Effect of Hydrostatic Pressure on Velocity of Shear Deformation of Single Crystals of Ice
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by G. P. Rigsby
PREFACE

The work described in this report was performed in the SIPRE laboratories by Dr. Rigsby, physicist, formerly of the Snow and Ice Basic Research Branch, under the general supervision of Mr. James A. Bender, Acting Branch Chief. Dr. Rigsby is now at U. S. Navy Electronics Laboratory, San Diego, California. The work was performed under SIPRE Project 22.1-8, Mechanics of plastic deformation of ice.

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SUMMARY

Apparatus was built for deforming ice crystals under hydrostatic pressures up to 350 atmospheres. Single crystals were placed in the mounts in such a way that the deformation occurred by gliding on the basal glide plane. It was found that the shear strain rate increased as the pressure was increased at constant temperature, but that the rate is practically independent of hydrostatic pressure when the difference between the ice temperature and the melting point is kept constant.
INTRODUCTION

That ice will deform at a faster rate under higher hydrostatic pressure than at normal atmospheric pressure has frequently been assumed in glaciological writings and has only recently been seriously questioned by physicists. Max Demorest's theory of extrusion flow in the ice-sheet type of glaciers, which has been a controversial subject for several years, is based primarily on the assumption that ice near the bottom of the glacier will flow or deform easier than that near the surface. Although it is recognized that there probably are great shear forces at depth in a glacier which may not be present near the surface, it seemed well worth while to try to find out experimentally what the effect of hydrostatic pressure is on the rate of deformation of a single crystal under constant shear conditions. As each 11.5 or 12 m of ice increases the hydrostatic pressure by approximately 1 atm (depending on the amount of entrapped air), a pressure chamber capable of withstanding 350 atm would duplicate the hydrostatic pressures found under about 4 km of ice. It is doubtful if thicker ice than this can be found on the earth today. Such a pressure chamber with the necessary apparatus was built and assembled at SIPRE in the fall of 1953. The various laboratory experiments were made during 1954 and 1955.

TEST APPARATUS AND EXPERIMENTAL PROCEDURES

A cylindrical steel chamber was built, 11 3/4 cm in diameter and 10 cm high, inside dimensions, with walls approximately 1/4 cm thick. Oil pressure was applied by a hydraulic jack through a fitting at the bottom of the cylinder, and a means of bleeding air from the system was provided by another fitting at the top. A gage for reading the pressure was put into the pressure line (Fig. 1).

A brass mount was designed in such a way that two pieces of ice were deformed at the same time, preventing any friction due to the sliding of metal on metal or metal on ice (Fig. 3). Brass guides were used along the center to keep the center pull straight. The two pieces of ice were cut from a single crystal and oriented so that the c-axis of each piece would always have the same angle (as close to 90° as possible) and symmetry with the applied force, to eliminate any discrepancies between the pieces possibly causing unequal forces. The crystal was prepared twice as thick as one side required, then split, and one half rotated 180° about the vertical axis. The ice-brass contact was saw-toothed in order to prevent slippage. A small amount of ice water was placed on the contacts with an eye dropper to freeze the ice to the mount; any excess was scraped off. The dimensions of all crystals deformed were approximately 1 1/2 x 1/2 x 1/4 in. (3.81x1.27x0.64 cm).

After a few experiments had been made, a thermocouple was mounted in the apparatus and placed about 1/8 in. from the ice.

The force for deforming the ice was transmitted to the sample mount by means of a 0.020 in. (0.508 mm) steel music wire through a hole of approximately the same diameter in the bottom of the chamber. It was found that a hole big enough for the wire to move easily could be made without causing appreciable oil leakage around the wire, even at pressures of 350 atm. The loss of oil was usually no greater than about one drop every 5 to 10 minutes at the highest pressure used. As the wire extending through the chamber wall was like a small hydraulic jack with a piston diameter of 0.020 in., compensating weights were removed as the pressure in the chamber was increased, in order to offset the force attempting to extrude the wire from the cylinder.

The amount of deformation was measured by looping the music wire once around the shaft of a helically wound potentiometer placed tangent to the wire (Fig. 1).
This potentiometer actuated a Brown recording potentiometer to give a chart of deformation versus time. Such a graph clearly shows small changes in the rate of deformation by changes in slope. Figures 7, 8, 9 and 10 show plots taken directly from the original charts except that time has been changed from the ordinate to the abscissa. An attempt has been made to duplicate the original curves by using frequent plotting points, except in Figure 9 where it was necessary to smooth the curve because recorder difficulty caused steps on the original chart.

Rectangular pieces of ice were first used, but, after only a small amount of deformation, the ice began to bend and pull away from the saw-toothed sides. It was found that, in general, the ice will bend rather than glide. Some slippage is required, of course, to bend the crystal. Figure 2a shows how the crystals bend and pull away from the mount when the unconfined sides pass the 90° position. This difficulty was mostly eliminated by cutting crystals in the shape of a parallelogram having angles of 60° and 120°, as in Figure 2b, and deforming them in the direction which tends to make rectangles of the original parallelograms. Crystals cut with angles of 30° and 150° were tried, but offered no advantage as the total shearing strain was only about 30°. Figure 3 shows the crystal cut at 30° and 150° and shows the mount in place ready for the cylinder.

Figure 4 shows a sample which was deformed far enough to pull away from the sides of the mount. In some samples, the ice crystal bent more than 90° at each end. The strain rate increases as the crystal bends, showing that the effective length of glide...
Shear Deformation of Ice Under High Hydrostatic Pressure

Figure 2. Sketch showing how ice specimens start to bend and pull away from mount (a) and how problem was solved (b).

Figure 3. Close-up view of ice sample showing method of mounting.

Figure 4. Deformed ice crystal showing bending and uneven gliding.

Figure 5. Two crystals deformed at the same time in the pressure chamber, showing greatest movement along only a few planes.
Figure 6. Photomicrograph of deformed ice crystal showing bending of glide planes at small offsets. Sample has been polished, but certain glide planes show by using special lighting techniques for photographing.

is shortened and that it takes less force to bend the crystal than to deform it by gliding only. In Figure 4, the lines parallel to the sides of the crystal are caused by differential movement on basal glide planes. Because of surface unevenness, these lines are easiest seen on samples before the sides have been polished, and leave no doubt that they are traces of the translation plane. The planes can still be brought out on polished sections by special lighting techniques (Fig. 6). Apparently the crystal-line structure is disturbed in these areas, though not cracked or broken.

Sometimes differential movement occurred primarily on only a few glide planes, giving a final steplike appearance (Figs. 4 and 5). The results were not used when this happened, as a more even distribution of differential movement on the glide planes seemed desirable. It was seen under the microscope that bending similar to that described above but on a smaller scale occurred at each step (Fig. 6). Uneven distribution of gliding always occurred to some extent, and it is believed that this caused the wide differences in the load found necessary to keep the deformation at a satisfactory rate. Such differences make it difficult to compare one sample with another. Small orientation differences probably affected the rate of deformation also, but it is thought that the orientations from crystal to crystal were within one or two degrees of each other. Apparently, once a crystal starts to deform by gliding on certain planes, there is little change in the number of active glide planes throughout the experiment, so that reliable information can be obtained with any change of conditions made on that crystal, but little correlation can be made from one crystal to another. Pressure changes were made on crystals under certain temperature conditions, but, because of the limited distance one crystal could be deformed, no single crystal was subjected to both temperature changes and pressure changes independently. It would be desirable to change the temperature with each of two or more pressure values using the same crystal.

The sample was prepared, frozen to the mounts, and placed in the pressure chamber. The chamber was filled with oil, all pressure lines connected, and the whole
system was bled to remove air bubbles. The pressure chamber was then placed inside a box containing a fan and a heating coil controlled by a thermostatic. The whole apparatus was placed in a cold room at -5°C. The air temperature in the box cycled between -2.8°C and -3.2°C over long periods of time. When a pressure increase or decrease was required, it was necessary to remove the weight, change the pressure, and wait until the temperature reached the desired value, since an adiabatic temperature change in the oil occurred with a change in pressure (Zemansky, 1943, p. 225).

EXPERIMENTAL RESULTS

The experiment was first performed at -5°C by changing the hydrostatic pressure and ignoring the adiabatic temperature change in the oil. A marked change in deformation rate was seen immediately after changing the pressure (Fig. 7). It was soon realized that the temperature of the oil was considerably raised by the increase in pressure. In another experiment, when a thermocouple was introduced into the oil, the temperature rise was measured to be about 4°C for a pressure increase of 350 atm. According to the data available (Dorsey, 1940, p. 603), the melting point of ice at this pressure should have been lowered more than 2.5°C. This indicates that the oil actually reached the melting point of the ice, although there were no visible effects of melting on the sample after the experiment was completed. This may have been because the temperature dropped rapidly owing to the large heat capacity of the thick steel walls of the pressure cylinder and the brass mount in direct contact with the ice. The same experiment was performed at -20°C and little if any change of deformation rate was detected with pressure change, apparently because the melting point was not approached (Fig. 8).

In an earlier experiment in the SIPRE laboratory, when deforming a single ice crystal at 1 atm by forcing it to glide on basal glide planes, it was discovered that, with a constant force, the crystal reached an almost constant rate of deformation after the initial slow start, and that the force could be removed overnight without affecting the rate upon resuming the experiment. The force could be applied even several days later and the same deformation rate continued without repeating the initial slow start. Thus, after a change of hydrostatic pressure, the deformation could

![Figure 7. Deformation vs time at varying hydrostatic pressure, ice specimen 1. Starting temp = -5°C; temperature changed adiabatically. Shear stress = 2.56x10^6 dynes/cm².](image1)

![Figure 8. Deformation vs time at varying hydrostatic pressure, ice specimen 2. Starting temp = -20°C; temperature changed adiabatically. Shear stress = 2.43x10^6 dynes/cm².](image2)
SHEAR DEFORMATION OF ICE UNDER HIGH HYDROSTATIC PRESSURE

Figure 9. Deformation vs time at varying hydrostatic pressure, ice specimen 3. Constant temp at -5°C. Shear stress = \(3.68 \times 10^6\) dynes/cm². (Curve somewhat smoothed because of malfunctioning of recorder.)

Figure 10. Deformation vs time at varying hydrostatic pressure, ice specimen 4. Constant temperature difference between ice temperature and melting point approximately 3°C. Shear stress = \(2.55 \times 10^6\) dynes/cm².

be discontinued until the temperature reached equilibrium with the air temperature in the box.

The experiment was then performed by deforming the sample at as constant a temperature as possible, varying only the pressure. This required several hours delay with weight removed after each change of pressure. Figure 9 shows that there is still an increase in rate of deformation with an increase of hydrostatic pressure. The shear strain rate at 293 atm is about double the rate at 1 atm, except for the last drop in pressure, where the higher strain rate is believed to be due to the bending described above. Table I gives the shear strain rates, shear stress, and viscosity for each change of pressure on each sample.

These results indicated that the experiment should also be performed at a constant temperature differential between the ice temperature and its melting point at the chosen pressure. About 3°C below the melting point was selected as suitable; it seemed desirable to work as close to the melting point as possible without any pressure melting occurring at the ice-brass contact because of the force exerted by the saw teeth of the mount. A temperature of approximately -3°C was maintained in the oil at 1 atm and -5°C (the laboratory temperature) at 270 atm. The calculated melting point for ice at this pressure is -2.15°C. Figure 10 shows the effect of pressure change on the deformation rate at a constant difference between ice temperature and melting point. It can be seen that there is no sharp change in slope accompanying the pressure change, contrary to the change in slope observed in the other two plots performed at or near the same temperatures. Table I shows a decrease in shear strain rate from \(1.13 \times 10^{-5}\) sec⁻¹ to \(0.63 \times 10^{-5}\) sec⁻¹ on increasing the pressure from 1 to 270 atm, but these are only average values between the beginning and the end of the period at one pressure. The slope gradually changes from the beginning to the end of the experiment, apparently independent of the pressure changes.

It is believed that the accuracy of the readings taken from the recorder is better than 0.001 cm.

CONCLUSIONS

It is concluded from these experiments that the shear strain rate for plastic deformation of single ice crystals oriented to deform by gliding on the basal glide planes is practically independent of hydrostatic pressure when the difference between ice temperature and melting point is kept constant.
Table I. Shear stress, shear strain rate, and viscosity at different pressures on ice specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Temperature (°C)</th>
<th>Pressure (atm)</th>
<th>Shear stress (dynes/cm²)</th>
<th>Shear strain rate (sec⁻¹)</th>
<th>Viscosity (poises)</th>
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<tbody>
<tr>
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<td>3.14x10⁻⁵</td>
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<td>0.631x10⁻⁵</td>
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REFERENCES
