FORMATION PROCESSES OF ICE FABRIC PATTERN IN ICE SHEETS

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ABSTRACT

Experimental studies on the formation process of the single maximum fabric of ice from its random fabric were carried out using both Greenland Dye-3 ice cores and artificially grown polycrystalline ice. From the observations of the rotation of c-axes of individual grains in thin specimens, an empirical equation was obtained for describing the rotation process of c-axes. Combined with another empirical equation on the relationship between the uniaxial strain of whole specimen and the uniaxial strain in individual grains of different c-axis direction, an equation was derived which describes the formation of single maximum fabric in bulk ice samples.

Computer simulation of the formation process was performed based on an equation starting from an artificially made random fabric pattern. From the results obtained by a stepwise simulation of 2% strain intervals, the degree of concentration expressed by θ_m, the angle which halves the number of grains in the fabric diagram is correlated with the accumulated strain in bulk ice (Fig. 8). The strain deduced by applying this relationship to the obtained θ_m for samples of Dye-3 ice core coincided well with actual strain which the samples had experienced. This implies that the equation is valid and the mechanism of c-axis rotation prevails in polar ice sheets.

INTRODUCTION

The formation mechanism of the characteristic fabric pattern of ice in various ice masses on the earth is of vital importance for interpretations of the flow history of ice masses, and for prediction of changes in properties and behavior of ice. It is generally recognized that the fabric pattern of ice in polar ice sheets gradually changes from a random pattern near the surface to the single maxima at depth.

Laboratory experiments have revealed the kinds of characteristic fabrics that can be obtained under certain conditions of the deformation of ice; the small girdle fabric pattern was obtained by the uniaxial compression test (Steinemann 1958, Watanabe and Ôura 1968, Tanaka 1972 and Huang, Ohtomo and Wakahama 1983), and a single maximum or two-maximum fabric was developed by simple shear experiments (Shumskii 1958, Rigsby 1960, Kamb 1972 and Duval 1981). However, no detailed experiments or analyses have been carried out clarifying mechanisms of the development of preferred orientation of c-axes in various experiments.

In general, the following can be considered as the three main mechanisms for the development of the ice fabric:

1) rotation of basal plane acompanied by deformation

2) grain growth

3) recrystallization

Although processes in natural ice masses should be governed by combinations of these mechanisms, it is desirable to study experimentally how these mechanisms contribute the formation of characteristic fabric pattern. In polar ice sheets where ice temperatures are very low, mechanisms (1) and (2) are considered to prevail over (3). With respect to (1), it has been reported that the c-axis rotated towards the compression axis when a single crystal of ice was subjected to uniaxial compression (Jones and Brunet 1978), and also when a thin specimen of polycrystalline ice was compressed (Wakahama 1964). However, the rotation angle of the c-axis was not correlated to the amount of uniaxial strain and this phenomenon was not considered to be related to the process of the fabric formation.

In the present work, the quantitative relationship between the rotation angle of c-axis and the amount of uniaxial strain was obtained from uniaxial compressive deformation experiments using thin specimens of polycrystalline ice. Deformation experiments of the same type were carried out for bulk specimens cut from an ice core taken from shallow depth in Greenland ice sheet. Random fabric of this core changed to the broad single maximum when the uniaxial strain reached 10%, and it is inferred that the same mechanism of c-axis rotation takes place in bulk polycrystalline ice when neither grain growth nor recrystallization take place in the process. Computer simulations were performed for the production of single maximum fabric using a constitutive equation describing the relationship between the rotation angle of c-axis and the amount of uniaxial strain.

EXPERIMENTAL PROCEDURES

Specimen preparation

In order to observe the rotation process of the c-axis of individual grains during the compressive deformation, thin specimens 2 mm thick and 30 x 20 mm^2 in area were prepared from both Dye-3 ice core and artificially grown polycrystalline ice. The latter was grown from the surface of pure water at a moderate rate, so that the c-axes became horizontal under a certain depth. When thin specimens were cut horizontally from this ice, it had two-dimensional random orientation fabric of c-axes. Its average grain size was 2 mm.

In the case of Dye-3 ice core (sample 1851, 1900 m depth and sample 1950, 2000 m depth), thin specimens were cut from the core so that the plane of the wide area was parallel to the core axis and its long axis made 45° with the core axis. Since both cores have the single maximum fabric, the c-axis of each grain lies on the plane of the thin specimen and angles between the compressive axis and the mean direction of c-axes of both cores are 40° and 60° respectively, with a standard error of 10°. Average grain sizes for the cores of sample 1851 and sample 1950 were 1.5 mm and 2.7 mm respectively.

For a study of the effect of compressive deformation on the random fabric, normal compressive tests were carried out with bulk specimens 20 x 20 x 70 mm^3. They were cut from Dye-3 ice core no. 120 (201

m depth) so that the long axis of the specimen was parallel to the core axis, and therefore, the specimen's compressive axis in the test coincided with that of the natural compressive stress in its original depth in the ice sheet. The c-axes fabric of this core is almost random and its average grain size is approximately 2 mm.

5 mm
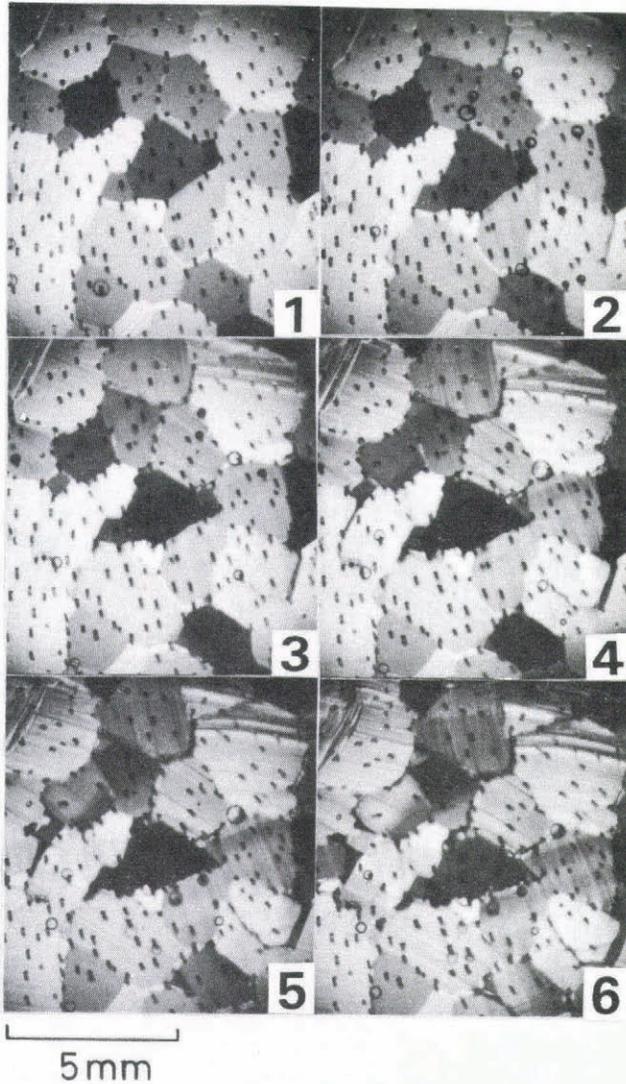
Fig.1. Photographs of a thin specimen through crossed polaroids during compressive deformation test no. 2. Axial strain for each is: 1) 0%, 2) 3.4%, 3) 6.5%, 4) 10.0%, 5) 11.5%, 6) 12.4%. Compression axis is in the top and bottom direction of the figure.

Uniaxial compression tests of thin specimens

Processes of the c-axis rotation were recorded on photographs of thin specimens intermittently taken on the process of uniaxial compression tests by transmitted light through the crossed polaroids which sandwiched the specimen. Thin sections of approximately 2 mm revealed clear images of individual grains and even of slip bands when they appeared by stress, as can be seen in Figure 1. Every compression test was carried out using a testing machine (for details of which see Higashi and Shoji 1979) under an atmospheric pressure or 20 MPa hydrostatic pressure with a constant strain rate in the order of $10^{-7}s^{-1}$. Experimental conditions including temperatures and the characteristics of the used specimens are given in Table 1. The thin specimen was also sandwiched by transparent acryllic-resin boards to avoid the buckling which may take place when such a specimen is compressed perpendicular to the thin section. This arrangement gave plane strain conditions.

Since it is expected that the rotation of the c-axis in an individual grain is related to internal strain, the internal local uniaxial strain of each grain was determined by the relative movement of several air bubbles in it (black dots in Figure 1). The least-square method of evaluating the plane strain using several data is developed from the standard method (Nye 1957a).

Uniaxial compression test of bulk specimens

Uniaxial compression tests with bulk specimens for the study of fabric change were carried out with constant strain rate of 4.38 x $10^{-7}s^{-1}$, under an atmospheric pressure. Experimental temperatures were $-13°C$ (test 5) and $-20°C$ (test 6). When the total strain reached 10%, the test was terminated; the specimen was immediately removed from the testing machine and horizontal thin section specimens were prepared . Such procedures were carried out in a $-20°C$ cold room.

EXPERIMENTAL RESULTS
Rotation of c-axes

Figure 1 shows six successive photographs of a thin section specimen taken before the deformation and when the total strain of the specimen reached 3.4%, 6.5%, 10.0%, 11.5% and 12.4% respectively in no. 2 test (Table 1). The slip bands appear in individual grain even when the total strain reached only 2% and they became clear as the strain increased. Since the c-axis must be perpendicular to the slip plane in each grain and it lay parallel to the plane of the wide area or to the plane of the figure, we can directly determine the c-axis of individual grains from these photographs. Angle χ between the specimen's compressive axis and the direction of the c-axis in each grain was measured using these determined c-axis direction at various increasing value of strain. We will call χ the misorientation angle of a grain. Decreasing tendency of χ with increase of the strain can be clearly seen in Figure 2 in which

TABLE 1.

Test no.	Specimen	Fabric	Temp. 0°C	Hydrostatic Pressure MPa	Strain Rate s^{-1}
1	Artificial Polycrystalline Ice	Random	-5	20	1.00×10^{-7}
2	Artificial Polycrystalline Ice	Random	-20	0.1	4.00×10^{-7}
3	Dye-3 Core, #1851	Single Maximum	-16	20	3.85×10^{-7}
4	Dye-3 Core, #1950	Single Maximum	-16	20	4.03×10^{-7}
5	Dye-3 Core, #120	Nearly Random	-13	0.1	4.38×10^{-7}
6	Dye-3 Core, #120	Nearly Random	-20	0.1	4.37×10^{-7}
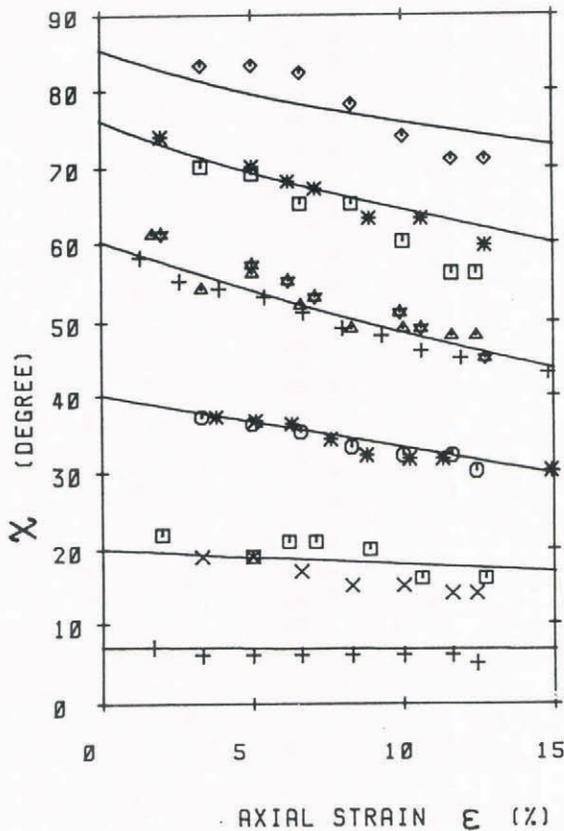
Fig.2. Changes of the misorientation angle χ with increasing strain ϵ. Several grains of different initial angle χ_0 are designated by different symbols. Solid lines show the relationship χ vs. ϵ by the equation 3.

Fig.3. Change of the nearly random fabric of Dye-3 core no.120 a) before the compression test, b) after test no. 5, c) after test no.6, and d) the simulated fabric diagram by equation 4, starting from a) and strained 10%. The center of each diagram coincides with the compression axis.

several examples of the change of χ from different values χ_0 of various grains are plotted against the total strain ϵ of specimens. They indicate that the c-axis rotates in individual grains as the deformation proceeds and the larger the value χ_0 the more rapid the rotation rate.

Change of the random fabric

Fabric diagrams for the originally undeformed, and deformed specimens in the tests at -13 °C and -20 °C are illustrated in circles of three diagrams of Figure 3. This figure shows clearly that the c-axes become concentrated after the deformation, a tendency quantitatively expressed in the following way. Accumulated fraction curves as shown in Figure 4 are drawn by plotting the accumulated fraction $F(\theta)$ of number of c-axes within certain misorientation angle θ against the values of θ divided into 5° intervals in this case. Three curves in Figure 4 exhibit $F(\theta)$ for three data sets corresponding to Figure 3(a), (b) and (c). The almost straight solid line for the initial random fabric change to those broken one for test no 5 and dotted one for test no 6. They exhibit a steep slope below 40° and gentle slope at larger angles than 60°, indicating the tendency that the fabric becomes concentrated toward χ approaches zero as the total strain increases. This process will be discussed and simulated in the next section with the aid of a formula obtained from the c-axes rotation process in the preceding subsection.

DISCUSSION

Rotation of c-axes

In the case of the compression test of a single crystal under restraint, it is well known that the normal to a slip plane rotates as it tends to become parallel to the compression axis (Schmid and Boas 1935). Since the basal plane is a dominant slip plane in ice crystal, the angle χ between the c-axis and the compression axis
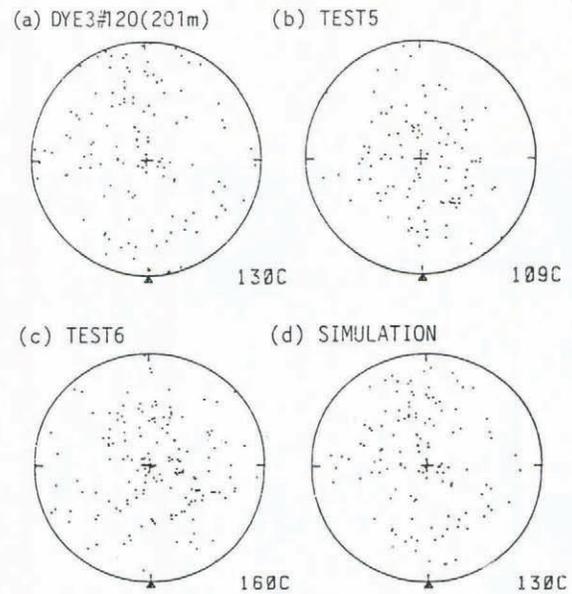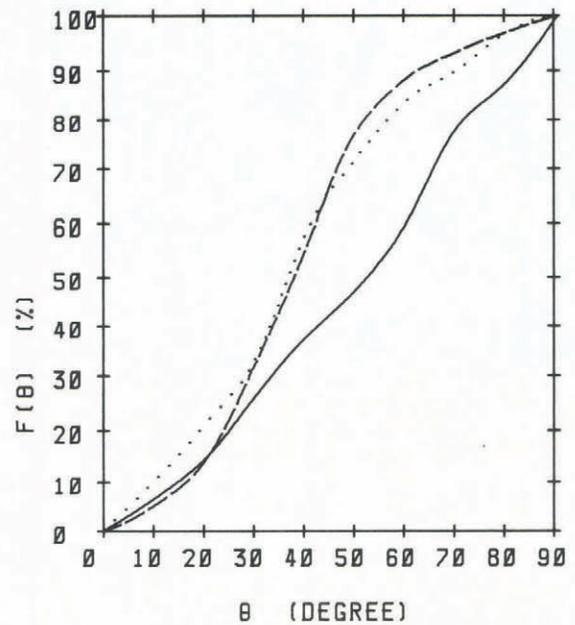
Fig.4. Cumulative fraction $F(\theta)$ curve for the fabrics of Dye-3 #120 before the test (——), after test 5 (– – –) and test 6 (. . .).

decreases from its initial value χ_0 with increase of the compressive strain ϵ according to the following equation:

$$\sin\chi = (1-\epsilon_s) \sin\chi_0 \qquad (1)$$

Individual grains in our thin specimens are considered to be restrained by their neighbours when they are deformed. Therefore, it is expected that the rotation of the c-axis of each grain could be correlated to the local compressive strain ϵ_g in the grain in such a way that ϵ_g is inserted for ϵ_s in eq. (1). ϵ_g in individual grains may be proportional to the gross axial strain ϵ of the polycrystalline plane specimen with a proportional
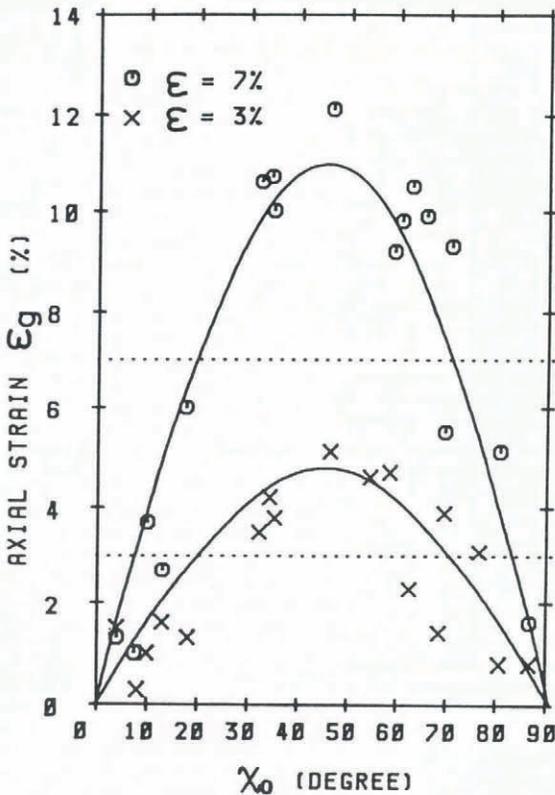
Fig.5. Relationship between the unixaial compressive strain ϵ_g of individual grains which had initial misorientation angle χ_0 after a certain total strain, 3% and 7%. Solid lines show equation 2.

constant as a function of χ_0. Figure 5 shows relationships between the measured ϵ_g of individual grains and their initial orientation angles χ_0 at two stages when the total axial strain reached 3% and 7%. Although data scatter considerably, they fit to the curve of an equation of the form:

$$\epsilon_g = \pi \epsilon \cos\chi_0 \cdot \sin\chi_0 \qquad (2)$$

This equation implies that the arithmetic mean of ϵ_g over χ_0 from $0°$ to $90°$ is equal to the total axial strain ϵ. Details of this implication together with its expansion to the three-dimensional case will be given elsewhere.

Inserting ϵ_g of this equation for ϵ_s in eq. (1), we obtain the changed orientation χ related to the total axial strain ϵ and the initial angle χ_0 of the orientation in the following form:

$$\chi = \sin^{-1} [(1 - \pi \epsilon \cos\chi_0 \sin\chi_0) \sin\chi_0] \qquad (3)$$

The solid lines in Figure 2 are the curves calculated by this equation (3) started from several certain initial χ_0s. Good coincidence of the curves on the plotted empirical data of χ vs. strain suggests that the rotation mechanism of c-axes envisaged to obey equation (1) is valid.

Formation of the broad single maximum fabric

As was described in the preceding subsection, the nearly random fabric of ice at comparatively shallow core of Dye-3 tends to concentrate into the broad single maximum when its bulk specimen was uniaxially compressed. In view of the fact that the c-axes of individual grains rotate so that the misorientation angle tends to decrease to zero degree in a thin polycrystalline specimen during the compressive deformation as described above, it is inferable that the same mechanism takes place for the concentration process of the c-axes in the bulk polycrystalline ice. Therefore, it can be expected that the broad single

maximum fabric will be produced in nature when polycrystalline ice body is subjected to the compressive deformation as the case in the upstream accumulation zone of an ice sheet.

For predicting the degree of c-axes concentration owing to the deformation, two computer simulations on the formation process of the broad single maximum fabric were carried out. The constitutive equation used for these simulations is as follows:

$$\Theta = \sin^{-1}[(1 - A\Delta\epsilon\cos\Theta_o \sin\Theta_o) \sin\Theta_o] \qquad (4)$$

This equation is of the same type as equation (3) because it should express the decreasing tendency of the misorientation angle Θ with increasing strain. The angle Θ is equivalent to χ in equation (3) but express the angle between the c-axis of individual grain and the compressive axis in a bulk polycrystalline specimen. Since the fabric pattern varies with increasing strain, the simulation should be performed stepwise with a certain strain interval $\Delta\epsilon$. The constant π in equation (3) is substituted by a parameter A which also varies with change of the fabric pattern.

The value of A can be determined by the following equation which is derived from an empirical fact that the uniaxial strain of a bulk specimen ϵ is equal to the arithmetic mean of the uniaxial strain ϵ_g of whole individual grains:

$$A = \frac{N}{\sum\limits_{i=1}^{N} \cos\Theta_{o1}\sin\Theta_{o1}} \qquad (5)$$

where N is the total number of grains of which misorientation angle Θ_{o1} are measured. Angle Θ_o in equation (4) is the initial value of Θ at each step of the simulation: the real initial value for each grain at the start and the resultant of the preceding step for the next step. Different values of A near 3 according to equation (5) were used in successive steps. In practice for the present, $\Delta\epsilon$ was taken as 2%.

The one simulation started from the fabric of Dye-3 no. 120 core which exhibited nearly random fabric as illustrated in Figure 3a. Fabric diagram shown in Figure 3d is the resultant fabric when ϵ reached 10%. It is comparable to those obtained by compression tests as illustrated in Figures 3b and 3c. Another simulation was carried out starting from an artificially-made random fabric as shown in Figure 6a in which 200 orientation of c-axes were selected by the use of random number generated in the computer. Results of

Fig.6. Simulated fabric diagrams started from artificially made random fabric with various degrees of uniaxial compressive strain. The compressive axis is in the center of each diagram.