Journal of Alloys and Compounds 661 (2016) 49–54

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

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

Saw-tooth-like bulk metallic glass structures with greatly enhanced energy-absorption performance

S.H. Chen [a], K.C. Chan [a,*], G. Wang [a,b], J. Yi [a]

[a] Advanced Manufacturing Technology Research Centre, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[b] Laboratory for Microstructures, Shanghai University, Shanghai 200444, China

ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form
11 November 2015
Accepted 17 November 2015
Available online 22 November 2015

Keywords:
Cellular materials
Energy absorption capacity
Bulk metallic glass
Shear bands

ABSTRACT

In this work, saw-tooth-like bulk metallic glass (BMG) structures were developed, exhibiting greatly enhanced energy-absorption performance as compared with existing cellular metals, such as conventional metal foams and BMG foams/honeycombs. The excellent energy absorption capacity is attributed to the change of the deformation modes from bending, buckling and collapse of the structural units in conventional cellular solids to large plastic deformation in the present BMG structures. Additionally, the energy absorption capacity of designed saw-tooth-like BMG structures can also be tuned by tailoring the periodic distribution of the structural units.

1. Introduction

Cellular solids with high energy absorption capacity have wide applications for crash protection and blast mitigation, such as in automotive industries, light-weight constructions and supporting cores of structural sandwich panels [1–6]. Due to the large energy absorption capacity by forming a steady plastic-flow stage, cellular metals have been studied extensively for energy-absorption purpose [7,8]. For example, Al and Al alloy foams have demonstrated a wide range of porosity, a high specific strength and a high energy absorption capacity [1,9]. Research findings have demonstrated that the energy-absorption performance of cellular materials is significantly influenced by the strength of the parent materials [7]. By replacing the parent Al alloys using metals with relatively-higher strength, some other alloy based foams have then been developed, such as steel foams [10], copper foams [11] and composite metal foams [12,13], exhibiting better energy-absorption performance.

As a novel class of structural materials, bulk metallic glasses (BMGs) are known to have relatively higher hardness and strength than their crystalline counterparts [14–16]. This enables BMGs to become ideal parent materials to fabricate cellular structures for energy-absorption applications. Some BMG structures, such as BMG foams [17–20] and honeycombs [21,22], have been developed and have demonstrated better energy-absorption performance than conventional Al foams. However, when compared with other alloy foams [10–13], the energy-absorption performance of these BMG structures shows no obvious advantages. Some recent work has shown that to increase the plastic deformation in the structural units could further improve the energy-absorption performance of BMG structures [23,24]. BMGs are able to demonstrate more plastic deformation behavior under complex stress states than uniform stress states [25–28]. In fact, in practical applications of structural materials, the material always deforms under complex stress states, rather than uniform compressive or tensile stresses [29–31]. In this work, by the use of the large plastic deformation behavior of BMGs under complex stress states, some saw-tooth-like BMG structures have been designed and fabricated, where the deformation modes are mainly plastic deformation under compressive testing. These BMG structures have demonstrated much enhanced energy absorption capacity than previously reported metal foams and BMG structures.

2. Experimental

The design of a single tooth unit of saw-tooth-like BMG

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

http://dx.doi.org/10.1016/j.jallcom.2015.11.100
0925-8388/

structures is shown in the schematic diagram in Fig. 1. The saw-tooth-like BMG structure consists of a substrate and periodically distributed tooth units. The distances between the symmetric planes of the tooth units (d_3 in Fig. 1) were tailored as 2.8 mm, 2.2 mm and 1.6 mm for specimens A, B and C, respectively. To fabricate the saw-tooth-like BMG structures, as-cast $Zr_{57}Cu_{20}Al_{10}Ni_8Ti_5$ (at.%) BMG rods of 5 mm diameter were prepared by suction-casting the melted ingots in a copper mold, from the pure elements of Zr, Cu, Al, Ni, and Ti. The amorphous atomic structure of the as-cast BMG specimens was confirmed using standard X-ray diffraction (XRD) analysis on a Rigaku SmartLab X-ray diffractometer. The saw-tooth-like structures were then fabricated from the as-cast rods using wire-cut electrical discharge machining (EDM) on an FI 240 SLP wire-cut EDM machine. After EDM, the side surfaces of the specimens were polished using abrasive paper with grit sizes from 150 to 2000. The relative densities of the saw-tooth-like BMG structures were calculated using the equation

$$\rho_r = \frac{\rho_s}{\rho_p} = \frac{n\frac{(d_1+d_2)}{2}h_1 + (n-1)d_3 + d_2}{[(n-1)d_3 + d_2]\text{of}(h_1 + h_2)} \quad (1)$$

where ρ_s and ρ_p are the densities of the saw-tooth-like BMG structures and the parent BMGs respectively, and n is the number of the tooth unit. The relative densities of specimens A ($n = 5$), B ($n = 6$) and C ($n = 8$) were calculated as 0.52, 0.56 and 0.62, respectively. Three saw-tooth-like structures with relative densities of 0.52, 0.56 and 0.62 respectively made of a high-strength stainless steel (SS316L) have also been prepared to make a comparison. Compression tests of the saw-tooth-like BMG structures were conducted on a servo-hydraulic 810 Materials Testing System (MTS) at a constant cross-head loading speed of 0.036 mm/min. After compressive testing, the side surfaces of the deformed specimens were examined using scanning electron microscopy (SEM) on a Jeol JSM-6490 scanning electron microscope.

3. Results and discussion

The compressive deformation behavior of the saw-tooth-like BMG structures is shown in Fig. 2a. Although BMGs are known to have a size effect [32,33], and the bulk form of a $Zr_{57}Cu_{20}Al_{10}Ni_8Ti_5$ BMG specimen of 5 mm diameter has very limited macroscopic

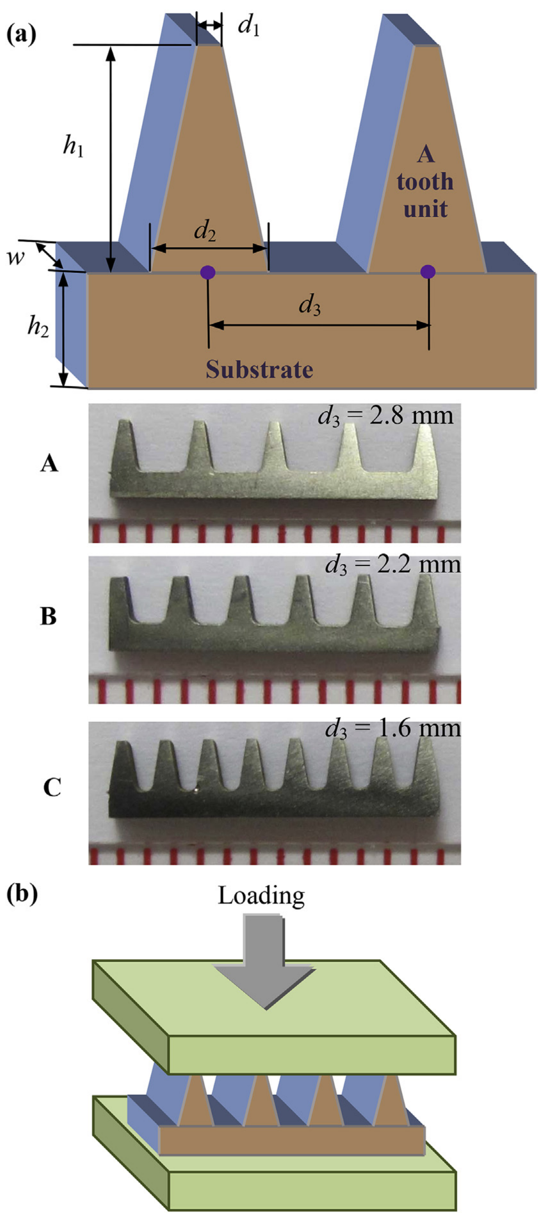

Fig. 1. (a) The schematic diagram of the designed saw-tooth-like BMG structures, where $h_1 = 2$ mm, $h_2 = 1$ mm, $w = 2$ mm, $d_1 = 0.33$ mm, $d_2 = 1$ mm, and $d_3 = 2.8$ mm, 2.2 mm and 1.6 mm respectively for specimens A, B and C, respectively. (b) The schematic diagram showing the compressive testing of the saw-tooth-like structures.

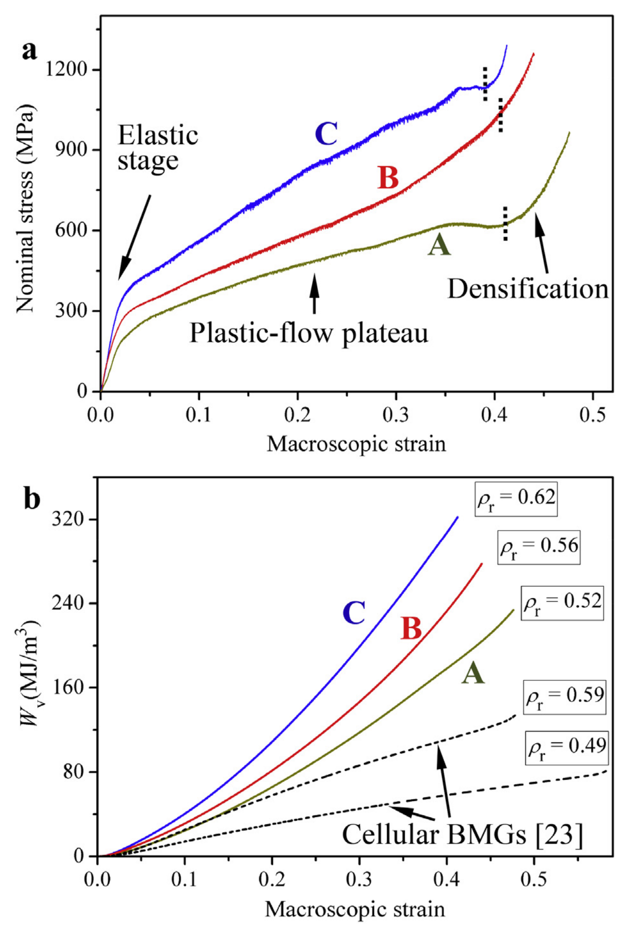

Fig. 2. The compressive testing results of the saw-tooth-like BMG structures (a) and the corresponding evolution of the energy absorption capacity (W_v) of the saw-tooth-like BMG structures (b). The dash lines in (b) show the evolution of W_v of two cellular BMGs with macroscopic cellular structures [23] for comparison.