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A Grain-Boundary Relaxation Peak of Antarctic Mizuho Ice Observed in Internal Friction Measurements at Low Frequency

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Abstract

A peak of the internal friction curve of Antarctic Mizuho ice crystals for the low frequency range, 4–9 Hz close to the melting point of ice was concluded as the grain-boundary relaxation peak of the ice crystals. The peak level, i.e., the maximum value of the internal friction, depended on the single crystal grain diameter of the ice specimen; the smaller the diameter, the larger the peak level.

1. Introduction

In two previous papers by the same authors,[1][2] the grain-boundary peak of the internal friction at low frequency on seven different kinds of ice and high density snow specimens close to the melting point of ice, and density dependency of the peak-levels on Antarctic Mizuho ice cores were reported. In this paper single crystal grain-size dependency of the peak-levels of the internal friction on the Antarctic Mizuho ice cores close to the melting point of ice will be reported.

2. Experiments and calculation

2.1 Measurements

Internal friction as well as shear modulus of the Mizuho ice cores was measured in a frequency range of 4 to 9 Hz and a temperature range of 96 to 272K by an inverted-type torsion pendulum[3] kept in a cold room of a temperature of 266±2.5K.[2] The free damping oscillation curves were recorded on a pen recorder kept at the outside of the cold room.

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2.2 *Calculation*

At first, logarithmic decrement α as a measure of the internal friction, and then tan δ was calculated.[2] The tan δ is related with α by:

$$\tan\delta = \alpha/\pi\ ,$$

where δ is the loss angle. The tan δ will be used as a measure of the internal friction in this paper.

3. Samples

3.1 *Mizuho ice samples*

Densities of the seven Mizuho ice cores taken from 39 to 144 m below the ground surface increased from 770 to 900 kg m^{-3} (Fig. 1). Horizontally sliced thin rectangular ice specimens of 8 cm long, 1.2 cm wide and 2 mm thick were twisted in the inverted-type torsion pendulum. The final size of the specimen was easily obtained with a specially designed tool[4] in an accuracy of ± 0.1 mm. Before the internal friction was measured, no visible crack was observed at all in each specimen.

3.2 *Size distribution of single crystal grains of specimens*

The size and shape of each single crystal grain of the specimen can be watched from photographs in Fig. 1 as far as air bubbles do not disturb the field of vision.

After measurements of the internal friction, single crystal grain size of the same specimens was measured in their enlarged color photographs ($\times 1.5$), taken under polarized light, using a circle scale graduated to 0.5 mm. The grain size was defined as the diameter of a circle whose area was regarded to be equivalent to that of the grain. As shown in Fig. 2, the grain diameter increases gradually with the depth except one specimen, No. 017. For two ice specimens, Nos. 68–A and 93–A which have large air bubbles, only the grain diameter range was determined. In the same figure, the weighted mean diameter of single crystal grains of the ice specimen was indicated by an arrow and the diameter increased from 0.7 to 5.5 mm with the depth.

4. Results and discussion

Two examples of the results of internal friction and shear modulus measurements of Mizuho ice cores as a function of temperature in a frequency

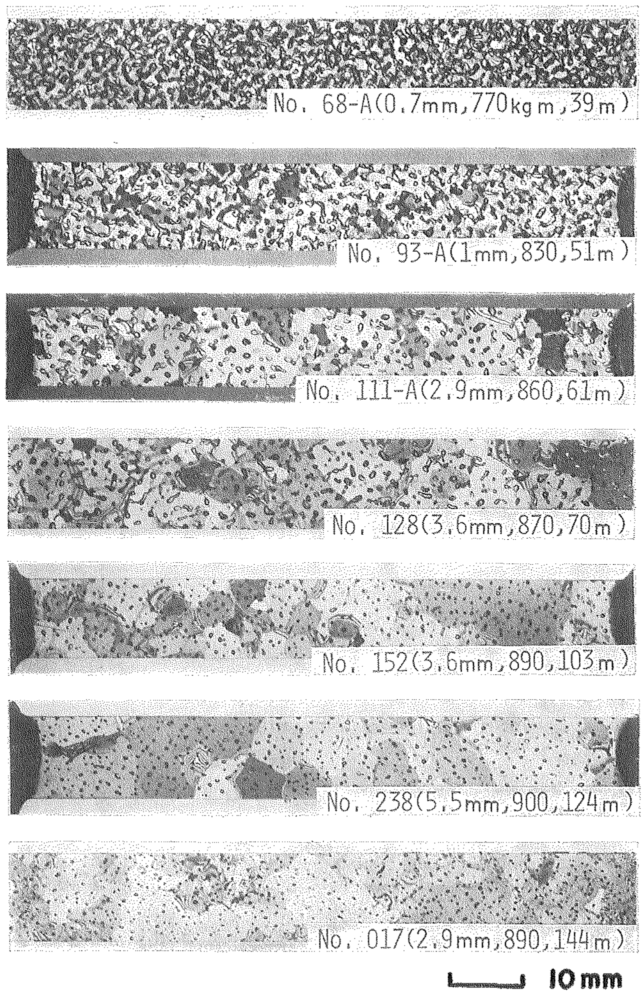

Fig. 1 Thin ice sections used for the internal friction measurement. Black ends of the specimen show top and bottom holders. Figures at the right-hand side indicate sample number, mean grain diameter, density and depth.

range of 4 to 6 Hz are shown in Fig. 3. Although the storage time in a cold room was different in each sample, there was no distinguishable difference in the results of the internal friction and shear modulus measurements. A curve of pure single crystal ice which was artificially grown at 266 K in a cold room by Bridgeman method, which was obtained by the same pendulum apparatus used in the present work is also shown in Fig. 3.

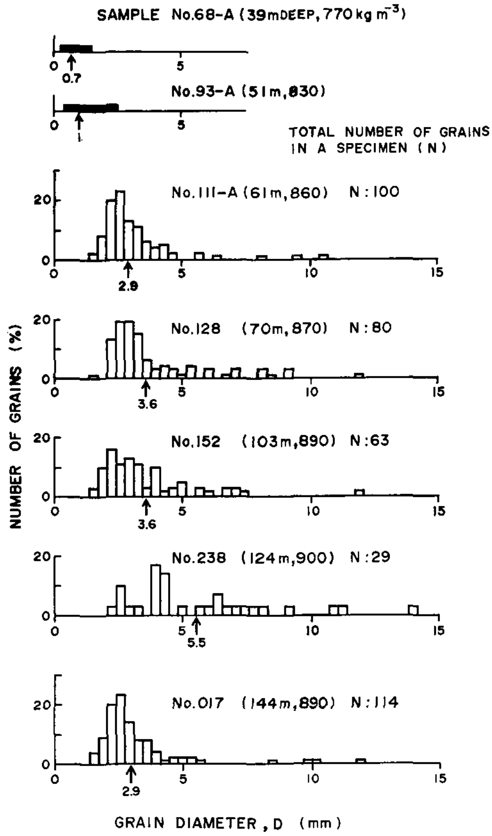

Fig. 2 Grain diameter distribution of ice specimens. Grading: $0.34 \leqq D < 0.68$ mm, $\cdots\cdots$ (D: diameter). The weighted mean diameter is indicated with an arrow. Sample number, depth and density are also shown above each distribution histogram.

Two remarkable peaks of internal friction were observed on all the Mizuho ice cores, while only one peak was observed on a pure single ice crystal. The higher peak of the two peaks of the Mizuho ice crystals is at around 265 K, which is close to the melting point of ice, and the lower one at around 150K. The higher peak is not observed in the pure single crystal ice. Both the lower peak of the Mizuho ice and the maximum of the pure single crystal ice correspond to their own mechanical relaxation peaks. The higher peaks of five of all the internal friction curves which were obtained for the Mizuho ice cores were drawn in an enlarged scale as shown in Fig. 4 with a curve of the pure

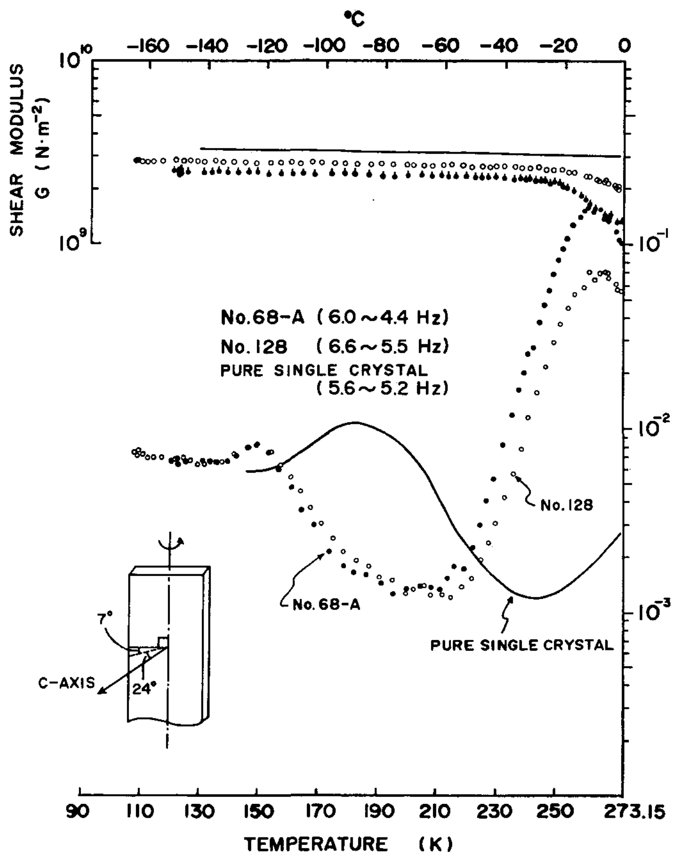

Fig. 3 Internal friction and shear modulus as a function of temperature. Samples No. 68–A and No. 128. Figures in parentheses indicate frequency in Hz from low temperature (for example, 6.0 Hz in No. 68–A) to high temperature (4.4 Hz). An internal friction curve for a pure single crystal ice is also shown. Angle between the C-axis and the torsional axis of the single crystal is shown at the left-bottom of the figure.

single ice crystal. As shown in the same figure, the smaller the diameter of single crystal grains of the Mizuho ice, the higher the internal friction. In the single ice crystal, the peak is close to zero. Therefore, it will be concluded that this peak is the grain-boundary relaxation peak. Table 1 shows a list of the grain-boundary internal friction peaks observed for the Antarctic Mizuho ice. A similar peak is observed close to the melting point of other seven kinds of ice crystals and high density snow,[1] while Kuroiwa[5] observed only a rapid

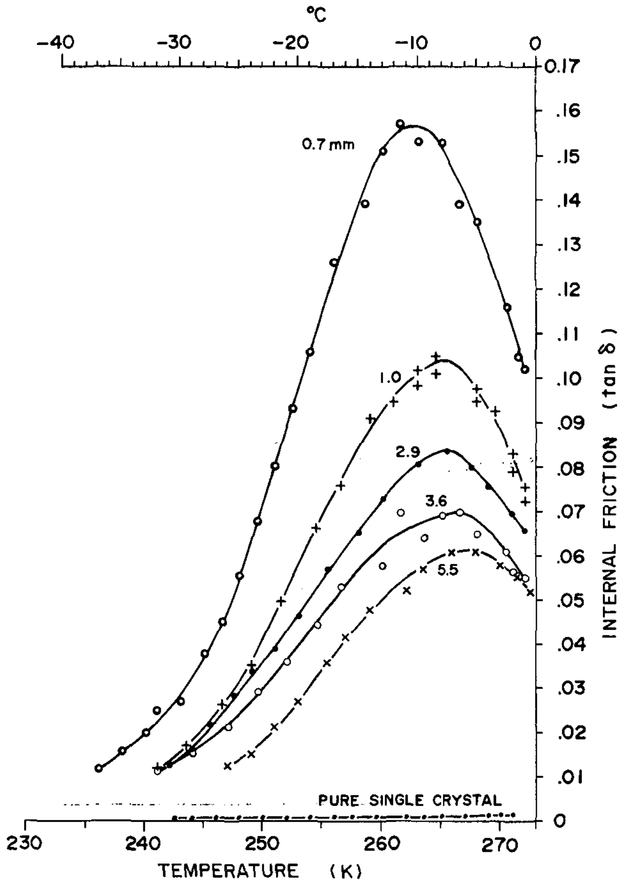

Fig. 4 Effect of grain size on the grain-boundary peak of the Antarctic Mizuho ice. The weighted mean diameter is 0.7 mm (sample No. 68–A, density 770 kg m^{-3}), 1. 0 (No. 93–A, 830), 2.9 (No. 111–A, 860), 3.6 (No. 128, 870) and 5.5 (No. 238, 900) from top to bottom, respectively as shown in the figure.

increase of tan δ near the melting point of some kinds of ice in high frequency measurements. For metals, Kê[6)7)] has observed the grain-boundary peak and the effect of grain size on the grain-boundary peak of aluminum wire.

The fact that the mechanical relaxation peak of the Mizuho ice cores is observed at the lower temperature side as compared to that of the pure ice crystal can be explained by the presence of impurities in the Mizuho ice cores as was discussed in two previous papers.[2)8)]

Table 1. Listing of grain-boundary internal friction peaks observed for Antarctic Mizuho ice

Sample No	Weighted mean grain diameter (mm)	Peak tan δ	Peak temperature (K)	Peak frequency (Hz)
68-A	0.7	0.156	262.7	4.8
93-A	1.0	0.104	265.5	5.8
111-A	2.9	0.083	265.7	4.6
128	3.6	0.070	266.4	5.7
152	3.6	0.065	266.1	4.7
238	5.5	0.061	267.5	5.0
017	2.9	0.064	262.6	7.6

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