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Static strengthening of frictional surfaces of ice

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Abstract

Systematic slide–hold–slide experiments were performed at $-10\ ^{\circ}\mathrm{C}$ on both first year sea ice and freshwater ice. The sliding velocity ranged from 10^{-6} to $10^{-4}\ \mathrm{m\ s^{-1}}$ and the holding time from $t_h = 1$ to 10^4 s under an apparent normal stress of 60 kPa. The experiments established that the shear stress required to re-initiate sliding increases with holding time, following a threshold period that increases with decreasing sliding speed. The effect is termed static strengthening and is found to scale as either $\beta \log t_h$ or t_h^m, where $\beta = 0.30 \pm 0.03$ and $m = 0.5 \pm 0.1$ for both materials. The effect is a large one: upon holding for $t_h = 10^4$ s the coefficient of static friction for both materials increases by about a factor of three, from $\mu_s = 0.5$ to $\mu_s = 1.4$. The behavior is explained in terms of the geometry and deformation of asperities that protrude from opposing surfaces and interact at points of contact, and a model is presented that incorporates creep, hardness and fracture.

Keywords: Ice; Static friction; Strength; Creep; Fracture

1. Introduction

Frictional sliding plays a fundamental role in ice mechanics, on scales large and small. In the geophysical arena, for instance, the process is a major factor in the deformation of the arctic sea ice cover [1–8] and in the tectonic evolution of Saturn's Enceladus [9,10] and Jupiter's Europa [11–13]. In cold ocean engineering it affects ice loads on off-shore structures, particularly vertically sided ones, through its effects on the ductile to brittle transition [14,15], on confinement-induced strengthening [14] and on the transition from Coulombic to plastic faulting [16,17].

At play are two stages: initiation of sliding and continuation. Initiation is characterized by the coefficient of static friction; continuation by the coefficient of dynamic or kinetic friction. Kinetic friction of ice on ice has been relatively well studied [18–26] and is governed at higher velocities (i.e. velocities greater than $\sim 10^{-2}$–$10^{-1}\ \mathrm{m\ s^{-1}}$ for warm ice nominally at $-10\ ^{\circ}\mathrm{C}$) by lubrication through the formation of a thin layer of melt water [18]; at lower velocities the process is governed by adhesion and creep deformation [20,21]. Static friction, in comparison, has received little attention. What is known from recent work by Lishman et al. [26] is that holding warm ($-10\ ^{\circ}\mathrm{C}$) saline ice under a low normal stress of 50 kPa for 10^3 s after sliding a few millimeters at $10^{-4}\ \mathrm{m\ s^{-1}}$ increases the coefficient of static friction by more than a factor of two. What is not known is the nature of that effect. This paucity of knowledge may not deter an understanding of the mechanics of cold ice in which thermally activated mechanisms operate relatively slowly [27], but may well impede predictions of the deformation of warm ice.

Thus it was with the aim of understanding static friction that the present work was undertaken. To that end we performed systematic slide–hold–slide (SHS) tests on both first year sea ice and freshwater ice. We present the results in this paper, and offer an interpretation in terms of the geometry and deformation of micro-asperities that protrude from opposing surfaces and interact at points of contact.

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2. Experimental procedure

2.1. The ice

The first year sea ice had been harvested during the winter of 2009 from the ice cover on the Beaufort Sea, at 71° N, 156° W, and then stored in the Ice Research Laboratory at Dartmouth. It was comprised of columnar grains of 6.1 ± 2.3 mm column diameter and possessed S2 growth texture (see Figs. 1 and 2 in Fortt and Schulson [25]). Its melt water salinity was 4–5 p.p.t. and its density at -10 °C was 918 ± 4 kg m^{-3}.

We produced the freshwater ice in the laboratory by following a procedure described elsewhere [16]. Briefly, presieved fragments were placed in a mold and then consolidated by radially freezing, while water flowed slowly through the center, bottom to top, to eliminate stresses. This produced equiaxed and randomly oriented aggregates

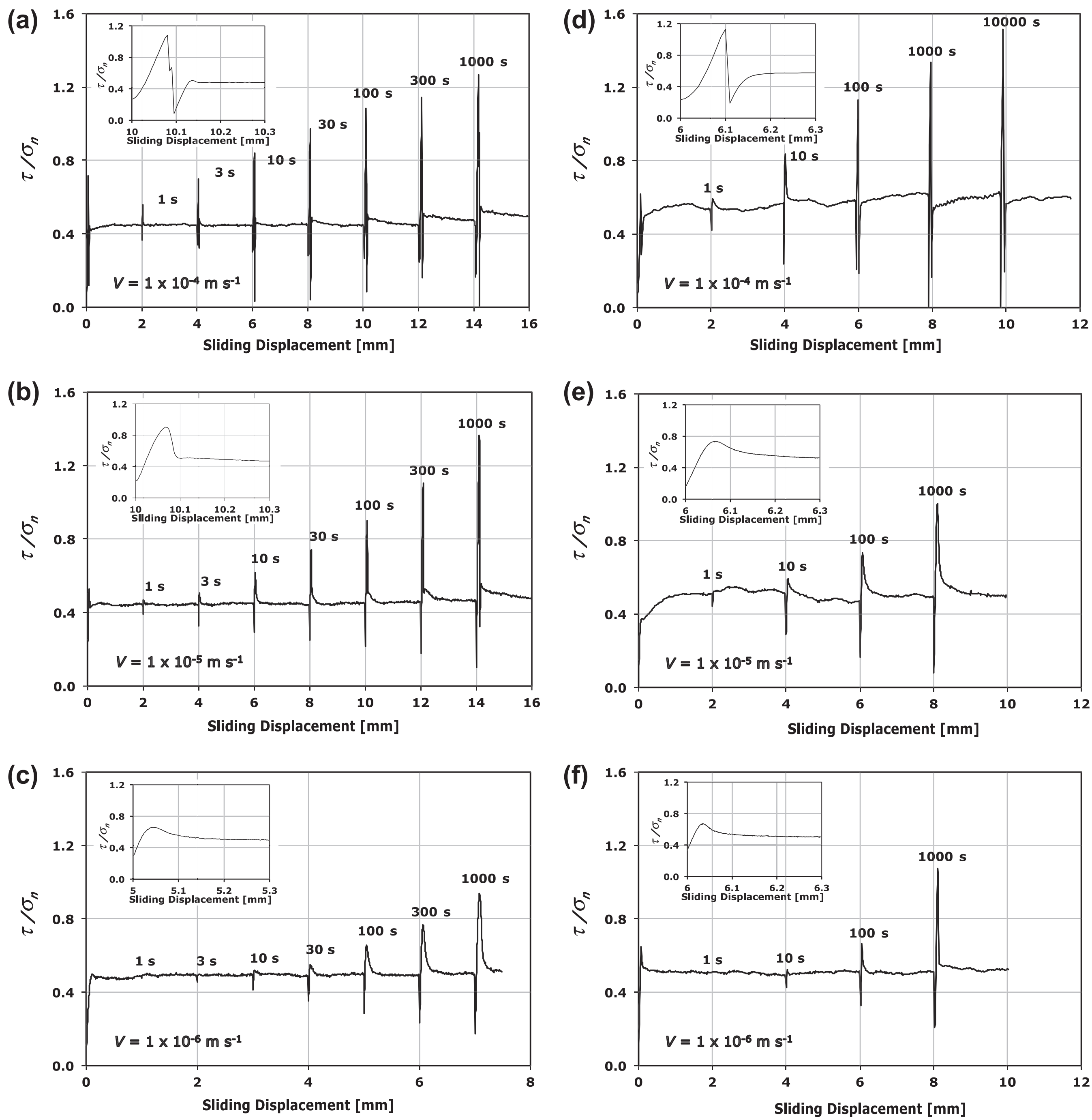

Fig. 1. Plots of frictional shear stress (τ) divided by normal stress (σ_n) vs. displacement from SHS tests at $-10°$ on first year sea ice (a–c) and freshwater granular ice (d–f) at actuator velocities of 10^{-6}, 10^{-5} and 10^{-4} m s^{-1}. The inserts show expanded segments of reloading (step 3) at the same velocity after holding for 100 s.