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Effect of stress concentration on plastic deformation of $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ bulk metallic glass under compressive loading

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ABSTRACT

The influence of different sources of stress concentration on the plastic deformation of the $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ metallic glass during room temperature compression tests is evaluated. Stress concentration introduced by sample geometry has a significant effect on the mechanical properties: in contrast to the specimen with square cross-section, which shows negligible plastic deformation, a substantial improvement in the plasticity can be achieved for the sample with round cross-section. Simulations of the stress distribution during the compression tests reveal that the stress concentration at the interface corners is responsible for the early fracture of the sample with square cross-section. Additionally, stress concentration during compression tests in the samples with square cross-section can be significantly reduced, and plastic deformation can be enhanced, by removing the interface corners as well as by reducing the friction arising between loading platens and specimen.

1. Introduction

Bulk metallic glasses (BMGs) are considered as brittle materials, in which plastic deformation at room temperature occurs through the generation and propagation of highly-localized shear bands [1]. However, recent results suggest that the brittle behavior of BMGs under compressive loading is not an inherent material property but it may depend on the testing conditions and sample geometry used. For example, plastic deformation of BMGs can be varied by changing the stiffness of the testing machine [2]. Large machine stiffness lowers the amount of elastic energy stored in the machine, promote the formation of multiple shear bands, thus improving the plastic deformation of the glass [2].

Enhanced plasticity under compressive loading can be achieved by reducing the contact friction at the platen-specimen interface. This has been attained for BMGs by the use of a soft metal as lubricant material between loading platens and specimen, which leads to a remarkable increase of plastic deformation [3]. Reducing the specimen size (at fixed aspect ratio and machine stiffness) has also positive effect on the room temperature plasticity of BMGs [4,5]. This result can be related to the size effect rather than to variations of free volume resulting from the different cooling rates of the samples, as demonstrated by Wu et al. [6,7]. Other effective approaches for alleviating the brittleness of BMGs under compressive loading are the reduction of the aspect ratio and the deviation from the conventional orthogonal geometry [8–10].

Stress singularities (i.e. stresses tending to infinity) arise at the interfaces or sharp corners between materials having large elastic mismatch [11]. In these materials, failure often initiates at the interfaces: the level of stress rapidly exceeds the yield strength in the stress concentration areas and the material deforms plastically [12]. Elastic mismatch, and thus stress concentration, may arise during compression tests of BMGs, where loading platens and specimen are usually characterized by different elastic properties [3]. This consequently reduces their plastic deformability. In order to alleviate the brittleness of bulk metallic glasses under compressive loading, it is therefore crucial to remove possible sources of stress concentration. Accordingly, in this work the influence of stress concentrations created during compression tests has been investigated for the $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ bulk metallic glass. Sample shape and geometry, and friction have been varied to reduce stress concentrations at the loading platen-specimen interface. The results reveal that brittle bulk metallic glasses can be made highly deformable by carefully designing the sample geometry and by selecting the proper loading conditions.

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2. Experimental

Glassy plates (dimensions $80^l \times 30^w \times 3^t\ mm^3$) with nominal composition $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ (at.%) were prepared by copper mold casting. Specimens with square ($3 \times 3\ mm^2$) and round (3 mm diameter) cross-sections and aspect ratio area/length = 1.5 were prepared from the as-cast plates by wire erosion. X-ray diffraction (not shown here) was used to confirm the amorphous structure of the specimens. The samples were tested at room temperature under compressive loading using an INSTRON 8562 testing facility (strain rate $1 \times 10^{-4}\ s^{-1}$). Both ends of the specimens were polished to make them parallel to each other prior to the compression tests. WC steel loading platens lubricated with MoS_2 grease or Teflon tape (thickness of ~90 μm) were used for the compression tests. The strain during compression was measured directly on the specimens using a Fiedler laser-extensometer. Compression tests were repeated at least three times for each condition in order to ensure reliability of the results. The simulations were performed using the Ansys software and focused on the elastic deformation regime. Both simulated samples have the same sizes as the experimental specimens.

3. Results and discussion

The schematic illustration in Fig. 1 shows the possible sources of stress concentration between two materials with large elastic mismatch. Stress concentration is introduced under an applied load at the interface edges between the two materials as well as at the interface corners, where the edges meet. The stress concentration depends on the angle α between interface and free edges [13] and, as demonstrated by Tariq et al. [9] for conical samples, the deviation from the orthogonal geometry (α = 90°) indeed enhances the plasticity of BMGs.

A way to reduce the stress concentration created by the interface corners is to use samples with round cross-section. In such a cylindrical geometry (inset in Fig. 2(a)), which is typically used for BMGs synthesized by casting, stress singularities related to the angle β (see Fig. 1) between interface edges [14] are removed. In order to analyze this aspect, the mechanical behavior of the $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ glassy specimens with square and round cross-sections were studied under compressive loading. The room temperature stress-strain curves of the samples and the corresponding mechanical data are displayed in Fig. 2(a) and Table 1. The material with square cross-section yields at about 1790 MPa stress and 2.15% strain. The stress slightly increases after yielding finally reaching a strength of 1815 MPa and 2.3% strain, giving rise to negligible plastic deformation. The change from square to round cross-section has a significant influence on the mechanical properties of the metallic glass. While the elastic strain is slightly reduced to 2.05%, the yield strength display a remarkable decrease to ~1690 MPa compared to the specimen with square cross-section. This is accompanied by the increase of the compressive strength to 1865 MPa. Most important, the round cross-section has a strong influence on the plastic strain, which reaches a value of about 2%.

The stress distribution induced by compression testing was quantitatively investigated on samples with square and round cross-sections by the finite element method. Fig. 2(b) and (c) show the representative images for the simulated von Mises stress distribution in the specimens with different cross-sections under the applied load of 1 kN. The stress distribution is highly heterogeneous in both samples; however, while for the square cross-section the maximum values of the von Mises stress are located at the corners, the stress distribution for the round cross-section is centrosymmetric and mostly located at the center of the sample. Moreover, the stress concentration at the corners of the square sample is higher than that at the center of the round specimen and the stress distribution gradient is stronger for the square cross-section. This makes the square sample more apt to deform and crack from the corners, leading to reduced plastic deformation capability. On the other hand, for the sample with round cross-section, the part of the material under high stress (i.e. the preferential location for the initiation of plastic deformation) is effectively constrained by the surrounding elastic matrix, resulting in enhanced plasticity.

Alternatively, the effect of the (sharp) interface corners on the stress concentration in samples with square cross-section can be eliminated by smoothing them [14] and by creating rounded corners (see inset in Fig. 3). Indeed, the new geometry alleviates the brittleness of the glass and the square samples with rounded corners exhibits a plastic deformation of about 4% (Fig. 3). On the other hand, the yield strength of the material is significantly reduced (1510 MPa) with respect to the sample with sharp corners (Table 1), most likely because of the reduced initial contact area of the specimen.

Stress concentration increases with increasing friction between the materials [12]. Consequently, enhanced plasticity should be achieved by reducing the friction at the materials interfaces. This has been observed for the $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ BMG [3]. The contact friction arising during compression testing was reduced by using Cu as soft compliant materials between loading platens and specimen, avoiding early failure of the glass. The soft material not only reduces friction, but being plastically deformed during compression it also exerts a pressure near the ends, locally assisting the lateral spreading of the glassy sample [3]. In order to further investigate this aspect, we have analyzed the effect of Teflon as lubricant material. Teflon was selected because, in contrast to soft metals, it is not expected to exert significant pressure near the ends of the specimen, therefore providing a suitable test for exclusively analyzing the effect of reduced friction. Furthermore,

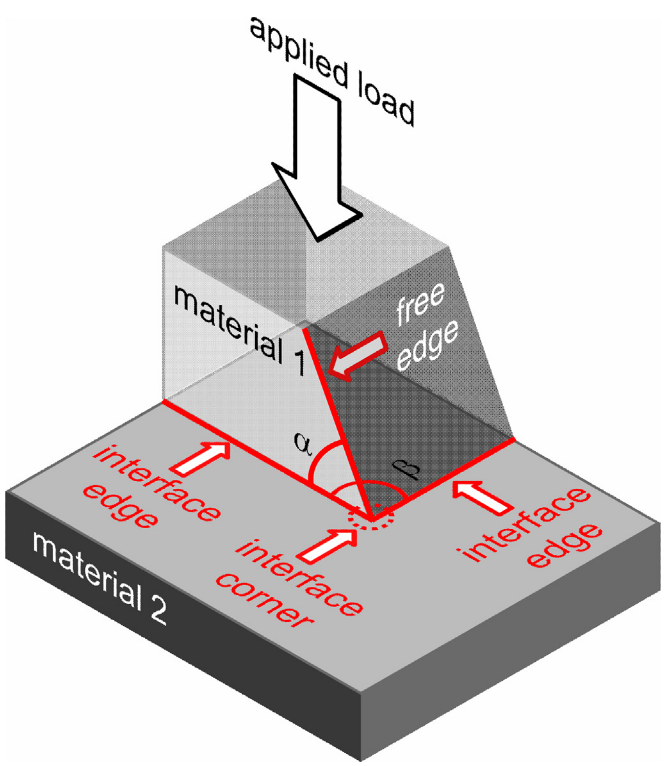

Fig. 1. Schematic illustration showing the possible sources of stress concentration between two materials with large elastic mismatch

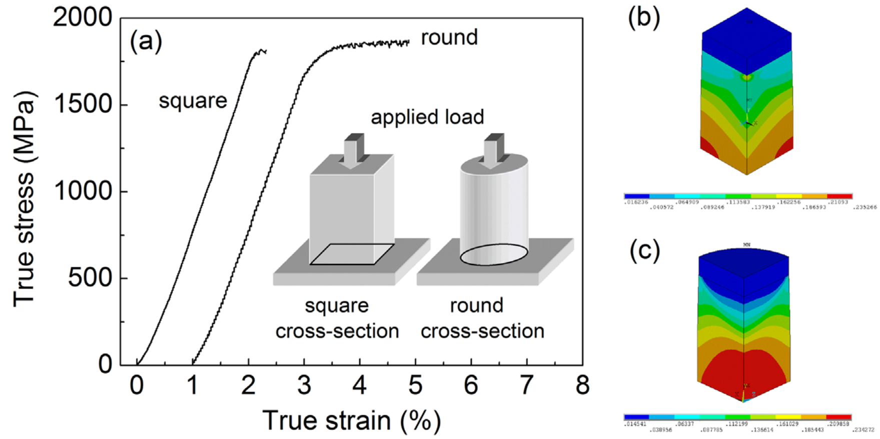

Fig. 2. (a) Room temperature stress-strain curves under compressive loading for the $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ bulk metallic glass with square and round cross-section (loading platens lubricated with MoS_2 grease) and (inset) schematic illustration of the sample geometries. Representative images for the simulated von Mises stress distributions for the samples with (b) square and (c) round cross-sections under the applied stress of 1 kN. Note that for clarity only one quarter of the samples is shown in the figure.

Table 1
Samples characteristics, loading conditions and related mechanical data for the $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ bulk metallic glass tested under compressive loading.

	σ_y (MPa)	ε_y (%)	σ_f (MPa)	ε_f (%)	ε_p (%)
Square cross-section MoS_2 lubricant	1790 ± 30	2.15 ± 0.15	1815 ± 20	2.3 ± 0.1	0.15 ± 0.18
Round cross-section MoS_2 lubricant	1690 ± 40	2.05 ± 0.1	1865 ± 20	4.05 ± 0.2	2.0 ± 0.22
Square cross-section rounded corners MoS_2 lubricant	1510 ± 40	1.7 ± 0.2	1710 ± 20	5.6 ± 0.1	3.9 ± 0.22
Square cross-section Teflon lubricant	1670 ± 30	1.9 ± 0.1	1830 ± 20	5.4 ± 0.1	3.5 ± 0.14

σ_y=yield strength; ε_y=strain at yield; σ_f=fracture strength; ε_f=fracture strain; ε_p=plastic strain

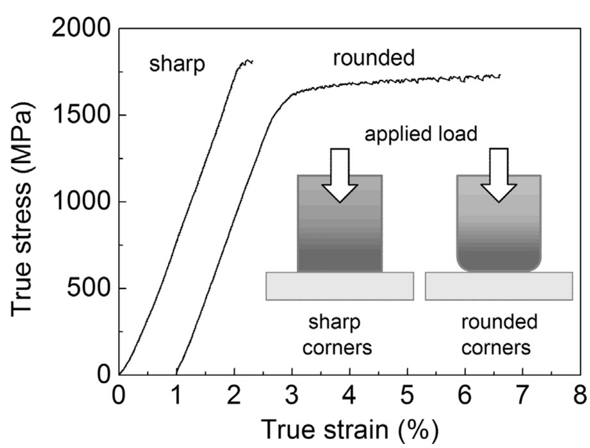

Fig. 3. Room temperature compressive stress-strain curves for the $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ BMG with sharp and rounded interface corners (specimens with square cross-section; loading platens lubricated with MoS_2 grease) and (inset) schematic illustration of the sample geometries.

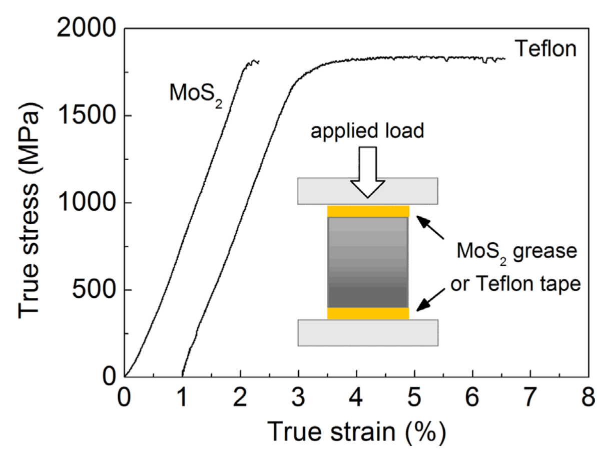

Fig. 4. Room temperature compressive stress-strain curves for the $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ samples with square cross-section tested with loading platens lubricated with the MoS_2 grease and tested by using Teflon as lubricant material between loading platens and specimen. (inset) Schematic illustration of the boundary conditions used for the compression tests.

contrary to semi-fluid lubricants, such as MoS_2, Teflon tape is less likely to be expelled and lost at the edges of the specimen, which would reduce the antifriction capability [15].

Fig. 4 displays the compressive stress-strain curves for the $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ BMG with square cross-section lubricated with the conventional MoS_2 grease and Teflon tape. Although lower than the sample tested under high-friction conditions (i.e. with MoS_2 grease), the yield strength (1670 MPa) of the specimen lubricated with Teflon is higher than the specimen with rounded corners (Fig. 3) and similar to that observed for the material with round cross-section in Fig. 2. On the other hand, the plastic deformation is ~3.5%, larger than the material with round cross-section (2%). This indicates that the reduction of friction at the platen-sample interfaces is the most effective tool to improve the room temperature plastic deformation of the $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ glass, without deteriorating the mechanical strength, as in contrast observed for the specimen with rounded corners.

4. Conclusions

The effect of the stress concentration resulting from the interface edges and corners on the mechanical behavior of the $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ bulk metallic glass has been investigated at room temperature under compressive loading. The results reveal a contrasting behavior between samples with square and round cross-sections: specimens with square cross-section exhibit negligible plastic deformation, whereas enhanced plastic deformation is observed for the samples with round cross-section. This behavior can be ascribed to the stress concentration arising at the interface between the loading steel platens and metallic glass specimens due to the elastic mismatch between the materials. The simulations of the stress distribution during compression tests corroborate that stress concentration at the corners is responsible for the early fracture of the samples with square cross-section with respect to the cylindrical specimens. Beside the change of cross-section, stress concentration during compression tests can be reduced, and plastic deformation can be significantly improved, by removing the interface corners as well as by reducing the friction arising between loading platens and specimen. These findings further indicate that the mechanical properties of BMGs under compression are extremely sensitive to the loading conditions. Therefore, reported data might not necessarily represent the inherent material properties and the comparison between different materials should be done under consistent conditions. This aspect is, however, not entirely detrimental, as it suggests that the room temperature brittleness characterizing metallic glasses can be mitigated by properly designing the sample geometry. This, along with the accurate selection of the loading conditions under service, can make bulk metallic glasses accessible for engineering applications.

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