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AN EXPERIMENTAL INVESTIGATION OF STRAIN RELAXATION
IN ICE

by

A.S. Krausz

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ETUDE EXPERIMENTALE DE L'ELASTICITE DIFFEREE DE LA GLACE

SOMMAIRE

On a étudié, à l'aide d'éprouvettes de glace colonnaire, la réduction de la déformation plastique (élasticité différée) qui se produit après l'annulation de la force appliquée. Les éprouvettes avaient été déformées par élongation à une température de -9° centigrade. Elles ont eu ensuite amplement le temps de reprendre leur forme.

Les résultats de l'expérience ont été analysés à l'aide d'une équation fondée sur la théorie de la vitesse de montée des dislocations. Le volume d'activation déterminant la vitesse du phénomène était le suivant:

$$0.35 \times 10^3 b^3 \leq V \leq 1 \times 10^3 b^3$$

où b est le vecteur de Burgers. L'auteur en conclut que les déviations et les montées perpendiculaires au plan de glissement n'ont qu'un effet négligeable sur la déformation de la glace et que le processus est commandé par le mécanisme de Peierls ou par la montée des crans hors de leur plan de glissement. L'auteur a également évalué l'importance des phénomènes d'intersection.

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Travaux de la Commission de la Recherche Scientifique

AN EXPERIMENTAL INVESTIGATION OF STRAIN RELAXATION IN ICE

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In the last ten years experimental techniques have been developed for the direct observation of the motion of dislocations in ionic and covalent crystals. Using the results obtained in these experiments a recent investigation on the rate theory of dislocation mobility (1) indicated that the usual strain relaxation* theories were inadequate. A detailed study (2) showed that this is indeed so, and a new theory was proposed for the description of the strain relaxation in crystalline materials.

The validity of the proposed rate theory of strain relaxation has to be investigated experimentally. A current test series on the plastic properties of ice provided an opportunity to do this; this paper reports the results of the strain relaxation experiments.

Theory

The analysis of the dislocation mobility experiments indicated that the plastic deformation process in LiF, NaCl, Si, Ge, InSb, GaSb, W, Fe - 3.25% Si, Zn, Ni, and Mo is associated with a linearly stress dependent activation enthalpy and an asymmetrical energy barrier (1). The description of any macroscopic experiment must be in agreement with the results of dislocation velocity measurements, and therefore, in the analysis of strain relaxation, the asymmetrical shape of the energy barrier and the linear stress dependence must be taken into consideration.

It has been shown (2) that the dislocation velocity v in strain relaxation can be described by the rate equation

* In this paper the term strain relaxation is used for the reverse plastic deformation which occurs after a specimen is unloaded.

$$v = A_f \exp \frac{V_f (\tau_{\text{eff}}^{\circ} - M\gamma)}{kT} - A_b \exp \left[- \frac{V_b (\tau_{\text{eff}}^{\circ} - M\gamma)}{kT} \right] \quad (1)$$

where subscripts *f* and *b* indicate the association of the quantity with the forward and the backward movement of the activated complex, *V* is the activation volume, $\tau_{\text{eff}}^{\circ}$ is the effective stress at the beginning of the strain relaxation, *M* is the relaxation modulus (3), γ is the strain in relaxation, *k* is the Boltzmann constant, and *T* is the temperature. The two pre-exponential factors are expressed in terms of physical quantities and were derived (1) from the activated complex theory (4) without introducing any experimental parameters.

The expression for the rate of strain relaxation follows immediately from Eq.(1) when the well-known equation of Orowan (5)

$$\dot{\gamma} = \alpha b \rho v$$

is introduced. Thus

$$\dot{\gamma} = \alpha b \rho A_f \exp \frac{V_f (\tau_{\text{eff}}^{\circ} - M\gamma)}{kT} - \alpha b \rho A_b \exp \left[- \frac{V_b (\tau_{\text{eff}}^{\circ} - M\gamma)}{kT} \right] \quad (2)$$

where ρ is the mobile dislocation density and *b* is the Burgers vector.

When long specimens of considerable weight are used the constant stress due to this weight leads to a factor

$$\frac{kT}{V_f WL} \left[1 - \exp \left(- \frac{V_f WL}{kT} \right) \right]$$

in the forward velocity term of Eq. (2), and to the factor

$$\frac{kT}{V_b WL} \left[\exp \left(\frac{V_b WL}{kT} \right) - 1 \right]$$

in the backward velocity term. In these expressions *W* is the specific weight and *L* is the length of the specimen. Thus the rate equation of strain relaxation for long specimens is

$$\begin{aligned} \dot{\gamma} = & \alpha \frac{b \rho kT}{V_f WL} \left[1 - \exp \left(- \frac{V_f WL}{kT} \right) \right] A_f \exp \left(\frac{V_f (\tau_{\text{eff}}^{\circ} - M\gamma)}{kT} \right) \\ & - \alpha \frac{b \rho kT}{V_b WL} \left[\exp \left(\frac{V_b WL}{kT} \right) - 1 \right] A_b \exp \left[- \frac{V_b (\tau_{\text{eff}}^{\circ} - M\gamma)}{kT} \right] \end{aligned} \quad (3)$$

Equation (3) was used for the analysis of the experimental results obtained with ice.

Experimental Procedure

Columnar-grained ice specimens, 50 x 100 x 1000 mm, were prepared using the technique already described (6). The specimens were cut so that the long axis of each columnar grain was perpendicular to the 50 x 1000 mm face. The [0001] axis was randomly oriented in the plane approximately parallel to this face. Most of the tests were carried out at $-9^{\circ}\text{C} \pm .5^{\circ}$.

In a typical experiment the specimen was deformed first in creep under a stress of 3.88 kg/cm^2 for about 6 hours to a strain of not more than 1×10^{-3} . At the end of this period the specimen was unloaded and allowed to relax for 16 hours. It was then reloaded and the creep and relaxation stages were repeated but the strain relaxation was continued to its full extent, i. e., until the contraction ceased and the specimen began to elongate very slowly under its own weight. In some of these experiments only one relaxation test was carried out. In these cases the relaxation was always continued to its full extent.

The length change was measured with three 7DCDT Sanborn differential transformers and monitored with one dial gauge during both creep and relaxation. An effort was made to obtain a satisfactory load-specimen alignment and accurate elongation measurements. The experimental arrangement designed to achieve this is shown in Fig. 1.

Experimental Results and Conclusions

A typical example of the strain relaxation behavior obtained in columnar-grained ice is shown in Fig. 2. The analysis indicated that the $\dot{\gamma} \propto \sinh V\tau$ expression derived from the usually assumed symmetrical energy barrier model cannot be fitted to the experimental results. The analysis also indicated that the empirical expression $\dot{\gamma} \propto \tau^n$, sometimes used to describe the stress relaxation and constant strain rate observations over a limited range, cannot fully describe the strain relaxation of ice.

Eight specimens were tested in strain relaxation; all of the experimental observations could be described well with Eq.(3). A typical example of the agreement obtained between the measured and calculated strain relaxation is shown in Fig. 2. This result is considered as supporting evidence for the proposed rate theory of strain relaxation.

A previous analysis (1) of Readey and Kingery's stress relaxation experiment in ice single crystals (7) indicated that V_f may be equal to V_b . The more complete measurements carried out in the present investigation provide enough information to lead one to expect that the rate-controlling mechanism in ice is associated with an asymmetrical energy barrier having different activation enthalpies and activation volumes for the forward and backward movement of the dislocations.

FIG. 1

The extensometer used in the tests, the method of applying the load, and the method for gripping the specimens

FIG. 2

A typical experimental result obtained in strain relaxation. The points indicate the measured values; the solid line was calculated from Eq. (3)

Analysis of the strain relaxation experiments showed that the activation volume for the forward movement of the dislocation is

$$0.35 \times 10^3 b^3 \leq V_f \leq 1 \times 10^3 b^3$$

where b is the Burgers vector. In the very low stress range the measurements were not accurate enough for an exact evaluation of the activation volume V_b . It was found that

$$V_b \approx 0.1 V_f.$$

The activation volume values indicate that the rate-controlling mechanism in ice at -9°C and at stresses up to about 3 kg/cm^2 may be the:

- a) Peierls' barrier,
- b) dislocation intersection, or
- c) nonconservative motion of jogs.

It seems improbable that either cross-slip or climb would have a significant effect on the plastic deformation of ice.

It is concluded that the observations strongly indicate that the strain relaxation of ice can be described fully with the proposed form of the rate theory of strain relaxation.

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