High density of shear bands in the Vitreloy bulk metallic glass subjected to high-pressure torsion

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Abstract. Plastic deformation by high-pressure torsion allows one to achieve high strains of bulk metallic glasses without their failure. It is shown that inclusions of the primary crystalline phase in the Vit105 alloy provoke the formation of cracks, and shear bands themselves have a complex composite structure and are prone to branching and merging during the development of deformation. The density of the bands reaches 1.76 μm⁻¹, with a distance between them 80-120 μm.

1. Introduction

Bulk metal glasses (BMGs) are apt to localized deformation at temperatures below the glass transition temperature \( T_g \), since the main mechanism of their deformation is the formation of narrow shear bands [1]. Because of this feature, BMGs have low plasticity at room temperature and are, as a rule, brittle materials.

At the same time, under conditions of omnidirectional compression, large strains can be achieved in BMGs. For example, during severe plastic deformation by high-pressure torsion (HPT), a large number of shear bands are generated. To date, many articles have been published on the HPT of amorphous alloys [2–7] including several reviews [8,9]. When a shear band appears, a shear affected zone extends at some distance from it, in which shear bands no longer arise. Thus, the limiting band density achieved by the HPT method is of interest.

2. Material and methods

The Vit105 alloy ingots with a standard composition Zr₅₂.₅Cu₁₇.₉Ni₁₄.₆Al₁₀Ti₅ were obtained by arc melting of pure components in an argon atmosphere. The material was remelted four times to achieve a chemical homogeneity. Then the melt was poured into a water-cooled copper mold forming a rod 10 mm in diameter. Disks with the thickness of 1 mm were then cut from the rod and deformed by HPT at room temperature under the pressure of 6 GPa. To form shear bands, the method described in [10] was used. Initial disks were cut into halves, the surface formed by the cut was polished, and the two halves
were subjected to HPT together, as shown on figure 1, a, by ¼ turn in anvils with a rough groove 0.8 mm thick and 10 mm in diameter.

![Scheme of joint HPT of two halves (a); appearance of the sample after HPT n = ¼ (b).](image)

### Figure 1. Scheme of joint HPT of two halves (a); appearance of the sample after HPT n = ¼ (b).

3. Results and discussion

Earlier it was shown that HPT treatment of such hard-to-deform materials as BMG leads to much less observed deformation [7,10] than the one predicted by the theory [11]. In this regard, rough-surfaced anvils were used. However, a large shift in the upper part of the sample relative to the lower one did not occur, and the assumed deformation was not achieved due to slipping. Nevertheless, a high density of shear bands is formed in the BMG during HPT, especially in the edge regions of the samples.

Shear bands form traces in the form of steps on the polished surface of the sample. There are two main systems of steps, radial and diagonal ones, the formation of both of them is associated with stress / strain distribution during the HPT deformation.

At the edges of the samples, in the region of the largest deformation, individual intense wide patterns in a bright contrast represent a combination of a very large number of smaller bands (figure 2, b). The amorphous matrix surrounding the set of bands is also covered with a system of shear bands in such a pattern that the intersecting shear bands divide the amorphous matrix into diamond-shaped regions, which in turn are divided into smaller diamond-shaped regions by bands of lower intensity. Apparently, a similar picture of the distribution of shear bands reflects the flow of the material at large deformations in confined conditions, at an increased hydrostatic pressure.

![Edge section of the BMG specimen subjected to joint HPT of two halves for n = ¼ (a); the same sample, at higher magnification (b), SEM-BSE.](image)

### Figure 2. Edge section of the BMG specimen subjected to joint HPT of two halves for n = ¼ (a); the same sample, at higher magnification (b), SEM-BSE.

The steps have different scales in height, from tens of nanometers to fractions of a millimeter, while large steps are not monolithic, but are themselves divided by shear bands into many steps down to the nanometer scale. It should be noted that the density of shear bands estimated from their traces in the form of steps, only in a first approximation correlates with the actual density of shear bands in the
material, since their spatial position is unknown. The distance between the largest steps is 80-120 microns, and, as their size decreases and the number increases, the interval decreases and reaches 100-150 nm. The density of the bands in this case is 1.76 µm\(^{-1}\), which is significantly higher than the achieved density of 0.09-0.14 µm\(^{-1}\) during deformation by compression [12]. Nevertheless, in the literature there are data on an even denser arrangement of bands, with a step of the order of 30 nm [13], which significantly exceeds the band density observed in this study. On the other hand, in BMG samples subjected to rolling even to a large strains, a noticeably lower density of shear bands was observed [14].

A characteristic feature of high-strain shear bands achieved with HPT is their branching observed at both ends of shear bands. Apparently, deformations under the action of a stress field, as they develop, are localized in the form of shear bands, in which stress is relieved, and shear bands, in turn, can branch and merge (figure 3, b). Higher number of rotations do not lead to an increase of the shear band density, the overall picture of deformation is formed already in the early stages of processing. However, according to recent data, internal structure and properties undergo changes [4].

![Figure 3](image)

*Figure 3.* Inclusions of the crystalline phase cause cracking upon deformation. Vit105, HPT n = 1/4, section 2/3 of the sample radius, SEM-BSE (a); shear band branching, HPT n = 5 + 1/12, section 2/3 of the sample radius, SEM-SE (b).

In not well homogenized samples, large clusters of a crystalline phase encapsulated in the amorphous phase were observed. The inclusions of this crystalline phase negatively affect the plasticity of the Vitreloy BMG. The origin of the crystalline phase can be associated with liquation in the liquid state. According to the results of energy dispersive spectroscopy, the inclusions are enriched in nickel and copper in comparison with the amorphous phase. Due to a deviation from the stoichiometric composition, the critical cooling rate was not reached, and a part of the material acquired a crystalline structure. The hard and brittle intermetallic crystalline phase, well distinguishable in the backscatter electron image mode, does not deform at the stresses achieved as a result of HPT (figure 3, a). The deformation is redistributed into the amorphous part of the material creating a characteristic pattern of "flowing" around the crystallite by shear bands, and the crystalline inclusion itself serves as a place for the nucleation of cracks, which, as a rule, do not propagate to the amorphous part of the material at the achieved strain, but can serve as stress concentrators upon further deformation.

It should be noted that the formation of shear bands in the amorphous phase when using the specified deformation scheme (figure 1, a) does not lead to an appearance of cracks, and, at the same time, inclusions of the crystalline phase provoke cracking of the material (figure 3, a). This is contrary to the observed toughening and ductilization effect of the crystalline phase in a uniform composite of bulk metallic glass with a ductile second phase [15], where the mechanically soft and ductile second phase acts as a stabilizing factor against the shear localization and critical crack propagation.
4. Conclusions
As a result of severe plastic deformation by high pressure torsion, a complex pattern of shear bands is formed in bulk metal glasses. Its feature is the existence of several preferential systems of orientations of shear bands, the composite nature of shear bands themselves, as well as their branching and merging during deformation. The plasticity of the amorphous part of the material allows one to deform it without cracking and destruction, while inclusions of the crystalline phase can provoke the formation of cracks. The density of the bands reaches 1.76 μm⁻¹, with a distance between them 80-120 μm.

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