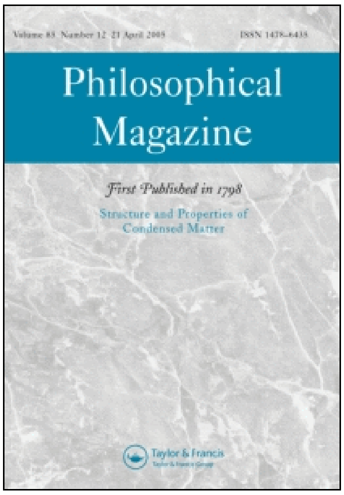

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Deformation behavior and enhanced plasticity of Ti-based metallic glasses with notches

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The plasticity of Ti-based metallic glasses with different aspect ratios can be improved by introducing two semicircular notches on the edges of the samples, owing to the interactions of shear bands (SBs) under conventional compression tests. The interaction of SBs can be ascribed to the easy initiation of SBs around the notches due to the large stress gradient, and the consequent blocking effect of notches on the propagation of shear bands. Additionally, the current findings provide a new way to understand the physical nature for the plastic deformation behavior of some brittle metallic glasses and supply an effective approach to enhance the plasticity to some extent.

Keywords: metallic glass; shear band; notches; stress gradient; plasticity

1. Introduction

As a result of several unique mechanical properties, such as high strength and high hardness, metallic glasses have attracted much attention from researchers [1–5]. However, in tension and compression tests, metallic glasses mainly fail along one major shear band (SB) and display near-zero plasticity, with the result that the low plasticity has significantly confined their engineering applications [6–12]. Therefore, many attempts using diverse approaches have been made to enhance their plastic deformation abilities by limiting the fast propagation of SBs [13–29]. It was found that some metallic glassy composites could be fabricated to improve their plasticity [13–15], e.g. by adding secondary phases or high-strength fibers into the amorphous alloys [16,17] or by preparing metallic glassy composites that contain ductile dendrites formed *in situ* [18]. The results demonstrated that the reinforced phases could limit the rapid propagation of SBs and change the expanding direction of SBs. In addition, the plasticity of metallic glasses can also be enhanced by changing other factors, such as aspect ratio [19–23], surface treatment [24–26] or loading mode [27]. For instance, the plentiful SBs might accommodate the high plasticity when the aspect ratio of the compressive specimen samples is smaller than 1.0 [19–23].

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Recently, by shot peening or some confined loadings, considerable plasticity was obtained in some Zr-based metallic glasses [24–26]. Furthermore, the small punch test (SPT) was also an effective method to create a large plastic strain (19.6%) by the formation of dense regular SBs under multiaxial loadings [27].

With regard to the previous investigations above, the approaches to improve the plasticity mostly focused on Zr-based metallic glasses that could exhibit larger plasticity [19,21–29]. It has been reported that an enhanced plasticity of Zr-based metallic glass specimens with lower aspect ratio can be obtained as a result of the confinement of the compression instrument [19]. Recently, the compressive plasticity of Zr-based metallic glasses was also improved from less than 1% to about 10% by installing two symmetrical notches on the edge of specimens with an aspect ratio of 2:1 [28,29]. But for some brittle metallic glasses, such as Ti-, Fe- and Mg-based metallic glasses [6,11,12], few investigations have been reported to improve their plasticity by changing the external factors, owing to their intrinsic embrittlement [30]. Therefore, these approaches stimulated us to ponder the question: can a considerable plasticity be induced in brittle metallic glasses by similar methods or by other techniques? For this reason, we conducted a series of compression tests on Ti-based metallic glasses with different aspect ratios that included two symmetrical semicircular notches on the edge of samples, as well as specimens without notches for comparison. The experimental results showed that the lower aspect ratio only had a weak effect on the improvement of plasticity, unlike the findings for Zr-based metallic glasses in [19]. In contrast, the specimens with two symmetrical semicircular notches displayed an obvious improvement in the plasticity. Furthermore, based on the theoretical analysis and the finite element simulation, the initiation and propagation of SBs, the plasticity of the metallic glasses with two notches was investigated. It is expected that the current results may be applied to understand and evaluate the plasticity improvement of some brittle metallic glasses, for example, to provide a way to measure experimentally the plasticity of these materials.

2. Experimental procedures

Ti-based metallic glass plates with nominal chemical compositions of $Ti_{40}Zr_{25}Ni_3Cu_{12}Be_{20}$ were prepared by arc-melting. The final plate had a rectangular shape, with dimensions $60 \times 30 \times 3\,mm^3$. The microstructure of the as-cast specimens was characterized by using a Leo Supra 35 scanning electron microscope (SEM), in addition to a Rigaku X-ray diffractometer (XRD) with Cu K_α radiation. XRD patterns revealed that the Ti-based metallic glass has a fully glassy structure. As illustrated in Figure 1, the metallic glass plates were cut into four kinds of specimens with the dimensions $3.0 \times 3.0 \times 3.0\,mm^3$, $3.0 \times 3.0 \times 4.0\,mm^3$, $3.0 \times 3.0 \times 5.0\,mm^3$ and $3.0 \times 3.0 \times 6.0\,mm^3$, each of which contained two semi-circular notches with a radius of 0.5 mm in the middle of the specimen edges. Samples without notches with the same dimensions as those in Figure 1 were also prepared.

Conventional compression tests were performed to measure the mechanical properties of the Ti-based metallic glass specimens under the MTS810 testing machine at room temperature in air. To obtain the strain value, we installed a strain gauge on the two crossheads to record the displacement values. The strain results

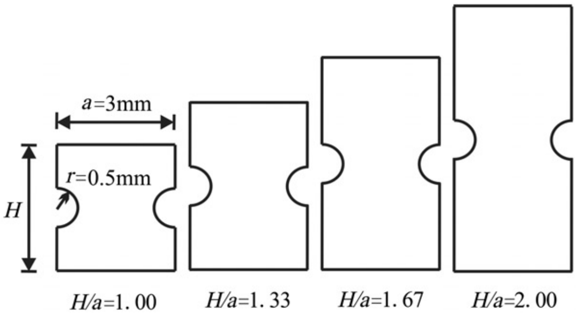


Figure 1. Illustration of the four kinds of notched specimens with different aspect ratios, H/a.

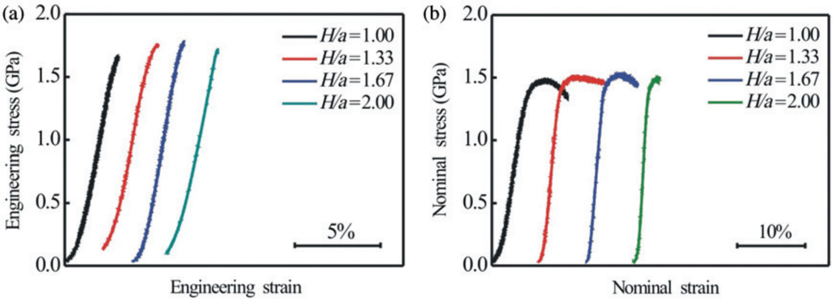


Figure 2. (a) Engineering compressive stress–strain curves for the four kinds of Ti-based metallic glass specimens without notches. (b) Nominal compressive stress–strain curves for the samples with two symmetrical notches.

were sufficiently accurate since the experimental equipment and strain gauge both had considerable precision. All the tests were conducted under a constant strain rate of $10^{-4}\,s^{-1}$. After the tests, all the specimens were observed using an SEM to reveal the deformation and fracture features. In addition, a finite element method (FEM) with the commercial finite element software ANSYS [31] was exploited for resolving and simulating the stress distribution of the specimens.

3. Results

Figure 2a displays the compressive engineering stress–strain curves for the four kinds of Ti-based metallic glass specimens without notches ($H/a = 1.0$–2.0, $a = 3.00$ mm). It can be seen that samples without notches exhibit near-zero plasticity, accompanied by a yield strength of ~1.80 GPa. The result for the specimen with $H/a = 2.0$ is identical to a previous finding [32]. The experimental results were repeatable since we tested four samples for each situation; the small difference in the yield strength might be caused by tiny interior differences of the samples, following more or less a Weibull law [33]. Obviously, the results are significantly different from those for Zr-based metallic glass [19,34]; the aspect ratio only has a small impact on the plasticity of the

Ti-based metallic glass in the present work. Subsequently, we carried out the compression tests on Ti-based metallic glass specimens with two symmetrical notches ($H/a = 1.0$–2.0, $a = 3\,\mathrm{mm}$); the related nominal compressive stress–strain curves are illustrated in Figure 2b. Here, we use nominal stress to describe the global stress in a specimen since the stress in the notched specimen is non-uniform. 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 called 'nominal' instead of 'engineering'. The main purpose was to make a comparison with the specimens without notches. The results in Figure 2b show that the yield strength is about 1.50 GPa, which is lower than those in the specimen without notches, due to the effect of stress concentration. However, the plasticity values of the specimens with different aspect ratios ($H/a = 1.0$–1.67) are obviously increased to 5.28%, 6.42%, 4.91%, respectively. For the sample with $H/a = 2.0$, the plasticity is 1.7%, which is obviously larger than the one without notches [32] but much lower than that (~10%) of the Zr-based metallic glass specimen [28,29]. This demonstrates that the notches can change the propagation of the SBs and obviously improve the plasticity of the specimens. However, since the Ti-based sample is more brittle than the Zr-based one [6], the enhanced plasticity is relatively small compared with the Zr-based results [28,29].

SEM images of the deformation features for the four specimens without notches are shown in Figure 3. It was found that all four specimens fracture along one major SB [32], suggesting a typical brittle fracture mode for metallic glasses [6]. The fracture images are also different from the results for the Zr-based metallic glass [19], which contain many tiny SBs around the major SB. The above findings confirm that the Ti-based metallic glass is considerably more brittle [6] and that plasticity can not be further improved even by decreasing its aspect ratio in comparison with the Zr-based glass [19].

The SEM images of deformation features for the samples with two notches are shown in Figure 4. Surprisingly, the four specimens in Figure 4 display larger plasticity than the specimen without notches [32]. Instead, a V-shape shear feature appeared around the notches (see Figures 4a–4c). Additionally, the fracture process is slow since two main shear bands interacted and formed the V-shaped feature (according to Figures 4a–4c). This implies that the SBs appeared on the notch regions first and developed into two major SBs. Then, the two major SBs intersected each other and confined the fast propagation of the major SBs.

To determine the shear deformation behavior in the four situations, the magnified images on the regions I–VI marked in Figure 4 are displayed in Figure 5, where the images in Figures 5a–5c correspond with the selected regions in Figure 4a. For regions I and II in Figure 4a and Figures 5a–5b, the major SBs are found to initiate from the regions around the notches. But for region III, two major SBs intersected on one region and hindered the fast propagation of the major SBs, which meant that the specimen could not fail along one major SB quickly. These results are unlike the features in Figure 3 and the previous compression results [32]. Similarly, the interactions of the SBs were also found in Figures 5d–5f, verifying that the interaction of SBs is the key factor to improve the plasticity. In Figures 4d and 5f, the specimen did not fracture completely along one major SB since the sample with a higher aspect ratio was able to provide an even wider space for the propagation of

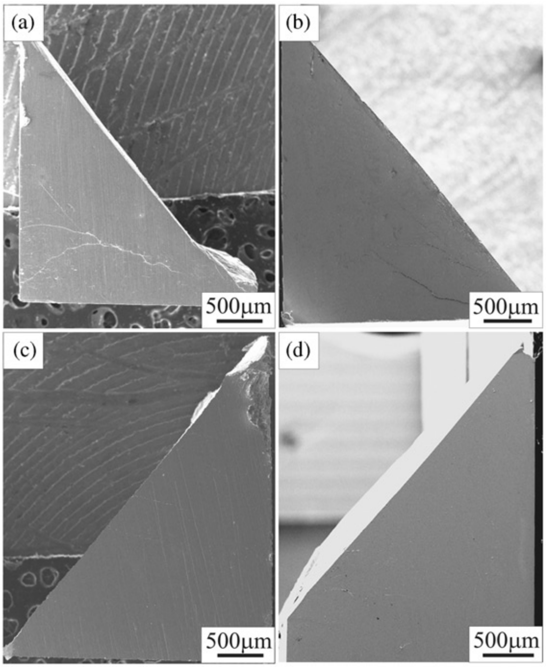


Figure 3. SEM images of the deformation and fracture morphologies of the four specimens without notches: (a) specimen with $H/a = 1.0$; (b) specimen with $H/a = 1.33$; (c) specimen with $H/a = 1.67$; (d) specimen with $H/a = 2.0$.

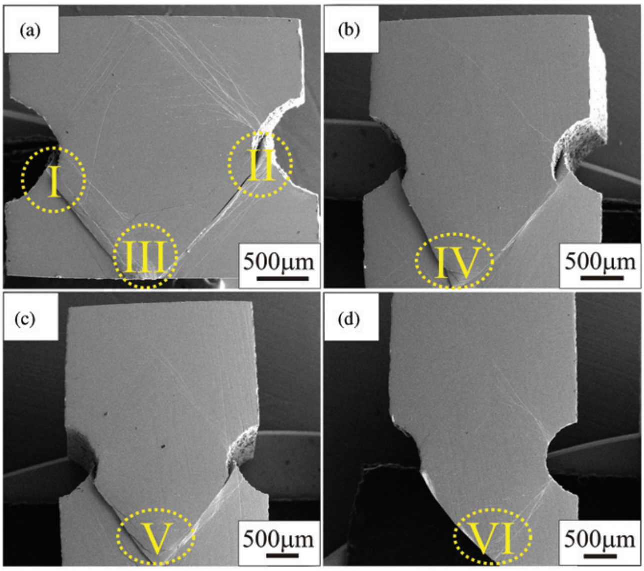


Figure 4. SEM images of the deformation features of the four specimens with notches: (a) specimen with $H/a = 1.0$; (b) specimen with $H/a = 1.33$; (c) specimen with $H/a = 1.67$; (b) specimen with $H/a = 2.0$. Six regions to be magnified are marked as I–VI.

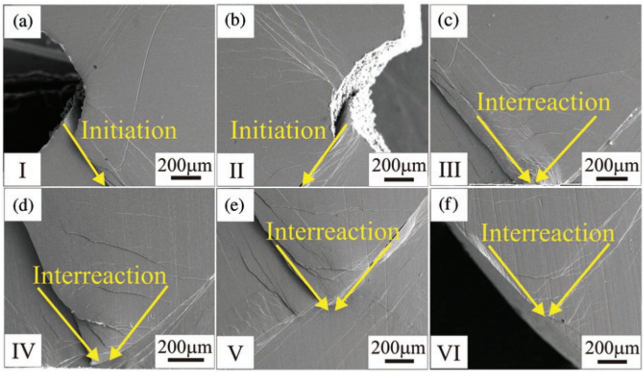


Figure 5. Magnified microscopic images for the regions selected in Figure 4.

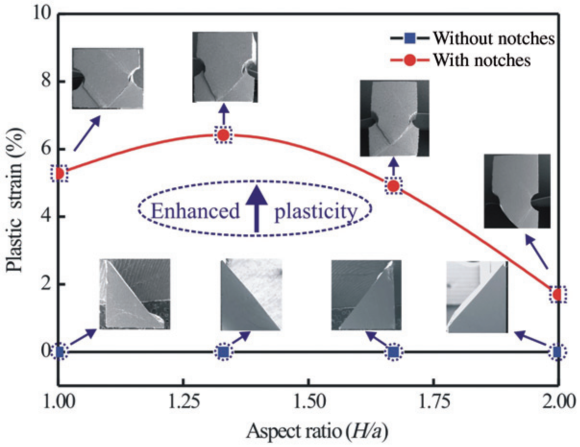


Figure 6. Dependence of nominal compressive plasticity on the aspect ratio H/a for the Ti-based metallic glass specimens.

SBs so that one major SB could run through the specimen in spite of the interaction of SBs. However, even in this situation, the sample also exhibits a larger plasticity (1.7%) than the specimen without notches [32].

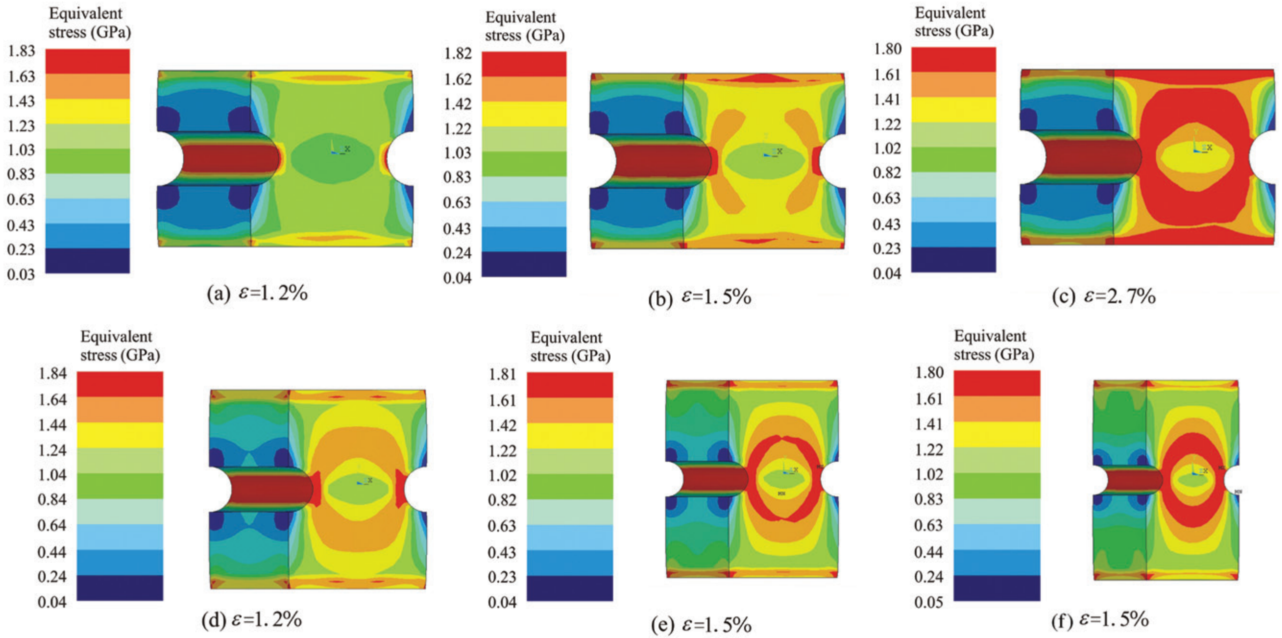
Figure 6 illustrates the effects of the aspect ratio (H/a) and the notches on the compressive plasticity of the Ti-based metallic glass. It can be clearly seen that all the samples without notches fail along one major SB and their plasticity is almost zero, indicating that the plasticity can not be enhanced by decreasing the aspect ratio. But for the samples with two symmetrical notches, the plasticity has been successfully increased to a large extent due to the interaction of SBs. Additionally, with the increment of the aspect ratio, the plasticity exhibits a slight decreasing trend, implying that the specimen with higher aspect ratio can not limit the propagation of SB more easily than the sample with lower aspect ratio because of the different confinement of the experimental instrument. In addition, for the notched specimen with $H/a = 1.0$, the plasticity is 5.28%, which is slightly smaller than that (6.41%) for the specimen with $H/a = 1.33$, which is related to the difference in the aspect ratio. For the sample with the smallest aspect ratio, though the deformation process is slow, due to the lower height, the two major SBs will reach the end of specimen earlier (as shown in Figure 4), compared with the one with $H/a = 1.33$.

According to Figure 4a, if the loading is increased, the specimen will fracture along one of the two major SBs. Therefore, the plasticity is smaller. But for the specimen with $H/a = 1.33$, according to Figure 4b, the major SBs did not reach the end of specimen, and so the specimen could undergo incremental loadings and display larger plasticity. In summary, the existence of two symmetrical notches can result in the interactions of SBs and improve the plasticity of the Ti-based metallic glass samples with different aspect ratios.

4. Finite element analysis

In this section, we report numerical simulations to describe the stress distributions in the notched samples using a finite element method (FEM) [31]. In the finite element model, the displacement loading is applied on one head of specimen and the other head is fixed. The simulated processes are divided into 10 sub-steps. Although the Ti-based specimen without notches displays little plasticity [32], the samples with notches (in Figure 2b) were found to exhibit an even larger plasticity than the specimens without notches (in Figure 2a). Therefore, two assumptions should be proposed to describe the simulated model. In the FEM model, an ideal elastic-plastic stress–stain curve was constructed with the corresponding yield strength of the Ti-based metallic glass. Concerning yield criterions [35–37], to consider compression yielding and large plasticity the von Mises criterion was applied to describe the yielding of metallic glass [36] and the simulated results demonstrate that this criterion was suitable for the current experimental results. To depict the propagation process of SBs, it is hypothesized that the regions where the equivalent stress has reached the yield strength value (1.80 GPa) in the FEM model can be considered as the initiation of the mature SBs.

For the Ti-based metallic glass, the elastic modulus and the Possion's ratio are 92.6 GPa and 0.354, respectively [38]. Therefore, the elastic-plastic model with a yield strength of 1.80 GPa was established and the numerical results for the equivalent stress are illustrated in Figure 7. Figures 7a–7c display the results for the sample with $H/a = 1.0$; the red regions demonstrate that the equivalent stress has reached the yield strength value. In Figure 7a, in this case the strain ε is 1.2% and the specimen does not yield globally, except that the region around the notches has reached the yield strength first, implying that the initiation of SBs will take place in the notched region, as illustrated in Figures 7a–7b. Then, with an increment of the displacement, i.e. for strain $\varepsilon = 1.5\%$, the SBs are found to propagate from the notches to the inside of the specimen, as marked in Figure 7b. But for Figure 7c, with strain $\varepsilon = 2.7\%$, the whole specimen has reached the plastic deformation process and the equivalent stress region in the specimen is just like an ellipse, as marked in Figure 7c, suggesting that the SBs might inter-react into a V-shaped fashion, which could be verified by the image in Figure 5c. Therefore, this situation illustrates that the specimen would not



(a) ε=1. 2%

(b) ε=1. 5%

(c) ε=2. 7%

(d) ε=1. 2%

(e) ε=1. 5%

(f) ε=1. 5%

Figure 7. Equivalent stress distribution of the four kinds of specimens with two symmetrical notches with different strains and aspect ratios: (a) $\varepsilon = 1.2$ % and $H/a = 1.0$; (b) $\varepsilon = 1.5$ % and $H/a = 1.0$; (c) $\varepsilon = 2.7$ % and $H/a = 1.0$; (d) $\varepsilon = 1.2$ % and $H/a = 1.33$; (e) $\varepsilon = 1.5$ % and $H/a = 1.67$; (f) $\varepsilon = 1.5$ % and $H/a = 2.0$. The elliptical dashed lines represent the yield stress regions. The red regions indicate that the equivalent stress has reached yield strength value.

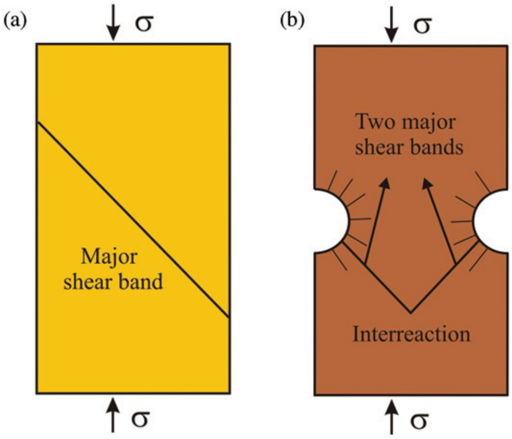


Figure 8. (a) Schematic illustration of major SB propagation in the specimen without notches. (b) Illustration of major SB interactions in the specimen with two symmetrical notches.

fracture completely because the yield stress region has not run through the whole sample in the plastic deformation stage, and the sample displays a considerable plasticity (5.28%). In a similar way, the compression process for the specimens with aspect ratios of $H/a = 1.33$, 1.67, 2.0 are also illustrated in Figures 7d–7f. The identical rules could be found according to the simulated results.

Therefore, according to the above experiments and the numerical results on the Ti-based metallic glass with two symmetrical notches, the large plasticity of the brittle Ti-based metallic glass is produced by causing the interaction of SBs, as illustrated in Figure 4. The main reason is that the interactions of major SBs will prevent the propagation from running through the whole sample rapidly and enhance its plastic deformation ability. Furthermore, Figure 8 displays the difference between the samples with two notches and without notches. The specimens without notches often fail along one major SB with near-zero plasticity [32], as shown in Figure 8a. In contrast, in Figure 8b, due to the two symmetrical notches, the regions around the notches might reach the yield stress value (in Figures 5a and 7a) and the SBs would initiate from the notched regions. With the increment of applied displacement, the SBs may extend to the internal regions of samples and inter-react into one point, resulting in a larger plasticity. The current idea may provide a novel way to conduct plasticity improvement for some brittle metallic glasses. In addition, it can be also applied to the optimum design on material structures, especially for small-scale complex construction.

5. Conclusions

In this work, we investigated the plastic deformation mechanism of metallic glasses in the case of the samples with different aspect ratios and two symmetrical notches. The results demonstrate that the plasticity of Ti-based metallic glass could not be improved obviously by decreasing the aspect ratio. In contrast, specimens with two semicircular notches could display a larger plasticity by the interaction of two major SBs. Furthermore, different from the previous methods to improve the plasticity of metallic glasses [13–27], the present results could supply a new technique for the enhancement of plasticity. More importantly, the idea of inducing an interaction of two major SBs caused by proper stress gradient might result in a steady shear deformation instead of the fast fracture in conventional compression tests [32]. Due to the stress concentration in Figure 8, the yielding can initiate under a lower loading. However, because of the large stress gradient, the whole specimen can not fracture quickly since the stresses in several regions have not reached the yield stress value. By given a continuous loading, more regions in sample might yield gradually. So, the fast fracture behavior could be replaced by a steady shear process. Moreover, instead of near-zero plasticity, the specimens can display considerable plasticity. Besides, the mechanical tests on the specimens with proper stress gradient might become a novel method to understand the shear deformation mechanism of some brittle metallic glasses.

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