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Effects of prestrain on the ductile-to-brittle transition of ice

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ABSTRACT

The ductile-to-brittle transition was investigated in prestrained columnar ice at −10 °C. Laboratory-grown specimens of freshwater and saline ice were prestrained under uniaxial across-column compression (to levels from $\varepsilon_p = 0.003$ to $\varepsilon_p = 0.20$, at constant strain rates in the ductile regime) and likewise reloaded (at rates from $1 \times 10^{-6}\mathrm{s}^{-1}$ to $3 \times 10^{-2}\mathrm{s}^{-1}$). Prestrain caused solid-state recrystallization as well as damage in the form of non-propagating microcracks. The ductile-to-brittle transition strain rate $\dot{\varepsilon}_{D/B}$ increased by a factor of 3–10 after prestrain of $\varepsilon_p = 0.035$ in both freshwater and saline ice, compared to that of initially undamaged ice of the same type. Additional prestrain had little further effect on $\dot{\varepsilon}_{D/B}$. The results are interpreted within the framework of a model (proposed by Schulson, 1990, and Renshaw and Schulson, 2001) that predicts the transition strain rate based on the micromechanical boundary between creep and fracture processes. Model parameters primarily affected by prestrain were the power-law creep coefficient B (more so than the creep exponent n), Young's modulus E and, by extension, the fracture toughness K_{Ic}.

1. Introduction

The macroscopic behavior of ice is known to be ductile when compressed slowly, but brittle when compressed rapidly [1]. The shift between those two behaviors occurs over a range of up to one order of magnitude in strain rate, $\dot{\varepsilon}$. Within this range is identified a critical rate of compression, the ductile-to-brittle transition strain rate, $\dot{\varepsilon}_{D/B}$, which is a function of external conditions (e.g., temperature, pressure) and of internal measures of the ice, including grain size, salinity, as well as damage (for review see Ref. [3]). The influence of damage presents something of a paradox, in that introducing cracks into a body might seem to make the material more brittle, but, in fact, that is not necessarily the case, as will become apparent. Damaged material (containing non-propagating cracks as a result of prior deformation) can behave in a ductile manner under the same loading conditions that cause brittle failure in virgin[1] material.

Previous work has investigated the ductile-to-brittle (D–B) transition in polycrystalline ice that was initially free from damage, for example, as a function of temperature [4], of confinement [5], or of grain size [6]. The mechanical behavior of damaged ice has been a less common subject of inquiry, although precedents include studies of damage in creep of columnar ice [7] and of granular ice [8–10], and in compression of granular ice at constant strain rates [11]. The effect of damage specifically on the D–B transition was explored in moderately prestrained columnar saline ice, in which $\dot{\varepsilon}_{D/B}$ increased by up to an order of magnitude in strain rate for across-column loading [12]. The level of uniaxial compressive prestrain ε_p was limited in that study to 0.035, and was imparted at one constant strain rate (1×10^{-5} s^{-1}). In the current work we extend the range of prestrain conditions to more fully investigate damage in both saline and freshwater columnar-grained ice that possesses the S2[2] growth texture.

The effects on the compressive ductile-to-brittle transition examined herein could be associated with the prestrain of other materials. For example, the strength of highly-confined rock within the earth's crust can be limited by its plasticity [14], which may depend on prior strain. Compressive prestrain of metals has been

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[1] We recognize that at the point of terminal failure material that is initially free from damage possesses microcracks that nucleated during loading. For convenience, we refer to such specimens as "undamaged" or "virgin" to distinguish their initial state from those in which damage has been imparted by specific levels of prestrain prior to testing.

[2] S2 designates columnar-grained ice in which the crystallographic *c*-axes are randomly oriented within, but essentially confined to, the horizontal plane, i.e., normal to the (mean) longitudinal axis of the vertical columns; S2 ice commonly occurs in natural ice covers [13].

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found to decrease ductility upon subsequent tensile loading (e.g., in steel at ambient temperature [15], or in stainless steel in creep [16]). To the authors' knowledge, however, no similar results to those reported in the present work on ice yet exist for other materials. The only other work on ice in which an effect of prestrain was studied relates to tensile ductility, where compressive prestrain of the magnitude explored in the present work imparted ductile behavior, manifested in elongations of 5% to 10% or greater [17,18].

2. Background

Schulson [1] and Renshaw and Schulson [2] developed a model shown to fit well to data for both the ductile-to-brittle transition and the failure strength of (undamaged) ice and of various types of rock. The pivotal concept expressed by this model is the micromechanical competition between two processes: the intensification and the relaxation of internal stresses at crack tips. Crack propagation culminates in brittle fracture, whereas crack blunting via creep culminates in ductility.

The model predicts the ductile-to-brittle transition strain rate for loading under uniaxial compression as

$$\dot{\varepsilon}_{D/B} = \left(\frac{E_0}{E}\right)\frac{(n+1)^2(3)^{\frac{n-1}{2}}BK_{Ic}^n}{n\sqrt{\pi}(1-\mu)c^{n/2}} \quad (1)$$

where E_0 is the Young's modulus of undamaged material, E is the effective Young's modulus (reduced by damage), n and B are the exponent and coefficient, respectively, in the power-law creep relationship ($\dot{\varepsilon} = B\sigma^n$ for axial stress σ), K_{Ic} is the fracture toughness, μ is the coefficient of kinetic friction, and c is the characteristic radius (or half-length) of cracks within the material. All of these parameters can be experimentally determined [3]. Below the threshold $\dot{\varepsilon}_{D/B}$, creep deformation is able to relax internal stresses, concentrated at the crack tips, before they exceed the yield strength of the material; above $\dot{\varepsilon}_{D/B}$, additional cracking leads to brittle failure [2].

The model incorporates the process of frictional sliding that occurs between opposing surfaces of an inclined crack under the action of shear stress. The coefficient of kinetic friction μ is a function of sliding velocity v and temperature T, and values may be obtained from the literature (more below).

For initially undamaged ice under ambient conditions, the creep exponent has been found to have a typical value of $n = 3$, from numerous studies, e.g., freshwater columnar ice [19,20], freshwater granular ice [21], and first-year sea ice [22]. We will show in our results that n remains fairly constant in prestrained ice; at least the evidence is not strong enough to conclude otherwise. Refer to Appendix A for the (re)derivation following Schulson [1] and Renshaw and Schulson [2] of Equation (1), which differs from previous expressions of the model that assumed elastic effects of damage to be negligible and set $E \approx E_0$.

3. Experimental methods

Freshwater ice and saline ice were both formed in the Ice Research Laboratory at Dartmouth College by unidirectional freezing of filtered ($\leq$20 μm) tap water (or, in the case of saline ice, a 17.5 ± 0.2‰ (ppt) solution of commercially-available “Instant Ocean” salt mixture), in tanks equilibrated to +4 °C. Freezing was controlled by placing a cold plate, chilled using a circulating bath set to −20 °C, on the surface of the water or solution, which was seeded with $\leq$ 4 mm equiaxed ice grains, to produce the S2 (orthotropic columnar) grain structure. The S2 growth texture was verified by the Langway [23] method using thin sections of the as-grown ice [see 24]. Statistics on the mass density, salinity, and grain diameter are listed in Table 1. Blocks of the ice were machined into 152 mm cubes, to a tolerance of 0.076 mm, aligning one edge of the cube parallel to the long axis of the columnar grains, identified as the x_3 direction. The ice was machined and tested at −10 °C.

The first stage of testing involved prestraining the cube-shaped specimens under uniaxial compression at constant strain rate $\dot{\varepsilon}_p$ in an across-column direction, identified as x_1. Loads were applied to the opposing x_1 faces of the specimen by polished brass brush platens fixed to servo-hydraulic controlled actuators. Levels of prestrain were specified from $\varepsilon_p = 0.003$ to 0.20 to impart permanent deformation to the ice. To avoid collapse of the specimens, the prestrain rate $\dot{\varepsilon}_p$ was kept in the ductile regime, either one or two orders of magnitude below the nominal ductile-to-brittle transition strain rate $\dot{\varepsilon}_{D/B,0}$ inherent to undamaged material, for each type of ice (at −10 °C, $\dot{\varepsilon}_{D/B,0} \approx 1 \times 10^{-3} s^{-1}$ for virgin saline ice, and $\dot{\varepsilon}_{D/B,0} \approx 1 \times 10^{-4} s^{-1}$ for virgin freshwater ice [5,4]). Table 2 lists which type of ice was tested at each prestrain condition.

After being prestrained, each parent specimen was quartered into subspecimens, retaining material along the center planes for thin sections. Before being measured and subsequently reloaded, the subspecimens were machined into rectangular prisms (120 mm × 60 mm × 60 mm, such as those photographed in Fig. 1) with the long dimension running across the columnar grains either parallel (x_1) or perpendicular (x_2) to the initial prestrain direction.

Porosity was measured before and after prestraining, calculated as $\phi = (\rho_0 - \rho)/\rho_0$, where ρ is the specimen mass density and $\rho_0 = 917.5$ kg m^{-3} is the expected density of pure ice, free of damage, bubbles, salinity, etc., at −10 °C and ambient pressure [25]. Although bubbles were not visible within the as-grown freshwater ice, its mean mass density (Table 1) was slightly below ρ_0, implying a porosity of $\phi = 0.0024 \pm 0.0014$. In contrast, as-grown saline ice contained visible pores and brine pockets; its mean porosity was $\phi = 0.015 \pm 0.013$ using the same value for ρ_0. Dynamic elastic properties (e.g., Young's modulus, E) were determined for undamaged and prestrained ice by measuring ultrasonic transmission velocities. See Snyder et al. [26], Snyder [24] for further details on the ice preparation, prestrain, and measurement procedures.

Finally, the rectangular prisms milled from the prestrained parent specimens were individually reloaded at a constant strain rate $\dot{\varepsilon}_r$, ranging from 1×10^{-6} to $3 \times 10^{-2} s^{-1}$, compressing uniaxially in the long across-column dimension (either x_1 or x_2). The loaded faces of the subspecimens were small relative to the bristle ends of the brass brush platens used in prestraining the parent specimens, so solid aluminum platens were used in this step instead. To reduce boundary confinement, a thin (~0.15 mm) sheet of polyethylene was placed between the subspecimen and each loading platen. Fig. 1 shows subspecimens of saline ice (a, after prestrain $\varepsilon_p = 0.10$ in this case) and freshwater ice (b, after prestrain $\varepsilon_p = 0.035$) situated between the platens prior to reloading.

The elapsed time between prestraining and reloading was held constant at 24 ± 6 hours. The results obtained following this reloading procedure were similar (as will be shown) to those of

Table 1
Measured mass density (at −10 °C), salinity (of melt), and columnar grain diameter (by linear intercept) of laboratory-produced freshwater ice and saline columnar-grained ice. Values are means ± one standard deviation.

Ice type	Mass density kg m^{-3}	Salinity ppt	Column diameter mm
Freshwater ice	915.3 ± 1.5	–	5.6 ± 1.9
Saline ice	903.6 ± 11.0	5.4 ± 1.1	4.4 ± 1.5