Journal of Alloys and Compounds 690 (2017) 176–181

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

# Tailoring residual stress to achieve large plasticity in $Zr_{55}Al_{10}Ni_5Cu_{30}$ bulk metallic glass

Yangyang Cheng, Shujie Pang, Chen Chen, Tao Zhang*

*Key Laboratory of Aerospace Materials and Performance (Ministry of Education), School of Materials Science and Engineering, Beihang University, Beijing 100191, China*

A R T I C L E I N F O

*Article history:*
Received 29 May 2016
Received in revised form
25 July 2016
Accepted 9 August 2016
Available online 11 August 2016

*Keywords:*
Metallic glasses
Laser processing
Rapid-solidification
Mechanical properties

A B S T R A C T

In order to explore the effect of residual stress state on the mechanical properties of BMGs, we utilized the laser surface melting to tune the residual stress distribution via changing the processing angle between the laser scanning direction and the axial direction in the $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG. It was found that the laser processing angle has a significant effect on the plasticity of the treated specimens. The improved plastic strains of the specimens treated by 60° and 90° laser processing angles are almost twice those of 0° and 30° treated specimens. Via finite element analysis, the variation of residual stress distribution with the processing angle was characterized, and the correlation between the residual stress state and the plasticity was discussed. This study could be expected to aid in the wide application of surface treatment for improving the mechanical properties of BMGs.



## 1. Introduction

Bulk metallic glasses (BMGs) usually fail catastrophically without obvious macroscopic deformation and strain hardening [1,2]. This raises a serious reliability issue for the potential application of BMGs as structural materials. Consequently, clarifying the underlying mechanism of deformation has been the focus of the research on BMGs in recent decades [3–6]. It is widely accepted that the poor plastic deformability of BMGs is resulted from the shear localization and the instable propagation of shear bands [7–9]. Therefore, many successful attempts have been made to control shear banding behavior to improve the plasticity of BMGs. From the perspective of elastic constants or heat of mixing among constituents, the intrinsic structure of BMGs (such as free volume content and nano-scale structural heterogeneity) is tailored via carefully tuning the composition to facilitate the formation of multiple shear bands and render the BMG with large plasticity [6,10,11]. Another emerging strategy to extrinsically improve the plasticity of BMGs is surface treatment, by which the residual stress is introduced in the near-surface zone of the treated BMGs [12–16]. When the treated BMG is subjected to compressive or tensile loading, the residual stress is coupled with the loading stress and can generate complex stress state. Compared with the BMG under uniform stress, the treated BMG under the complex stress field exhibits enhanced plastic deformation. For example, the laser surface melting (LSM) can generate tensile residual stress on the surface layer of the treated BMG and compressive residual stress on the nether part, thus rendering the BMG with outstanding ductility under compressive and bending tests [12,13]. Alternatively, through mechanical attrition or shot peening, compressive residual stress and pre-existing shear bands on the surface layer are introduced, and the treated BMG even displays slight tensile plasticity [15,16].

Generally, the introduced tensile/compressive residual stress varies along the thickness direction of BMGs, showing a roughly parabolic profile [7,12,15]. Accordingly, the combination of the introduced residual stress and the loading stress can result in the formation of stress concentration and stress gradient. This leads to that shear bands firstly appear at the region where the maximum stress reaches the initiation stress of shear band, and then gradually expand with the increasing applied stress [9]. Additionally, a number of studies have verified the significant effects of the stress concentration and stress gradient on the formation of multiple shear bands and the inhibition of their propagation by conducting bending tests or using the BMG specimens with designed artificial defects (notch or pore) [8,17,18]. Therefore, the tensile/compressive residual stress, introduced by the surface treatment, can make the shear bands initiate easily and expand difficultly.

Due to the difficulty in measuring the distribution of residual

* Corresponding author.
*E-mail address:* zhangtao@buaa.edu.cn (T. Zhang).

http://dx.doi.org/10.1016/j.jallcom.2016.08.075
0925-8388/

stress of BMGs, the previous studies only considered the residual stress along the longitudinal direction of the treated specimens [7,12,15]. However, indeed, the introduced residual stress is multi-axial stress and exists in the transversal direction [19,20]. It is reasonable to infer that the multi-axial residual stress contributes to the enhanced plasticity of the treated BMGs. Accordingly, we suppose that tuning the intensity of residual stresses in the longitudinal and transversal directions may alter the gradient stress field in the treated BMG subject to loading, and consequently optimize the mechanical properties.

In the present work, the laser surface melting (LSM) was utilized in the $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG to explore the effect of tensile residual stress distribution on the mechanical properties. As illustrated in Fig. 1, we changed the processing angle between the laser scanning direction and the axial direction (loading direction) of the specimen to expect that various residual stress distributions could be obtained. Via finite element analysis, the residual stress field was characterized. The results demonstrate that the specimens treated by different laser processing angles possess different residual stress distributions. Interestingly, under compressive tests, the plastic strains of the specimens treated by 60° and 90° laser processing angles are almost twice those of 0° and 30° treated ones. The present study would be of significance in extending the potential applications of surface treatment in BMGs.

## 2. Experimental procedures

Alloy ingots with a nominal composition of $Zr_{55}Al_{10}Ni_5Cu_{30}$ (at.%) were produced by arc-melting the mixtures of pure metals with purities above 99.9%, in a Ti-gettered argon atmosphere. Each ingot was turned over and remelted four times to ensure compositional homogeneity. From the ingots, rectangular rods with a dimension of 1.7 mm × 1.7 mm × 50 mm were fabricated by copper mold casting method and their amorphous structure was identified by X-ray diffraction (XRD) using Bruker AXS D8 X-ray diffractometer with Co Kα radiation (wavelength, 0.17902 nm). For laser surface melting, the glassy specimens were cleaned with distilled water and acetone. The LSM was carried out using a 180 W Nd:YAG laser at a beam scanning speed of 250 mm/min with a focused beam diameter of 0.8 mm, pulse frequency of 8 Hz, pulse width of 1 ms, average laser fluence of 0.55 J/mm$^2$, wavelength of 1064 nm and a partial overlapping (50%). The processing angles between the laser scanning direction and the axial direction of the specimens were 0°, 30°, 60° and 90° (Fig. 1). The amorphous structure of the treated specimens was also confirmed by XRD. The enthalpy difference ($\Delta H$) below the glass transition temperature of the as-cast and the treated specimens was assessed using a differential scanning calorimeter (DSC) at a heating rate of 0.33 K/s. Uniaxial compressive testing was performed on the laser treated specimens with an aspect ratio of 2:1 at a strain rate of $8 \times 10^{-4}$ s$^{-1}$ on SANS 5504 testing machine at room temperature, and five specimens were tested to ensure the reproducibility of the results. Morphologies of the deformed and fractured specimens were observed by CamScan 3400 scanning electron microscope (SEM).

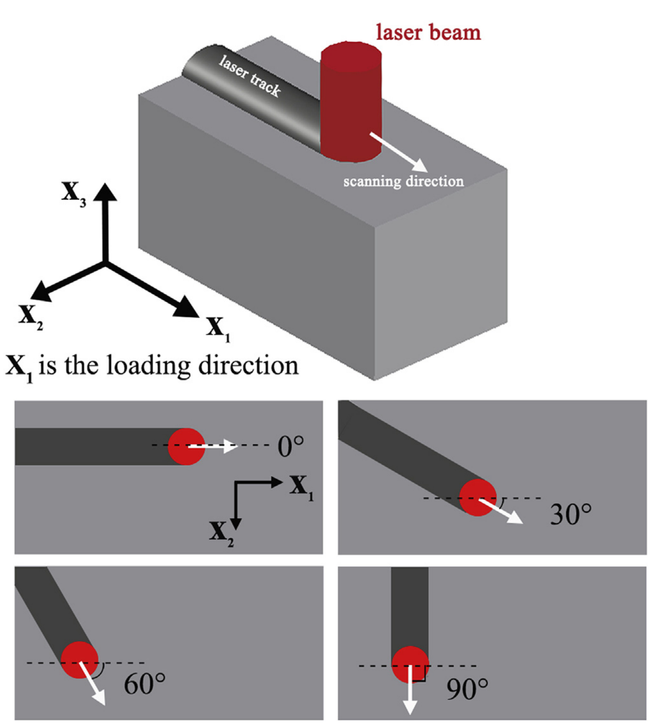


**Fig. 1.** Schematic illustrating the process of LSM.

## 3. Results

Fig. 2 (a) presents the XRD patterns of the specimens before and after the LSM. The broad diffraction hump without crystalline Bragg peak confirms the fully amorphous structure of the treated specimen. Besides, there is almost no change in $\Delta H$ below glass transition temperature between the as-cast and the LSM treated specimens (Fig. 2 (b)), implying that the treated specimens are not relaxed.

Engineering stress-strain curves of the as-cast and the treated specimens under uniaxial compression are shown in Fig. 3 (a). It can be seen that the treated specimens exhibit larger plastic strain than the as-cast one. After the yielding plateau, the treated specimens do not fail catastrophically until the stress decreases gradually by about 200 MPa, while for the as-cast one the stress abruptly drops. More interestingly, the processing angle has a significant effect on the plastic strain of the treated specimen. For comparison, the variation of the plastic strain with the processing angle was plotted in Fig. 3 (b). It is notable that the plastic strains of the specimens treated by 60° and 90° are almost twice those of the specimens treated by 0° and 30°.

The deformation and fracture features of the specimens were characterized by SEM. Fig. 4 shows the representative lateral morphologies of the deformed as-cast and 0° & 90° specimens which were unloaded after compression plastic strain of about 1%. To clearly reveal the propagation of shear bands, the front surface and the side surface of the rectangular specimens were observed. For the as-cast specimen (Fig. 4 (a)), there are only a few primary shear bands on the surfaces, and the secondary shear bands are hardly visible. Nevertheless, the 0° and 90° treated specimens (Fig. 4 (b) and (c)) exhibit profuse primary and secondary shear bands, and the intersecting between them induces the deflection, branching and arrest of shear bands. Furthermore, we measured the shear band inclination angle with respect to the loading axis. For the as-cast specimen, the majority of the shear band angles are 43°–45° in agreement with the previous reports that the angle is ≤ 45° for compression [9,21], but the angles of the 0° and 90° treated specimens are mostly 48°–51°. This contradiction implies that after the LSM the introduced residual stress coupled with the loading stress can generate a stress state different from that of uniaxial compression, and consequently affect the propagation direction of the shear band.

After the final failure, the lateral and fractured morphologies of the as-cast and 0° & 90° treated specimens are shown in Fig. 5. It can be seen that the edge of the fracture surface of the as-cast specimen is straight (Fig. 5 (a1)), while the edges of the treated