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Dual character of stable shear banding in bulk metallic glasses

Y. Yang [a,*], J.C. Ye [a], J. Lu [b], C.T. Liu [a]

[a] *Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong*
[b] *Department of Manufacturing Engineering and Engineering Management, The City University of Hong Kong, Kowloon Tong, Kowloon, Hong Kong*

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ABSTRACT

In this work, a systematical study of the stable shear banding behavior is performed across a wide range of alloy compositions of bulk metallic glasses (BMGs). Through microcompression, it can be demonstrated that the stable shear banding behavior could exhibit a dual character of stochastic and deterministic propagations. Different from the stochastic character, which is found insensitive to sample sizes, the deterministic character displays a clear trend of a sample size effect, which can be captured by the energy balance principle. Based on the theoretical framework laid out in this work, a correlation between the plastic energy dissipation and the sample size effect is established, which can be then utilized to explore the influence of the alloy's chemical compositions on the behavior of shear-induced material softening. Finally, the energy-based formalisms aimed to quantify the shear banding size effect in MGs are discussed.

1. Introduction

Since their advent in the 1960s [1], metallic glasses (MGs) have been regarded as a promising structural material due to their unique combination of mechanical properties, such as remarkable yield strengths, high elastic limits and superb hardness [2]. However, they are also plagued by the lack of material microstructures. As a consequence of their intrinsic amorphousness, MGs possess no microstructural features to impede the threatening growth of their flow defects. At the atomic-scale, the flow defects of MGs are free-volume zones, which are essentially loosely bonded atomic clusters trapped within elastic media. In uniaxial mechanic testing, those free-volume zones coalesce, evolving into shear bands upon yielding, and the catastrophic propagation of the shear bands then result in the brittle-like fracture in MGs. To overcome the apparent brittleness, substantial research efforts have been devoted to unveiling the deformation mechanisms in MGs [3–12].

Owing to the enduring research efforts, malleable MGs have be successfully synthesized/acquired by means of alloy design [13], sample size reduction [9–11,14,15], formation of porous structures [16,17] and dispersion of toughening phases in the original amorphous matrix [18–20]. Despite the success of these approaches in delaying or even suppressing catastrophic shear banding, it is still an open question for the dominant deformation mechanism that can lead to such a brittle/plastic behavior in different monolithic MGs. On one hand, it was suggested that the plasticity or brittleness of MG alloys should be related to their conventional mechanical properties, such as the Poisson's ratio and fracture toughness [21]. Based on those properties MG alloys can be naturally differentiated into two groups. For example, Zr- and Pd-based MGs are usually regarded as intrinsically ductile while Mg- and Fe-based MGs as intrinsically brittle [21]. On the other hand, it was proposed that the observed plasticity/brittleness in MGs may result from a size effect [9,10,22–24]. Below a critical size, all MGs deform similarly in a plastic manner; while the difference in their deformation behavior emerges only above a certain sample size. In other words, if the final failure is dominated by the catastrophic propagation of a major shear band, the plastic and brittle failures observed in uniaxial mechanical tests are just two different manifestations of the same deformation mechanism. In such a case, it can be inferred that, for a given sample size, one may witness the seemingly brittle versus plastic behavior between two different MGs if the sample size was less than the critical size of one alloy composition but larger than that of the other. Now, the question arises. How do shear bands behave in different MGs if they are all being stabilized? The answer to this question is not trivial as it involves the confounding effects of sample size and material's chemical composition on the shear-banding kinetics.

In this current work, we intend to provide a comprehensive investigation of the stable shear banding behavior among different MGs at ambient temperature, which could reveal the possible interrelation among serrated plastic flows, sample sizes and MG alloy compositions and, thereby, provide a mechanistic understanding for

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* Corresponding author. Tel.: +852 27666652; fax: +852 23654703.
E-mail address: mmyyang@polyu.edu.hk (Y. Yang).

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the shear banding kinetics in MGs. To this end, the microcompression approach was adopted here to avoid the catastrophic shear band propagation as usually observed in bulk samples.

2. Materials and experiments

For the microcompression study, six different MGs were selected in total to cover the range of alloy compositions from the typical ductile to brittle type as categorized by their fracture toughness [21], including $Zr_{55}Cu_{23}Ni_5Al_{10}Nb_2$, $Zr_{55}Cu_{30}Ni_5Al_{10}$, $Zr_{50}Cu_{37}Al_{10}Pd_3$, $Cu_{46.25}Zr_{44.25}Al_{7.5}Er_2$, $Mg_{58}Cu_{31}Nd_5Y_6$ and $(Fe_{44.3}Cr_5Co_5Mo_{12.8}Mn_{11.2}C_{15.8}B_{5.9})_{98.5}Y_{1.5}$ (in atomic %). Their atomic structures were characterized using the X-ray diffraction method, which showed the typical amorphous structures in these alloys (not shown here). Prior to the microcompression experiments, the surfaces of the bulk MG samples were mechanically polished to a mirror finish. Subsequently, the Quanta 3D 200 dual-beam focused-ion-beam (FIB) and scanning-electron-beam (SEM) system (FEI Company, Hillsboro, OR) was used for the fabrication of micropillars. By using the sequential ion-milling approach [15,23,25], a series of micropillars were carved out on the polished sample surfaces, which had the diameters and aspect ratios ranging respectively from ~ 1 μm to ~ 7 μm and ~ 2:1 to ~ 5:1. Note that one micropillar with an aspect ratio as high as ~ 11 was also tested without buckling [Fig. 1a] and the results show the similar trend as that of the others. Due to the ion-beam divergence, the micropillars were slightly tapered with an average taper angle of ~ 2°. To conduct the microcompression experiments, the TriboIndenter™ nanoindentation system (Hysitron Inc., Minneapolis, MN) equipped with a 10 μm flat-end diamond nanoindenter was employed. The microcompression experiments were then carried out at displacement control with the constant nominal strain rate of about 6.5×10^{-3}.

3. Results and discussion

3.1. Serrated plastic flows in microcompression

Similar to the reported results for other MGs [9,14,15,22–24,26], all six MG alloys were compressed to extensive plastic deformation without sudden fracture in the microcompression tests. Fig. 1a–f present the typical serrated load-displacement curves obtained from the MG micropillars at different sample geometries, which all resulted from the stable propagation of shear bands after the

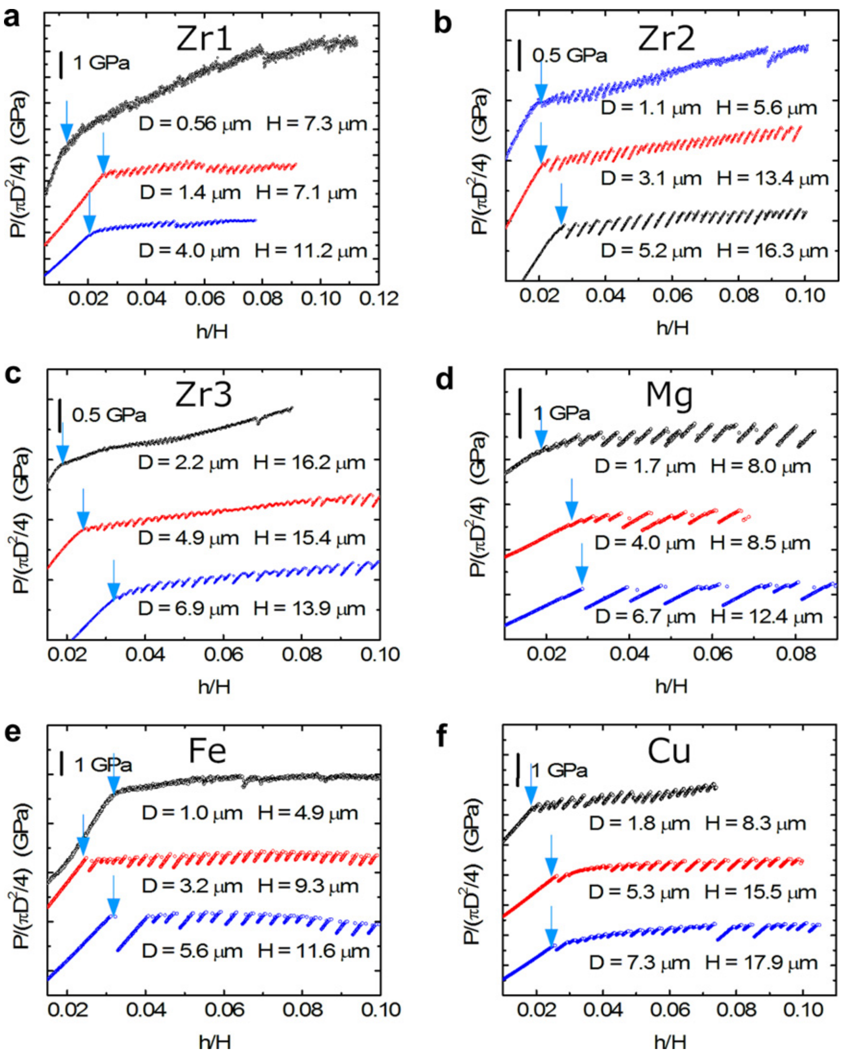

Fig. 1. The typical load-displacement curves obtained from different sample geometries for (a) $Zr_{50}Cu_{37}Al_{10}Pd_3$, (b) $Zr_{55}Cu_{30}Ni_5Al_{10}$, (c) $Zr_{55}Cu_{28}Ni_5Al_{10}Nb_2$, (d) $Mg_{58}Cu_{31}Nd_5Y_6$, (e) $(Fe_{44.3}Cr_5Co_5Mo_{12.8}Mn_{11.2}C_{15.8}B_{5.9})_{98.5}Y_{1.5}$, and (f) $Cu_{46.25}Zr_{44.25}Al_{7.5}Er_2$ (note that the arrows in the subfigures indicate the transitions from apparent elasticity to serrated plastic flows).