Effect of high-pressure torsion on the mechanical behavior of a Zr-based BMG

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Abstract. The effect of high-pressure torsion (HPT) on the structure and mechanical properties of a Zr-based bulk metallic glass (BMG) was investigated. The structure of the BMG changes significantly after HPT processing. In tensile tests, the BMG samples before and after HPT processing are brittle under a stress of about 1700 MPa. For the first time, three-point bending tests of the HPT-processed BMG were performed. In the three-point bending tests of the initial BMG and that after HPT processing, the strength exceeds 3000 MPa and plastic flow is observed.

1. Introduction

Bulk metallic glasses (BMGs) arouse a keen interest due to their specific structure and unique properties \cite{1,2}. However, BMGs exhibit a limited tensile ductility \cite{1,2}. In previous years, studies of the effect of various treatments on the structure and properties of BMGs were conducted \cite{3-5}. High-pressure torsion (HPT) is of great interest for the processing of metallic materials. The HPT processing of amorphous alloys leads to considerable changes in their structure and properties \cite{6-13}. HPT processing may lead to nanocrystallization in the amorphous phase \cite{8,9} or the formation of a cluster-type amorphous structure \cite{10,11}. During tensile tests at room temperature, initial BMGs undergo brittle fracture \cite{1,2}. This makes it impossible to trace the evolution of ductility in BMGs under various treatments. Amorphous alloys exhibit ductility during upsetting tests and three-point bending tests \cite{14}. Three-point bending is a much «milder» test procedure than tension. However, samples of amorphous materials produced by HPT have the shape of disks with a diameter of 10 mm and a thickness of 0.2-0.7 mm. Conducting the three-point bending tests of microspecimens that can be cut out from disk-shaped samples of such a size is a complicated task. To perform such tests, we used a unique facility for the three-point bending testing of small-sized specimens, designed in Ufa (Russia). This paper reports the first results from the three-point bending tests of the HPT-processed BMG.
2. Results and discussion
As the initial material, we used plates with a size of $75 \times 24 \times 0.75$ mm from the Vit105 BMG Zr$_{52.5}$Cu$_{17.9}$Ni$_{14.6}$Al$_{10}$Ti$_5$ (at. %), produced by LIQUIDMETAL Ltd, USA. HPT processing was carried out under an applied pressure of 6 GPa for 5 and 30 complete revolutions with a rotation speed of 1 rpm at a temperature of 20 °C. As a result, samples with a thickness of 0.2-0.3 mm and a diameter of 10 mm were produced.

The amorphous structure was investigated by X-ray diffraction (XRD) under Cu radiation employing a Rigaku Ultima IV device. The diffraction patterns were taken with a step size of 0.05 degree and 10-second exposure per point. According to XRD, the structure of the as-cast Vit105 BMG and that after HPT processing is amorphous [14].

The principle of the three-point bending test is shown in figure 1. A specimen is subjected to bending with a constant rate of $10^{-3}$ s$^{-1}$ in the middle between supports until it fractures. During the testing, the load applied to the specimen measured, the deflection values were recorded by a videocamera.

\[ \sigma_f = \frac{3FL}{2bh^2} \]

where $F$ is the applied load, N; $L$ is the support span, mm; $b$ is the width of the specimen, mm; $h$ is the thickness of the specimen, mm. The relative flexural strain $\varepsilon_f$, a dimensionless quantity or %, is calculated according to the formula:

\[ \varepsilon_f = \frac{6sh}{L^2} \]

where $s$ is the deflection, mm.
During tensile tests, the Vit105 BMG before and after HPT processing undergoes brittle fracture under a fracture stress of about 1700 MPa. At the same time, during three-point bending tests the fracture stress of the Vit105 BMG exceeds 3000 MPa and plastic flow is observed (figure 2). It is worth noting that the strength values of BMG depend on the testing technique. Much higher strength values of the BMG were observed during three-point bending tests, as compared to the strength values observed during tensile tests [15]. The plastic deformation to failure during the three-point bending tests of the initial Vit 105 BMG is 2.5% (for the specimen thickness 0.37 mm) (table 1).

![Figure 2](image-url)

**Figure 2.** Three-point bending test results of the Vit105 BMG in the initial state and after HPT for n=5, HPT for n=30.

| Table 1. Three-point bending test results of the Vit105 BMG in the initial state and after HPT. |
|---|
| **Vit105 BMG (manufactured in the USA)** | **Thickness h, mm** | **YS, MPa** | **Maximum stress, MPa** | **ε, %** | **Plastic deformation to failure, %** |
| initial | 0.37 | 3100 | 3840 | 4.6 | 2.5 |
| HPT n = 5, 20 °C | 0.37 | 3250 | 3660 | 4.3 | 1.4 |
| HPT n = 30, 20 °C | 0.39 | 2870 | 3200 | 3.4 | 0.2 |

As it was expected, the plastic deformation to failure increases with decreasing specimen thickness. After HPT processing for n=5, some ductility is still observed, although HPT does not increase ductility relative to the initial state. After HPT n=30, the brittle fracture of the specimens observed. We should note that this paper reports only on the first results, and further studies with more statistical data are required for come to definite conclusions. However, the used procedure of the three-point bending test enables evaluating the variation of ductility in the BMG after HPT processing and opens a possibility of varying further the HPT processing regimes (temperature, strain, groove shape) in order to identify the HPT regimes providing an increase in ductility.

3. Conclusions

The procedure of the three-point bending testing was used for measuring the mechanical properties of the Vit105 BMG after HPT in microspecimens with sizes of 10x2x0.5 mm. The studies have shown that at tensile tests, the Vit105 BMG before and after HPT undergoes brittle fracture under a fracture stress of about 1700 MPa, whereas during three-point bending tests the fracture stress exceeds 3000
MPa and plastic flow is observed. This procedure opens a possibility for finding the HPT processing regimes, which provide an increase in the ductility of the BMG.

**Acknowledgements**
The authors are grateful to Saint-Petersburg State University for research grant No. 6.65.43.2017, for the research grant from the DFG under contract No. HA1344/30-1. The authors acknowledge the support of RFBR grant No. 17-08-00974.

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