On the Mechanism of Fatigue Crack Advance in Ductile Materials

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Notched copper single crystals of 6 x 6 mm square cross section were cyclically deformed in fully reversed four-point bending with the bending axis c parallel to the bottom of the notch. The geometry and the two orientations A and B used are shown in fig. 1a. Furthermore crystals with a diagonal notch as shown in fig. 1b were cyclically deformed in push-pull.

The cyclic deformation tests were carried out in a hydraulic closed loop testing machine at frequencies from 50 to 0.1 Hz. The amplitude was controlled to give a constant crack advance rate. Pictures of the fracture surfaces as well as of the side faces of the specimens were taken with a Scanning Electron Microscope.

Results and Discussion

Usually fatigue fracture surfaces in single crystals are very irregular and far from being plane. Under the circumstances described here, however, they are macroscopically plane with a roughness of some 100μ only.

Figures 2a, b show the fracture surfaces of the bending specimens of orientations A and B, respectively. The bright lines indicate the crack front position after every 400 cycles. The lines were generated by temporarily reducing the load amplitude.

Due to the bending, there is a force that tries to make the crack front parallel to the bending axis. This gives a unique control over the direction of the crack front that cannot be obtained in uniaxial tests. This control together with the plane fracture surface and the well-defined and homogeneous material properties of high-purity single crystals gives excellent reproducibility of the crack shape as well as of the crack advance rate (±1.5%). In fig. 2 (as in all other figures) the crack front is moving downward, the parts near the surface lag behind. This is presumably due to the better possibility near the surface to relax stress concentrations by sidewise deformation (plane stress vs. plane strain).

In the A crystals, the bending axis is a <001> direction and the crack front is therefore forced to lie along the bisector of the two available <011> directions in the fracture plane, which are the only possible directions according to the coarse slip model of fatigue.[1,2,3] As shown in figs. 3a and 4a by the fatigue striations, the crack front indeed breaks up microscopically into small segments that are parallel to these <011> directions. This is true for crack advance rates of fractions of a micron/cycle (fig. 3a) up to 35 μ/cycle (fig. 4a). These results show convincingly that there is a strong tendency for the fatigue crack front to lie parallel to <110> directions as required by the coarse slip model of fatigue.[1,2,3] The same conclusions have to be drawn from the B crystals: In the middle of the specimen the crack is forced a priori to be parallel to an <011> direction and long straight striations are found. (The left side of figs. 3b, 4b is representative of this area.) Where the surface influence bends the crack back macroscopically, this can be accomplished microscopically only by having segments of the crack front lie perpendicular to the bending axis because this is the only other <011> direction available in the fracture plane (right side of figs. 3b and 4b).

Plastic Zone

From figs. 2 to 4 it is obvious that the influence of the surface is very strong and slip lines on the surface do not always reflect the situation in the interior. In order to observe the true

slip distribution accompanying the formation of the striations, one must have straight striations from surface to surface. To accomplish this, obviously two requirements have to be met: A <011> direction must be parallel to the crack front, and the crack front must form an acute angle with both surfaces as in figs. 2a and 2b. These requirements are fulfilled in the configuration of fig. 1b. Figures 5a, b show the resulting straight striations that may be as much as 500μ apart depending on the prescribed amplitude.

Figure 6 shows the slip lines on the surface of the specimen together with the opening and closing crack. The slip is strictly confined to slip planes emanating from the crack tip (fig. 7), and the geometrical configuration is exactly that predicted by the model for low cycle fatigue (on each slip system more than one slip line activated during one stress cycle).[1,2,3]

Striation Formation

Whenever the deformation processes during closing of the crack are not exactly the opposite of those during opening of the crack (cf. fig. 6), the fracture surface will deviate from a plane and show striations of various profiles[4] but the striations will always be parallel to a <011> direction as found experimentally.

Summary:

The direction of the crack front in a single crystal of copper was forced by flexural deformation into a direction that is forbidden according to the coarse slip model of fatigue. The crack responded to this by breaking up microscopically into segments that were oriented as the model predicts. If on the other hand the requirements of the coarse slip model are fulfilled a priori, striations as long as several millimeters and some 100μ apart can be generated. Then the slip accompanying the advancing crack can be observed at the surface, and it agrees in all respects with the predictions of the model.

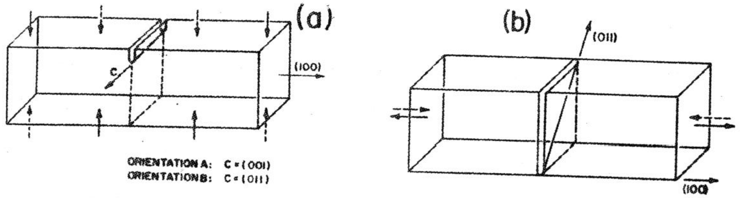

Fig. 1a, b: Specimen geometry and orientation.

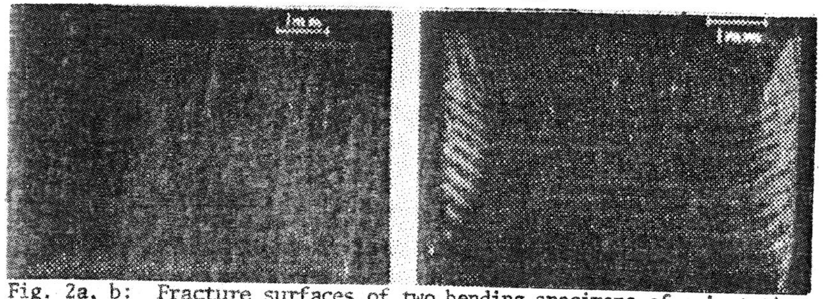

Fig. 2a, b: Fracture surfaces of two bending specimens of orientation A and B, respectively, with markings that show successive positions of the crack front (moving downward). 400 cycles between two markings.

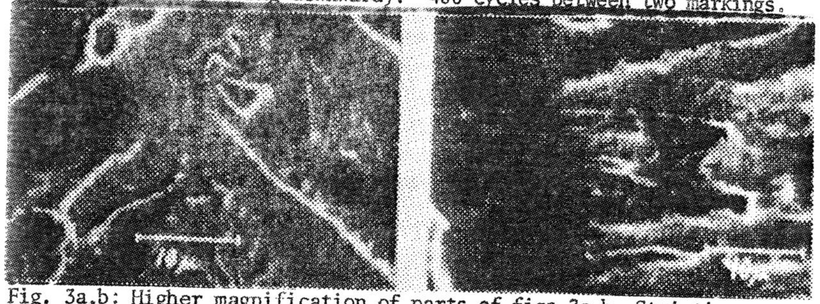

Fig. 3a,b: Higher magnification of parts of figs.2a,b. Striations are always parallel to <110> directions independent of macroscopic crack direction. Striation spacing or crack advance per cycle: 0.5µ. Fig.3a: Representative area of center of fig.2a. Fig. 3b: Border between center and surface influences area of fig.2b, showing the switch of striation direction from parallel to perpendicular to the bending axis.

Fig. 4a,b: Correspond to figs. 3a,b, but were taken from specimens with larger crack advance rates (30µ/cycle and 13µ/cycle, respectively).

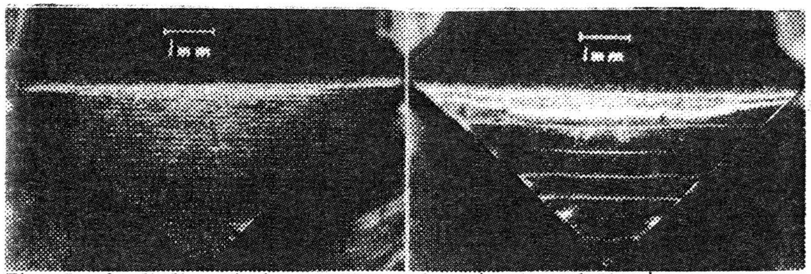

Fig. 5a, b: Undisturbed striations of 60µ/cycle and 500µ/cycle, respectively on fracture surface of push-pull specimens (fig. 1b).

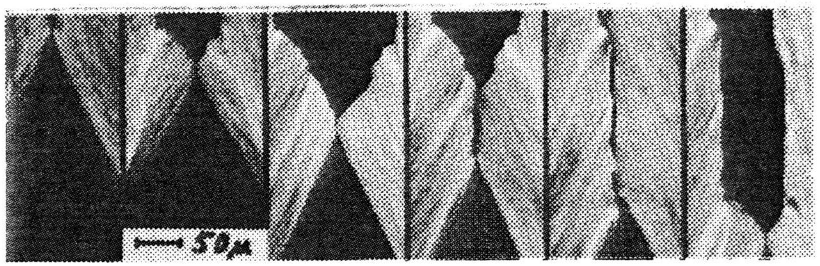

Fig. 6: The crack tip at successive moments during one stress cycle and the beginning of the next cycle. Unloading for examination partly closes the crack due to residual stresses and produces the vertical segments in the borders of the opened crack tip.

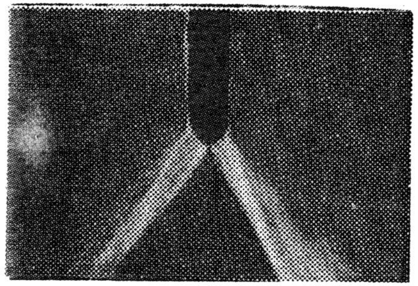

Fig. 7: Plastic zone of opening crack. Electropolished when crack was closed. Then pulled to open crack. Slip is strictly confined to slip planes emanating from the crack tip. Same magnification as fig. 6.

References

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