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THE ACTIVATION VOLUME ASSOCIATED WITH THE PLASTIC DEFORMATION OF ICE

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L'ACTIVATION DU VOLUME ASSOCIEE A LA DEFORMATION PLASTIQUE DE LA GLACE

SOMMAIRE

Des expériences sur la relaxation des contraintes ont été conduites sur des cristaux de glace simples, doubles, triples et quadruples, afin d'obtenir des renseignements sur le procédé de contrôle de taux. Les résultats ont été analysés selon la théorie du taux développée anterieurement. L'étude indique que la barriere d'énergie est asymétrique et que le taux de procédé de contrôle du taux est associé à la barrière Peierls, avec le mécanisme d'intersection de dislocation, ou avec le mouvement non-conservateur des crans. Il semble invraisemblable que la montée contrôlerait le mouvement de dislocation dans la glace.

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THE ACTIVATION VOLUME ASSOCIATED WITH THE PLASTIC DEFORMATION OF ICE

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Abstract

Stress relaxation experiments are carried out on single, bi, tri and quadri crystals of ice to obtain information on the rate controlling process. The results are analyzed with the rate theory developed previously. The study indicated that the energy barrier is asymmetrical and that the rate controlling process is associated with the Peierls barrier, with the dislocation intersection mechanism, or with the non-conservative motion of jogs. It seems unlikely that climb would control the dislocation motion in ice.

§ 1. Introduction

It has been observed both in nature and under laboratory conditions that, as water freezes, ice tubes and needles occasionally grow from the frozen surface. The growth mechanism has been investigated in detail and reported [1]. In the course of the growth study, it was realized that these tubes and needles offer particularly suitable specimens for the investigation of some of the physical properties associated with single, bi, tri and quadri crystals. The plastic deformation of the needles is of special interest because they are grown without being subjected to any mechanical effect, a condition seldom achieved for ice with the conventional methods of bi, tri and quadri crystal growth. The availability of good bi, tri and quadri crystals together with the lack of information on their plastic behavior made a study of the associated thermally activated process a timely project. The results of this investigation are now reported.

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§ 2. Experimental procedure

Ice needles, about 50 mm in length and 1.5 to 2 mm in diameter, were grown with the technique reported previously [1]. In all of the seventeen specimens that were tested, the grain boundaries were straight and parallel to the specimen axis over the whole length of the crystals. The angle between the C-axis and the specimen axis varied from 25 degrees to 70 degrees.

Stress relaxation tests were carried out in tension at several strain levels on a Tinius-Olsen U-Celtronic testing machine. The specimen was frozen into two metal grips and kept at 263°K ± 0.2°K in a cold chamber. The chamber was cooled with four IFB-32-015-G1 Frigistor solid state heat pumps controlled with a simple on-off circuit using a YSI No. 44002 precision thermistor. To facilitate the analysis, the measurements were made until no further load change had occurred.

Strain rate change experiments as well as creep tests both in tension and in bending were also carried out. Only the stress relaxation results were used for the detailed analysis of the rate-controlling mechanism because, for ice, the transition effects are very pronounced in the strain rate change and creep tests. It can be noted, nevertheless, that both of these sets of observations support the conclusions derived from the stress relaxation studies.

§ 3. Discussion

The experimental results were analyzed with the theory developed in a series of recent investigations [2, 3]. These studies indicated that the thermally activated dislocation movement in ionic and covalent crystals can be described with a linearly stress dependent apparent activation energy and that the rate-controlling mechanism is associated with an asymmetrical energy barrier. Using the absolute rate theory, it was shown that the stress dependence of the dislocation velocity can be expressed as [2, 4–6]

$$v = A'_{\mathrm{f}} \exp \frac{V_{\mathrm{f}} \tau_{\mathrm{eff}}}{kT} - A'_{\mathrm{b}} \exp \frac{-V_{\mathrm{b}} \tau_{\mathrm{eff}}}{kT} \tag{1}$$

where

$$A' = \kappa \frac{kT}{h} l \frac{Q}{Q_r} \exp\left(-\frac{\Delta E}{kT}\right).$$

The subscripts f and b indicate respectively that the quantity is associated with the forward or backward movement of the dislocation, V is the activation volume, τ_{eff} is the effective stress acting on the dislocation, κ is the transmission coefficient, l is the average distance travelled by the dislocation after each activation, Q_r and Q are the partition functions of the initial and activated state respectively, ΔE is the activation energy; the other symbols have their usual meaning.

The relationship between the dislocation velocity and the stress rate measured in stress relaxation can be derived from Orowan's equation [7]

$$\dot{\gamma} = \alpha b \rho v(\tau_{\text{eff}})$$

where $\dot{\gamma}$ is the strain rate, α is a geometrical factor, b is the Burgers vector and ρ is the mobile dislocation density. In stress relaxation

$$\dot{\gamma} = \left(\frac{\partial \gamma}{\partial t}\right)_{T,\text{structure}} = -\frac{1}{\lambda}\left(\frac{\partial \tau_{\text{eff}}}{\partial t}\right)_{T,\text{structure}}$$

where λ is the composite elastic modulus of the specimen and testing apparatus [8]. Hence,

$$\left(\frac{\partial \tau_{\text{eff}}}{\partial t}\right)_{T,\text{structure}} = -\lambda \alpha b \rho v(\tau_{\text{eff}}) \tag{2}$$

Combining (2) with (1) the stress relaxation can be described as

$$\left(\frac{\partial \tau_{\text{eff}}}{\partial t}\right)_{T,\text{structure}} = -\lambda \alpha b \rho A'_{\text{f}} \exp\frac{V_{\text{f}}\tau_{\text{eff}}}{kT} + \lambda \alpha b \rho A'_{\text{b}} \exp\frac{-V_{\text{b}}\tau_{\text{eff}}}{kT}$$

$$= -A_{\text{f}} \exp\frac{V_{\text{f}}\tau_{\text{eff}}}{kT} + A_{\text{b}} \exp\frac{-V_{\text{b}}\tau_{\text{eff}}}{kT} \tag{3}$$

Because (1) was derived for ionic and covalent crystals, it is reasonable to expect that the plastic deformation of ice is controlled by a similar thermally activated process. Using this assumption, the stress relaxation in ice could be analyzed in terms of physical quantities using (3).

It was found that (3) described well the experimental observations for all of the crystals. A typical example is shown in Fig. 1. This result is important because the agreement indicates that the mechanism of plastic deformation of ice is associated with an asymmetrical

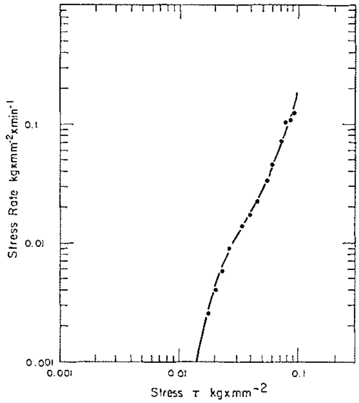

Fig. 1. A typical stress relaxation rexult. The symbols represent the experimental values, the curve was calculated with (3). No effort was made to obtain the best fit. The activation parameters are,

$$A_f = 0.005 \text{ kg mm}^{-2} \text{ min}^{-1}$$

$$A_b = 0.015 \text{ kg mm}^{-2} \text{ min}^{-1}$$

$$\frac{V_f}{kT} = 36 \text{ kg}^{-1} \text{ mm}^2$$

$$\frac{V_b}{kT} = 47 \text{ kg}^{-1} \text{ mm}^2$$

triangular energy barrier and justifies the assumption made in using (3).

In stress relaxation studies, the change of the effective stress τ_{eff} is often represented in function of the logarithm of time t. It is useful, therefore, to illustrate the stress relaxation behavior of ice obtained in the present investigation in this coordinate system as well. An example is shown in Fig. 2.

The good agreement obtained between the theory and the experimental results supports the use of (3) for the evaluation of the activation volume. The analysis shows that the activation volume in the forward direction is

$$0.4 \times 10^{-20} \text{ cm}^3 < V_f < 9 \times 10^{-20} \text{ cm}^3$$

and in the backward direction

$$0.5 \times 10^{-20} \text{ cm}^3 < V_b < 22 \times 10^{-20} \text{ cm}^3.$$

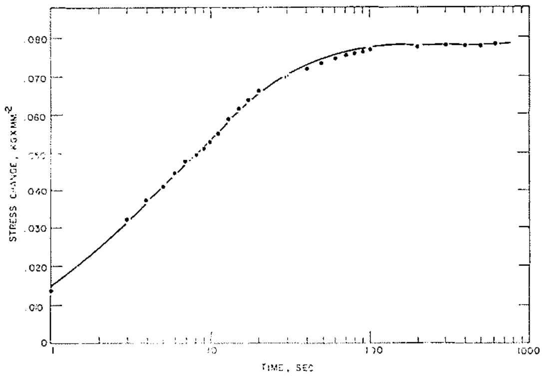

FIGURE 2

Fig. 2. A typical stress relaxation result in which the stress change is plotted in function of the logarithm of time. The symbols represent the experimental values and the curve was calculated from (3) by numerical integration. The activation parameters are,

$$A_f = 0.00027 \text{ kg mm}^{-2} \text{ min}^{-1}$$

$$A_b = 0.001 \text{ kg mm}^{-2} \text{ min}^{-1}$$

$$\frac{V_f}{kT} = 53.2 \text{ kg}^{-1} \text{ mm}^2$$

$$\frac{V_b}{kT} = 52.0 \text{ kg}^{-1} \text{ mm}^2$$

These activation volumes indicate that the rate-controlling mechanism in ice may be one of the following:

1. Peierls barrier
2. dislocation intersection, or
3. nonconservative motion of jogs.

It is unlikely that dislocation climb would have any effect on the plastic deformation of ice single, bi, tri and quadri crystals. This conclusion confirms the results obtained in previous studies carried out on polycrystalline ice [9] and on ice single crystals [10]. For all of the investigated single, bi, tri and quadri crystals, the deformation behavior and the activation parameters were similar indicating that the rate-controlling process is not affected by the grain boundaries. The usually observed difference in the stress exponents of single and polycrystalline ice is, therefore, due to the internal stress and not to a difference in the rate-controlling mechanism.

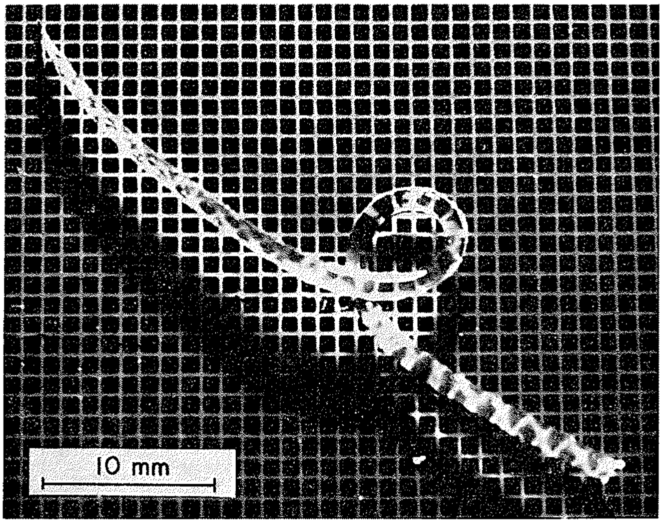

Fig. 3. Ice needle bent into a loop in about one minute at $-10°C$.

§ 4. Note

It is of interest to mention a rather striking observation made during the bending tests. The investigated small diameter crystals could be bent readily into a full loop over a period of time as short as 1 minute (Fig. 3). The crystals did not break during this severe deformation but, occasionally, separation along the grain boundary did occur. It was usually possible to straighten the crystals after bending.

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