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Publisher's version / Version de l'éditeur:

The Royal Society of Canada, Symposium on the Physics and Chemistry of Ice, Ottawa, 14-18 Aug. 1972., pp. 362-364, 1972

NATIONAL RESEARCH COUNCIL OF CANADA
CONSEIL NATIONAL DE RECHERCHES DU CANADA

ACTIVATION ENERGY FOR CREEP OF COLUMNAR-GRAINED ICE

BY

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Reprinted from
THE ROYAL SOCIETY OF CANADA SYMPOSIUM ON
THE PHYSICS AND CHEMISTRY OF ICE
held in Ottawa, August 14 to 18, 1972
p. 362–364

RESEARCH PAPER No. 569
OF THE
DIVISION OF BUILDING RESEARCH

Price 10 cents OTTAWA NRCC 13398

L'ENERGIE D'ACTIVATION POUR LE CHEMINEMENT DE LA GLACE GRANULAIRE EN COLONNES

SOMMAIRE

Des mesures effectuées sur un seul spécimen de glace granulaire en colonnes à des températures de −5° à −40° C ont indiqué que l'énergie d'activation apparente pour le cheminement de ce genre de glace est de 15.5 kcal/mol lorsque la glace est soumise à une contrainte de compression de 9.8×10^4 N/M^2 (1 kgf/cm^2). La présente analyse indique que la déformation est contrôlée par des procédés de diffusion et que l'on peut expliquer la différence entre l'énergie d'activation mesurée et celle de l'auto-diffusion dans la glace par le fait que le module d'Young dépend de la température.

Activation Energy for Creep of Columnar-Grained Ice

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The apparent activation energy for creep of columnar-grained ice subjected to a compressive stress of 9.8×10^4 N m^{-2} (1 kgf/cm^2) is found to be 15.5 kcal $mole^{-1}$ from measurements made on a single specimen over the temperature range −5 °C to −40 °C. The analysis indicates that the deformation is controlled by diffusion processes, and that the difference between the measured activation energy and that for self-diffusion in ice can be explained by the temperature dependence of Young's modulus.

1. Introduction

Investigations by Higashi et al.,[1] Jones and Glen,[2] and Muguruma[3] indicate that the activation energy for the time-dependent deformation of single crystals of ice at temperatures within 50 C degrees of their melting point is about the same as that for self-diffusion. Similar behavior has been observed by Muguruma[3] and Gold[4] for polycrystalline ice, suggesting that the deformation is controlled by the diffusion process. This conclusion is based, in part, on the equality that has been observed for several materials between the activation energy for creep at high temperatures and the activation energy for self-diffusion.[5]

Several theoretical expressions have been suggested for relating strain rate to temperature and stress when the temperature is greater than about $0.5T_m$, where T_m is the melting temperature in absolute degrees. A form that may be appropriate for ice for relatively low stress is the following given by Weertman:[6]

$$\dot{\varepsilon} = AD\left(\frac{\sigma}{E}\right)^m \left(\frac{\sigma\Omega}{kT}\right), \quad (1)$$

where $\dot{\varepsilon}$ is the strain rate, σ is the stress, $D = D_0 \exp(-Q_d/kT)$ is the coefficient of self-diffusion, Q_d is the activation energy for self-diffusion, k is Boltzmann's constant, E is Young's modulus, Ω is the atomic volume, T is the absolute temperature, and A and m are constants. Ramseier[7] found good agreement between his observations on granular ice and the expression

$$\dot{\varepsilon} = BD(\sigma/E)^n, \quad (2)$$

where B and n are constants.

If the stress is sufficiently small, m in Eq. (1) may be zero, and the equation has the same form as that developed by Nabarro[8] and Herring[9] for creep due only to the diffusion of vacancies. In this case the strain rate is proportional to the stress. No experiments have been carried out for a sufficiently long period of time to demonstrate that ice will undergo Nabarro–Herring creep, but observations indicate that if it does the stress must be less than about 5×10^4 N m^{-2} (0.5 kgf cm^{-2}).

Observations were undertaken on the creep of polycrystalline ice under a load of 9.8×10^4 N m^{-2} (1 kgf cm^{-2}) to obtain information on the apparent activation energy and possible deformation mechanisms that occur at low stress levels. The ice used was columnar-grained with a bias in the crystallographic orientation of the grains. Preliminary results of this investigation are presented in this paper.

2. Description of Ice and Test Arrangements

The ice was grown by a method[10] that produces a columnar-grained structure for which there is a marked preference for the axis of crystallographic symmetry in each grain to lie in the plane perpendicular to the long direction of the columns. The projection of the axes on that plane had a random orientation.

A specimen 5 by 10 by 25 cm^3 was machined from the ice in such a way that the 10 by 25 cm^2 face was perpendicular to the long direction of the columnar grains. The average grain size increased gradually in the direction of freezing, and its value perpendicular to the long direction of the grains ranged from about 0.14 cm^2 per grain to 0.30 cm^2 per grain. No steps were taken to purify the water, except to deaerate it before freezing. Its electrical conductivity prior to freezing was about 137 μmho.

A simple lever apparatus was used to apply a constant compressive load of 9.8×10^4 N m^{-2} to the 5 by 10cm^2 face (i.e. perpendicular to the long direction of the columns). Earlier work by Gold[11] had shown that when this type of ice is subjected to this condition of load the deformation is essentially two-dimensional, with no significant creep strain in the long direction of the columnar grains. Strain was determined by measuring the movement between the upper and lower loading plates by means of two dial gauges mounted on either side of the specimen.

Physics and Chemistry of Ice, Ed., E. Whalley, S. J. Jones, and L. W. Gold, Royal Society of Canada, Ottawa, 1973.

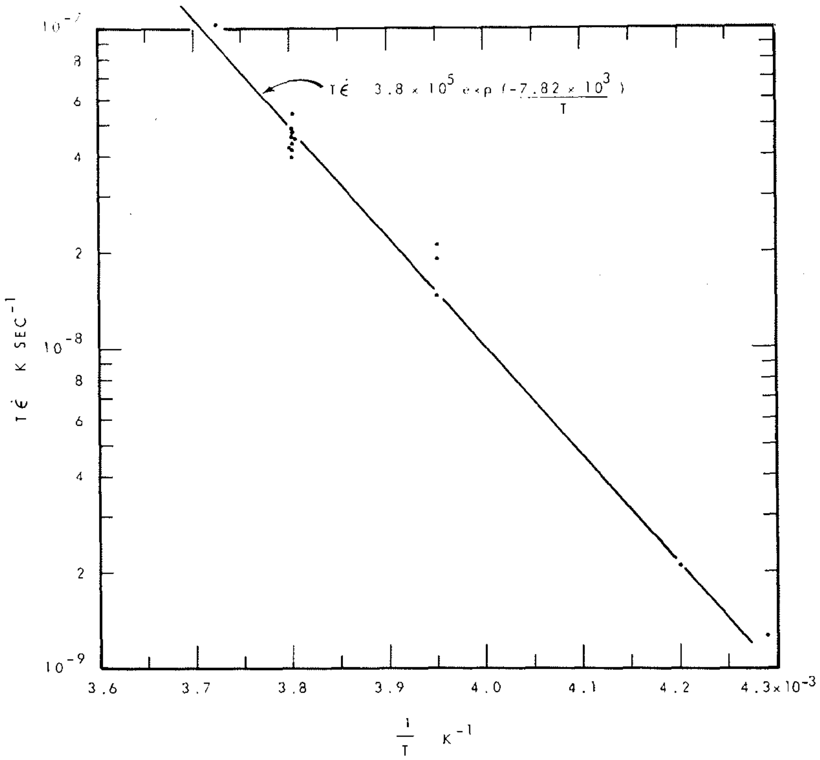

FIG. 1. Plot of log $T\dot{\epsilon}$ against $1/T$.

Observations of the strain rate were made on one specimen at temperatures of −5, −10, −15, −20, −30, and −40 °C. The test has run for a period of almost four years, and is still in progress at the time of writing. Total strain is at present a little over 2 per cent. The experiment is being carried out in a cold room in which each temperature setting could be maintained to within ±0.2 C degrees. The specimen was wrapped in polyvinyl film to prevent sublimation during the test period.

3. Results and Analysis

The observations show that the creep rate increases initially with time and subsequently decreases, the maximum occurring at a strain of 0.35%. This behavior is similar to that observed by Gold[11] for the same type of ice and larger stress, and indicates that the deformation is not controlled by the Nabarro–Herring process. It is assumed that the secondary creep rate is described by Eq. (1).

About 1.7% of the more than 2% strain imposed on the specimen took place at the temperature of −10 °C. The largest amount of strain that occurred at one time at that temperature was about 0.5%. When the total strain exceeded 0.65%, it was observed that the change in strain rate with strain at −10 °C was relatively small. For each test temperature, the strain rate was constant to within the accuracy of the measurements for strains up to about 0.2%. Strain rates were determined for this interval of strain or smaller.

The value of $T\dot{\epsilon}$ K s^{-1} was calculated for each interval for which the total strain of the specimen was greater than 0.65%. Log $T\dot{\epsilon}$ was plotted against $1/T$ (Fig. 1). The plotted points indicate a linear relation, the least squares estimate being

$$T\dot{\varepsilon} = 3.8 \times 10^5 \exp(-7.82 \times 10^3/T). \quad (3)$$

Figure 1 and Eq. (3) indicate that

$$\partial(\ln T\dot{\varepsilon})/\partial(1/T) = -7.82 \times 10^3 \text{ K}, \quad (4)$$

which gives an apparent activation energy of 15.5 kcal mole^{-1}. From Eq. (1)

$$\frac{\partial(\ln T\dot{\varepsilon})}{\partial(1/T)} = -\frac{Q_d}{k} + \frac{mT^2}{E}\frac{dE}{dT}. \quad (5)$$

Ramseier[12] found that Q_d = 0.62 eV (14.3 kcal mole^{-1}) from measurements of the self-diffusion of tritium in ice monocrystals. This gives $Q_d/k = 7.20 \times 10^3$ K. Comparing Eq. (4) with Eq. (5) gives

$$\frac{mT^2}{E}\frac{dE}{dT} = -0.62 \times 10^3 \text{ K} = \text{const} \tag{6}$$

or, for the temperature range of the observations,

$$E = E_1 \exp\left(\frac{0.62}{m}\frac{\Delta T}{T_1 T}\right), \tag{7}$$

where E_1 is Young's modulus at temperature T_1 and $\Delta T = (T_1 - T)$. From Eq. (7)

$$m = \frac{0.62 \times 10^3 \Delta T}{\ln (E/E_1)\, T_1 T}. \tag{8}$$

Young's modulus of columnar-grained ice has a significant dependence on temperature over the temperature range 0 to −40 °C. From Gold,[13] $E = 5.7 \times 10^9$ N m^{-2} for $T = 273.2$ K and 8.3×10^9 N m^{-2} for $T = 233.2$ K. Using this information to solve for m in Eq. (8) gives

$$m = 1.04.$$

4. Discussion

It is probable that for low stress ($<5 \times 10^4$ N m^{-2}) the strain rate of columnar-grained ice is directly proportional to the stress, whereas in the stress range of 3×10^5 to 10^8 N m^{-2} it is proportional to stress raised to a power of between 3 and 4[4]. A stress of 9.8×10^4 N m^{-2} is, therefore, probably in a transitional region so that a value of about 1 for m, which according to Eq. (1) gives a value of about 2 for the stress exponent, is not unreasonable.

The analysis has indicated the possible significant influence that a temperature-dependent Young's modulus has on the apparent activation energy for time-dependent deformation of polycrystalline ice. Ramseier[7] has also shown this effect for granular-type ice using Eq. (2) as the basis for analysis. The observations available are not adequate for determining which, if either, is the correct form. If deformation is controlled, however, by the climb of dislocations by the diffusion process, the equation for strain rate should include a stress effect on the diffusion coefficient. This is approximated at small stress by the term $\sigma\Omega/kT$ in Eq. (1).

5. Conclusion

Observations on the creep of columnar-grained ice due to a compressive stress of 9.8×10^4 N m^{-2} indicate that deformation is controlled by a diffusion process probably associated with the climb of dislocations out of their glide planes. The difference between the observed apparent activation energy of 15.5 kcal mole^{-1} and that associated with self-diffusion may be explained by the temperature dependence of Young's modulus.

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the director of the division.

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