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**DOES THE STRENGTH OF ICE DEPEND ON GRAIN SIZE AT
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RÉSUMÉ

Des mesures de la résistance de la glace à la traction sont analysées de nouveau afin d'illustrer que les premiers résultats des essais ne révélaient pas l'influence réelle de la granulométrie. On montre que la forme impropre du spécimen, la difficulté que pose le contrôle du taux de déformation et du taux de contrainte pendant les essais ainsi que la présence d'un grand nombre d'inclusions dans le matériau ont influencé les résultats.

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DOES THE STRENGTH OF ICE DEPEND ON GRAIN SIZE AT HIGH TEMPERATURES?

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Introduction

Currier and Schulson [1] confirmed an earlier proposal of Michel and Drouin [2, 3] that tensile strength, σ_f , of polycrystalline ice decreases with increasing grain size, d , according to the Hall-Petch relation. All the measurements were made at a high homologous temperature of $0.96 T_m$ (-10°C), where T_m is the melting point in Kelvin. Currier and Schulson, however, reported an increase in tensile strength of about 50 per cent for a decrease in grain size from 7.3 to 1 mm, whereas Michel and Drouin reported one of about 300 per cent for the same range of grain sizes. Muguruma too has proposed a Hall-Petch type of relation for the upper yield stress of ice under compression [4], but Jones and Chew [5] found that grain size has no significant effect on upper yield stress. There is clearly reason for further discussion.

The author suggests that the results reported by Muguruma [4] for a grain size range of 2 to 6 mm are misleading because his specimens were unacceptably small ($5 \times 20 \times 25$ mm); that they are an example of a reasonable conclusion drawn from data of questionable value. This was also true of Michel and Drouin's hypothesis of a grain size effect based on strength measurements of three different types of ice: congealed frazil slush, S-4 ice with grain size of about 1.5 mm; granular T-1 ice of grain size 2 to 3 mm; and transversely isotropic S-2 ice of grain size in the range 5 to 9 mm (see classifications in Ref. 6). Although the types of ice differed significantly in average strength, there was no apparent dependence on grain size for the results for either T-1 ice or S-2 ice.

All the tests carried out by Currier and Schulson [1] were performed under a truly constant, closed-loop, controlled cross-head displacement rate, $\dot{x}$, or under a nominally constant strain rate, $\dot{\epsilon}_n = \dot{x}/\ell$, where ℓ is the effective specimen length. For the chosen $\dot{x} = 2.3 \times 10^{-3} \text{ mm s}^{-1}$ and $\ell = 231$ mm for the cylindrical specimens, the nominal strain rate $\dot{\epsilon}_n$ was $1 \times 10^{-5} \text{ s}^{-1}$. The reported discrepancy of one order of magnitude between nominal strain rate of $1 \times 10^{-5} \text{ s}^{-1}$ and the measured specimen deformation rate of $1 \times 10^{-6} \text{ s}^{-1}$ (between end caps) is indicative of a compliant testing machine [7] and raises many questions [8, 9]. Primarily, how constant was the rate during a given test? Were all the specimens deformed at the same rate? These are vital questions. Strength of ice at such a high temperature ($0.96 T_m$) is rate sensitive [7 - 9]. Loading conditions and temperature must be constant if the effect of grain size on strength is to be clearly defined.

Analysis

If loading rate is constant, as claimed [1], and fracture strength, σ_f , varies systematically with grain size, the fracture time, t_f , should also exhibit a systematic variation with grain size, d . Currier's [10] observations (Fig. 1) do not indicate any systematic pattern, suggesting that the loading conditions for the series reported [1] might be far from ideal. This is confirmed in Fig. 2, which illustrates the dependence of tensile strength on average strain rate to fracture [11], $\dot{\epsilon}_f = \epsilon_f/t_f$, where ϵ_f is the measured strain at fracture for the tests carried out by Currier [10]. Thus the specimen strain rates were not constant at $1 \times 10^{-6} \text{ s}^{-1}$, but varied over a wide range (600 per cent) from $6 \times 10^{-7} \text{ s}^{-1}$ to $3.6 \times 10^{-6} \text{ s}^{-1}$.

Note the two necked-down samples (N) exhibiting higher strain rates. This is to be expected [9]. The necked-down samples had a diameter of 69 mm, whereas other cylindrical samples were 91 mm in diameter. The two samples, with about 50 per cent reduction in cross-sectional area, were significantly softer than other samples in relation to the stiffness of the system. The machine could therefore transfer higher deformation rates to these specimens for the same cross-head rate.

FIG. 1

Interdependence between grain size and fracture time observed by Carrier [10]

Hawks and Mellor [12] conducted tensile tests on dumb-bell shaped samples of granular T-1 ice of average grain size of 0.7 mm at -7°C ($0.97 T_m$). They used quasi-constant cross-head rates and discussed the dependence of strength as a function of $\dot{\epsilon}_n$, measuring the displacement between end caps and estimating the strain in the gauge section by using a correction factor. Their tabulated results also showed a discrepancy (about two orders of magnitude) between $\dot{\epsilon}_n$ and the estimated values. Although they did not discuss strengths in terms of measured strain rates, their data provided an excellent opportunity to compare their results with recent observations. The dependence of σ_f on $\dot{\epsilon}_f$, tabulated in Ref. 12, is also shown in Fig. 2. The bars attached to each point indicate the maximum and minimum values tabulated for each group of samples.

The strength values obtained by Hawks and Mellor [12] were significantly higher than those of Carrier and Schulson [1, 10] for about the same $\dot{\epsilon}_f$, in spite of the fact that the temperature was higher. It would be premature, however, to credit these higher strengths to differences in grain size alone without first examining the differences in the microstructure of the samples and the response of the test system. Details are not available, but the ice used by Hawks and Mellor [12] was described as bubbly. The bubble (air or water vapour) density in the ice used by Carrier and Schulson [1, 10] was reported to be in the range of $2 \times 10^9 \text{ m}^{-3}$ and $3.5 \times 10^8 \text{ m}^{-3}$ for fine- and coarse-grained ice, respectively. The number of air bubble inclusions varied greatly with grain size. Moreover, almost every grain seems to have had a few bubbles attached to it. The question arises, what is the effect of these inclusions on strength?

Another important fact should be mentioned. The strain rate actually imposed in the "gauge section" of each specimen used by Carrier and Schulson [1, 10] could be even lower than $\dot{\epsilon}_f$ estimated from the measurements of total strain between the end caps, that is from the sum of the deformation of the gauge section and the compliant "end zone" of each specimen in which the grains are smaller than those in the gauge section [13]. Thus, the results in Fig. 2 for Refs. 1 and 10 would move towards the lower strain rate (and hence closer to those of Ref. 12) when the strain rate in the gauge section was measured.

Making transparent columnar-grained ice is (relatively) simpler than making bubble-free granular ice. It is possible to prepare bubble-free, transversely isotropic S-2 ice [8], but no tensile strength data with information on σ_f and t_f are available. There is available, however, information regarding the rate sensitivity of stress, σ_{fc} , for the formation of the first large internal cracks under uniaxial compression, with load applied perpendicular to the columns [14]. The data are also shown in Fig. 2 as a function of average strain rate, $\dot{\epsilon}_{fc} = \epsilon_{fc}/t_{fc}$, where ϵ_{fc} and t_{fc} are the corresponding strain and time, respectively. Strains were actually measured by

gauges mounted directly on the samples. The coarse-grained ice samples were completely free of bubbles [8]; the finer-grained samples also were transparent, but not strictly bubble-free. Elongated air bubbles about 0.1 mm in diameter and 0.5 to 1.0 mm in length were distributed uniformly in the finer-grained ice, with a number density of $8 \times 10^5 \text{ m}^{-3}$. Figure 2 does not show any grain size dependence of the strain rate sensitivity of σ_{fc} . It is worth noting also the apparent correspondence between these results and those of Hawks and Mellor [12].

As the initial loading paths are nearly linear for constant cross-head rate tests [8, 9, 14] and load and time can be measured fairly accurately, stress rate analysis could be appropriate for tensile fractures. All the results shown in Fig. 2 are presented in Fig. 3 in terms of the corresponding average rate to fracture or first cracks, $\dot{\sigma}_f = \sigma_f/t_f$ and $\dot{\sigma}_{fc} = \sigma_{fc}/t_{fc}$. An apparent correspondence between the observations of Refs. 12 and 14 and the significant difference between these and the observations reported in Ref. 10 are again apparent (stress rate for Ref. 10 varied over 300 per cent between 2.2 and $6.6 \text{ MN} \cdot \text{m}^{-2} \text{ s}^{-1}$). The higher stress rates recorded for necked-down samples are also noticeable.

Figure 3 also shows a line representing a stress-rate sensitivity of tensile strength, proposed by Kubo in 1941 [15],

$$\sigma_f = \dot{\sigma}_f / (6.0 \times 10^{-4} + 0.7 \dot{\sigma}_f) \quad (1)$$

This was for columnar-grained natural river ice at -10°C in the experimental stress rate range of 3.3×10^{-3} to $3.3 \times 10^{-2} \text{ MN} \cdot \text{m}^{-2} \text{ s}^{-1}$. Equation (1) seems to satisfy the results of Refs. 1 and 10 and two first-crack observations made in Ref. 14 on fine-grained S-2 ice.

Discussion

Fracture occurs if cracks, either inherent in the material or nucleated during deformation, can propagate under applied stress [16]. Pre-existing flaws will be discussed first. An estimate of flaw size, $2L$, can be made from σ_f by the application of Griffiths' criterion

$$\sigma_f = \left(\frac{2E\gamma}{\pi L} \right)^{1/2} \quad (2)$$

where E is Young's modulus and γ is the effective surface energy.

Goodman's [17] fracture toughness measurements for fracture times less than about 20 s in conjunction with the results in Fig. 3 indicate that plastic work prior to crack propagation is not large for rates of loading higher than about $0.1 \text{ MN} \cdot \text{m}^{-2} \text{ s}^{-1}$. This simplifies the estimation of crack size, at least for high loading rates. For $\gamma = 0.109 \text{ J} \cdot \text{m}^{-2}$ [18] and $E = 9.5 \text{ GN} \cdot \text{m}^{-2}$ [19], equation (2) gives crack length of 0.2 and 2 mm for σ_f of 2.5 and $0.8 \text{ MN} \cdot \text{m}^{-2}$, respectively. The stress range, in fact, covers the entire range of tensile strength values illustrated in Figs. 2 and 3 and reported for all types of ice in Refs. 2 and 3. Thus, the size of existing flaws could determine strength and scatter. As the entire range of crack sizes estimated could be easily accommodated within the grain boundaries of even finer-grained ice, the effect on strength of grain size alone might not be detectable unless improvements are made in fabricating flawless, or crack-free, ice.

It has been pointed out that crack tip plasticity prior to crack propagation was expected to increase with decrease in loading rate below about $0.1 \text{ MN} \cdot \text{m}^{-2} \text{ s}^{-1}$, the range used in most experiments. Kubo's empirical equation (1) is consistent with this possibility (Fig. 3). A similar trend is evident in the results of Hawks and Mellor [12]. Kubo's lower strength values [15], in comparison with those of Ref. 14 (Fig. 3), could be due to large flaws in the natural river ice he used. The question arises whether the results obtained by Currier and Schulson [1, 10] were also affected by pre-existing flaws. Two high stress-rate observations on the formation of the first crack in fine-grained S-2 ice are consistent with Kubo's results. It is possible that the cracks in the two tests were generated by elongated bubbles in this ice.

Observations on the formation of first large cracks in clear ice under compression and its rate sensitivity have provided insight into the mechanical behaviour of ice. High-temperature crack nucleation processes were certainly operative in the production of these cracks in virtually flawless (macroscopically) columnar-grained S-2 ice [8, 14]. Their width seemed to depend on cross-sectional grain size, but no significant differences were noticed in their length: that of the first large cracks varied a great deal, from a few mm to a few cm. Thus, the dimensions of the nucleated cracks were indeed compatible with the geometry of the constituent grains. Such direct observations have important consequences. The level of stress shown in Figs. 2 and 3 and the length of the cracks were sufficient to satisfy the conditions necessary, according to earlier calculations, to propagate cracks under tensile mode of loading.

FIG. 2

Dependence of strength and stress to first large cracks on average strain rate

FIG. 3

Dependence of strength and stress to first large cracks on average stress rate

Nucleation of the first large cracks in tension could also dictate the ultimate strength of columnar-grained ice. As the rate sensitivity of the formation of the cracks (Figs. 2, 3) and the length of the flaws were not affected by cross-sectional grain size, the tensile strength of S-2 ice with load applied normal to the length of the columnar grains might not show any grain size effect either. This is simply speculation, however, although the results presented in Refs. 2 and 3 provide some evidence of it. The author would like to carry out further direct tensile tests on pure S-2 ice to verify this point.

Visible cracks were observed to form in S-2 ice soon after a few low-amplitude acoustic emissions were recorded [14]. First acoustic emissions were recorded only after stress exceeded about $0.4 \text{ MN}\cdot\text{m}^{-2}$. This stress level coincides closely with the results of acoustic emission measurements carried out simultaneously with tensile tests on granular ice [10], when it was shown that stress at the onset of acoustic emission does not depend on grain size. The minimum stress for the onset of emissions was $0.44 \pm 0.17 \text{ MN}\cdot\text{m}^{-2}$. These observations raise the question of what mechanism of nucleation of acoustic emission (and possible microcracks) there might be that would not depend on grain size. A new high-temperature crack nucleation criterion, based on a critical grain-boundary sliding displacement, has been proposed [20] and is now supported by experiment with metals [21].

Conclusions

Tensile tests on fresh-water ice [1-4, 10, 12] have been affected by choice of improper specimen geometry and by interaction between the testing machine and test specimens. Analysis suggests that the use of ice with large numbers of inclusions could have played an important role in propagating inherent flaws in all the reported results. The Griffith criterion for fracture could cause an apparent grain size effect if size of inherent flaws or size of nucleated cracks are controlled by grain size. If the effect on strength of grain size alone is to be examined, experiments should be performed on inclusion-free ice under truly constant stress-rate, or under truly constant strain-rate with the gauge mounted on the specimen.

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