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EXPERIMENTAL INVESTIGATION OF FRICTION COEFFICIENT OF LABORATORY ICE

Lennart Fransson[1], Aniket Patil[2], Henrik Andren[1]

[1] Luleå University of Technology, Luleå, SWEDEN

[2] Northern Research institute Narvik, NORWAY

ABSTRACT

Friction processes of rubber on ice, steel on ice and ice on ice have been investigated by measuring contact forces in controlled laboratory experiments. A carefully prepared ice plate was rotated at a constant speed and brought into contact with a ring on which torque and normal load was measured. Replicas of the different types of standardized ice surfaces were studied in microscope. Friction of rubber on ice reached a maximum value at a sliding speed of abt. 100 mm/min. At a temperature of -10°C this maximum friction coefficient decreased with increasing ice surface roughness. Friction of steel on ice increased with decreasing speed and no maximum value was obtained. Ice sliding on ice at low speed resulted in high friction forces when sintering took place.

INTRODUCTION

First it should be mentioned that it is important to understand and characterize the actual ice surface properties in connection with all measurements of the friction coefficient μ between ice and other surfaces. Ice is a unique material in many ways not only because of its spectacular low friction to steel surfaces. No other crystalline materials show such strength at the very melting point, but on the other hand its surface properties changes rapidly with time due to sublimation and re-crystallisation.

In this paper we wanted to avoid getting into the questions about what is causing the low friction of ice. But it was impossible to set up good test procedures without taking a stand in some issues. For instance the work of Tusima (1977) has been a great inspiration and it seems plausible that most of the friction mechanisms in our tests are caused by adhesion. Friction could then be understood in terms of yield pressure and shear strength of small ice asperities on top of the solid ice. Tusima used a steel ball that was partly ploughing into the ice but that type of unwanted resistance due to wear exist in most friction tests. Ordinary sliding tests also suffer from an unknown pressure distribution on the contact area. The "real contact area" at normal pressure levels and cold temperatures is only a fraction of the projected but the contact becomes almost complete when a water film is present. Therefore it is obvious that friction is a term that may involve an assembly of different mechanisms.

When friction is modelled numerically it is common to use so-called rate and state models in which friction is a function of the relative velocity of the two surfaces and a state variable. It is then possible to simulate stick-slip and viscous behaviour. The bristle model proposed by Haessig and Friedland (1991) can be described as a number of flexible bristles where the bond snaps at a certain deformation. It is an attempt to simulate microscopic contact points that form and break randomly. This model divides the state into regimes depending on built up elastic deformation in the bristle which helps to understand the transition between static and dynamic friction. At higher speed frictional heating and melting is assumed increasingly important. Frictional heating of the ice is usually used as explanation why locked tires have such a poor grip compared to rolling tires.

In the present paper results from friction tests with rubber on ice, steel on ice and ice on ice is discussed. Rubber is softer than ice and will deform more than the other materials. Surface roughness was expected to have a strong influence on friction especially for soft rubber. Much effort was therefore put into ice surface preparation and measurements of the surface roughness of ice.

ICE SURFACE PREPARATION

In this initial stage of our ice friction research we developed a simple method to grow sufficient good ice in the laboratory. Crystal orientation affects friction (Tusima, 1977) but also the mechanical properties and possibly the pattern of grain boundaries on polycrystalline ice. A water basin made of stainless steel with the dimensions 2 x 1 x 0.3 m (length, width, depth) was placed in a cold room. Ordinary tap water was pored into the basin and the water was cooled down to the freezing point. Then the water body was stirred to get close or slightly below 0°C. Initial ice formation was triggered by powdering the surface with sieved snow or sprayed rime when snow was missing. The seeded ice crystals in the basin grew more or less into vertical columns with uniform size. Close to the poorly insulated basin walls the ice became different and was not used in the tests. The air temperature was held constant at -10°C after seeding and freezing took about 36 hrs. Target ice thickness was 40 mm which was thick enough to handle the plates and they could easily be cut with an electric chain saw. The ice was cut and stored in a freezer in another cold room. Our laboratory ice is shown in cross-polarized light where the crystals appear in different colours, see Figure 1.

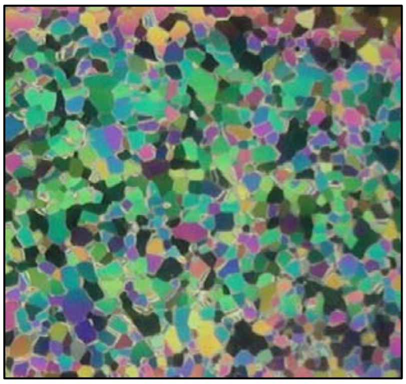

Fig. 1. Horizontal thin section (50mm x 50mm) close to the upper surface of the laboratory ice

The ice plates were first planned on both sides with a rotational planar tool. This procedure resulted in a smooth wavelike surface with about 10 micron amplitude. The upper surface used for friction tests was planned in two perpendicular directions. The difference between the ice plates was small and on an area of 250 mm x 250 mm we were able to get a consistent topography of small waves. Direct measurements of surface roughness with a clock gave Ra less than 10 µm. After planning we tried different methods to prepare the surfaces. These methods were: grinding with ceramic sandpaper, scratching with a saw blade from band saw and flooding with a thin water layer.

Also grinding and scratching was done in two perpendicular directions. Crushed ice and rime was gently removed with a soft brush. In most of the tests we used three standardized ice surfaces with the indicated target roughness.

1. planned ice, Ra=6-8 µm
2. ground ice, Ra = 60 µm
3. scratched ice, Ra = 120 µm

It was of course impossible to make identical surfaces with the earlier described methods but we thought it was consistent enough for this purpose. Surface preparation was done in the same cold room as the friction tests where the temperature was held constant over a long time. Surface roughness was studied in detail using the casting material Master Exact. This is a binary liquid, mixed together, pressed down on the ice surface and hardened over time (Andren and Wennstrom, 2007). Sublimation at dry conditions was strong and therefore the surface preparation was done immediately before every test series. Microscope investigations on the replicas showed the smoothing effect very clearly, see Figure 2.

Table 1. Surface roughness Ra measured on replicas at different exposure time in the cold room (-10 C)

Time after manufacture	Planned Ra, µm	Ground Ra, µm	Scratched Ra, µm
0	**6-8**	**16**	**150**
2 hours	**-**	**13**	**108**
1 day	**1**	**5**	**92**

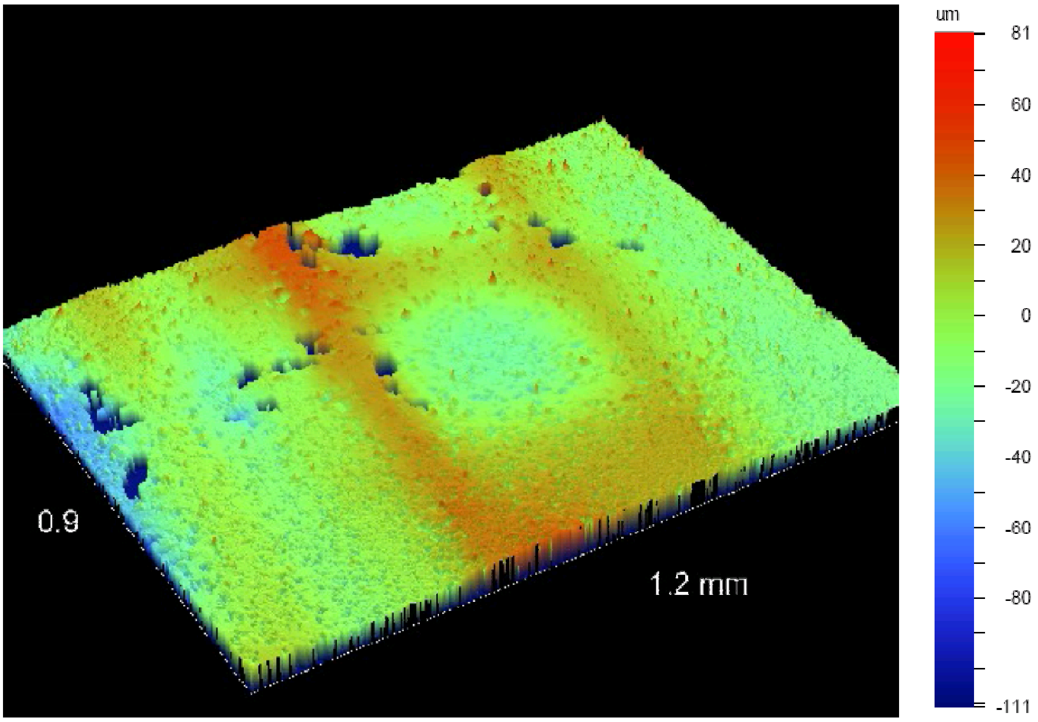

Fig. 2a. Ground ice surface, 2 hrs after manufacture

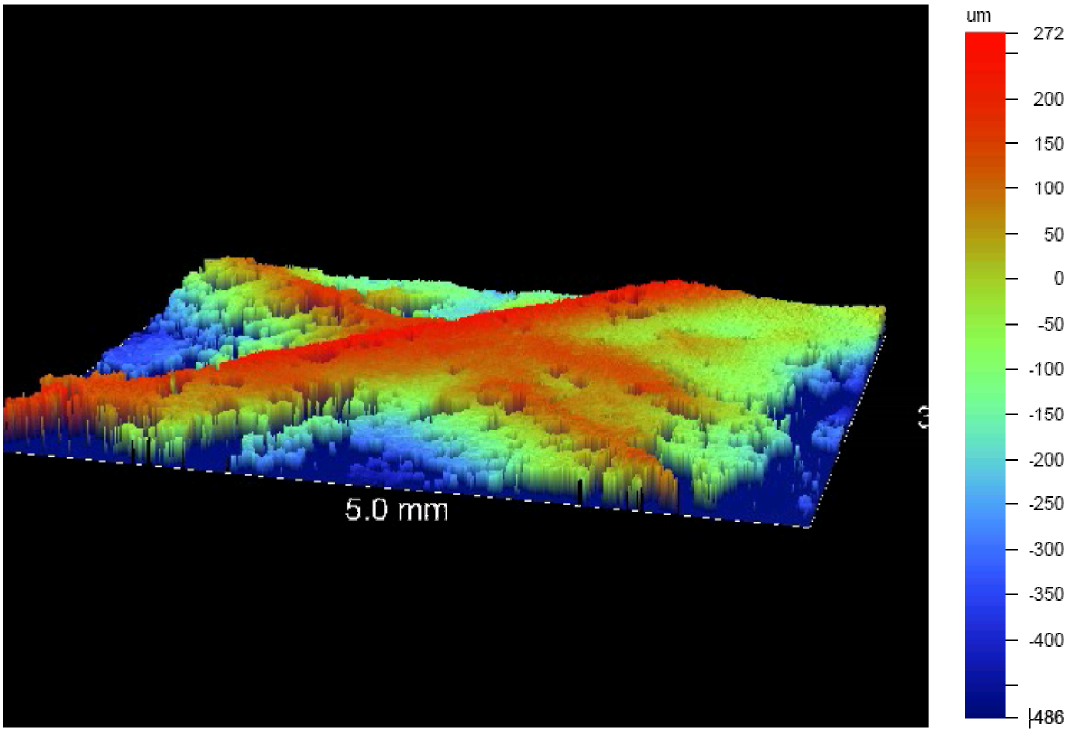

Fig. 2b. Scratched ice directly after manufacture

EXPERIMENTAL SET-UP

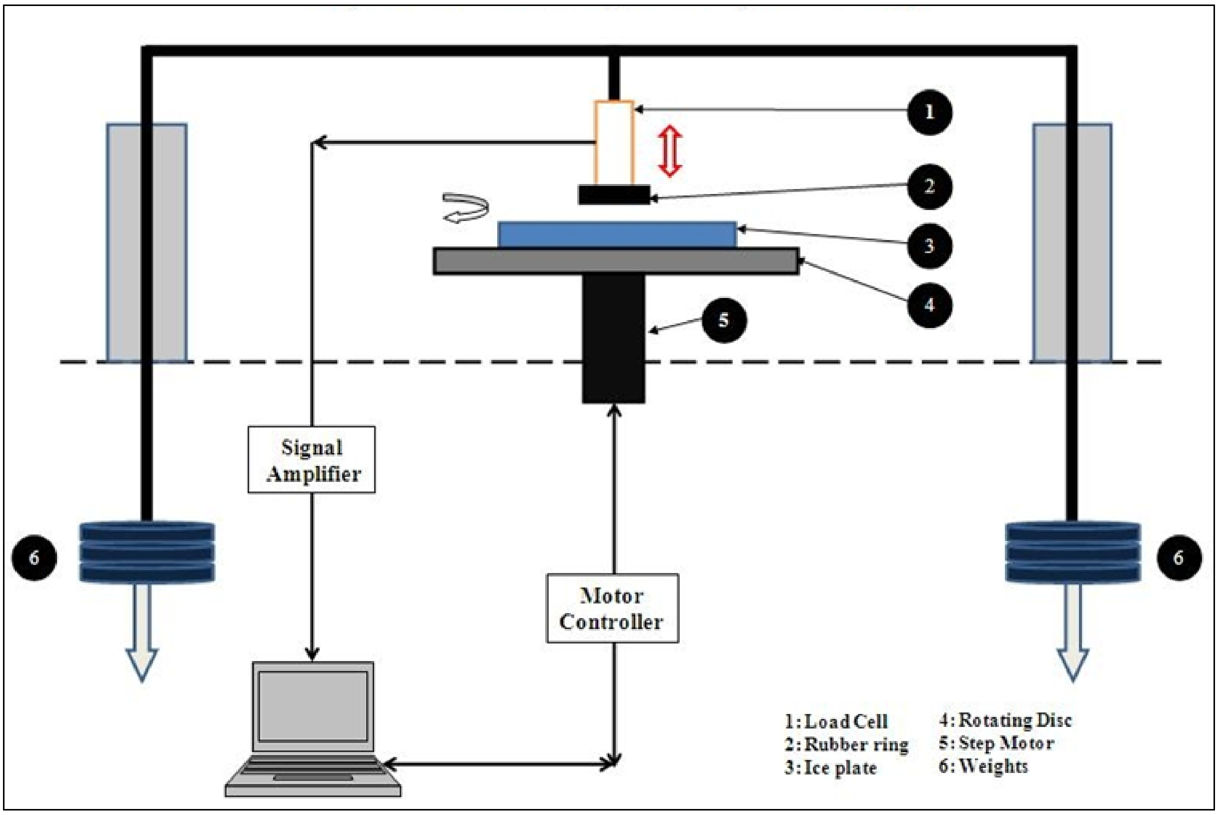

Fig. 3. Schematic diagram of the experimental setup

A flat ring of rubber, steel or ice was pressed down to the ice with a constant normal force *N*. The ring was subjected to an increasing torque M_v as the ice was rotating. The torque reached a maximum value after a certain rotation of the ice plate. A typical graph of the torque during a friction test with rubber on smooth ice at low speed is shown in Figure 4. The friction coefficient was assumed proportional to the ratio between torque and normal force. A similar method has also been used to measure friction on ice surfaces in the field with some success. The friction coefficient was calculated from

$$\mu = 3 \cdot \frac{D^2 - d^2}{D^3 - d^3} \cdot \frac{M_v}{N} \qquad (1)$$

where *D* and *d* are the outer and inner diameter of the ring, respectively. Rotation speed was kept constant during the tests with the help of a step motor and a gearbox with the ratio 1:30. Speed on the step motor was increased in seven steps from 0.1 to 100 rpm. This resulted in a variation of the relative velocity on the periphery of the ring from 0.72 mm/min to 720 mm/min. The sliding velocities given in Table 2 were calculated at the periphery of the ring assuming that the specimen was in a fixed position.

The friction tests were run at a room temperature of -10°C and -3°C**.** One test series with 4-7 tests could be carried out on the same plate without overlapping. First test was always made at the lowest speed which helped to temperate the ring specimen to the ice.

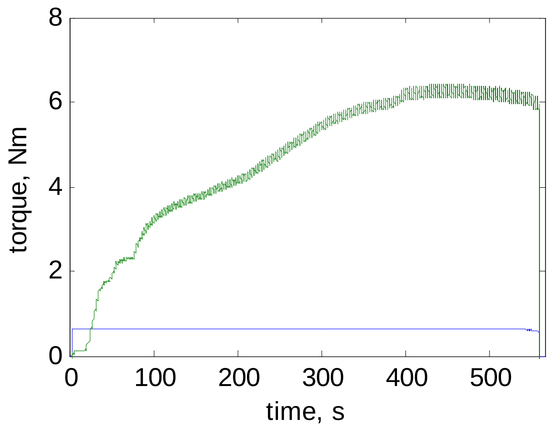

Fig. 4. Plot of torque on the rubber specimen when the sliding speed was 0.72 mm/min

RESULTS

Rubber on ice

In these tests a flat ring of rubber, vulcanized to a steel plate, was pressed down to the ice with a pressure of about 200 kPa. The outer and inner diameter of the rubber ring was *D* = 69.8 mm and *d* = 50 mm, respectively. The hardness on the 7 mm thick rubber layer was measured to 64 Shore A.

The first test results given in Table 2 indicated that the rubber-ice friction coefficient increases with speed only on ground ice. On smooth surfaces like the flooded ice no significant rate effect could be traced. As expected we got a lower friction coefficient on the ice surface that had been flooded. One of the problems with this test procedure was that the rubber ring was in contact with the ice for a longer time at slow velocities and it may have contributed to an increased adhesion. Tests with a constant dwell time before rotation could eliminate this possible source of error. Another problem was that the air humidity and thus the ice surface properties might have changed between the test series.

Table 2. Friction coefficients for rubber on ice (average of four tests). Room temperature = -5°C.

Speed, mm/min	Planned ice Ra=6-10	Ground ice Ra=10-15	Flooded ice
0.72	0.328 ± 0.020	0.249 ± 0.025	0.258 ± 0.024
7.2	0.321 ± 0.020	0.310 ± 0.014	0.283 ± 0.009
72	0.318 ± 0.015	0.349 ± 0.004	0.224 ± 0.034

All friction graphs were plotted on logarithmic scale of speed (V) in the unit mm/minute. The same pattern was found for both temperatures. First there is an increase in friction coefficient and after a certain speed a rapid decrease can be seen. Calculated friction coefficients as a function of speed is shown in Figure 5.

Maximum friction for this type of rubber was obtained at a critical speed of about 100 mm/min. Ice and rubber were assumed to show visco-elastic behaviour at lower speed that resulted in a increased friction coefficient as the speed was increasing. At velocities higher than the critical, frictional heating was assumed to create a water film at certain contact points and thus reducing the possible friction. In this case the surface roughness played an important role. Friction dropped suddenly on smooth ice and more gradually on rough ice. Friction became substantially lower when the temperature was raised from -10°C to -3°C on smooth ice. Salt or radiation from the room lights seemed to create a thin water film on the ice surface at -3°C. When the friction coefficient was as low as 0.2 on smooth and warm ice it was not much lowered at higher speed. Friction was less sensitive to temperature changes on rough ice but more sensitive to velocity.

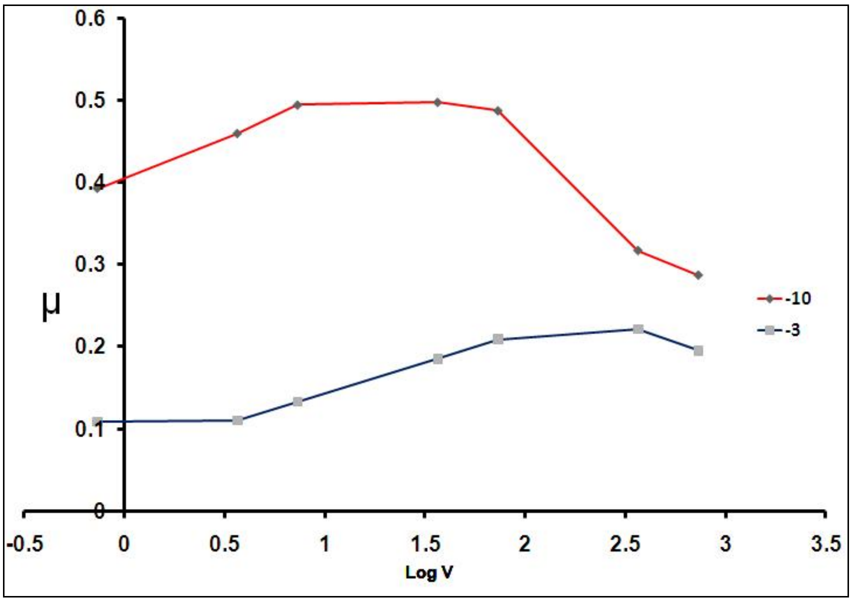

Figure 5 a. Rubber on planned ice

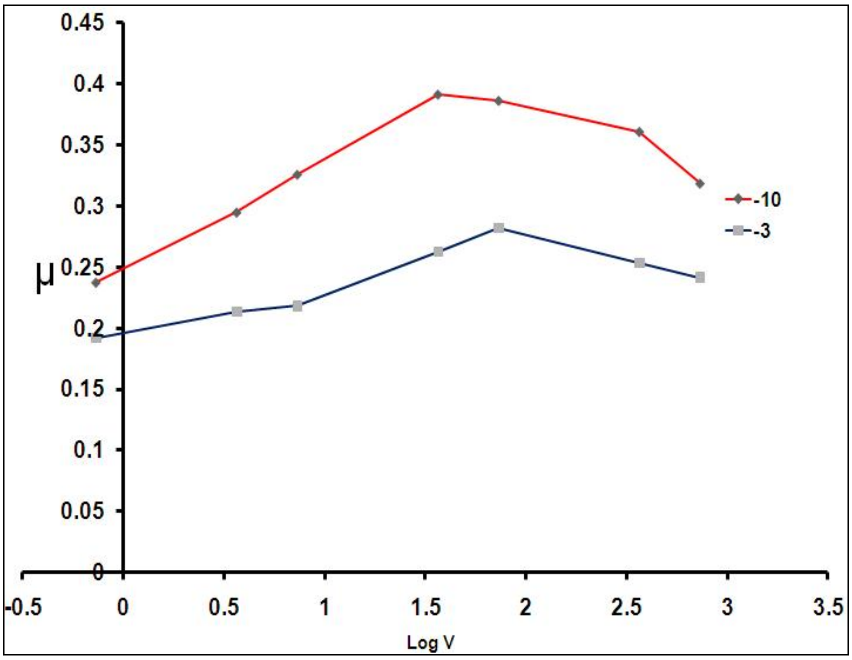

Figure 5 b. Rubber on Ground ice

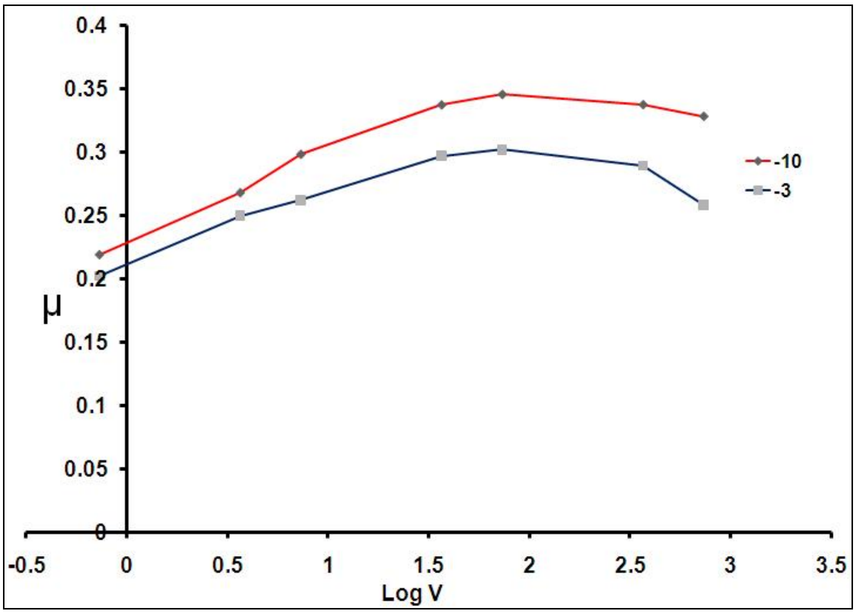

Figure 5 c. Rubber on Scratched ice

Steel on ice

A test ring of steel was made with the same dimensions as the rubber ring. The surface in contact with ice was machined and polished and cleaned from oil. Friction tests were carried out with the same set-up with a normal pressure of 200 kPa. Friction between the steel ring and the different ice surfaces are shown in Figure 6. Due to the increased stiffness all contact points were sliding at the same speed when the two surfaces were put into contact. It is assumed that the ice is yielding at the contact points and the contact area became larger at lower speed. Therefore friction was slightly increased with decreasing speed. No significant influence from the surface roughness can be traced. The obtained friction coefficients (0.02 – 0.04) were very close to those reported by Tusima (1977) and other sources.

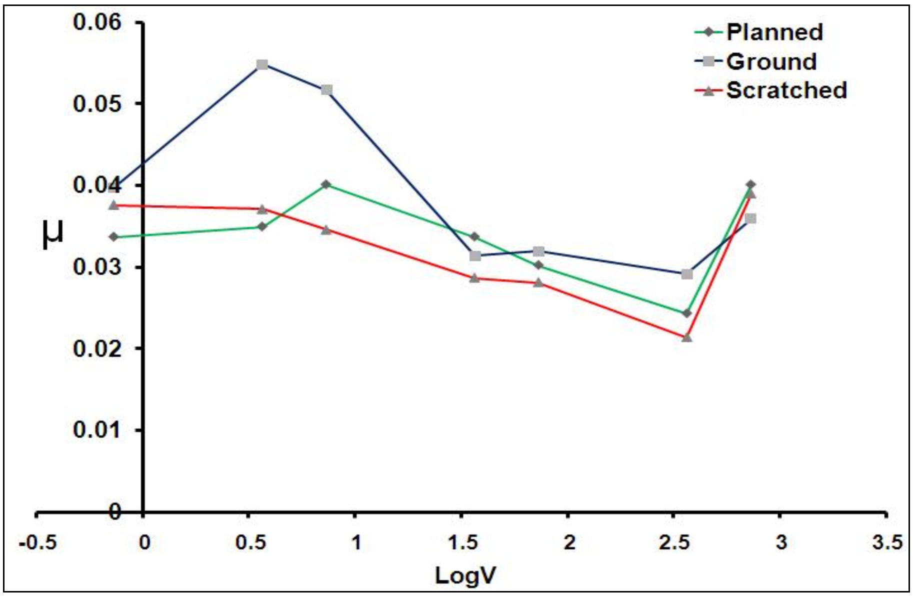

Fig. 6. Steel-ice friction vs. sliding speed. Test temperature = -10°C

Ice on ice

A ring of ice was cast on the steel ring. Surface tension made the ice ring thicker at the centre. This curved surface was made flat on a width of 5 mm before it was put in the testing machine. The normal pressure had to be reduced to abt. 140 kPa to avoid fracture of the ice ring. At low speed sintering was observed at several points between the two ice surfaces, see Figure 8. This resulted in failures of the sintered ice and high measured friction. At a speed higher than 100 mm/min the kinetic friction was reduced to 0.2. But as soon as the two surfaces were standing still and kept together they were stuck at certain points.

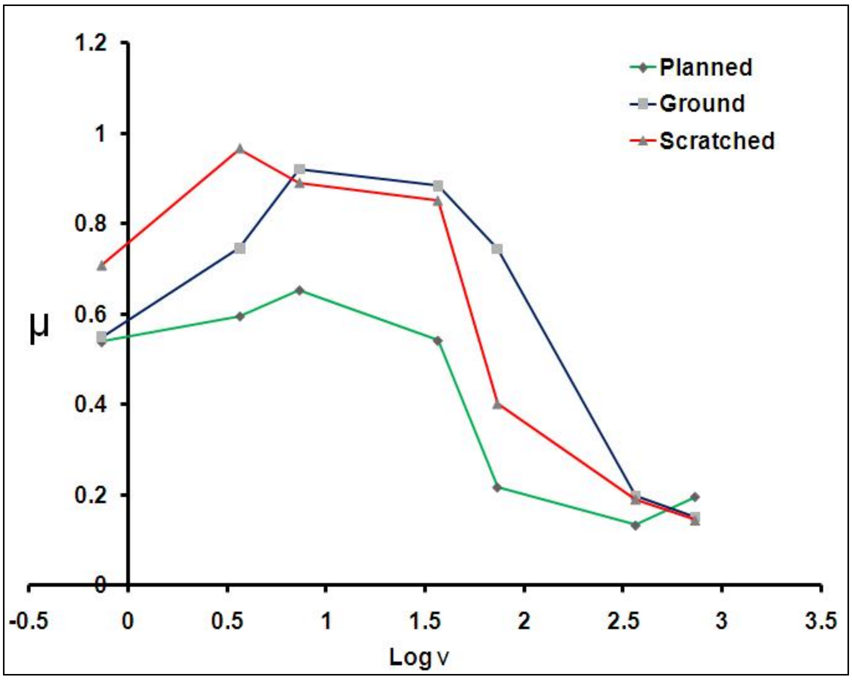

Figure 7. Ice-ice friction vs. sliding speed. Test temperature = -10°C

Fig. 8. Photo on the ice-ice contact where sintering is shown as a white spot.

DISCUSSION

In the rubber tests the normal pressure was held constant at 200 kPa. Tests at higher pressure levels might have resulted in increased frictional heating at the same speed and thus different friction coefficients. A phenomenon of frictional heating is well investigated in Higgins et al. (2008) paper on wear of rubber from ice. Increase in speed at a certain temperature gave this effect and produced a thin layer of water. This thin layer of water acted like a lubricant which resulted in decrease of the friction force. At elevated temperature, this phenomenon occurred very fast.

At an extremely slow sliding speed the friction coefficient for steel on ice might become higher than the values obtained at 0.72 mm/min. Frederking and Barker (2002) tested painted steel on sea ice and got a maximum of 0.08 when the ice stopped. Corroded steel contains voids that can be filled with ice and sintering could therefore contribute to higher friction on ice at slow speed. Maeno and Arakawa (2004) proposed an improved shear adhesion theory where sintering increased the friction force at low sliding speed. The friction coefficient should then be expressed

$$\mu = (1 + \frac{\Delta s}{s})\frac{\tau}{\sigma} \qquad (2)$$

where Δs is the increased contact area of each asperity during the contact time. A function was also suggested on how Δs will be increased. It was however seen in our experiments that sintering was a random process depending on roughness. On a larger area only a few contact spots were needed to cause high friction forces. Fortt and Schulson (2007) suggested that this peaked shape of friction curves versus sliding velocity was due to a change in sliding behaviour. In their sliding experiment on cracked surfaces they noticed that the sliding was ductile-like at slow speed and brittle-like at high speed which also could be seen on the load-time curve. It is also possible that frictional heating prevents cohesion or sintering at high speed.

CONCLUSIONS

Friction testing with rotating ice on a ring-shaped specimen proved to be both practical and accurate. The test set-up focused on shear adhesion and the measured friction force should be relatively free from edge effects and other unwanted forces when a small contact area is used.

Along with surface topology, speed and temperature play important roles in determining the friction coefficient on ice surfaces. Our experiments showed that there is a critical speed for rubber and ice which gave the highest friction coefficient. Rubber friction on planned ice dropped from 0.4 to 0.1 when the temperature was increased at low sliding speed. This type of drastic change did not happen on the rough ice. Therefore we suggest that comparison of winter tires and similar field tests should be done on ice with a controlled roughness higher than Ra = 10 micron.

In case of ice-ice friction tests the friction coefficient was much higher than on other surfaces. Higher roughness caused higher friction which indicates that the contact pressure on asperities governs the sintering process. Ice-ice contact is also possible when a porous material slides on ice.

ACKNOWLEDGEMENTS

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