Early Stage Crack Tip Dislocation Morphology in Fatigued Copper

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Observations of dislocation structures around the fatigue cracks in the early stage in polycrystalline copper were made through an ultrahigh voltage electron microscope operating at 2000 kV. Ladder-like structures and initial cracks within them were frequently observed. These dislocation structures were formed prior to the crack initiation, and the crack was initiated and propagated within these structures accompanied by no appreciable dislocation entanglements in the earliest stage. On the other hand, cell structures were observed around the cracks which appeared to have grown into the subsequent stage (the stage between Stages I and II). Cell size ahead of the crack tip was not so small, and it seemed that the crack was able to propagate across the cells. On the basis of these observations, the mechanisms of fatigue crack initiation and propagation in the early stage in copper bulk-specimens are briefly discussed.

EXPERIMENTAL PROCEDURE

Polycrystalline OFHC copper (99.99 pct) supplied in the form of 3 mm thick plate was machined into specimens having cross section of $3 \times 8$ mm. The specimens were then annealed at $850^\circ C$ ($1123K$) for 2 h in vacuo, and finally electropolished to remove the surface layer by about 30 $\mu m$ before testing. The grain size was about 100 $\mu m$ in diameter.

Using Shimadzu UF 15 fatigue testing machine operating in plane bending at 33 Hz, the specimens were cycled with stress amplitude $\sigma = \pm 11.0$ kg/mm$^2$ [108 MN/m$^2$] corresponding to a lifetime $N = 1.0 \times 10^6$ cycles. The tests were terminated at 80 pct the life; and observations were made for the cracks in the early stage formed in such fatigued specimens.

Thin foils containing microcracks were prepared as follows: First, surfaces of the fatigued specimens* were protected by an electrodeposited copper layer approximately 2 mm thick. They were then cut longitudinally into slices (1.8 mm thick) perpendicular to the specimen surface by means of a milling cutter. The slices were thinned first mechanically with emery paper and then electrolytically in order to remove the damaged layer. The area including cracks near the interface between the specimen and electrodeposited layer was thinned using jet electropolishing. Finally, the area was electropolished in the usual method until perforation took place.

The foils were examined in an ultrahigh voltage electron microscope operating at 2000 kV.

OBSERVATIONS AND DISCUSSION

Dislocation Structures Around Stage I Crack

Ladder-like dislocation structures were observed penetrating through the matrix (vein structure) from the specimen surface to the interior. Fig. 1 shows dislocation arrangement below the surface and an initial crack formed at the bottom of an intrusion shown by the arrow. Although indistinct, the ladder-like structure is formed near the side of the crack.

More direct evidence of the relationship between the ladder-like structure and fatigue crack in the earliest stage (so called Stage I) is shown in Fig. 2(a), (b) and (c). Because the surface layer of the specimen had been electropolished by $\approx 2 \mu m$ prior to electropolishing, no intrusion is present in (a) and (b) of Fig. 2. Fig. 2(a) contains two distinct ladder-like structures parallel to each other, extending about 100 $\mu m$ into the interior, which is comparable to the mean grain size. At the end of one of them an initial crack was formed but not in the other one. Similar result is also seen in Fig. 2(c),

*Deposit electroplated on the specimen surface directly is apt to be separated from the specimen during thinning process, so some specimens were slightly electropolished before electroplating.
Fig. 1—Dislocation structure in the subsurface area and microcrack initiated at the bottom of an intrusion; ladder like structure, though indistinct, is seen in the vicinity of the crack (108 MN/m²)

in which no surface layer is removed. These observations suggest that ladder like structures are formed before microcracks are initiated and that the cracks in this stage propagate along these structures. There were found two kinds of crack routes along the ladder like structures; one is in the middle portion of them (Fig. 2 (a) and (b)) and the other the interface between matrix and them (Fig. 2 (c)). In each case, neither marked dislocation tangles as found in Stage II crack nor fine cells (0.1 μm) were observed at just ahead of the crack tip. This is also the case with the dislocation structure near the sides of the crack. These results suggest that the ladder like structure is preserved fairly well after the crack has been initiated and propagated. This means that extensive strain concentration suggested by Klesnil and Lukas does not occur at the area just ahead of the crack in such an early stage. The direction of crack growth coincides with that of persistent slip band ladder, that is, one of the traces of {111} slip planes, which many workers have already identified. The crack plane (111) cannot have two other cooperative slip systems crossing each other at the front of the crack. This is in contrast with the case of crack planes for Stage II proposed by Pelloux or one by Bowles et al.; (100) or (110). If the motion of many dislocations in the secondary slip planes take place at the crack front, it will result in deviation of the crack from a (111) plane and also will produce many tangles or cell structures as a result of interaction with that in the primary slip plane. These are not the case with present observations. In fatigue tests in a small plastic strain range on copper single crystals, Finney and Laird have observed that all the plastic strain was localized into persistent slip bands after saturation hardening, in which cooperative movement of primary links between the walls comprising the persistent slip band structure took place. They also concluded that crack initiation was a simple geometrical consequence of the irreversibility of primary dislocation emergence at the surface in the persistent slip band traces. If the ladder like structure is considered as the channel for primary dislocations, the model proposed by Finney and Laird is applicable to our experimental results (the initiation and the propagation of the crack along the ladder like structure).

Crack Growth Succeeding Stage I

Cell structures were observed around fairly long cracks or ones with tortuous route (Fig. 3). These cracks are thought to be in a transition stage (the stage between Stages I and II) by the following reasons. The cell size around the tips as well as the sides of the cracks is about 2 μm. This is not so small as that (≈0.1 μm) observed beneath the fracture surface of the crack in Stage I and Stage II in copper. Purcell and Weertman observed well developed cell structure near the Stage II crack in copper single crystal specimen. They pointed out that the diameter of the cells decreased as the closer they were to a fatigue crack.