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Variations of ice friction regimes in relation to surface topography and applied operating parameters

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Abstract. To evaluate the effects of surface topography, ice and ambient conditions on the sliding behaviour of steel samples on ice, in the present study friction and velocity measurements were performed with steel samples having different surface roughness values and distinct surface structures. It was shown that the influence of surface roughness on friction and sliding velocity is strongly dependant on ice conditions and the applied experimental parameters due to the formation of different friction regimes.

1. Introduction

In ice friction, depending on the contact conditions and operating parameters such as temperature, sliding velocity and contact pressure, different processes and mechanisms prevail, which define different friction regimes: boundary, mixed or hydrodynamic friction [1]. One of the main parameters defining the ice friction regimes is the thickness of the lubricating liquid-like layer (LLL) on ice with respect to the roughness of the ice and the slider [2,3]. Generally, in different friction regimes different friction levels prevail, thus understanding of boundaries and transitions between different friction regimes is essential for the control of ice friction.

In winter sports, high velocities are desired and therefore the drag between the slider and the ice/snow surface should be minimal. Minimal drag can typically be correlated with the optimal LLL thickness which is dependent on a myriad of parameters and boundary conditions and is anything but straightforward. In a previous study [4], it was shown that depending on the tribometer type, different effects of surface roughness on the coefficient of friction and sliding velocity were observed. On an inclined ice track tribometer, the samples with higher roughness reached lower velocities than the samples with lower roughness, while on oscillating tribometer samples with higher roughness provided lower friction than the samples with lower roughness.

To further evaluate the observed effects, in this study, ice friction measurements were performed with steel samples having different surface roughness values and distinct surface structures. An oscillating tribometer measuring the coefficient of friction and an inclined ice plane measuring the sliding velocity of the steel samples were used to determine the sliding ability.

2. Experimental

2.1. Samples

All samples were manufactured from the Uddeholm Ramax HH steel, which is a chromium alloyed, corrosion-resistant holder steel supplied in a high pre-hardened condition. All samples were cut to

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dimensions of 35 mm x 18 mm x 14 mm and polished to mirror polish (Ra < 0.01 µm). Steel samples having two distinct surface textures were prepared: one by polishing and abrading the samples in sliding direction and another one by sandblasting and polishing [5]. In Figure 1, sample topographies and roughness values Ra of the tested samples are presented. For sample denotation, G stands for "grooved samples", while SP stands for "sandblasted and polished samples". Sample G1 is the control sample, while samples G2 and G3 were further treated by roughening with different grade sandpapers to achieve parallel grooves in the direction of sliding, having two different depths respectively. Samples SP240, SP150 and SP30 were sandblasted and polished to achieve different surface structures and roughness values.

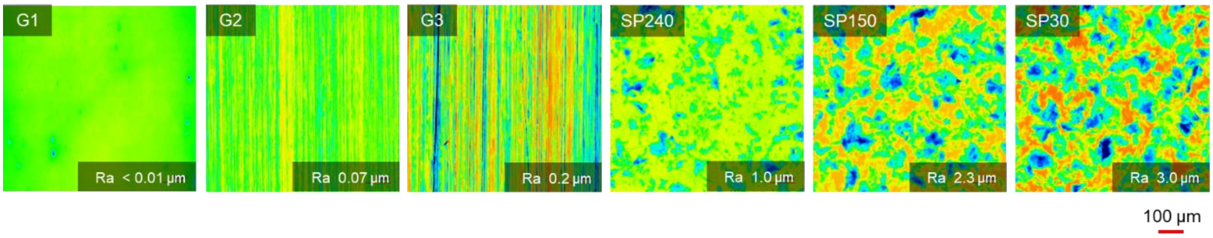

Figure 1. Surface topographies and roughness values Ra of the tested samples.

2.2. Ice preparation

In tribological tests on the oscillating tribometer, four different test conditions were applied within 2 different test series (Table 1). As can be seen from Table 1, the main difference between the test series 1 and 2 lies in the steel sample temperature: in the test series 1, before the test, the steel sample was kept in a freezer at around -18°C, while in the test series 2, the steel sample was kept in the cooling chamber and had a temperature close to that of the ambient atmosphere (around 5°C).

Before each test series, a new ice surface was prepared. The ice rink was 20 mm wide, 80 mm long and 5 mm deep. For ice formation, 18 ml of distilled water was used to which 0.5 ml of tap water was added to accelerate ice crystallization. To achieve a homogeneous temperature and crystallization rate within the ice volume, the sample was cooled for 40 min. Due to the expansion of the water volume under sub-zero temperatures, when ice was formed, it had a curved surface, therefore, the surface was smoothened with an aluminium plate having surface dimensions of 45 mm x 28 mm. The smoothening of the ice surface was performed at a normal load of 692 N at a sliding velocity of 0.08 m/s until the height difference between the left and the right side of the ice track was lower than 100 µm. Usually, this was achieved within 10-20 min of sliding the aluminium plate back and forth.

Table 1: Ambient and ice conditions for different test setups on the oscillating tribometer.

Test series	Test setup	Ambient temperature (°C)	Ambient RH (%)	Ice surface temperature (°C)	Ice bulk temperature (°C)	Sample temperature (°C)
1	1-1A	7.7±0.8	42±7	ca. -8.0	ca. -9.0	ca. -18.0
2	2-1A	2.7±0.3	15±1	-8.6±0.5	-9.1±0.0	ca. 5.0
	2-2A	3.0±0.5	20±3	-8.7±0.3	-8.7±0.3	ca. 5.0
	2-2B	6.7±0.3	53±4	-8.3±0.4	-8.7±0.2	ca. 5.0

Tests on the inclined plane tribometer were conducted at different ice and air temperatures to see how ambient conditions influence the results. All known ambient conditions for inclined plane tests are summarized in Table 2. Test 1 was conducted at lower ambient temperatures than Test 2. The ice was frozen identically for all the test setups. The temperature was -10°C while the ice was frozen layer by layer (5 layers in total). Each new layer was poured on the previous one and warm water was used to ensure a better mixture of the layers. Before experiments, the ice surface was levelled with a specifically developed planer that also creates a small groove on the ice surface. The groove guides freely sliding samples in a straight line while they are sliding down the inclined plane. Small ice debris was removed from the planed ice with a moist sponge to ensure a smooth ice surface. The same ice was used in all experiments which were conducted on the same experiment day. The sample groups were tested on different days (two experiment days in total).

Table 2: Ambient and ice conditions for different tests on the inclined plane tribometer.

Samples	Test setup	Ambient temperature (°C)	Ambient RH (%)	Ice surface temperature (°C)	Sample temperature
G	1	-1.6±0.2	63±2	-9.1±0.2	ca. -1.6°C
	2	-0.8±0.3	64±3	-9.0±0.2	ca. -0.8°C
SP	1	-3.5±0.5	64±3	-7.0±0.2	ca. -3.5°C
	2	-0.4±0.3	75±3	-2.0±0.3	ca. -0.4°C

2.3. Friction measurements

A universal modular designed tribometer (RVM1000, Werner Stehr Tribologie GmbH, Germany) was used in oscillating mode. Tests were performed at a constant normal load of 52 N. In each friction test, initially, a running-in phase was employed for 60 s at 0.1 m/s resulting in 120 cycles. Afterwards, 7 increasing velocity steps (0.02, 0.05, 0.10, 0.14, 0.19, 0.29 and 0.38 m/s) were employed. In each velocity step at least 10 cycles were performed and at the same time, for each velocity step, a minimum of 3 s duration was employed. Further details on the experimental setup can be found elsewhere [4].

2.4. Velocity measurements

Steel samples were slid down a 3 m long ice path tilted at an angle of 16 ± 0.5°, which was sufficient to promote sliding of steel samples without stacking in the start position. Samples always started the movement from a steady-state (using a start gate) and accelerated freely sliding down the ice surface. To measure the sliding time, optical sensors allowing time measurements with 0.01 s resolution were used. From the time measurements, the average sliding speed of the samples was calculated. The total distance between the first and the last optical sensor was 2850 mm. Each sample was tested 40 times. From 40 measurements, 3 fastest and 3 slowest results were eliminated. The results shown in the graphs herein represent the average of the selected 34 measurements. Further details on the experimental setup (inclined plane tribometer) can be found elsewhere [4].

3. Results

In Figure 2, the coefficient of friction of sandblasted and polished samples at two different ice and atmospheric conditions are presented. From Figure 2a it can be seen that for test setup 1-1A coefficient of friction decreased with sliding velocity and slightly increased with decreasing surface roughness. Higher friction of the smoother samples could be correlated with their large contact area which resulted in higher adhesive forces than for the rougher samples with a smaller contact area. From Figure 2b, for test setup 2-2A, coefficients of friction significantly decreased as compared to test setup 1-1A. This is most probably correlated with a higher sample temperature resulting in the formation of a LLL. At the same time, in Figure 2b the influence of surface roughness is not as pronounced; however, it can be observed that it has an inverse effect on friction as in test setup 1-1A. Namely, for test setup 2-2A, coefficient of friction with rougher samples was higher than for the smoother samples, which was especially pronounced at low velocities.

In Figure 3, results with grooved samples are presented for different ice and atmosphere conditions. From Figure 3a, it can be observed that the coefficient of friction increased with sliding velocity and at the same time, the coefficient of friction increased with surface roughness. From Figure 3b, at higher ambient temperature and humidity and/or on a run-in ice surface (in test 2B, ice surface was additionally run-in) coefficient of friction decreased, the influence of roughness remained unchanged, while the influence of velocity was less pronounced than in test setup 2-1A.

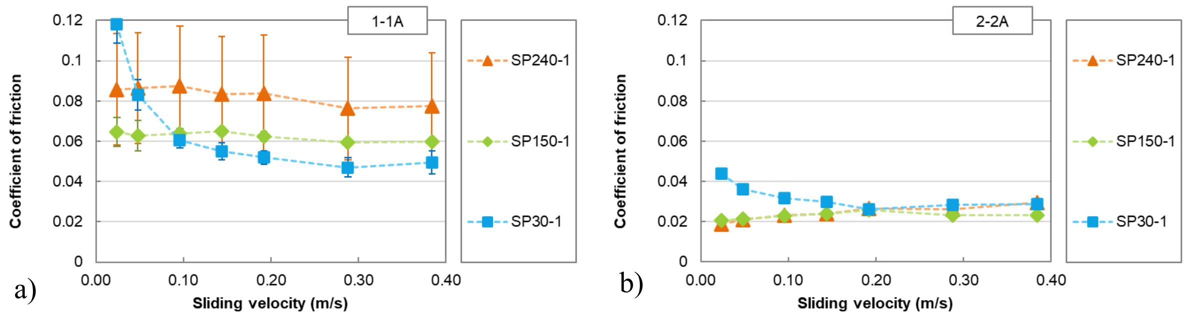

Figure 2. Coefficient of friction of sandblasted and polished samples at two different ice and atmosphere conditions: (a) test setup 1-1A, (b) test setup 2-2A.

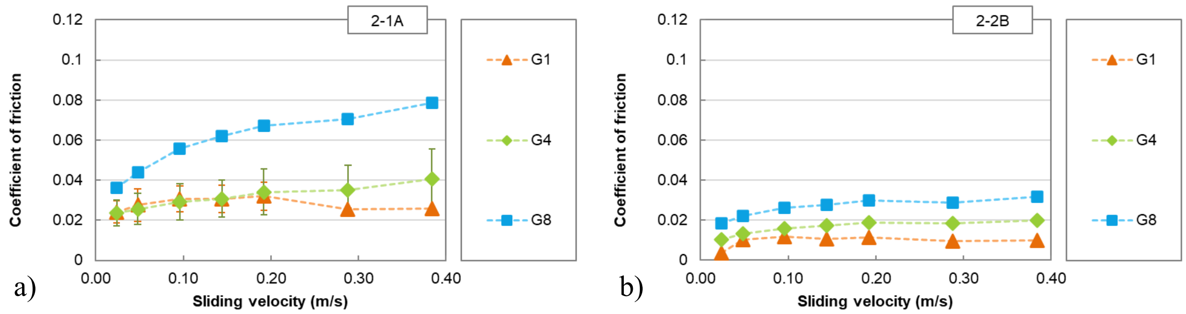

Figure 3. Coefficient of friction of grooved samples at different ice and atmosphere conditions: (a) test setup 2-1A (b) test setup 2-2B.

In Figure 4, test results from the inclined plane tribometer are shown. As shown in Table 2, test 1 was conducted at lower ambient temperatures thus providing a “dryer” ice surface while test 2 provided “wetter” ice surface. For both sample types, a trend of decreased sliding velocity for rougher surfaces can be observed. With grooved samples, at higher ambient temperature (test 2) higher sliding velocities were achieved, while with sandblasted and polished samples an opposite trend was observed. The decrease of sliding velocity at higher temperatures could be caused by a thicker LLL resulting in increased hydrodynamic drag for such isotropic surfaces at low normal loads. Figure 4 indicates a pronounced influence of the ambient conditions on the sliding velocity and suggests that changes in the ambient conditions might have a larger effect on sliding performance of the steel samples than their surface texture modifications.

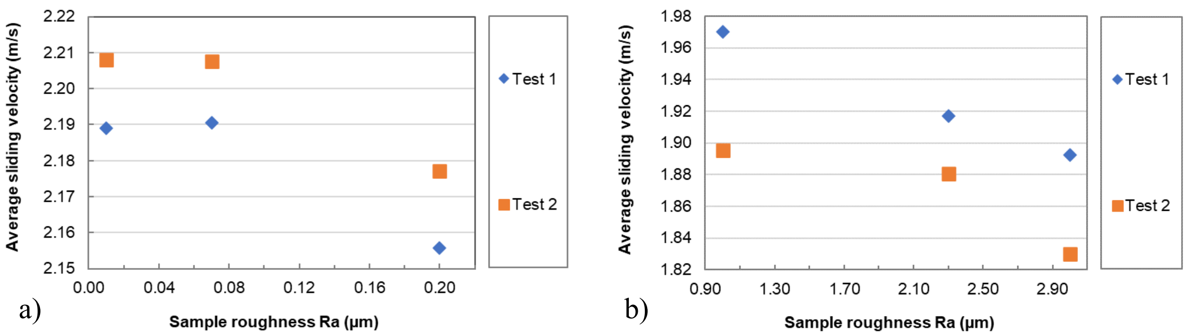

Figure 4. Average sliding velocity on the inclined plane tribometer for (a) grooved and (b) sandblasted and polished samples. Test 1 was performed at lower air and ice temperatures than test 2. Each sample group was tested on a different day.

4. Discussion

In the present study, an inverse roughness-friction correlation was observed for the sandblasted and polished samples tested at different boundary conditions on an oscillating tribometer. Most probably, the inverse roughness-friction correlation occurred due to the difference in the steel sample temperature. In the test 1-1A, where samples with higher roughness provided lower friction values, the initial sample temperature was approximately -18°C, thus in the contact areas between the steel sample and ice, LLL viscosity was lower or even freezing of the LLL could have occurred on a small scale. Since the smoother samples have a larger contact area with the ice surface, more "freezing" points could have formed which resulted in higher friction values. In test series 2, where warmer samples were used, freezing of the LLL did not occur. On the contrary, steel samples melted the ice surface due to heat transfer from the relatively warm samples. Due to a larger contact area with the smoother samples, LLL formed more effectively, resulting in lower friction values. For the grooved samples, the influence of surface roughness on friction was similar as for the sandblasted and polished samples in test series 2, which most probably is correlated with the similar sample temperature in both tests and thus more efficient LLL formation for the smoother steel samples.

Inclined ice plane tests showed a deteriorated sliding ability at higher ambient temperatures for the sandblasted and polished samples, while for the grooved samples an opposite effect was observed. Different influence of the ambient temperature indicates that with different surface structures, thickness of the LLL and the corresponding hydrodynamic drag can vary significantly.

5. Conclusions

In the present study it was observed that:

1. At very low sample temperature, the influence of surface roughness had an inversely different effect on friction compared to tests which were performed with higher sample temperatures. This effect was correlated with different heat transfer effects between the sample and the ice for different sample temperatures.
2. In the inclined ice plane tests sliding velocity decreased with the roughness of the steel samples regardless of their texture type.
3. For similar sample conditions, results on the oscillating tribometer and the inclined ice plane are in good correlation.

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