THE FRACTURE OF ICE Ih

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RESUME

La rupture fragile de la glace est considérée du point de vue physique. La fracture en traction uniaxiale est discutée en terme de nucléation et de propagation de fissures. La fracture en compression uniaxiale est décrite en termes de résistance à la fracture,de déformation en fond de fissure,de frottement de type coulombien et d'interactions des fissures avec une faute de cisaillement. Des modèles sont présentés et sont comparés avec les résultats expérimentaux.

ABSTRACT

The brittle fracture of ice is considered from a physical viewpoint. Fracture under uniaxial tension is discussed in terms of crack nucleation and crack propagation. Fracture under uniaxial compression is described in terms of fracture toughness, end constraint, Coulombic friction, and crack interactions within a shear fault. Models are presented and are compared with experimental results.

INTRODUCTION

Polycrystalline ice Ih exhibits both brittle and ductile behavior, depending upon the conditions of loading. Under uniaxial tension at strain rates above $\approx 10^{-7}s^{-1}$ and under axial compression at rates above $\approx 10^{-3}s^{-1}$ the material is brittle at terrestrial temperatures. At lower rates it is ductile and exhibits > 1% inelastic strain. The brittle behavior is a reflection of the operation of only two easily activated slip systems of the form {0001} <11$\bar{2}$0> and two are insufficient for grain to grain contiguity. The ductile behavior results from textural (i.e., fabric) changes originating in thermally activated microstructural restorative processes, such as dynamic recrystallization (1,2). Regardless of its behavior, however, ice cracks internally during loading and this process, if not counteracted by healing, eventually leads to fracture.

This paper considers the brittle fracture of ice Ih from a physical viewpoint. A companion paper (3) addresses fracture toughness. Attention is placed upon behavior under uniaxial tension and under uniaxial compression, with emphasis on recent studies at Dartmouth on the properties of equiaxed and randomly oriented fresh-water ice. The tensile behavior was discussed earlier (4-6), but is combined here with new data on the compressive behavior to provide an overview of the subject.

FRACTURE UNDER UNIAXIAL TENSION

Two criteria must be satisified before ice, intitially free from cracks and pores, fractures under tension: inelastic flow must be sufficient to nucleate cracks; and the tensile stress must be sufficient to propagate them (4). The first criterion follows from the fact that the total axial strain under nucleation-controlled fracture always exceeds the elastic strain, by a factor of 1.5 to 2.0. The second follows from the observation that under certain conditions (given below) cracks are stable upon nucleation and propagate only under higher applied stresses.

Nucleation can be understood in terms of the internal concentration of shear stress. The pile-up of dislocations at grain boundaries is one mechanism, and leads to the following form of expression for the axial stress to nucleate a crack (7):

$$\sigma_T^N = \sigma_o + k\,d^{-1/2} \qquad \text{--- (1)}$$

where d is the grain size, σ_o is a measure of the inherent resistance of the lattice to slip and k is a measure of the effectiveness with which grain boundaries impede the transmission of slip from one grain to another. In more fundamental terms, k can be written (7):

$$k = \langle m \rangle \left(\frac{3\pi\ \gamma G}{8\ (1-\upsilon)} \right)^{1/2} \qquad \text{---} (2)$$

where <m> is the Taylor orientation factor, γ is the surface energy, G is the shear modulus and υ is Poisson's ratio.

Crack propagation can be understood in terms of linear elastic fracture mechanics. Accordingly, the tensile stress to propagate a crack proportional in size to the grain size is given by an expression of the form:

$$\sigma_T^P = K\, d^{-1/2} \qquad \text{---} (3)$$

where K is a measure of the fracture toughness, K_{IC}, of the geometry of the microcracks, and of the degree to which the cracks interact. For internal penny-shaped cracks which do not interact and which are oriented at 90° to the tensile axis, K can be written:

$$K = \left(\frac{\pi}{2\alpha} \right)^{1/2} K_{IC} \qquad \text{---} (4)$$

where α relates the diameter of the propagating crack to the grain size.

Figure 1 illustrates these relationships. Crack nucleation controls the fracture of more coarsely grained ice and occurs after very little inelastic deformation. Crack propagation, on the other hand, controls the fracture of more finely grained material and occurs after significant inelastic flow. In the latter case the ductility increases as the grain size decreases and occurs as the applied stress increases from σ_T^N to σ_T^P. The "ductility" results in part at least from additional cracking when grains favorably oriented for slip shed load to grains less favorably oriented.

The grain size, d_c, which distinguishes the more finely grained ice from the more coarsely grained material is termed the critical grain size and can be expressed as:

$$d_c = \left(\frac{K - k}{\sigma_o} \right)^2 \qquad \text{---} (5)$$

This is a microstructural statement of the brittle to ductile transition and, as noted below, is a function of the loading conditions. As the strain rate decreases, for instance, the tendency is for K to increase and for k and σ_o to decrease, thereby raising d_c.

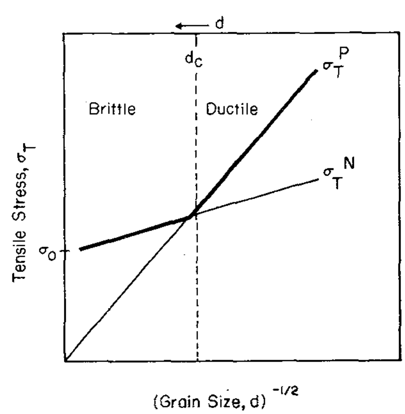

Figure 1. *Schematic sketch of the effect of grain size on the stress to nucleate* (σ_T^N) *and to propagate* (σ_T^P) *cracks under uniaxial tension.*

The above assertions are supported by the results of systematic experiments at -10°C on defect-free, laboratory-grown ice Ih of controlled grain size loaded under strain-rate control in a servohydraulic testing machine. When strained at the relatively high rate of $10^{-3}s^{-1}$, polycrystals of grain size spanning that which occurs in nature (1mm to 10mm) fracture after very little inelastic deformation, Figure 2. The fracture stress is proportional to (grain size)$^{-1/2}$, Figure 3, and is well described by Equation 1. The intercept is σ_o = 0.51 MPa and the constant of proportionality is k = 0.030 MPa • m$^{1/2}$. Appropriate values of the constants in Equation 2 (G = 2300 MPa; υ = 0.35, <m> = 3, γ = 0.1 J/m^2) yield a theoretical value of k = 0.06 MPa • m $^{1/2}$, in fair agreement with the measurement. When the ice is strained at the lower rate of $10^{-6}s^{-1}$, similar behavior is observed for the more coarsely grained polycrystals (d >1.5mm), but now k is reduced to 0.020 MPa • m$^{1/2}$ (5). The differences between the measured and the theoretical value of k suggest the operation of a thermally activated mechanism which relaxes the stress concentrated at grain boundaries. The fracture surface is normal to the tensile axis and the two halves of the fractured specimen are free from cracks, Figure 4. These last points imply that the first crack propagated in a mode-I manner either immedately or shortly after it nucleated. Crack nucleation thus controls the tensile fracture under the above conditions.

Polycrystals strained at the lower rate of $10^{-7}s^{-1}$ exhibit different behavior. Fracture now occurs after noticeable inelastic deformation, Figure 5, and the inelastic strain increases with decreasing grain size, Figure 6. The tensile strength again increases with decreasing grain size according to (grain size) $^{-1/2}$, but now tends to zero, and not to σ_o, as the grains become very large, Figure 7. The functional relationship is well described by Equation 3 in which K = 0.050 MPa • m$^{1/2}$. The fracture surface is again normal to the tensile axis, but the two halves of the test specimen now contain remnant or non-propagated cracks, Figure 8. From these observations it is concluded that crack propagation controls fracture at the lower rate.

The second conclusion is confirmed by the fact that the value of K calculated from Equation 4 agrees very well with the measured value, if one assumes that the cracks which propagated were only slightly larger than the largest remnants; i.e.,

$$K = \left(\frac{\pi}{2 \times 3.7}\right)^{1/2} \times (0.08) = 0.052 \text{ MPa} \cdot \text{m}^{1/2}.$$

The factor 3.7 appears for α and was obtained by measuring the size of the largest remnant cracks, Figure 9; the value K_{IC} = 0.080 MPa • m$^{1/2}$ was obtained from separate measurements of fracture toughness at -10°C at high loading rates (8) and is the average value for the range of grain sizes (1 to 10mm) examined. (K_{IC} is dependent upon grain size, but the dependency is small and does not substantially change the foregoing arguments. Also, the cracks are somewhat elliptical, rather than circular, in shape and their peripheries are irregular, (9). Again, these more detailed features do not substantially alter the above arguments.)

The other point that the experiments support is the concept of a critical grain size. The behavior at the higher rate of straining ($10^{-3}s^{-1}$) suggests that d_c <1mm, while that at the lower rate ($10^{-7}s^{-1}$) suggests that d_c > 10mm. The implication is that at an intermediate rate, d_c should fall somewhere between these extremes, and it does. At $10^{-6}s^{-1}$, d_c = 1.5mm (5).

In summary, the fracture of uncracked ice Ih under uniaxial tension can be quantitatively understood in terms of the nucleation and the propagation of cracks, at least at strain rates of the order of $10^{-3}s^{-1}$ and lower and at relatively high homologous temperatures.

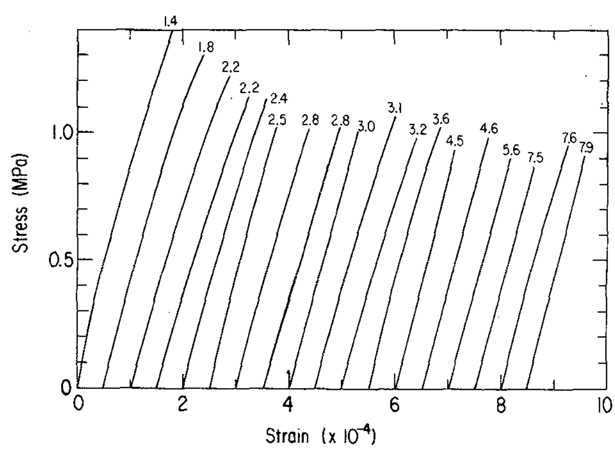

Figure 2. Stress-strain curves for equiaxed and randomly oriented aggregates of fresh-water ice Ih of varying grain size (given in mm beside each curve), strained in tension at $10^{-3}s^{-1}$ at -10°C. (From Lee and Schulson, 1986).

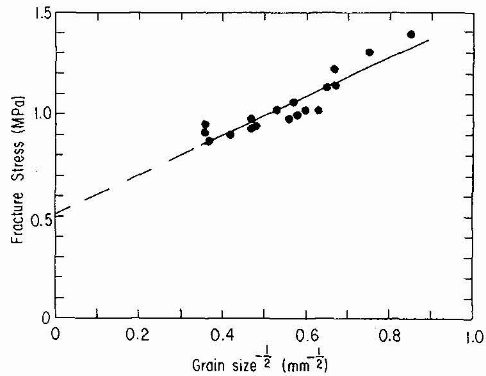

Figure 3. Tensile fracture strength versus (grain size)$^{-1/2}$ from curves in Fig. 2.

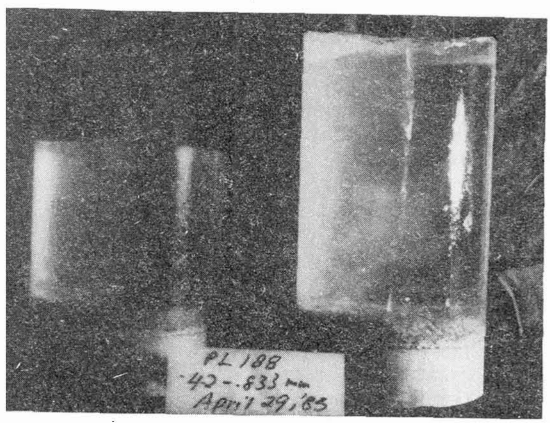

Figure 4. Photograph of a typical test specimen broken in tension at $10^{-3}s^{-1}$ at -10°C. Note absence of internal cracks.

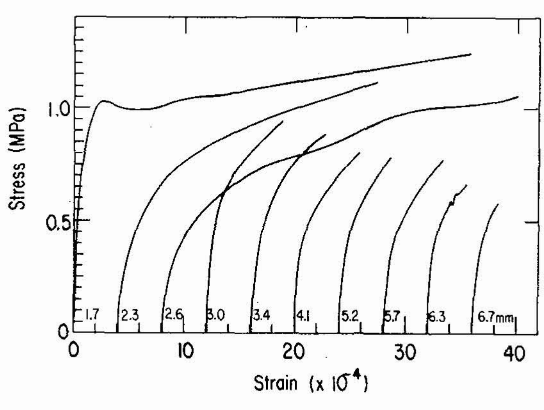

Figure 5. Stress-strain curves for ice (as Fig. 2) strained in tension at $10^{-7}s^{-1}$ at -10°C. (From Lee and Schulson 1986).

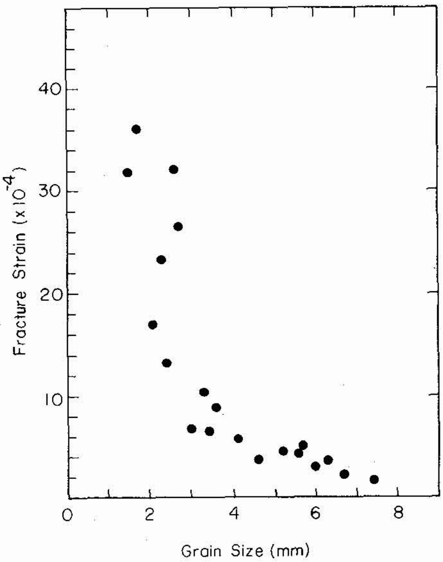

Figure 6. Total strain to fracture versus grain size from Fig. 5.

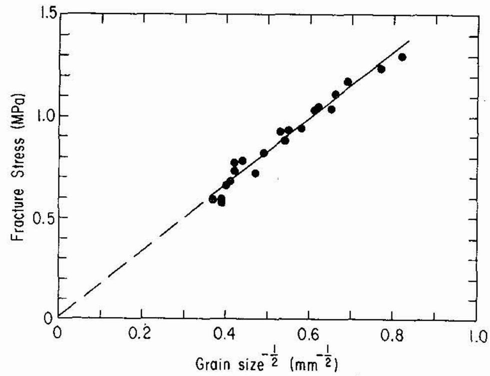

Figure 7. Tensile fracture strength versus (grain size)$^{-1/2}$ from curves in Fig. 5.

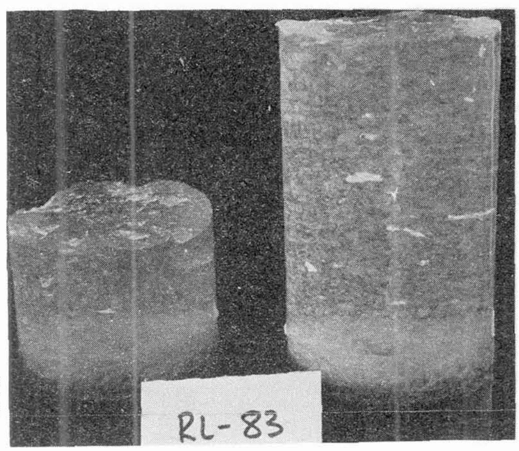

Figure 8. Photograph of typical test specimen broken in tension at $10^{-7}s^{-1}$ at -10°C. Note internal cracks.

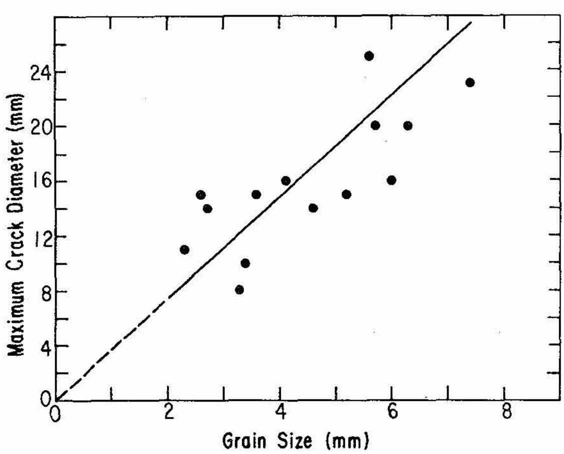

Figure 9. Maximum crack diameter versus grain size of remnant cracks in test specimens broken at $10^{-7}s^{-1}$ at -10°C. (From Lee and Schulson 1986).

FRACTURE OF CRACKED ICE UNDER TENSION

In nature ice more often than not contains cracks, and so the question arises: Does the fracture of cracked ice occur through the propagation of a pre-existing crack once the principal tensile stress across the plane of the crack reaches the level described by Equation 3?

The answer depends upon the size of the cracks and possibly upon the degree to which they have healed. Size can be measured, or at least estimated, and with the aid of equations 1 to 4 and with parametric values appropriate for the conditions of interest can be judged to be sufficient or not. The critical diameter, $2a_c$, is given by:

$$2a_c = \frac{\pi}{2}\left(\frac{K_{IC}}{\sigma_o + k\,d^{-1/2}}\right)^2 \qquad \text{--- (6)}$$

and is shown in Fig. 10 for high rate ($10^{-3}s^{-1}$) straining at -10°C. Cracks within a randomly oriented polycrystal of grain size d = 3mm, for instance, will propagate if they exceed 10mm in diameter, but will not if they are smaller. In other words, even though the ice is cracked, its strength may still be controlled by the nucleation of new cracks. Hoxie (9) established this point through a systematic investigation of the tensile strength of ice freshly pre-cracked under radial compression or under uniaxial tension. His results are shown in Fig. 10.

Yet, even if the pre-existing cracks are judged to be supercritical, they may not propagate. Healing, such as the blunting of crack tips and localized bonding across the surface of internal cracks, occurs relatively quickly (i.e., within hours) at temperatures around -10°C (9,10) and acts to lessen the effectiveness with which cracks concentrate stress. Healing could thus account for the two stable "supercritical" cracks noted in Figure 10. The quantitative distinction between young and old cracks has not yet been formulated, but work on the kinetics of healing has begun by Colbeck (11). The effect is expected to increase the slope of the curve in Fig. 10 and must be considered when judging the stability of cracks under load.

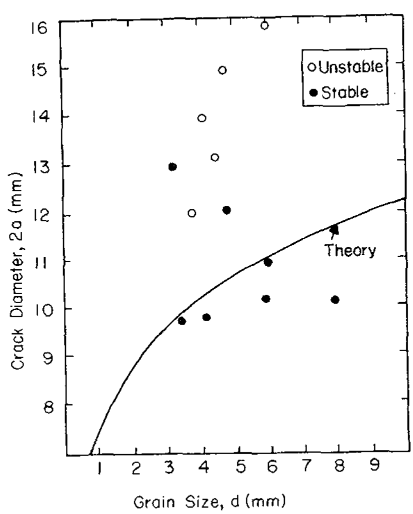

Figure 10. Critical crack diameter versus grain size for granular ice Ih strained in tension at $10^{-3}s^{-1}$ at -10°C. The data were obtained from tensile tests on pre-cracked ice.

FRACTURE OF SEA ICE UNDER TENSION

Another question concerns the relevance of the foregoing theory to the strength and fracture of sea ice.

Sea ice is a composite of ice Ih and of the secondary phases brine, gas and sometimes precipitated salts, organized in a manner which reflects the atmospheric and oceanic conditions under which it formed.

The grains are usually columnar or candle-like in shape and contain the brine as plate-like arrays of pockets oriented along the direction of growth. The spacing of the platelets ranges from 0.1mm to 1mm and decreases with increasing growth velocity, apparently through a reciprical square root relationship characteristic of the solidification of two-phase materials. The c-axes of the columnar ice are oriented within the plane of the sheet, frequently in a direction parallel to the direction of the near- surface ocean currents. The material is thus more complex than the randomly oriented, equiaxed fresh-water ice considered above. Correspondingly, its mechanical behavior is more complex.

Systematic studies of the tensile fracture of sea ice are now underway at Dartmouth. A guiding point in this work is the early observation of Anderson and Weeks (12) that the fracture path is along the brine platelets, at least when a significant component of the applied tensile stress acts normal to the platelets. This feature implies (13) that the brine pockets act as stress concentrators and thus lower the tensile strength relative to that of fresh-water ice. Another guide is the work of Goetze (14). Using linear elastic fracture mechanics, he predicted that the tensile strength of sea ice is directly proportional to (total porosity)$^{-1/2}$. He then showed that the data available at the time (obtained mostly from ring specimens) were consistent with this view, Figure 11. Crack propagation, in other words, appears to be strength-limiting.

It appears, therefore, the fracture of sea ice and of fresh-water ice are similar.

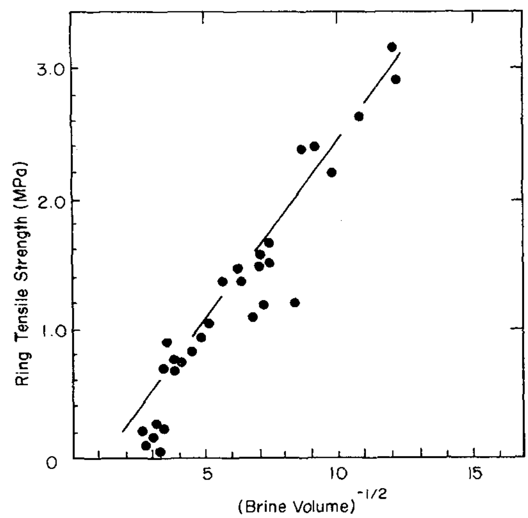

Figure 11. Fracture strength (ring tensile strength) versus (brine volume)$^{-1/2}$ of sea ice. (From Goetze 1965).

BRITTLE FRACTURE UNDER UNIAXIAL COMPRESSION

Fracture under a uniaxial compressive load is more complicated than fracture under tension. Crack nucleation and propagation are still important, but now crack sliding, crack interaction and Coulombic shear must be considered. A complicating factor in developing a model of brittle fracture under compression is that failure occurs within a few seconds of loading ($\dot{\varepsilon} > 10^{-3}s^{-1}$).
It is difficult, therefore, to distinguish events. Nevertheless, the observations which have been made and which are described below do allow the following scenerio to be created.

We imagine five stages, Figure 12. Stage-1 is an elastic stage in which no permanent changes occur within the ice. Stage-2 begins at a higher stress when cracks begin to nucleate within the body of the ice. The end-zones remain essentially crack-free, owing to a friction-related radial confining stress which increases as the ice cracks. Stage-3 begins at a higher stress still when, in the manner described by Ashby and Hallam (15) and by Nemat-Nasser and Horii (16) for brittle solids, wing cracks begin to initiate on favorably oriented cracks. The wings constitute out-of-plane extensions, and form in order to reduce to K_{IC} the mode-I stress intensity factor, K_I, which exists at the tip of the cracks. K_I originates from the induced, in-plane shears stress which, when sufficient to overcome the Coulombic frictional resistance, causes the opposing surfaces of the crack to slide. During stage-3 cracks continue to nucleate, the damaged ice continues to expand away from the end zones, and the radial confining stress increases. Stage-4 begins at an even greater axial stress when, again as described by Ashby and Hallam (5) and by Nemat-Nasser and Horii (16), the wings begin to grow through the field of short cracks into longer cracks which are aligned along the direction of the main compressive load. The growth occurs to maintain K_I at K_{IC} at the tip of the wing. K_I now originates mainly from the wedging open of the mouth of the wing through the continued sliding of the opposing faces of the parent. Cracks continue to nucleate, but within grains which are increasingly poorly oriented for slip.

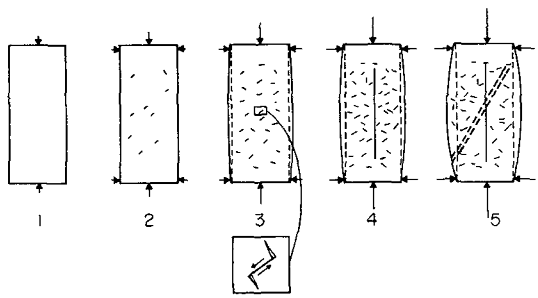

Figure 12. Schematic sketch of five separate stages in brittle fracture under compression with end constraints: stage-1, elastic; stage-2, crack nucleation; stage-3, wing crack initiation; stage-4, wing crack growth; stage-5, shear faulting.

If the material were not confined at ends, it would fracture during stage-4, i.e., when one of the wings grows, under an increasing axial load (15), to a length sufficient to cause buckling or to cause axial cleavage. However, it seems that a fifth stage is required, at least in an experimental situation when end constraints are difficult to avoid.

Stage-5 is not necessarily the continuation of the previous stage. Rather, it is viewed as the development of a shear fault through the collective action of an ensemble of favorably oriented cracks, followed by the growth of this "nucleus" into a full macroscopic shear fracture. Stage-5 could be termed intrinsic fracture, after Argon (17), as opposed to extrinsic fracture.

Supporting this view are a number of experimental observations on the compressive fracture at -10°C at $10^{-3}s^{-1}$ of equiaxed and randomly oriented fresh-water ice to which end-caps were bonded. (The caps were made from a fiber reinforced phenolic resin ("synthane") whose elastic modulus, Poisson's ratio and coefficient of thermal expansion are similar to those for ice.) The strain-strain curves, Figure 13, exhibit slight negative curvature which is a manifestation of the increase in the number density of microcracks during straining. The fractured material , Figure 14, is opaque relative to its transparency prior to testing, a further manifestation of the high number density of the cracks. Either conical end pieces bonded to the caps or two pieces of ice sheared off plus granulated ice constitute the products of failure, and the remnant pieces contain axial cracks (Figure 14). The fracture surfaces are inclined at ≈ 30° to the principal compressive axis, implying a Coulombic frictional coefficient of ≈ 0.6 (see Equation 8 below). And the surfaces are lightly covered with granulated ice which renders them milkier in appearance than the damaged material as a whole.

Concerning the strength-limiting step, it is clear that crack nucleation is not critical. This point is evident from the fact that the ice does not fail upon the nucleation of the first crack, and from the fact that the failure strength (13 MPa to 4 MPa at -10°C, see below) is several times greater than the nucleation stress (0.5 MPa to 1.5 MPa). Nucleation occurs under the same uniaxial stress in compression as in tension (Equation 1). Nor is the strength limited by the initiation of the wings on the most favorably oriented cracks. Ashby and Hallam (15) show that wings on internal cracks are stable in PMMA and Nemat-Nasser and Horii (196) show that they are stable in glass and in a resin. Ice should be no different. It also appears that the strength is not limited by the growth of the wings, because the ultimate collapse of the end-capped specimens does not occur through slabbing. Rather, the strength seems to be limited by the shear faulting.

The details of this process are not clear. However, the faulting probably begins when a loaded shear plane which is relatively dense with favorably oriented cracks develops more cracks under the intensified shear stress acting in the plane of the existing cracks, Figure 15 a & b. Wings may subsequently form on the pre-existing cracks and lead to grain-sized regions which are almost surrounded by cracks. Linkage may then occur through the breaking off of grain-sized fragments which may then be ground into still finer fragments as the fault eventually fails, Figure 15c. That Nemat-Nasser and Horii (16) did not observe crack nucleation, but only wing formation, when loading a resin containing an ensemble of closely spaced cracks lying in two closely spaced parallel shear planes does not mean that nucleation as envisaged here will not occur in ice, because the ease with which cracks nucleate in the two materials may differ.

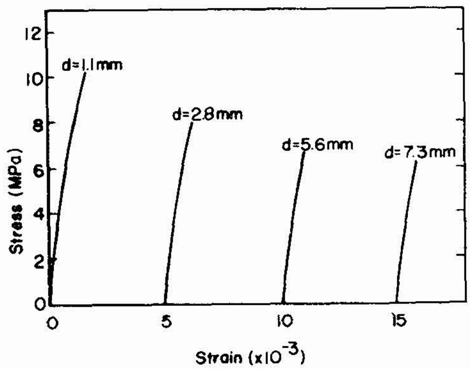

Figure 13. Stress-strain curves for equiaxed and randomly oriented aggregates of fresh-water ice Ih strained in compression at $10^{-3}s^{-1}$ at -10°C.

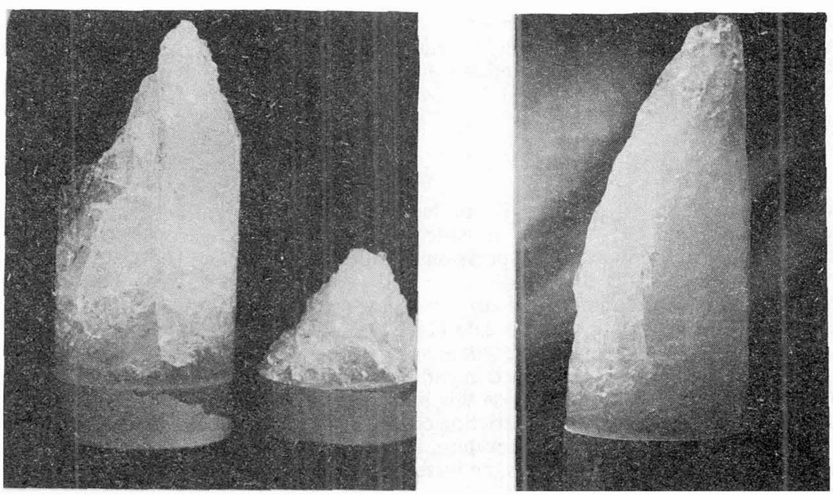

Figure 14. Photographs of ice Ih (as Fig. 13) compressed to failure at $10^{-3}s^{-1}$ at -10°C. Note the milky appearance (compared to the transparent appearance of ice fractured in tension, Figs. 4 and 8), the axial cracks and the sheared fracture surface.

The strength, therefore, is thought to be limited by the step preceding crack linkage. Wings propagate until they interact with adjacent wings and then stop. The stopping is suggested because Ashby and Hallam (15) observed such a phenomenon in PMMA. Accordingly, the brittle compressive strength, σ_c, should then be directly proportional to K_{IC} and to the (characteristic microstructural length) $^{-1/2}$ and it should reflect the Coulombic character of the micro-sliding across the crack faces. Thus, by equating the characteristic microstructural length to the grain size (since cracks in ice are directly proportional to the grain size, as shown by Cole (10) and by Lee and Schulson (6), σ_c may be written as:

$$\sigma_c = \frac{Z\, K_{IC}\, d^{-1/2}}{(1 + \mu^2)^{1/2} - \mu} \qquad \text{---(7)}$$

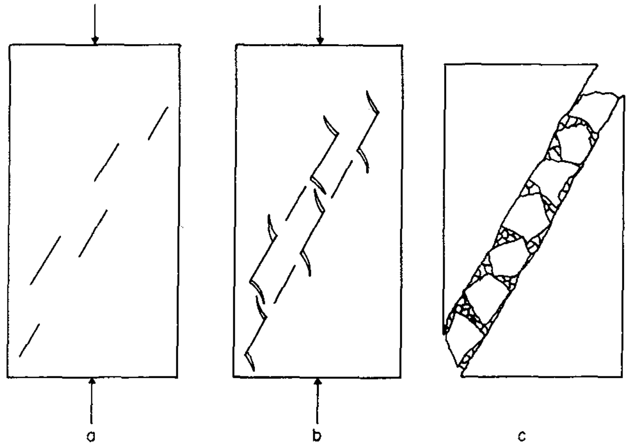

Figure 15. Schematic sketch of three steps in the shear faulting (stage-5, Fig. 12) of ice fractured under a uniaxial compressive load but with constrained ends: a) fault nucleation; b) fault growth; c) fault failure.

Z is a parameter which denotes the orientation of the plane on which the induced tensile stress is a maximum, the number density of the cracks within the shear fault and the interaction amongst such cracks. The denominator incorporates the relationship :

$$\frac{1}{\mu} = \tan 2\Psi_C \qquad ---(8)$$

where μ is the coefficient of friction of ice on ice and Ψ_C is the angle between the direction of the principal compressive load and the plane on which the shear stress effective in forming the wings is a maximum. Equation 7 is similar to the expressions derived by Ashby and Hallam (15) for the initiation and the growth of wings on isolated cracks.

The model, although incomplete, is supported by measurements during the compressive tests described above. Although scattered, the data (18,19) show that σ_c is directly proportional to $d^{-1/2}$, Figure 16. The data also show that the strength increases by a factor of 2.5 as the temperature drops from -10°C to -50°C. This effect can be explained in part by the unusual increase in toughness with decreasing temperature, but cannot be accounted for on this basis alone because K_{IC} increases by only 50% from -10°C to -50°C (3). The other factor is the friction coefficient which, in keeping with the report by Barnes et al. (1), increases with decreasing temperature, at least over the range from 0°C to -18.5°C. When coupled with the increase in the toughness, an increase of 33% in the friction coefficient would account for the thermal effect.

The other observation that supports the model and which underlines the importance of frictional sliding is the reduction in the brittle compressive strength upon increasing the strain rate above $10^{-3}s^{-1}$. This effect has been reported several times over the years (e.g., see Michel [20]) and we have observed it too (19). Upon increasing the rate to $10^{-1}s^{-1}$, the strength falls by ≈30% (Fig. 16). This effect cannot be explained in terms of toughness, because at -10°C K_{IC} is rate independent above ≈ 10 kPa • $m^{1/2}s^{-1}$ (8). Within our regime K > 100 kPa • $m^{1/2}s^{-1}$. However, the effect can be explained in terms of a reduction in the coefficient of sliding friction. The crack sliding rate, δ, is directly proportional to the applied strain rate and to the grain size, implying that for $\varepsilon = 10^{-3}s^{-1}$, the range of sliding velocities corresponding to our grain sizes is $\delta \approx 10^{-6}$ m • s^{-1} to 10^{-5} m • s^{-1}. At the higher strain rate, $\delta \approx 10^{-4}$ m • s^{-1} to 10^{-3} m • s^{-1}. At these rates μ decreases with increasing δ (1). In fact, if one assumes that the friction coefficient of one face sliding upon the opposite face scales with the numbers given by Barnes et al. (1), then the increase in strain rate should promote a reduction of ≈ 15% in the friction coefficient and, according to the model, a reduction of 30% in the strength. The last point is in good agreement with experiment.

Given the apparent validity of the model, a number of implications follow. One is that the compressional end-constraint arising from the use of synthane end-caps bonded to the ice increases the brittle compressive strength . Without this constraint fracture would probably occur through axial splitting. The functional relationship of the strength to grain size and to toughness would still be as noted in Equation 7, but its relationship to frictional resistance would probably be of the more sensitive form $\sigma_c \propto (1 - \mu)^{-1}$ as noted by Ashby and Hallam (15) for wing crack growth. A related implication is that compressional confinement along the full length of the test specimen, and not just at the ends, should increase the tendency for failure via shear faulting instead of axial cleavage. This transition has already been noted by Richter-Menge (21) in experiments on laboratory-grown saline ice strained at -10°C at rates above $\approx 10^{-3}s^{-1}$ by loading along the growth direction. The other implication is that the brittle compressive strength should decrease to a plateau when plotted against strain rate, once the crack sliding velocity is so high that the friction coefficient approaches zero. Again assuming the data of Barnes et al. (1) to be relevant, the plateau is expected at a rate of $\approx 1\ s^{-1}$ at -10°C.

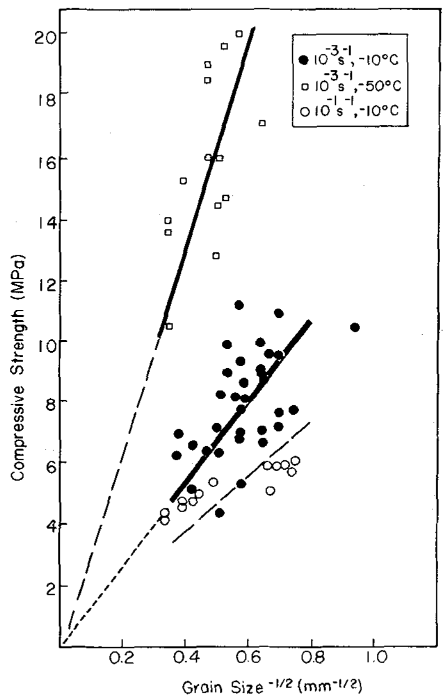

Figure 16. Uniaxial compressive fracture strength of ice Ih (as in Fig. 13) versus (grain size)$^{-1/2}$, as a function of temperature and strain rate.

LIMITATIONS

The ideas invoked in all of the above discussion and the attendant models are limited to the so-called quasi-static loading regime where dislocations can move quickly enough to accommodate strain and where a single crack can relieve the tensile stress. In the dynamic regime, other ideas and other models are necessary. Internal cracking still occurs, but a much larger number of cracks is needed to relax the tensile stress. More energy is consumed during fracture and the fracture strength is higher. At $\approx 10^4 s^{-1}$ for instance, the tensile strength of fine-grained fresh-water ice Ih ($d \approx 1$mm) at -30°C is $\approx$17MPa (22) compared with $\approx$1.5 MPa at $10^{-3}s^{-1}$ at -10°C. Correspondingly, the fractured ice is fragmented.

The transition from the "quasi-static" to the "dynamic" regimes is difficult to estimate, but is thought to be around 10 s^{-1}. This is only a very rough estimate and is based upon dislocation and crack velocities being unable to exceed the speed of sound and upon a moderate ($\approx 10^8$ / m^2) dislocation density. Nevertheless, it cautions against the application of the models presented above to a regime in which they do not apply.

CONCLUSION

The brittle fracture of polycrystalline ice Ih, when strained at rates within the so-called "quasi-static" regime ($\varepsilon < 10s^{-1}$), has been described in terms of physical processes. Under uniaxial tension, either crack nucleation or crack propagation controls fracture, the latter being the more important at low rates and within fine grained aggregates. Under uniaxial compression, fracture appears to be controlled by the formation of a shear fault, at least when the ends of the material are constrained. Accordingly, the fracture toughness and the Coulombic frictional resistance to crack sliding play major roles in limiting the strength. Generally, theory and experiment are in good agreement.

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COMMENTS

S.KIRBY

Just a comment to support your contention that the frictional properties are linked to the compressive strength of ice. We have done compression tests on ice where shear fracture is observed at temperatures between 11 and 158 K. We also done ice friction tests at temperatures between 11 and 115 K at various sliding rates and conclude that frictional resistance is insensitive to variations in these parameters over the range of those test conditions we explored. The shear fracture strength of ice is also insensitive to variations in temperature and shortening rate, consistent with the hypothesis that friction on sliding cracks is involved in determining the fracture strength since the effects of T and deformation rate an friction seems to track those effects on fracture strength.

Answer :

I think it would be interesting to do experiments at temperature between your highest (108 K) and our lowest (223 K). Is the same time it is gratifying that theorys seem to fit together.

P.DUVAL

To obtain the friction coefficient μ, you compare the friction between ice and rocks and between two ice surfaces. What do you think about this comparison ? It seems that the friction coefficient between ice and granite is high compared with the expected friction coefficient between two ice surfaces ($\lesssim 0.1$ at - 10°C).

Answer :

Barnes et al (1971) noted that a layer of ice forms on polished granite when the rock is cold. They added that the shear process that leads to friction, is ice shearing ice. For this reason, I used their observations. However, they did not define "cold". It is possible, therefore that at higher temperatures ($\gtrsim$ - 10°C) the sliding of ice on granite leads to a higher coefficient of friction than the sliding of ice on ice. Caution is appropriate in applying, their number to the case of discuss.

P. SAMMONDS

The failure process through wing crack growth proposed by Ashby al Hallan (Acta Met. 1986) may not be the whole story. Work currently being undertaken at Peking University by Prof. Wang Ren suggests that in some materials fine microcracking occurs at an angle of perhaps 120°C around from the wing crack, and this may be responsible for crack-crack linkage and formation of the macroscopic skew failure. How applicable the Ashby-Hallan model is and when this other observed effect may come into play would probably depend on material inhomogeneity.

Answer :

The A.H. model does not include the generation of new cracks. In this case, the cracks are assumed to exist before loading but not to increase in number density during loading/straining. In ice and other materials cracks continue to nucleate. As a result, the nucleus of a shear fault can develop and then, through its growth, eventualy lead to shear fracture.

S.MURRELL

You showed diagrams of the interaction of overlapping wing cracks. Dr. Sheila Hallam in her works with PMMA models, demonstrated the detachment of fragments trapped between such wing cracks (see Dr. Hallam's paper). We have also observed this phenomenon by scanning electron-microscopy of deformed rocks (see Fouseha, Murrell et Barnes 1985, Int. J. Rock Mechs. Min. Sci. Geomech. Abstr.), and we believe this is an important process in the formation of fault gouge (the fragmented material trapped in a shear fault zone).

Answer :

I agree. My figure 15 c is an attempt to show this process schematically. The finer pieces within the fault are envisaged to form via the rolling/sliding of the larger pieces over each other.

R.W.WHITWORTH

What is the time scale over which your model requires some recovery to occur in tensile fracture ? Our topographic experiments suggest that recovery can be significant over periods of order 10 minutes at - 20°C.

Answer :

The time scale is of the order of minutes to hours at temperature between - 20 °C and - 5°C and at strain rates around 10^{-6} s^{-1}.