MEASUREMENTS OF FRICTIONAL SLIDING OF COLD ICE AT -175 °C. E. M. Schulson[1] and A. L. Fortt[1], [1]Thayer School of Engineering, Dartmouth College, 8000 Cummings Hall, Hanover, NH 03755, USA.

Introduction: Frictional sliding is a fundamental process underlying tectonic activity within the crusts of Enceladus and Europa and of other icy satellites [1-14]. This paper describes a double-shear system and a first set of measurements of the kinetic (dynamic) coefficient of friction of ice sliding slowly upon cold ice at -175 °C, under low normal stresses. The work is part of a systematic study of the friction of cold ice.

The Experimental System: The experimental system was constructed specifically for this work. It is a symmetrical, double-shear device, Fig.1, in which one block, termed the slider, is pushed symmetrically between two others, termed pads. The normal forces F_N are applied using levers whose mechanical advantage, both calculated and measured, is F_N/F_W=3.1. In the present experiments F_N is held constant for each set of conditions. The frictional force F_F is measured using a calibrated load cell attached to the slider though a rod of Macor (chosen for its low thermal conductivity). The slider velocity V is controlled by the actuator of a servo-hydraulic loading machine.

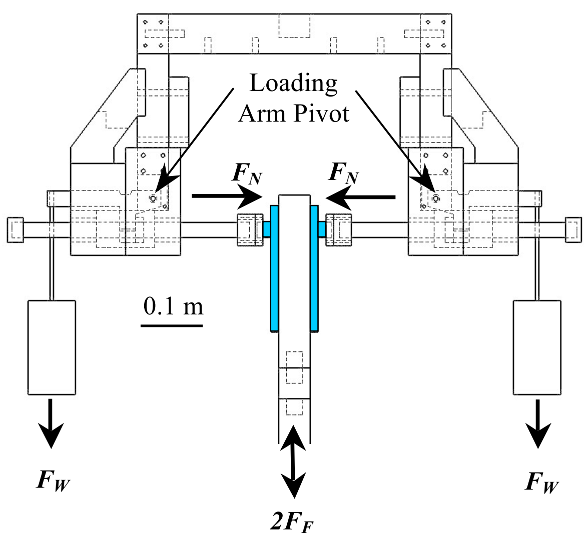

Fig. 1. Engineering drawing of double shear device.

An important consideration was the stiffness of the levers. If too compliant, instabilities that mimic stick-slip could set in should cold ice exhibit velocity weakening in the manner of warm ice [15,16]. Trial tests were thus performed at -10 °C. They revealed that the levers, after an up-grade, were sufficiently stiff.

The system is housed within a chamber attached to the loading machine, which itself is housed within a cold room. The chamber, Fig. 2, is cooled using liquid nitrogen that is passed through four cooling fins placed above and below the slider and pads. Temperature within the chamber is monitored by eight thermocouples; it is controlled by the flow rate of LN_2, which is governed by an electronic actuator. In these experiments, temperature was controlled to ± 1 °C.

Fig. 2. Photograph of testing system in a cold room showing MTS model 810 uniaxial loading frame and normal/side loading device, box for containing nitrogen gas and oxygen sensor suspended from ceiling.

Experimental procedure: Two kinds of polycrystalline ice were examined: equiaxed/randomly oriented aggregates, termed granular ice, and columnar ice. Both kinds were prepared from fresh-water using standard procedures, described elsewhere [17,18]. Granular ice was examined of two grain sizes, d=1 mm and d=8 mm (as measured using the method of linear intercepts); the columnar ice was of one column diameter, d=5±2 mm and was oriented in the sliding system such that sliding occurred in a direction across the columns. In each experiment, both slider and pads were made from the same kind of ice; their dimensions were 25×46×76 mm^3 (slider) and 25×41×41 mm^3 (pad). The sliding surfaces were prepared using a horizontal mill and possessed a surface roughness before sliding of 1.1 ± 0.4 × 10^{-6} m (measured over a length of 8 mm in the direction of sliding). It is assumed that at the test temperature, the ice possessed the hexagonal crystal structure, denoted ice Ih, and not the Ic cubic structure. The sliding velocity was varied from V=5×10^{-8} m s^{-1} to 1×10^{-3} m s^{-1} . Five different levels of normal stress were applied, from σ_n=0.02 MPa to 0.1 MPa. Sliding distance was limited to δ=2 mm, except at the lowest velocity where the distance was limited to δ=1 mm. Sliding distance was set following preliminary experiments that revealed that the frictional force F_F reached a more or less constant level well before this limit. In total, 70 tests were run.

Results and Discussion: Fig. 3 shows a typical F_F-δ curve. The frictional force first rises and then tends to level off to a steady-state value. In deriving the friction coefficient (defined below), the average of the highest and the lowest forces was used, as measured over the second half of the course of δ=1-2 mm (δ=0.5-1 mm at the lowest velocity).

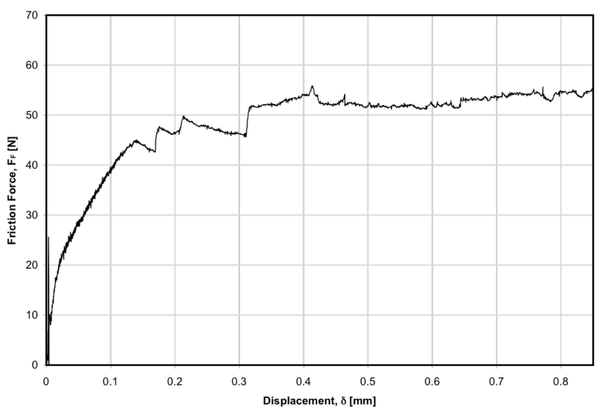

Fig. 3. Typical F_F vs. δ curve. $V=5\times10^{-8}$ m s^{-1}, F_N=130 N, granular ice (d=8 mm).

The kinetic coefficient of friction μ was obtained as follows: The forces F_F and F_N were first converted to shear stresses τ and normal stresses σ_n, respectively, by dividing by the apparent area of contact, taking into account that two pads were used. From plots of τ vs. σ_n the friction coefficient was determined from the slope $\mu=d\tau/d\sigma_n$. In all cases examined here, τ scaled linearly with σ_n, implying that over the range examined the coefficient of friction is independent of normal stress.

Fig. 4 plots the friction coefficient vs. sliding velocity. Over the range examined, the coefficient increases with increasing velocity, from $\mu=0.39 \pm 0.09$ at the lowest velocity to $\mu=0.77 \pm 0.04$ at the highest. There was some evidence that the friction coefficient of the more finely grained ice may be slightly greater than that of the more coarsely grained ice, although a firm conclusion awaits further work because the more finely grained material was somewhat bubbly and thus less dense (880 vs. 915 kg m^{-3}). Barring a possible effect of grain size, the friction of columnar ice appeared not to be significantly different from that of granular ice.

Interpretation and implications await a more complete set of results. At this juncture, suffice it to note that the transition from velocity-strengthening to velocity-weakening that is seen at higher temperatures of -40 °C and above over the same range of sliding velocity [15,16] is absent at -175 °C. This may not be surprising, for the mechanism of velocity-weakening—namely, frictional melting—is less likely to operate when cold ice slides slowly over itself.

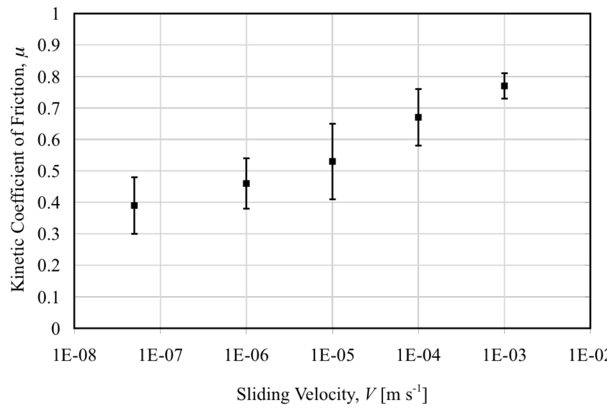

Fig. 4. Kinetic coefficient of friction vs. sliding velocity of ice on ice at -175 °C.

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