FRICTION OF ICE.

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Introduction: This abstract describes a continuation of earlier work [1] and presents measurements on the effect of temperature, velocity, normal stress, surface roughness and hold time on the coefficient of friction of ice on ice under conditions relevant to tectonic activity within the crusts of Enceladus, Europa and other icy satellites.

The Experimental System: In brief, the experimental system is a symmetrical, double-shear device, in which one block, termed the slider, is pushed symmetrically between two others, termed pads. The normal forces F_N are applied using levers and the frictional force F_F is measured using a calibrated load cell. The slider velocity V is controlled by the actuator of a servo-hydraulic loading machine. The system is housed within a chamber that is cooled using liquid nitrogen. The temperature was controlled to ± 1 K.

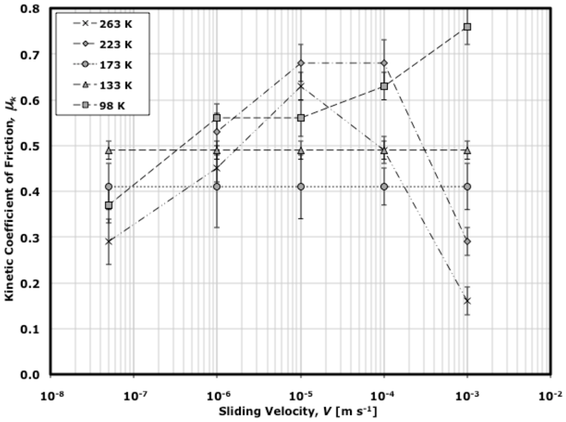

Fig. 1. μ_k vs. V for freshwater ice.

Experimental procedure: Both granular and columnar freshwater ice were examined; however, statistical analysis of the data did not reveal a significant effect on the kinetic coefficient of friction of either grain size or ice type and so we have not differentiated between the freshwater ice types. In addition, we also tested columnar ice of the binary $H_2O\text{-}MgSO_4$ system that was grown in the laboratory though unidirectional eutectic solidification (termed MS11).

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 $0.4 \pm 0.2 \times 10^{-6}$ m (measured over a length of 8 mm in the direction of sliding). 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=21 kPa to 98 kPa. Five different temperatures were examined, 98 K, 133 K, 173 K, 223 K and 263 K (only 98 K was examined for the MS11 ice). Sliding distance was limited to δ=2 mm, except at the lowest velocity where the sliding 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.

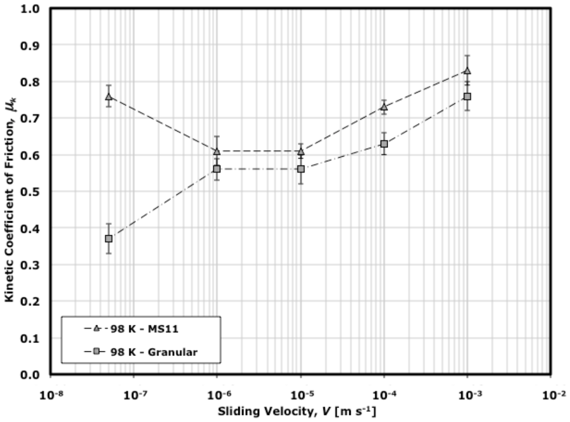

Fig. 2. μ_k vs. V for MS11 and freshwater ice at 98 K.

To investigate the effect of surface roughness we abraded at 263 K the as-milled surfaces of pad and slider. We rubbed the surfaces in a circular manner against either 100 grit (finer, producing a surface roughness of $R_a = 6.3 \pm 1.0 \times 10^{-6}$ m) or 36 grit (coarser, producing a surface roughness of $R_a = 12.1 \pm 2.0 \times 10^{-6}$ m) sand-paper that was placed on a flat slab of granite. Subsequently, the ice was allowed to slide 20 mm at 263 K and 1×10^{-4} ms^{-1} under a normal stress of 60 kPa, after which the surface roughness was re-measured.

To investigate the effect of hold time on the static coefficient of friction, μ_S (calculated from plots of the initial peak of shear stress versus displacement) we performed experiments at 98 K, 173 K, 223 K, 243 K and 263 K in which after sliding a distance of 2 mm, the actuator was stopped for a time while maintaining a normal stress of σ_n = 60 kPa. Following this period, the actuator was reactivated at the initial velocity for another 2 mm, stopped again, held for a longer time, reactivated at the same speed, and so on. The holding ranged from 1 second to 10^4 seconds. The experiments were performed in triplicate for each combination of conditions.

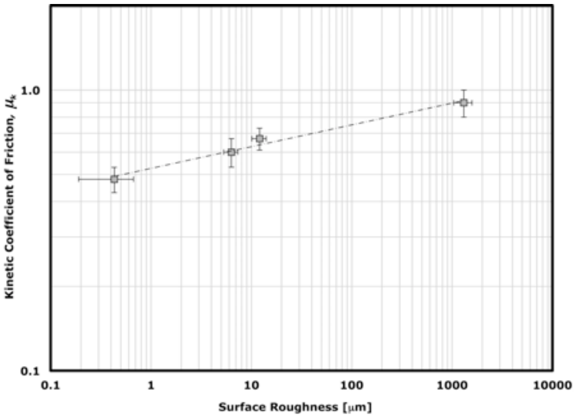

Fig. 3. R_a vs μ_k. $V = 10^{-4}$ m s^{-1}, $\sigma_n < 2$ MPa, $T = 263$ K.

Results: The kinetic coefficient of friction μ_k was obtained by converting the forces F_F (average of the highest and the lowest friction forces was used over the second half of the sliding displacement) and F_N to shear stresses τ and normal stresses σ_n. From plots of τ vs. σ_n the kinetic friction coefficient was determined from the slope $\mu_k = d\tau/d\sigma_n$. In all cases examined here, τ scaled linearly with σ_n implying that the coefficient of friction is independent of normal stress over the range examined. The effect of each variable is considered below.

Temperature and Velocity: Figure 1 plots the coefficient of friction vs velocity for each of the five temperatures examined. The behavior of the coefficient of friction appears to be temperature dependent. At the two higher temperatures, two different effects are evident. Over the lower end of the range ($V \leq 10^{-5}$ m s^{-1}), the coefficient increases with increasing velocity, termed *velocity strengthening*; at higher velocities it decreases, termed *velocity weakening.* In comparison, at 98 K the coefficient increases with increasing velocity over both the lower and the higher range, but appears to be velocity-independent over the intermediate range $10^{-6} \leq V \leq 10^{-4}$ m s^{-1} where $\mu_k = 0.58 \pm 0.07$. At the two intermediate temperatures the coefficient of friction appears to be velocity independent. This is not to say that there is no effect of velocity at the intermediate temperatures, but that a significant effect could not be detected based upon the data we collected.

MS11 Ice: Figure 2 compares the coefficients of friction obtained from MS11 ice to those obtained from granular freshwater ice. The coefficients are similar at all but the lowest velocity, where the coefficient from MS11 is much higher than for freshwater ice.

Surface Roughness: Figure 3 plots the roughness against friction and includes earlier measurements [2] of μ_k from still rougher surfaces (Coulombic shear faults, $R_a = 1.3 \pm 0.3 \times 10^{-3}$ m). The figure indicates a small but systematic increase in μ_k with increasing roughness, with $\mu_k \propto R_a^S$ where $s = 0.08$ ($R^2 = 0.98$). We found that the roughness appears not to have changed significantly upon sliding 20 mm.

Hold-time: Figure 4 shows that at higher temperatures, $\Delta\mu_S$ (where $\Delta\mu_S = \mu_S - \mu_k$) increases logarithmically with time t, scaling as $\Delta\mu_s \propto \ln t\beta$, where $\beta = 0.096$ ($R^2 > 0.97$). Less hardening is observed at 243 K and still less at 223 K for a given time, although logarithmic dependence persists for $t \geq 10$ seconds and the exponent has about the same value ($\beta_{243} = 0.11$; $\beta_{223} = 0.098$); for shorter periods $\Delta\mu_S$ increases more slowly, particularly at 223 K, suggesting either different functionality or a different value of β for ageing for short times $t < t_0$. All holding tests were performed in triplicate, and so this early stage is most probably not an anomaly of too few tests. At the two lowest temperatures (173 K and 98 K), hardening could not be detected upon holding, even to 10^4 seconds.

Implication: Implications regarding sliding along faults in Europa and Enceladus will be discussed.

Acknowledgements: The work was supported by NASA's Outer Planets Research Program, grant no. NNX09AU27G.

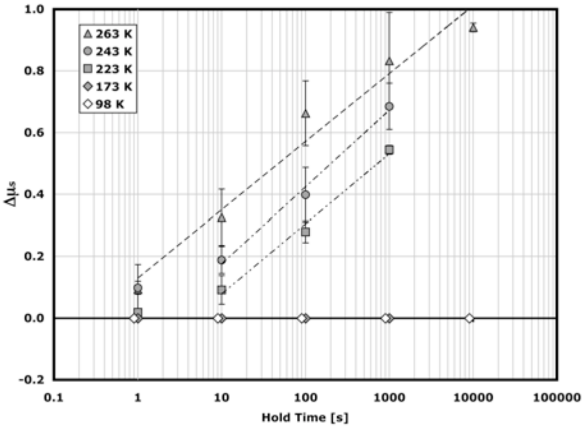

Fig. 4. Graph illustrating the effect of hold time and temperature on $\Delta\mu_s$. $V = 10^{-4}$ m s^{-1}, $\sigma_n = 60$ kPa.

References: [1] Schulson E. M. and Fortt A. L. (2011), *Lunar Planet. Sci. XXXXII,* abstract 1416. [2] Fortt A. L. and Schulson E. M. (2007) *Acta Mat., 55*, 2253-2264

Figures and text are from article in preparation for the Journal of Geophysical Research.