ANALYSIS OF SURFACE DISTURBANCES ON POLISHED SURFACES OF SINGLE CRYSTAL SPECIMENS CONTAINING A MODE I CRACK

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The aim of this work was to study the stress and strain fields around the tips of cracks loaded in tension in single crystals of two materials, copper as a representative of the f.c.c. crystals, and iron silicon alloy as a representative of the b.c.c. crystals. In this work is described an attempt to explain (or "predict") which slip systems will be activated in which sector around the crack tip for the plane strain conditions on the specimens surface by the "principal stress" method. Results given for several cases of crack orientations in single crystals of both tested materials show good agreement of the flow patterns observed with those predicted by the principal stress method.

INTRODUCTION

The importance of studying the plastic deformation of single crystals was recognized long time ago in works by **Taylor** and **Elam** (1,2,3). They studied the distortion and fracture of aluminum and iron single crystals, both in tension and compression, and observed that these two materials, when loaded, behave very differently, and that the difference in their behavior stems from their different crystallographic structures. The current view is that plastic deformation in single crystals takes place mainly as shear on certain crystallographic planes, "slip planes", and on these planes only parallel to certain directions, "slip directions", i.e., on a limited number of "slip systems".

Experiments were carried out in order to analyze stress and deformation fields around the tip of stationary cracks in single crystals. Mainly, the idea was to check the prediction that, depending on the orientation of the crack plane and the direction of the crack growth in the single crystal, two different types of

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plastic deformations will occur. The stress field around the tip of a stationary Mode I crack in an elastic ideally plastic crystal, as derived by Rice (4), consists of several angular sectors stressed to the yield level and with constant stresses within each sector. The stresses and displacements jump discontinously from sector to sector across the sector boundaries. The rays along which discontinuities in the stress and deformation fields occur either coincide with, or are perpendicular to, the traces of slip planes made active by the local stress state. In the former case the deformation is expected to be that of regular shear, that can be accomplished either by activation of internal sources or by emitting dislocations from the crack tip along the slip planes passing through the crack front. In the latter case the deformation is that of the kink-type shear, and internal sources of dislocations are needed since they can not be emitted from the crack tip.

THEORETICAL BACKGROUND

A Cartesian coordinate system used in this analysis is fixed at the crack tip and oriented so that the x_1 axis is pointing in the crack growth direction, the x_2 axis is perpendicular to the crack plane, and the crack front lies along the x_3 axis. Polar coordinates associated with the crack tip are r and θ and the relations

$$\partial r / \partial x_\alpha = e_\alpha; \qquad \partial \theta / \partial x_\alpha = h_\alpha / r \tag{1}$$

govern the transformation to polar coordinates, where e_α and h_α are the components of the unit vectors **e** and **h** in the radial and angular directions, respectively, see Figure 1.a.

The slip systems of the crystal capable of producing (possibly in combination with activity of other systems) sustained plane flow are represented as traces in the x_1x_2 plane, which is usually referred to as the "physical plane"; (the plane of observation of the surface disturbances by slip plane traces is in this context sometimes referred to as the "figure plane"). Once the yield surface for the particular crack orientation in the single crystal is calculated it is possible to determine which slip planes are potentially active within each sector around the crack tip, following the method given in (4). Since the stress state in the sector corresponds to a vertex state of the yield surface, see Figure 1.b., the slip systems that might be activated correspond to both adjacent flat segments that meet at the vertex, see Figure 1.c. It is thus reasonable to expect that more than one slip system can be activated within each sector. However, the full plane stain solution, at least for ideally plastic small scale yielding (**Rice**, **Hawk**, and **Asaro** (5)), shows that the most pronounced flow occurs along the stress discontinuities at the sector boundaries. Flow at such a boundary involves only the single family of slip plane traces corresponding to the flat segment between the vertices defining the the stress states on the two sides of the boundary. When we observe the polished surfaces of the specimen we can notice that there are sectors within which only one set of slip plane traces is visible, or we can observe "empty" sectors without slip plane traces disturbing the surface. This happens whenever one or more of the slip plane traces involves dislocations all having Burgers vector parallel to the figure plane, because the dislocation "steps" in that case do not disturb the surface. One of the solutions for this problem is to cut the specimen in such a way that its surfaces are strictly perpendicular to the crack front, as was done in the work by **Neumann** et al.(6), and others.

EXPERIMENTAL PROCEDURE

Specimens used in the experiments were prepared from 99.9999 % pure copper and iron silicon alloys containing 2.7 and 3.0 % of silicon. Copper single crystals were grown from the melt by the Bridgeman technique in argon, in a specially designed graphite mold, and the iron silicon single crystals were obtained from the Max Plank Institute in Düsseldorf. Crystals were cut in the desired orientation, "extended" with attachments of brass or steel, prenotched and precracked, polished, and then loaded in four point bending. All the details of the lengthy preparation of the specimens are given in dissertation by **Nikolić** (7), and will not be given here for the sake of brevity.

ANALYSIS OF SURFACE DISTURBANCES ON POLISHED SPECIMEN SURFACES

The appearance of the surface disturbances caused by the slip plane traces was quite different from those in previous works on similar problems, like works by the group at the Institute for Metal Forming in Düsseldorf, see **Neumann** et al. (6), **Vehoff** and **Neumann** (8), etc. The explanation for this is in the different nature of the tests performed here and in the mentioned works. They studied specimens that were fully plastically deformed and with such a geometry for which plasticity theory predicts an absence of stress triaxiality, and concentration of plastic flow in front of the crack. Indeed, in front of the crack tip in their figures we can see "empty" sectors without slip plane traces which is not the case in the majority of our experiments.

The experiments that were performed here were in four point bending. The motivation for this was to obtain a more complex flow pattern around and ahead of the crack tip, since in the bending tests the triaxiality of stresses, a characteristics of well contained yielding, is retained in front of the crack tip even at fully plastic conditions. This also seems to be the cause of the major problem that arose in the present experiments which was that the flow patterns obtained did not resemble closely those predicted by the theoretical plane strain considerations given in (4). The reason is that with strong triaxiality of stresses in front of the crack tip the whole surface region of the specimen seems to be more dominated by the plane stress conditions.

Principal Stress Analysis

The common feature of all surface disturbances results, that are presented here, is that the slip plane traces corresponding to slip systems activated in "sectors" around the crack tip were almost always "mixed up", with respect to the plane strain solution. The reason for this is that on the surface the plane stress conditions are dominant and the plane strain solution is not valid. Here is described an attempt to explain (or "predict") which slip system will be activated in which sector around the crack tip for the plane stress conditions on the specimens surface, (7), Rice (9).

We start from the assumption that the principal stress directions and ratios in the plane stress state, at the surface of the specimen, are approximately the same as for the in-plane components of the plane strain theoretical solution, that describes the conditions near the crack tip in the specimen interior. Stresses in all sectors around the crack tip were evaluated from the plane strain solution given in (4). Keeping only the in-plane components of stresses from the plane strain stress tensor, we can determine the value and orientation of the maximum principal stress in each sector around the crack tip. This then enables us to determine the direction of the maximum shear stress corresponding to each sector. From the orientation of the maximum shear stress we can approximately estimate which slip plane will be activated in each sector.

There is no good theoretical reason why the assumption about the principal stresses in plane stress and plane strain being approximately the same should be made, though there is a certain plausibility to it. It actually provides the rationalization of the surface disturbances observed in our experiments. It also further points to the control of surface disruption patterns by plane stress modes of the plastic yielding. This also points to the fact that the patterns at the surface are, to some extent, controlled by underlying plane strain deformation mode that is plausibly similar to theoretical predictions of (4). For some sectors around the crack tips of considered specimens slip plane traces predicted by this analysis did coincide with the slip plane traces actually observed on the specimens, and for several of the sectors this analysis failed to give the correct predictions.

F.C.C. Crystals - Copper

Specimen # 12. Orientation of the crack in this single crystal is the following: **Crack plane (101); Crack tip along the [$10\bar{1}$] direction, crack growth direction [010].** The expected stress and displacements discontinuities predicted by the plane strain solution lie at angles 54.7, 90, and 125.3^{0}; **with the slip plane traces making angles of 35.26, 144.73, and 90^{0} with the x_1 axis.**

This is the case of crack orientation for which the deformation is expected to be that of the kink type shear on inclined bands ahead of the crack.

The complete field of slip plane traces is shown in Figure 2. We can observe the heavily deformed zone at the very tip of the crack, positioned at 90^{0} to the x_1 axis, and there is the evidence of double slip in the sector ahead of the crack. The principal stress analysis predicts for this sector that slip plane traces that make angles of 35.26^{0} and 144.73^{0} with the crack growth direction should be visible. Incidentally, the plane strain solution predicts the same. In Figure 2 lines are drawn where there seems that discontinuities between different sectors exist, though their position can not reliably be measured. These discontinuities are not so distinctive and only the discontinuity at 90^{0} is clearly noticeable. We can see that in sector behind this discontinuity, i.e., the sector starting at 90^{0}, there are two sets of slip plane traces visible, and they correspond to ($\bar{1}1\bar{1}$) and ($1\bar{1}1$) planes. The traces that correspond to the ($\bar{1}\bar{1}\bar{1}$) planes are predicted by the principal stress analysis. The sector behind the crack tip that borders on the crack surface has no slip plane traces.

Analyzing the slip plane traces observed on this specimen we can conclude that sectors of stresses are "distributed" around the crack tip according to the plane stress conditions and following the stress path on a three dimensional plane stress yield surface, rather than the stress path indicated in the plane strain solution. Appearance of the slip plane traces indicates that active slip planes are correctly predicted by the principal stress method.

B.C.C. Crystals - Iron Silicon Alloy (2.7 % Si)

Specimen # 8. Orientation of the crack in this single crystal is the following: **Crack plane (010); Crack tip along the [10$\bar{1}$] direction, crack growth direction [101]**. The expected stress and displacements discontinuities predicted by the plane strain solution lie at angles 54.7, 90, and 125.3^0; with the slip plane traces making angles of 35.26, 144.73, and 90^0 with the x_1 axis.

This is the case of crack orientation for which the deformation is expected to be that of the kink type shear on inclined bands ahead of the crack.

The complete field of the slip plane traces is shown in Figure 3. As can be observed in all Fe-Si specimens, there is a characteristic curving of the slip plane traces. Since this feature was visible on all specimens, not only on overloaded ones, this can not be attributed to the lattice rotations. The reason for the slip plane traces curvature is the phenomenon known as pencil glide, which is very common in b.c.c. crystals. There was another specimen tested with the same orientation, but the slip plane traces field seemed more filled for this one, and one of the reasons for this is that specimen # 8 was loaded to the fully plastic limit. Ahead of the crack tip we can even observe the double slip, corresponding to the (110) type of planes and not to the (112) type of planes predicted by the plane strain solution. The (121) planes can not disturb the figure plane for this orientation of the specimen. The yield surface of the b.c.c. crystals is made of flat segments corresponding to both (110) and (112) planes. In this sector we observe the traces of the (110) type of planes, since the stresses in this sector ahead of the crack tip were large enough to activate the "outer" segments of the yield surface corresponding to the (110) types of planes. In the sector behind the crack tip stresses were not large enough to activate the (110) planes. The sector ahead of the crack tip ends at about 35^0, when the slip plane traces of the (011) planes vanish, and the traces of the (01$\bar{1}$) planes start to curve excessively. The curvature of the slip plane traces is so dramatic that it seems that actually there is no discontinuities and the slip plane traces of one system gradually curve till they become parallel to traces of the other system. The "discontinuity" at an angle of 70^0 with the crack growth direction which is so distinctive is artificial and the source of it is in illumination of the specimen, which was tilted in the optical microscope to enhance the slip plane traces. The set of slip plane traces that makes an angle of 90^0 with the x_1 axis is visible in the sector behind the crack tip, that starts at 90^0. This set corresponds to the (101) planes and should be visible both in this and the previous sector as is predicted by both the plane strain and the principal stress analysis. This is again one of the cases when these two analyses give the same results as to which set of slip plane traces should be visible in certain sector. On the other hand we can not see this set of traces in the sector behind the 90^0 discontinuity and this is explained y the gradual curvature of the slip plane traces from one to another orientation.

CONCLUSION

The experiments were set to provide Mode I conditions around the crack tip and this was meant to be achieved by loading specimens in four point bending. This was the cause that due to the high triaxiality of stresses ahead of the crack tip as a consequence the conditions at the surfaces of the specimens were dominated by the state of plane stress. In order to analyze the sets of slip plane traces the "principal stress analysis" was developed, based on the assumption that the principal stresses and their ratios are approximately the same in the plane stress state at the surface as in plane strain. There is no good theoretical reason for an assumption like this, but the method provided a rationalization of the slip plane traces fields observed on surfaces of specimens. This also showed that the patterns at the surface are controlled by an underlying plane strain deformation mode.

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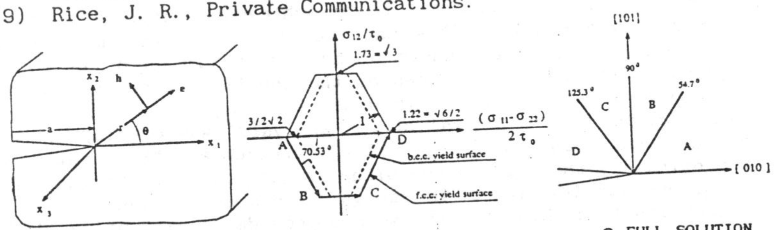

a COORDINATE SYSTEMS **b** YIELD SURFACE **c** FULL SOLUTION

Figure 1.

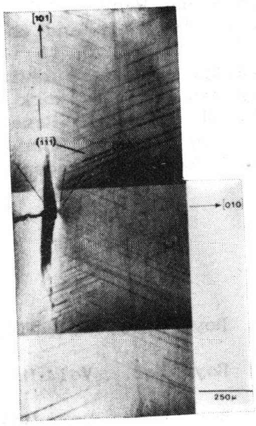

Figure 2. Cu SPECIMEN # 12

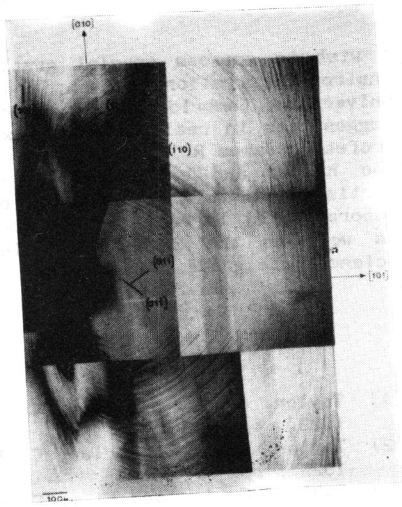

Figure 3. Fe-2.7% Si SPECIMEN #8