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# Effect of hydrostatic pressure on shear banding behaviors in bulk metallic glasses

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ABSTRACT

We report the effect of hydrostatic pressure on shear banding behaviors of a bulk metallic glass (BMG) $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ (Vit 1). A confining sleeve technique was used to apply multiaxial compression. The density of shear bands increased along a direction with the increase of hydrostatic pressure from 0 MPa to 550 MPa. Interestingly, as the hydrostatic pressure increased to 680 MPa, branching phenomenon was emerged in the shear band, and shear bands were intersected with the hydrostatic pressure further increased to 960 MPa. At the maximum hydrostatic pressure of 1940 MPa, intersection sites increased and branching phenomenon could be also observed simultaneously. The present results suggest that the hydrostatic pressure has an important influence on the formation and propagation of the shear band in BMGs.



## 1. Introduction

Bulk metallic glasses (BMGs), which possess many excellent properties including high strength, elastic deformability and reasonable fracture toughness, have attracted a broad range of attentions in many potential applications [1,2]. However, plastic deformation of BMGs at room temperature is highly localized into shear bands that may limit their applications as structural materials [3–5]. Thus, the shear banding behavior in BMGs has attracted much interest due to the scientific meaning and practical implications [6–10]. Owing to the lack of long-range atomic order, the fundamental mechanisms of shear banding in BMGs are distinctly different from those in crystalline metals [11,12]. The dislocation motion, grain rotation and heat softening are the main mechanism in crystalline materials, and free volume coalescence of shear transformation zones (STZs) or collective rearrangement of clusters of atoms to accommodate shear strain, induces shear banding in metallic glasses. These microscopic differences also map to significantly diverse macroscopic behavior. For example, crystalline solids can deform at constant volume because the periodicity along slip planes provides identical atomic positions for shearing. Hence continuum plasticity theories of crystalline metals invoke only the deviatoric stress. As for BMGs, a sheared portion cannot find such a perfect fit, and the shear transformation of the STZs requires a significant local dilatation. As a consequence, the mechanical behavior is sensitive to the dilatational components of the stress tensor. This demonstrates the effect of pressure, including the tension/compression asymmetry, high hardness values and enhanced the crack tip blunting etc [13–16]. Thus, the pressure sensitivity of plastic deformation and fracture in BMGs has been a topic of active research [17–23]. By far, whether the pressure-dependence affects the shear banding behaviors in BMGs is unclear, and few experimental data are currently available for the effect of hydrostatic pressure on the shear banding behavior of BMGs. What is more, the characterization of the effect of hydrostatic pressure on the shear banding behavior in BMGs is very important for the potential engineering applications. To this aim, the effect of the hydrostatic pressure on the shear banding behavior in BMGs at room temperature is presented in this paper. The results should contribute to comprehending the plastic deformation mechanism and predicting the processability in engineering application.

Master ingots with the composition of $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ were prepared by arc melting the desired elements (with a purity of 99.9%) together under a purified Ar atmosphere with magnetic mixing for several times. Cylindrical specimens of 5 mm in diameter and 70 mm in length were obtained from the pre-alloyed ingots by suction casting into a copper mold. The obtained metallic glass cylinders were confirmed to be non-crystalline by conventional X-ray diffraction. Then, the metallic glass cylinders were cut into samples with 5 mm in diameter and 5 mm in length, and the surfaces were finely polished. The used fixture system was composed of confining sleeves and two finely polished inserts with the same cross section as that of the specimen used in the compression test. The sleeves and disks are made of YG8 and YG15 Cemented Carbide, respectively.

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The mechanical properties of the materials used for the fixture system are listed in Table 1. To achieve various confining stress levels, the outer diameter of the confining sleeve was chosen according to the diameter ratio ($b/a$=1.74, 2.12, 2.44, 3.06) [17], and confined specimens were sandwiched between the two inserts. The radial expansion of specimen was restricted, which result in uniform lateral stress on the specimen surface along the radial direction. Ideally, it is assumed that the inner diameter of the sleeve is exactly the same with the specimen diameter, and the effect of the two diameters mismatch on measuring confining stress can be found in Ref. [17]. Since the friction could affect both the shear angles and plasticity [18], an aspect ratio of 1.0 was chosen to reduce the friction between the sample and platen, and the friction between the sleeve and the specimen was also minimized by using high-pressure lubricant. Simultaneously, it is assumed that the confining sleeve deformation remains uniform during compression tests. Therefore, the friction between the specimen and the sleeve can be negligible, and a simple analytical solution can be applied to deduce relevant quantities such as the confining stress. Axial compression experiments were conducted under a speed of 0.09 mm/min using RGM-100A material testing system, the specimen stress can be further resolved into two types of stress.

As shown in Fig. 1, $\sigma_{11}$ is the measured stress component, $\sigma_0$ is the uniaxial compressive stress component without the confining sleeve, $\sigma_c$ is the confining stress. Then, the hydrostatic pressure $p$ can be deduced by the following formulas:

$$\sigma_{11}=\sigma_0+\sigma_c \quad (1)$$

$$\sigma_{22}=\sigma_{33}=\sigma_c \quad (2)$$

$$p=(\sigma_{11}+\sigma_{22}+\sigma_{33})/3=(\sigma_{11}+2\sigma_c)/3=\sigma_{11}{}^{3}\!/_{4}2\sigma_0/3 \quad (3)$$

Therefore, one can estimate the maximum hydrostatic pressure applied to the specimen,

$$P_{max}=(\sigma_{11})_{max}\text{-}2\sigma_0/3 \quad (4)$$

A series of tests were conducted at room temperature, and the fracture stress and strain can be obtained via using this compression-confining technique. After compression tests, all the samples were examined using the scanning electron microscope (SEM, JSM-6380W) to reveal characteristics of shear bands.

The average failure strain (defined as the strain at which the flow stress drops to 80% of its maximum value) as a function of the hydrostatic pressure of Vit 1 alloy is shown in Fig. 2. Without the confining sleeve, the failure strain is about 3%. For the samples confined by sleeves, one can see that the samples exhibit different macroscopic plasticity via different hydrostatic pressure tests. In general, the failure strain tends to increase with the hydrostatic pressure.

However, the maximum uniaxial compressive stress ($\sigma_0$) is in the range of 1.86–1.93 GPa and the average value is 1.89 GPa, which indicates that the difference between them can be negligible. The result is consistent with the experimental observation of Lu et al. and Lewandowski et al. for the identical alloy [17–21], and the hydrostatic pressure has different effects on the plastic flow and fracture behaviors of BMGs. Since localized shear band is the unique feature of plastic flow of BMGs at room temperature, such a dependence relationship could arise from the shear banding behaviors..

To further shed light on the effect of hydrostatic pressure on the shear banding behaviors of BMGs, we performed SEM observations on the shear band patterns for all the failure samples. It should be noted that the failure samples without confinement were also selected for comparison. From Fig. 3, the upper corner of the fracture surfaces was formed after the confining sleeve failed. There are only few shear bands on the specimen without the sleeve confined (Fig. 3(a)). When the hydrostatic pressure 550 MPa is applied to the sample using the compression-confining technique, the density of shear bands is higher than

**Table 1**
The mechanical properties of materials of specimen and fixture.

| Materials | Compressive strength (GPa) | Tensile strength (GPa) | Elastic modulus (GPa) | Poisson's ratio $v$ |
|---|---|---|---|---|
| $Zr_{41.2}Ti_{13.8}Ni_{10}Cu_{12.5}Be_{22.5}$ | 1.86 | 1.72 | 95 | 0.352 |
| YG8 | 4.47 | 1.89 | 540 | 0.21 |
| YG15 | 3.66 | 2.25 | 579 | 0.22 |

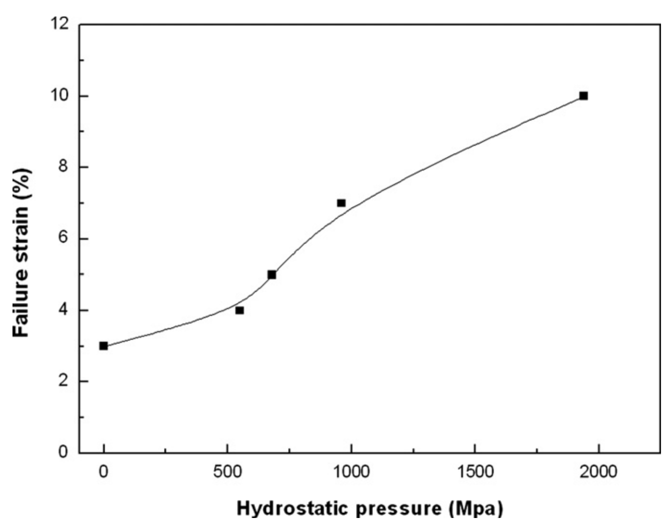

**Fig. 2.** Plot of the failure strain as a function of hydrostatic pressure for Vitreloy 1.

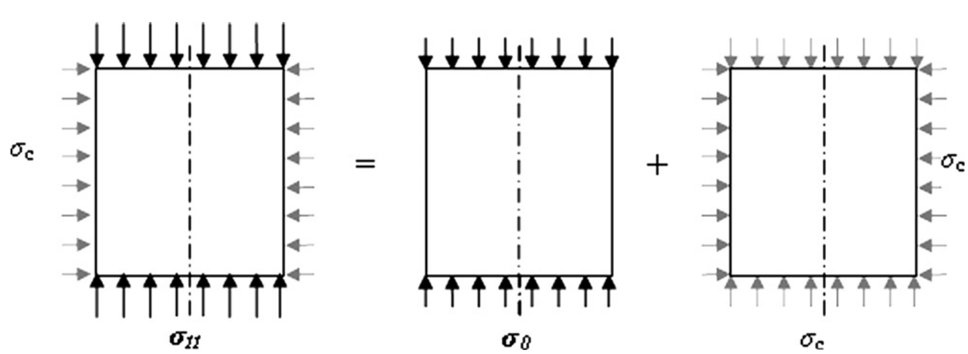

**Fig. 1.** Effect of confinement on stress state of a cylindrical specimen.