

AN ICE TRACK EQUIPPED WITH OPTICAL SENSORS FOR DETERMINING THE INFLUENCE OF EXPERIMENTAL CONDITIONS ON THE SLIDING VELOCITY

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The ability to slide on ice has previously focused on the measurement of friction coefficient, and not the actual sliding velocity which is affected by it. The performance can only be directly measured by the sliding velocity, and so the objective was to design and setup a facility to measure velocity, and determine how experimental conditions effect it. Optical sensors were placed on an angled ice track to provide a sliding velocity measurements along three sections and the velocity for the total sliding distance. Experimental conditions included the surface roughness, ambient temperature and load. The effect of roughness was best reported with a Criterion of Contact that showed a similar sliding velocity for metal blocks abraded with sand paper smoother than 600 grit. In searching for the effect of temperature, the highest sliding velocity coincided with the previously reported lowest coefficient of ice friction. Load showed the greatest velocity increase at temperatures closer to the ice melting point suggesting that in such conditions metal block overcome friction forces more easily than in solid friction. Further work needs to be conducted on a longer ice track, with larger metal surfaces, heavier loads and faster velocities to determine how laboratory experiments can predict real-life situations.

Keywords: *Inclined plane, measurement approach, sliding on ice, ice friction, surface roughness, sliding velocity.*

1. INTRODUCTION

Studies on sliding over ice have predominantly measured friction coefficient over an inherently unstable ice surface – the measurement of friction and the unstable ice surface have slowed progress. An approach giving a measure of sliding needs to be introduced concurrently with a deeper understanding on the changes of ice after passage of a sliding object. This work will discuss an alternative test to the measure of ice-friction as an indicator of the performance.

Most tests have been conducted within a laboratory setting to quantify the friction responsible for movement over ice. Beside several uncommon methods like shear strength, adhesion and stick-slip tests [1–4] most popular ring on disk [1,5–7] or pin-on-disk [8] tests move a material surface repetitively over the same ice path and therefore modify the ice surface with a thin layer of water [6,9] leading to a

departure from initial ice condition. Sliding over fresh ice has been made possible by moving the sliding object over a spiral path [10]. Others tests have used a devoted linear tribometer for measuring the ice friction [11–14]. In these situations, the object is not free to move over ice, but is fixed to a mechanism that controls testing conditions (such as load, and velocity) and measures the ice friction. Ice friction is then used to predict the performance instead of measuring the sliding time, or calculating the sliding velocity, both of which directly related to the performance.

Studies of sliding over ice have seldom used the materials engineering paradigm that considers a material microstructure, determines the properties and then seeks a relationship with the performance. Ice friction, the material property of interest, has been the main focus of studies to differentiate between different material geometries, contact profiles and materials surfaces in contact with ice. An alternative way of assessing improvements in the sliding over ice could be to look at the sliding time or the sliding velocity as performance indicators. Focusing studies on the performance will provide clearer indicators of testing conditions and material surfaces that lead to better results, narrowing down the test conditions or material surfaces that need more detailed investigation.

This work will consider sliding down an angled surface to evaluate movement over ice in laboratory conditions. Interaction with ice will be over relatively fresh ice that is more representative of material interaction with ice, than the thin water film that remains from the previous interaction with ice. The use of sensors along the sliding path will show the sliding velocity at different distances, allowing the interaction with ice to be assessed at different velocities.

In order to measure movement over ice, we propose the measuring the movement of an object down an angled ice surface. This test setup could be used to determine the static ice-friction as well as the sliding velocity at different test conditions (temperature, humidity, load, surface wettability, surface roughness, etc.). Two different type experiments could be conducted:

- 1) *Determination of the static friction coefficient.* The sample is placed on a horizontal ice surface and one end is slowly raised until a critical angle α is reached when the sample starts moving. The static friction coefficient can be calculated as the tangent of the angle α as known from basic physics. This requires an accurate method of measuring the angle of the plane because angle differences between similar surface treatments might be difficult to notice;
- 2) *Determination of the sliding velocity.* The time is recorded for samples (with the same geometry and weight) that move down an inclined ice plane past motion detection sensors for calculating the velocity at different distances, Fig 2. The use of a gate opening mechanism minimizes the influence of the operator.

The static friction coefficient measurement has been commonly used for centuries, and is well known to anyone who has studied basic physics, but the use of an inclined plane for determining sliding-ability is rarely discussed, especially in the

field of ice friction; therefore, this research is focused on measuring the sliding velocity.

The objective of this work is to determine whether sliding down an angled ice surface provides a useful indicator of sliding over ice for choosing conditions for better sliding times. Test conditions representing the environmental conditions (ambient temperature), the sliding object (load and surface roughness) will be altered to investigate the sliding velocity.

2. MATERIALS AND METHODS

Preparation of the ice track

The ice was prepared by pouring hot water (~ 70°C) into a U-shaped profile and freezing 5 layers to build up the total thickness of 30 mm with the goal of achieving homogeneous ice without cracks and air inclusions. The time necessary for freezing at -10°C was approximately 48 h.

A guide track (groove) was made by planning the middle of the track to a flat surface with U-shaped walls so that the sample slid a similar path without possibility of rotating (inset of Fig 2). The central lowered sliding path ensured that the blocks did not touch the sensors or profile metallic sides and protects block from falling out of the track. Loose debris arising from the planning operation were removed with a moist sponge. Afterwards track was left untouched during all experiment day.

Preparation of the blocks

Stainless steel samples (made 35 mm long, 18 mm wide and 14 mm high) were milled from an austenitic-ferritic steel (containing 82,6% Fe, 0,12% C, 13,4% Cr, 1,6% Ni, 1,3% Mn, 0,2% Si, 0,2% V and 0,1% S) to a weight of 67 ± 0.5 g. The blocks were then polished on a *334 TI 15 semi-automatic polisher* (Mecatech, UK) to an average surface roughness, Sa of ~ 8 nm. The surfaces were then modified with parallel scratches by abrasion under a load of 10 N on sandpaper (grit designations of 400, 600, 2000 and 3000). Scratches were made by moving the block in a forward and backward direction for a total distance of 2400 mm [15].

Characterization of the surface roughness

Since the surfaces contained a directional roughness, the surface roughness measured in 3D is more appropriate to obtain the roughness along the scratches instead of a 2D roughness, that typically measures the roughness perpendicular to scratch direction. Previous work not only showed that a 2D measure is insufficient [15], but further indicated that a 3D measure needed a more detailed representation, such as the Criterion of Contact (CCr). Consideration of the surface roughness term in CC, labelled as CCr for sliding on ice is following:

$$CC_r = \frac{R_{Sm}}{S_a} \quad (1)$$

where: CC_r – Criterion of Contact roughness parameter component;
 R_{Sm} – mean spacing between roughness asperities at the mean line, measured in movement direction (mm);
 S_a – arithmetical mean height of the surface asperities (μm).

The roughness characterization using CC_r combines roughness measure in the vertical direction (S_a) with roughness measure in the horizontal direction (R_{Sm}) forming a ratio that characterizes the average steepness of the asperities, Fig 1. A larger ratio represents flatter asperities (smoother surface), but smaller ratio - steeper asperities (rougher surface).

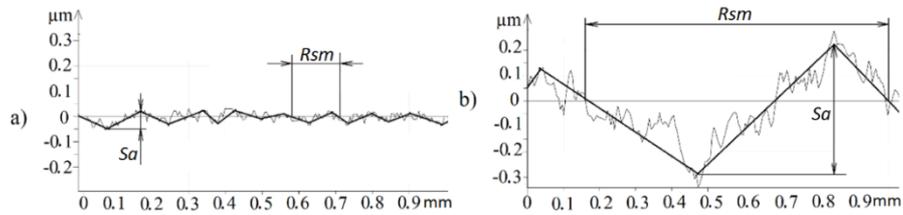


Fig. 1. A schematic of the Criterion of Contact for: a) polished surface; b) surface abraded with 400 grade sandpaper

Surface roughness was measured by *Form Talysurf Intra 50* profilometer (Taylor Hobson, UK) with a *112/2009 stylus* ($2\ \mu\text{m}$ tip) at a speed of $0.5\ \text{mm/s}$ and cut-off of $0.25\ \text{mm}$. 400 parallel profiles were taken in a $2 \times 2\ \text{mm}$ area [15].

Method for measuring the sliding velocity

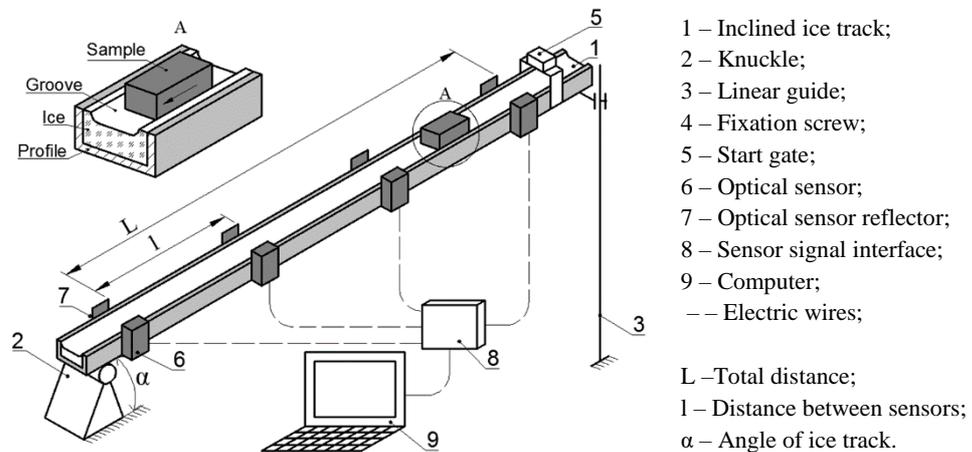


Fig.2. Setup for measuring the sliding velocity of a metal block down an ice track.

The ice track was free to rotate at one end and fixed at the opposite end to set the angle α for sliding experiments. The start gate was raised by an electromagnetic actuator to allow the block to start sliding freely, without influence from the operator, and move past the first optical sensor where the start time was logged and sensors 2, 3 and 4 to determine the time and hence the sliding velocity at each distance, Fig 2. Sensors were positioned $1100 \pm 1\text{mm}$ between each other and the total distance, L was $3300 \pm 1\text{mm}$. Optical sensors *SOEG-RSP-Q20-PS-S-2L* (Festo, GER) sent the signals to the *FluidSIM input/output* (Festo, GER) collection module and then the *EasyPort* (Festo, GER) interface and further to the computer where calculations were made for the sliding velocity at each distance. The equipment measured sliding time with an accuracy of 0.01 seconds.

The sliding angle, selected as 16° higher than the minimum to initiate sliding, was kept constant to provide a comparison of sliding velocity from differently prepared blocks. The block glided down the ice slope and passed by the 2nd, 3rd and 4th set of optical sensors to provide an average velocity relative to the earlier optical sensor, positioned 1100 mm further up the ice track. The average velocity in each section as well as the entire distance was then calculated.

The first experiment looked at the use of the ice track, but the remaining three experiments investigated the influence of experimental conditions on the sliding velocity. In the experiment on the use of the sloping ice track, the sliding velocity was determined at different distances. The other three experiments looked at the impact of experimental conditions on the sliding velocity – the sliding block surface condition, the temperature and the load on the sliding block. Eighty measurements were made for each test sample.

Table 1

Conditions for evaluating the effect of temperature, roughness and load on the sliding velocity.

Experimental condition	Effect of roughness	Effect of temperature	Effect of block load
Temperature, ($\pm 1^\circ\text{C}$)	-5.5	-13.0; -8.0; -3.0	-8.0; -5.5; -3.0
Block surface treatment	Polished, 3000, 2000, 600, 400	Polished; 3000; 600	Polished, 600
Block load, ($\pm 1\text{ g}$)	67	67	67; 127; 157
Number of blocks	13	6	4

The first experiment examined the average velocity in the upper third, the middle third and the lower third sections of the ice track. For this experiment, all four sets of sensors were used. Ambient temperature was set to -5.5°C . The average velocity over the entire length was then determined and closer attention was given to the effect of experimental conditions on the sliding velocity.

Since the metal surface roughness will affect the ice friction, roughness was addressed first condition for more detailed testing. Surfaces were abraded with 400 grit sand paper at one extreme, or polished on an auto polisher at the other extreme.

This experiment reduced the number of surface roughness conditions in further experiments. The same experiments were performed 3 times on different days, to assess the repeatability.

The effect of ambient temperature on sliding velocity was then investigated at three different surface roughness conditions. The end points were chosen at -13°C for close to dry friction and at -3°C for friction including a significant water interlayer which thickness do to the lack of specific equipment was not measured.

Finally, three different block weights were chosen. The first block with a size of 35 mm long, 18 mm wide and 14 mm high was left as it was but the blocks with heavier weights had additional block with identical geometry placed on top of them. To produce the same dimensions for additional blocks, the heaviest one was made of lead but lightest one from same stainless steel as basic blocks.

3. RESULTS AND DISCUSSION

The arrangement of four sensors along the ice track provided four different measures of the sliding velocity. An average velocity was reported for each section, and an average velocity for the full length of the ice track, Fig. 3. It appeared that the increase in velocity within the second section was slower than the first section, but increased more than twofold in the third section. The range of velocity from 1.4 m/s to 5.2 m/s covered the mid-range of velocities investigated by other researchers [5,7,10,13]. By arranging the sensors closer to each other will tend to instantaneous velocities tending towards 10 m/s, the maximum reported by others. As a result, this test facility provides a test setup that would be comparable to previous ice friction studies.

This sliding velocity test facility is flexible in that it can measure the velocity at any location along the ice track by changing the location of the sensors. Additional sensors may also be selected to provide more sliding velocities at selected locations.

Abrasion with sand paper influenced the sliding velocity. In all cases, the metal block abraded with a 2000 grit sand paper showed the fastest sliding velocity, Fig. 3. This suggests that smoother surfaces do not necessarily slide faster. A close examination of the average velocity in the last section of the ice track showed that a slightly rougher metal block glided at a velocity comparable to the 2000 grit sand paper surface. This makes the 600 grit abraded metal block worthy of closer attention, and so was included in further experiments.

The effect of surface preparation was best represented with the Criterion of Contact to show the influence on sliding velocity, Fig. 4. The average peak height represented by Sa show a weak correlation with the sliding velocity and it is noticeably difficult to show comparison of similar smooth surfaces with rougher ones at the same graph, Fig. 4a. Results showed that a maximum sliding velocity was reached when the surface asperities were significantly flat but with less contact

area than polished surface has, Fig. 4b. At $R_{Sm}/S_a > 700$, the average sliding velocity over the entire length of the ice track showed a plateau.

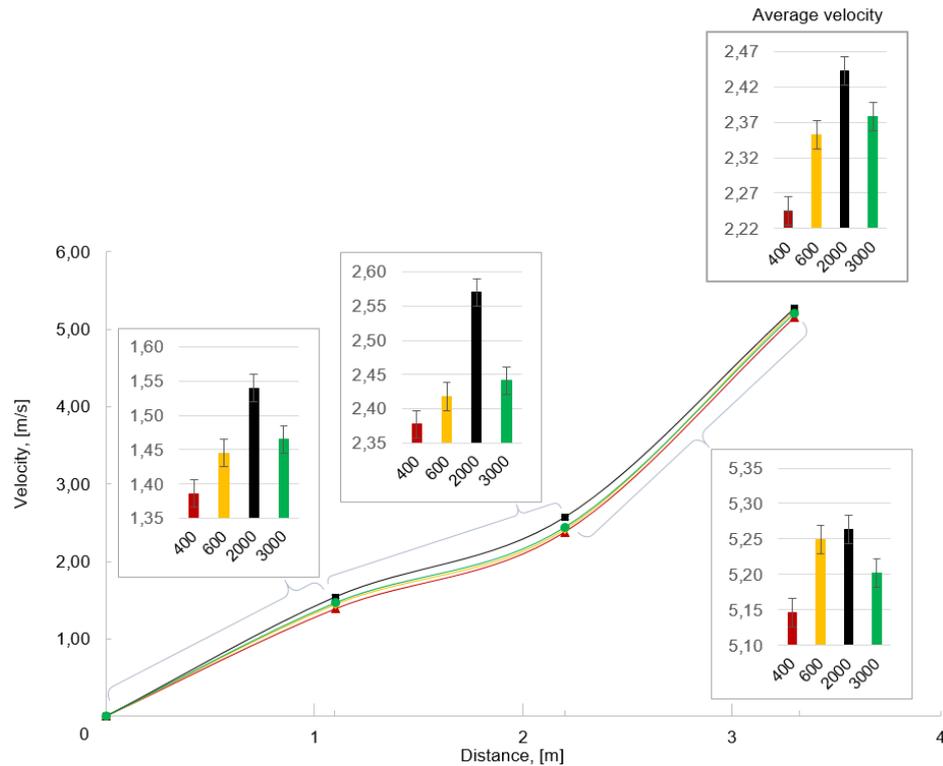


Figure 3. The average velocity within the three sections and the total length of the ice track. Insets show the sliding velocity of metal blocks abraded with 400 grit, 600 grit, 2000 grit and 3000 grit sandpapers.

Along with the point of contact is the effective stress of the peaks on the ice surface. When there are fewer and steeper peaks interacting with the ice surface, then peak height will become more important in determining the stress imposed by the peaks that dig into the ice. A larger stress by the steeper peak will slow the movement on ice.

The 2000 grit, 3000 grit and polished surfaces showed a comparable velocity when testing at an ambient temperature of -5.5°C .

The ambient temperature caused a further change in the sliding velocity. Previous experiments showed comparable sliding velocities at -5.5°C , Testing at colder conditions (at -13°C) led to overall decrease in sliding velocity, and more similar sliding velocities, but an increase in temperature to -3.0°C reduced the sliding velocity, and separated the results more clearly, Figure 5. These results are similar to the ice friction measurements determined by others, showing a minimum between -8°C and -3°C . The smallest ice friction will be associated with a larger acceleration and a resulting larger velocity. The minimum in ice friction should then directly correlate with a maximum acceleration and the highest velocity.

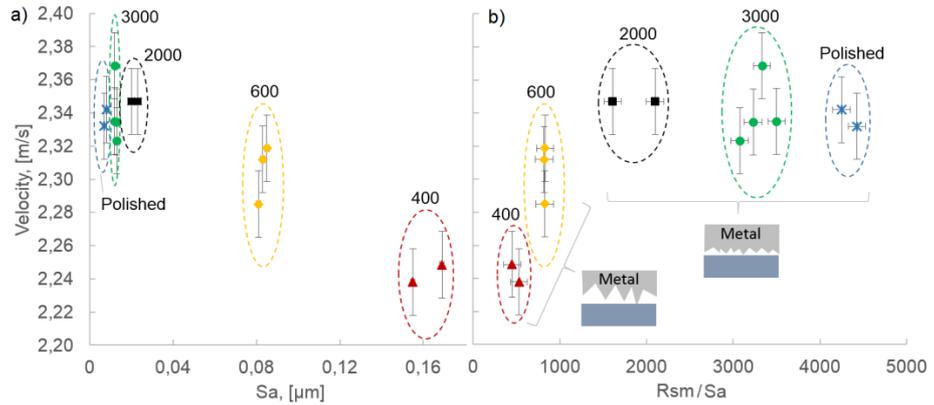


Figure 4. Influence of the metal contact with ice on the average sliding velocity (modified from [15]) shown with: a) the surface toughness S_a ; b) the Criterion for Contact roughness parameter ratio R_{sm}/S_a .

A change in ice friction has been correlated with a water film present at the sliding interface. Greater friction occurs from solid ice friction (the movement of metal against ice) but the introduction of a water film reduces the friction. This faster sliding velocity shown in laboratory test conditions is supposedly linked to the thin water layer. Even though everyone agrees such layer exists there are still no unified and safe method for measuring the thickness of this layer.

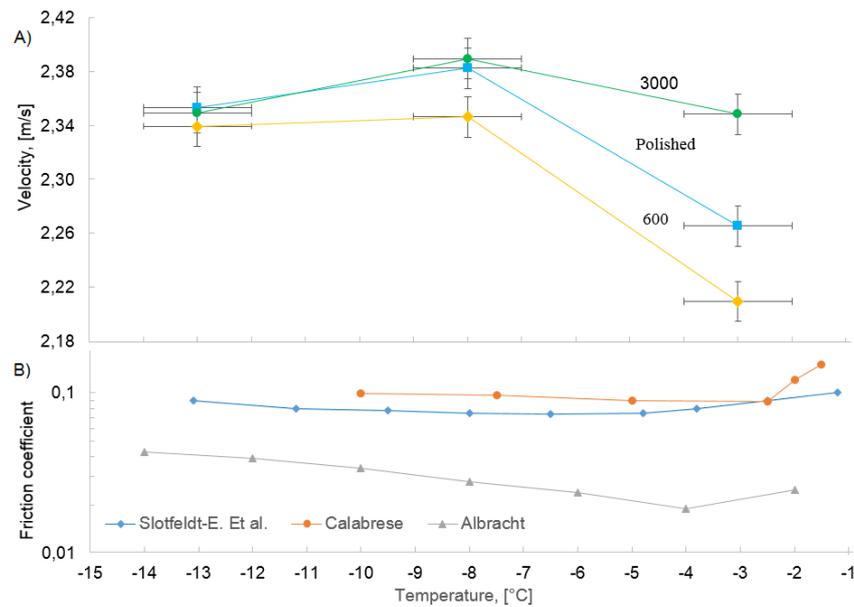


Fig. 5. Influence of temperature on the average sliding velocity, compared to the ice friction determined by others [5]. A minimum in ice-friction will be associated with a larger acceleration and hence a higher velocity.

A thicker film then creates viscous drag to slow the movement of the metal on ice. The viscous drag could possibly explain the pronounced reduction in sliding velocity for the polished surface that would have the best wetting conditions. It appears that a slight roughness, as shown by the 3000 abrasion, aids the sliding on ice if small contact pressures are applied to contacting surfaces.

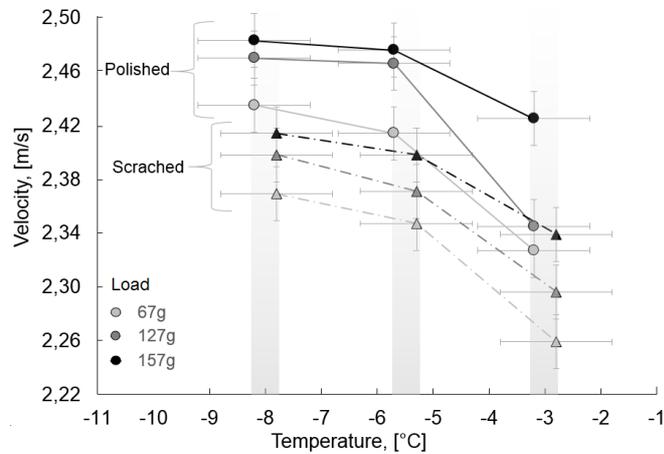


Figure 6. The influence of load on the sliding velocity of polished and 600 grit roughened metal blocks at -8.0 °C, -5.5 °C and -3.0 °C.

A load on the sliding metal block increased the sliding velocity for both polished and 600 grit abraded surfaces. The total effect from an increase in load cannot be seen since the air drag for the larger block geometry is presently not known, that decreases the sliding velocity. Regardless of the air drag, a greater load introduced a larger potential energy that is expected to result in a greater velocity. It is noteworthy that a temperature close to the melting point of ice results in greater increases in velocity that suggests that the heavier load overcomes viscous drag of the water more effectively at -3°C than the solid friction at -8°C.

The sliding velocity measured within the laboratory with four sensors on the ice track showed the ability to clearly distinguish the effect of surface abrasion, temperature and load. Given that the sliding conditions at the metal-ice interface may change with velocity, this setup will allow a closer study of sliding velocity at different distances and within specified distance intervals by changing the location of the sensors. Alternatively, additional sensors can be added to provide a larger number of sections available for analysis.

This setup used flat metal blocks leading to more pronounced effects. A large contact area provided interaction of the metal surface with the ice. Viscous drag in these conditions is thought to have been greater compared to cylindrical pieces that result in a lower degree of interaction. Testing at the laboratory scale can also be conducted on a mini sled like arrangement with two runners that would require a wider ice track. This degree of flexibility with the sample geometry and ability to

determine the sliding velocity as a performance measure velocity offers a valuable measure for quickly comparing different conditions to narrow down the number of blocks or experimental conditions that can be subjected to more detailed investigation.

4. CONCLUSIONS

The setup for measuring the sliding velocity provided an average sliding velocity at each of the distance intervals, and also along the full length of the ice track. The velocity of the metal block at different locations could be used to determine how experimental parameters influence the sliding velocity at different distances. The average sliding velocity over the entire length showed that, a) surfaces abraded with sandpaper smoother than 600 grit slid similarly, b) the higher sliding velocity occurred at a temperature that coincided with previous measurements of ice friction and, c) that an increase in load led to faster sliding especially at temperature closer to the melting point of ice.

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EKSPERIMENTU UZSTĀDĪJUMU IETEKMES UZ SLĪDĒŠANAS ĀTRUMU PĒTĪJUMI IZMANTOJOT LEDUS PLAKNI AR OPTISKAJIEM SENSORIEM

J. Lungevičs, E. Jansons, K.A. Gross

Kopsavilkums

Līdzšinējie pētījumi, kuros apskatīta objektu spēja slīdēt pa ledu, pamatā orientēti uz berzes koeficienta noteikšanu nevis slīdēšanas ātruma izmaiņu noteikšanu. Tā kā materiāla funkcionalitāti labāk izsaka tā slīdēšanas ātrums, nevis berzes koeficients, šī pētījuma ietvaros tika izveidota mērīšanas sistēma, kura ļauj noteikt paraugu slīdēšanas ātruma izmaiņas, kā arī ļauj novērtēt dažādu eksperimenta uzstādījumu ietekmi uz ātruma izmaiņu. Iekārta izveidota kā slīpā plakne, kuras sānos piestiprināti optiskie sensori, kuri ļauj veikt vidējā slīdēšanas ātruma noteikšanu plaknes trijos starpposmos, kā arī visas distances garumā. Tika apskatīts vai ar iekārtas palīdzību iespējams noteikt slīdošā parauga raupjuma, gaisa temperatūras un pieliktā svara ietekmi uz slīdēšanas procesu. Virsmas raupjuma raksturošanai izmantots kontaktkritērijs, kurš uzrāda, ka virsmas, kuras sagatavotas ar smalkāku smilšpapīru par 600. marku uzrāda ļoti tuvus slīdēšanas ātrumus. Apskatot temperatūras ietekmi, novērots, ka lielākais slīdēšanas ātrums vērojams līdzīgā temperatūru diapazonā kā citu autoru darbos, kuros šajā apgabalā novērots zemākais berzes koeficients. Pieliktajam svaram ir lielāka ietekme uz rezultātiem pie gaisa temperatūrām, kuras tuvas ledus kušanas robežai, liekot domāt, ka šajā situācijā paraugiem ir vieglāk pārvarēt bremzējošos spēkus nekā sausās berzes gadījumā. Turpmākajos pētījumos nepieciešams pārbaudīt iegūtās likumsakarības izmantojot garāku slīpo plakni, lielākus svarus un attīstot lielākus ātrumus, lai redzētu vai laboratorijas rezultāti sakrīt ar reālām dzīves situācijām.