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DEPENDENCE OF CRACK FORMATION ON CRYSTALLOGRAPHIC
ORIENTATION FOR ICE

by

L. W. Gold

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IMPORTANCE DE L'ORIENTATION DE LA STRUCTURE CRISTALLINE SUR LA FORMATION DE DISLOCATIONS DANS LA GLACE

SOMMAIRE

L'auteur expose ses observations au sujet de la propagation des dislocations dans la glace polycristalline à structure colonnaire, soumise à une charge constante de compression appliquée perpendiculairement au grand axe des colonnes. Les trois quarts environ des dislocations observées traversaient les cristaux et les autres se produisaient aux joints des grains. Le plan des dislocations avait tendance à se placer parallèlement à la direction d'application de la charge. Les dislocations traversant les cristaux tendaient à se propager soit parallèlement, soit perpendiculairement au plan de base du cristal. Les deux tiers au moins des dislocations des joints de grains impliquaient des joints où le plan de glissement de l'un ou des deux grains adjacents était presque parallèle ou perpendiculaire au joint. L'auteur montre que ces observations concordent avec l'hypothèse exigeant la formation d'un nombre minimal de systèmes de glissement indépendants pour qu'un grain obéisse à une déformation arbitraire provoquée par les contraintes dues aux joints voisins.

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DEPENDENCE OF CRACK FORMATION ON CRYSTALLOGRAPHIC ORIENTATION FOR ICE¹

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ABSTRACT

Observations are reported of crack propagation in columnar-grain, polycrystalline ice subjected to constant compressive load applied perpendicular to the long axis of the columns. About three-quarters of the cracks observed were transcrystalline and the remainder occurred at grain boundaries. The plane of the cracks tended to be parallel to the direction of the applied load. Transcrystalline cracks tended to propagate either parallel or perpendicular to the basal plane. At least two-thirds of the grain boundary cracks were associated with boundaries for which the slip plane of one or both of the adjacent grains was close to parallel or perpendicular to the boundary. It is shown that the observations are consistent with the hypothesis that a minimum number of independent slip systems are required for a grain to conform to an arbitrary deformation under constraints imposed by neighboring grains.

A study by Gold (1960) showed that internal cracks form in columnar-grain ice during creep under constant compressive load applied perpendicular to the long direction of the grains. The cracks, which usually involved only one or two grains, were long and narrow and their plane tended to be parallel to the direction of the applied stress. Subsequently, a study was undertaken of crack formation in the surface of ice plates due to the application of a thermal shock (Gold 1963). In this case the cracks formed so quickly that little if any plastic strain would have been expected to occur before their formation. Under this condition of stressing, it was observed that crack propagation tended to be parallel and perpendicular to the basal plane. Similar observations of crack propagation along preferred crystallographic planes, including cracks formed as a consequence of plastic strain, have been made on numerous metals and nonmetals (Low 1963). A study was undertaken to determine if a dependence of crack propagation on crystallographic orientation also occurred for cracks formed in ice during creep. This paper reports the results of that study and discusses some of the implications of the observed behavior.

STRUCTURE OF THE ICE

The ice was prepared by unidirectional freezing of deaerated tap water, using a technique described by Gold (1960). This produced a columnar-grain ice with grain size between 1 and 6 mm. Because of the conditions of growth there was a strong tendency for only those grains to survive that had their axis of hexagonal symmetry, that is the $\langle 0001 \rangle$ direction, approximately perpendicular to the direction of freezing. The ice from which specimens were prepared, therefore, had a marked preference for the basal plane of each grain

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to be parallel to the long direction of the grain. The $\langle 0001 \rangle$ direction of each grain had no preferred orientation in the plane perpendicular to the long direction of the grains. Grain size tended to increase gradually in the direction of growth.

EXPERIMENTAL METHOD

Three methods were used to study the dependence on crystallographic orientation of the direction of crack propagation during creep.

All observations were made in a cold room maintained at a temperature of $-9 \pm 0.5^\circ\text{C}$.

Method 1

Specimens 4 by 8 cm in cross section and 20 cm long were prepared by milling so that the long direction of the grains was perpendicular to the 8-by 20-cm face. The specimens were placed in an open-top box with ends made of $\frac{3}{8}$ -in. lucite and sides of polyethylene sheet. The box, about 5 cm deep, 9 cm wide, and with an inside length equal to the length of the specimens, was placed in a small bench-type testing machine (Hounsfield tensometer) so that the 8- by 20-cm face of a specimen and the open top of the box faced upwards. A compressive load was applied to the 4- by 8-cm faces, perpendicular to the long direction of the grains. The orientation of the stress with respect to the long direction of the grains and the basal planes is shown in Fig. 1.

FIG. 1. Sketch showing orientation of the columnar grains, basal planes, and cracks with respect to face of specimen and directions of load. Angle α random in size in plane parallel to face of specimen.

The box was filled with kerosene to a depth just sufficient to cover the upper surface of the specimen. As this preserved features that developed on the surface of the ice, they could be observed by microscope and photographed during deformation. Three tests were conducted at average stresses of 5.5, 9, and 10 kg/cm². Slip lines parallel to the basal plane and low-angle boundaries initially perpendicular to that plane formed during deformation and were readily visible. These markings were used to establish at the surface the direction of cracks relative to the trace of the basal plane.

Method 2

Specimens 5 by 10 cm in cross section and 25 cm long were prepared by milling so that the 10- by 25-cm face was perpendicular to the long direction of the grains. The specimens were subjected to a constant compressive stress of between 4 and 20 kg/cm² for a sufficient length of time to allow a number of cracks to form. The specimens were then removed from the testing machine and sectioned perpendicular to the long direction of the grains. The exposed surface was prepared by milling and melting briefly on a warm plate or by polishing with a piece of soft leather. The direction of the trace of the basal plane of grains containing cracks exposed at the surface was determined using either the thermal etch technique described by Krausz (1961) or the etch pit technique of Higuchi (1958). In the thermal etch technique the direction of cracks was determined relative to the direction of low-angle boundaries.

Method 3

Three specimens 5 by 10 by 25 cm long were machined as for Method 2. Each specimen was wetted with kerosene and covered with a thin, transparent plastic sheet to prevent evaporation of surface features during load. A stress of 14.0 kg/cm² was applied to each specimen and the three were deformed 0.5, 1.0, and 1.5%, respectively. Immediately after completion of the test and before removal of the plastic film the surface of grains containing cracks was observed with a microscope.

RESULTS

The angle θ between the plane of a crack and the direction of the applied stress was determined for 566 cracks, θ being measured in the plane perpendicular to the long direction of the grains. The percentage of cracks whose planes were at an angle greater than $\pm\theta$ to the stress is plotted against $\sin |\theta|$ on normal probability paper in Fig. 2. It may be seen from the figure that the frequency distribution for the cracks is close to normal. It was approximately normal as well when plotted against $|\theta|$. The significant point for the present discussion, however, is that the maximum in the frequency distribution occurs for θ equal to 0 deg, that is, when the plane of the crack is parallel to the direction of the applied compressive stress.

The relation between the direction of the trace of the crack at the surface and the crystallographic orientation was observed for 528 cracks. Of these, 121 occurred at grain boundaries and 407 were transcrystalline. Two hundred and six transcrystalline cracks were parallel to the basal plane, 106 were

FIG. 2. Percentage of cracks with sine of angle between the plane of crack and direction of stress greater than $\sin |\theta|$ plotted using normal probability coordinates.

perpendicular to that plane, 14 were indeterminate but were either parallel or perpendicular to the basal plane, and 81 were irregular.

Figure 3(a) is an example of a crack parallel to the basal plane in one grain, perpendicular to it in a second grain, and perpendicular to irregular in a third. Low-angle boundaries can be seen in the grain in which the crack is parallel to the basal plane. Note the abrupt change in direction of the crack surface at the point of intersection of that surface with the low-angle boundary. Such abrupt changes in direction could be followed into the ice to the limit of observation with the microscope. A second example of a crack parallel to the basal plane with associated low-angle boundaries is shown in Fig. 3(b). In both cases the features were obtained by Method 3. The size and shape of the crack beneath the surface under observation could be observed visually without difficulty.

It should be emphasized that in Fig. 3 the cracks are shown in section; the long direction of each crack is perpendicular to the plane of the photographs. The direction of the stress is parallel to the long direction of each photograph.

Figure 3(c) is an example of a crack parallel to the basal plane in one grain and perpendicular to it in a second, as is shown by etch pits. Figure 3(d) is an example of a crack parallel to the basal plane, as shown by low-angle boundaries obtained by thermal etching. A second crack in an adjacent grain is irregular, but tends to be perpendicular to the basal plane at both edges.

Figure 3(e) is an example of surface cracks that were sometimes observed to form in basal planes. In the example shown the plane of the crack is approximately perpendicular to the applied stress. Note the low-angle boundaries, a feature that was always observed to be associated with such cracks.

For at least 85 of the 121 grain boundary cracks observed, the basal plane of one or both of the two grains making up the boundary was either parallel or perpendicular to the boundary. An example is shown in Fig. 3(f), where a large triangular crack occupies almost the whole length of a grain boundary. In this case the basal plane of one grain is almost perpendicular to the boundary

FIG. 3. Examples of the formation of cracks in ice. (Applied compressive stress parallel to long edge of photographs.)

(a) Crack perpendicular to slip lines in grain on left side, parallel to slip lines in center grain, and irregular to perpendicular to slip lines in right-hand grain. Note low-angle boundaries in center grain. The slip lines are assumed to be parallel to the trace of basal planes at surface.

(b) Crack parallel to slip lines. Note low-angle boundaries and severe distortion of grain at lower left of crack.

FIG. 3. (c) Crack parallel to basal plane in left grain and perpendicular to it in right as shown by etch pits. The darkened edge of pits is due to reflection from one of the prism planes perpendicular to the basal plane.

(d) Crack A, on lower left parallel to basal plane as shown by low-angle boundaries. Crack B, in middle, irregular but tends to be perpendicular to basal plane at each edge.

FIG. 3. (e) Surface cracks parallel to basal plane (A, surface cracks; B, low-angle boundary). Note displacement of low-angle boundary at cracks.

(f) Grain boundary crack with basal plane of top grain almost perpendicular to boundary. Note irregular crack in grain on right-hand side, and associated low-angle boundary. Grain boundary crack triangular area at A.

PLATE IV

FIG. 4. Example of deformation of columnar grains due to imposed strain. Note highly deformed region at grain boundaries.

and at an angle of about 18 deg to it in the second grain. It is of interest that the crack has opened up considerably at one edge. This widening did not appear to be associated with grain boundary sliding, but rather with the propagation of irregular cracks for a short distance into the neighboring grain. The deformation near the triple point associated with the irregular cracks was accommodated by the formation of a low-angle boundary.

DISCUSSION

Taylor (1938), Hauser and Chalmers (1961), and Groves and Kelly (1963) are among those who have given consideration to the number of independent slip systems required for a grain in a polycrystalline solid to undergo an arbitrary change in shape and still conform to the shape of neighboring grains. The results of the present experiments will now be discussed from the point of view of such geometric considerations.

Studies such as those by Nakaya (1958) and Glen and Perutz (1954) have demonstrated that slip occurs much more easily in the basal plane of ice than in nonbasal planes. Glen and Perutz (1954) and Steinemann (1954) could find no definite evidence of a preferred slip direction in the basal plane; Kamb (1961) has presented a theoretical argument justifying this observation. Because of these slip properties and the fact that the basal planes tended to be parallel to the long direction of the grains, it would be expected that the deformation of the columnar-grain ice used in the present experiments would be almost two-dimensional. Observations by Gold (1960) did show that the creep strain in the direction of the long axis was much less than that perpendicular to that axis for strains of up to 3%; that is, the initial creep behavior closely approximated the condition of plane plastic strain.

Using the same argument presented by Taylor (1938) to show that at least five independent slip systems are required to allow a grain to undergo an arbitrary change in shape, it can be shown that at least two are required for plane plastic strain. If only one family of slip planes is available, nonuniform internal stresses can be expected to develop owing, for example, to constraints imposed on grains by their neighbors and pileup of dislocations at incompatible grain boundaries. These nonuniform stresses can be expected to induce other modes of deformation.

When the columnar-grain ice was first subjected to deformation, each grain had only one independent family of slip planes by which to undergo a change in shape. Observation of surface features indicated that even for creep strains of up to 3% other families of slip planes did not participate in the change in shape of grains to nearly the same extent as the basal planes. This point is illustrated in Fig. 4 where the imposed change in shape is accomplished in the central part of the grains primarily by slip on basal planes and formation of low-angle boundaries. Possible evidence of slip on nonbasal planes was confined almost entirely to the highly deformed region adjacent to grain boundaries, where most of the differences between allowed change in shape of adjacent grains appeared to be accommodated. This behavior is in agreement with the hypothesis, discussed by Hauser and Chalmers (1961), that relatively large stress concentrations sufficient to initiate slip on secondary

slip systems can be established in the immediate vicinity of incompatible grain boundaries.

If the initial change in shape of a grain occurs primarily by slip on a single family of planes, then for those grains with the normal to their slip planes at an angle greater than 45 deg to the direction of the applied stress, the creep strain in that direction will be greater than that perpendicular to it. Similarly, for those grains with the normal to their slip planes at an angle less than 45 deg, the creep in the direction of the stress will be less than the perpendicular component. If the structure remains continuous, then for the former case the grains will probably be subjected to a tensile stress perpendicular to the applied compressive stress. When the slip planes are parallel or perpendicular to the applied load, or close to those positions, it will be difficult for the grain to deform and transverse tensile stresses could be expected to develop. The stresses that are set up will, of course, depend on the orientation of neighboring grains. The situation in Fig. 4, for example, appears to be a case where two grains with their basal planes close to the direction of the applied stress were subjected to a transverse stress that was compressive.

This discussion points out that because of the characteristics of slip for ice, transverse tensile stresses can be expected to develop when the perpendicular to the basal planes of grains is between 45 and 90 deg to the direction of the applied stress or when the basal plane is close to perpendicular to that direction. As potential crack nuclei grow during deformation, cracks can be expected to form at those sites where the size of the nucleus is appropriate and where there is sufficient strain energy to propagate the crack and create the new surface. For example, Fig. 3(e) appears to be a case of crack formation due to stresses associated with the separation of low-angle boundaries as discussed by Stroh (1958). It is possible also that the cracks shown in Figs. 3(a), (b), and (d) were initiated by stresses associated with low-angle boundaries or the pileup of dislocations at grain boundaries.

The present study shows that even when the conditions required for the formation of a crack are approached gradually, transcrystalline crack propagation still tends to take place parallel and perpendicular to basal planes. The tendency, suggested in the foregoing argument, for internal tensile stresses to develop parallel or perpendicular to the basal plane of some grains because of their inability to conform to the deformation would contribute to this behavior.

About one-quarter of the observed cracks occurred at or included grain boundaries. Observations indicate that these cracks tended to form at boundaries that were not compatible with the applied strain field and across which a tensile stress could be expected to develop. The large crack shown in Fig. 3(f) is a good example. Slip cannot be readily transmitted across the boundary at which the crack developed because of the orientation of the slip planes of the adjacent grains with respect to the stress and to each other. The orientation of the slip planes of the grain on the right side of the photograph, furthermore, is such that as the grain deformed under the compressive stress it would develop a wedge-action on the boundary.

The foregoing discussion indicates that the crack-forming process in ice during creep is controlled by the characteristics of the slip behavior, the nonuniform internal stresses that can be developed because of that behavior, and the tendency for ice to cleave along the basal plane and planes perpendicular to the basal plane, probably the prism planes. It suggests also that because slip was confined primarily to only one family of planes in each grain, the ice was able to conform to the deformation only by violating one of the conditions assumed when determining the minimum number of independent slip systems required; that is, that the deformation is one of constant volume. This indicates that the stress required to initiate cracks in ice is small enough that cracks are able to form before the stress is relieved by polyslip or other modes of deformation. The formation of cracks would relieve internal stresses, and thus allow deformation in the immediate vicinity to proceed more readily. Crack formation, development of low-angle boundaries, etc. should have an effect, therefore, on the deformation behavior of ice, particularly of ice that has never been deformed before. Such an effect has been reported by Krausz (1963) and Gold (1965).

There was no evidence that twinning occurred during deformation of the columnar-grain ice. This fact, along with the availability of only a single family of slip planes at the beginning of deformation and the two-dimensional nature of that deformation, makes the ice used in the present experiments particularly interesting. It provides perhaps one of the most primitive systems available for the study of the initial plastic response of polycrystalline material to an applied load; and its behavior demonstrates very well the consequences of the development of internal nonuniform stresses due to variation in response of individual grains to deformation. Formation of internal cracks is visual evidence of the gradual breakdown of structure that can occur as a result of such nonuniform stresses, which, if able to continue, will result ultimately in the failure of the test specimen.

CONCLUSION

Cracks that form under conditions of constant compressive load in columnar-grain ice with basal planes of grains tending to be parallel to the long direction of the columns are inclined to have their plane parallel to the applied load. Transcrystalline cracks tend to propagate parallel or perpendicular to the basal plane. There is a tendency, as well, for cracks to form in grain boundaries for which the basal plane of one or both of the adjacent grains is parallel or perpendicular to the boundary. This is considered evidence that cracks are initiated and propagated along preferred planes in ice, or at grain boundaries, at those sites where the crystallographic orientation of the grains is such that they cannot conform readily to the deformation.

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REFERENCES

- GLEN, J. W. and PERUTZ, M. F. 1954. *J. Glac.* **2**, 397.
GOLD, L. W. 1960. *Can. J. Phys.* **38**, 1137.
——— 1963. *Can. J. Phys.* **41**, 1712.
——— 1965. *Can. J. Phys.* **43**, 1414, 1423.
GROVES, G. W. and KELLY, A. 1963. *Phil. Mag.* **8**, 877.
HAUSER, J. J. and CHALMERS, B. 1961. *Acta Met.* **9**, 802.
HIGUCHI, K. 1958. *Acta Met.* **6**, 636.
KAMB, W. B. 1961. *J. Glac.* **3**, 1097.
KRAUSZ, A. S. 1961. *J. Glac.* **3**, 1003.
——— 1963. *Can. J. Phys.* **41**, 167.
LOW, J. R. 1963. *Progr. Materials Sci.* **12**, 1.
NAKAYA, U. 1958. Res. Rept. 28, U.S. Army Cold Regions Research and Engineering Laboratories, Hanover, N.H., U.S.A.
STEINEMANN, S. 1954. *J. Glac.* **2**, 404.
STROH, A. N. 1958. *Phil. Mag.* **3**, 597.
TAYLOR, G. I. 1938. *J. Inst. Metals*, **62**, 307.