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Buckling of metallic glass bars

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ABSTRACT

Uniaxial compression tests of slender metallic glass bars of composition $Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$ (at.%) have been conducted. It was found that the Zr-based metallic glass bars have a tendency to buckle elastically or plastically rather than to yield or fracture if its slenderness ratio is over a critical value. The elastic buckling undermines the intrinsic strength of the metallic glass, but the plastic buckling imparts the metallic glass a benign failure mode and avoids the catastrophic brittle fracture. The phenomena are understood by the unique stress state across the bar. The result has implication for the measurement of mechanical properties of bulk metallic glasses and is of significance in the application of metallic glass members in engineering structures.

1. Introduction

Due to the lack of tensile ductility at room temperature, bulk metallic glasses (BMGs) and their derivatives, as potential structural material with high strength and good elasticity, are usually tested in uniaxial compression to determine the mechanical properties [1–4]. Rod shaped BMG specimens for compression test generally have an aspect ratio (i.e. height/diameter) of 2 as recommended by ASTM [3]. The aspect ratio is often deliberately reduced [5], sometimes even below unit, to explore the size dependence of the strength and plasticity. In sharp contrast, there are, to date, sparse reports on the compressive performance of BMGs with high aspect ratios, e.g. 3 or above. For a BMG specimen with a constant diameter, a lower aspect ratio actually means a smaller specimen volume which contains fewer flaws, such as pores, micro-cracks etc. that are induced during the casting and machining process [6]. It alleviates the detrimental influence of the flaws on the inherent mechanical properties of BMGs. On the other hand, once yielding occurs, most BMGs are very prone to localize the plastic strains in the shear bands [1]. Since elastic strain energy is stored inside loaded specimen, the bands in a long BMG rod is more likely to shear in a runaway manner than in a short one, because the energy needed to dissipate per unit area in the shear plane is proportional to the length [6]. This favors short (i.e. low aspect ratio) specimens by virtue of the structure stability. However, the slender members, such as columns, beams and bars, are inevitably employed in engineering structures [7]. More importantly, a slender specimen is different from a stubby one in terms of the failure mode. A bar that is sufficiently slender will buckle rather than yield or fracture under a compressive load [7,8]. For BMGs, the deforming characteristics of slender samples have not received any attention and therefore remain unexplored [1,9].

According to the conventional Euler buckling model [7], the critical stress, σ_E, for a slender bar of a length, l, is

$$\sigma_E = \frac{\pi^2}{(kl/r)^2} E \quad (1)$$

where E is Young's modulus, r is the smallest radius of inertia of the cross section, and k is a dimensionless factor depending on the end restraints. The ratio l/r is called the slenderness ratio (SR) that scales with the aspect ratio. For BMGs, Young's modulus is about 30% smaller than that for the corresponding crystals, and the elastic limit is about twice that for a crystalline material [1,10]. From Eq. (1), it can be concluded that metallic glass is more likely to buckle than its crystalline counterpart with the same end constraints and SR when compressed [4]. Nevertheless, if σ_E exceeds the yield stress, σ_y, of the material, the specimen will yield first and then deform plastically or fracture before the buckling has a chance to intervene. For instance, the σ_E value of a BMG column with the most common aspect ratio of 2 (i.e. SR of 8) and two clamped ends (i.e. k of 0.5) is ~0.62E according to Eq. (1), about 31 times as large as the yield stress, σ_y (~0.02E). Thus, BMG samples tested by compression, reported in the literatures, usually yield rather than buckle [1]. Recently, Demetriou et al. [4,11] examined the yield behavior and strength of amorphous Pd-based foams, and they found that the buckling of the intracellular membranes played a vital role in the foam deformation. However, the dimensions of the membrane were on the order of tens of microns, even smaller than the plastic zone thickness in BMGs. Furthermore, there are so many membrane struts in the foam that it is impossible to identify the exact behavior of a single strut despite understanding the foam's overall performance.

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In this paper, we report the deforming behavior and failure mode of slender Zr-based BMG specimens. Elastic buckling and plastic buckling are both observed in uniaxial compression experiments. We emphasize that the failure mode of the Zr-based BMG buckles rather than yields when the SR increases. A unique manner of shear band development during the buckling is witnessed, which is attributed to the stress gradient across the specimen. Based on the performance of slender BMG bars, the buckling, compared to the catastrophic shearing-off or brittle fracture, is considered to be a more benign failure mode.

2. Experimental methods

Alloy ingots with nominal composition of $Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$ (at.%) were prepared by arc-melting high purity metals under a Ti-gettered purified argon atmosphere, which was then suction-cast into a plate form with dimensions of 70 mm × 12 mm × 1.6 mm in a water-cooled copper mold. Its glassy nature was ascertained by the x-ray diffraction (XRD) technique. The plate was cut into bar shaped specimens for the compression tests. All the specimens were carefully machined and polished to eliminate the surface flaws, and more importantly, to ensure the top and bottom ends were flat and as parallel as possible to each other, and were perpendicular to the longitude loading axial. Uniaxial compression tests were conducted at a strain rate about 10^{-4} s^{-1} at room temperature. The specimens undergoing plastic buckling were observed by scanning electron microscope (SEM) to investigate the features of the developed shear bands in detail.

The dimensions, SRs and σ_Es for the elastic buckling of the specimens are listed in Table 1. As $r = \sqrt{I/A}$ in which I is the smallest area moment of inertia and A is the area of the cross section [7], the SR can be readily calculated. The σ_E value is obtained with an E of 88.6 GPa [10,12], and $k = 0.5$ and 0.7 which correspond to the fixed–fixed end restraint and fixed–pinned end restraint, respectively.

3. Results and discussion

3.1. The issue of plasticity in BMGs

Although extensive efforts have been made to improve the plasticity of BMGs, the experimental data on the plasticity are extremely scattered, sometimes even contradictory [2,3,13–18]. For most Zr-based BMGs, there are two typical ways for the shear band development in the same specimen, as shown in Fig. 1 [13,18]. If the first primary shear band forms in the bottom corner (see Fig. 1a), the upper part of the specimen can slide along this primary shear band, and the capacity loss of load, caused by the reduction of the effective load-bearing area (the red line in Fig. 1), can be duly compensated by the support from the tip P touching the platen. The first primary shear band is stopped and the second one is initiated and develops in a similar way, and the process will continually repeat itself [18]. In this way, "plasticity" is obtained. Conversely, if the first primary shear band forms in the middle of the specimen (see Fig. 1b), the load capacity cannot be compensated immediately by the P' support, and will drop dramatically in the ensuing deformation. Eventually, the specimen is sheared off prematurely and shows poor plasticity.

Fig. 2a shows two stress–strain curves for specimens A1 and A2 with similar dimensions. A1 is sheared off after only about 0.2% plastic strain, whereas A2 sustains more than 0.6% plastic strain without fracture.

Table 1
Summary of the dimensions, SRs and σ_Es ($k = 0.5$, fixed–fixed; $k = 0.7$, fixed–pinned; $E = 88.6$ GPa) of $Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$ specimens.

No.	Length (mm)	Width (mm)	Thickness (mm)	SR	σ_E (GPa)	
					k = 0.5	k = 0.7
A1	4.50	1.08	0.82	19.0	9.68	4.94
A2	4.52	1.08	0.82	19.1	9.59	4.89
B1	11.39	1.54	0.68	58.0	1.04	0.53
B2	10.84	1.54	0.68	55.2	1.15	0.59
B3	8.44	1.03	0.58	50.4	1.37	0.70
B4	7.00	0.93	0.49	49.5	1.43	0.73
C1	9.16	0.98	0.72	44.1	1.79	0.92
C2	9.08	1.53	0.96	32.8	3.25	1.66
C3	10.46	1.50	1.47	24.6	5.78	2.94
C4	4.79	1.44	0.78	21.3	7.71	3.93

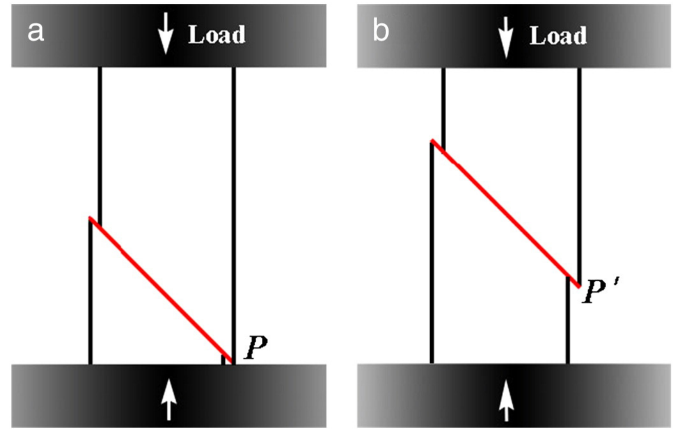

Fig. 1. Schematic of two typical ways for shear band development in a Zr-based BMG. (a) The first primary shear band forms at the bottom corner of the sample. (b) The first primary shear band forms in the middle of the sample.

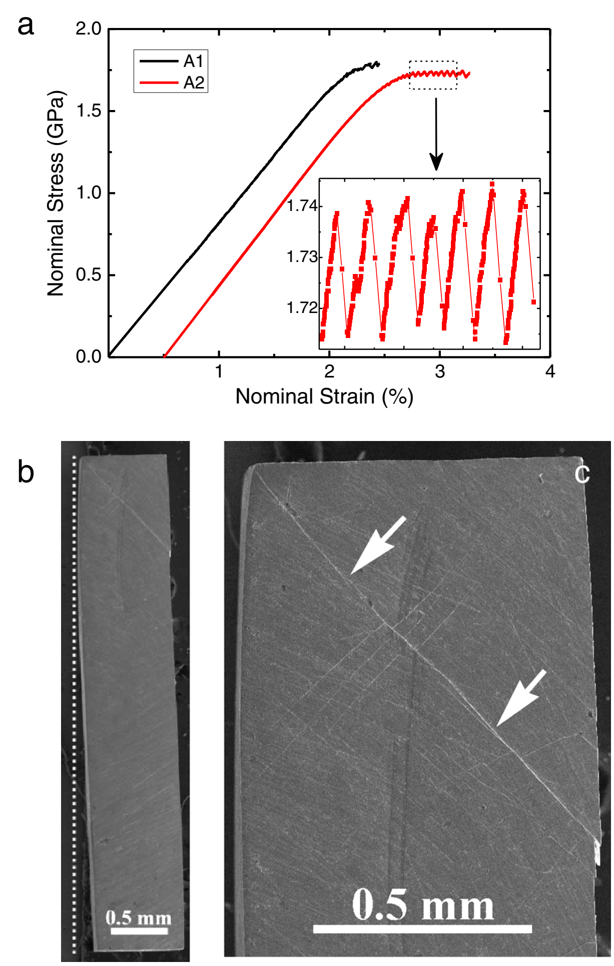

Fig. 2. Investigation on the deformation behavior of stubby samples A1 and A2. (a) Strain–stress curves of A1 and A2 in compression. The inset shows the regular serrations in the plastic deformation regime of A2. (b) A SEM profile of A2 whose top part is magnified in (c).