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**THE APPROACH TO SIMILAR TERTIARY CREEP RATES FOR ANTARCTIC CORE ICE AND LABORATORY PREPARED ICE**

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Australia***RÉSUMÉ**

Des expériences de déformation de la glace soumise à une compression uniaxiale font l'objet de ce compte rendu. Les échantillons étudiés comprennent de la glace isotrope et de la glace anisotrope soit préparée en laboratoire soit provenant d'un cylindre prélevé au sommet du Law Dome, en Antarctique. Il y a des différences inexplicables dans les taux de déformation minimaux atteints par la glace isotrope du cylindre et par celle du laboratoire. Les taux de déformation minimaux sont plus hauts pour la glace anisotrope que pour l'isotrope à condition que l'anisotropie soit compatible avec la configuration des forces de déformation. En déformation tertiaire on atteint un taux de contrainte constant associé au développement d'une texture en petit anneau et les cristaux atteignent une dimension stable. On propose que cette déformation tertiaire est de nature permanente.

**ABSTRACT**

An account is given of ice deformation experiments in uniaxial compression. Samples studied include isotropic and anisotropic ice, laboratory prepared and from a core drilled at the summit of Law Dome, Antarctica. There are unexplained differences in the minimum strain rates attained by isotropic ices from the core and from the laboratory. Minimum strain rates for anisotropic ice are higher than for isotropic ice provided that the anisotropy is compatible with the stress configuration. In tertiary creep a constant strain rate is attained, associated with the development of a small circle girdle crystal orientation fabric, and an equilibrium crystal size. It is proposed that this tertiary creep is steady state.

**INTRODUCTION**

Some laboratory studies of the flow of polycrystalline ice have concentrated on the secondary or minimum creep of laboratory prepared samples with random crystal orientations. These studies have usually employed constant stress or constant strain rate tests in various stress configurations. Natural ice masses however exhibit well developed preferred crystal orientation fabrics - the result of total strains far greater than those required for laboratory samples to reach minimum strain rate. The times and strains involved in the flow of polar ice masses are large and thus in all but the upper layers of these ice masses, the flow is more appropriately described by the accelerating and tertiary stages of the creep curve.

More recent laboratory studies of ice flow have therefore concentrated on the development of higher tertiary strains, and on the associated crystallographic changes. It has been found that for the deformation of laboratory prepared isotropic ice samples, a preferred crystal orientation fabric develops between strains of about 1% and 10% [1]. Concurrently, the crystals tend to an equilibrium size, apparently dependent on test stress and temperature [2]. The strain rate increases during this strain interval, to a maximum value at about 10% strain. This maximum strain rate, for constant stress tests, is maintained for as much as a further 35%

strain and for uniaxial compression and extension, is a factor of approximately 3 greater than the minimum isotropic strain rate [1]. For simple shear, the enhancement factor - the ratio of anisotropic creep rate to minimum isotropic creep rate - might be as high as 9 [3,4].

The aim of the present work is to compare the creep and crystallographic properties of natural and laboratory prepared isotropic ice with those of anisotropic ice. The paper describes uniaxial compression experiments on ice samples collected from a core drilled at the summit of Law Dome, Antarctica. Because the core site is a localised summit, it is a near stationary point in the ice mass, and the dominant stress configuration through the vertical is understood to be unconfined compression. This is supported by studies of the surface strain [5] and by the crystal orientation fabrics from the core (to be published in detail elsewhere).

#### EXPERIMENTAL TECHNIQUE

Three different ice types were tested for the current study. These were (1) isotropic laboratory ice prepared by the method described by Jacka and Lile [6], (2) ice at a depth of 120 m from a core from the summit of Law Dome, Antarctica, and exhibiting a near random crystal orientation fabric, and (3) ice from deeper layers of the core displaying degrees of anisotropy. The density of the 120 m core ice was measured by a bulk method and found to be  $0.90 \text{ Mgm}^{-3}$ . At this depth then, sufficient compaction has occurred to provide high density ice, yet insufficient strain has accrued to develop a non-random crystal orientation fabric.

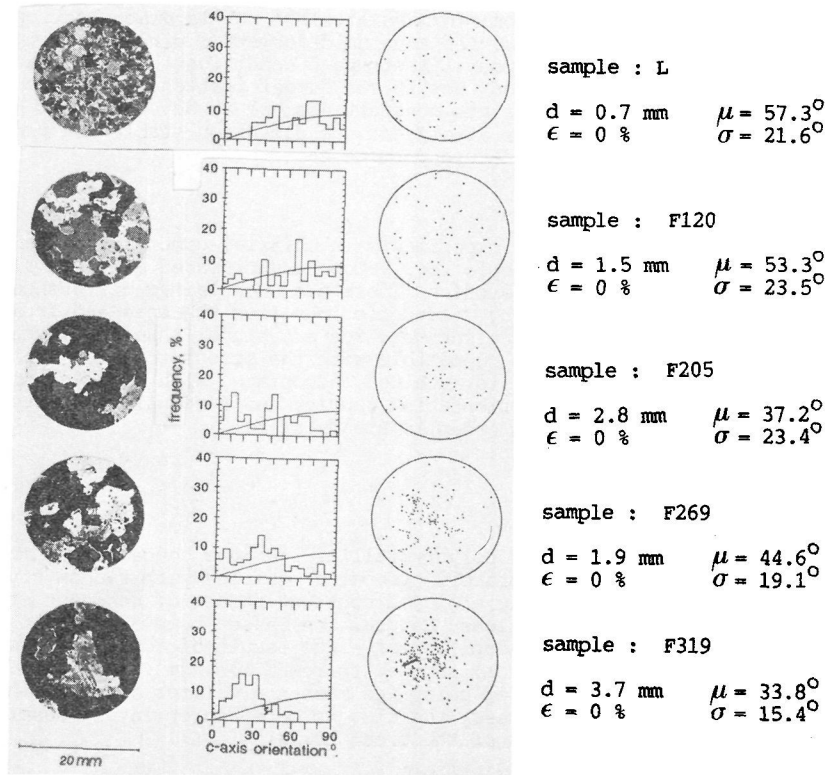


Figure 1 Thin section photographs, crystal orientation fabrics and associated c-axis frequency distribution diagrams for ice test samples. Samples are designated 'L' for laboratory prepared ice and 'F' for core ice. Numbers following an 'F' indicate the depth of core samples. Also indicated are mean crystal diameter,  $d$ , total octahedral shear strain,  $\epsilon$  and the mean,  $\mu$  and standard deviation,  $\sigma$  of the c-axis angles to the vertical. The sine curve indicates a uniform distribution of c-axes.

Figure 1 shows crystallographic data for the ice test specimens prior to experimentation. The sample preparation technique [6] has been shown to be reliable for producing ice with random crystal orientation fabrics as illustrated for the laboratory prepared sample in Figure 1. The density of the laboratory prepared sample was  $0.91 \text{ Mg m}^{-3}$ . The crystal orientation fabric for the 120 m core sample also displays a near random pattern. The final three fabric diagrams of Figure 1 were measured on ice from depths of 205, 269 and 319 m in the core. The age of the ice at 319 m was approximately 800 a. Each of these three fabric diagrams indicates a non-random pattern, there being a greater degree of anisotropy with increasing depth.

Williams and Jacka [7] found for isotropic polycrystalline ice, that minimum strain rate was dependent on laboratory test specimen diameter. In order to eliminate any effect of sample size or shape on the comparisons of laboratory ice flow and core ice flow, each test specimen was cut and machined to the same size (i.e. cylinders of 25.4 mm diameter and 65.0 mm length).

Mean crystal diameter,  $d$  was measured at the conclusion of each test. This parameter was estimated by the relation

$$d^2 = 4A / \pi N$$

where  $N$  was the number of complete crystals within an area,  $A$  of the thin section.

A direct load uniaxial compression apparatus [6] was used to test samples at an octahedral shear stress of 0.2 MPa and at a temperature of  $-3.3^\circ\text{C}$ .

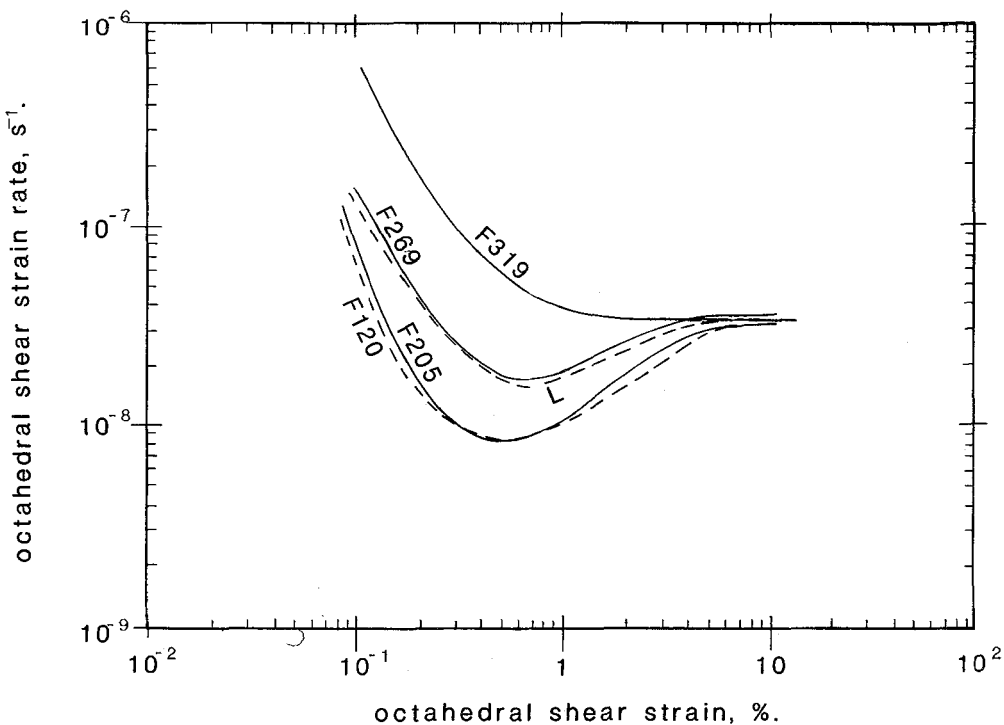


Figure 2 Octahedral shear strain rate plotted as a function of octahedral shear strain for initially isotropic (dashed curves) and anisotropic (solid curves) ice samples tested at 0.2 MPa and  $-3.3^\circ\text{C}$ . Curves are labelled according to the notation described in the caption to Figure 1.

MINIMUM STRAIN RATES AND THE APPROACH TO TERTIARY CREEP

Figure 2 shows creep curves resulting from uniaxial compression tests on each of the samples. The creep curves describe the characteristic shape, displaying the primary, minimum, accelerating and constant creep rate tertiary stages. The minimum strain rate for the isotropic core ice was approximately a factor of 2 lower than for the laboratory prepared isotropic ice. This was despite the precautions taken to equalize parameters (e.g. sample size, impurity content, sample density) which might affect flow results. Several recent ice mechanics reviews [8, 9, 10] have noted the substantial discrepancies among different ice creep studies, both laboratory and field based. The above result highlights the need expressed in those reviews for thorough experiment description and for laboratory interchange of test samples.

In the tertiary stage, the two initially isotropic ices exhibited very similar creep rates. This would seem to indicate that the factors causing the minimum strain rate discrepancy are at least partially accounted for by the onset of tertiary creep and thus that these factors are related to the physical/chemical properties of the ice, rather than to the experimental technique or apparatus. Jacka [2] reported closer matches of strain curves as tertiary creep was approached. Closer matching of crystallography also occurred. This too would indicate that differences in the minimum creep rates were due to properties of the ice samples.

Notwithstanding the apparant discrepancies between the two isotropic ices, and comparing the results from each of the core samples, an increase in minimum strain rate with core depth was observed and it would seem that minimum strain rate is

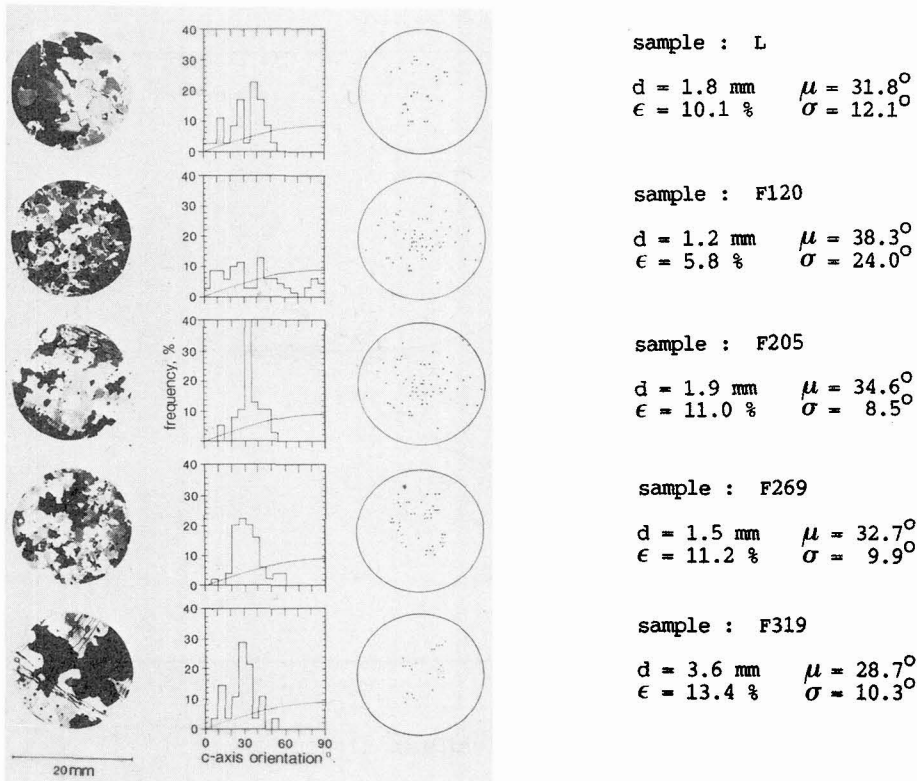


Figure 3 Crystallographic data at the conclusion of the tests. Associated creep curves are shown in Figure 2. Statistical parameters are defined in the caption to Figure 1.

related to the strength of the crystal orientation fabric. From Figure 1, the crystal orientation fabric and associated c-axis distribution histograms for the core sample from 205 m depth exhibited some vertical tendency. This was apparently insufficient however, to significantly affect the minimum creep rate, which was similar to that obtained for the isotropic sample from 120 m depth. By a depth of 269 m, the crystal orientation fabric had further developed (Figure 1), and the minimum flow rate attained was a factor of about 2 greater than that for the isotropic core sample. Finally, for the sample from a core depth of 319 m, the crystal orientation fabric was sufficiently developed to facilitate tertiary flow immediately the recoverable primary creep had been accounted for. Thus no clear minimum strain rate was exhibited, and the tertiary strain rate was similar to the tertiary strain rates ultimately attained by each of the other samples.

Figure 3 shows the crystallographic data at the conclusion of the tests. For each test except the one on initially isotropic core ice, the resulting fabric was a weak small circle girdle. Although there is some vertical tendency evident for the initially isotropic core sample, the fabric is not as well developed. This is the expected result, since this sample underwent only 5.8% octahedral shear strain. Each of the other tests underwent at least 10% strain. Mean crystal diameters at the test conclusions were in the range 1.2 to 1.9 mm for each sample except the 319 m depth core sample, despite an initial crystal diameter range of 0.7 to 2.8 mm. For the 319 m depth sample, the mean crystal diameter was 3.6 mm - hardly different than the initial size. For most of the samples then, a similar crystal size was attained.

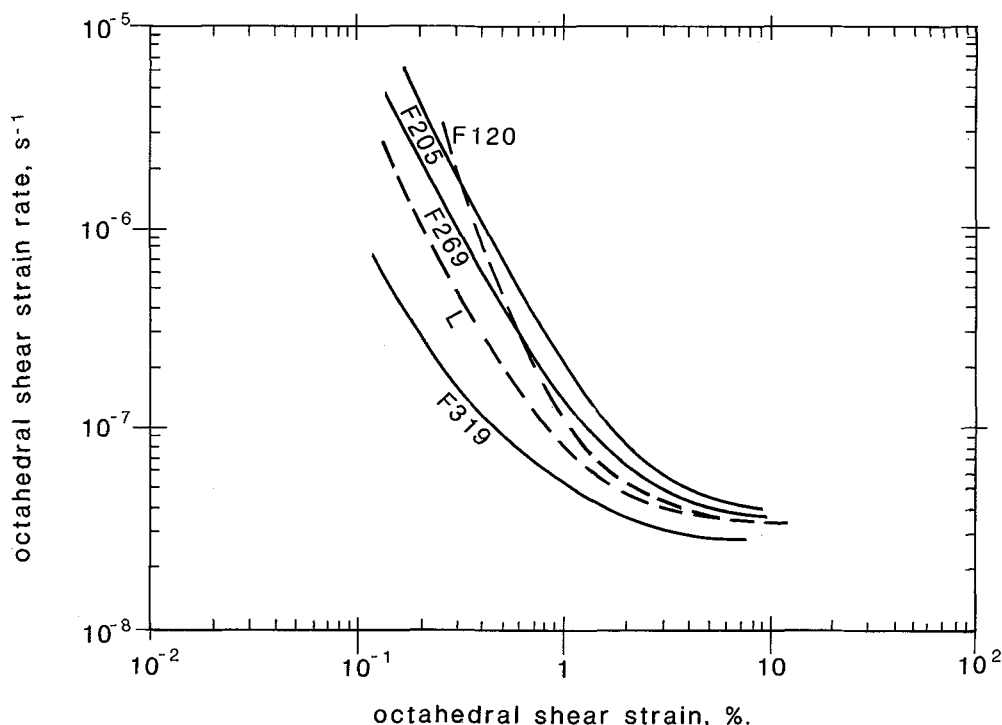


Figure 4 Octahedral shear strain rate plotted as a function of octahedral shear strain for the creep tests on anisotropic ice. The ice samples tested were the resulting samples from the tests described by Figures 2 and 3. The tests were carried out at 0.2 MPa and  $-3.3^{\circ}\text{C}$ .

ANISOTROPIC TERTIARY CREEP

Each of the anisotropic samples resulting from the previous set of tests was retested, again at  $-3.3\text{ }^{\circ}\text{C}$  and at an octahedral shear stress of  $0.2\text{ MPa}$ . The resulting creep curves were similar to each other and are shown in Figure 4. The curves are similar to the creep curve described by the 319 m core sample of the previous set of tests. Again, once the recoverable primary strain was accounted for, tertiary creep was attained with no intermediate minimum. The crystal orientation fabrics developed by each of the previous tests then, were sufficiently well developed to facilitate tertiary creep. The final flow rate for this set of tests was in addition, the same as that attained in the previous set. So despite the continued accumulation of total strain applied to the samples, the tertiary strain rate remained unchanged.

Figure 5 shows the crystallographic data measured at the conclusion of this final set of tests. The small circle girdle fabric is strengthened in each case. The final crystal diameters were all in the range  $1.2$  to  $2.0\text{ mm}$ . With the exception of the  $319\text{ m}$  depth sample, the crystal size had thus not significantly altered during this final set of tests. The final crystal diameter for the  $319\text{ m}$  depth sample was  $2.0\text{ mm}$ . It had therefore decreased to a value nearer that obtained for the other samples, despite the difference noted at the conclusion of the earlier set of tests. For this sample then, an equilibrium crystal size seems to have developed, however the total strain required for this was larger. Initially, this sample exhibited the largest degree of anisotropy, and the largest crystal size.

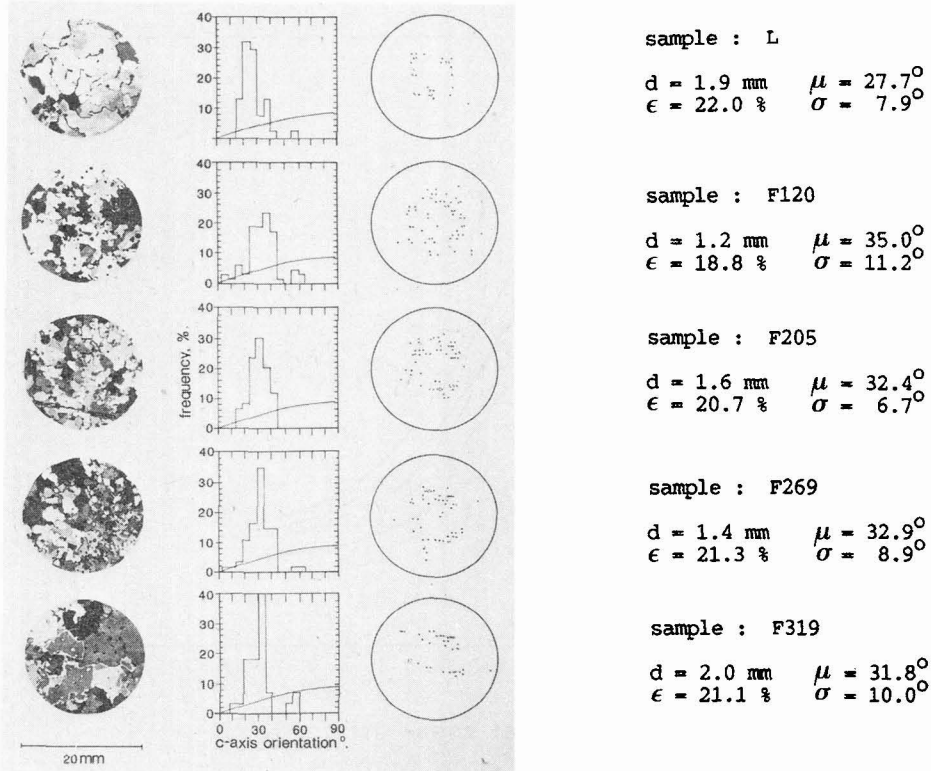


Figure 5 Crystallographic data at the conclusion of the tests on anisotropic ice. Associated creep curves are shown in Figure 4. Statistical parameters are as defined in the caption to Figure 1.  $\epsilon$  is the total octahedral strain undergone.

## OVERVIEW AND CONCLUSIONS

The results obtained in the present study have confirmed several earlier findings. For initially isotropic and anisotropic ice, it has been confirmed (cf: [1, 2]) that at sufficiently large strains (approximately 10%) a tertiary creep stage is attained in which the strain rate is constant. This constant strain rate is maintained for at least a further 35% strain, and is a factor of 3 to 4 greater than the minimum isotropic strain rate.

Along with the attainment of tertiary creep, a preferred crystal orientation fabric (for uniaxial compression, a small circle girdle) develops. Even though the constant tertiary strain rate is attained at approximately 10%, the fabric continues to strengthen and to rotate towards the compression axis until about 30% strain. Henceforth, the fabric pattern also remains unchanged.

Also with the attainment of tertiary creep, an equilibrium crystal size is established. The actual value of the equilibrium crystal size seems to be dependent on the test parameters (stress and temperature), but independent of the initial crystal size.

A rheological system is in steady state when all the variables describing its behaviour are constant with time. Evidence has been produced in this paper indicating that strain rate, crystal orientation pattern and crystal size are all constant with time (over a strain interval of at least 35%) for the tertiary stage of the creep curve. Furthermore, this has been shown for both laboratory prepared ice and Antarctic core ice, and for initially isotropic and initially anisotropic ice. It is finally proposed here then, that the constant tertiary creep is in fact steady state.

## ACKNOWLEDGEMENTS

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## COMMENTS

L. LLIBOUTRY

You have shown (and convinced yourself, because we were already convinced in Grenoble) that the minimum creep rate has no physical meaning and should be dropped. Why then have you used it to assess the influence of grain size ? The softness-grain size relationship should be different for transient creep and for steady tertiary creep.

Answer :

I believe the minimum creep rate does have physical significance. It is a unique,



identifiable point on the ice creep curve, independent of time. It is therefore useful for comparison purposes with past tests which have not attained tertiary creep. However, for application to the flow of natural ice masses, the study of tertiary flow is of far greater importance.

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R.GAGNON

How do the bubbles, which were visible in some of your thin sections, figure in your analysis ?

Answer :

The bubbles, visible in the thin section of the core ice samples, are not considered to have a large effect on the flow results. I believe that the fact that the creep rates for the laboratory ice (which were bubble free) and the field ice were particularly similar in tertiary flow, demonstrates this.

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S.MURRELL

Your conclusion, that steady state creep occurs beyond 10 per cent strain after the minimum creep rate point has been passed (at about percent strain), is in accordance with experience with creep in metals in which steady state creep also occurs beyond 10 per cent strain (but in this case the steady -state strain- rate is the minimum rate).

If creep involves a competition between strain hardening (strain-dependent) and recovery processes the ice results suggest that either strain softening can be induced or that recovery is at a lower rate at low strains (this seems likely in any case).

Answer :

"Strain-softening" is induced by the development of the preferred crystal orientation fabric.

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J.W.GLEN

What temperature was the specimen kept at between stressing ?

Answer :

The experiment temperature of  $-3.3^{\circ}\text{C}$  was maintained by heating the air within an insulated box surrounding the apparatus. The ambient temperature was  $-20^{\circ}\text{C}$ , and before tests were unloaded, the heater was turned off. So between stressings, the temperature was  $-20^{\circ}\text{C}$ .

In addition, the sample preparation between testing was done as quickly as possible, usually taking less than 1/2 hour.

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S.KIRBY

Do you have an explanation of the sample diameter effect on minimum creep rate ?

Answer :

I believe it is due to the effect of sample/platten bonding. This topic is being investigated further in our current work.