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## PRELIMINARY STUDY OF FRICTION BETWEEN ICE AND SLED RUNNERS

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**Résumé.** Le coefficient de friction de la glace a été mesuré par la décélération d'un traveau (bob-sled) glissant sur une couche de glace obtenue en chambre froide. En cours de glissade, l'augmentation de la température entraîne une baisse du coefficient de friction du patin "tendre," cependant pour un patin dur l'augmentation légère du coefficient de friction semble indiquer que la théorie des lubrifiants liquides est applicable seulement au matériau tendre.

**Abstract.** The effects of runner material and surface conditions on the friction between runners and ice were studied by measuring the velocity of a free-sliding sled. Smooth runners showed lower friction at around  $-1^{\circ}\text{C}$  than around  $-10^{\circ}\text{C}$  as expected, but the friction of rough runners showed little temperature dependence.

### 1. Introduction

Anybody who has stepped on a patch of ice recognizes that ice can be very slippery. Bruises and broken bones are commonplace among careless pedestrians who walk on ice. The poor traction of tires on icy roads has caused many fatal automobile accidents. On the brighter side, the slipperiness of ice makes it possible to enjoy winter sports such as skiing, skating and sledging and to transport heavy cargoes over ice and snow by sled.

The most popular explanation for the low friction of ice is lubrication by a thin layer of water between the slider and the ice melted from the ice either by the heat of friction (1) or by high pressures (2).

Tusima (3) measured the friction between a steel ball and ice at speeds low enough to preclude fluid lubrication. He explained that the coefficient of friction  $\mu$  between solid materials and ice, expressed as

$$\mu = \text{shear adhesive strength/compressive yield strength,}$$

is low because the shear adhesive strength of ice around the melting point is much smaller than its compressive yield strength.

If lubrication by a liquid film is required to reduce drag, thinning of the water layer due to leakage must be taken into account. Furushima (4) used a highly simplified roughness profile to calculate the liquid film support and the rate of squeezing under speed skates, and found that liquid lubrication was effective at roughnesses lower than  $0.2\ \mu\text{m}$  or perhaps even  $0.05\ \mu\text{m}$ .

The studies mentioned above are based on theoretical models and on testing accomplished under idealized conditions. Our intention was to identify the basic problems involved in ice resistance incurred under the dynamic conditions of real sledging for immediate application by the U.S. Olympic Bobsled Team. Such resistance would include not only frictional resistance but also energy dissipation processes such as groove formation, the crushing of ice protrusions, foundation vibration, etc.

## 2. Experimental

A small sled weighing 60 kg was propelled across an ice sheet grown in a coldroom. We tried to simulate real bobsled run conditions as closely as possible in regard to runner surface, stress under the runner, and ice conditions. The velocity was limited to less than 1/20 of an actual bobsled's speed due to the space limitation.

The model sled (Fig. 1) had a pair of runners mounted in parallel grooves on runner holders attached to a 30- × 30-cm-square aluminum plate. A set of lead blocks provided contact stress levels under the runners comparable to those on a real bobsled. The runners were made of ½-in. round rod material; both front and rear ends were rounded. Different sets of runners made of three different materials (see Table 1) and surface treatments could be mounted by loosening three bolts that fastened each runner to its holder. The runner materials had different hardnesses, and it was difficult to produce identical surface conditions for each run. Abrasive paper and a leather strop were used to smooth the runner surfaces. However, the depth of the grooves cut with the abrasive paper differed from one material to another, and the leather strop was not equally effective for all material surfaces. Also, abrasive substances accumulated on the ice surface roughened the smooth runners and smoothed the rough runners. Bulk runner temperature was measured by thermistors and thermocouples inserted in 11-mm-deep wells.

Table 1. Properties of runner materials.

	1010 low carbon steel	304 stainless steel	MP35N
Runner no.	1,2,7,8,14,17	3,4,9,10,16	5,6,11,12,13,15,18
Thermal conductivity ( $\lambda$ )	68 W/mK (CRC)	17 W/mK (CRC)	10 W/mK (Latrobe)
Rockwell A hardness (H)	51 (as measured)	58 (as measured)	71 (as measured)
Corrosion resistance	Visibly poor	Good	Good
Notes	Soft and easy to machine.	Intermediate values of hardness and thermal conductivity.	Tough to machine but allowed fine surface finish; hard enough to retain finish.

A 20-cm-long aluminum shutter mounted parallel to the direction of motion was used to measure the sled's velocity. The duration of the interruption of a narrow beam of light by the shutter was measured by a photo sensor and an electronic counter. By the measurement of initial ( $v_i$ ) and final ( $v_f$ ) velocity between optical gates 4.6 m ( $L$ ) apart, an average coefficient of friction  $\mu$  was calculated through energy considerations:

$$\mu = (v_i^2 - v_f^2)/2gL \quad (1)$$

where  $g$  is the gravitational acceleration.

A 4½-in. (11.43-cm) diameter Parker-Hannifin pneumatic cylinder was used to accelerate the 60-kg sled to a suitable speed (1.5 m/s) in a minimal distance. An operator-controlled solenoid valve between the accumulator and the cylinder advanced or retracted the ram of the cylinder.

A pair of polyethylene guides attached to the ice container directed the sled during the first 30 cm of its travel. Although the guides were adjusted carefully, the course taken by the sled could not be predicted beyond the first 2 m of its run, and only a few runs traced the same track as the preceding run. Soft spots on the ice sheet would deflect the sled, sometimes causing it to hit the wall or even turn around. Data from such runs were rejected.

The sled was stopped at the other end of the ice track by a shock absorber made of a pair of smaller pneumatic cylinders. A frame of angle irons around the entire box strengthened it and acted as fenders.

The ice was grown in a plywood box (1 × 5 m × 0.2 m deep) lined with a sheet of polyethylene.

A layer of snow 3 cm deep was spread in the box first and saturated with water. After the first layer had frozen solid the procedure was repeated to form a second layer. The top of this frozen layer was scraped evenly and a thermocouple was inserted. Five more layers of ice, each about a centimeter thick, were grown. As a final touch, a clean rag saturated with hot water was dragged across the ice surface, resulting in a  $\frac{1}{2}$ -mm layer of ice. This process was then repeated. Asperities created during testing were removed both by buffing with a floor polisher and by scraping manually two days before each series of runs.

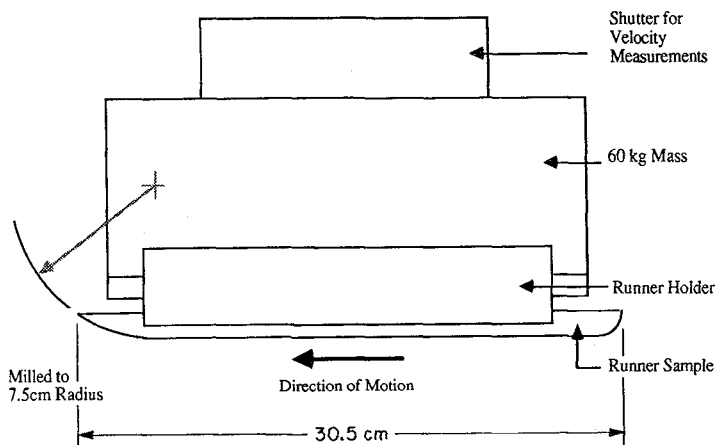


Fig. 1. Side view of the model sled.

The hardness and roughness of the runners were measured three times during the course of the tests. Changes in roughness of the 1010 steel were detected and the runners were repolished or re-roughened to reestablish the original surface conditions. We also made replicas of the runner and ice surfaces on several occasions for qualitative observation under the microscope.

At the beginning of each testing session, the selected runners were attached to the sled. For the raised runner temperature tests, the sled, with the runners, was placed on a heated aluminum plate to warm up. Measurements of ice, air and runner temperature were made before each series of runs began. For each run, the compressed air pressure, interval of light interruption by the shutter at two locations, and the runner temperatures (last 33 series only) were recorded. At the end of a sequence of runs with the same runner, the air, ice and runner temperatures were recorded again. The ice temperature was usually slightly lower than the coldroom temperature, probably because of sublimation of the ice in the dry atmosphere.

### 3. Results

#### General

The model sled was run more than 700 times over the ice sheet using 18 different surface-finished runners made from three materials. These cylindrical runners displayed little directional stability. Any imperfection on the ice surface, such as a groove left by a previous run or a natural asperity (isolated small protrusion), could cause the sled to start sliding sideways, turn around or even spin uncontrollably. When the sled entered the second gate at an angle the apparent length of the optical shutter was shortened, which caused the calculated final speed to be faster than the initial speed. These results were rejected. Generally, the standard deviation of the one series of measurements remained within 10% of  $\mu$ .

We attempted to obtain at least ten repetitive readings for each combination of runners, surface treatment and runner temperature. In total, about 100 runs were rejected as meaningless.

#### *Effect of runner temperature*

In an attempt to find the effect of runner temperature on the coefficient of friction, the runners were heated on a warm aluminum plate before a series of runs. As the runners cooled back down to ambient temperature during subsequent runs a change in friction could be observed.

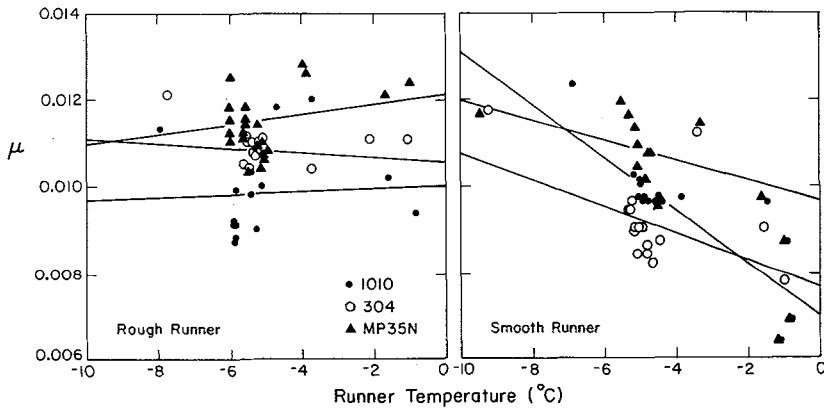


Fig. 2. Effect of temperature on coefficient of friction for rough and smooth runners. All ice temperature data were presented.

One series of tests was done at relatively high ice temperatures, around  $-5^{\circ}\text{C}$ . The effect of temperature was not clear due to a narrow temperature range and too much scatter in the data. At ice temperatures around  $-10^{\circ}\text{C}$ , the results were more meaningful. The effect of runner temperature on  $\mu$  is shown in Figure 2. For smooth runners, the higher the runner temperature the lower the friction, whereas for rough runners the opposite trend was found.

Scatter was considerable in some heated runner tests, but a regression analysis over the entire set of data shows that runner temperature affects rough runners differently than smooth runners.

At the low-temperature end, rough runners sometimes displayed lower friction than smooth runners. This result is surprising since we roughened the runners by pressing abrasive paper against a rotating runner so that grooves were cut perpendicular to the direction of motion, hardly advantageous for reducing the friction.

#### *Effect of runner surface*

Aside from the tests with smooth and rough runners described in the previous section, tests were performed with more highly polished runners (HP), as well as with a pair of runners which had deep longitudinal scratches (L) made in them with coarse sandpaper, and with a pair of scratched and stropped runners (LS). The two latter runners were intended to have more directional control than the perfectly round contact surface would offer. No quantitative measurements of directional stability were made, but controllability seemed to improve somewhat, though friction increased, in particular for the runner that was scratched only. Polishing the longitudinally scratched runner surface with the strop and jeweler's rouge reduced the friction considerably. On warmer ice, particularly with the MP35N, friction was lower after this treatment than when it was polished as usual, and friction was nearly as low as for the highly polished, stropped runner. Comparison of these friction data is difficult since roughness measurements were difficult to obtain and roughness changed during the tests.

The surface condition of the runners seems to have been affected by abrasive dust particles contained in the ice grown in the coldroom. Tests usually involved the runners sliding at least 100 m on the ice sheet. Surface replicas taken at the front end of a runner made of 1010 mild carbon steel after about 50 m showed that soft materials such as this suffer substantial abrasion. Therefore, surface conditions may not have been the same even in one series of tests, in particular for the soft materials. The surface conditions eventually became consistent after several series of tests, but the runners no longer had their original roughness.

#### *Effect of runner material*

According to frictional melting theory, materials with lower thermal conductivity should retain more of the heat generated by friction, thus melting more ice and producing a thicker lubricating water layer that results in lower friction (5). Contrary to these expectations, MP35N, which had the lowest thermal conductivity among the three materials we used, generally showed the highest friction when polished as usual (S) and when roughened (R).

However, when the runners were highly polished (HP), those with lower thermal conductivity glided better, both at  $-10^{\circ}\text{C}$  and at  $-3^{\circ}\text{C}$ . MP35N, with the lowest thermal conductivity, showed the least friction in the highly polished condition, followed by the slightly more conductive 304 stainless steel and then by the highly conductive 1010 low carbon steel. The lowest friction coefficients obtained in the entire study came from tests at  $-3^{\circ}\text{C}$  using highly polished MP35N runners.

During most tests comparing runners with the regular degree of polishing, 304 stainless steel showed the least friction, except at  $-3^{\circ}\text{C}$ , where 1010 appeared most slippery. Among rough runners, 1010 performed best, while MP35N yielded the highest friction coefficient.

This ranking may have been due to the fact that asperities on the runner surface, which would increase the friction, are most easily abraded on a softer material such as 1010 or even 304, rather than an extremely hard one such as MP35N. One would thus expect a gradual lowering of the friction in rough runner tests with the soft 1010. However, such a trend is not clear in our data.

The runners used by previous researchers were generally made of materials softer than mild steel. Usually, prolonged pre-test runs were made to establish good contact so that the longitudinal grooves on the runner would be well-matched with the ice surface profile. Such surface conditions would be equivalent to a smooth surface in the direction of the grooves. The effects of the thermal conductivity observed are probably caused by such surface conditions. The effects of hardness would mostly control the surface abrasion in the case of metallic runners. Since the elastic modulus of ice is very low (less than 1/10 that of most metals) the Hertzian contact area would be little affected.

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