Materials Science & Engineering A 606 (2014) 196–204

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Deformation behavior of bulk metallic glass structural elements

S.H. Chen, K.C. Chan*, L. Xia

Advanced Manufacturing Technology Research Centre, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong

ARTICLE INFO

Article history:
Received 20 February 2014
Received in revised form
13 March 2014
Accepted 25 March 2014
Available online 1 April 2014

Keywords:
Bulk metallic glass
Structural element
Shear bands
Deformation mode

ABSTRACT

Macroscopic bulk metallic glass (BMG) structures have been investigated as potential structural materials in recent decades, due to their superior energy absorption ability and excellent mechanical properties. However, lack of understanding the deformation mechanisms of BMG structures significantly hindered their potential structural applications. In the present study, through macroscopic geometrical control, five BMG structural elements (struts) have been designed and investigated under both tensile and compressive loadings. Under tension, the particular BMG structural elements show tunable large macroscopic axial elongations, which are mainly attributed to the controllable plastic deformation in localized regions and the straightening of the curved segments in the BMG structural elements. Under compression, three different deformation modes are observed in the BMG structural elements. This work is of significance in understanding the deformation behavior of macroscopic BMG structures.

1. Introduction

As an emerging class of structural materials, bulk metallic glasses (BMGs) have been studied extensively in recent decades [1,2]. They are known to have good mechanical, physical and chemical properties compared with their crystalline counterparts and conventional metals and alloys [1,3–5]. In recent advancements, due to the high compression and bending plasticity of BMG strut elements at the sub-millimeter scale [6], some BMG structures such as metallic glass foams [7–11] and BMG honeycombs [12,13] exhibit a large energy absorption ability and room-temperature plasticity under compression. By designing micro-cellular structures, certain macroscopic tensile ductility has also been achieved in metallic glasses [14]. Macroscopic BMG structures have large potential in structural applications, and the construction of BMG structures has become a new research direction for exploring the applications of BMGs. However, the application of BMG structures has been hindered by two key issues. Firstly, the reported literature has seldom focused on the deformation behavior of macroscopic BMG structures under tensile loadings. Compared to the high compressive plasticity of metallic glasses, the brittleness of metallic glass under tension makes it very challenging to develop a macroscopic BMG structure with large global tensile ductility [15,16]. Secondly, although the deformation mechanisms of BMG foams under compressive tests have been studied extensively [7–11,17,18], the geometry and sizes of the pores are difficult to be controlled accurately, and the detailed deformation mechanisms of the curved struts are barely revealed.

Our recent work has demonstrated that, at a designed complex stress state, a curved BMG is able to exhibit a large axial elongation under tensile loading [19]. Although the macroscopic axial elongation does not result from uniform plastic deformation of BMGs, this macroscopic axial elongation can be controlled through precise geometrical design, providing a feasible route to uncover the deformation mechanisms of macroscopic BMG structures. In view of the complexity of macroscopic BMG structures, in the present paper, five different BMG structural elements (struts), including four curved BMG structural elements with various curvature radii, and a straight BMG specimen, have been fabricated. The deformation behavior of these BMG structural elements (struts) under both tensile and compressive loadings is investigated, and the corresponding deformation mechanisms are analyzed and discussed. This work provides guidance in understanding the deformation mechanisms of macroscopic BMG structures.

2. Experimental

2.1. Materials and fabrication of as-cast BMG specimens

Commercial elements of Zr, Cu, Al, Ni and Ti with purities of 99.8%, 99.999%, 99.99%, 99.999%, and 99.995% respectively were used to fabricate as-cast BMG specimens. Master alloy ingots with composition of $Zr_{57}Cu_{20}Al_{10}Ni_8Ti_5$ (at%) were first fabricated from the pure elements in an arc melter under an argon atmosphere. Then, after remelting the ingots for five times, as-cast cylindrical

* Corresponding author. Tel.: +852 27664981.
E-mail address: kc.chan@polyu.edu.hk (K.C. Chan).

http://dx.doi.org/10.1016/j.msea.2014.03.094
0921-5093/

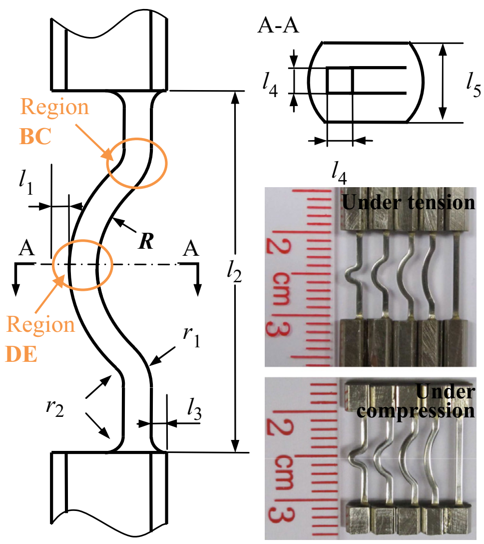

Fig. 1. Schematic illustration of the curved BMG specimens, where $l_1=0.4$ mm, $l_2=10.6$ mm, $l_3=0.4$ mm, $l_4=0.8$ mm, $l_5=2.4$ mm, $r_1=1.1$ mm, $r_2=0.3$ mm and the variation $\boldsymbol{R}=6$ mm, 3 mm, 1.5 mm, 0.3 mm respectively (for the variation $\boldsymbol{R}=6$ mm, $l_1=0.9$ mm). The inset optical images show the prepared tensile and compressive specimens with $\boldsymbol{R}=0.35$ mm, 1.55 mm, 3.05 mm and 6.05 mm correspondingly from left to right as well as the straight specimens.

BMG rods of 3 mm diameter were prepared by suction casting the melted ingots into a water-cooled copper mold [20]. The amorphous state of the as-cast BMG specimens was confirmed using standard X-ray diffraction (XRD) analysis with Cu-K$_\alpha$ radiation on a Rigaku SmartLab X-ray diffractometer.

2.2. Design and fabrication of BMG structural elements

Four curved $Zr_{57}Cu_{20}Al_{10}Ni_8Ti_5$ BMG structural elements of $\boldsymbol{R}=6$ mm, 3 mm, 1.5 mm and 0.3 mm (noted as R60, R30, R15 and R03 respectively) were designed as illustrated in Fig. 1. The straight specimens (conventional tensile specimens, noted as R00) with same cross-sectional dimensions (l_4) and reduced section lengths (l_2) were also fabricated for comparison. The designed five BMG structural elements were produced from the as-cast rods using wire-cut electrical discharge machining (EDM) on a FI 240 SLP wire-cut EDM machine. After EDM, the machined surface layers consisting of spark temperature zones were removed using abrasive paper with grits from 150 to 2000, and the prepared specimens are shown in the insets in Fig. 1. The final dimensions of the $\boldsymbol{R}$ values were 6.05 mm, 3.05 mm, 1.55 mm and 0.35 mm for each variation, and the final value of l_4 was 0.7 mm. The glassy structure of the prepared BMG structural elements has also been checked using the XRD analysis to ensure the elimination of the spark temperature zones.

2.3. Mechanical testing

The tensile tests of the structural elements were conducted on a servo-hydraulic 810 Material Test System (MTS) at room temperature with a cross-head displacement rate of 0.06 mm/min. The macroscopic axial elongations of the structural elements were recorded using an extensometer. In addition to the tensile tests to failure, the R60, R15 and R03 specimens with corresponding axial elongations of 4.9%, 9.7% and 10.3% respectively without fracture were also obtained to compare the plastic deformation in specimens with various curvature radii. After tensile testing, the side surfaces of each specimen were inspected using a Jeol JSM-6490 scanning electron microscope.

The compressive tests were also conducted on the MTS with same cross-head displacement rate. In view of the two-stage deformation mode in the R03 specimen, the compression tests of this specimen were divided into two steps. In the first step, the continuous loading of the R03 specimen was terminated at an axial displacement of 1.1 mm. Thereafter, in the second step, this specimen was reloaded to the axial displacement of 2.19 mm. The side surfaces of the compressive specimens at each step were also examined using the scanning electron microscope.

2.4. Finite element modeling (FEM) analysis

To characterize the stress distributions of the curved BMG specimens, FEM analysis was carried out using commercial ABAQUS package based on an ideal elastic–plastic constitutive model. Although such model cannot capture the detailed information of the nucleation of shear bands, it is good to simulate the distribution of shear bands in yielded regions [21,22]. The material parameters used in the FEM analysis were 0.36 for Poisson's ratio [23], 82 GPa for Young's modulus [23] and 1.635 GPa for yield stress [19]. Under tension, FEM analysis was used to simulate the distribution of the Mises stress in the deformed R60, R15 and R03 specimens before fracture. Under compression, FEM analysis was used to examine the Mises stress distribution in both the R30 specimen before yielding and the deformed R03 specimen in the first step of the compression tests.

3. Deformation behavior of the BMG struts under tension

3.1. Tensile testing results

Fig. 2 shows the tensile load vs. macroscopic axial elongation curves of the five BMG specimens. The R00 specimen shows a typical brittle behavior with an elastic elongation of about 2.25%; however, the curved specimens exhibit large macroscopic elongations, and the curved specimens with smaller curvature radii exhibit larger macroscopic axial elongations. The average macroscopic axial elongations of the R00, R60, R30, R30, R15 and R03 specimens are 2.25 ± 0.13%, 5.23 ± 0.55%, 8.24 ± 1.34%, 10.51 ± 1.43% and 10.89 ± 1.78% respectively. Moreover, the curved specimens have decreasing slopes in the load–axial elongation curves at small elongations till reaching the maximum loads, especially for the specimens with $\boldsymbol{R}$ values smaller than 6.05 mm. This indicates that highly localized stress concentrations may occur in curved specimens with smaller curvature radii, and part of the specimen yielded far earlier than the yielding of the whole specimen [20]. With the complex stress states resulting from the designed curvature radii, a range of macroscopic axial elongations have been achieved in the BMG structural elements.

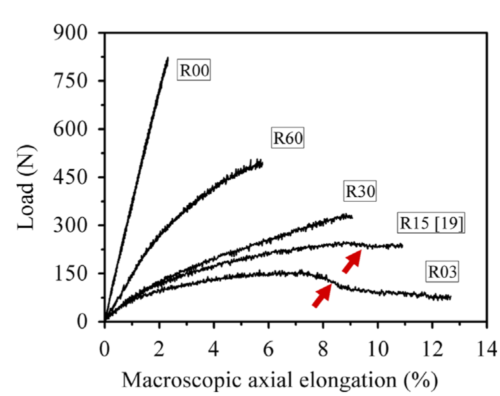

Fig. 2. Load–macroscopic axial elongation curves of the BMG structural elements under tensile loading, where the arrows show decreasing of the loads.