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On the restoration of strength through stress-driven healing of faults in ice

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ABSTRACT

New experiments have revealed that stress-driven healing of faults in saline ice, when confined under biaxial compressive stress of $\sigma_h = 60$–750 kPa for a period from $t_h = 3$ s to 18 h at a temperature from −30 to −3° C, restores compressive strength to the body. The strength increases with confinement, time and temperature, scaling as $\sigma_h t_h^n \exp(-nQ/RT)$ where $n = 0.29 \pm 0.02$ and $Q = 50 \pm 6$ kJ mol^{-1}. A model of the restoration is developed in terms of creep of asperities that interact across the plane of the fault and is applied to healing of the arctic sea ice cover.

1. Introduction

In a recent paper on friction of warm ice [1], it was shown through slide-hold-slide experiments that the coefficient of static friction of both freshwater and saltwater material increases upon holding under normal load, scaling with the logarithm of time in a manner similar to that exhibited by metals [2], rock [3] and glassy polymers [4]. The effect was termed static strengthening, or healing, and was explained and then modeled in terms of a creep-controlled increase in the real (as opposed to apparent) area of contact through the interaction of asperities that protrude from opposing surfaces. Once loading resumes, newly bonded joints eventually rupture under the action of shear-induced tensile stress at which point sliding starts again. Implicit in the model is the idea, supported by sub-second sintering [5], that the timescale for bonding of the interface is short relative to the timescale of deformation. In performing the analysis, the average diameter of the asperities was derived to be ~30 μm.

Static strengthening suggests the possibility that strength can be significantly restored to a fractured body. In mind is the arctic sea ice cover and Coulombic shear faults that form ubiquitously therein during winter [6–10]. The features weaken the cover by serving as localized zones along which inelastic deformation is concentrated through frictional sliding. Other examples where healing may be important include strike-slip like features that lace through the icy crust of Jupiter's Europa [11,12] and "tiger stripe" rifts within the icy crust of Saturn's Enceladus [13,14]. Both crusts encase putative oceans. The question is: during periods of dormancy when sliding stops owing to a reduction in driving loads, can the faults heal sufficiently under the action of stress alone—i.e., in the absence of any contribution from the freezing of a liquid penetrant– to restore significant compressive strength to the body as a whole?

To provide some basis for answering this question, we describe in this paper the results of a series of experiments in which faults in saline ice were allowed to heal under relatively low normal stress of 60–750 kPa for periods from 3 s to 18 h at temperatures from −30 to −3° C. We show that the kinetics of healing obey an Avrami-like relationship, and then interpret the behavior in terms of the creep of asperities.

2. Experimental procedure

2.1. The ice

Ice was produced in the laboratory by following an established procedure [15]. In short, water of 17 ppt salinity was placed in a 1000 L tank, equilibrated to around 4° C, and then, upon seeding with fragments of ice, was unidirectionally solidified, top down, to

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create over a period of a week or so a plate ~20 cm thick. Solidification was achieved by placing an aluminum plate, cooled to −16° C, atop the tank. The resulting material possessed a columnar-grained microstructure of ~5 mm column diameter and a crystallographic texture in which the c-axes of the individual grains were more or less randomly oriented within the horizontal plane of the ice (termed S2 ice [16]). Distributed throughout the volume of the grains and at the grain boundaries were sub-mm pores that contained a mixture of brine and air and which comprised about 5% by volume of the material. The melt-water salinity and density, respectively, were measured to be 4.5 ± 0.5 ppt and 875 ± 47 kg m^{-3}.

For reference, the long direction of the columnar grains (i.e., the direction of solidification) is termed X_3 and the two orthogonal directions (in the plane of the cover) are termed X_1 and X_2. Prismatic-shaped specimens of approximate dimensions 180 mm (along X_1), 100 mm (along X_2) and 40 mm (along X_3) were milled from the plate.

2.2. Production of shear faults

Through-thickness faults were created in three ways. The first was to compress the specimen biaxially by proportionally loading along directions X_1 (σ_{11}, major stress) and X_2 (σ_{22}, minor stress) such that $\sigma_{22}/\sigma_{11} = 0.1$; i.e., by loading across the columns [17]. This we did using a servo-hydraulic loading system housed within a cold-room. Temperature was held at −10° C and strain was applied along X_1 at a constant rate of 1×10^{-2} s^{-1}. Natural shear faults formed after shortening ~0.1%, with a plane inclined ~30° to X_1 and parallel to X_3. These we term Coulombic faults owing to the role of frictional sliding in their production [17]. Coulombic faults possessed a small amount of cohesion that led to residual compressive strength of σ_o ~0.5 MPa (more below), probably related to the freezing of a small amount of melt-water produced through frictional heating [18].

The other two kinds of fault were created artificially. One kind was made by cutting the ice using a band-saw. Like the natural faults, the plane of the saw-cut, one per specimen, was oriented ~30° to X_1 and parallel to X_3. The other was made in the same manner, followed by polishing of the opposing faces with a warm glass plate to reduce roughness (defined below), listed in Table 1. The artificial faults possessed no cohesive strength and so, to keep the two halves of the specimen together for later testing, the two apexes were welded with drops of freshwater. The weld imparted a residual compressive strength of σ_o~0.1 MPa. As will become apparent, healing of the artificial faults was almost indistinguishable from healing of the natural, Coulombic faults. For that reason, and for the relative ease of preparing artificial faults, most of the results presented below were obtained from artificial faults.

We measured roughness, Ra, in a non-contact manner, using a Zygo light interferometer (profilometer), model New View 7300, calibrated on site using a chemical vapor deposited silicon carbide standard. Each surface was scanned five times, each time over an area of approximately 2×12 mm^2, thereby obtaining a series of profiles. Roughness was taken to be a measure of profile residuals from a mean ordinate, and was defined by the relationship $R_a = \frac{1}{l}\int_0^l |Z(x)|dx$ where l denotes the length of the scanned area and Z (x), the profile residual.

Table 1
Roughness (mm) of three kinds of fault.

Natural fault	Saw-cut	Smooth saw-cut
0.26 ± 0.13	0.09 ± 0.02	0.06 ± 0.02

2.3. Healing

To effect healing, the fault-bearing specimens were biaxially compressed in a manner that produced no shear stress on the plane of the fault; i.e., by setting $\sigma_{11} = \sigma_{22}$. This created a compressive healing or hold stress, σ_h, of the same magnitude acting across the fault. As already noted the healing/hold stress was held constant and was varied from $\sigma_h = 60–750$ kPa for periods of time ranging from 3 s to 18 h at a temperature that was varied from −30 to −3° C.

2.4. Strength

The brittle compressive strength of the healed material was measured by loading the ice uniaxially along X_1 at −10° C at a constant strain rate of 5×10^{-3} s^{-1}. Strength was defined as the maximum load supported by the ice divided by the X_2–X_3 cross-sectional area. Reproducibility was assessed through multiple measurements under each combination of fault, pressure, holding time and temperature, generally in either duplicate or triplicate; occasionally as many as four or five measurements were made.

3. Results and observations

For each kind of fault, strength was restored with time under all conditions of holding. The degree of restoration, however, varied with holding conditions, from rather little for shorter time under lower normal stress at lower temperature of healing to almost complete for longer time under higher stress at higher healing temperatures. The figures below illustrate this behavior and the subsequent analysis quantifies the kinetics and the apparent activation energy of the process. Standard errors, unless shown explicitly by vertical bars through the points in the figures, are generally smaller than the diameter of the points.

3.1. Restoration of strength

Fig. 1a shows the effect of hold time on the as-measured strength, σ_c, of specimens that contained a Coulombic fault that was healed at −10° C under a normal stress that spanned the range from $\sigma_h = 60–750$ kPa. Note the residual strength, σ_o, of ~0.5 MPa of as-faulted material, mentioned above. After 18 h (64,800 s) under the normal stress of $\sigma_h = 750$ kPa the strength reached that of fault-free, virgin material, σ*, taken from the literature [19] to be $\sigma^* = 4.9$ MPa at −10° C at 5×10^{-3} s^{-1}. This implies complete restoration under those conditions. Under a lower healing stress of $\sigma_h = 250$ kPa less than 15% of the strength was recovered in the same time; and upon healing under a still lower stress of $\sigma_h = 60$ kPa hardly any recovery was detected, even after 18 h.

Fig. 1b shows the same behavior in specimens that contained a saw-cut. Again, after 18 h of healing restoration was essentially complete under $\sigma_h = 750$ kPa, but less so under lower stresses. The weld-induced residual strength was σ_o ~0.1 MPa. Upon subtracting the residual strength from the measured compressive strength, it was found that the restored strength, $\sigma_r = \sigma_c - \sigma_o$, appears to be independent of the character/roughness of the fault, Fig. 1c, at least after healing under 750 kPa. This result was rather surprising. Perhaps, it is a reflection of the plasticity of asperities that characterize the interface (more below) and, as for the case of ductile metals [20], may mean that each asperity has smaller asperities on top of it at all scales [21,22].

Concerning the roles of stress and temperature, Fig. 2 shows that the restored strength of specimens with saw-cuts increases linearly with healing stress, and Fig. 3 shows that over the range of temperature from −30 to −3° C (upon holding a saw-cut for 1000 s under stresses of $\sigma_h = 500$ and 750 kPa) the restored strength