What types of grain boundaries can be passed through by persistent slip bands?

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Three typical interactions of persistent slip bands (PSBs) with different types of grain boundaries (GBs) were investigated and analyzed in fatigued copper crystals. The results show that PSBs cannot transfer through all types of large-angle GBs, regardless of their orientation with respect to the stress axis. Secondary slip was often observed near the GBs, leading to strain incompatibility. When the slip systems of the two adjacent crystals are coplanar, the transmission of a PSB across a GB strongly depends on the slip directions of the two adjacent crystals. It was found that only the low-angle GBs can be passed through by PSBs, and accordingly they are insensitive to intergranular fatigue cracking. For a special copper bicrystal with coplanar slip systems, the ladderlike dislocation arrangements within the adjacent PSBs become discontinuous and a dislocation-affected-zone appears near the GB due to the difference in the slip direction of the two adjacent crystals. Therefore, the necessary conditions for the transmission of a PSB across a GB are that the neighboring grains have a coplanar slip system and identical slip directions.

Grain boundaries (GBs) often become the barrier to slip activation and block the movement of dislocations during plastic deformation. However, slip bands may pass through some special GBs, and can transport some dislocations across a GB into the adjacent grain. Correspondingly, several criteria for slip transmission mechanisms across a GB have been proposed.[1–3] However, all those criteria are based on the observations in metals subjected to uniaxial plastic deformation. The interactions of slip bands with GBs in fatigued metals are relatively complicated and have seldom been reported.[4] Since intergranular cracking is one of the important fatigue damage modes in polycrystals, the interactions of slip bands with different GBs often affect the intergranular fatigue cracking process, and furthermore control the fatigue damage mechanism. In the fatigued copper crystals, persistent slip bands (PSBs) often carry most of the plastic strain and have a special dislocation arrangement with a ladderlike structure.[5] The peculiar dislocation patterns of PSBs have been extensively investigated by using transmission electron microscopy,[5] whereas studies on the interactions of PSBs with GBs are fairly rare.[6] Strictly speaking, the conditions for a PSB to extend across a GB should be that the surface slip traces pass through the GB and the ladderlike dislocations between the adjacent grains are continuous. In other words, the transmission of a PSB across a GB should be more difficult than the transmission of surface slip bands, as reported previously.[1–3] Until now, it was not clear whether PSBs can fully pass through a GB and if this is dependent on the type of GB. In this paper, we report on the conditions for transmission of PSBs through GBs in fatigued copper crystals.

Bulk copper bicrystal plates were grown from oxygen-free high-conductivity (OFHC) copper of 99.999% purity by the Bridgman method in a horizontal furnace. The bicrystal fatigue specimens with a GB plane parallel, perpendicular, or tilted to the stress axis were spark

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machined from the bicrystal plates. Some of the bicrystals have a $\Sigma3$, $\Sigma13a$, or $\Sigma19b$ coincidence GB, but most of the bicrystals possessed a random large-angle GB. In addition, crystals with a columnar grain structure were also grown by this method. The misorientation between the adjacent grains in the columnar crystals was determined to be in the range of 3–5°. Fatigue specimens with low-angle GBs perpendicular or parallel to the stress axis were prepared. In those crystals, there are three types of GBs: (i) large-angle GB, all the slip systems of the two adjacent crystals are not coplanar; (ii) low-angle GB, all the slip systems of the two adjacent crystals have a coplanar slip system and nearly the same slip directions; (iii) a $\Sigma19b$ GB in a $[\bar{4}1520]/[18\bar{2}7]$ copper bicrystal. The primary slip systems of the two crystals are coplanar, but the slip directions have an angle of 13.8°. Cyclic push–pull tests were performed on all the specimens with a Shimadzu servo-hydraulic testing machine at room temperature in air under constant plastic strain control. The slip morphologies near the GBs of the fatigued specimens were observed in a S360 scanning electron microscope (SEM). For the dislocation observations, the SEM electron channeling contrast (ECC) technique was used for the present investigation because this technique is extremely convenient for the specimen preparation and large-area observations. Additionally, this technique can be used to study the dislocation arrangements at some special sites, such as within deformation bands[7] and ahead of cracks.[8] Therefore, it is convenient to reveal the interactions of GBs with dislocations within PSBs in the present investigation.

For the bicrystals containing the type I GBs, the typical interactions of surface slip bands with the GBs are shown in Fig. 1(a). All the slip bands terminate at the GBs, no matter whether the GB is perpendicular, parallel, or tilted to the stress axis. When the GB is parallel to the stress axis, a GB affected zone with secondary slip bands is often observed during cyclic deformation,[9] as shown in the Fig. 1. The resolved shear stress of the bicrystal is 34.7 MPa, which is obviously higher than the resolved shear stress (28–30 MPa) activating PSBs in copper single crystals.[10] Therefore, the large-angle GBs always strengthen the bicrystals as they block the passing of PSBs through a GB.[9] When the GBs are perpendicular or tilted to the stress axis, the strain incompatibility also exists near the GBs.[11–13] Furthermore, the dislocation observations show that all the PSBs are not continuous across the GBs and often become irregular or discontinuous as they reach the GB due to the strong incompatibility of plastic strain.[11,12] However, the phenomenon of PSBs transferring through the type I GBs was never observed. Besides, in $[\bar{1}49]/[\bar{1}49]$ and $[001]/[\bar{1}49]$ copper bicrystals with large-angle GBs, Peralta and Laird[13] also found that the GBs block the passing of PSBs, and this leads to intergranular fatigue cracking. All these results indicate that PSBs cannot transfer through GBs provided that the GBs in such bicrystals are large-angle type. In other words, the transmission of PSBs across a large-angle GB is impossible, regardless of the type of the GB. Because the activated slip systems of the adjacent grains have no common slip plane and often intersect at a large angle, which blocks the passing of dislocations, the accumulated dislocations near the GBs often cause the formation of intergranular fatigue cracks [Fig. 1(a)].

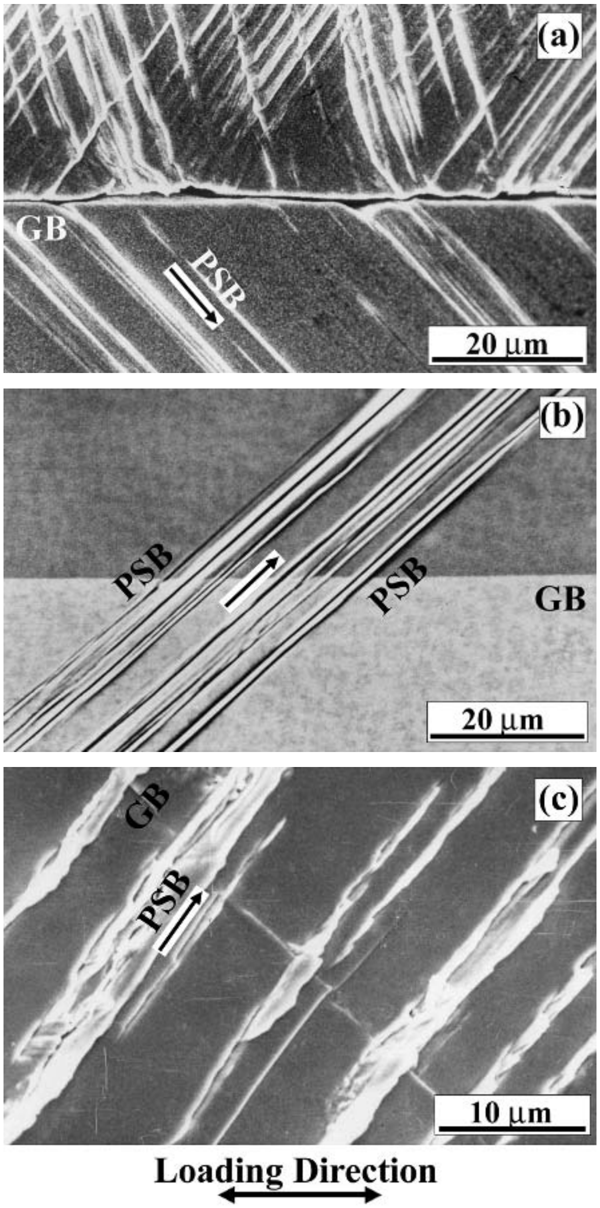

FIG. 1. Interactions of slip bands with three different types of GBs in fatigued copper crystals: (a) severe plastic strain incompatibility near a large-angle GB, (b) transmission of PSBs across a low-angle GB, (c) transmission of PSBs across a large-angle $\Sigma19b$ GB.

From the results above, the question arises, what happens when the slip systems of the two crystals are coplanar beside a GB after cyclic deformation?

Experimental observations showed that the surface PSBs have a good one-to-one relationship across low-angle GBs and a special Σ19b GB, as shown in Figs. 1(b) and 1(c). In addition, there is no secondary slip in the vicinity of the GBs, indicating that the plastic strain near the two types of GBs should be compatible. The slip morphology implies that surface PSBs transfer though the two GBs without interruption. For the columnar crystal, its resolved shear stress of PSBs is 29.0–29.6 MPa, which is nearly the same as the stress (29–30 MPa) of PSBs in the $[\bar{4}1520]/[18\bar{2}7]$ bicrystal.[12,14] This indicates that the two types of GBs did not play a strengthening role in the slip deformation of the two crystals, which is consistent with their slip morphology, as shown in Figs. 1(b) and 1(c). When the specimen surfaces are polished again, and reexamined, it can be seen that the ladderlike PSB structure still has good continuity across the low-angle GB, as shown in Fig. 2(a). This confirms that not only the surface PSBs can pass through the low-angle GB, but also the ladderlike dislocation patterns within the PSBs are continuous. For the $[\bar{4}1520]/[18\bar{2}7]$ copper bicrystal, their surface PSBs also have a good one-to-one relationship across the Σ19b GB,[15] as in Fig. 1(c), which is similar to the finding near the low-angle GB. However, the SEM-ECC observations clearly reveal that the ladderlike dislocation arrangements within the PSBs in one grain terminate at the GB, as shown in Fig. 2(b). At the end of the PSB, as indicated by the arrows, the dislocation arrangements become irregular and lose the ladderlike structure, indicating the existence of a stress concentration at the GB. In the adjacent grain, the dislocation arrangement within PSBs does not display any ladderlike feature, which can be explained by the difference in the orientation of the two crystals. This means that the dislocation arrangement within PSBs has no continuity across the Σ19b GB even though the adjacent slip systems are coplanar. With further cyclic deformation, it is found that a fatigue crack never initiates along the low-angle GBs in columnar crystals but always originates from the Σ19 GB in the bicrystals. Figure 2(c) clearly reveals a typical intergranular fatigue crack along the Σ19 GB in the bicrystal. Therefore, the difference in the fatigue cracking along the two types of GBs provides indirect evidence for and against the transmission of PSBs across GBs.

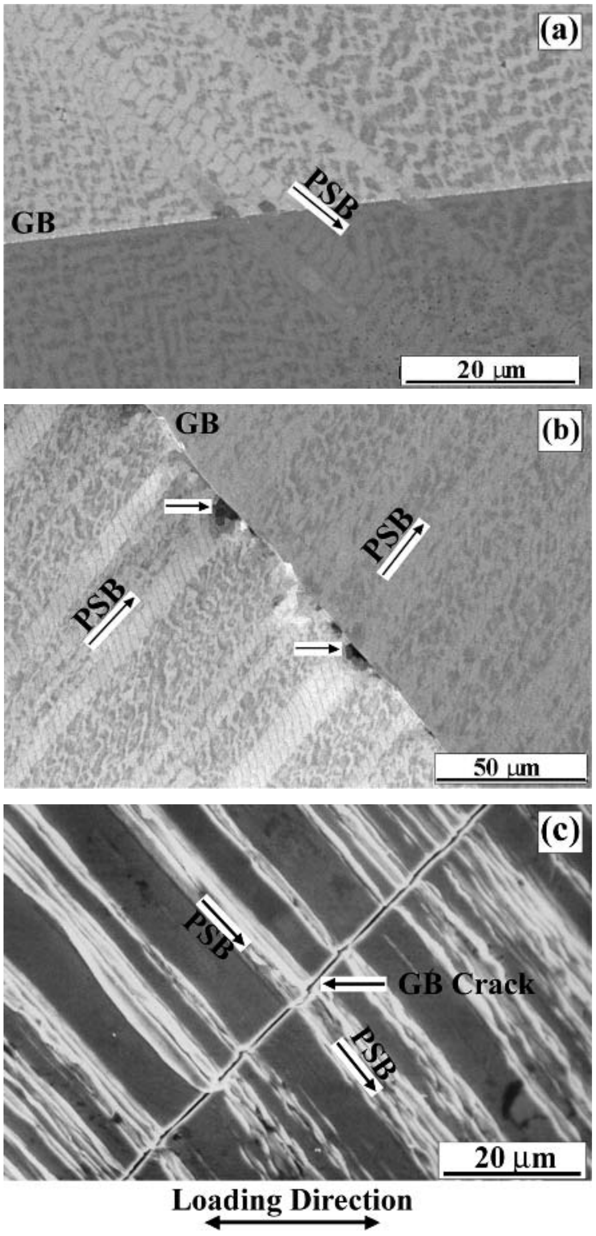

FIG. 2. ECC images of the dislocation patterns near the GBs on the surfaces of the specimens: (a) continuous ladderlike structure of PSBs across the low-angle GB, (b) discontinuous ladderlike structure of PSBs beside the large-angle Σ19b GB, (c) intergranular fatigue cracking along the large-angle Σ19b GB.

To further verify the continuity of dislocation arrangements near the two types of GBs, a more direct method is to investigate the dislocation arrangements on their common slip planes. The results show that the dislocation patterns near the low-angle GB are still continuous, as shown in Fig. 3(a). Those parallel dislocation walls can also transfer through the low-angle GB. Since the slip direction of a PSB is perpendicular to the dislocation walls, as indicated by the arrows, the slip directions of the two crystals should be nearly the same. The present observation further proves the transmission of PSBs across the low-angle GBs. However, for the $[\bar{4}1520]/[18\bar{2}7]$ copper bicrystal, one of the interesting findings is that a dislocation-affected zone (DAZ) appears near the Σ19b GB on the common slip plane [Fig. 3(b)]. The width of the DAZ is about 5–10 µm, and the DAZ is somewhat similar to the dislocation-free zone in fatigued copper polycrystals.[6] In addition, there are irregular dislocation arrangements (marked by the arrows) at the end of the PSBs in Fig. 2(b). The width of the irregular dislocation region is nearly the same as that

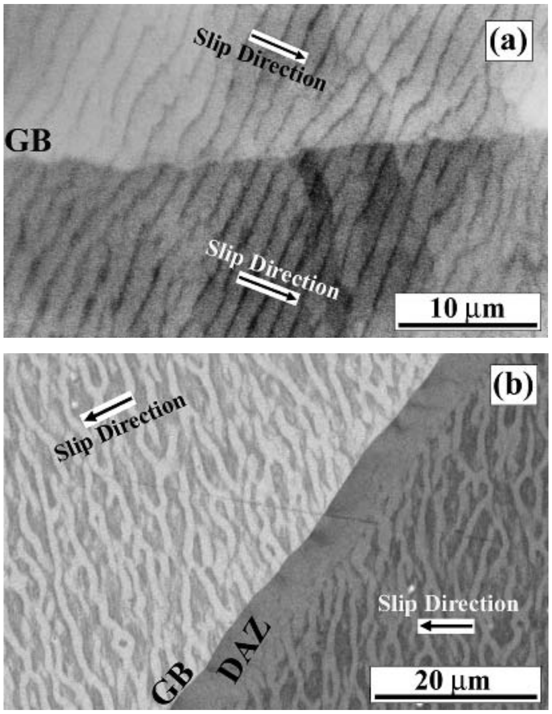

FIG. 3. ECC images of the dislocation patterns on the common primary slip plane: (a) continuous dislocation walls across a low-angle GB, (b) discontinuous dislocation walls beside the large-angle $\sum$19b GB.

of the DAZ. From Fig. 3(b), as indicated by arrows, it is clear that the slip directions of the two crystals appear at an angle larger than that beside the low-angle GB in Fig. 3(a). Therefore, the formation of the DAZ should be attributed to the blocking effect of GB to the dislocations due to the obvious difference in the slip directions of the two crystals. The present observation of the DAZ gives direct evidence for the blocking movement of dislocations near the $\sum$19b GB. Although the two component grains have a coplanar slip system; however, the PSBs cannot fully transfer through the $\sum$19b GB due to the existence of the DAZ near the GB induced by the difference in the slip directions of the two component grains in the $[\bar{4}1520]/[18\bar{2}7]$ bicrystal.

From the observations above, it can be concluded that the PSBs can continuously pass through the low-angle GBs, and move the ladderlike dislocations from one grain to another. The transmission of the dislocations across low-angle GBs results in an intrinsic insensitivity to intergranular fatigue cracking.[14] However, none of the large-angle GBs in copper bicrystals (or polycrystals) can be passed through by the PSBs due to the blocking effect of GBs on dislocations. Consequently, fatigue cracks always nucleate at large-angle GBs.[14,16] For some special large-angle GBs, the coplanar slip system only allows for passing through of the surface PSBs. However, the dislocations cannot be fully transported by PSBs from one grain to the adjacent grain due to the difference in slip directions of the two neighboring crystals, which result in intergranular fatigue cracking. In essence, the transmission of a PSB across a GB strongly depends on the crystallographic relationship of the adjacent grains, rather than the GB structure itself. It is suggested that the necessary conditions for the transmission of PSBs across a GB are that the neighboring grains have a coplanar slip system and identical slip directions.

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