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Comparison of fatigue cracking possibility along large- and low-angle grain boundaries

Z.F. Zhang *, Z.G. Wang

State Key Laboratory for Fatigue and Fracture of Materials, Institute of Metal Research, The Chinese Academy of Sciences, 72 Wenhua Road, Shenyang, 110015, PR China

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Abstract

In this paper, intergranular fatigue cracking possibility along large- and low-angle grain boundaries (GBs) was compared by using a copper bicrystal with embedded grains. It was found that secondary slip lines were always activated near the large-angle GB segment owing to the plastic strain incompatibility and those slip bands couldn't pass through the GB. However, the slip bands showed a good one-to-one correlation across the low-angle GB segment without the operation of secondary slip. If the cyclic number was high enough, fatigue cracks firstly initiated along the large-angle GB segment, but no fatigue crack could be observed along the low-angle GB segment. With the help of the electron channelling contrast (ECC) technique in SEM, the fatigued dislocation patterns near the GBs were observed. Those observations provided a direct evidence on the interactions of persistent slip bands (PSBs) with GBs. Based on the experimental results, the dependence of intergranular fatigue cracking on the interaction modes of PSBs with different kinds of GBs is discussed. A defect model (including dislocations and vacancies) leading to intergranular fatigue cracking is proposed. Because the defects carried by PSBs beside a large-angle GB are often piled-up, i.e. 'piling-up of defects', and make a contribution to fatigue cracking along the large-angle GB segment. On the contrary, the defects carried by PSBs can pass through the low-angle GBs and be moved into the adjacent grain. This process is defined as 'passing-through of defects' and cannot lead to the fatigue cracking along the low-angle GB.

Keywords: Cyclic deformation; Large-angle grain boundary; Low-angle grain boundary; Fatigue cracking

1. Introduction

Fatigue crack nucleation plays a substantial role in fatigue failure of materials. For monocrystalline materials, fatigue cracks often develop from the surface roughness caused by the interaction of the surface with persistent slip bands (PSBs) [1–3]. For pure polycrystalline materials, numerous experimental observations have revealed that twin boundary (TB) [4,5], grain boundary (GB) [6–9] and the interface of PSBs with matrix all may become the preferential sites to initiate fatigue cracks. Kim and Laird [6] have developed a step-mechanism for intergranular fatigue crack nucleation in polycrystalline copper fatigued at high strain amplitudes. Later, for lower strain amplitude, it is recognized that the intergranular cracking is often associated with the interactions of PSBs with GBs and a PSB-GB mechanism for intergranular fatigue cracking was proposed by Mughrabi [7] and developed by Christ [8]. In fact, intergranular cracking is a dominant mode in bicrystals [9–16] and polycrystals [6–8,17–20] fatigued at intermediate or high strain amplitudes. To improve the bulk properties of polycrystalline materials, Watanabe [19], Lim and Watanabe [20] introduced a concept of 'GB design and control (GBDC)', which emphasized that the performance of materials can be improved by increasing the number of some 'special' GBs in polycrystals. Based on the concept of GBDC, it is necessary to determine what kinds of GBs belong to the 'special' category and are not susceptible to fatigue crack initiation. In general, GB can be classified into large- and low-angle type, or high, low Σ value and random GB. Lim [17] has investigated the relation of

* Corresponding author. Tel.: +86-24-23843531.
E-mail address: zhfzhang@imr.ac.cn (Z.F. Zhang)

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intergranular cracking with the Σ value of GBs in polycrystalline nickel and found that GBs other than coherent TBs and those with $\Sigma < 5$ are susceptible to intergranular cracking. Recently, the distribution of GB types along intergranular cracks in Ni_3Al polycrystals were measured by Lin and Pope [18]. They found that low-angle GB and symmetrical Σ3 GB are particularly strong, and all high-angle GBs, independent of their Σ, are weak. In this paper, based on the observations about the interactions of PSBs with the two types of GBs in a copper bicrystal with embedded grains, the difference in intergranular fatigue cracking possibility along large- and low-angle GBs will be compared and revealed with the help of the electron channelling contrast (ECC) technique in SEM [21–29].

2. Experimental procedure

To clarify the effects of large- and low-angle GBs on fatigue cracking, a copper crystal, in which several grains G_E inlaid a matrix grain G_M, was grown from OFHC copper of 99.999% purity by the Bridgman method in a horizontal furnace. In particular, it was found that those embedded grains G_E nearly had the same orientation and those GBs beside the adjacent grains G_E belong to the low-angle type with a misorientation of about 3°. But, the matrix grain G_M has different orientation with those embedded grains G_E, therefore forming a large-angle GB between the grains G_M and G_E. The fatigue specimen and the constitution of the component crystals in the crystal are shown in Fig. 1(a) and (b), respectively. Hereafter, for briefly, the 'crystal' is referred to as bicrystal. Consequently, the difference in intergranular

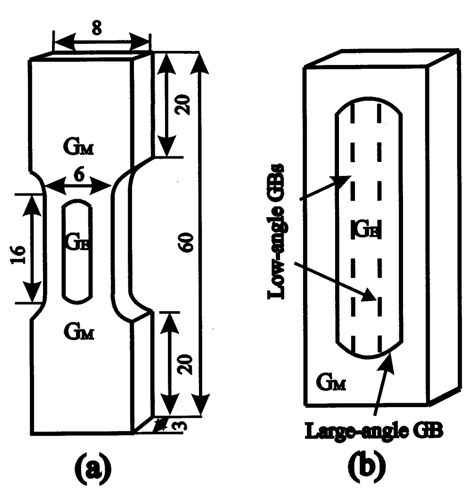

Fig. 1. Fatigue specimen of the bicrystal. (a) Geometrical dimension of the bicrystal; (b) constitution of the component crystals in the gauge part of the bicrystal.

fatigue cracking possibility along the large- and low-angle GBs can be compared by cyclic deformation of the bicrystal. First, the bicrystal specimen was electropolished carefully for surface observation. Then, a symmetrical push-pull test was performed on a Shimadzu servo-hydraulic testing machine under constant plastic strain control at room temperature in air. A triangle wave with a frequency range of 0.05–0.3 Hz was used. The applied axial plastic strain amplitudes ($\Delta\varepsilon_{pl}/2$) were in the range of 2.2×10^{-4}–1.5×10^{-3} for different cycles. After cyclic deformation, the slip morphology and fatigue cracks on the bicrystal surface were observed by optical microscopy (OM) and scanning electron microscopy (SEM), respectively. To reveal the interaction of PSBs or dislocations with GBs, the dislocation patterns of the bicrystal were observed by the SEM-ECC technique as reported in our recent work [21–24] and the associated literature [25–29].

3. Results

3.1. Surface slip morphology observation

Fig. 2 shows the whole slip morphology of the cyclically saturated bicrystal after four-step cyclic loading. The primary slip bands distributed all over the area of the matrix grain G_M. The observations along the GB segment from A, B, C to D indicated that some secondary slip lines were activated within both grains G_M and G_E except for the primary slip, as shown in Fig. 3(a). These secondary slip lines did not propagate over a long distance from the GB and showed no one-to-one correlation across the GB. Besides, there is also one group of slip bands within the embedded grain G_E except near the GB. The slip bands within the embedded grain G_E are very coarse and can cause some slip-affected zones on the grain G_M. In particular, all the primary and secondary slip lines were terminated at the GB segment from A, B, C, to D and could not pass through. The observations are in good consistent with those near the large-angle GBs in other copper bicrystals [10–16,21–23]. However, it was found that the slip bands can transfer through the GB segment from D, E, F to G continuously, as shown in Fig. 3(b). Meanwhile, no secondary slip lines were stimulated along the GB segment from D, E, F to G. As reported previously [21], we had known that PSBs could pass through low-angle GBs continuously in columnar copper crystals during cyclic deformation. Since it was determined by the EBSP technique that there existed some low-angle GBs between the embedded grains G_E. Apparently, the GB segment from D, E, F to G should belong to the low-angle type. Whereas, the GB seg-

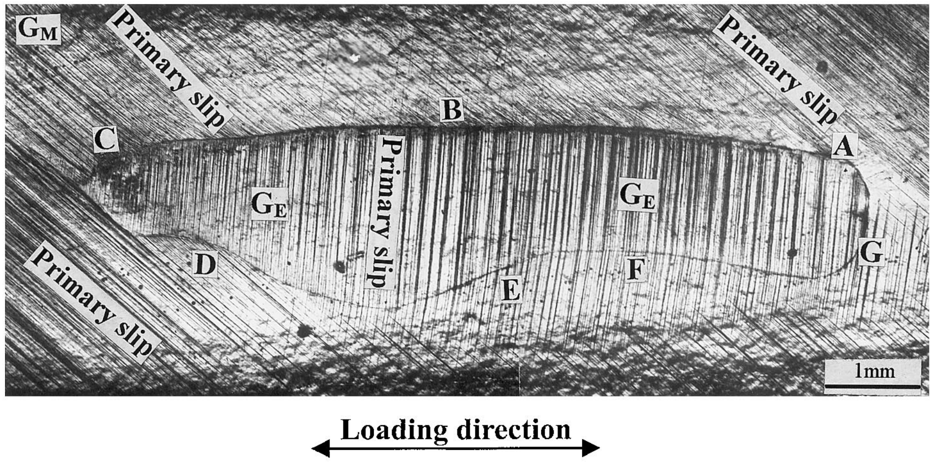

Fig. 2. Surface slip morphology of the bicrystal cycled at the axial plastic strain amplitudes of 2.2×10^{-4} for 2×10^4 cycles, 5.4×10^{-4} for 5×10^3 cycles, 1.0×10^{-3} for 3×10^3 cycles and 1.5×10^{-3} for 2×10^3 cycles, respectively.

ment from A, B, C to D should belong to the large-angle type. From these observations, it is indicated that large-angle GB often stimulates the operation of secondary slip, whereas, the slip bands can transfer through low-angle GB without producing secondary slip during cyclic deformation.

3.2. Observations on the fatigue cracking

The observations by SEM show that no fatigue crack initiated along the surface slip bands of the bicrystal and only some coarse profiles can be found. However, a fatigue crack can be clearly seen along the large-angle GB segment from A, B, C to D. Fig. 4(a) shows fatigue cracking at the site B along the GB segment, which is parallel to the stress axis. The intergranular cracking may be caused by the serious plastic strain incompatibility near the GB segment. Fig. 4(b) shows fatigue cracking at the site C along the GB segment, which is at about 25° to the stress axis. It is indicated that intergranular fatigue cracking can nucleate simultaneously along an identical large-angle GB, independent of the interaction angles among PSBs, GB and stress axis.

The observations along the low-angle GB segment from D, E, F to G show that no intergranular fatigue crack can be clearly seen. Fig. 5(a) and (b) illustrate the interactions of PSBs with the GB segment at different sites from D, E, F to G, showing no obvious intergranular cracking. Those PSBs across the low-angle GB segment are continuous and still show a good one-to-one correlation even at high magnification. It is indicated that the plastic strain near the low-angle GB segment should be compatible and the low-angle GB cracking was more difficult than at the large-angle one, independent of the interaction angles of PSB, GB and stress axis. Those results are in consistent with the previous observations in fatigued copper bicrystals and multicrystals [14].

3.3. Observations on dislocation patterns by SEM-ECC technique

Instead of the commonly used TEM technique, the SEM-ECC technique was adopted for observing the dislocation patterns in the present study. In comparison

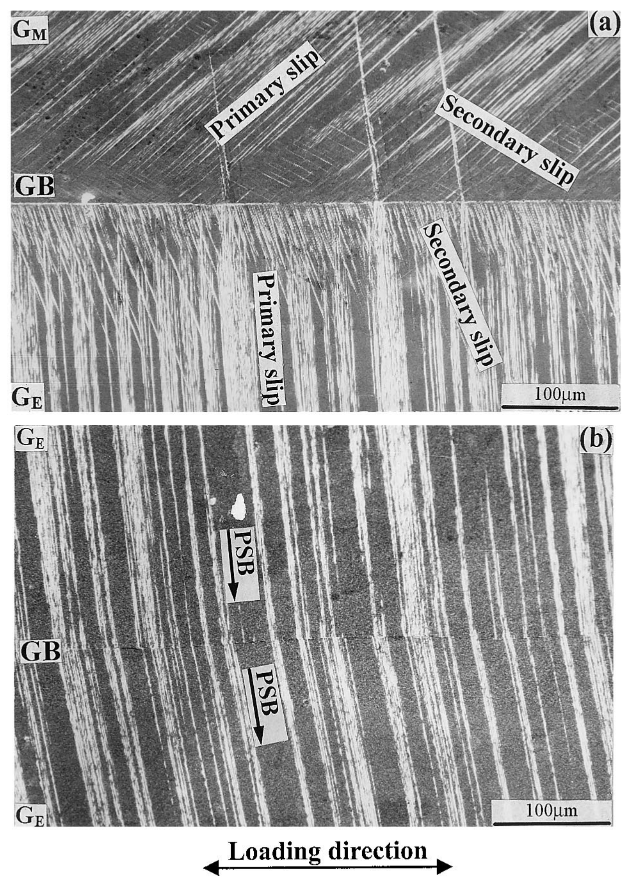

Fig. 3. Surface slip morphology near the GBs in the bicrystal. (a) At the site B of the GB segment; (b) at the site F of the GB segment.

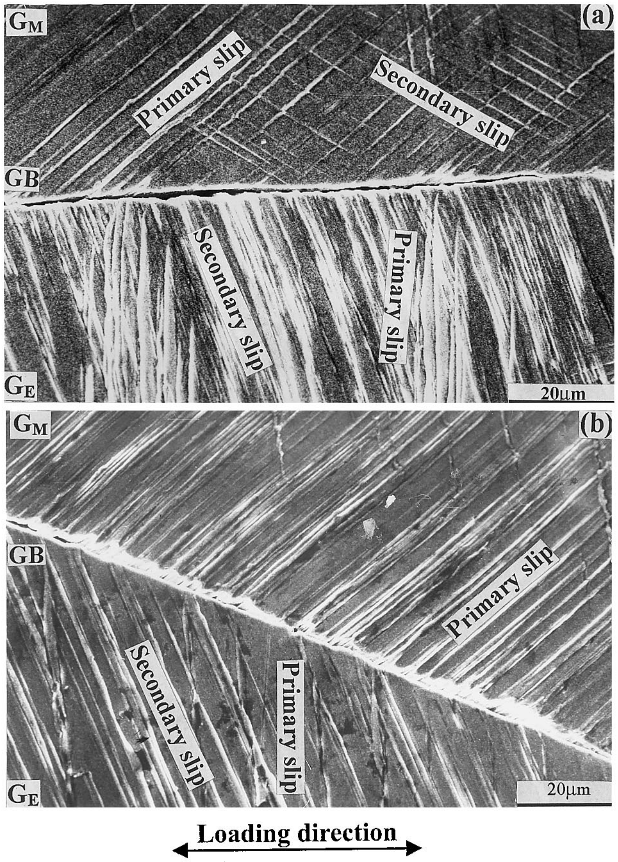

Fig. 4. Fatigue cracking along the GB segment from A, B, C, to D. (a) Fatigue cracking at the site B; (b) fatigue cracking at the site C.

with TEM, the SEM-ECC technique shows many attractive features. Especially, it is extremely suitable for studying the dislocation arrangements over a large specimen area and at some special sites, for example, the vicinity of GBs [21–24], deformation bands [28] and cracks. Obviously, the dependence of intergranular fatigue cracking on the interactions of PSBs with GBs can be clearly revealed with the help of the SEM-ECC technique. The results show that dislocation patterns near different GB segments in the copper bicrystal were also different. Within the matrix grain G_M, both PSBs and veins formed after cyclic deformation, similar to those in copper single crystal [30,31]. Fig. 6(a) and (b) show that the PSBs in both grains G_M and G_E can reach the GB segment from A, B, C to D, but can not transfer through it and become irregular and discontinuous. This finding is consistent with the surface slip morphology (Fig. 4(a)). The discontinuous dislocation structures beside a large-angle GB was also observed in $[\bar{3}45]/[\bar{1}17]$ and $[\bar{5}913]/[\bar{5}79]$ copper bicrystals during cyclic deformation [22,23,32]. It is indicated that large-angle GBs often become the barrier to slip deformation and lead to the piling-up of dislocations. However, as shown in Fig. 7(a), the dislocations carried by PSBs can pass through the low-angle GB segment continuously even though the PSB structure observed on this surface is irregular. This also agrees with the surface slip morphology (Fig. 4(b)) and the dislocation patterns beside low-angle GBs in the columnar copper crystals [21]. Afterwards, the bicrystal was sectioned along the middle part parallel to the stress axis to reveal the dislocation arrangements in the interior of the embedded grains. It was found that the embedded grains are approximately 1.5 mm in depth and the ladder-like PSB structures were more striking than those on the surface (Fig. 7(a)). In particular, there are several GBs in the interior of the embedded grains and the PSBs beside the low-angle GBs are also continuous, as shown in Fig. 7(b). Since it has been recognized that PSBs can often transfer through low-angle GBs continuously, the present observations further indicate that PSBs can nucleate in the interior of grains and the interaction modes of PSBs with different kinds of GBs are quite different.

4. Discussion

It has been well known that the plastic strains are carried by PSBs during cyclic plastic deformation in

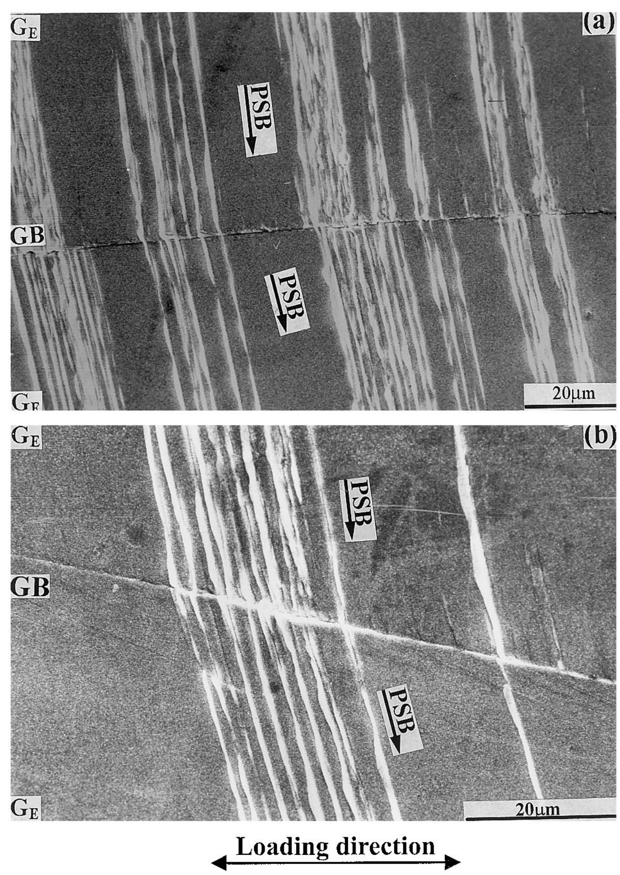

Fig. 5. The observation along the GB segment from D, E, F, to G. (a) At the site F of the GB segment; (b) at the site E of the GB segment.

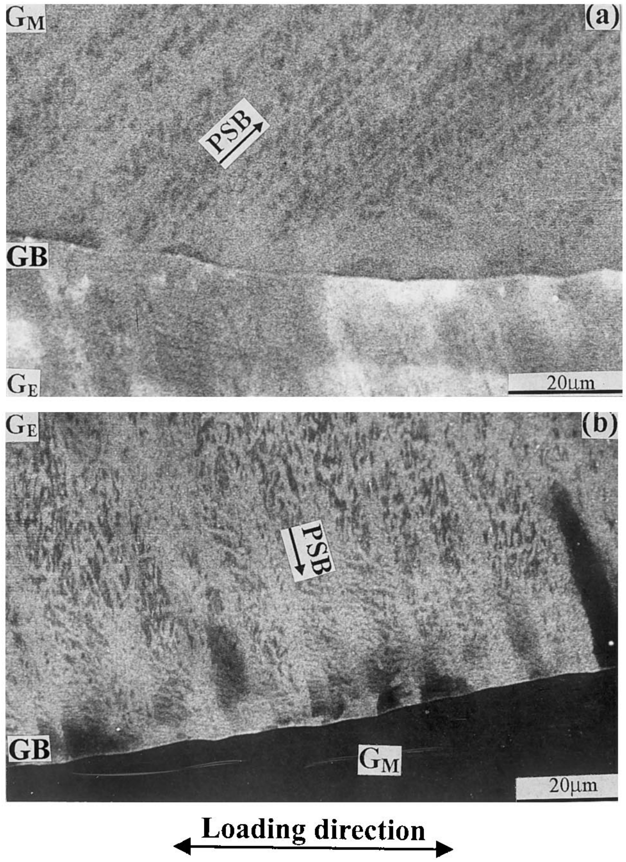

Fig. 6. Dislocation patterns near the GB segment from A, B, C, to D observed by the SEM-ECC technique. Micrographs (a) and (b) showing discontinuous distribution of dislocations beside the GB.

metallic materials and some defects (including dislocations and vacancies) are often produced [30,31]. PSB may become a carrier or channel transporting the residual dislocations or vacancies from the interior of grains into GBs (including large- and low-angle GBs). The interactions of PSBs with a large- and low-angle GBs can be simply illustrated in Fig. 8(a) and (b). When a PSB meets a large-angle GB, the carried residual dislocations will be piled-up at the GB but not be transported into the adjacent grain, as shown in Fig. 8(a). It can be proved by the observations in Fig. 6(a) and (b) since the dislocations beside the GB became irregular and discontinuous. Meanwhile, the PSBs within the adjacent grain can also transport some residual dislocations into the GB. If the Burgers vector sums of those residual dislocations carried by PSBs from adjacent grains into a large-angle GB are $\boldsymbol{b}_{G1}$ and $\boldsymbol{b}_{G2}$, respectively, the Burgers vector sum $\boldsymbol{b}_{Lar\text{-}GB}$ of the residual dislocations piled-up at the GB can be expressed as

$$\boldsymbol{b}_{Lar\text{-}GB} = \boldsymbol{b}_{G1} - \boldsymbol{b}_{G2} \tag{1}$$

For the present large-angle GB, $\boldsymbol{b}_{G1}$ will be not equal to $\boldsymbol{b}_{G2}$ owing to the great misorientation beside the adjacent grains. Consequently, the Burgers vector sum $\boldsymbol{b}_{Lar\text{-}GB}$ of the residual dislocations piled-up at the large-angle GB will be not equal to 0, i.e.

$$\boldsymbol{b}_{Lar\text{-}GB} \neq 0 \tag{2}$$

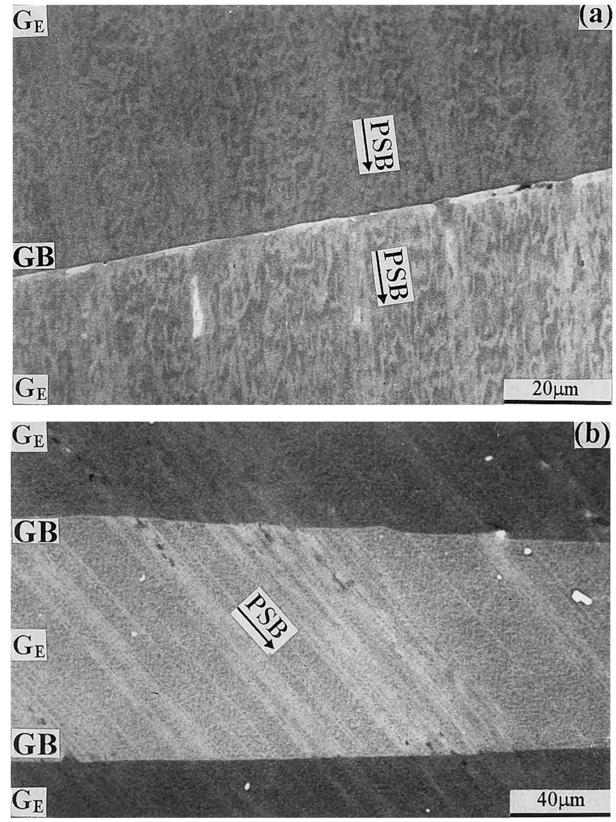

Fig. 7. Dislocation patterns near GB segment from D, E, F, to G observed by the SEM-ECC technique. Micrographs (a) and (b) PSBs transferring through the GB continuously.

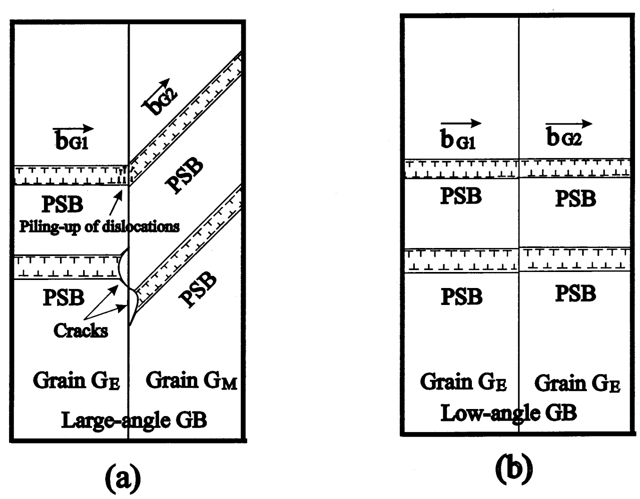

Fig. 8. Interaction modes of PSBs with large- and low-angle GBs. (a) Interaction of PSBs with a large-angle GB, showing the intergranular cracking by piling-up of defects; (b) interaction of PSBs with a low-angle GB, showing the passing-through of defects.

Besides, as shown in Fig. 3(a), the large-angle GB often stimulated the operation of secondary slip, which is very similar to the previous results [10–14,21]. Likewise, these secondary slip bands can also introduce some additional dislocations into the large-angle GB during cyclic deformation. Meanwhile, another kind of defect, i.e. vacancy, can also be produced and moved by PSBs. As the residual dislocations or vacancies within the large-angle GB are accumulated to high enough in density, the fatigue cracking will occur along the GB under external stress. We can define this process as 'piling-up of defects'. For those reasons, it is suggested that fatigue cracking should be an intrinsic phenomenon along the large-angle GB.

Similarly, PSBs can also transport residual dislocations into the low-angle GB. However, it was found that PSBs can transfer through the low-angle GB continuously during cyclic deformation, as shown in Fig. 3(b). In particular, the dislocations carried by PSBs can also pass through the low-angle GB continuously, as shown in Fig. 7(a) and (b). Therefore, the interaction of PSB with the low-angle GB can be simply illustrated in Fig. 8(b). The PSBs within adjacent grains are nearly coplanar and have the same slip direction owing to the small misorientation. Accordingly, the Burger vector sum $\boldsymbol{b}_{\text{Low-GB}}$ i.e. of $\boldsymbol{b}_{\text{G1}}$ and $\boldsymbol{b}_{\text{G2}}$ of the residual dislocations within the low-angle GB should be basically equal to 0,

$$\boldsymbol{b}_{\text{Low-GB}} = \boldsymbol{b}_{\text{G1}} - \boldsymbol{b}_{\text{G2}} \cong 0 \quad (3)$$

It means that residual dislocations can be transported into the adjacent grain by the coplanar PSBs and can not be piled-up at the low-angle GB during cyclic deformation. This can be proved by the previous observations [21,22] and in Fig. 7(a) and (b). Meanwhile, no secondary slip was activated near the low-angle GB and the additional dislocations can not be introduced during cyclic deformation. Therefore, the residual dislocations or vacancies can be moved into adjacent grain by PSBs but not be piled-up at the low-angle GB. This process can be defined as 'passing-through of defects'. As a result, the residual dislocations or vacancies within a low-angle can not be accumulated to build up high enough in density and the formation of a fatigue crack along the low-angle GB will be impossible. As discussed above, it is indicated that the interaction modes of PSBs with different kinds of GBs may be responsible for the difference in intergranular fatigue cracking possibility between the large- and low-angle GBs.

5. Conclusions

The SEM-ECC technique can be successfully applied to investigate the dislocation patterns and the interactions of PSBs with different kinds of GBs, as well as further reveal the intergranular fatigue cracking possibility. By cyclic deformation of a copper bicrystal with some embedded grains, it is found that the large-angle GB often becomes obstacle to slip deformation and stimulates the operation of secondary slip systems. It means that there should exist serious plastic strain incompatibility near the large-angle GB. However, not only the PSBs, but also the dislocations can transfer through the low-angle GB continuously, showing good plastic strain compatibility. As a result, it is observed that fatigue cracking always takes palace along the large-angle GB, other than the low-angle GB. The reason is that PSBs can not pass through the large-angle GB, but can transfer through the low-angle ones during cyclic deformation. Based on the observations on surface slip morphology and dislocations, a model of defect aggregation for intergranular cracking, i.e. 'pilling-up of defects' and 'passing-through of defects' was proposed. It is suggested that intergranular fatigue cracking along a large-angle GB might be an intrinsic phenomenon and strongly depends on the interaction modes of PSBs with GBs during cyclic deformation.

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