ON THE FORMATION OF EXTRUSION-INTRUSION PAIRS DURING FATIGUE OF COPPER

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ABSTRACT

Single-crystalline specimens of copper were fatigued at room temperature in tension-compression under stress control. After hardening well into saturation isolated extrusion-intrusion pairs could be produced on the primary as well as on secondary slip systems. Details were studied by scanning electron microscopy and other metallographic techniques.

KEYWORDS

Fatigue, crack initiation, persistent slip band, extrusion, intrusion, single crystal, copper.

INTRODUCTION

Since the recognition of persistent slip bands (PSBs) as a bulk phenomenon (e.g. Thompson, Wadsworth, Louat, 1956; Helgeland, 1965) much work has been done to reveal their nature. The discovery of a dislocation structure which is completely different from that in the matrix (e.g. Laufer, Roberts, 1966; Lukáš, Klesnil, Krejčí, 1968; Woods, 1973) led to models of how the dislocation structure in the matrix changes into that in PSBs (e.g. Kuhlmann-Wilsdorf, Laird, 1977; Winter, 1978).

On the other hand, comparatively little attention has been paid to the nucleation of PSBs at the surface. It is known that the intersection of PSBs with the specimen surface exhibits a notch-peak profile, i.e. a cluster of extrusions and intrusions (e.g. Woods, 1973; Winter, 1974; Finney, Laird, 1975). It is also known that PSBs broaden during further cycling, at least under stress control (Neumann, 1967; Roberts, 1969). So it is obvious that the nucleation of a PSB is equivalent to the formation of the first extrusions and intrusions.

Furthermore some models of the formation of extrusion-intrusion pairs (EIPs) make very specific predictions about the sign of the EIPs (Neumann, Fuhlrott, Vehoff, 1979), which can be determined at isolated EIPs only. Therefore the aim of this work is to carry out experiments leading to the formation of isolated EIPs and to study the relative frequencies of isolated extrusions, isolated intrusions, and of the two possible signs of EIPs.

EXPERIMENTAL

Seeded single crystals with square cross sections of 36 mm^2 and lengths of 110 mm were grown from 99.99 % copper in a split graphite mould under a vacuum of less than 1 mPa. All crystals were oriented for single slip with a Schmid factor of 0.495. The traces of the primary slip planes on two of the four sides were perpendicular to the specimen axis. A gauge length of 10 mm with square cross section of about 20 mm^2 was produced by electrolytical cloth polishing (Ahearn, Monaghan, Mitchell, 1970). The critical resolved shear stresses of the virgin crystals were about 1.0 to 1.5 MPa.

All experiments were carried out in tension-compression using a computerised closed loop hydraulic fatigue machine operating at 40 Hz. Cycling was performed under instantaneous total strain control in order to avoid cyclic creep of the specimens, which ocurred during hardening under symmetric stress control (see also Grosskreutz, Mughrabi, 1975). The most extreme positive and negative values of strain were adjusted by a minicomputer in such a way that the stress range and the mean stress had the desired values. The time constants for the stress range control and the mean stress control were 5 and 100 cycles, respectively. From the measured stresses and strains the compliance and the plastic strain amplitude were calculated by the computer.

All crystals were cyclically hardened by increasing the resolved shear stress amplitude from zero to 30 MPa within 30000 cycles. During this stress build-up the plastic shear strain amplitude showed strain bursts as described earlier (Neumann 1968), see Fig. 1.

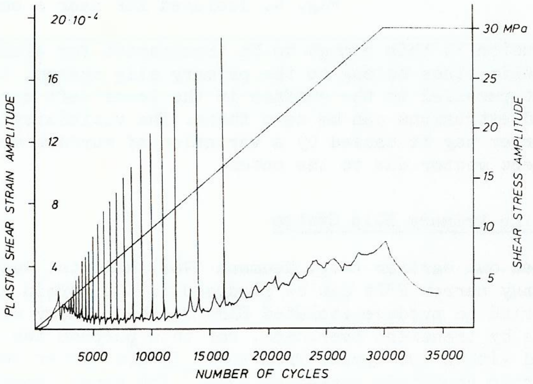

Fig. 1. Resolved plastic shear strain amplitude and resolved shear stress amplitude versus number of cycles.

After the stress build-up the stress amplitude was held constant at 30 MPa with zero mean stress. Then the plastic shear strain amplitude decreased nearly exponentially to $2\cdot10^{-4}$ within 5000 cycles. After this hardening procedure it was impossible to detect any PSBs, EIPs, or other surface roughness by an optical microscope.

The plastic shear strain amplitude of $2\cdot10^{-4}$ lies well within the plateau found by other workers in experiments with constant plastic shear strain amplitude (e.g. Winter, 1974; Mughrabi, 1978). After about $2\cdot10^5$ cycles the first PSB became visible, and ultimate fatigue failure occurred after about 10^6 cycles. The PSBs preferably started from an edge of the specimen gauge length. A possible reason for this feature may be slightly higher strains at the edges due to bending stresses caused by a small misalignment of the grips. Another more likely reason may be derived by the following approach: PSBs are known to nucleate at the specimen surface, possibly because escaping dislocations facilitate slip and thus promote the rearrangement of dislocations. In a specimen with square cross section the edges are obviously the places, where dislocation egress is easiest, so that they become preferred nucleation sites of PSBs.

RESULTS AND DISCUSSION

Two different views for the formation of EIPs are possible:

1. EIPs form according to some irreversibility of slip in tension and compression. The growing intrusion develops into a stage-I crack (Neumann, 1968; Neumann, Fuhlrott, Vehoff, 1979).
2. Stage-I cracks develop due to Thompson's mechanism of repeatedly oxidizing the fresh surface at slip steps (Thompson, Wadsworth, Louat, 1956). EIPs form at these pre-existing stage-I cracks due to the asymmetry, which is introduced by crack closure (Neumann, Fuhlrott, Vehoff, 1979).

In order to be able to distinguish between these two views the question arises if isolated extrusions or intrusions do exist, since according to the second model an intrusion is a prerequisite for the formation of an EIP, so that isolated intrusions are expected while isolated extrusions are not. According to the first model only pairs of extrusions and intrusions should be observed. Furthermore the signs of the EIPs are of interest, since the second model necessarily yields a sign according to Fig. 2a, whereas the first model allows for both geometrically possible signs. A hint for the preponderance of one sign may be found in previous observations of crack nuclei at the concave side of PSBs which corresponds to Fig. 2a (Neumann, 1967).

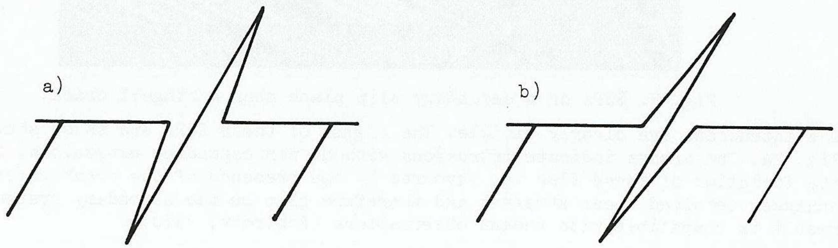

Fig. 2. The two geometrically possible signs of EIP.

In order to determine the sign of EIPs, they must be well separated from each other: if there is a cluster of EIPs they can overlap and make up more complicated structures like those in PSBs. Therefore the aim of our experiments was to produce isolated EIPs.

Coarse Slip Lines.

It was tried to form EIPs at coarse slip lines, which were produced by minute tensile strains of the order of 10^{-4}. It proved to be impossible to obtain such pairs at the site of coarse slip lines, although the specimens were cycled until failure. Final fracture was caused by stage-I cracks, which formed far away from the slip lines, whereas at the slip lines no further slip activity could be observed. A possible reason for this behaviour may be that back slip near the coarse slip lines was inhibited by high internal stresses due to the large local strains within the coarse slip lines.

EIPs on Secondary Slip Systems.

If a large fatigue crack develops, marked EIPs on a secondary slip system are often observed near the crack. Figure 3 shows the primary crack and EIPs on a secondary slip system as well as slip lines of still another secondary system.

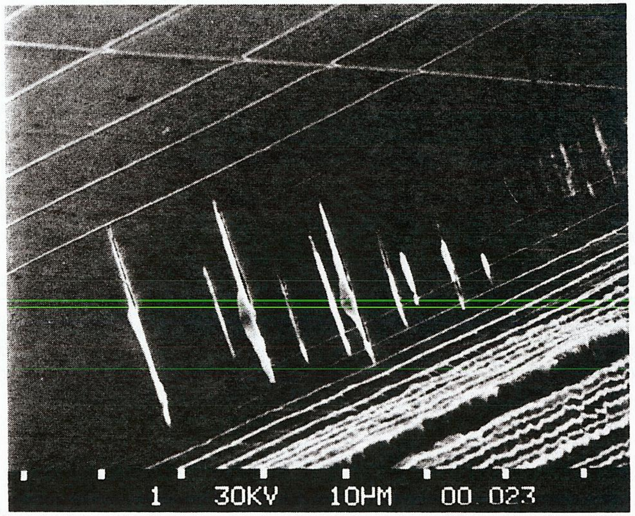

Fig. 3. EIPs on a secondary slip plane near a stage-I crack.

The intrusions are clearly visible. The signs of these EIPs are those shown in Fig. 2a. The arrows indicate intrusions without corresponding extrusions. Obviously the formation of these EIPs was favoured by the presence of the crack which led to enhanced resolved shear stresses and therefore slip on the secondary system. This result is compatible with recent observations (Fuhlrott, 1978).

Because of the unknown crack shape below the surface it was tried to get the required stress concentration in a better way: a cyclically hardened specimen was notched, so that the resolved shear stress on secondary slip systems was high in the immediate vicinity of the notch root. Because of the unknown local shear stresses due to the notch the nominal stress amplitude was increased from 1 to 10 MPa within 100 cycles. This stress amplitude was held constant for 100 cycles followed by a reduction of the stress amplitude to 1 MPa within 100 cycles. Then the area near the notch root was inspected with an optical microscope without dismounting the specimen. Usually after these first 300 cycles no slip lines or EIPs could be seen. Consequently, cycling was continued with stresses 10 % higher than before, until some slip lines were found. From this point on cycling was continued with constant nominal stress amplitude.

Figure 4 shows an EIP on the secondary system running from A to B.

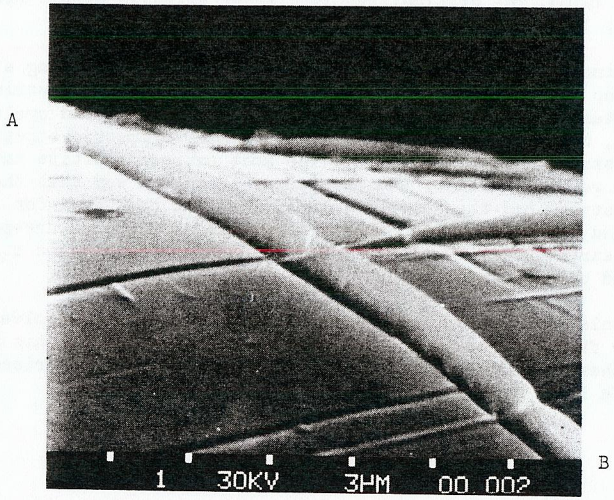

Fig. 4. Isolated EIP near a notch.

The extrusion is thin enough to be transparent for electrons of 30 keV. The other visible slip lines belong to the primary slip system, the Burgers vector of which is almost parallel to the surface in the lower left corner of the picture, so that no marked extrusions can be seen there. The visibility of extrusions in the upper right corner may be caused by a variation of surface orientation with respect to the Burgers vector due to the notch.

EIPs on the Primary Slip System

As pointed out earlier (e.g. Neumann 1967; Roberts, 1969; Winter 1974; Mughrabi 1978), many narrow PSBs can be produced if the strain amplitude is high. Therefore it was tried to produce isolated EIPs on the primary slip system of unnotched specimens by transient overloads. For this purpose the shear stress amplitude was increased within 100 cycles from 30 to 35 MPa. After 100 cycles at 35 MPa with shear strain amplitude exceeding $4 \cdot 10^{-3}$ the gauge length was covered with slip lines, some of which were accompanied by isolated EIPs. Also single intrusions could be found but never single extrusions. All EIPs observed had the sign shown in Fig. 2a. During further cycling the first PSB developed at that site, where EIPs had been closest to each other.

Another way to produce isolated EIPs has been provided by experiments in which PSBs nucleated at the edge of the specimen (see above). These PSBs taper off on the two faces adjacent to the edge, ending in isolated EIPs. Figure 5 shows two of those pairs.

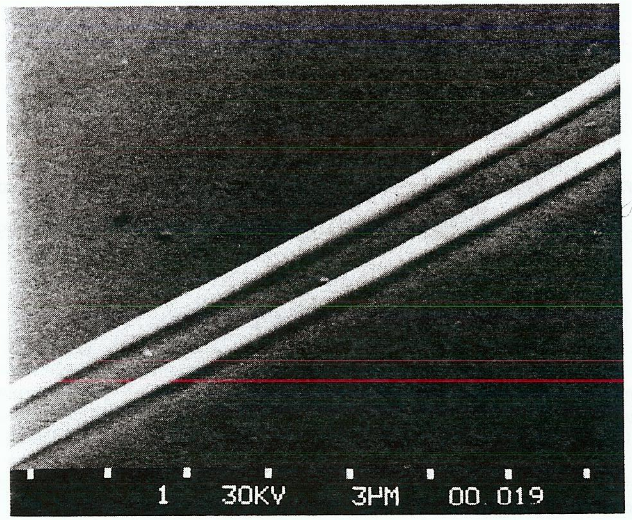

Fig. 5. Two EIPs on the primary slip system.

Again the signs of the EIPs are that of Figure 2a, the intrusions are hidden behind the extrusions, since the viewing direction is into the acute angle between extrusion and specimen surface.

In general, one can say that EIPs on all slip planes have the sign shown in Fig. 2a. An intrusion on the other side of the extrusion was never observed at magnifications limited only by the resolution of the scanning electron microscope. The major difference between EIPs on secondary and primary slip system is that the latter often extend over several millimeters, while the former have lengths of less than 50 micrometers. This is of course due to the fact that the necessary stress and strain concentrations on the secondary systems can only be produced within small areas.

CONCLUSIONS

1. EIPs do not form at coarse slip lines which were produced by one tensile or compressive overload.
2. Isolated EIPs can be produced by sufficiently smooth cyclic overloads on the primary slip system as well as on secondary slip systems if stress concentrators are introduced.
3. Isolated intrusions but no isolated extrusions were observed.
4. All EIPs were of one sign only (intrusion at the obtuse angle between extrusion and surface).
5. The results favour the ratcheting mechanism whereby EIPs are formed at preexisting stage-I cracks (Neumann, Fuhlrott, Vehoff, 1979).

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