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Achieving the desirable compressive plasticity by installing notch cluster in metallic glass

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ABSTRACT

In this work, the compressive global plasticity depending on different settings of notch cluster was investigated on Zr-based metallic glass by experiment and finite element simulation. In experiment, it was found that a large plasticity could be generated by changing the distance of notch pairs which could make the shear bands (SBs) interact with each other and block the rapid shear banding. By introducing the Mohr–Coulomb yielding criterion and the associated flow rule, an elastic–plastic model was built up to describe deformation process for all specimens by means of finite element method (FEM). Combined with the experimental results, it demonstrated that the large plasticity was attributed to the intersection of multiple SBs which was caused by V-shaped plastic strain regions according to FEM results. Finally, conclusive parameters were tentatively proposed to work as the direct and fundamental basis for fabrication of new metallic glass based porous materials or composites.

1. Introduction

As the structural materials, bulk metallic glasses (BMGs) have attracted loads of interests due to the several properties such as high strength, high hardness as well as high fracture toughness [1–7]. However, the key weakness of the metallic glass is low plasticity which means that the metallic glass sample usually fracture along one SB under tension and compression loading owing to its isotropy and shear localization [8]. Therefore, how to improve the plastic deformation ability of metallic glass has been a popular topic for many researchers. It was reported that the rapid propagation and extension of SBs could be confined strongly by adding secondary-phase particles or high-strength fibers into the amorphous alloys [9,10], which could finally result in a large plasticity. Actually, the major pathway for improving the plasticity of metallic glasses is to restrain the initiation and propagation of SBs and have multiple SBs interacted together.

Recently, the notch effect on metallic glass has been prevalent since it was reported that the installation of different notches could largely enhance the plastic deformation of metallic glass due to the interaction of SBs initiated from notch regions [11]. Moreover, this kind of notch effect is also available for brittle Ti-based metallic glass [12], implying that installing notches may be a general approach to plasticity improvement though plasticity individualities of different metallic glass rely on its central shear deformation features [13]. Besides, it was concluded that densification and hardening induced by notch could lead to a global larger plasticity compared with the smooth samples [14]. In addition, the improved tensile ductility and toughness could be achieved by installing different settings of heterostructures [15], implying that the suitable setting of notches or holes could definitely improve the global plasticity of metallic glass specimens. In fact, notched sample could be simply regarded as one part of porous materials [15] and it could yield different plastic deformation behaviors if we alter the geometrical locations of notch cluster. However, the previous approaches mostly focused on one or two notches [11–14] without considering notch cluster. Then, based on the above concerns, the present work investigated the plasticity of Zr-based metallic glasses with different notch clusters by means of experiment and simulation. The major purpose of our work is to provide a direct pathway to describe the effect of notch cluster on global plasticity of metallic glass sample, which could doubtlessly work as a fundamental guidance for porous metallic glass fabrication.

2. Experimental procedures

A Zr-based metallic glass alloy, with nominal chemical compositions of $Zr_{52.5}Ni_{14.6}Al_{10}Cu_{17.9}Ti_5$, was prepared by the arc-melting

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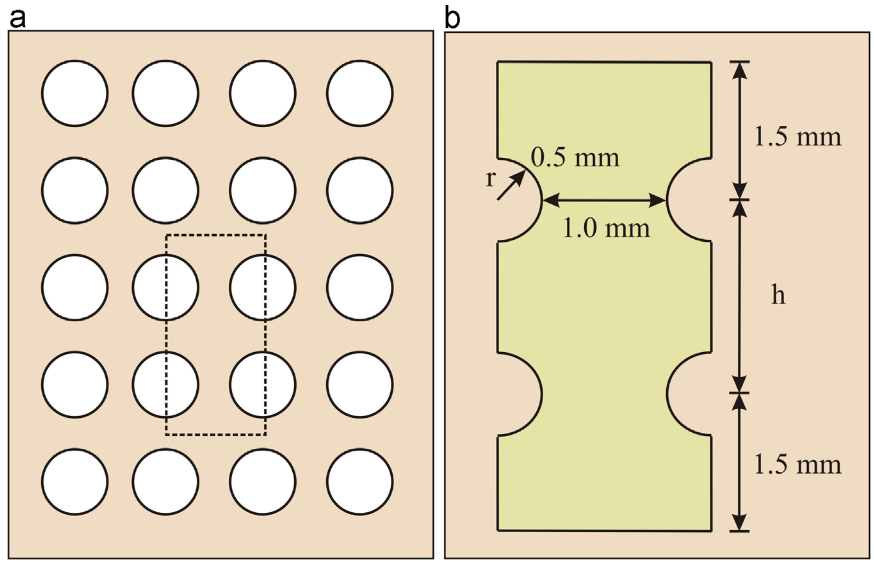

Fig. 1. (a) Simplified illustration of porous metallic glass. (b) Notched sample in which two pairs of semicircularnotches are installed with different distance h in vertical direction. The radius of semicircular notch is 0.5 mm and the width of specimen is 2.0 mm. Additionally, the dimension of *h* is designed as 1.5 mm (specimen A), 2.0 mm (specimen B), and 3.0 mm (specimen C).

method. The final plate had a rectangular shape, with the dimension of $60 \times 30 \times 3$ mm^3. Fig. 1(a) shows the simplified illustration of porous metallic glass. If the notched sample was considered as one unit of the porous metallic glass, one could obtain the notched sample as displayed in Fig. 1(b) in which, two pairs of semi-circular notches are installed with different distance *h* in vertical direction. In this work, the radius of semi-circular notch is 0.5 mm and the width of specimen is identically 2.0 mm. The thickness of specimen is 2.0 mm. The dimension of *h* is designed as 1.5 mm (specimen A), 2.0 mm (specimen B), and 3.0 mm (specimen C). Then, conventional compression tests were applied in order to measure the mechanical properties of the metallic glass specimens with the INSTRON 8862 testing machine at room temperature in air. All the tests were conducted at a strain rate of about 10^{-4} s^{-1}. For each kind of design, I have made three samples in order to verify the repeatability. During each test, I recorded the yield strength and maximum strength as well as the plasticity to make a comparison. All the three samples displayed the similar deformation behaviors, suggesting that current compression tests are repeatable. The deformed specimens were observed with a LEO Supra 35 scanning electron microscope (SEM) to reveal the deformation and fracture morphologies. In addition, a finite-element method (FEM) with ANSYS was adopted to simulate the stress distributions of the specimens. It could display the numerical results of the nodes by dispersing the whole model into many finite elements.

3. Experimental results

3.1. Compressive stress–strain responses

Fig. 2 displays the engineering compressive stress–strain curves of specimens A, B and C. Here, an engineering stress, i.e. the ratio of the applied force to the minimum bearing area of the specimen (2.0 mm $\times$ 1.0 mm) is applied to represent the global stress since the stress distributions in the specimens with notches are non-uniform [16]. Following the previous reference [17], the yield strength that corresponds to the formation of a major shear band is determined by the crossover point from elastic to plastic portions with a very small offset of 0.05%. As shown in Fig. 2, the yield strength of specimen A is ~1.75 GPa which is quite close to the value of unnotched sample

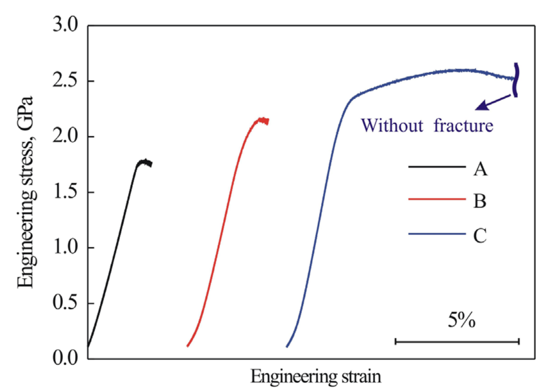

Fig. 2. Compressive engineering stress–strain curves for three specimens (AC).

1.80 GPa [5,11]. Besides, the plasticity is about 0.5% which is also consistent with that for unnotched specimen [5,11]. However, for specimen B, the yield strength is 2.14 GPa, appearing as an obviously larger strength than specimen A though the minimum bearing area is the same (2.0 mm $\times$ 1.0 mm) for both specimens A and B. Besides, the plasticity is still around ~0.5%, same as specimen A. However, different from specimens A and B, engineering stress–strain curve of specimen C illustrates much larger yield strength (2.35 GPa) and plasticity ($>6.7\%$). Actually, the specimen C did not fracture even though the plasticity reached 6.7%. In order to capture the shear deformation features at this moment, the test was stopped at this moment and the deformed specimen C was moved out for SEM observation. In brief, under different values of *h* (see Fig. 1(b)), various yield strength and plasticity were obtained, reflecting that the geometrical locations of notch cluster could influence global plastic deformation behaviors of notched metallic glass specimens. More important is, the maximum plasticity ($>6.7\%$) was found when *h* is 3.00 mm, conveying a significant information which might be the basic parameter for fabrication of porous metallic glass materials.

3.2. Shear deformation features

In order to catch the shear deformation morphologies when yielding happened, all the three samples were firstly moved out for the first scanning by SEM once the engineering stress of specimens