure damage [23].

Our previous studies indicated that the residual stresses obtained by LSP treatment were beneficial to the plasticity of metallic glass [24]. The main purpose of the current study is to discuss the effects of LSP treatment on the structure and mechanical properties of $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ (vit1) BMG. The underlying mechanism for the change of the mechanical properties is analyzed in terms of free volume induced by LSP. The fracture surface morphologies and side surface morphologies of the as-cast and

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http://dx.doi.org/10.1016/j.optlastec.2016.07.003
0030-3992/

LSP treated vit1 BMG are characterized by scanning electron microscopy (SEM).

2. Experimental procedures

Master ingots of $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ (at%) were prepared by arc melting and mixing elemental pieces with a purity above 99.9% on a water-cooled copper hearth in a high purity argon atmosphere. To ensure the homogeneity of composition, each ingot was remelted for three times. Rectangular-shaped specimens with thickness of 3 mm were obtained by suction casting into a water-cooled copper mold. The specimens before LSP treatment were prepared with dimensions of 30 mm × 5 mm × 0.8 mm (length × width × thickness). All the surfaces were polished by 400#, 800# and 1200# waterproof abrasive paper sequentially, and then were further mechanically polished with 1 μm diamond paste in order to observe the surface topography after fracture.

A schematic of the LSP process was shown in Fig. 1. The experiments were carried out on the surface of the specimens using a Q-switched Nd:YAG laser with a wavelength of 1064 nm and a frequency of 10 Hz. The energy was measured by a Field MaxII power meter and used at constant of 600 mJ/pulse. The time duration of the laser pulses was about 8 ns. The laser beam was focused in a diameter of 1.2 mm through a focusing lens and calibrated by Kodak photo sensitive paper. The aluminum foil with 30 μm thickness was used as ablative overlay to minimize undesirable thermal effects on vit1 surface. The quartz glass with 3 mm thickness was placed on the ablative overlay as the confinement layer to get the desired plasma confinement effect. The LSP treated region was 30 mm × 5 mm (length × width) on both the upper and the bottom vit1 BMG surface. The spacing between two adjacent laser spot was set to 1 mm so as to obtain a continuous laser shock region. A German D8-ADVANCE X-ray diffraction (XRD, Cu-Ka) was used to confirm the phase structure of metallic glass. The thermodynamic properties of the as-cast and LSP treated specimens were investigated by a differential scanning calorimeter (DSC) at a heating rate of 20 K/min under a continuous argon flow. The parameters of thermal properties were obtained with an accuracy of ± 1 K. The average structural relaxation exothermic enthalpy values of vit1 BMG were calculated with three groups. The hardness testing was performed at room temperature using a HVS-1000 microhardness tester under 1.96 N load with 10 s dwell time. Three point bending tests were performed on a computer controlled SANS testing machine with a constant displacement rate of 0.1 mm/min at room temperature. A schematic diagram of the three pointing bending test was illustrated in Fig. 2. The bent specimens were examined using a Hitachi SU-70 scanning electron microscope.

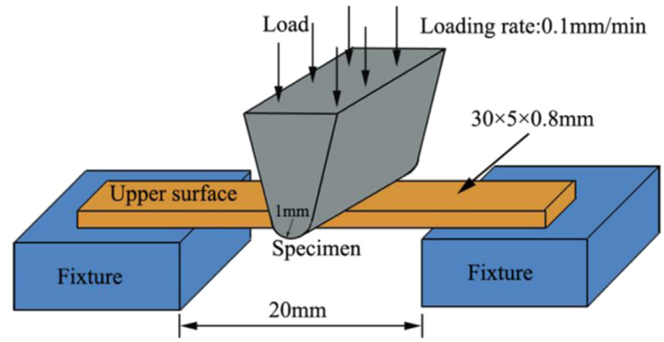

Fig. 2. Schematic diagram of the apparatus in the three-point bending test.

3. Experimental results

XRD patterns recorded from the surfaces of the as-cast and LSP treated vit1 alloys are shown in Fig. 3. For the as-cast specimen, the pattern consists of a typical broad halo with no detectable crystalline Bragg peaks, which confirms its amorphous structure. And, for the LSP treated specimen, it can be clearly seen that XRD pattern still displays no sharp diffraction peaks, which suggests that LSP does not induce any crystallization in the vit1 BMG. The bright filed TEM image and corresponding selected area electron diffraction patterns for the LSP treated specimen are shown in Fig. 4. No crystallization is detected within the LSP treated area, which further confirms the homogeneous amorphous structure of the LSP treated sample.

The DSC curves of the as-cast and LSP treated vit1 BMG specimens are shown in Fig. 5. The amount of vit1 BMG is obtained from the top surface of the LSP treated layer in order to study the structural modification of the specimen. The specimens display a similar endothermic characteristic with a distinct glass transition region and a supercooled liquid region, followed by crystallization processes. The onset relaxation temperature, the onset glass transition temperature, the onset crystallization temperature and the crystallization peak temperature of the as-cast and LSP treated

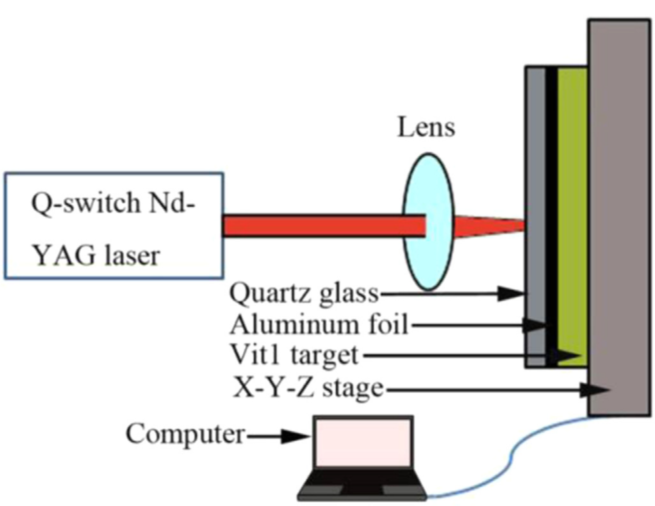

Fig. 1. Schematic illustration of the LSP treatment.

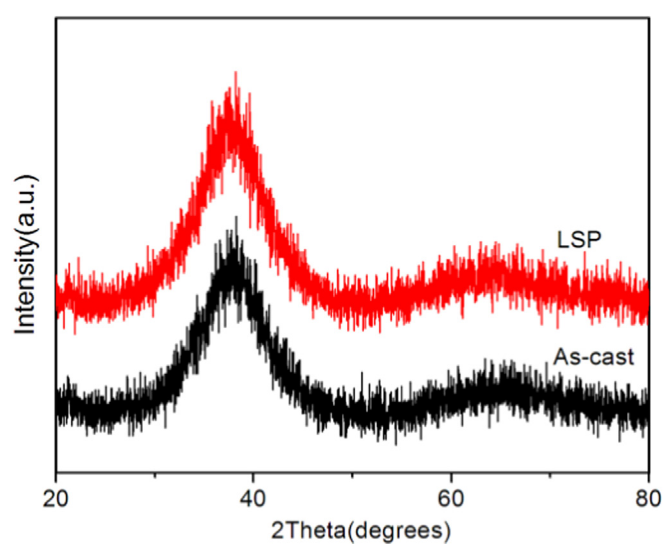

Fig. 3. XRD patterns of the as-cast and LSP treated vit1 BMG.