The effect of pre-existing subgrains on the fatigue crack nucleation in pure aluminium

Fatigue crack nucleation and propagation in pure metals have been investigated by optical and electron microscopy over more than 20 years [1–5]. It has been shown that the majority of fatigue cracks begin at grain boundaries at high applied stress [4, 5], while slip-band cracking is dominant when the applied stress is low [3]. A gradual transition from grain-boundary nucleation to slip-band cracking was observed [6] when the applied stress was changed from high to low stress. Since the pure metals investigated by previous workers [1–6] were without pre-existing substructures before fatigue, one may ask in what way will the pre-existing substructures produced by thermomechanical treatment affect the fatigue crack nucleation, crack propagation and the patterns of substructures developed by fatigue. The effect of pre-existing subgrains on the cell structure in fatigued Al was investigated by Jahn *et al.* [7]. In this work, we experimentally examined the fatigue crack initiation, with emphasis on the grain boundary and slip band, in pure Al with and without pre-existing subgrains by the use of scanning electron microscopy. It is our hope that the information obtained will help to explain better the fatigue properties of thermo-mechanically treated metals which have pre-existing subgrains.

The purity of the aluminium investigated was 99.9%. The chemical composition of the samples is given in Table I. Homogenized pure Al plates were cold-rolled to a 80% reduction ratio in thickness. These rolled sheets were then annealed at 200 or 300° C for various times. Equi-axed subgrains were observed in specimens annealed at 200° C for a time period longer than 2 h. The average subgrain size was 2.4 μm. These specimens are called specimen S. Full recrystallization was found in specimens after annealing at 300° C for a time period longer than 0.5 h. These specimens are called specimen F. The average recrystallized grain size was about 100 μm. All specimens were fatigued by cyclic bending stress with zero mean stress. The direction of fatigue stress was parallel to the rolling direction of the specimens. The amplitude of the stress was such that the fatigue life N_f is $10^4 \leqslant N_f \leqslant 3 \times 10^5$ cycles. Fresh fracture surfaces and free surfaces just after fatigue were investigated using SEM (JSM-U3) operating at 25 or 10 kV.

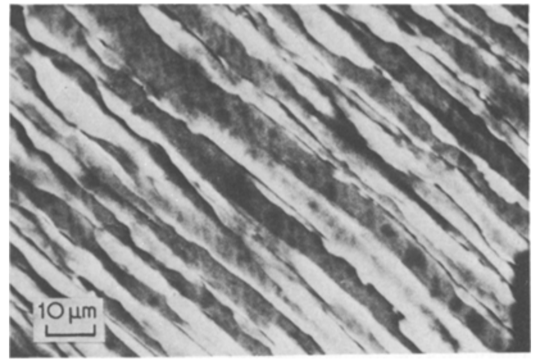

Figure 1 Typical SEM on the free surface of fatigued specimens S.

While fatigue-induced slip bands were developed frequently along only one direction in each grain for specimen S, as shown in Fig. 1, two intersecting slip bands either of wavy or planar type were always formed on specimen F, as shown in Fig. 2. The degree of slip activity is less in specimen S than in specimen F due to the presence of pre-existing subgrains since the dislocation can be pumped into the sub-boundaries during

Figure 2 Typical SEM on the free surface of fatigued specimen F.

TABLE I Composition of the Al sample (wt %)

Si	Fe	Cu	Pb	Zn	Bi	Sn	Al
0.06	0.004	0.004	0.003	0.003	0.0075	0.0065	balance

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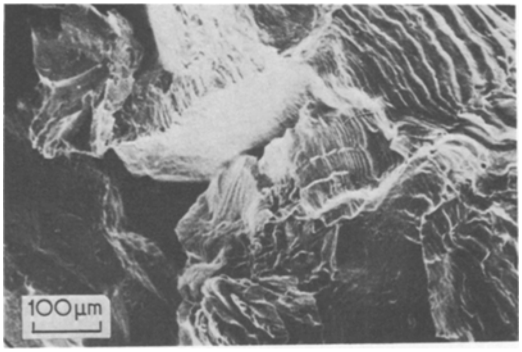

Figure 3 Typical SEM fractograph of fatigued specimen F.

fatigue operation such that the strain distribution is more uniform in specimen S than in specimen F. This may explain why the slip bands induced by fatigue were usually along only one direction in specimen S. Since slip bands were found to be one of the dominant fatigue crack initiation sites in both specimens F and S, as shown in Figs. 1 and 2, the fatigue crack initiation should be more difficult for specimen S than specimen F such that specimen S should possess longer fatigue life. This statement is in agreement with our experimental results which showed that specimen S could stand much longer fatigue life [8] than specimen F if the same fatigue stress amplitude was applied.

Both slip bands and grain boundaries, especially the intersection of grain boundaries, were found to be the dominant fatigue crack nucleation sites on both specimens S and F. Fig. 2 clearly indicates the fatigue crack nucleation at a triple point of grain boundary for specimen F. The grain-boundary cracking on the free surface after fatigue was observed much more frequently in specimen F than in specimen S, and the fracture surface of specimen F always revealed cracks which surrounded islands approximately 100 μm in size as shown in Fig. 3. Since the size of the islands on the fracture surface of specimen F and the grain size of specimen F are approximately equal we consider the fracture intergranular. This phenomena was never observed on the fracture surfaces of specimen S. The stress in the grain-boundary region is higher than that in the area away from the grain boundary such that stress gradient exists in the vicinity of the grain boundary [9]. Secondary slip systems near the grain boundary are easily activated due to this stress gradient. Cross-slip resulting from this activation enhances the irreversibility of slip. The incompatibility of induced strain in the grain boundary must be accommodated. If the slip systems in adjoining grains are equally stressed, the strain incompatibility can be accommodated and no crack nucleates. If one is less stressed than the other, grain-boundary sliding occurs so as to form a step for accommodation [5]. A crack nucleates from this step, then propagates along the grain boundary with the help of the stress concentration of this step. In specimen S, the stress gradient at the grain boundary is considerably reduced due to the more uniform strain distribution, by the presence of neighbouring sub-boundaries. Hence crack nucleation from a grain boundary of specimen F is much easier in the initial fatigue hardening stage in which the fatigue-induced cellular structure is not yet accomplished. The intergranular fatigued cracking on both the free surface and the fracture surface frequently observed in specimen F as indicated by Figs. 2 and 3, confirms this consideration.

Fatigue striations were observed on the fracture surfaces of all fatigued specimens. The striation patterns were similar on specimens S and F. The pre-existing sub-boundaries in specimen S showed no traces on the fatigue striation. How the sub-structure of metals affects the crack propagation, and thus the striation pattern, is an interesting subject. Wilkins and Smith [10] indicated that the sub-structure was formed in the area closed to a crack tip in aluminium and aluminium alloys during fatigue; however, void formation or crack nucleation ahead of the main crack was not observed and crack propagation did not take place along the sub-boundaries. Since sub-structures are always developed in the vicinity of a fatigue crack tip [10, 11] in metals having medium or high stacking-fault energy even if there is no pre-existing subgrains, the striation pattern of specimen F is supposed to be similar to that of specimen S due to the plastic flow mechanism of crack propagation. The high-voltage transmission electron microscope observation by Gardner *et al.* [11] indicated that the crack initiation of fatigue took place at the sub-boundaries in particle-free beryllium and iron single crystals. If the crack propagation in pure Al is along the subgrain boundaries, one will still observe no sub-boundary traces on the striation pattern through the general scanning electron microscope since the sub-structures close to the crack tip are very small ($\lesssim 1\,\mu m$) and the discontinuity of the sub-boundary path between adjoining subgrains is much less.

From the discussions above we would suggest two reasons which may explain why the fatigue properties of specimen S are superior to those of specimen F. The degree of crack nucleation at a slip band is less in specimen S than in specimen F due to the introduction of pre-existing subgrains, since the dislocations can be pumped into the sub-boundaries such that the strain distribution is more uniform in specimen S. The grain-boundary crack nucleation is more difficult in specimen S since the stress gradient at a grain boundary is considerably reduced by the presence of pre-existing subgrains.

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