STRESS-STRAIN TESTS OF ICE CORE DRILLED AT MIZUHO STATION, EAST ANTARCTICA*

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Abstract: The mechanical property of one ice sample (No. 143) taken from the 100 m depth at Mizuho Station was investigated with the stress-strain tests in uniaxial compression at temperatures of $-6°$ and $-16°C$. Strain rate employed in experiments ranged from 10^{-7} to 10^{-6} s^{-1}.

Stress-strain curves obtained are classified into two types: stress-yield type and stress-saturation type, according to the occurrence and non-occurrence of yield drop due to the internal cracking. The relationships between the maximum stress obtained from the curves and the strain rate (the stress dependence of the strain rate) thus obtained were compared with those for core samples taken at Byrd Station. It was found that Mizuho core sample resembled Byrd core sample No. 145 (300 m depth) in the mechanical property shown in the relationships stated above Peculiarity in the property exhibited at $-16°C$ experiments is interpreted by the generation of cracks during deformation of high strain rate.

1. Introduction

Mechanical properties of glacier ice, especially of that in deep parts of ice sheet are most requisite for the establishment of the flow dynamics of the large ice mass like that of Antarctica. Our recent studies on mechanical properties with the use of deep core ice from Byrd Station, Antarctica (HIGASHI and SHOJI, 1974 and 1979, SHOJI and HIGASHI, 1979) revealed that the properties were very dependent on different modes of the fabric pattern of ice at various depth. It was also found that cavities and cracks generated by the relaxation of the deep core ice after it it released from hydrostatic pressures at the depth affect the mechanical properties, that is to say, they soften the ice.

Although it is an interesting subject to interprete mechanical properties in terms of both intra- and intergranular crystal defects like dislocations and boundaries, it is also interesting and necessary to see whether the same properties can be found with the core ice at other parts of Antarctic ice sheet. The 15th and 16th Japanese Antarctic Research Expedition (JARE) drilled ice cores down to a depth

* Research paper No. 39 of the Ice Research Laboratory, Department of Applied Physics, Faculty of Engineering, Hokkaido University.

of 140 m at Mizuho Station (70°41.9′S, 44°19.9′E) in January 1975. Core samples were brought back to Japan and several samples from an approximately 100 m depth were distributed to us for a quick comparative study of their mechanical properties. This paper describes the experiments carried out for the study and interpretes the results obtained in comparison with those of the Byrd core samples. Although the good sample for preparing enough specimens for the tests in various conditions was only No. 143 (100 m depth), it was found that the mechanical properties of the Mizuho core ice at this depth resembled to those of the Byrd core ice taken from the 300 m depth.

2. Experimental Procedures

Only the core sample No. 143 taken at a depth of approximately 100 m was used for the experiments, because it was large enough to cut into about 10 specimens. Average grain size of this sample is 5 mm. Fabric studies of the Mizuho cores by NARITA (1978) revealed that the core ice taken from the same depth in 1972 was not preferably oriented and its bubble density was $3.5 \times 10^{8} m^{-3}$.

Specimens of the dimensions $20 \times 20 \times 90$ mm were cut from the core of 12 cm diameter and 75 cm length by a band saw. Long axis of each specimen was inclined 45° against the core axis. This way of preparation of specimens was based on our experiences in the former study of the Byrd cores (HIGASHI and SHOJI, 1974).

Core samples taken from the depth (deeper than 500 m) under Byrd Station gradually tend to exhibit preferred orientation and at the middle depth (from 1300 m to 1500 m) the fabric pattern shows single maximum: the preferred *c*-axis orientation is almost parallel to the core axis or the vertical direction. Such strongly preferred samples were easily deformed by gliding on the horizontal plane of the core, when test specimens were so prepared as their long axes made 45° with the core axis. Comparison of the data of mechanical tests of specimens prepared in this way revealed that the gliding stress on the horizontal plane of the core is a measure of the mechanical property of glacier ice in association with the orientation fabrics. In an anticipation that the same may hold with the Mizuho core ice, we cut the specimen in such a way as described above.

Surface of a specimen was polished mechanically to remove any remaining strain due to the cutting and then specimens were left in a cold room for a few days to let the surface thin strained layer evaporated.

The compressive testing machine used for the present experiments is the one designed for our previous study of the effect of high hydrostatic pressure on mechanical properties of polycrystalline ice (HIGASHI and SHOJI, 1979). Since all experiments were to be carried out under an atmospheric pressure this time, the testing machine was operated in the vacant pressure tank. Machine speeds were selected between 10^{-8} to 10^{-7} $m \cdot s^{-1}$ which corresponded to the strain rate from

10^{-7} to $10^{-6}\,s^{-1}$. The stress-strain relation was recorded on a chart of a X-Y recorder through a wire strain-gauge (stress) and a potentiometer gauge (strain). The lower end of a specimen was frozen to the lower stationary plate of the machine while the upper end was set free under the moving upper plate at a distance of 1 or 2 mm. While the upper plate was moving downward without contacting a specimen, the frictional stress level of the testing machine caused by the friction between the driving shaft of the machine and the hole at the bottom of the tank was measured in each mechanical test. This frictional stress was substracted from the total stress recorded on the chart to obtain the true stress applied on a specimen. This true stress was used to draw the stress-strain curves as shown in Fig. 1. The experiments were carried out at temperatures of $-6°$ and $-16°C$ because of the limited supply of samples.

3. Results of Experiments

Two typical types of stress-strain curves obtained in the present experiments are shown in Fig. 1 (a) and (b). It took approximately 1 or 2 days to obtain one such curve. The curve of Fig. 1 (a) which has a stepped yield drop was reported by several investigators (MUGURUMA, 1969; HAWKES and MELLOR, 1972). Such sudden stress drops which appeared near 1% strain in this case are common even in the tensile tests of polycrystalline ice, when cracks are generated in specimens in the process of deformation of high strain rate. In the present experiments, generation of cracks was observed when the strain rate was high and such a yielding type stress-strain curve was obtained.

The stress-saturation type curve as shown in Fig. 1 (b) was obtained in the case of low strain rate and this is the same type as those obtained in tensile tests of the Byrd core samples (HIGASHI and SHOJI, 1974). In the case of this type, no crack generation was observed.

Either the yield stress in the curve of yielding type or the saturated stress in the

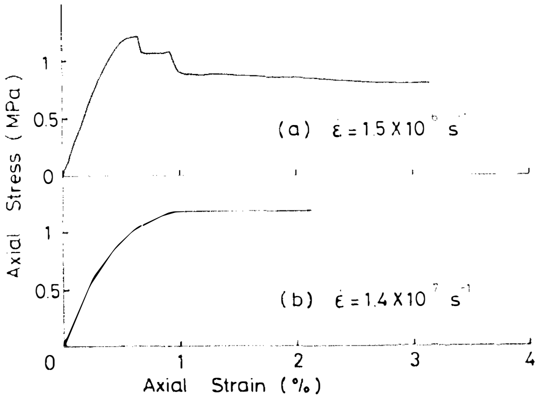

Fig. 1. Typical stress-strain curves with Mizuho core No. 143.

stress saturation type curve was adopted as the axial stress for drawing the ralationships between the stress and the strain rate as shown in Figs. 2 and 3. When the date were obtained from the yielding type curve, a letter c was attached to the data point of figures.

The present experimental results at $-6°C$ are shown in Fig. 2 with open circles, in comparison with those of Byrd core No. 145 (300 m depth) obtained at $-10.5°C$ and expressed by black dots. Stress (σ) dependence of the strain rate ($\dot{\varepsilon}$) of both cases is quite similar, the value of number of power m is approximately 2 if the power law $\dot{\varepsilon} \propto \sigma^{m}$ is adopted for expressing the relationship.

Experimental results obtained at $-16°C$ are shown in Fig. 3 by open circles in comparison with those of Byrd core No. 817 (1300 m depth) obtained at $-15.5°C$. Since Byrd core No. 817 exhibited strong preferred orientation, the stress dependence of the strain rate is very different with two types of the cutting of specimens. In this figure, black dots and large solid circles are for the specimens whose long axes are inclined 45° (called I specimens) and perpendicular (T specimens) to the core axis respectively. As the preferred orientation of the c-axes of core No. 817 was almost the same as the core axis (vertical in ice sheet), almost all grains in the I specimen had easy glide planes (0001) inclined 45° against the tensile axis in experiments, and therefore I specimens exhibit higher strain rate than T specimens in which the easy glide plane of individual grain is almost parallel to the tensile axis.

Three experimental data in the present experiments of Mizuho core No. 143 are between those of I and T specimens of Byrd core No. 817 and they are disposed

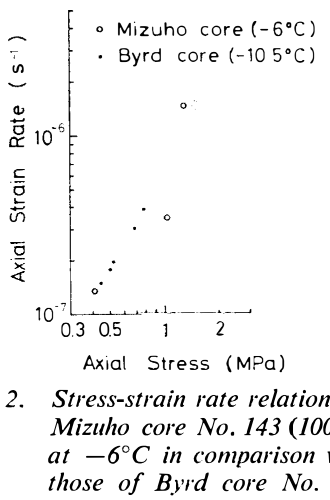

Fig. 2. Stress-strain rate relations of Mizuho core No. 143 (100 m) at $-6°C$ in comparison with those of Byrd core No. 145 (300 m).

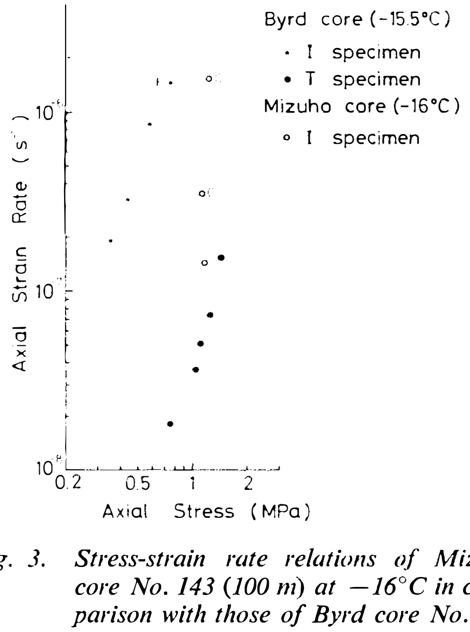

Fig. 3. Stress-strain rate relations of Mizuho core No. 143 (100 m) at $-16°C$ in comparison with those of Byrd core No. 817 (1300 m). The letter F means fractured specimen.

almost vertical in the figure. This disposition means that the number of power *m* is very large, almost infinite if we adopt the power law for the stress dependence of the strain rate. This tendency to have a large number of power for the cracked specimen will be discussed in the next section.

4. Discussion and Concluding Remarks

Resemblance of the stress dependence of the strain rate between Mizuho core No. 143 and Byrd core No. 145 at $-6°C$ as shown in Fig. 2 can be attributed to the similarity of the structural characters of both cores. Mean diameter of grains of both cores is the same, approximately 5 mm. The bubble- and crack density with the Byrd core ice was $2.7\times10^8 m^{-3}$ and $4\times10^7 m^{-3}$ respectively. This bubble density is almost the same as that of the Mizuho core ice described in Section 2. The fabric study was not carried out with Byrd core No. 145 but was done with No. 146 which was taken just below No. 145 and the result is shown in Fig. 4 with that of Mizuho core (NARITA *et al.,* 1978). Either of them does not show very strong preferred orientation as the single maximum exhibited with Byrd core ice at the middle depth. Therefore, if the structural features of glacier ice can be characterized by its grain size, bubble density and fabric pattern, those two samples are very similar in structural aspects and it is quite natural that we obtained the similar mechanical property.

It is shown in Fig. 3 that Mizuho core No. 143 is harder than the easy glide specimens (I specimens) and when the strain rate is lower, it is close to the hard glide specimens (T specimens) of Byrd core No. 817. Those properties may be principally due to the fact that many of the easy glide planes in grains of Mizuho core No. 143 did not coincide with the plane of maximum shear stress (45° with

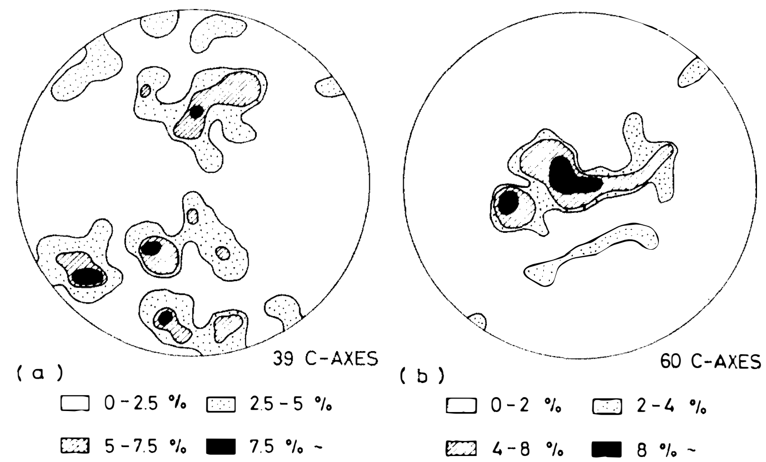

Fig. 4. (a) Fabric diagram of Mizuho core taken at 94.6 m (NARITA et al., 1978), (b) Fabric diagram of Byrd core No. 146 (301 m). The projected planes are both perpendicular to the core axis.

specimen axis) in tests. Difference between the I- and T-specimens was interpreted by the orientation of easy glide planes in grains against the tensile axis for the case of the Byrd core ice (Higashi and Shoji, 1974). Existence of many air bubbles in this specimen does not seem to have much effect on the mechanical property except that they might be nuclei of cracking.

The almost vertical disposition of three data points with the Mizuho core shown in Fig. 3 can be interpreted as follows. Since the yield stress of two upper data points attached with the letter c was determined from the yielding type stress-strain curve like Fig. 1 (a) and this type was associated with generation of cracks in the specimen, they may be considered as the stress at which the first crack was generated. At such a low temperature as -16°C, the ice became more brittle than at -6°C and the cracking started at approximately 1.2 MPa axial stress. This tendency of the data, nearly vertical disposition or nearly infinite number of power, was also observed in tensile tests of the Byrd cores in which they fractured at the almost constant stress of approximately 1 MPa at -10°C when specimens were subjected to higher strain rate (Higashi and Shoji, 1974). In this case, specimens were cut longitudinally from the core which had nearly single maximum preferred orientation and, therefore, easy glide planes made 45° with the plane of maximum shear.

If we consider mechanisms of deformation in the case of yielding associated with generation of cracks, this case should correspond to the field of dislocation glide with crack formation (DGC) in the deformation mechanism map of ice proposed by the present author and Higashi (Shoji and Higashi, 1978). It was shown in this map that if we trace, on the iso-strain-rate line about $10^{-6} \sim 10^{-7} \mathrm{s}^{-1}$, the field changed abruptly at about -10°C from the dislocation creep field to the DGC field. Therefore, the data shown in Fig. 2 (-6°C) are in the dislocation creep field while those in Fig. 3 (-16°C) belong to the DGC field. Increasing tendency of the number of power m from 2 to an infinity in the present experiments conforms to the increase of m from 3 in the dislocation creep field to 5 in the DGC field.

Since the hydrostatic pressure at a 100 m depth in the ice sheet is not so high, the mechanical property exhibited by the experiments at atmospheric pressure should be enough to be used in the flow dynamics of the ice sheet at this depth. However, some other experiments under hydrostatic pressure in the order of 30 atmospheric pressure is under way to see the effect of closure of air bubbles.

In conclusion, the stress-strain tests of No. 143 (100 m) Mizuho core ice exhibited that its mechanical properties resemble those of No. 145 (300 m) Byrd core ice and the resemblance is ascribed to their similarity in structural features. Deviation of the data at lower temperature (-16°C, Fig. 3) from the normal power low relationship in the stress dependence of the strain rate was interpreted by the generation of cracks in specimens when they were subjected to higher strain rate. Systematic mechanical tests with core samples of various depths in conjunction with their structural features should be interesting and useful. It may be pertinent to note here that the creep experiments at low stress level, another type of mechanical tests, are going on by NARITA and MAENO in the Institute of Low Temperature Science, Hokkaido University.

Acknowledgments

The author wishes to express his appreciation to Professor A. HIGASHI, Faculty of Engineering, Hokkaido University, for his helpful advice and suggestions in preparing the manuscript of this paper. He is also grateful to Mr. H. NARITA, Institute of Low Temperature Science, Hokkaido University, for the supply of structural and fabric data of the Mizuho core samples.

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(Received June 8, 1978; Revised manuscript received August 31, 1978)