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Difference in fatigue cracking behaviors of Cu bicrystals with the same component grains but different twin boundaries

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Two Cu bicrystals with identical component grains involved in twinning relationship but different boundaries were cyclically deformed. The results reveal that the coherent twin boundary (CTB) strongly resists fatigue cracking while the incoherent twin boundary (ITB) is intrinsically prone to nucleate fatigue cracks. It is suggested that the same dislocation motions interacting with the ITB and CTB in different ways is the fundamental reason for the distinct fatigue cracking behaviors.

Keywords: Bicrystal; Grain orientation; Dislocation; Twin boundary; Fatigue cracking

Crystalline materials generally consist of a large number of grains and there could be grain boundaries (GBs) of different geometry or characters between two fixed grains. It is well established that various GBs play different and significant roles in the mechanical properties of materials [1,2]. Based on their characteristics and misorientation, GBs can be divided into three general categories: random high-angle GBs (HAGBs), low-angle GBs (LAGBs), and twin boundaries (TBs). Normally, random HAGBs are particularly effective obstacles to dislocation motion resulting in remarkable strengthening, but they often act as preferential fatigue cracking sites due to the stress concentration and strain incompatibility generated by the pileup of dislocations [3,4]. In contrast, LAGBs, which permit dislocations to penetrate, show strong resistance to fatigue cracking but a weak strengthening effect [4,5]. Recent research has demonstrated that coherent twin boundaries (CTBs) can not only impede but also accommodate dislocation motion [6,7], showing tunable fatigue performance [8–11]. Usually, there are extensive steps bonded with CTBs which could be identified as incoherent twin boundaries (ITBs) and also play an important role in the mechanical properties of materials [12–14]. Clearly, the boundary between two twinning-related grains could be either a CTB or an ITB. Based on a vast body of experimental and simulation studies [15,16], the CTB is considered as a coherent {111} interface, whereas the Σ3{112} ITB can be represented as a set of Shockley partial dislocations. Nevertheless, the fatigue cracking behavior of ITBs has been little investigated and remains elusive.

So far, the intrinsic fatigue cracking mechanisms of CTBs, LAGBs and random HAGBs have been systematically studied using a series of bicrystals and polycrystals [4,9,17]. It has been found that intergranular fatigue cracking is related to the grain orientations on both sides of the boundary [4,9,18]. For instance, the probability of cracking of CTBs increases with the difference in the Schmid factors of the two adjacent grains [9,10]; random HAGBs parallel to the loading direction more easily form fatigue cracks due to the higher differences between the slip vectors of the two component grains [18]. In fact, in addition to the grain orientations, the GB characteristics also have a significant impact on the cyclic deformation behaviors [19]. However, it is usually difficult to separate the roles played by the GB characteristics and grain orientation. It is intriguing and significant to explore how a GB behaves during cyclic deformation when its character changes with constant component grains. Generally, ITBs and CTBs with different characteristics are orthogonal and share the same component grains. Thus two Cu bicrystals with the same component grains possessing an ITB and a CTB, respectively, were cyclically deformed in this study in order to compare the two types of boundary. Investigation of the cyclic deformation behaviors of the two bicrystals was intended not only to clarify the fatigue cracking behavior of the ITB but also to provide an opportunity to distinguish the effect of GB character on the fatigue cracking behavior.

The bulk bicrystal used here was grown from oxygen-free high-conductivity Cu of 99.999% purity by the Czochralski method. As sketched in Figure 1a, there are

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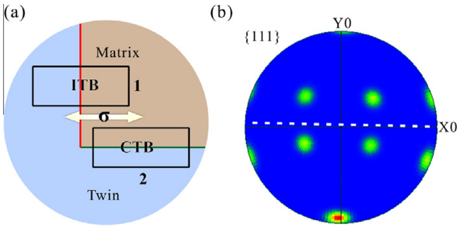

Fig. 1. (a) The preparation of the two specimens, and (b) the {1 1 1} pole figure of the bulk Cu bicrystal.

two orthogonal TBs in the bulk material and its crystallographic orientation was determined by electron backscatter diffraction (EBSD). From the {1 1 1} pole figure shown in Figure 1b it can be derived that there is twinning relationship between the two component grains. The white dashed lines in Figure 1b represent the common {1 1 1} lattice plane, i.e. the theoretical twinning plane. Two kinds of bicrystal specimens were then cut from the bulk materials: one has a perpendicular ITB while the other has a parallel CTB; both specimens have identical component grains as illustrated in Figure 1a. All the fatigue specimens were ground and electropolished carefully before cyclic deformation. Symmetrical push–pull tests were performed with an Instron E1000 testing machine at increased shear stress amplitude at room temperature in air [20,21]. A triangular wave with a frequency of 1 Hz was used. The specimens were cyclically deformed until some fatigue cracks could be detected by scanning electron microscopy (SEM). After the SEM observation of the surface, the specimens were electropolished again and examined by the electron channeling contrast technique [22] in the scanning electron microscope to investigate the dislocation configurations.

The cyclic deformation and fatigue cracking morphologies of the bicrystals are shown in Figure 2. The slip bands (SBs) in the two component grains meet at the CTB with good correspondence with each other as indicated in Figure 2a. There are no secondary SBs operating near the CTB and only a small difference exists between the slip morphology at the areas far from and near the CTB, which contributes to the good strain compatibility near the CTB. Under cyclic deformation, fatigue cracking nucleated along the SBs preferentially as shown in Figure 2b while the CTB was intrinsically strong and resisted fatigue cracking [18,20,21]. The bicrystal with the ITB perpendicular to the loading direction shows distinct slip morphology. It can be seen from Figure 2c that most of the SBs from the two component grains cease at the ITB and there is no correspondence between them. With increasing numbers of cycles, the deformation morphologies near the ITB become more complicated and an ITB-affected zone forms as occurs near HAGBs [4]. In the affected zone, some secondary SBs operated on one side of the ITB which can be seen in Figures 2d and e. Finally, the fatigue crack nucleated along the ITB rather than along the SBs. Comparatively speaking, the strain compatibility near the ITB is worse than that near the CTB. In addition, there are some CTB steps along the ITB and it can be seen from Figure 2f that the SBs are symmetric about the CTB like that shown in Figure 2a. It is interesting to find that when the propagated ITB fatigue crack encounters a CTB, it extends along the SBs. Therefore, it can be concluded that the CTB parallel to the loading direction shows high resistance to both initiation and propagation of fatigue cracks [8,23].

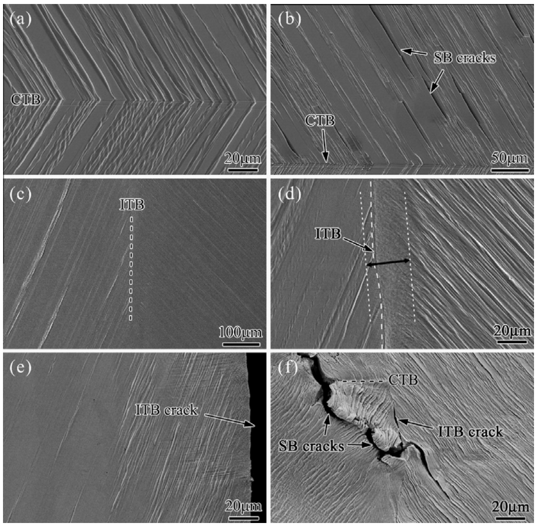

Fig. 2. (a) Slip morphology and (b) fatigue cracking of the bicrystal with the CTB parallel to the loading direction; (c) the full view; (d) the ITB-affected zone; (e) the ITB crack; and (f) the cracks near the ITB and CTB junction of the bicrystal with the ITB perpendicular to the loading direction.

The dislocation configuration of the fatigued bicrystals is shown in Figure 3. Dislocation walls corresponding to the surface SBs exist on both sides of the CTB and some dislocation walls are continuous across the CTB as shown in Figure 3a, implying that some dislocations can pass through the CTB. In addition, the CTB has little effect on the dislocation configurations in its vicinity. The dislocation pattern near the CTB differs little from that in the grain interior far from the CTB [18,20]. However, there is significant difference between the dislocation patterns near and far from the ITB. With the operation of secondary SBs in the vicinity of the ITB, dislocation walls aligned along different directions and dislocation cells form on either side of the ITB, respectively, both of which terminate at the ITB, as displayed in Figures 3b and d. It seems that the dislocations mainly piled up at the ITB as occurred at HAGBs [4,24]. Under the interactions of multiple SBs, dislocation cells can form in a wide area near the ITB fatigue crack as exhibited in Figure 3c. Meanwhile, dislocation ladders or walls are mainly seen aligned along one direction embedded in dislocation veins in the grain interior with the operation of the primary slip system. Unlike the

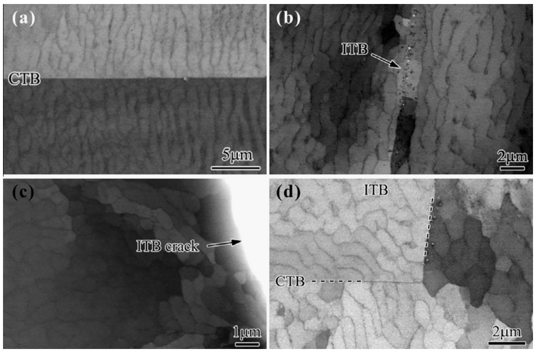

Fig. 3. (a) The dislocation arrangement near the CTB parallel to the loading direction; the dislocation arrangements (b) around the ITB perpendicular to the loading direction; (c) near the ITB fatigue crack; and (d) at the ITB–CTB junction.