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BY

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DEFORMATION MECHANISMS IN ICE*

L. W. Gold

Numerous observations on the creep of ice and its dependence on temperature and stress have been published in recent years (1-4). Attention has been directed, primarily, to determining the dependence of the steady-state creep rate in the secondary creep stage to the constant applied load. Some investigators have considered deformation processes and their possible relation to the observed creep behavior. Glen attributes the acceleration that occurs in the tertiary stage to recrystallization (2, 5); and Steinemann has shown that recrystallization will take place in thin sections of granular ice that has been strained more than 2%. It has been reported that the average grain size of ice that has been severely strained is smaller than the average grain size before the load was applied (5, 6). These observations are similar to those made on metals deformed at high temperatures.

Shoumsky describes for ice six mechanisms of deformation and associates each mechanism with the applied load and accompanying creep rate (7). The first four mechanisms, which become important in turn as the creep rate increases, are basal slip in the single crystal; slight disturbances of lattice, grain growth, and grain-boundary migration; distortion of the crystal lattice, polygonization and primary recrystallization; intercrystalline sliding accompanied by reduction in grain size and quite severe disruption of the original fabric. At higher rates of strain, fracture along preferred planes and perhaps melting will occur.

During the course of experiments on crack formation in ice subject to a constant compressive load, some information was obtained on the deformation mechanisms that occurred. It is the purpose of this paper to describe these mechanisms, relate them to similar observations that have been made on ice and other materials, and discuss their significance with respect to the

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deformation behavior of ice. This will be done in four sections. The first section contains a description of the ice and the experiments. In the second section the deformation mechanisms observed are described and discussed briefly. The response of a grain to the applied load and the role that the deformation mechanisms play in determining this response are discussed in the third section. Finally, deformation mechanisms are discussed with respect to the observed creep behavior, and some generalizations on the behavior of ice in certain engineering problems are presented.

Description of Ice and Experiments

The ice used in the experiments was made from deaerated tap water in a galvanized tank about 26 inches in diameter and 24 inches deep. Two balloons were placed under a weighted platform at the bottom of the tank and filled with air. This air was maintained at a constant pressure by connecting the balloons to a tube submerged in a column of ethylene glycol. When cooled sufficiently, the water was seeded with fine-grain snow spread densely enough to cover the surface completely. As the water froze, the change in volume forced air from the balloons into the column of glycol. In this way the water froze at almost constant pressure, there being only a slight increase with time because the tension in the rubber of the balloons decreased as they deflated.

Air-free ice plates up to 6 inches thick could be produced without difficulty. Because the freezing was unidirectional, the ice had a columnar grain structure, the long axis of the grains being parallel to the direction of freezing. Thin sections cut normal and parallel to the direction of freezing are shown in Fig. 1a and b.

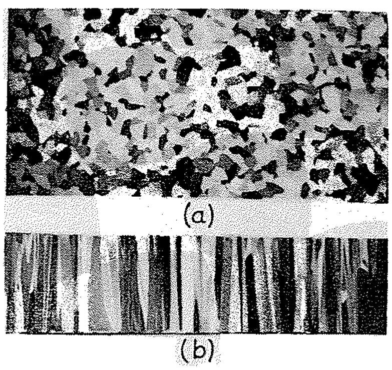


Fig. 1. Thin sections cut normal (a) and parallel (b) to the direction of freezing of columnar grained ice.

It had been hoped that seeding the water with snow would ensure a random distribution in the orientation of the crystallographic c-axis of the grains; but because ice grows more readily perpendicular to the c-axis than parallel to it, this random distribution was not obtained. Within 2 centimeters of the seeded surface there was a marked tendency for the c-axis to be perpendicular to the direction of growth. Observations on 100 grains of a specimen cut at least 5 centimeters from the seeded surface showed that 40% had their c-axis between 85° and 90° to the growth direction, 29% had their c-axis between 75° and 85°, and the remainder between 60° and 75°. The basal plane had therefore a preferred orientation parallel to the long axis of the columnar grains, but a random orientation in the plane perpendicular to the freezing direction. Because of the preferred direction of growth, the grains were slightly tapered, and the average grain size increased gradually in the direction of growth. Ice prepared by this technique has an average grain diameter between 1.50 and 7.0 millimeters.

Observations were made on rectangular blocks of two sizes: 5-by-10-by-25-cm and 2.5-by-5-by-15-cm. The blocks were cut so that the long axis of the grains was perpendicular to either the 10-by-25-cm or the 5-by-15-cm face. All the test pieces were prepared from ice from which the upper 2 centimeters containing the transition region associated with the freezing technique had been removed.

Experiments

The author has shown that when a compressive stress is applied perpendicular to the long axis of the grains in columnar multigrained ice, the cracking activity that results depends on the applied stress and the structure (8). Because of the degree of deformation that occurred during the early experiments, no conclusions could be stated regarding the dependence of the direction of the crack on the crystallographic orientation of the grain in which it formed. Two sets of experiments were designed to investigate this dependence.

In one set, the 2.5-by-5-by-15-cm blocks were submerged in kerosene in a horizontal position and a compressive load was applied to the 2.5-by-5-cm faces. Surface features that would normally be removed by evaporation if exposed to air were preserved in this way. Observations were made on the ice with a microscope during deformation. Three experiments of this kind were carried out, with loads between 5 and 9 kg/cm^2 applied for 60 to 100 hours. These experiments will be referred to as the "kerosene experiments."

In the second set of experiments, a compressive load was applied to the 5-by-10-cm faces of the 5-by-10-by-20-cm blocks, just long enough for about 10 cracks to form. The ice was then removed and sectioned parallel to the 10-by-20-cm face. The crystallographic orientation of the grains in which the cracks formed was determined using Higuchi's technique (9). Although these experiments gave information on the dependence of crack formation on crystallographic orientation, their primary purpose was to investigate the dependence on the applied stress of the time to formation of the first cracks.

In the second set of experiments creep was measured with a special extensometer with a gauge length of 15 centimeters and sensitivity of about 2.5×10^{-6} strain units. The creep that occurred during these tests was always less than 0.1%.

Observations on the deformation mechanisms were made during the course of the experiments just described and the earlier experiments by Gold. All the experiments were carried out at a temperature of $-9.5 \pm 0.5°$ C. Papers that describe in detail the observations of the dependence of crack formation on time and on crystallographic orientation are being prepared.

Description of the Deformation Mechanisms

Slip Bands

The formation of slip bands requires a little comment because it is such a familiar feature of the deformation of solids, particularly of metals. In the kerosene experiments, the bands became visible within 1/2 hour after the application of a load of about $5.5 kg/cm^2$. At this time the strain did not exceed 0.5 by 10^{-3}. With time, the bands became more distinct. Typical examples can be seen in Figs. 2 and 3.

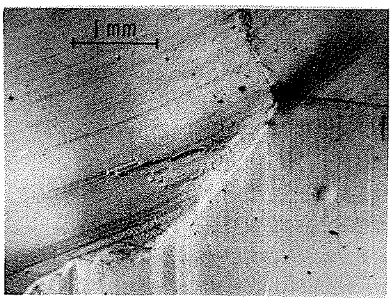


Fig. 2. Evidence of slip on prismatic planes. Note crack at triple point.

Near their melting points single crystals with hexagonal symmetry usually deform by slip on the basal and prismatic planes. Nakaya (10), Steinemann (11), and Glen and Perutz (12) have observed that for ice, slip occurs predominantly on the basal

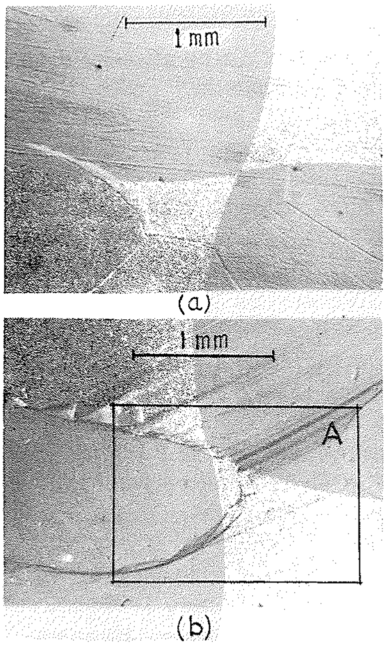


Fig. 3. Grain-boundary migration. (a) Observed 5 1/2 hours after the application of a compressive load of 5 kg/cm^2. (b) Same site 61 hours, 40 minutes after the application of the load. Insert A locates area shown in Fig. 3a.

plane and that little or no evidence has been found of slip on the prismatic planes. This conclusion is supported by observations made in the kerosene experiments. In one experiment, however, evidence observed at the surface of two grains suggested that glide on prismatic planes had occurred. The specimen was subject to a load of about 8 kg/cm^2. Figure 2 shows one of these surface features, photographed about 30 hours after the application of the load. Notice that this feature is confined to the triple-point region and associated with grain-boundary and slip-line distortion, suggesting a high local stress. A similar association has been found by Hauser and others (13) for the occurrence of slip on prismatic planes in magnesium. The second evidence of prismatic slip was the same as the first, except that it was observed immediately after the load was removed, on a face parallel to the long axis of the grains. The second feature was not associated with a triple point as was the first, but there was evidence of deformation normal to the surface.

It would appear that near the melting point the loading conditions required to cause prismatic slip in ice must be very special. It was assumed, therefore, that the slip lines define the trace of the basal plane at the ice surface. The slip bands can thus be used to determine the plane containing the crystallographic c-direction but not the angle between this direction and the ice surface.

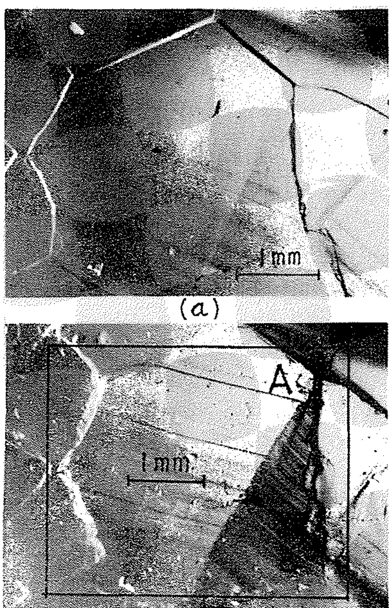
In Fig. 2, only the features raised above the ice surface are considered evidence of prismatic slip. The short lines not associated with a raised feature were observed quite often and will be discussed further under subboundary formation.

Grain-Boundary Migration

Grain-boundary migration was one of the first signs of change in the grain-boundary configuration. An example of this is shown in Fig. 3a; the direction of compressive stress is parallel to the long direction of the photographs. The first evidence of boundary movement was observed about 1/2 hour after the application of the load, when the creep strain was less than 0.05%.

The degree to which boundaries etch in successive positions shows that migration must occur quite rapidly, and that boundaries remain stationary in their new positions for some time. This observation is in agreement with that made on other materials on the migration of boundaries under stress (14).

Practically every boundary observed showed evidence of migration. In some cases the boundaries became very irregular (Fig. 4b). In experiments on the creep of ice beams, Krausz (15) has observed cases of grains that were completely consumed by their neighbors, although no example of this was observed in the kerosene experiments.



(b)

Fig. 4. Small-angle boundary. (a) 5 hours after application of load of 9 kg/cm^2. Compressive stress parallel to long direction of photograph. (b) The same area 70 hours, 25 minutes after the application of the load. Shadow in upper right caused by internal crack. Note small surface cracks. Insert A locates area shown in Fig. 3a.

Small- Angle Boundaries, Kink Bands

Small-angle boundaries were observed to form in the kerosene experiments before deformation had exceeded 1%. These boundaries were always perpendicular to the slip bands during the early stages of deformation. As the deformation increased, it became clear that in some cases they were associated with the formation of kink bands. Kink bands, first reported by Orowan (16), are a familiar feature in the deformation of some metals, particularly those with a hexagonal symmetry (17). Their formation is a mechanism by which a bending moment, transverse to the slip direction, can be relieved in crystals with only one or two possible slip directions. Dislocations generated by the deformation are absorbed at the small-angle boundaries separating the bands. This causes a slight difference between the orientation of the grains on either side of the boundary, the difference increasing with deformation. An example observed in the kerosene experiments is shown in Fig. 4, where the applied load was 9 kg/cm^2.

Gervais and others (18) have shown that in high-purity aluminum the plane of kinking bisects the angle between the slip planes on either side of the kink boundary, and that the line of intersection of the kink plane and the slip planes is perpendicular to the slip direction. Rotation associated with the change in orientation across the plane of kinking is about the line of intersection. Because of the columnar structure of the ice used in the experiments and the bias in the crystallographic orientation, this line of intersection would tend to be parallel to the long axis of the grains. Subboundary and kink band formation, therefore, probably involve the whole grain and not just the part observed at the surface. This was proved by observing, with polarized light, thin sections cut perpendicular to the long axis of the grains from the center of a deformed test piece. Since there is a slight change in orientation at the plane of kinking, the kink bands show up very clearly under polarized light, as may be seen in Fig. 5. Higuchi's

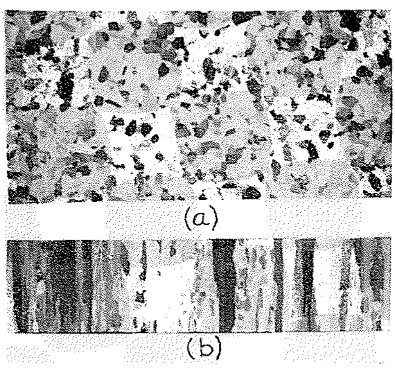


Fig. 5. Thin sections perpendicular (a) and parallel (b) to the long axis of columnar grained ice deformed about 6% by a compressive load of 9 kg/cm^2. Note evidence of kink band formation in section perpendicular to the long axis of the grains.

technique was used to show that the boundaries of the bands are approximately perpendicular to the basal plane.

In Fig. 5 it may be seen that in some cases the kink band features are continuous and can be traced through a number of grains, clearly demonstrating how the mode of deformation of one grain can be strongly influenced by that of its neighbor.

In some grains, the bending moment was not relieved by the formation of small-angle boundaries or kink bands. In these cases the slip plane developed a marked curvature, the region of curvature often having a rough appearance, with numerous short line features perpendicular to the curved slip lines. Examples of curved slip lines and short line features can be seen in Figs. 2, 3b, and 6. The short lines appear to be short small-angle boundaries.

Distortion of Grain Boundaries

As the deformation increased, the boundaries of most grains became severely distorted. Examples of this are shown in Figs. 4b and 6a and b. Severe distortion of the grain boundary regions has been considered evidence of fragmentation. Suiter and Wood (19) and Ramsey (20) considered that the continuous background that they observed in their X rays of deformed magnesium and and zinc, respectively, was due to such debris. The upper and lower boundaries of the central grain in Fig. 6a do appear to be in a fragmented condition.

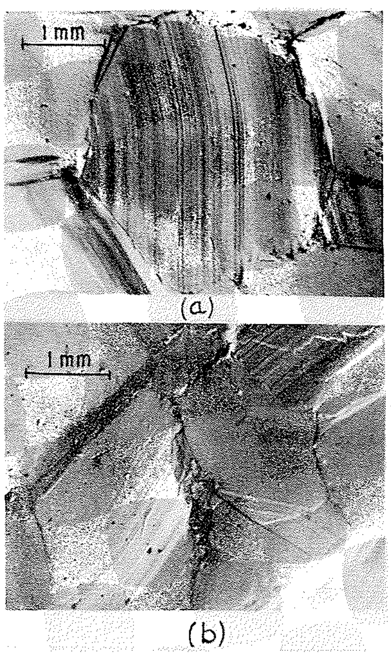


Fig. 6. Examples of grain-boundary distortion. (a) Photograph taken 30 hours and 45 minutes after application of load of 9 kg/cm^2. (b) Photograph taken 33 hours and 45 minutes after application of load of 9 kg/cm^2.

Close examination of some deformed boundaries in the kerosene experiments showed cell formation by the orthogonal system of sliplines and subboundaries with subsequent relative rotation. At some sites the slip planes on two adjacent grains were so orientated that the boundary developed steps and had the appearance of a staircase. At other sites, the constraints at the boundary were such that small cracks developed. Some boundaries had a narrow region that appeared to be highly disturbed (Fig. 6). For the temperature, deformation rates, and duration of load used in the experiments, the slip planes and subboundaries observed retained their identity during deformation. No surface evidence of recrystallization was observed.

Crack Formation

One of the interesting deformation features observed was that of crack formation. Earlier work had shown that for the ice structure symmetry, temperature, and load geometry used, these cracks can be either intercrystalline or transcrystalline; they propagate in the direction of the long axis of the grain; and their plane tends to be parallel to the direction of stress (8). Subsequent observations have shown that the time to formation of the first cracks has an approximate logarithmic dependence upon the applied stress; that crack formation is rare during the primary creep stage for stresses below about 6 kg/cm^2; and that the transcrystalline cracks tend to be either parallel or perpendicular to the basal plane.

Many investigators now consider that for all cases where crack formation is time dependent as well as stress dependent, the cracks nucleate at sites where the moving dislocations associated with the creep process are blocked. At these sites the stress resulting from blocked dislocations increases until it exceeds the local strength of the material. Since the movement of dislocations is along preferred planes in the crystal, it is to be expected that crack formation will be related to crystallographic orientation. There is now considerable experimental evidence supporting this hypothesis. An excellent review of current thinking on crack formation can be found in the Proceedings of the International Conference on Fracture held in Swampscott, Massachusetts (21).

In the experiments where load was applied only long enough for about 10 cracks to form, and then the ice sectioned and the crystallographic orientation of the grains determined by the technique of Higuchi, 132 cracks were studied. Sixty-seven % of the cracks were transcrystalline and the remainder intercrystalline. The surface trace of 31% of the cracks was observed to be parallel to the surface trace of the basal plane; that of 15% was perpendicular to the trace of the basal plane; that of 9% was either perpendicular or parallel; that of 12% was neither. Figure 7a is an example of a crack whose surface trace is parallel to the basal plane.

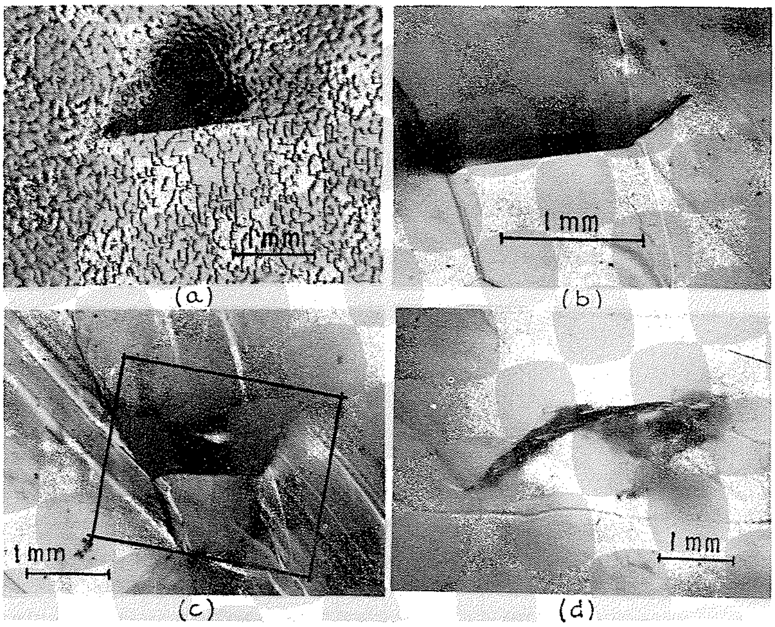


Fig. 7. Cracks during deformation. (a) Example of crack whose surface trace is parallel to the basal plane. The etch pits were formed using the technique of Higuchi. (b) Example of transcrystalline crack formation observed 6 1/2 hours after the application of a compressive load of 9 kg/cm^2. Direction of load parallel to long edge of photograph. (c) Same site as Fig. 7b, 45 hours later. Insert A locates area shown in Fig. 7b. (d) Crack involving a combination of grains and grain boundaries. Compressive stress parallel to the long dimension of the photograph.

In the kerosene experiments it was possible to observe the cracks during deformation. Figure 7b is an example of a crack involving two grains. In one it is parallel to the basal plane and in the second, perpendicular. Figure 7c is the same crack 45 hours later. Note the subboundaries that have formed in association with the deformation. Note also that although the crack has opened considerably, little if any grain-boundary sliding has occurred. Accommodation between grains is associated rather with slip along basal planes and grain-boundary migration. Figure 7c is a good example of how the initial dependence of crack formation on crystallographic orientation can be masked by the deformation.

Many cracks involved only one grain. In these cases one edge of the crack would often be at the grain boundary. If the crack involved more than one grain, it would usually change direction abruptly at the grain boundary so as to be either parallel or perpendicular to the basal plane. If the crack was not either parallel or perpendicular to the basal plane, it tended not to propagate very far into that grain and was usually irregular, sometimes showing a tendency to curve into the basal plane.

In some cases the crack geometry was quite complex, involving a number of grains. For even these cases, a dependence of crack formation on crystallographic orientation can be observed for most of the grains involved. An example is shown in Fig. 7d, where the crack has propagated along the grain boundary and into three neighboring grains. In one case the crack is perpendicular to the basal plane, in a second, parallel. In all the photographs shown in Fig. 7, the crack is viewed approximately parallel to its plane and normal to the short direction.

Cavities

A deformation feature that has received attention lately is the formation of internal cavities (22, 23). These cavities are usually observed at grain boundaries or at the intersection of slip planes or slip planes and subboundaries of metals deformed in tension. One possible mechanism of their formation is considered to be the coalescence of microscopic holes either in the material to begin with or generated during creep. There is evidence that cavities can serve as nuclei from which cracks can develop.

Cavities were easily visible at a magnification of about 10 × before the creep strain has exceeded 3% under a compressive load of about 8 kg/cm^2. The cavities were in the region of grain boundaries, grain-boundary triple points, and the intersection of slip planes and subboundaries. Sometimes cavity formation was great enough to form a continuous column. Such a column, with cavities in the background is shown in Fig. 8.

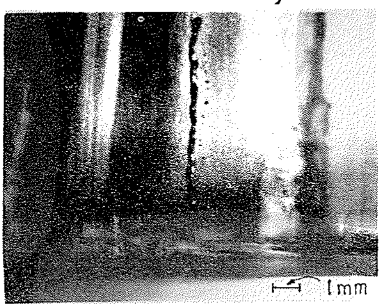


Fig. 8. Cavity formation in multigrained ice.

Recovery and Recrystallization

Although there was no surface evidence of recrystallization during deformation for the temperature, creep rates, and periods of loading used in the experiments, evidence of recovery and recrystallization was observed to occur at the surface and internally after the load had been removed. Figure 9 shows for the same region shown in Fig. 3 the grain-boundary rearrangement that occurred after the load had been removed. Note the irregular

Fig. 9. Recrystallization and polygonization at the same site as in Fig. 3. The rearrangement of grain boundaries occurred after the load had been removed (total deformation about 2.5%).

grain boundaries and polygonization associated with these irregularities; note also the subboundary that terminates at a slip plane feature in the grain in the lower left-hand corner. The ice was etched by immersing in kerosene.

Thin sections cut from ice deformed 70 or more hours under loads between 5 and 10 kg/cm^2 showed extensive recrystallization. This may be seen by comparing Figs. 1 and 5. The thin sections cut parallel to the long axis of the grains show clearly a tendency for the columnar structure to be transformed into a granular one. Figure 5 shows also that recrystallization appears to be primarily associated with the grain-boundary region. No evidence was obtained to show that recrystallization occurred during or after deformation. It is quite possible that the evidence for recrystallization bears the same relationship to conditions during deformation as Fig. 9 does to Fig. 3.

Unusual Creep Behavior

Gold observed that for the ice and conditions of loading used in compressive creep experiments an initial increasing creep rate with time was sometimes observed (8). This observation has been confirmed by subsequent experiments on creep under compressive load and by investigations by Krausz (The creep of ice in bending. Report in preparation), who has studied some of the features of this behavior manifest in the deformation of ice beams.

Similar behavior has been reported for ice single crystals (11, 12, 24). For single crystals the effect extends over deformation of some 10 to 20%; for multigrained ice the effect is associated with the primary creep stage, and is completed before deformation has exceeded 0.5% under the conditions of loading used. The unusual behavior is irreversible. On subsequent reloading, the creep curve is of the normal type. With repeated loading and associated deformation, the observed creep curve becomes more reproducible as long as loading conditions are identical and certain restrictions are placed on the recovery time. An example of the unusual creep behavior and the creep behavior observed on subsequent reloading is shown in Fig. 10.

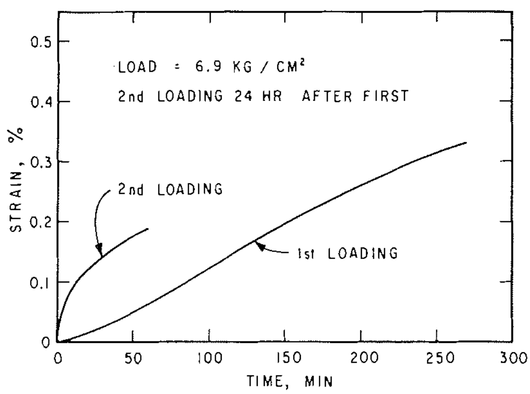


Fig. 10. Unusual creep behavior of ice.

Response of a Grain to an Applied Load

Taylor (25) has pointed out that the deformation of a crystal can be completely determined by measuring the strain in six independent directions. If the volume remains constant during deformation, these reduce to five. From this he deduces that a crystal can be deformed at constant volume into any arbitrary shape as long as slip can occur in five independent directions. It would be expected that an aggregate of such crystals could be deformed and contact maintained between the crystals without introducing major disorder in the boundary regions. If the number of operative independent slip directions is less than five, local stresses that oppose the applied stress will develop owing to the constraints imposed by neighbors. These constraints are probably the main source of the increase in the resistance to deformation of an aggregate over its constituent crystals.

For the experiments on multigrained ice described in this paper, the load was applied perpendicular to the long axis of the grains. There was a strong preference for the basal planes of the grains to be parallel to this axis. This resulted in deformation that was predominantly two-dimensional, the creep in the direction of the long axis of the grains being much smaller than that perpendicular to it (8). For two-dimensional deformation of this character, the requirement postulated by Taylor of five independent directions in which slip can occur is reduced to two, these being in the plane of the deformation.

Ice has only one effective slip plane, and resistance to slip within this plane is independent of direction (11, 12, 26). There is, therefore, only one slip direction available to each columnar grain for the loading conditions used. As the ice is deformed, the inability of the grains to conform to this deformation must result in local stresses between grains. The deformation mechanisms that have been described are the ways by which a grain responds to these local stresses. They replace the second independent slip direction that a columnar grain requires to undergo an arbitrary change in shape in the plane perpendicular to its long direction.

The first response of ice to an applied stress is an elastic deformation that apparently involves the movement of dislocations. Evidence for this can be found in the observations of Bryant and Mason (27) and Gold (28). This is followed by non-reversible slip with associated movement of dislocations, creation of dislocation generating sources, and establishment of slip zones or bands. The imperfections present initially in the structure, or generated subsequently, will migrate in such a direction as to reduce the local stresses developed in grains by the constraining action of neighbors. In cases where the appropriate bending moment is established, subboundaries and kink bands will be formed. If the dislocations are not absorbed at the subboundaries and are not blocked internally, they will migrate into the grain-boundary region.

Observations indicate that slip and subboundary, kink band formation or bending are sufficient to allow the central part of a grain, but not the boundary region, to conform to the imposed deformation. The sometimes extensive reorganization of the structure that occurs in this region suggests that most of the accommodation that must be made between grains during deformation takes place here. The first sign of this reorganization is grain-boundary migration. The combination of grain-boundary migration and slip is often sufficient initially to satisfy the deformation requirements of some boundaries for the ice used (Fig. 3). As deformation increases, greater reorganization such as cell formation is required. If the material in the boundary region is to undergo the required relative translation and rotation without structural failure (cracking), sufficient imperfections such as dislocations must be available. If the rate at which these imperfections are made available to the region is not sufficient to allow the local deformation to conform to that applied, the local stress will increase, and microcracks may form. This cracking can produce highly fragmented regions (Fig. 6a).

Cavities are a particularly interesting feature of deformation. They probably form in planes transverse to local tensile stresses established by the compressive load. Although they may act as nuclei from which cracks can form, no evidence was obtained that showed that this was so. Their formation at triple points and intersection of glide planes and subboundaries is in agreement with a mechanism suggested by Gifkins (29). Cavity formation is a mechanism that should result in the reduction of local tensile stresses.

Some grains are so oriented that their basal plane is either parallel or perpendicular to the principal stresses and have no operative slip plane. These grains may be considered as hard sites within the aggregate. Their neighbors must deform around them. Under a compressive load, material will tend to flow away from a hard site in a direction perpendicular to the applied stress.

A grain with its slip direction either parallel or perpendicular to the applied stress will thus be subject to compression in the direction of that stress, and to tension in the perpendicular direction. It is to be expected that the tensile stress will tend to increase with deformation. If the increase is great enough, a crack will result. The formation of the crack may be aided by the growth under the applied stress of potential crack nucleation sites such as cavities. Once the crack has formed, the grains associated with it can more easily conform to the applied deformation. Because of the direction of local tensile stresses, the plane of the cracks tends to be parallel to the applied compressive stress. It is significant that the plane also tends to be parallel or perpendicular to the basal plane. It is of interest that these cracks form during the primary creep stage. For creep under compression they are a stable modification of the structure, even for severe deformation such as is shown in Fig. 7b and c and can be considered as "accommodation" cracks.

The lower the creep rate, the fewer are the accommodation cracks that form and the longer is the time required for the first to develop. For specimen temperature of $-10^{\circ}C$ and creep rates corresponding to an applied stress of about 6 kg/cm^2, such cracks are rare. This suggests that processes that go on in the boundary region, such as grain-boundary migration, cell and cavity formation, in association with slip, cavity, subboundary, and kink band formation, are able to maintain the stress below the local failure strength. Under these conditions crack formation is no longer required as a deformation process in the primary and secondary creep stage.

Deformation Mechanisms and Creep Behavior

Practically all the observations on the deformation mechanisms that have been recorded in this paper were made during the primary and secondary stages of creep. Only for experiments with higher loads did the deformation include the tertiary stage. In these cases the observations were only on the character of the crack formation that occurred.

The deformation mechanisms observed are in general agreement with the scheme proposed by Shoumsky (7). In addition to the mechanisms that he describes, others such as kink band and cavity formation, and accommodation cracking were observed. Shoumsky relates the mechanisms to the applied load and associated creep rate. Experiments suggest that for a given temperature, creep rate is probably the major factor in determining what mechanisms are required for a grain to conform to the applied deformation. At low creep rates grain-boundary migration, subboundary, kink band, and cavity formation, polygonization, and bending are likely to be sufficient. For higher creep rates accommodation cracking during the primary creep stage and greater distortion in the grain boundary region occur. In addition to creep rate, the amount of deformation and the duration of the load are probably important as well. This appears to be true for the unusual creep behavior and is probably true for the onset of tertiary creep as indicated by the observations of Steinemann (1).

Although the resistance to slip on the basal plane of previously undeformed single crystals decreases with increasing deformation, this is not considered to be the source of the unusual creep behavior observed in multigrained ice, except perhaps for the very first part of the deformation. This view is supported by the observation that resistance to deformation of the aggregate is much higher than the resistance of the basal plane, and for the conditions of the experiments, the unusual creep behavior in the aggregate is completed before the strain has exceeded 0.5%. For the single crystal the unusual creep behavior extends over some 10 to 20% strain.

The ice used in the experiments was always maintained within 10°C of its melting temperature. It would be expected that as long as the pressure in the water was not allowed to increase while freezing, there should have been little or no deformation of grains in a specimen prior to the first application of load. The experiments suggest that the unusual creep behavior of previously undeformed multigrained ice is related to the variety of ways by which a grain will adjust to the deformation of its neighbors. These ways appear to be established in the primary creep stage. Their formation is an irreversible process, determined by the local crystallographic orientation and grain boundary geometry, the character of the applied load, the rate of straining, and presumably, the temperature. If the ways by which a grain will deform are established during primary creep, this suggests that the deformation rate for secondary creep may be determined by the rate at which dislocations and other imperfections generated by the applied load will diffuse to the cell and grain boundaries.

Steinemann (1) and Glen (2) suggest that tertiary creep is associated with recrystallization. None of the experiments with lower loads were continued to deformations where this would be observed. It was only for loads in excess of about 15 kg/cm^2 that the observations included the tertiary stage of creep. For these tests the accommodation cracking was very extensive. Onset of tertiary creep appeared to be associated with the breakdown of the structure by the accommodation cracking and subsequent failure along planes approximately parallel to the maximum shear direction (8). Cracking of a character different from the accommodation cracking was associated with these planes.

Application to Ice Engineering

Although the ice used in the experiment described had a unique grain structure and grain crystallographic orientation, it is possible to present some generalizations pertinent to ice engineering. For slip to occur on the basal planes of ice there must be a shear stress in that plane. On application of a load such a stress will be present initially in most grains, but it will be maintained only for those cases where the load subjects the ice to a shear stress. There are a number of practical examples of loading where it is quite possible that the basal planes are not subject to such a shear stress.

For example, when an ice cover on a lake or river is subject to a changing air temperature, the principal thermal stresses that develop are equal in the plane parallel to the surface. This is true as well for a stationary concentrated load, and to a first approximation for slowly moving loads. If the basal planes of the grains are parallel or perpendicular to the ice surface, a situation that can occur under some field conditions, the shear stress on them will be zero. This would explain why thermally stressed ice covers can remain stressed for quite appreciable periods of time, and will often crack when drilled or walked upon. If thermal stresses can be maintained for appreciable periods, they can have a very significant effect on the bearing capacity of the ice, particularly for ice thicknesses less than 50 cm. Many of the ice failures that have occurred in the normal operation of Canadian pulp and paper companies are thought to be the result of stresses or associated cracks formed in the cover by changing temperature.

Considerable attention has been given in recent years to various laboratory and field tests for determining values of the properties of ice required for the solution of engineering problems. Because the deformation response of ice depends on the relationship between the applied stress, the grain-boundary configuration and the crystallographic orientation of the grains, as well as the magnitude of the stress and the temperature, there is certainly some question as to whether numbers obtained from such tests can be used for the solution of engineering problems involving ice under quite different load conditions. It is possible that the solution of such problems will have to be obtained from direct field observations, and that the greatest usefulness of load tests will be to indicate the quality of the ice involved.

Summary

Polycrystalline, columnar grained ice, with the basal plane of each grain approximately parallel to its long axis, cannot deform under an applied load without stresses being set up in the grains due to the constraints imposed by neighbors. These stresses cause grain-boundary migration, subboundary, kink band, and cavity formation, and accommodation cracking. Along with slip on the basal plane, these stress-induced processes allow the grain to conform to the applied deformation. The various ways by which a grain will deform during a load test appear to be established in the primary creep stage. The experiments indicate that deformation thereafter proceeds by relative translation and by rotation about the boundaries and accommodation cracks established during primary creep. This suggestion leads to the hypothesis that secondary creep rate is controlled by the rate of diffusion of imperfections generated by the applied load.

The dependence of the deformation of ice on the grain-boundary configuration, crystallographic orientation, and the nature of the applied load should be taken into consideration in some engineering problems, particularly those in which there may be no shear stress on the basal planes. It should also be considered when applying results obtained from laboratory and field tests on ice, particularly from small-scale tests.

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