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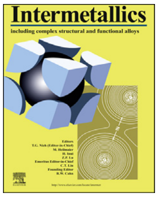

Mutual interaction of shear bands in metallic glasses

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ABSTRACT

Shear banding is the main plastic deformation mode in metallic glasses. Even though there are many researches focused on the initiation and propagation of shear bands, the interaction among them has not been systematically studied. Using an atomic force microscope, we investigated the mutual interaction of shear bands at the surface of $Cu_{50}Zr_{50}$ metallic glass ribbons at the nanoscale. At the sites of the interaction, the propagation direction of one shear band can be changed by the pre-existing one, and the offset is the vector sum of the two bands. Under external stress, one shear band can be decomposed into several tiny bands and more materials could be taken into the deformation zones. Therefore, more energy can be dissipated and the deformation could be more homogeneous for the mutual interaction process. These results are useful for a mechanistic understanding of the evolution and suppression of shear band propagations, as well as the design of metallic glasses with improved plasticity.

1. Introduction

Shear banding is a narrow slip region with highly localized shear deformation, which is a typical plastic deformation mode in crystalline and non-crystalline materials [1–3]. Shear bands (SBs) are particularly important for metallic glasses (MGs) since they play a crucial role in controlling the plasticity and failure of this system at ambient temperature [1,4,5]. However, the catastrophic failure of the SB has limited the potential applications of MGs for decades even though they have many attractive properties [1,5–8]. For the improvement of the mechanical properties of MGs, one key issue is to fully understand SBs, such as the nucleation, propagation and interaction [1,9–22]. As the theoretical meanings of the interaction of linear defects of dislocations in crystalline materials [23], it's essential to know how SBs interact with each other and contribute to the plasticity during the deformation process. While considerable attentions have been paid to clarify the initiation and propagation of SBs, the mutual interaction among them remains unclear. The reason behind the dilemma is that the details of the interaction of SBs are difficult to be obtained since this process is confined to narrow regions of tens nanometers [1,3]. Unlike the dislocations in crystalline metals, it's hard to observe SBs within the samples, especially for the sites of the interaction [24,25]. If we want to explore the interaction at the surface of MGs, the large surface roughness of the polished samples will essentially cover the information of tiny SBs with small shear offsets.

In this work, the mutual interaction of SBs at the nanoscale was studied using an atomic force microscope (AFM) on the smooth surface of MG ribbons. Detailed 3D information at the sites of the interaction was gained for the first time. These results will bring a better understanding of the evolution and suppression of SBs, which are critical for the design of MGs with improved mechanical properties.

2. Experimental procedure

$Cu_{50}Zr_{50}$ (at.%) MG was selected as a model system [26]. The alloy ingots were prepared by arc melting with high purity copper and zirconium under a Ti-gettered argon atmosphere. Ingots were re-melted 5 times to achieve chemical homogeneity. The ribbons with a cross section of 2.0 mm × 0.05 mm were prepared using a melt spinning method. The fully amorphous structure of the samples was confirmed using the methods of x-ray diffraction (XRD, Bruker D8 ADVANCE, Cu $K\alpha$) and differential scanning calorimetry (DSC, Perkin-Elmer DSC 8000) in Fig. 1. The SBs with different interaction behaviors were prepared by a cutting process using a pair of scissors. In this way, we can control the propagation and interaction of SBs. The surface profiles of the ribbons with various interactions were scanned using an AFM (Bruker Dimension Icon) with an AC-240 silicon probe. All images were processed using the

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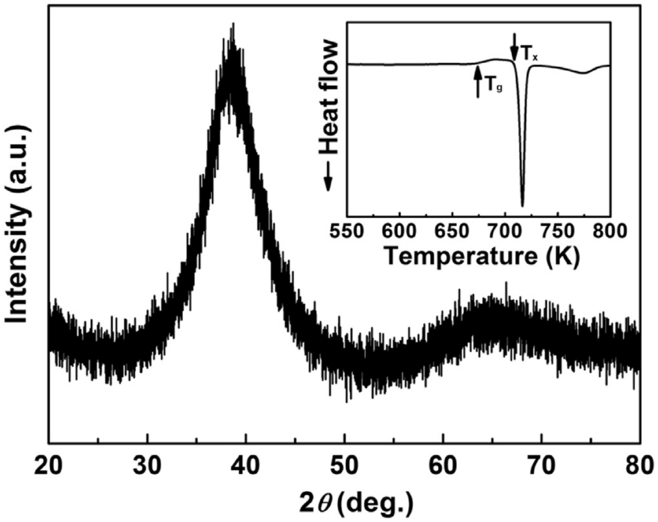

Fig. 1. The X-ray diffraction pattern and differential scanning calorimetry curve of the as-quenched $Cu_{50}Zr_{50}$ ribbon. The glass transition temperature T_g and crystallization temperature T_x were marked by arrows.

WSxM software [27].

3. Results and discussion

By properly controlling the parameters of the spinning process, ribbon samples with a surface roughness less than 1 nm can be obtained, which is an ideal model for further study the interaction of SBs at the nanoscale since the influence from the surface fluctuation can be negligible. Compared to the bulk samples, there is no mechanical polishing is needed for the MG ribbons. Therefore, the surface is pollution-free for the AFM measurement. They are the reasons for the selection of the ribbon samples in this study. Shear bands are usually prepared using a compression, tension or bending process with a controlled load. However, compression and bend methods are not suited for the thin ribbon samples. In the process of a tensile test, the sample will break in the form of a single or few main SBs. In our work, to introduce multiple SBs with different interactions, the ribbons were sectioned into several small pieces using a pair of scissors. After sever deformation, along with the edge of the ribbons, plenty of tiny SBs appeared vertical to the direction of the cutting, which offer us a unique way to investigate the interaction of SBs on the surface. Since the patterns after the deformation is complex, only representative and simple sites were selected for detailed discussion. As shown in Fig. 2, there are three SBs with shear offsets of hundreds of nanometers. Compared to the ordinary ways to introduce the SBs, this is a simple method without polishing or pollution at the surface of the samples. The directions of cutting process and propagation of SBs were presented by arrows in Fig. 2(c) since the drive force decreased along the direction of the black arrow.

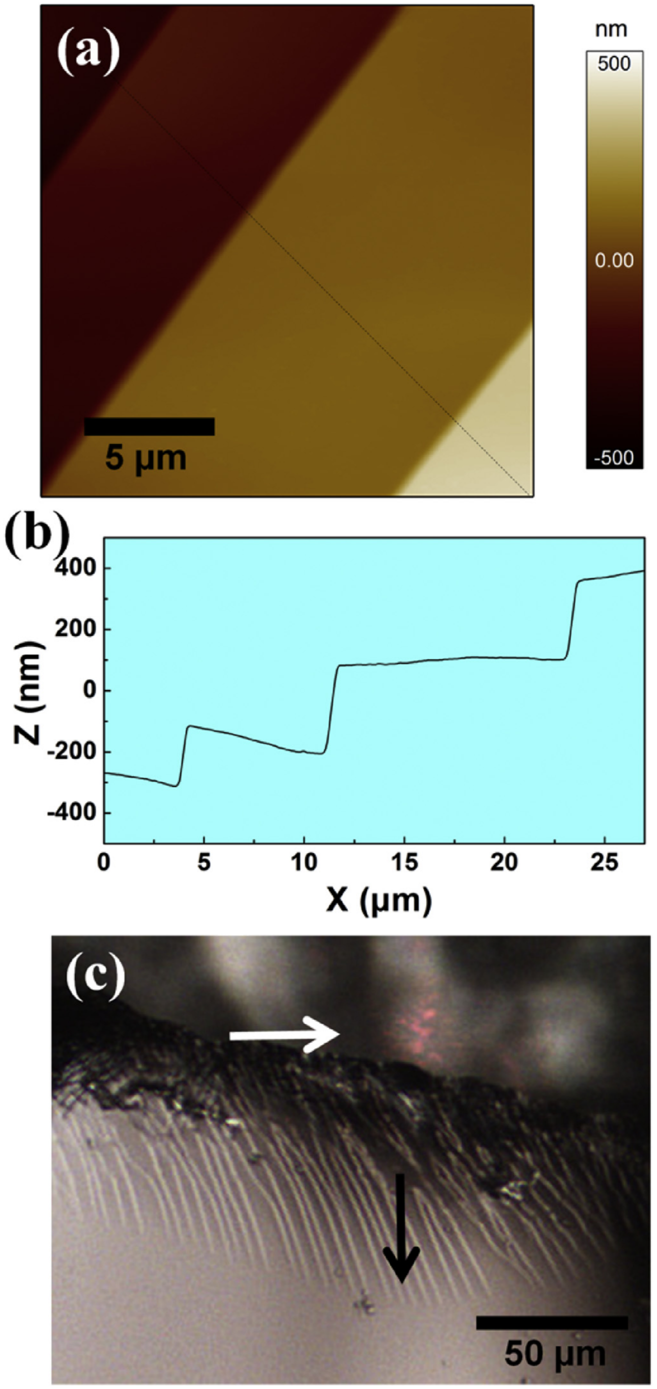

Fig. 2. (a) The map of the SBs steps for the MG ribbon with a smooth surface. (b) The height profile of the shear offsets corresponding to the dotted line in (a), which can various from one to hundreds of nanometers. (c) The edge of the ribbon sample after the cutting process. The white arrow presents the direction of the cutting process and the black arrow presents the propagation direction of the bands.

Relying on the shear front propagation model, the patterns and propagation of SBs were discussed as follows [28–30]. In Fig. 3(a–b), they are the surface topographies of the interaction of two SBs and the corresponding 3D profile. From the same crossing angle and height of the shear offset, it can be concluded that the two parts marked with yellow line belong to the same SB2. Considering that the propagation direction of SB2 was influenced by SB1 (the appearance of the sudden kink and the return to the original path for SB2) and the integrity of SB1, it's reasonable to deduce that the formation of SB1 was earlier than that of SB2. The arrow with white color in Fig. 3(a) is the direction of the cutting process, and the propagation direction of the SBs can be deduced as the direction of the black arrow. The details of the interaction process is described as follows: at the initial stage, SB2 with a shear offset of 21 nm propagated towards the SB1 from the right side (Fig. 3(f)). The height and shear direction of the two SBs before the interaction are shown in Fig. 3(c), corresponding to the dotted line1 in Fig. 3(a). When SB2 met with the pre-existing SB1, the direction of SB2 changed to the path of SB1. This phenomenon can further