Fracture Toughness K_Q and Fractography of S1 Type Freshwater Ice

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ABSTRACT

Macrocrystalline S1 type freshwater ice was tested at -10^oC using the four-point-bend loading configuration. Fractographic analyses were carried out on the fracture surfaces of the specimens tested. Different fracture toughness values of S1 ice were associated with different fracture mechanisms and grain sizes. Specimens with larger regular grains showed higher fracture toughness values than those with smaller irregular grains. Cleavage fracture was found to occur in specimens showing higher fracture toughness values while decohesive rupture occurred in specimens with lower values. This evidence partially accounts for the wide scatter in the results on fracture toughness of S1 freshwater ice reported here and also found by other investigators.

KEYWORDS

Fracture toughness; fractography; freshwater ice.

INTRODUCTION

The general procedure followed in most of the fracture toughness tests reported to date has been to assume that LEFM conditions apply. The fact that river or lake ice is anisotropic and nonhomogeneous has typically been ignored.Few efforts have been made to thoroughly characterize the microstructure of the ice being tested to elucidate the nature of the cracking that has occurred in each fracture event. Fracture toughness values reported to date represent "apparent" values computed using the maximum load of the load versus time record, the initial fabricated crack length, and LEFM expressions. In view of the above remarks, the fracture toughness values discussed in this paper will be represented by the symbol K_Q, where

$$K_Q = K_{apparent}^{initiation} = K_{\rm I}(a, \rho, P_m) \tag{1}$$

in which P_m represents the maximum load, ρ is the fabricated crack-tip radius, and a is the fabricated initial crack length. The notation in (1) symbolically represents the inherent assumptions involved and the lack of a fracture toughness testing standard for each or any type of ice.

The present paper explores the results reported by Dempsey et al. (1988) by closely examining the microstructure of the macrocrystalline ice tested and by fractographic analyses of the fracture surfaces. In this context, the notation introduced in Eq.(1) is especially relevant. For the specimen sizes used, fracture initiation actually involved only a few macro-crystals, each of which was irregularly oriented to give a particular "global" anisotropy along the crack front. The use of plane stress or plane strain assumptions and LEFM expressions is simply not applicable but is useful when used in a comparative manner.

In the last decade, there has been a number of investigations into the fracture toughness of freshwater ice (a survey of the relevant literature is to be found in a recent paper by Dempsey et al., 1988). Wide scatter of the toughness values was obtained even when testing conditions such as ambient temperature, loading rate and specimen geometry were kept the same. For example, Kollé (1981) found that the fracture toughness values of S1 ice were 240 ± 79 and $186 \pm 82\text{kPa}\sqrt{m}$ at $-17°$C for two types of crack orientations,respectively. The toughness values reported by Danilenko (1985) were $330 \pm 90\text{kPa}\sqrt{m}$ at $-10°$C and $440 \pm 150\text{kPa}\sqrt{m}$ at $-15°$C for a chosen crack orientation.

Clearly, there is a need to explain the scatter if a criterion for a valid K_{IC} measurement, given a certain ice type, is to be established. The experimental errors, specimen size, microstructural features such as grain size and crystallographic orientation may all be causes of scatter. It is also expected that the scatter might be an indication of different fracture mechanisms operating during fracture.

Care was taken to minimize the experimental errors during all stages of the testing program. Four groups of specimens of different sizes were used to examine whether the specimen size was a primary cause of the scatter. The emphasis of this study, however, was placed on the fractographic analyses through which the fracture mechanisms of the specimens tested could be investigated.

S1 Type Freshwater Ice and Experimental Procedure

As defined by Michel and Ramseier (1971), S1 ice is referred to as the ice type with the c-axes of most grains of the ice sheet being vertically or near vertically oriented. This type of ice was grown at $-10°$C in an insulated tank measuring 45cm deep in a cold room at Clarkson University. Typical structure sections demonstrating the macrocrystalline nature of the S1 type are presented in Fig. 1. The distinct feature of S1 ice is its coarse columnar grains (Fig.1a) with their diameters varying from less than 10 mm(Fig.1c) to about 100 mm (Fig.1b).

The growth orientation texture of such ice is shown in Fig. 1(d) which consists of 79 basal plane poles measured by a universal stage from the horizontal sections cut from the same ice sheet. It can be seen that about 60 percent of the grains in the ice sheet have their c-axes vertically or near vertically oriented.

The loading configuration used by Dempsey et al.(1988) was the four-point-bend type (major span four times the depth, initial crack length half the depth). Specimens were milled to good accuracy (0.5 mm) and the initial cracks cut using a bandsaw. The crack planes were perpendicular to the top surface of the ice sheets. Four groups of specimen sizes were tested, based on the depth 32, 48, 64, and 80 mm respectively (width equalling the depth). The specimens of each group came from the same ice sheet. All specimens were machined and tested at $-10°C$. The fracture test were carried out on an MTS 810 closed loop, servohydraulic test system. The complete details of these tests and the evaluation of the results are presented in the paper by Dempsey et al.(1988) and are reproduced in Table 1.

Table 1. The Results of Fracture Tests of S1 Ice
(Dempsey et al.,1988)

No.	w (mm)	h (mm)	a/w	K ($kPa\sqrt{m}s^{-1}$)	E_{eff} (GPa)	K_Q ($kPa\sqrt{m}$)	δ_f (μm)
A34	32.1	32.0	0.50	241.0	7.2	674.9	57.2
A35	32.1	32.2	0.53	182.5	4.4	346.7	33.5
A36	32.3	32.5	0.51	196.8	4.9	374.0	48.0
B13	46.1	46.0	0.52	198.3	5.9	357.0	45.2
B14	47.1	47.2	0.50	212.6	6.4	446.4	51.4
B15	47.8	46.5	0.51	239.9	6.4	311.9	36.8
B16	46.9	46.9	0.51	84.0	6.7	151.2	15.8
B17	47.4	46.1	0.51	132.6	-	132.6	-
C1	63.4	64.7	0.51	132.0	4.6	171.6	32.6
C2	65.1	63.8	0.49	115.8	-	196.8	-
C3	62.5	64.2	0.54	181.8	11.8	272.7	25.5
C4	64.5	63.6	0.50	136.9	6.7	356.0	42.3
C5	63.4	64.7	0.50	134.4	7.4	255.3	64.9
D22	80.7	80.2	0.50	93.0	7.7	297.7	38.5
D23	79.8	79.9	0.50	94.3	6.8	339.3	48.7
D24	80.5	78.9	0.50	88.8	6.9	293.0	41.9
D25	80.2	81.1	0.49	93.1	7.7	493.6	63.6
D26	79.6	80.5	0.48	77.5	4.9	116.2	21.2
D32	79.6	80.7	0.50	85.4	5.0	153.7	29.3

w: depth; h: thickness; E_{eff}: effective Young's modulus; δ_f: CMOD

Two points are immediately obvious from these results:

(1) Despite the fact that the efforts were made to minimize the experimental errors, the scatter is significant. This can be attributed to the large grains and the preferred c-axis orientation of the S1 ice used in this program. The following discussion will make this point clear.

(2) Almost the same degree of scatter occurred in all four specimen sizes alike, indicating that the range of specimen sizes tested was not large enough to nullify the anisotropy and inhomogeneity of the microstructure. In fact, it would seem that variations in grain size and orientation of the ice crystals are predominantly responsible for the scatter.

FRACTOGRAPHY AND MICROSTRUCTURE

The grain size of S1 type ice is two or three orders greater than that of metals; it is thefore possible to use macrofractography to examine the fracture mechanisms for the specimens tested . In this study, an ordinary camera was used to take the photographs of the fracture surfaces. The fracture characteristics on the fracture surfaces were clearly visible.

The macrostructures of the specimens in each group are shown in Fig. 2. Each set of photographs in Fig. 2a, 2b, 2c and 2d are from groups A, B, C and D, respectively. The pictures in the left column of the figure correspond to the specimens with highest K_Q values while the pictures in the right column of the figure corespond to the lowest K_Q values in each group(refer to Table 1). For each set of photographs, the grain sizes of the specimens in the left column are more regular and significantly larger than those in the right column. The effects of grain size on fracture toughnes of S1 ice are evident.

It was found that the c-axes of most grains of the specimens with higher K_Q values showed uniform and vertical or near vertical orientations while the specimens with lower K_Q values showed irregular c-axis distributions. This can be illustrated by Fig. 3 which shows the distributions of c-axis orientations for some specimens in group D (for associated macrostructures, refer to Fig.1

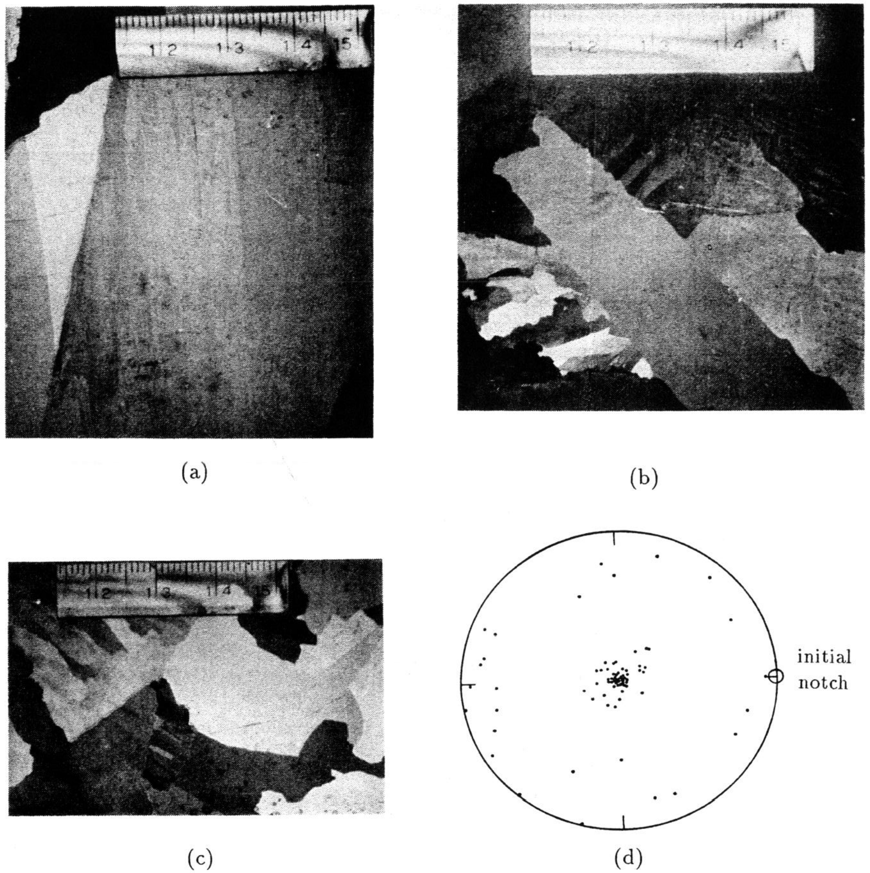


Fig.1. Macrostrcture of S1 ice. (a) vertical section from specimen D25. (b) horizontal section from D22. (c) horizontal section from D32. (d) Stereographic projection of basal planes of S1 ice measured from horizontal sections. The orientation of the initial notch is shown in the figure(circled).

and Fig.2). From Fig. 3 about 80 or 90 percent of the grains in specimen D22 and D25 had their c-axes vertically or near vertically oriented. For specimens D32 and D26 less than half of grains showed vertical c-axis orientation,while more than half of grains were near horizontally oriented. Similar situations were found in group A, B, and C.

The variation of c-axis orientations between the specimens may partially account for the scatter in this test. Since ice I_h has a hexagonal crystal structure, its surface energy and dislocation

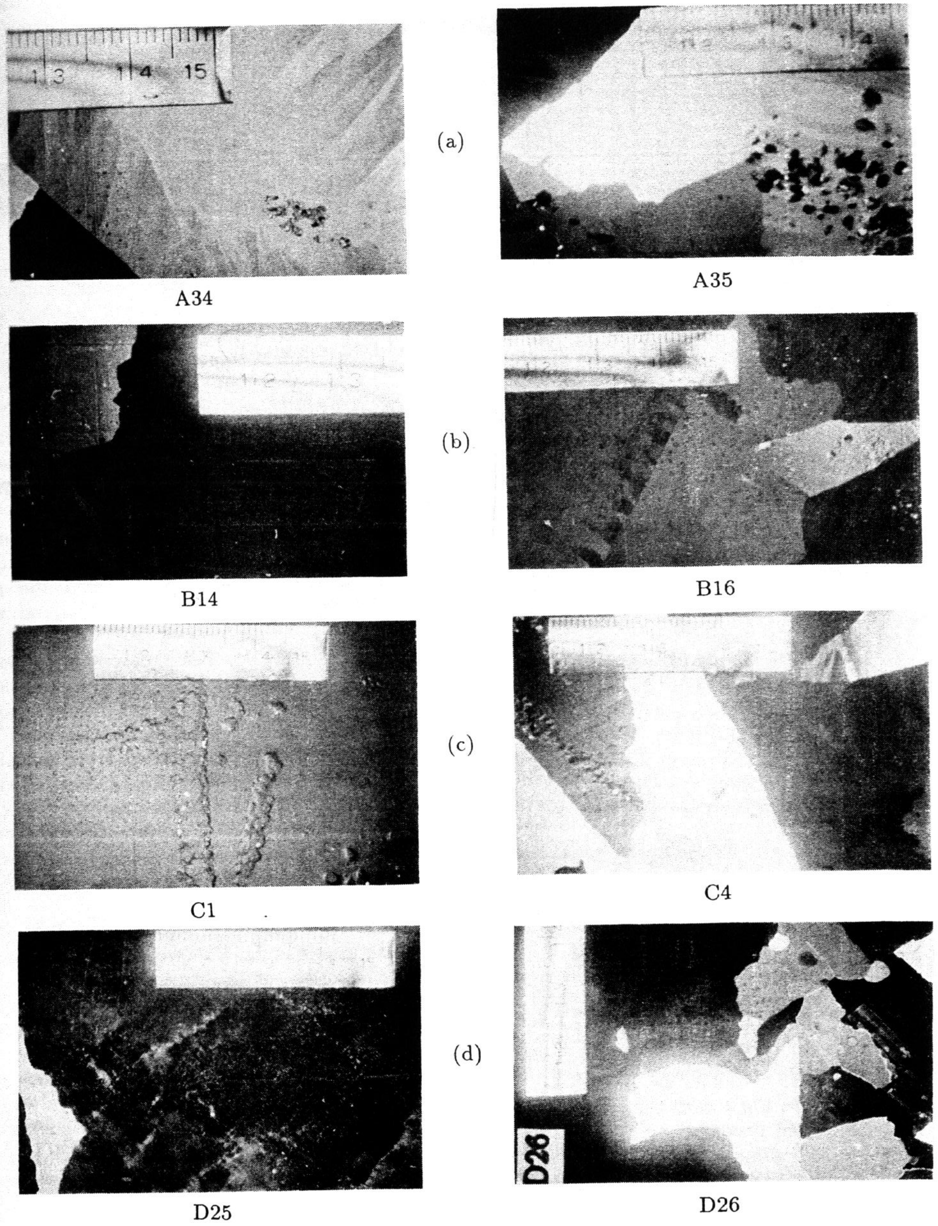
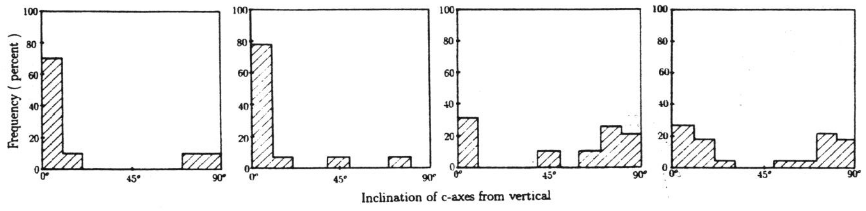


Fig. 2. Macrostructure of ice specimens showing regular larger grains (left column) and irregular smaller grains (right column) in each group. (The pits on some pictures were caused by sublimation)



(a) (b) (c) (d)

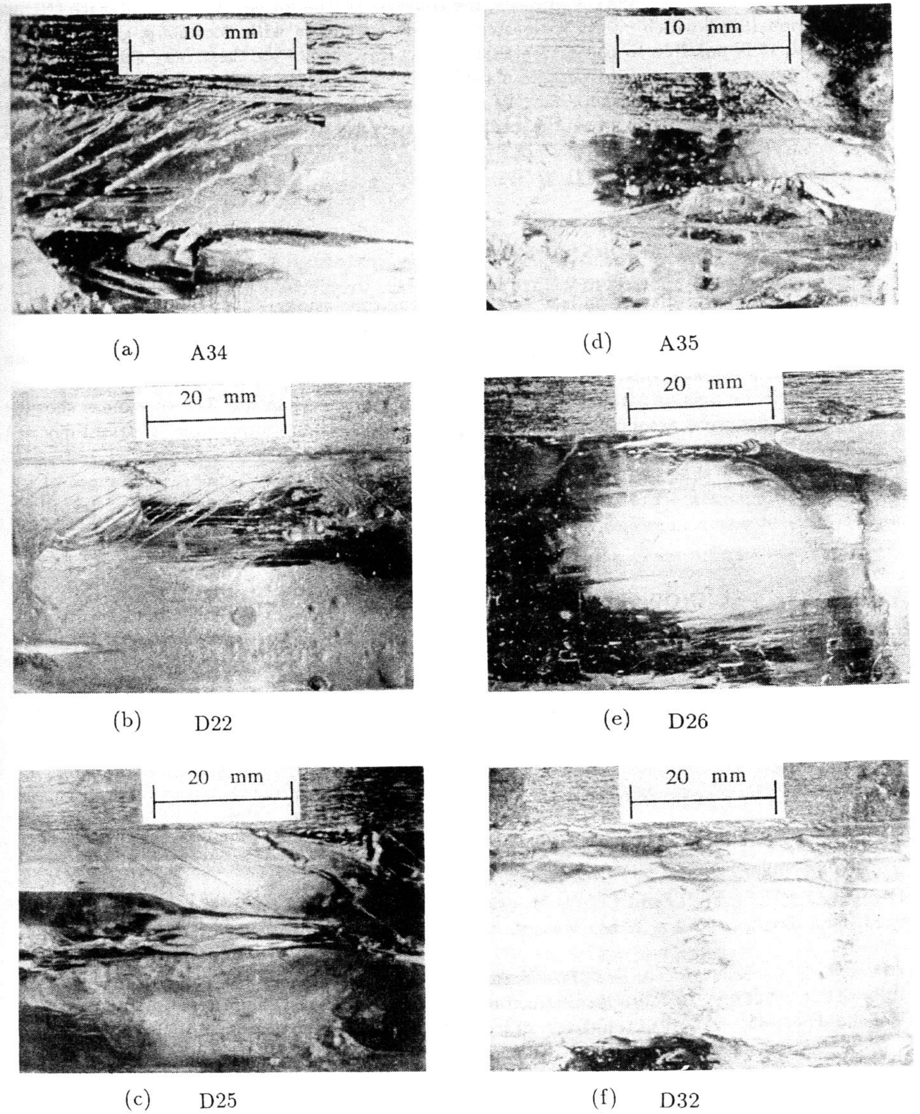
Fig. 3. Orientation distributions of c-axes. (a),(b),(c) and (d) for specimen D22, D25, D26 and D32 respectively.

mobility are dependent on crystal orientation (Hobbs, 1974). The coarse columnar grains each have preferred crystallographic orientation in the ice specimens. Therefore, it is not surprising to see the anisotropy of the fracture toughness of this ice. In fact, Kollé (1981) showed that the fracture toughness of ice specimens with notches perpendicular to the basal planes was 30% higher than that of specimens with notches parallel to the basal planes. In the present study, for those specimens with most grains showing vertical c-axis orientations,the initial notches were essentially perpendicular to the basal planes and did show higher K_Q values, while the specimens with more grains showing horizontal c-axis orientations evidenced much lower K_Q values.

Some results of fractographic analyses are presented in Fig. 4. The photographs in the left column of Fig.4 are from the specimens with higher K_Q values while those in the right column were from the specimens with lower K_Q values. For the specimens in the left column, pronounced cleavage fracture is recognized by the distinct surface features such as river patterns (Fig.4a), feather markings (Fig.4a, b) and Wallner lines (Fig. 4b). Large cleavage steps and planes are visible as well. Since it was believed that the c-axes of most grains in these specimens were vertically oriented (refer to the previous discussion), these cleavage planes are probably the $\{10\bar{1}0\}$ or $\{11\bar{2}0\}$ planes. A further important observation is that the cleavage surface is mainly confined to one grain close to the initial crack tip. The evidence suggests that the propagating cleavage fracture could not transit into the next grain, but instead chose to rupture along the grain boundaries.

By contrast, the specimens in the right column of Fig.4 show pure decohesive rupture. This type of fracture is almost exclusively associated with intergranular fracture appearances and usually occurs at elevated temperatures. For metallic materials, at temperatures above about 0.5 T_m, where T_m is the melting point in degrees Kelvin, deformation can occur by grain boundary sliding because of the existence of weak grain boundaries. The test temperature of this study was -10°C (0.96 T_m). It is then reasonable to believe that the grain boundaries of the ice specimens were considerably weakened. Therefore, it can be anticipated that within this temperature the larger the grain boundary area is, the weaker the material will be. This is true when we relate the fractographs in Fig.4 with the macrostructures in Fig.1 and Fig.2. The specimens with smaller grains ruptured decohesively and showed lower K_Q values. The specimens with larger grains fractured first along certain cleavage planes in a single grain and then along the weaker path of the grain boundaries and showed higher K_Q values.

In the tests discussed above, the fracture toughness values for the specimens with larger grains were higher than those for specimens with smaller grains. This observation is consistent with



(a) A34
(d) A35
(b) D22
(e) D26
(c) D25
(f) D32

Fig. 4. Macrofractographs for group A and group D.
(a) and (b) show river patterns and feather markings. Big cleavage steps and planes are visible. (b) shows feather markings and Wallner lines (The pits on it are caused by sublimation). (d), (e) and (f) show the decohesive rupture features.

the results of Danilenko (1985). Curiously, the converse is true for equiaxed granular ice (Nixon and Schulson,1986) which shows increasing fracture toughness with decreasing grain size. In this regard, it is possible to conjecture that for certain types of ice there may exist an equicohesive temperature,just as for metallic materials (Dieter, 1986) . Above this temperature the grain boundary region is weaker than the grain interior and strength increases with increasing grain size. Below this temperature the grain boundaries are stronger than the grain interiors and strength increases with decreasing grain size.

CONCLUSIONS

The above results and discussion lead to the following conclusions.

1. The specimen size range was not sufficient to reduce the scatter significantly.
2. Different fracture toughness values of S1 ice were caused by different fracture mechanisms, grain sizes and c-axis orientations. The specimens showing higher K_Q values had larger grain sizes, uniform vertical c-axis orientations and a cleavage fracture mechanism. The specimens showing lower K_Q values were associated with smaller grain sizes, nonuniform c-axis distributions and decohesive rupture.
3. It is suggested that there may exist an equicohesive temperature for certain types of ice. Above this temperature the strength of ice increases with increasing grain size, and below this temperature strength increases with decreasing grain size.

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