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Relationship between the fatigue cracking probability and the grain-boundary category

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ABSTRACT

In this paper, the probability of fatigue cracking along different kinds of grain boundary (GB) and persistent slip bands (PSBs) is considered in the light of data obtained by cyclic deformation of copper bicrystals and columnar crystals. It is found that, in copper bicrystals, fatigue cracks always nucleate and propagate along large-angle GBs, irrespective of whether the GB is perpendicular, parallel or inclined to the stress axis. On the contrary, for columnar copper crystals containing small-angle GBs, PSB–matrix interfaces become the preferential sites for initiation of fatigue crack; fatigue cracking along the small-angle GBs was never observed. For a special $[\bar{1}34]/[18\,\bar{2}\,7]$ copper bicrystal with a $\Sigma = 19\text{b}$ GB and a common primary slip plane, GB cracking also results in fatigue failure. Based on the results above, the interactions of dislocations carried by PSBs with GBs, including 'pile-up of dislocations', 'passing through of dislocations' and 'partial passing-through dislocations', are discussed. It is suggested that the probability of fatigue cracking in fatigued copper crystals increases in the order of small-angle GBs, PSBs and large-angle GBs.

§ 1. INTRODUCTION

Modern materials science has been developed on the basis of the relationship between the microstructure and the performance of materials. Nowadays, it is generally recognized that the control of properties, improvement in performance or development of a new property can be achieved by controlling the microstructure. Grain boundaries (GBs) and phase boundaries are important elements in the microstructure of most engineering metallic materials. Recently, the role of GBs in materials development has been given much attention by materials scientists and engineers (Watanabe 1988, Aust *et al.* 1994, Randle 1998). It is found that almost all GB properties strongly depend on their type and structure. Accordingly, the bulk properties of polycrystals containing various types of GB are the result of a collective effect of individual GBs. In general, GB cracking, which weakens polycrystals, is a very common phenomenon after cyclic deformation. Several GB cracking mechanisms have been proposed (for example Kim and Laird (1978), Mughrabi *et al.* (1983), Christ (1989) and Richter and Burmeister (1997)). However, up to now the relationship between the probability of fatigue cracking and GB type has not been clarified. In this letter, we shall summarize the evidence from recent studies on the fatigue behaviour of copper bicrystals and columnar crystals. The purpose of this work is to

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determine whether there are some special GBs that are intrinsically strong against fatigue cracking, and furthermore to reveal the mechanism of intergranular cracking.

§ 2. FATIGUE CRACKING ALONG LARGE-ANGLE GRAIN BOUNDARIES

It has been reported that, during cyclic deformation of $[001] \perp [\bar{1}49]$, $[\bar{1}49] \perp [\bar{1}49]$, $[\bar{3}45] \perp [\bar{1}17]$, $[\bar{1}34] \perp [\bar{1}34]$, $[\bar{1}23] \perp [\bar{3}35]$ and $[\bar{5}\,9\,13] \perp [\bar{5}79]$ copper bicrystals with a perpendicular GB, fatigue cracks always nucleate and propagate along large-angle GBs at first (Hu and Wang 1997a, b, c, 1998, Peralta and Laird 1997, 1998, Zhang *et al.* 1998, 1999a, b). However, fatigue cracking along persistent slip bands (PSBs) was not observed on the surfaces of these copper bicrystals, irrespective of whether a low or high strain amplitude was employed; only the extrusions of PSBs could be seen. It has been suggested that intergranular fatigue cracking is the predominant damage mode in copper bicrystals with a perpendicular GB. In particular, the fatigue lives of bicrystals are decreased in comparison with those of single crystals owing to the presence of a GB.

In $[\bar{1}35]//[\bar{1}35]$, $[\bar{1}35]//[\bar{2}35]$, $[\bar{2}35]//[\bar{2}35]$, $[\bar{6}79]//[\bar{1}45]$, $[\bar{4}\,9\,16]//[\bar{4}\,9\,27]$ and $[\bar{1}25]//[\bar{4}79]$ copper bicrystals with a parallel GB, it was found that strain incompatibility or secondary slip in the vicinity of the GB became more serious on increasing the strain amplitude and the number of cycles (Hu *et al.* 1996, Zhang and Wang 1998a, Zhang *et al.* 1999b, c, 2000). With further cyclic deformation, fatigue cracks still initiated along the parallel GB at first, gradually linking to each other and producing intergranular cracking (Zhang *et al.* 1998, 1999b). However, the PSBs were not found to become the cracking sites on the component crystal surface. These results indicate that GBs in bicrystals are also the preferential sites, leading to fatigue cracking even though they are parallel to the stress axis. In addition, intergranular fatigue cracking was also observed in a [134]/[134] copper bicrystal with a tilted large-angle GB by Hu and Wang (1998).

From the results above, it can be concluded that intergranular fatigue cracking is the predominant damage mode even though the orientations of the component crystals and the GB structures are obviously different in these copper bicrystals. In other words, GB cracking was the preferential damage mode in the copper bicrystals, irrespective of whether the large-angle GB is perpendicular, parallel or inclined to the stress axis. In our opinion, the phenomenon above is natural and can be explained by the pile-up of dislocations at GB proposed by Mughrabi *et al.* (1983) and Christ (1989). Figure 1 illustrates that all the PSBs terminate at a large-angle GB, but cannot pass through it during cyclic deformation. This phenomenon has been supported by many previous studies on bicrystals (Hu *et al.* 1996, Hu and Wang 1997a, b, c, 1998, Peralta and Laird 1997, 1998, Zhang and Wang 1998a, b, 1999, 2000, Zhang *et al.* 1998, 1999a, b, c, 2000). In fact, PSBs can carry almost all the plastic strain during cyclic deformation of bicrystals and will become a carrier or channel transporting residual dislocations and vacancies from the interior of grains into the GBs. However, all the large-angle GBs always become a barrier preventing the dislocations from passing through. Therefore, those residual dislocations and vacancies must be piled up at the GB. When those residual dislocations and vacancies accumulate to a sufficiently high density, intergranular fatigue cracking will take place under external stress. This process can be described by the pile-up of dislocations.

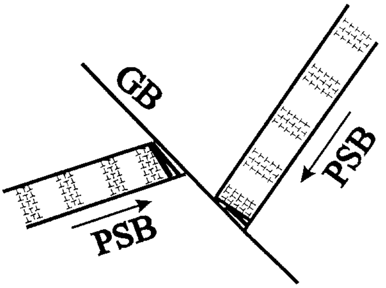

Figure 1. Diagram of interactions between PSBs and large-angle GBs in copper bicrystals, showing the pile-up of dislocations.

§ 3. FATIGUE CRACKING OF COLUMNAR CRYSTALS

To investigate the possible role of small-angle GBs in fatigue cracking, cyclic deformation was performed on columnar copper crystals containing such GBs under a constant plastic strain amplitude. After cyclic deformation, it was found that the PSBs transferred through the small-angle GBs continuously (Zhang and Wang 1998a, Zhang *et al.* 1998). Pile-up of dislocations at the small-angle GBs was never observed. The interactions of PSBs and dislocations with a small-angle GB are illustrated in figures 2 (*a*) and (*b*) respectively. It is apparent that dislocations carried by PSBs on common slip planes can also transfer through the GB continuously because the primary slip planes and directions of the adjacent grains are nearly the same. It was found that all the fatigue cracks initiated along the PSBs as long as the number of cycles was high enough (Zhang *et al.* 1998). Fatigue cracks were not found to nucleate along small-angle GBs whether or not they were perpendicular or parallel to the stress axis. It therefore appears that PSB cracking is the dominant damage mode between small-angle GBs and PSBs. This result is quite different from the mechanism of fatigue cracking along large-angle GBs in the copper bicrystals. According to the interactions of PSBs with the GB (figures 2(*a*) and (*b*)), the columnar crystals containing small-angle GBs can actually be regarded as a 'single crystal'. As a consequence, PSB cracking was observed in fatigued columnar crystals rather than small-angle GB cracking as in copper single crystals (Hunsche and Neumann 1986). We can define this interaction as the passing through of dislocations, which leads to the impossibility of fatigue cracking along small-angle GBs.

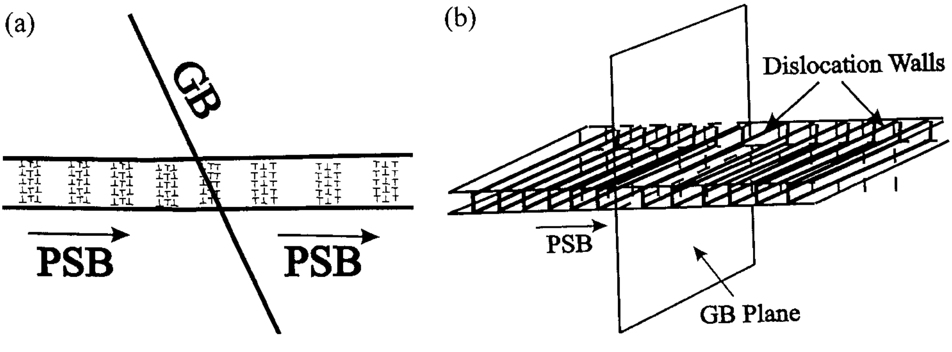

Figure 2. (*a*) PSBs passing through a small-angle GB, (*b*) continuous dislocation walls beside a small-angle GB.

§ 4. FATIGUE CRACKING ALONG SPECIAL GRAIN BOUNDARIES

Sometimes, there exists some special GBs belonging to the large-angle type, in which adjacent grains contain a common primary slip plane across the GB. If cyclic deformation is performed on a bicrystal containing such GBs, the common slip bands will be activated and transfer through the GB continuously like that in fatigued columnar crystals. Thus, the GB has a characteristic of a small-angle GB too. In our previous work, a $[\bar{1}34]/[18\,\bar{2}\,7]$ copper bicrystal containing such a GB and different slip directions of two crystals was investigated (Zhang *et al.* 1999d, Zhang and Wang 2000). It was expected that the GB would be intrinsically strong, resisting fatigue cracking unlike that in the copper bicrystals described previously. However, after cyclic deformation, it was found that fatigue cracks still nucleated along the GB preferentially, as shown in figure 3 (*a*), although the surface slip bands beside the GB still have a good one-to-one relation (Zhang *et al.* 1999d), showing that PSBs transferred through the GB. As the number of cycles was increased, fatigue crack propagated along the special GB step by step, resulting in intergranular fracture. Before GB cracking began, it was observed by the scanning electron microscopy–electron channelling contrast technique as reported by Zhang and Wang (2000) that, indeed, the dislocations carried by the common PSBs could not pass through the GB continuously, as shown in figure 3 (*b*). Because the slip directions of the two crystals are different, a dislocation-affected zone (DAZ) formed near the GB on the common primary slip plane (figure 3 (*c*)). The interactions of PSBs and dislocations with the GB are illustrated in figures 4 (*a*) and (*b*). In spite of the fact that the surface PSBs transferred through the GB, the dislocations could not pass through the GB continuously during cyclic deformation. In the end, dislocations will also be piled up at the GB and result in the formation of the DAZ. We can define this process as the partial passing through of dislocations and the DAZ should be responsible for the GB cracking.

§ 5. SUMMARY AND CONCLUSIONS

By comparing and reviewing probability of fatigue cracking along different kinds of GB, the following conclusions can be drawn.

(1) For all large-angle GBs, irrespective of whether parallel, perpendicular or inclined to the stress axis, intergranular fatigue cracking is the predominant damage mode during cyclic deformation of copper bicrystals. This phenomenon is natural and can be explained by the pile-up of dislocations at large-angle GBs.

(2) For the columnar copper crystals containing small-angle GBs, the PSB–matrix interfaces are the favourable sites for fatigue cracking in comparison with the small-angle GBs. This phenomenon can be explained by the passing through of dislocations at the small-angle GBs.

(3) For the copper bicrystal containing a special GB, which is transferred by common PSBs, the GB is still the preferential site leading to fatigue cracking. The reason is that the primary slip directions of the two crystals are different, so that the dislocations carried by the common PSBs cannot pass through the GB continuously during cyclic deformation. This phenomenon can be defined as the partial passing-through of dislocations at the special GB.

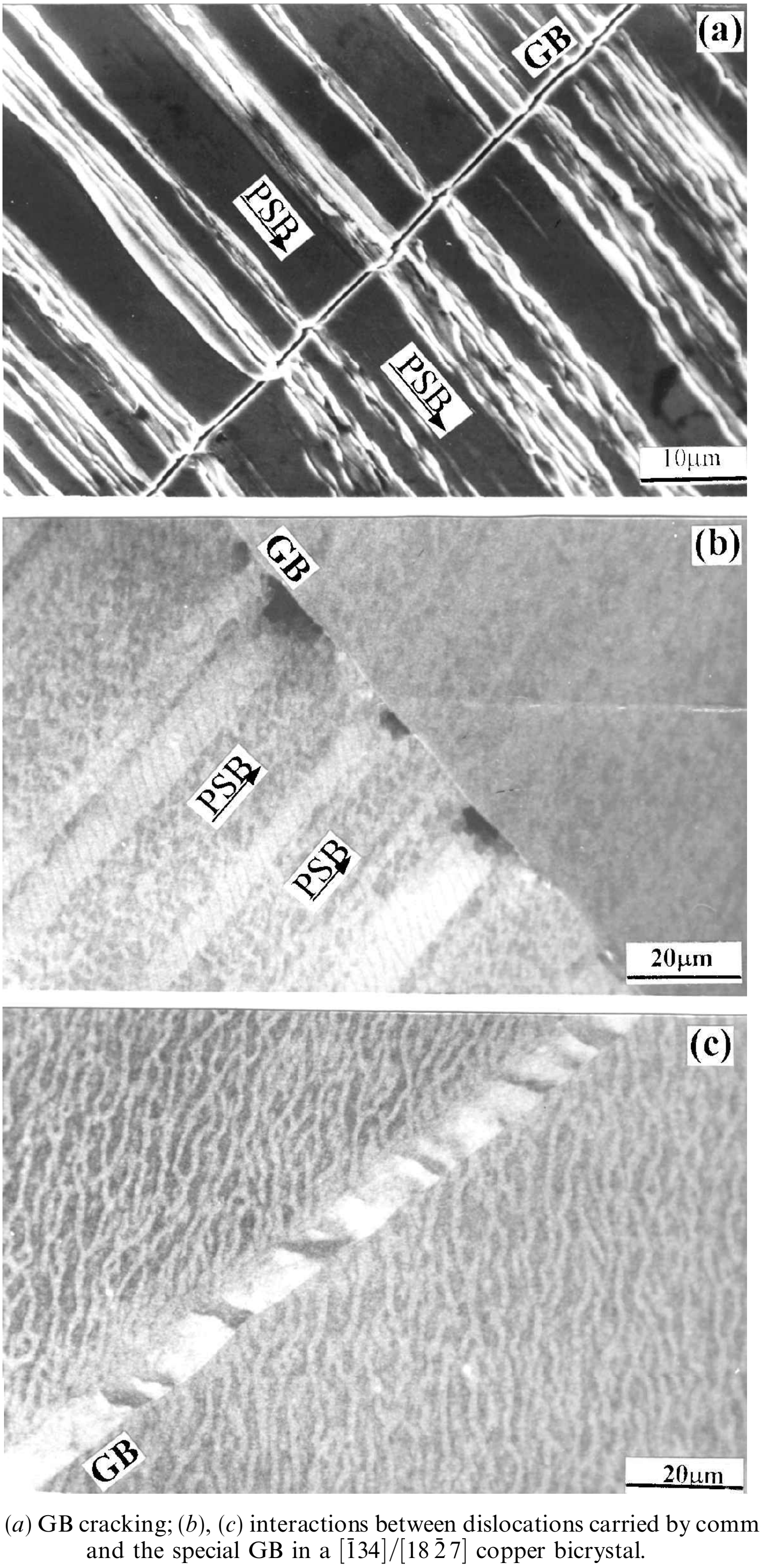

Figure 3. (*a*) GB cracking; (*b*), (*c*) interactions between dislocations carried by common PSBs and the special GB in a $[\bar{1}34]/[18\,\bar{2}\,7]$ copper bicrystal.

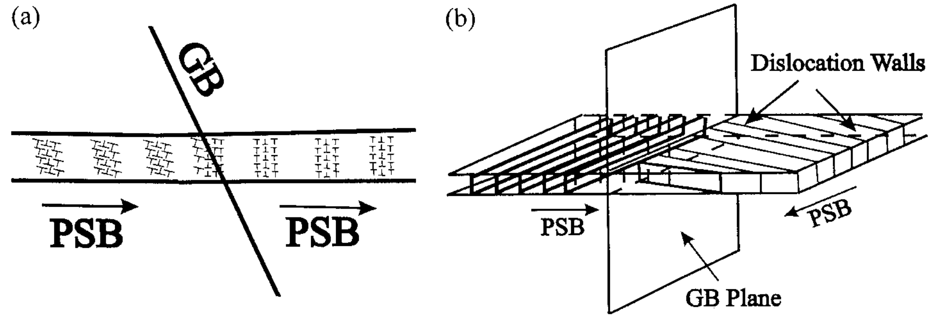

Figure 4. Sketch of interactions between PSBs and the special GB in a $[\bar{1}34]/[18\,\bar{2}\,7]$ copper bicrystal; (*a*) PSBs passing through the GB; (*b*) discontinuous dislocations beside the GB.

(4) The probability of cracking in fatigued copper crystals increases in the order small-angle GBs, PSBs and large-angle GBs.

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