TEM studies of shear bands in a bulk metallic glass based composite

In 1980's the discovery of multicomponent systems with exceptional glass forming ability enabled the synthesis of metallic glasses at relatively low cooling rates, 10^{-1}-10^{2} K/s, and at larger thickness [1,2]. Bulk metallic glasses normally have very high yield stress, σ_y=0.02•Y (Y is Young's modulus), high elastic limit of about 2%, but fail with very little global plasticity, typically along a localized shear band at a 45 degree angle with respect to the applied stress [3].

Deformation mechanisms of metallic glasses attracted a lot of attention from both theoretical and experimental sides (e.g. [4-10]). Most of the experimental work, however, was done using scanning electron microscopy (SEM). Transmission electron microscopy (TEM) studies of shear bands were not very successful so far due to the relatively small structural changes in the shear bands, frequently undetectable by TEM.

We have studied a two-phase $Zr_{56.3}Ti_{13.8}Cu_{6.9}Ni_{5.6}Nb_{5.0}Be_{12.5}$ alloy, prepared by *in-situ* processing [11]. The alloy consists of amorphous and crystalline phases. Such multiphase materials and composites based on a glassy matrix were developed in attempt to improve ductility and toughness of metallic glasses (e.g. [12]). The presence of the second phase particles was found to hinder shear band propagation and promote formation of multiple shear bands [5]. To analyze the propagation of shear bands in a bulk metallic glass based composite, we have performed *in situ* straining TEM experiments at room temperature. The experiments were carried out at the Center for Microanalysis of Materials at the University of Illinois at Urbana-Champaign

The typical microstructure of the alloy prior to deformation is shown in Figure 1. It consists of the crystalline phase (β) with a bcc structure (see inset in Figure 1) and the glassy matrix. The `spotty" contrast within the crystals is likely to originate from ordered domains. Extra reflections can be observed in the electron diffraction patterns indicating ordering.

In-situ tensile deformation leads to the formation of the shear bands. Propagation of a shear band in a thin specimen creates a step at the surface and changes the mass-thickness contrast in the TEM in the region of the shear band. Fig. 2 shows bright field TEM images of the shear bands which were formed at the edge of the specimen. Depending on the orientation of the shear direction with respect to the electron beam, the shear band appears either lighter (Fig. 2a) or darker (Fig. 2b) compared to the surrounding material [13]. Shear band branching frequently occurs, indicated by arrows in Fig. 2. Also, it has been observed that the shear bands frequently change their ``plane", which results in the change of the contrast from light to dark and wavy appearance.

TEM allows measurements of the shear band dimensions. The *width* of the shear band is defined as the dimensions in the shear ``plane" , where as the *thickness* of the shear band is the size in the direction orthogonal to the slip ``plane”. The width of shear bands was typically around 120-200 nm in the studied alloy and the maximum thickness was measured as 10 nm. Measurements of a shear band width in the same alloy from a surface step in the SEM give slightly larger value of about 300 nm. However, it should be borne in mind that in cases when shear bands are not parallel to the specimen surface, we can measure only the projected width of the shear band and this can be limited by the specimen thickness.

An interaction of the shear bands with the β-phase is illustrated in Fig. 3. A very interesting phenomenon can be observed here, namely localization of the deformation in the crystalline phase, evidently imposed by the geometry of slip in the amorphous matrix. This result is in an excellent agreement with the SEM analysis of shear bands in this alloy, which suggested the localization of deformation in the crystalline dendrites [5]. Tilting experiments revealed that dislocations are responsible for the localized deformation in the crystalline phase.

TEM observations of the specimens deformed in a bulk form showed an increase of the dislocation density compared to the undeformed specimens, which correlates with the results obtained during *in situ* experiments. Therefore, the processes occurring during deformation of the thin specimens reflect to a large extent deformation in a bulk material.

Figures

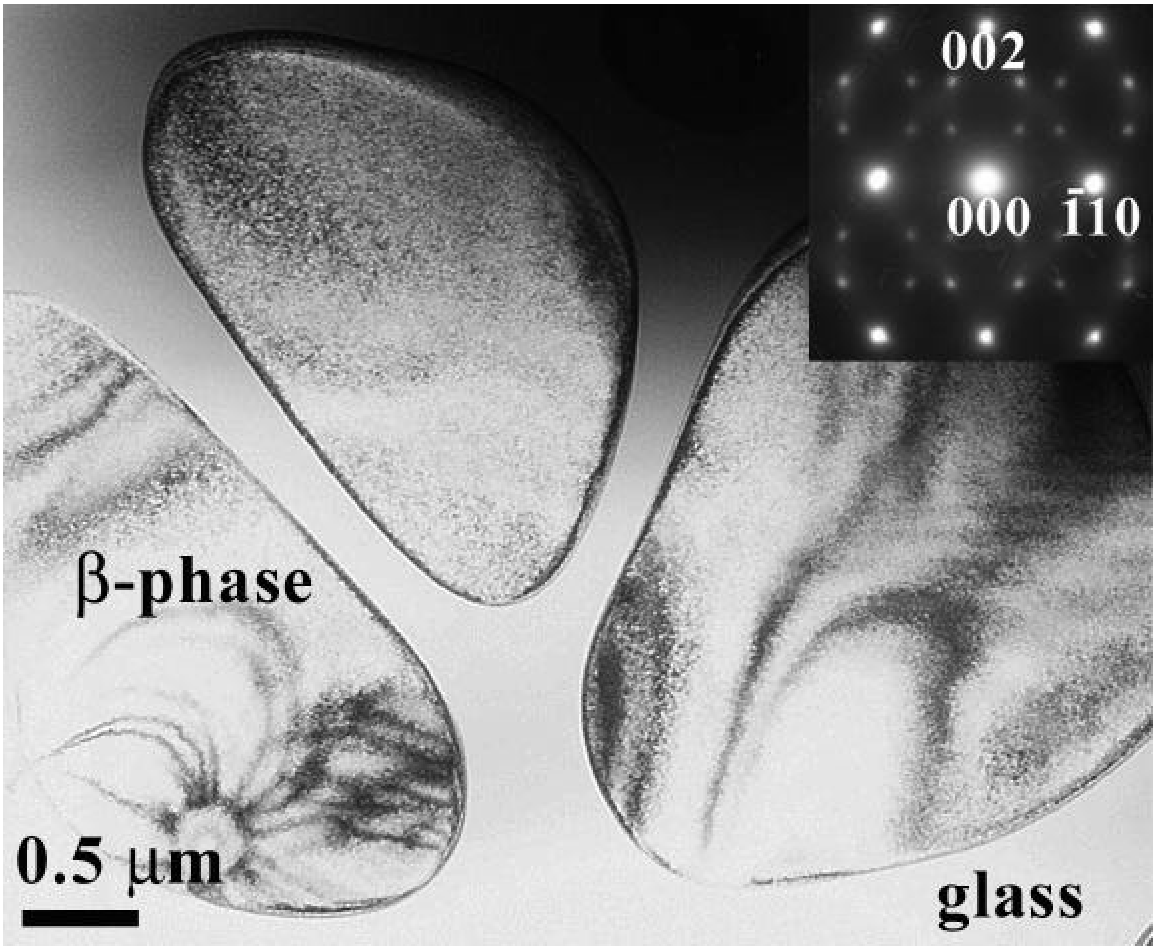


Fig. 1. TEM micrograph of the microstructure of the composite material. Diffraction pattern in the inset is a [110] zone axis of the β-phase.

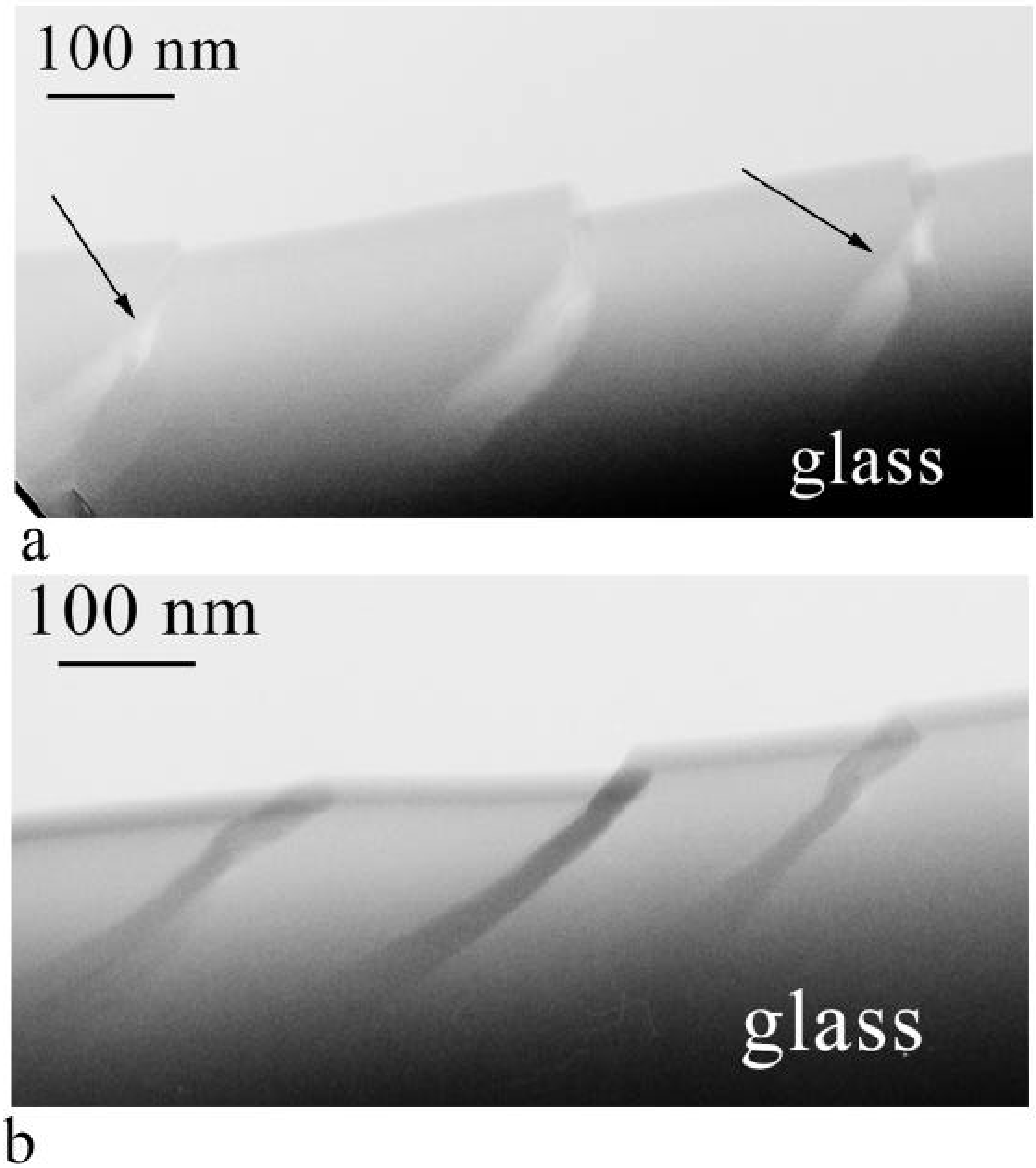
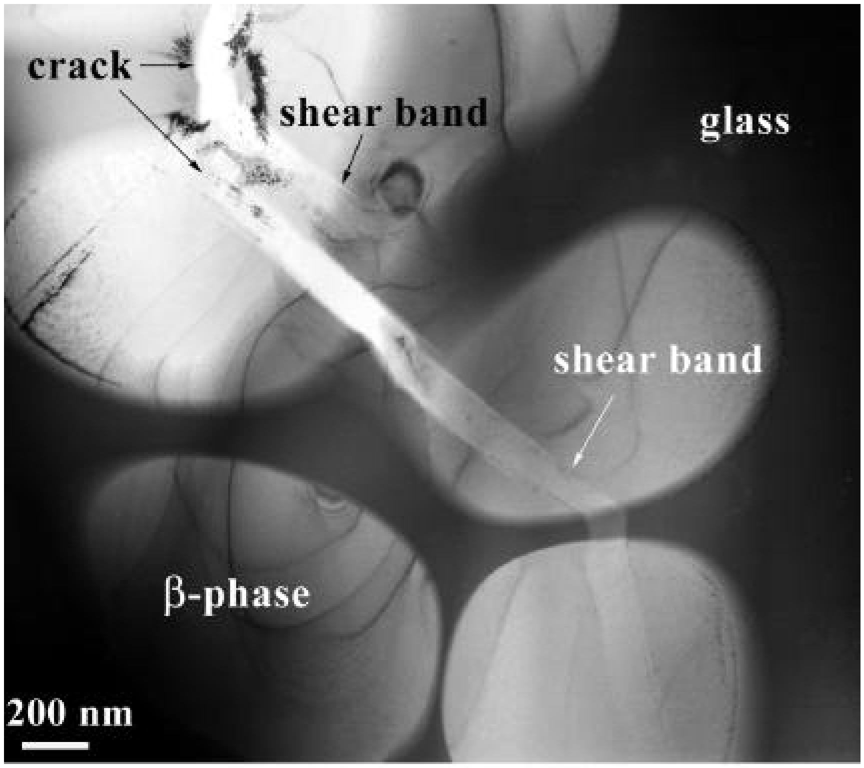


Fig. 2. Bright field images of the shear bands. (a) and (b) represent the same area of the specimen at different tilt angles.



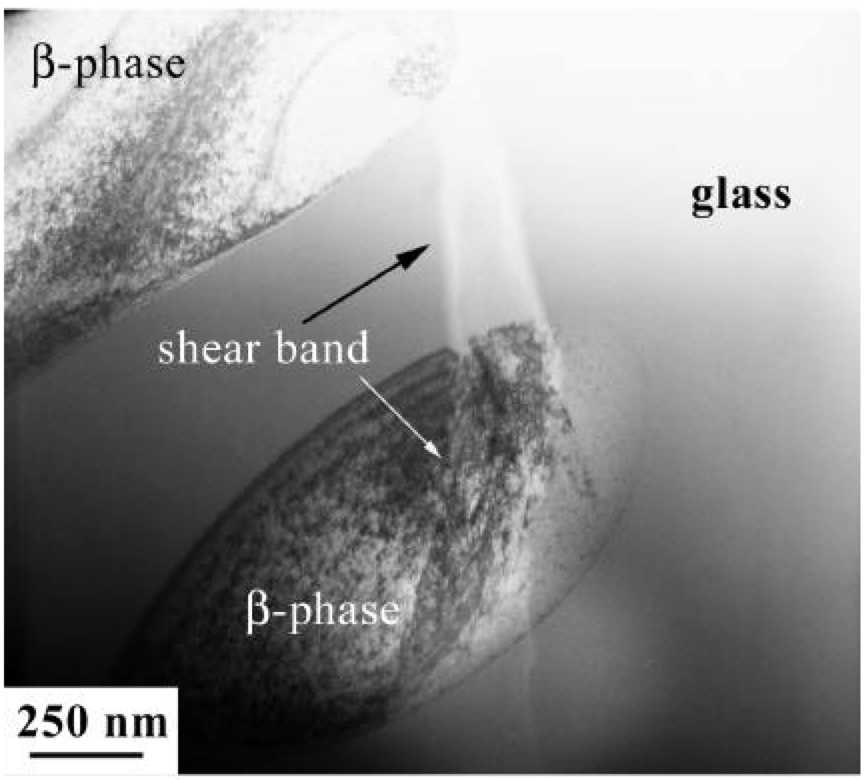


Fig. 3. TEM images illustrating localization of deformation in the β-phase.

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