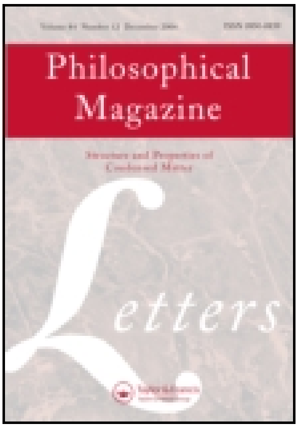

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Enhanced plastic deformation in a metallic glass induced by notches

J.X. Zhao [a], R.T. Qu [a], F.F. Wu [a b c], S.X. Li [a] & Z.F. Zhang [a]

[a] Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, China

[b] School of Materials Science and Engineering, Liaoning University of Technology, 169 Shiying Street, Jinzhou 121001, China

[c] School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

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Enhanced plastic deformation in a metallic glass induced by notches

J.X. Zhao[a], R.T. Qu[a], F.F. Wu[abc], S.X. Li[a] and Z.F. Zhang[a]*

[a]*Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, China;* [b]*School of Materials Science and Engineering, Liaoning University of Technology, 169 Shiying Street, Jinzhou 121001, China;* [c]*School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China*

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It is shown that the compressive plasticity of a metallic glass, namely $Zr_{52.5}Ni_{14.6}Al_{10}Cu_{17.9}Ti_5$, can be improved by the introduction of two symmetrical notches. The enhanced plasticity may be ascribed to a blocking effect of the propagation of shear bands caused by large stress gradients around the notches. In contrast to ceramic specimens with similar notches, the plasticity enhancement of metallic glass induced by notches can provide a new approach to understanding its unique mechanism of deformation.

Keywords: metallic glass; shear bands; notches; plasticity; deformation

1. Introduction

Metallic glasses are of interest for several mechanical properties attractive in structural materials, such as high strength and high hardness, and have consequently received much attention by many researchers [1–4]. However, their engineering application is restricted by their low plasticity [5–8]. Different approaches have been made to improve this. On the one hand, metallic glass composites have been fabricated in different ways with the aim of obtaining an enhanced plasticity [9,10], for example, by the addition of secondary phases or high-strength fibres into the amorphous alloys [11–13], or by preparing composites containing *in situ* formed ductile dendrites. These studies demonstrate that reinforced phases can restrain the rapid propagation of shear bands (SBs) and change the expansion direction so that the plasticity of metallic glasses can be improved. On the other hand, it has been found that an abundance of SBs can accommodate higher plasticity under compression when the aspect ratio of the compressive specimens is smaller than 1, compared to the situation at an aspect ratio of 2 [14–18]. Additionally, it has been found that large plasticity could also be obtained by shot peening [19]. In addition, a small punch test (SPT) was found to be an effective method of stimulating more SBs under multiaxial loading [20,21]. It has been demonstrated that metallic glasses can contain regularly arranged fine multiple SBs with large plastic strain (19.6%) [21].

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*Corresponding author. Email: zhfzhang@imr.ac.cn

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All the above-mentioned research work demonstrates that metallic glass can display different plastic deformation abilities by changing intrinsic or external factors.

In this study, we show that one can enhance the plasticity by introducing two symmetrical notches within metallic glass specimens. Compared with the results on ceramic specimens containing two notches, the samples display a large plasticity which can be regarded as a unique deformation mechanism.

2. Experimental procedures

A Zr-based metallic glass alloy, with nominal chemical composition $Zr_{52.5}Ni_{14.6}Al_{10}Cu_{17.9}Ti_5$, was prepared by arc melting. The final plate has a rectangular shape, with dimensions $60 \times 30 \times 3\,mm^3$. As illustrated in Figure 1a, the metallic glass plate was cut into four kinds of specimens, designated as A, B, C and D, with dimensions $3.0 \times 3.0 \times 6.0\,mm^3$, containing semi-circular notches having a radius of 0.5 mm. The lengths between the center of the semi-circular notches and the end of specimen are indicated in Figure 1a. Conventional compression tests were applied to measure the mechanical properties of the metallic glass specimens with an MTS810 testing machine at room temperature in air. All the tests were conducted at a strain rate of about $10^{-4}\,s^{-1}$. After the tests, the specimens were examined with a

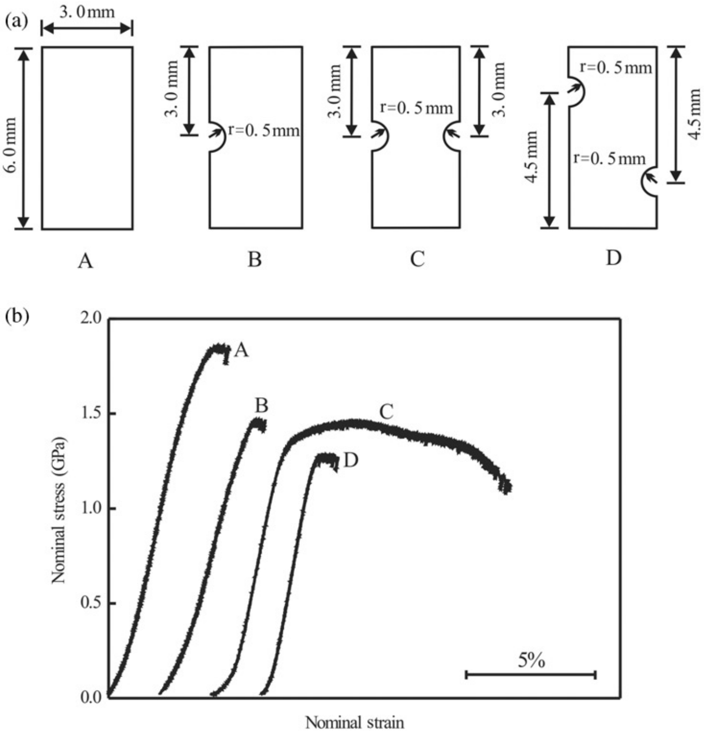

Figure 1. (a) Schematic illustration for the four kinds of specimens (A, B, C and D) in the compression tests; (b) nominal stress–strain curves for the different samples.

LEO Supra 35 scanning electron microscope (SEM) to reveal the deformation and fracture morphologies. In addition, a finite element method (FEM) with the commercial software ANSYS was exploited for simulating the stress distribution of the specimens with notches. This could display the numerical results of the nodes by dispersing the whole model into many finite elements [22].

3. Results and discussion

In Figure 1b, the nominal compressive stress–strain curves for the four kinds of specimen A, B, C and D are displayed. We applied a nominal stress to represent the global stress since the stress in the notched specimen was nonuniform. For comparison, we selected the area of the notched specimen end as the nominal area. Because of the existence of notches, the stress and strain are designated 'nominal' instead of 'engineering'. As shown in Figure 1b, curve A of the smooth sample shows only a small plasticity (about 0.3%) with a yield strength of ~1.80 GPa [4,23]. The values of plasticity of samples B and D with one notch or two dissymmetric notches are not so high (about 0.5–1.0%); however, their yield strengths have the values ~1.50 GPa (sample B) and ~1.25 GPa (sample D). In contrast, sample C, with two symmetrical notches, displays a large plasticity of nearly 10%, as shown in curve C in Figure 1b, and its yield strength is ~1.50 GPa. Obviously, the reduction in yield strength arises from the stress concentrations around the notches. However, the large plasticity shown by curve C is quite different from that revealed by a conventional compression test on an identical Zr-based metallic glass [23], suggesting that further understanding for the enhanced plasticity when notches are present is required.

SEM images of the deformation features are shown in Figures 2a–d corresponding to samples A–D in Figure 1a. At high compressions, three of the specimens (A, B and D) fractured into two parts along a major SB [4,23]. Their shear fracture angle was about 41°, which is consistent with the results obtained in uniaxial compression tests [4,23]. However, specimen C did not split into two parts although the plastic strain had reached 10%. Instead, an intersection of two major SBs was formed around the notches with a shear angle of about 40°, as shown in Figure 2c. Near to the notches, displayed as regions I and II, large stress concentrations were first produced. Then, in region III, two major SBs intersected with each other and had an out-plane displacement with many SBs at the tip of extrusive region. In the region IV, several small SBs also intersected without shear fracture. It was decided that these findings needed a detailed investigation to analyse the related stress distribution in the specimens with different notches.

Schuh [24] has systematically investigated the initiation of SBs in metallic glass near a stress concentration. For samples with semi-circular notches, several approaches [25,26] based on elastic mechanics report that the stress concentration around notches could change the stress distribution. However, these analytical models were mostly based on a 2-D infinite plane, which is not suitable for 3-D structures as in this case. So here finite element analysis [22] was employed to describe the stress distribution in the notched specimens. In the finite element modeling (FEM), the elastic modulus and Poisson's ratio of metallic glass are taken as 97.8 GPa and 0.362, respectively [23]. In detail: (1) An ideal elastic–plastic

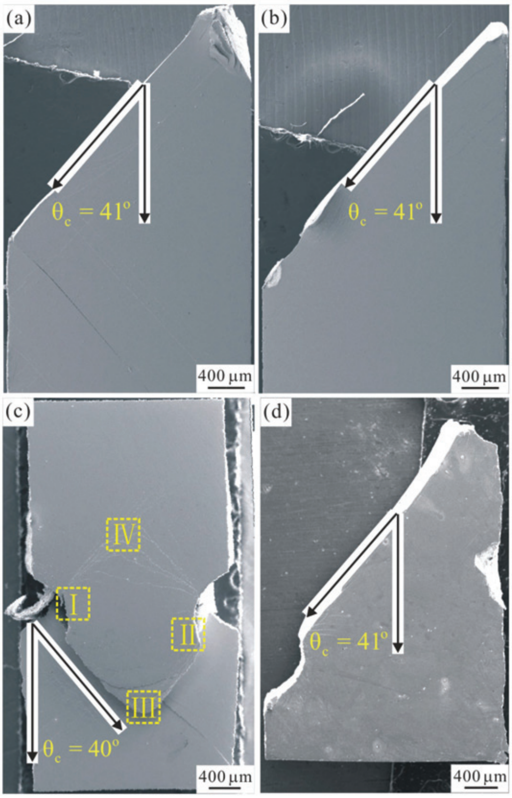

Figure 2. (a)–(d) Deformation images of the four specimens corresponding to A, B, C and D in Figure 1a, respectively. The related fracture angles are marked. In (c), several selected regions are named as I, II, III and IV for further discussion in the text.

stress–stain curve is constructed by FEM with a yield strength of 1.80 GPa. For the yield, the Mohr–Coulomb and the unified tensile criteria are suitable for the tensile yielding of metallic glasses [27,28]. When considering the compression yield and the large plasticity in this study, the von Mises criterion was applied to the yield process [29]. (2) For depicting the propagation process of SBs, it is hypothesized that the regions where the equivalent stress has reached the yield strength (1.80 GPa) in the FEM model can be considered as indicating the formation of SBs in samples since SBs should be formed once yielding begins. Moreover, a displacement control model, in which the displacement loading was exerted on one end of the specimen and the other end was fixed without displacement, was built by finite element software to describe the deformation processes, the simulated processes being divided into 10 substeps. Then, as shown in Figure 3, based on the von Mises criterion, the equivalent stress distribution is obtained. For the specimen with two notches, as shown in Figure 3a, when the applied displacement is 0.08 mm, it is found that the equivalent stress around the notches reached the yield strength of 1.80 GPa, indicating that the majority of SBs are first initiated around the notches.

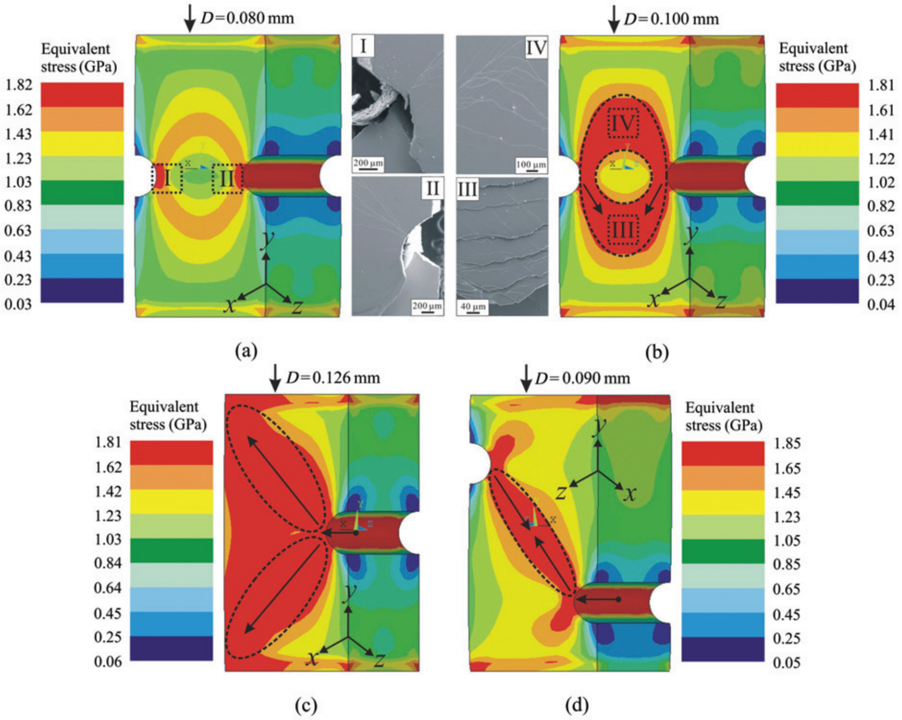

Figure 3. (a) Equivalent stress distribution for specimen C simulated by finite element software with an applied displacement of 0.080 mm. (b) Simulated equivalent stress distribution with an applied displacement of 0.100 mm. Magnified images of the four regions marked as I, II, III and IV are displayed. (c) Equivalent stress distribution of specimen B with an applied displacement of 0.126 mm. The arrow expresses the propagation direction of the SBs. (d) Equivalent stress distribution of specimen D with an applied displacement of 0.090 mm. The arrow represents the SBs expanding direction.

According to the stress–strain curve C in Figure 1b, the maximal stress is 1.50 GPa and using $\varepsilon = \sigma/E$, the elastic strain ε_E is about 1.5%. Compared with Figure 3a, the total strain is $\varepsilon = 0.080/6 = 1.3\%$, suggesting that the specimen at this moment had been near to the plastic deformation process (red regions in Figure 3a). Moreover, as in Figure 3b, in which the yield region has been expanded, the applied displacement is 0.100 mm. At this moment, considering that the V-shaped (red) region has been formed, shear deformation may take place in the y–z plane. Besides, because of the resistance in the y direction, the V-shaped region can also shear along the x direction, as shown in Figure 2c. Then the specimen is in a steady shear deformation state and shows considerable plasticity. We selected SEM images in different regions (I–IV) for further observations, as shown in Figures 2c and 3. In regions I and II, owing to the larger stress around the notches, the earlier shear deformation appeared there (see the magnified images in Figure 3a). However, for region III, as displayed in Figure 2c, two major SBs crossed and expanded along the x direction, with numerous SBs in the x direction, according to Figure 3b. In region IV, some SBs intersected during the shear deformation, implying that the SBs propagated from the notches to the internal regions on account of the nonuniform stress distribution. For comparison, the equivalent stress distributions of the samples containing one notch and two dissymmetric notches were simulated; these are shown in Figures 3c and d with applied displacements of 0.126 and 0.090 mm separately. As shown in Figure 3c, the yield stress (red) regions have run through the whole specimen. Therefore the sample should rupture at this moment. In a similar way, in Figure 3d, with an applied displacement of 0.090 mm, the yield stress (red) regions have also passed through the samples, and the specimen should fracture with low plasticity.

Combining the above experimental results with the finite element simulation, we find that a proper arrangement of notches, such as the symmetric array shown in Figure 2c, results in a large-scale stress gradient which greatly improves the plasticity. As shown in Figure 3b, when the specimen has displayed plastic deformation, owing to the stress gradient around the notches, the yield stress concentrates in the dotted annular region (in Figure 3b) which cannot run through to the boundaries of the specimen. With an increment in loading, the yield stress regions should be enlarged, displaying a steady shearing behavior. In addition, as illustrated in Figure 2c, when two major SBs intersect at one point, it is difficult for the SBs to run through the whole specimen thereby creating a larger plasticity. Therefore, to improve the plasticity of metallic glasses, introducing large-scale stress gradients in the specimens is an effective way. An appropriate stress gradient confines the propagation of SBs thereby avoiding fracture and promoting plastic deformation, as illustrated in Figure 2c. In such a case, because of the constraint by the large-scale stress gradient and the interaction of the SBs, the samples may display a steady shear behavior with a large plasticity. Conversely, as shown by the situations in Figures 3c and d, the yield stress (red) regions caused by the stress distribution (marked as dotted elliptical regions) will run through the boundaries of specimen quickly and the specimen will fail rapidly with a low plasticity.

As shown above, the plasticity of metallic glass can be improved by introducing two semi-circular notches. We have also performed compression tests on another brittle material, namely the ceramic $Ti_3Si_3C_2$ with the same dimensions as specimens A and C in Figure 1a. The ceramic was sintered from a 2Ti/2Si/3TiC powder mixture at 1300°C for 60 min by the pulse-discharge sintering (PDS) technique [30]. The nominal compressive stress–strain curves are shown in Figure 4a. It can be seen that the $Ti_3Si_3C_2$ sample with two semi-circular notches displays near-zero plasticity, similar to the specimen without notches. SEM images after the compression tests are shown in Figures 4b and c, which correspond to the specimen without notches and the one with two notches, respectively. It is apparent that the $Ti_3Si_3C_2$ sample with two notches fails in a shear mode without any plasticity, which is quite different from the metallic glass specimen. This contrastive experiment verifies that the improvement in plasticity by the introduction of two symmetrical semi-circular notches is unique to the metallic glass.

4. Conclusions

An enhanced plasticity induced by making two symmetrical notches in a specimen of a metallic glass has been found under compression tests. When the shear

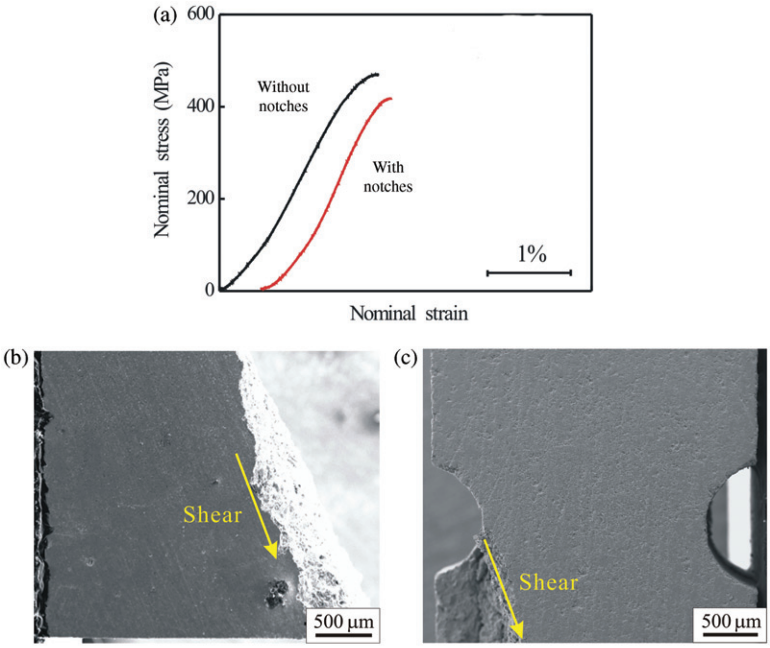

Figure 4. (a) Nominal stress–strain curves for ceramic samples without notches and with two notches. (b) Deformation image for the specimen without notches. (c) Image of the sample containing two notches. The arrow shows the shear directions.

deformation process is subjected to a large-scale stress gradient created by the notches, the metallic glass displays a relatively high plasticity. In view of this study, the following two conclusions can be reached: (1) Unlike previous methods, this technique may supply a way to induce stress gradients by changing the geometrical shape for the purpose of plasticity improvement of metallic glass; (2) Compared with the ceramics, the plasticity improvement caused by the introduction of two semi-circular notches may be a unique deformation mechanism for metallic glasses.

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