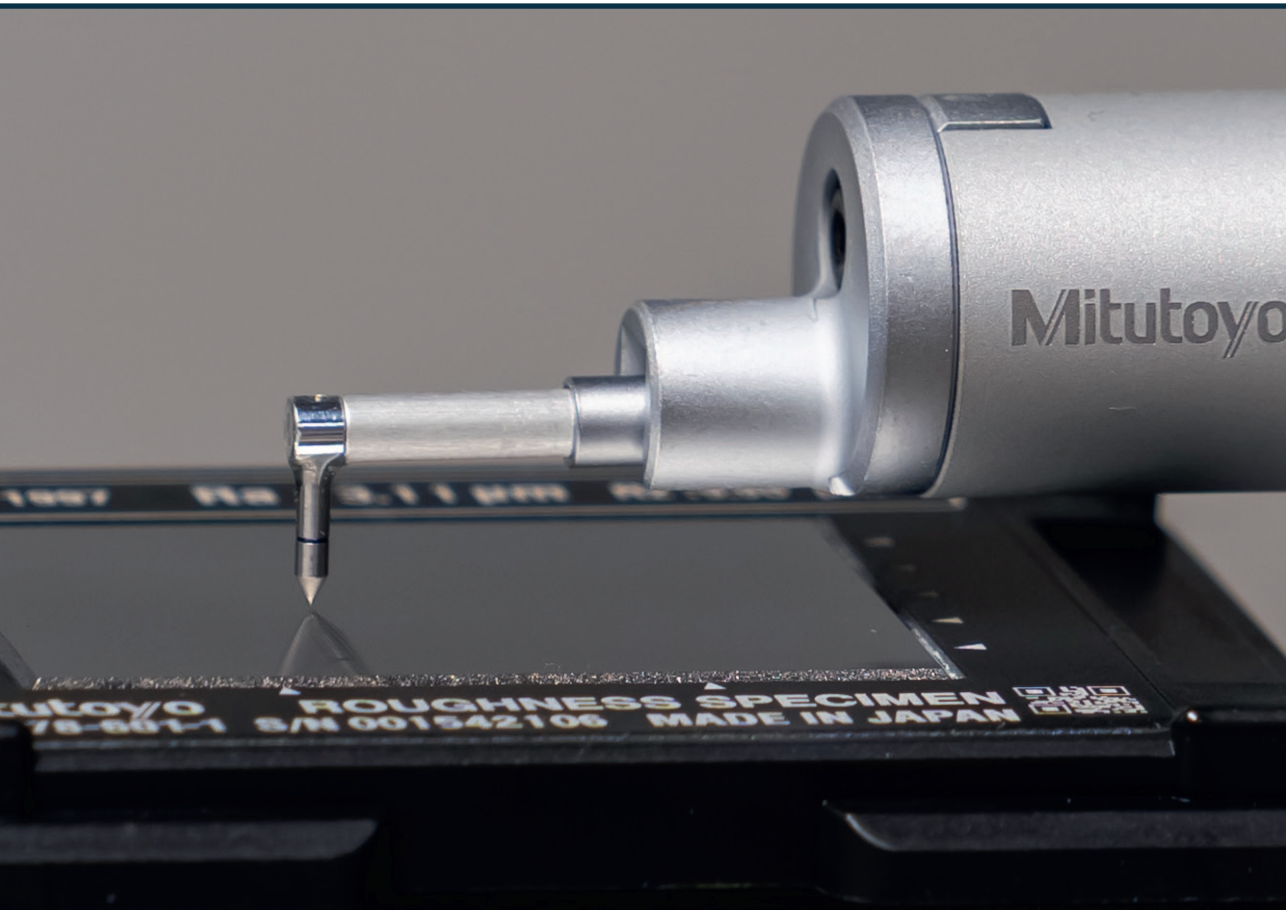
RIGA TECHNICAL UNIVERSITY

Jānis Lungevičs

EFFECT OF STAINLESS STEEL SURFACE MACROGEOMETRY AND MICROGEOMETRY ON THE COEFFICIENT OF SLIDING FRICTION ON ICE

Summary of the Doctoral Thesis



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RIGA TECHNICAL UNIVERSITY
Faculty of Mechanical Engineering, Transport and Aeronautics
Institute of Mechanics and Mechanical Engineering

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EFFECT OF STAINLESS STEEL SURFACE MACROGEOMETRY AND MICROGEOMETRY ON THE COEFFICIENT OF SLIDING FRICTION ON ICE

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the Doctoral Thesis has been submitted for defense at the open meeting of the RTU Promotion Council on July 3, 2023, at 10:00 at the Faculty of Mechanical Engineering, Transport and Aeronautics of Riga Technical University, 1 Paula Valdena Street, Room 106.

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University of Ljubljana Slovenia

DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Jānis Lungevičs ……………………………. (signature)
Date: ………………………

The Doctoral Thesis is a thematically unified collection of articles. It consists of a summary in Latvian and English and seven publications in SCI-indexed journals. Publications are written in English; the total number of pages is 78, including electronically available supplementary information.

CONTENT

OVERVIEW OF THE THESIS

The actuality of the topic

The friction of solid bodies on ice is a relatively little-studied phenomenon influenced by many interrelated factors. These factors range from ambient air and ice temperature, air humidity, movement velocity, the geometry of the sliding body, surface texture orientation, applied pressure, chemical and physical properties of the sliding body, hardness of the ice surface, and others. The interaction of these parameters determines the formation of a thin water layer, known as a liquid-like layer (LLL), on the ice and its thickness [1]–[34]. Despite several attempts by researchers to understand the formation of a liquid-like layer and its influence on the coefficient of friction of the sliding body on the ice, the lack of complex and unified metrological support has impeded a reliable explanation of this phenomenon.

To better comprehend the coefficient of friction on ice, there is a need for holistic information about the interaction between the surfaces of the sliding body and ice and the boundary layer between them. Multiple studies have indicated the significant role played by the sliding body's macrogeometry and microgeometry on the coefficient of friction on ice [3], [16], [24], [29], [31]–[33], [35]–[38], and experimental studies prove it [16], [19], [24], [26], [33], [35], [39]. However, it is still unclear how surface macrogeometry and microgeometry affect the coefficient of friction on ice and which surface geometry component plays a more substantial role.

Theoretically focused studies simplify the texture of the sliding body, considering only the body's form while ignoring waviness and roughness. Such theoretical studies are essential, but the accepted simplifications do not allow analyzing the true nature of the process because macro geometric bodies, in reality, will always have micro geometric textures that affect the surface contact area between the body and the ice [3], [40]–[43]. On the other hand, experimentally oriented studies [16], [24], [29], [31]–[33], [35]–[37], [44] focus on the sliding body's roughness component, ignoring the macro geometry (shape or form). Literature analysis revealed that in previous studies, the surface of the entire solid body is judged considering only roughness parameters obtained in a small, localized area, typically less than 10 % of the entire body surface [15]. In addition, the texture measurements of this already small area are digitally filtered according to ISO 25178-2 recommendations. With filtering operations, texture form and waviness components are removed, further converting the final texture image and increasing the chances that researchers mislead themselves about the actual texture that interacts with ice (see Fig. 1). Therefore, the author of the Doctoral Thesis perceives the issues mentioned above as significant problems that hinder the progress of ice tribology research.

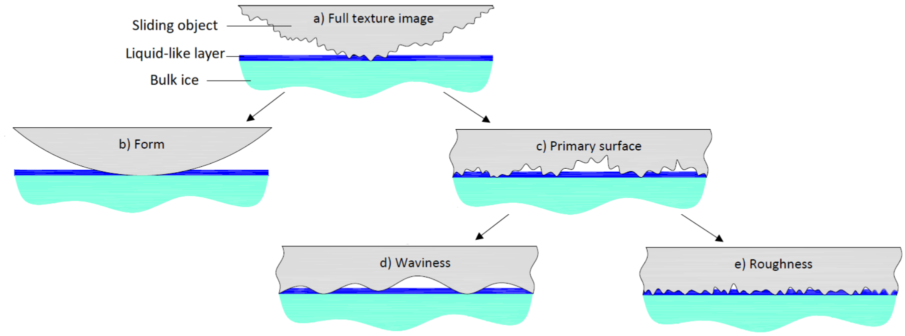

Fig. 1. Schematic representation of sliding body texture components: a) full texture image that represents the true complexity of the surface; b) only the form component of the surface that represents the macrogeometry of the surface; c) primary surface that consists of surface waviness and roughness representing microgeometry of the surface; d) waviness component of the surface; e) roughness component of the surface.

While in reality, full texture defines contact with ice, researchers often use only the filtered roughness component. The schematic representation shows that the contact with ice might be completely misinterpreted by following a standard methodology where only roughness is considered [15]. The author of the Thesis hypothesizes that the interaction of the solid body surface with ice can be reliably evaluated if all surface texture components (form, waviness, and roughness) are considered, as only the combination of these three components provides holistic information about the actual contact area that determines the surface coefficient of friction on ice.

Another factor affecting the ability to analyze macrogeometry and microgeometry influence on the coefficient of friction is the choice of parameters that characterize the surface geometry. So far, the most commonly used are standardized texture parameters (the arithmetic average of profile height deviations from the mean line) Ra or (the arithmetic average of surface height deviation from the mean plane) Sa. However, Ra or Sa values can be identical for differently produced textures with different coefficients of friction on ice (see Fig. 2). This problem highlights that relying only on the roughness parameter to describe the surface contact with ice is insufficient.

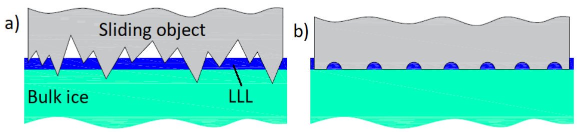

Fig. 2. Schematic representation of the interaction between a sliding body, ice, and liquid-like layer (LLL): a) surface with peaks; b) surface with depressions. In both cases, the surface roughness parameters, such as Sa or Ra, might have the same mathematical value, but the friction on ice differs, i.e., the surface with peaks will increase friction, while the surface with depressions will reduce it [15].

The gathered information hypothesizes that analysis of the surface coefficient of friction on ice is unreliable without complete knowledge of surface macrogeometry and microgeometry and the parameters that characterize it.

Aim and objectives

The Doctoral Thesis aims to develop a new methodology for sliding body surface macrogeometry and microgeometry measurements for the coefficient of friction on ice determination (further referred to as methodology).

The following main tasks were completed to achieve the goal:

1. Analysis of previously known studies and methodologies.
2. Development of experimental procedure.
3. Experimental research.
4. Development of a new methodology of sliding body surface macrogeometry and microgeometry measurements for the coefficient of friction on ice determination.
5. Approbation of the newly developed methodology.

Research methods

To achieve the aim, quantitative and qualitative research methods, and the listed experimental equipment for conducting practical measurements were used.

An auto polisher *334 TI 15 Mecatech* (Presi, France) was used to prepare the experimental sample's initial surfaces. The final sample textures were manufactured using fabric-based sandpapers of different grain sizes (M3, USA), shot blasting equipment *SBC-420* (Power plus, China), a CNC milling machine *Vertical Center Smart 530C* (Mazak, Japan), and *Libra Ti: sapphire* femtosecond laser system (Coherent, USA).

Surface textures were measured and characterized with the following instruments:

- Contact-type profilometer *Form Talysurf Intra 50* with standard stylus *112/2009* (Taylor Hobson, UK).
- Confocal microscope *VK-X250/260* (Keyence International NV/SA, Belgium).
- Optical microscope *Eclipse LV150* (Nikon, Japan).
- Scanning electron microscope *S-4800* (Hitachi, Japan).
- Atomic force microscope *Smena NT-MDT* (NT-MDT Spectrum Instruments, Russia).

Tribological experiments were conducted with two different tribometers:

- *Inclined plane tribometer* (RTU, Latvia). The tribometer records the sample sliding time in defined distances. From these data sliding velocities at various sliding distances were calculated and used as indirect friction describing parameters, i.e., higher velocity values relate to the lower coefficient of friction, and vice versa.
- *V-Research GmbH oscillating type tribometer RVM1000* (Werner Stehr Tribology GmbH, Germany). The tribometer measures the friction force between the ice and the surface of the steel sample. Static and dynamic coefficient of friction (COF) is calculated from the measured friction forces and applied load values.

A *Proscan 520* thermometer (Dostmann, Germany) and a contact-type thermocouple *TP-122-100-MT-K* (Czaki, Poland) were used to measure the ice temperature. Air temperature and air humidity were monitored with *P330 Temp* (Dostmann, Germany).

Sample 3D texture measurements were post-processed in the *Talymap Gold* software (Mountain Maps, France). Statistical methods used in data processing: descriptive/descriptive statistics. Display of results is provided in the form of graphs, pictures, and tables. Tables and graphs were created in *Excel 2018* software (Microsoft, USA). *Solidworks 2022* and *AutoCAD 2022* computer programs were used in image preparation.

Scientific novelty

- A new methodology of sliding body surface macrogeometry and microgeometry measurements was developed for the coefficient of friction on ice determination: both macrogeometry and microgeometry must be included to determine the coefficient of friction on ice.
- It was found that sliding body surface macrogeometry and microgeometry influence on coefficient of friction on the ice must be analyzed considering the sliding body surface temperature: changes in sliding body surface temperature can inverse the coefficient of friction trend for the same surface texture.
- It was proven that surface contact area measurements according to the new methodology allow comparing variously manufactured surface texture influence on the coefficient of friction on ice, which was impossible with previously known methodologies.

Theses to be defended

1. *The newly developed methodology of sliding body surface macrogeometry and microgeometry measurements for determination of the coefficient of friction on ice*. The new methodology includes surface contact area measurements used for contact pressure between the sliding body and ice calculations necessary for tribology experiment result interpretation. According to the new methodology, the whole complexity of the sliding body surface is considered, ensuring a comparison of sliding body surfaces created using various manufacturing methods, which was not possible with previously known methodologies.
2. *Contact area measurements should be used to analyze the coefficient of friction on ice.* The experimental data obtained when contact pressure between the stainless steel surface and ice was higher than 1 MPa proved that the contact area and coefficient of friction have a strong correlation (proportion of variance from 0.9 to 1). The surface texture parameters (Sa, Ssk, Sku, Sds) from previous methodologies have a proportion of variance from 0.5 to 0.9.
3. *The sliding body surface temperature must be considered during the coefficient of friction on ice determination.* It has been proved that in the considered experimental settings, when the contact pressure between the stainless steel surface and ice was higher than 1 MPa, the same surface texture could either increase or reduce the coefficient of friction on ice, depending on the sliding body surface temperature. If the sliding body surface is colder than the ice surface, the reduction of contact areas between the sliding body and ice reduces the

coefficient of friction, but if the sliding body surface is warmer than the ice surface, the reduction of contact areas increases the coefficient of friction.

Practical significance of the Thesis

A new methodology for sliding body surface macrogeometry and microgeometry measurements for the coefficient of friction on ice determination has been developed. This methodology allows analyzing differently manufactured surface macrogeometry and microgeometry that influences the coefficient of friction on ice. This methodology can be used to characterize surface textures manufactured for different functionality, i.e., in some applications coefficient of friction must be increased and in some reduced. Examples where the coefficient of friction should be reduced are:

- Winter sports: Improvement of ice skate blades, bobsleigh runners, skeleton runners, luge runners, curling stones, ski edges, and ice sailing blades. Controlling friction on ice is essential to optimize athlete performance and prevent accidents.
- Construction: Friction on ice is important in constructing and maintaining buildings in cold climates. For example, anti-icing and deicing methods are used to prevent ice buildup on roofs, gutters, walkways, road signs as well as wind turbine blades.
- Transportation: Ice breaker ship front treatment could reduce the friction-caused energy losses while the ship pushes itself on ice to break it. Deicing textures for airplane surfaces would prevent using chemicals that melt the ice.

Some examples where the coefficient of friction should be increased:

- Transportation: Friction between tires and ice affects the handling and safety of vehicles during winter driving.
- Health and safety: Understanding friction on ice is crucial for preventing falls and injuries during winter. Proper footwear with effective treads is essential for maintaining balance and stability.

The new methodology developed in the Doctoral Thesis could also be applied to analyze other tribological pairs, not only metal-ice included in this Doctoral Thesis because the actual contact area determines the coefficient of friction between any surfaces.

The results of the Doctoral Thesis were used to improve the equipment of the Latvian luge team. This is confirmed by the National Luge team coach and head of engineering Mārtiņš Rubenis, in the document in the Thesis Appendix 8).

Approbation of the Doctoral Thesis

Presentations at international scientific conferences *(In total, 11 presentations; the 7 most important are listed)*

1. Lungevics, J., Jansons, E., Velkavrh, I., Boiko, I. *Ice tribology investigation using different test setups*. Riga Technical University 63rd International Scientific Conference *Mechanical engineering technology and heat engineering*. Riga, Latvia, 13 October 2022. *Published in Book of Abstracts.*

2. Velkavrh, I., Kafexhiu, F., Wright, T., Lungevics, J., Jansons, E., Boiko, I. *Tribological investigations in a cold environment for winter sports applications: comparative ice friction measurements in different test rigs*. Nordic Tribology Symposium 2022, Alesund, Norway, June 14–17, 2022. *Published in Book of Abstracts.*
3. Lungevics, J., Jansons, E., Boiko, I., Velkavrh I. *Influence of stainless-steel texture on friction properties sliding on ice*. RTU 60th International Scientific Conference. October 14, 2019, Riga, Latvia.
4. Jerane, I., Gross, K. A., Lungevics, J., Pluduma, L. *The Effect of Patterning and Surface Contact on the Sliding Speed over Ice*. The 1st International Conference on Nature Inspired Surface Engineering (NISE 2019). June 11–14, 2019, New Jersey, USA. *Published in Book of Abstracts.*
5. Lungevics, J., Jansons, E., Gross, K. A. *Surface Texture Characterization for Ice Friction Research*. 45th Leeds–Lyon Symposium on Tribology *Smart Tribology Systems*. September 4–7, 2018, Leeds, UK. *Published in Book of Abstracts.*
6. Lungevics, J., Jansons, E., Gross, K. *Skeleton Runner Roughness and Surface Contact Area Influence on Sliding Ability: Field Experiments*. Material Science & Applied Chemistry 2018, October 26, 2018, Riga, Latvia. *Published the conference proceedings idexed in SCOPUS.*
7. Lungevics, J., Jansons, E., Rudzitis, J., Gross, K. A. *Use of Inclined Plane with Additional Time Measurements for Investigating Surface Slidability on Ice*. 12th International Conference *Mechatronic Systems and Materials Intelligent Technical Systems*. July 3–8, 2016, Bialystok, Poland. *Published in Book of Abstracts.*

Patents

1. Jansons, E., Lungevičs, J., Boiko, I. *Portable slip detection device and method*. Patent No. LV15660B, 20.03.2023, owner – RTU.
2. Jansons, E., Lungevičs, J., Leitāns, A., Boiko, I. *Multifunctional equipment and method for assessing the tribological properties of materials and coatings*. Patent application No. LVP2022000037, 29.04.2022, owner – RTU
3. Lungevičs, J., Jansons, E., Stiprais, K., Gross, K. A. *Apparatus and method for determining sliding properties*. Patent application No. LV15305B, 20.03.2018, owner – RTU.

Publications *(7 publications that form this Doctoral Thesis are listed. In total, 17 publications are related to the Doctoral Thesis topic. All publications are indexed in SCOPUS or other databases)*

1. Gross, K., Lungevics, J., Zavickis, J., Pluduma, L. *A Comparison of Quality Control Methods for Scratch Detection on Polished Metal Surfaces*. Measurement, 2018, Vol. 117, pp. 397–402. ISSN 0263-2241. Available: doi:10.1016/j.measurement.2017.12.022.
2. Jansons, E., Lungevics, J., Gross, K. *Surface Roughness Measure that Best Correlates to Ease of Sliding*. 15th International Scientific Conference *Engineering for Rural Development*: Proceedings. Vol. 15, Jelgava, Latvia, May 25–27, 2016, pp. 687– 695. ISSN 1691-5976. Available: https://www.tf.llu.lv/conference/proceedings2016/Papers/N127.pdf.

3. Velkavrh, I., Lungevics, J., Jansons, E., Klien, S., Voyer, J., Ausserer, F. *The Influence of Isotropic Surface Roughness of Steel Sliders on Ice Friction Under Different Testing Conditions*. Lubricants, 2019, Vol. 7, No. 12, pp. 50–63. ISSN 2075-4442. Available: doi:10.3390/lubricants7120106.
4. Velkavrh, I., Voyer, J., Wright, T., Lungevics, J., Jansons, E., Boiko, I. *Variations of ice friction regimes in relation to surface topography and applied operating parameters*, IOP Conf. Ser. Mater. Sci. Eng. 1140 (2021) 012033. Available: https://doi.org/10.1088/1757-899X/1140/1/012033.
5. Jansons, E., Lungevics, J., Jerane, I., Gross, K. *A Smaller Bearing Ratio, as a Surface Texture Measure, Promotes Faster Sliding on Ice*. Journal of Tribology, 2021, Vol. 143, No. 11, Article number 111801. ISSN 0742-4787. e-ISSN 1528-8897. Available: doi:10.1115/1.4049704**.**
6. Lungevics, J., Jansons, E., Boiko, I., Velkavrh, I., Voyer, J., Wright, T. *A Holistic Approach towards Surface Topography Analyses for Ice Tribology Applications*. Frontiers in Mechanical Engineering, 2021, Vol. 7, No. 1, pp. 42–56. ISSN 2297-3079. Available: doi:10.3389/fmech.2021.691485**.**
7. Gross, K., Lungevics, J., Jansons, E., Jerane, I., Wood, M., Kietzig, A. *Surface Hierarchy: Macroscopic and Microscopic Design Elements for Improved Sliding on Ice*. Lubricants, 2021, Vol. 9, No. 103, Article 103. ISSN 2075-4442. Available: doi:10.3390/lubricants9100103.

Structure of the Doctoral Thesis

The Doctoral Thesis is a collection of seven publications included in SCI journals with a summary in Latvian and English. All publications are written in English, comprising 78 pages, including electronically available supplementary information. Figure 3 is a graphical abstract showing to which Doctoral Theses tasks each publication refers.

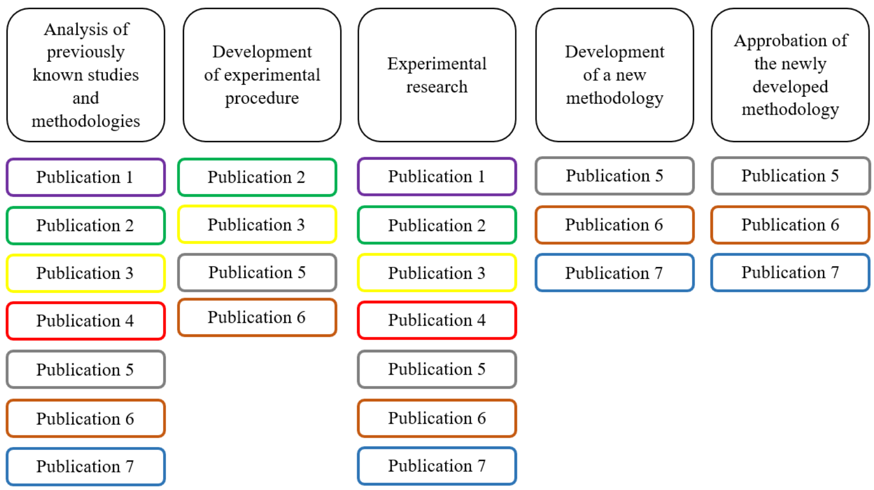

Fig. 3. Graphical abstract of the Doctoral Thesis structure.

The following list highlights each publication's content, results, and the Doctoral Thesis author's personal contribution to these publications. All corresponding authors confirm the Doctoral Thesis authors' personal contribution. Their hand-signed document that proves it is presented in the Thesis Appendix 9.

Publication 1

A Comparison of Quality Control Methods for Scratch Detection on Polished Metal Surfaces [45]**.** The research paper compares various measurement methods for controlling surface quality and analyzing nanometer-scale scratches on mirror-like smooth surfaces. The results showed that AFM ensures the highest resolution and information in three dimensions, but the method is unsuitable for large objects, significantly limiting its usability. It was also concluded that the light microscopy method detected 70 % of scratches visible by AFM, making it an efficient and precise method, but the results are available only in 2D interpretation. The SEM was ideal for detailed observations but had limitations to sample size and preparation. Due to low measured point density and small measured surface area, the contact type 3D profilometer failed to detect nanometer-scale scratches. Still, it provides the ability to obtain 3D surface measurements of large objects, making it suitable for real-life object surface measurements.

Author's personal contribution: conceptualization, investigation, analysis, visualization, writing and reviewing, and editing.

Publication 2

Surface Roughness Measure that Best Correlates to Ease of Sliding [26]**.** The study analyses why the 2D profilometry method alone may not successfully characterize surface textures that slide on the ice. It was also emphasized that the 2D profile measurement positioning on the surface could cause significant result variation, suggesting that 3D profilometry should be used. The relation to commonly used 2D profilometry parameters and tribology measurements was shown. The Criterion of Contact for surface texture characterization was introduced and compared with the roughness arithmetic mean height parameter. It was concluded that knowledge of the Criterion of Contact ensures defining optimal surface asperity height and spacing ratio that promotes better surface sliding on ice.

Author's personal contribution: conceptualization, investigation, methodology, analysis and validation, writing and preparation of the first draft.

Publication 3

The Influence of Isotropic Surface Roughness of Steel Sliders on Ice Friction Under Different Testing Conditions [6]**.** Within this study, the same test samples were compared on two different tribometers at various environmental conditions. This Doctoral Thesis is the first known study in ice tribology where the same samples are tested on two setups and the results are compared. Inclined plane type and oscillating type tribometers were used in this study. It was concluded that both setups are sensitive enough to detect texture variation influence on tribological performance. It was also shown that environmental conditions and sample temperature significantly influence tribological performance.

Author's personal contribution: conceptualization, investigation, methodology, analysis and validation, writing and preparation of the first draft.

Publication 4

Variations of Ice Friction Regimes in Relation to Surface Topography and Applied Operating Parameters [4]**.** The research aims to study surface textures and surface temperature's influence on tribological performance. The results showed that the changing sliding body surface temperature from +5 °C to –18 °C increased the coefficient of friction on ice four times. It was also discovered that the contact area between the sliding body surface and ice could have an inverse effect on the coefficient of friction at different sliding body surface temperatures, i.e., if the sliding surface temperature were lower, a larger contact area resulted in a higher coefficient of friction. However, if the sliding body surface temperature exceeds the ice temperature, a larger contact area provides a lower coefficient of friction. This study concluded that sliding body surface temperature must be considered during the coefficient of friction on ice determination.

Author's personal contribution: conceptualization, investigation, analysis, visualization, writing and preparation of the first draft.

Publication 5

A Smaller Bearing Ratio, as a Surface Texture Measure, Promotes Faster Sliding on Ice [7]**.** Newly developed sliding body surface macrogeometry and microgeometry measurement methodology are introduced. The study explains why previously known surface texture characterization methodologies and used parameters are unsuitable for comparing tribological experiments for samples with differently manufactured surface textures. It was proven that a new methodology, where information about the entire surface was considered and expressed as a bearing ratio curve, ensured comparison between differently manufactured surfaces and their tribological performance.

Author's personal contribution: conceptualization, investigation, methodology, analysis and validation, writing and preparation of the first draft.

Publication 6

A Holistic Approach Towards Surface Topography Analyses for Ice Tribology Applications [15]**.** This paper discusses the newly developed surface macrogeometry and microgeometry measurement methodology in more detail. The paper includes an in-depth analysis of surface characterization methodologies and surface texture parameters used in previous ice tribology studies conducted by other researchers. The benefits of the new methodology were described and validated by analyzing sandblasted surface tribological performance in two different experimental setups. A correlation between various sliding body surface texture parameters and tribology experiment results was demonstrated.

Author's personal contribution: conceptualization, investigation, methodology, analysis and validation, writing and preparation of the first draft.

Publication 7

Surface Hierarchy: Macroscopic and Microscopic Design Elements for Improved Sliding on Ice [5]**.** Surface macrogeometry and microgeometry influence on sliding body surface tribological performance are discussed, highlighting the importance of considering all surface texture components (form, waviness, and roughness). Practical examples of how sliding body surface macrogeometry and microgeometry combination define final tribological performance are discussed. The benefits of newly developed sliding body surface macrogeometry and microgeometry measurement methodology are discussed and shown graphically.

Author's personal contribution: conceptualization, hierarchy, investigation, visualization, and storyline development with visuals and text.

MAIN RESULTS OF THE DOCTORAL THESIS

1. Introduction

Ice is a crystalline solid composed of water molecules. The most common form of ice is hexagonal ice, referred to as I_h, which contains six-fold symmetry (see Fig. 4 a)) [1], [2]. A repeating pattern of hydrogen bonds between adjacent water molecules characterizes the ice structure. These hydrogen bonds give ice its characteristic properties, including its low density and hardness. Due to its molecular structure, ice is less dense than liquid water. This is because the hydrogen bonds in ice create open spaces between molecules, resulting in a less compact structure. For this reason, ice floats in liquid water [1], [2]. Ice hardness ranges from 15 to 35 MPa depending on ice temperature [1]–[3], [46]. Ice is also brittle and has a low shear strength, which is prone to breaking when subjected to stress. This makes ice a challenging material to work with. Additionally, ice has a low thermal conductivity, meaning it does not transfer heat well [1], [2].

The unique chemical structure of ice gives it a broad range of physical properties, including its slipperiness. This phenomenon can be attributed to several parameters governing its molecular structure and interaction with the surrounding environment and objects. The slipperiness of ice is defined by its low coefficient of friction, which arises due to the presence of a thin layer of water molecules on its surface, known as a liquid-like layer (LLL) [1]–[3], [11], [16], [28], [32]. Ambient conditions and contact with a warmer surface influence the formation of LLL. The thickness of LLL on ice essentially defines the friction regime that will occur during an object sliding on ice. If LLL thickness exceeds sliding body roughness asperity amplitude, a fully hydrodynamic regime with a low coefficient of friction occurs. However, very thin LLL could cause a boundary friction regime where mechanical interlocking of sliding body texture asperities and ice occurs, resulting in a higher coefficient of friction [2], [11], [16], [27], [32]. These principles are summarized in the following Stribeck curve (see Fig. 4 b)), where the coefficient of friction on ice is shown on the vertical axes, and movement velocity is on the horizontal axis.

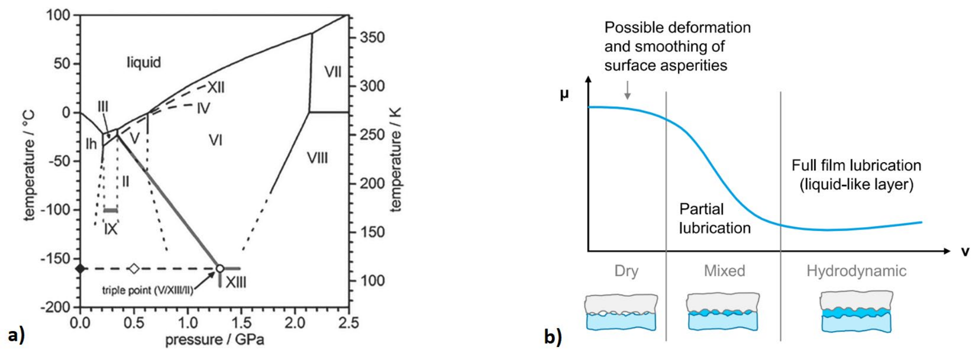

Fig. 4. a) Phase diagram of ice [1]; b) the Stribeck curve for the ice friction. The coefficient of friction on ice is shown on the vertical axes, and movement velocity is on the horizontal axis [6].

The slipperiness of ice is also influenced by the pressure exerted on its surface by external forces and movement velocity [2], [11], [16], [28], [32]. For example, ice can become more slippery when subjected to frictional heating, such as when a skater glides over ice [3], [40], [42], [47], because the friction causes the water molecules in the surface layer to melt, creating a liquid-like layer that further reduces the coefficient of friction.

Another parameter that can significantly influence the slipperiness of ice is its temperature [1]–[3], [16], [19], [32], [48], [49]. As the temperature of ice increases, it starts to melt and form a thicker liquid-like layer, thereby reducing its coefficient of friction. Conversely, as the ice temperature decreases, the water molecules on its surface start to freeze, creating a rougher surface that increases its coefficient of friction.

The coefficient of friction is affected by the contact area between the sliding body and the ice since the contact area directly influences the magnitude of the interfacial forces acting between the two materials. The frictional forces arise primarily due to the interlocking of asperities on the contact surfaces and the materials' deformation at the interface. The contact area controls the number of asperities in contact and the extent of deformation, thereby determining the overall frictional resistance. A larger contact area leads to a greater number of interlocking asperities. Conversely, a smaller contact area would result in less interlocking. The contact area also plays a role in heat dissipation during sliding, where a larger area allows for more intense heat transfer from the sliding body to the ice. Hence, the contact area is a crucial parameter in determining the frictional behavior of sliding bodies on ice, and carefully controlling it is essential for surface engineering for various applications.

Figure 5 summarizes the most influential parameters that define surface friction on ice.

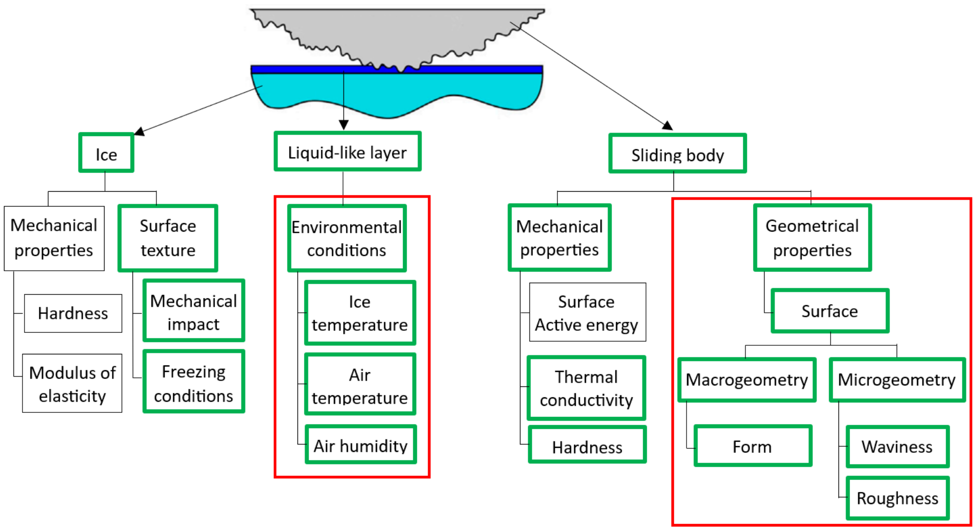

Fig. 5. Most influential parameters that define surface friction on ice. The parameters marked green are considered in the Doctoral Thesis. The parameters marked red highlight parameters primarily addressed in the Doctoral Thesis.

In conclusion, the slipperiness of ice is due to the formation of a thin layer of water molecules on its surface, which reduces its surface coefficient of friction. The parameters that influence the slipperiness of ice include ambient air and ice temperature, air humidity, movement velocity, the contact area between the sliding body and the ice, surface texture orientation, contact pressure, chemical properties of the sliding body, hardness of the ice surface, and others. A better understanding of these parameters and their interconnection can improve the design of products that can enhance or reduce friction in various applications. Primarily the Doctoral Thesis focuses on sliding body geometrical property measurements and characterization to improve understanding of surface interaction with ice and liquid-like layer.

2. Literature analysis

Within the doctoral Thesis, a new methodology for sliding body surface macrogeometry and microgeometry measurements and analysis was developed and approved. The Thesis author realized that such a method is necessary after noticing that many times in his experiments, identical test samples with the same roughness values, which should perform the same in friction tests, had a noticeably different tribological performance. This observation made the author hypothesize that some crucial information about the test sample geometry was missing, hiding the explanation of why these apparently identical test samples have different friction with ice. Knowing this problem, the Doctoral Thesis author researched how other scientists have measured and characterized their test sample surfaces in ice friction studies. The literature review summarized in **Publications 1**, **2**, **5**, and **6** [7], [15], [26], [45] concluded that each research group working on this topic has its unique approach, equipment, and methods for preparing, measuring, and interpreting test sample geometry. Unfortunately, none of these methods included holistic information about the test sample geometry. Mostly only the roughness of the surface was considered, suggesting that other research groups might face the same issues with unreliable test surface description, so the work on a new surface macro geometry and microgeometry measurement and post-processing method began.

The first step in new methodology development was finding the most suitable measurement tool for the task. Different measurement tool capabilities, advantages, and disadvantages were compared and examined in **Publications 1** and **6** [15], [45]. Table 1 summarizes the measurement tool comparison presented in **Publication 6**.

Table 1 [15]

Limitations of the surface topography measurement tools (symbols +, ?, and X stand for "measurement is possible", "measurement might be possible", and "measurement is not possible", respectively)

	Form	Waviness	Roughness	Limitations	Typical measurement limits
2D measurements					
Profilometer – contact	+	+	+	Stylus tip radius > 1 µm	Profile length: 100 mm Height: 2 mm
Optical microscope	X	?	+	Surface reflection, contrast	Area: 200 × 200 mm
SEM	X	?	+	Sample preparation	Area: 5 × 5 mm
3D measurements					
Coordinate measurement machine	+	?	X	Stylus tip diameter > 300 µm	Produced in small and large sizes
Contour measurement machine	+	+	?	Stylus tip radius > 25 µm	200 x 100 mm Height: 60 mm
Non-contact profilometer	+	+	+	Light absorption Reflection Steep asperity slopes	Area: 150 × 200 mm Height: 2 mm
Contact profilometer	+	+	+	Stylus tip radius > 1 µm	200 × 100 mm Height: 2 mm
AFM	X	?	+	Limited sample size	Area: 200 × 200 µm Height: 50 µm

Even though all compared measurement tools are useful and have their advantages, it was concluded that the contact-type profilometry is best suited for this task due to the following reasons:

- All three surface components (form, waviness, and roughness) can be measured. This approach provides the possibility to perform one measurement, which can afterward be analyzed using all surface components together or separately if needed.
- A broad measurement range is possible, allowing work with larger objects that can later be used in field tests.
- Heavy samples can be measured (up to 10 kg), ensuring that large test objects like bobsleigh or skeleton runner can be measured.

It was also concluded that a 3D contour measurement machine and 3D coordinate measurement machine (CMM) would be the best complementary tool for larger amplitude form measurements, and an atomic force microscope (AFM) is needed if minor amplitude scratches or patterns on small polished surfaces with very great details must be examined [45].

The next step was investigating what type and size samples were used in known studies, how their geometry was measured, and which parameters were used to characterize the geometry. Comparison is discussed in **Publication 6**. It was concluded that only a tiny fraction of the whole sliding body surface was typically measured (see Table 3), meaning that information about the investigated surface's entire geometry was missing. Table 2 summarizes surface texture parameters other researchers have used in the ice tribology field.

Table 2 [15]

Texture parameters used in the known ice tribology studies

	2D parameters
Ra	The arithmetical mean deviation of the assessed profile. Defines surface asperity average height [10], [26], [29], [37].
Rdq	Root mean square (RMS) slope of profile. Defines the steepness of the asperities [10].
Rsm	The mean width of the roughness profile elements [26], [37], [50]. Defines how densely packed or stretched roughness asperities are.
	3D parameters
Sa	Arithmetical mean deviation of the assessed surface [26], [45], [50].
Sq	RMS roughness [16].
Ssk	The skewness of the surface. Characterizes whether a sample has asperities on top of the flat surface or dimples/scratches below the flat surface [24], [33].
Sku	Kurtosis of the surface. The measure of the asymmetry of the probability distribution of a real-valued random variable about its mean [24], [33].
S10z	Ten-point height. Indicates surface height calculated using only 5 highest asperities and 5 lowest valleys. It gives better insight into texture asperity's actual amplitude. Due to the involvement of the 5 highest asperities, this parameter might change rapidly if the sample starts to wear [24].
Sz	The maximum amplitude of the surface texture. Indicates the height between the surface's highest asperity and deepest valley. As far as only the highest and lowest points are used, this parameter will change rapidly if the sample wears [22].
Sfd	Fractal dimension. Characterizes the complicity of texture. If the parameter value aspires to the number 2, the surface is smooth and less complex. If the parameter aspires to the number 3, the surface is more complex and thus has a larger theoretical contact surface [33], [35].
	Non-standardized parameters
β	Attack angle. The angle between the sample surface, which is considered flat, and snow (ice) roughness asperity slope [35].
KK	The criterion of contact. It is calculated as Rsm/Sa ratio. Indicates the steepness of asperities, i.e., a larger ratio represents smoother surfaces with low and wide asperities, but a smaller ratio represents high and densely packed asperities [26].

Besides the parameters described in Table 2, the bearing ratio curve (Abbot–Firestone curve) has been used to characterize sliding surfaces in ice tribology [7], [10], [36]. It describes the cumulative probability density function of the surface profile height.

Table 3 summarizes the data used by other research groups in their studies of experimental samples, surface measurement methods, and surface parameters.

Table 3 [15]

Examples of sample geometry, surface measurement equipment, and obtained surface texture parameters used by other research groups (abbreviations: n/s – not stated, L – length, W – width, H – height, R-radius)

Sample type and dimensions (mm)	Measured lengths/areas (mm)	Equipment	Calculated parameters	Ref.
Pin: Diameter = 3	0.4 × 2.8	Confocal microscopy	Ra, Rq, Rsk, Rku	[10]
Pin, dimensions: n/s	0.5 × 0.5	Stylus 3D profilometer	Ra, Rdq, Ssk, Sku, Sfd (D)	[33]
Ring type slider: outer diameter = 25.4; inner diameter = 23.4; H = 1	Profiler: n/s AFM: n/s SEM: 0.2 × 0.2	Non-contact profilometer, AFM, SEM	Ra, microscale bump diameter	[29]
Steel ski: L = 487.5; W = 30; H = 30	1.7 × 1.8 3.3 × 3.3 8.2 × 7.8 11.3 × 11.3	Focus variation microscope	Sa, Sz, Ssk, Sku	[22], [24]
Steel runner: L = 150; W = 8; H = 20; runner transversal radius = 4	0.05 x 0.05	AFM	Sa, St	[22]
UHWMPE polymer samples: n/s	0.4 × 0.5	Interferometer, SEM	Attack angle	[35]
UHWMPE ski sole on aluminum body: L = 65; W = 40; H = n/s	0.5 × 1	Confocal microscopy	Width of the ridges	[9]
Laser textured skis with attachable metallic base plate: L = 200; W = 20; H = 0.5	0.6 × 0.6	SEM, Optical profilometer	Dimple diameter and depth	[8]
Silicon carbide spheres: R = 0.75; 6.00 Soda-lime glass spheres: R = 1.84 Sapphire sphere: R = 1.59 Model ice skate: R ≈ 22	0.2 × 0.2	laser-scanning confocal microscopy	Sq	[16]
Steel block: L = 35; W = 18; H = 14	2 × 2 20 × 10 32 × 16	Interferometer Contact type profilometer	Ra, Rsm, Rz, Rpk, Sa, KK, Sdq, Ssk, Sku	[6], [7], [26]

The literature review indicated that 12 different surface geometry describing parameters had been used. A common problem with these parameters is that they are calculated for the roughness component of the surface using different filter (cut-off) values, and roughness amplitude can be only a fraction of the whole surface texture amplitude. Figure 6 shows an example of different interpretations about the surface one can get if full surface measurement is available and what is visible if only a small section of the entire surface is measured. Previously known methods suggest small section measurement with the following roughness component filtration.

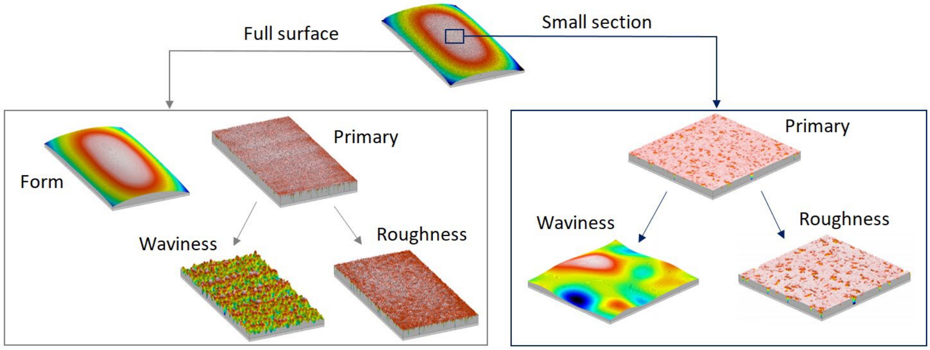

Fig. 6. Sample surface observation possibilities depend on the measured area of the sample. Full surface measurements provide essential information about surface macrogeometry (form) and microgeometry (waviness and roughness). On the other hand, small section measurements might have a higher measured point density, thus providing more details about the microgeometry, but information about the form is unavailable [15]. Missing information on the surface form can reduce the possibility of analyzing surface interaction with ice.

Figure 7 shows a workflow for the most common surface measurement approach and obtained result post-processing in the ice tribology research field. The measured surface is filtered multiple times during this approach, and only the filtered roughness component is considered, neglecting all information about the surface macrogeometry that might have the largest impact on the surface's final tribological performance.

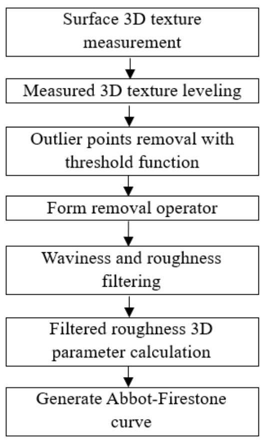

Fig. 7. Previously used 3D topography processing methodology.

Literature analysis concluded that a new unified approach for surface macrogeometry and microgeometry measurements and analysis was needed to include whole surface complexity in the research process.

3. Experimental research

Development of this Doctoral Thesis was based on conducting multiple practical experiments on two different tribometer setups. This study is the first known in the ice tribology research field when the same samples are tested on different tribometer setups, providing the unique possibility of comparing the observations from different methods. Such testing possibilities were possible due to the designed experimental sample size and geometry described below. The obtained tribology experiment results provided information on surface macrogeometry and microgeometry influence on friction on ice and allowed to compare tribology measurements from different test setups to double check surface geometry influence tendencies.

Experimental samples

All experimental samples of the Doctoral Thesis that were tested on tribometers were made as rectangular blocks with the following dimensions: 35 mm length, 18 mm width, and 14 mm height (see Fig. 8). The samples were processed in the same batch to ensure that the initial geometry was identical. Sharp edges and corners of the blocks were rounded to reduce edge collision with ice bumps.

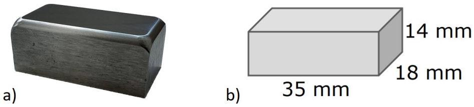

Fig. 8. a) Photo of experimental sample; b) sketch of experimental sample geometry.

The samples were made from the high corrosion resistance stainless steel Ramax HH (Uddeholm, Sweeden) with the following chemical composition and physical properties.

Table 4

Uddeholm Ramax HH stainless steel chemical composition [51]

Element	C	Si	Mn	Cr	Mo	Ni	V	S
%	0.12	0.2	1.3	13.4	0.5	1.6	0.2	0.1

Table 5

Uddeholm Ramax HH stainless steel physical properties [51]

Property	At 20 °C
Density, kg/m^3	7700
Modulus of elasticity, Mpa	215000
Coefficient of thermal expansion per °C from 20 °C	10.8×10^{-6}
Thermal conductivity, W/m °C	24
Specific heat capacity, J/kg °C	460
Tensile strength Rm, MPa	1140
Yield strength $Rp_{0.2}$, MPa	990
Elongation A_5, %	12
Hardness, HB	330 ± 5

The experimental sample's test surface was polished with auto polisher *334 TI 15 Mecatech* (Presi, France). Detailed information about the polishing process is given in **Publication 7**.

The final sample textures were manufactured using different methods, i.e., abrading with fabric-based sandpapers (**Publications 2**, **4,** and **5**), shot blasting (**Publications 3**, **4**, **5**, and **6**), CNC engraving (**Publications 5**, and **7**), and femtosecond laser system engraving (**Publication 7**).

Tribology experiments

Two different types of tribometers were used to test the experimental sample's tribological performance. Both setups could control ambient conditions around the machine, allowing one to set different environmental conditions.

The inclined plane tribometer (see Fig. 9), developed by Riga Technical University engineers, measures the sample's sliding time in defined distances. Average sliding velocities at various sliding distances were calculated using known distances and measured time and used as indirect tribological performance describing parameters, i.e., higher velocity values mean lower coefficient of friction and vice versa. The inclined plane tribometer working principle and used experimental settings are described in **Publications 2**, **3**, **4**, **5**, **6**, and **7**. During the Doctoral Thesis research, the inclined plane tribometer underwent several phases of improvement. Each improvement ensured a more stable climate around the tribometer and improved the resolution of the obtained result and ergonomics during the tests.

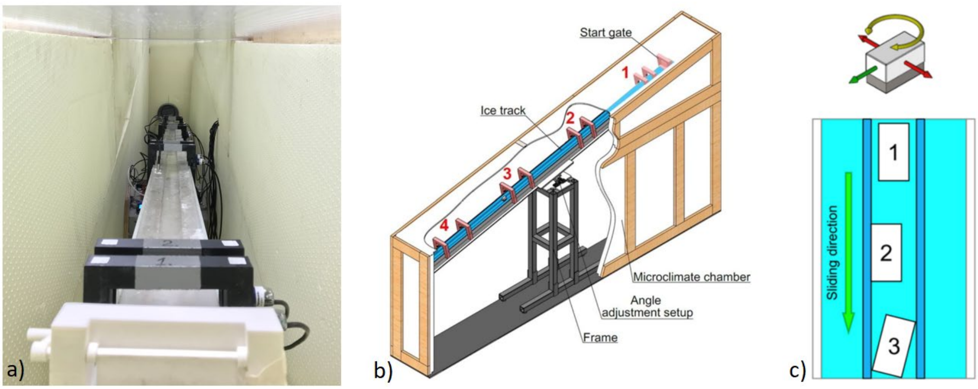

Fig. 9. a) Photo of the inclined plane tribometer; b) a schematic sketch of the inclined plane tribometer [7]; c) degrees of freedom of the steel samples during the tests on the inclined plane tribometer: 1 – ideal movement position; 2 – unwanted lateral translation of the sample; 3 – unwanted rotation of the sample [6].

The second tribometer used in the Doctoral Thesis was an oscillating type tribometer (see Fig. 10) *RVM1000* (Werner Stehr Tribology GmbH, Germany) located in the *V-Research GmbH* (Dornbirn, Austria) tribology laboratory. The oscillating tribometer measured the friction force between the ice and the surface of the steel sample. Static and dynamic coefficients of friction were calculated from the measured friction forces and applied load values. Calculated coefficients of friction were used to compare sample tribological performances. The tribometer working principle and used experimental settings are described in more detail in **Publications 3**, **4**, and **6**.

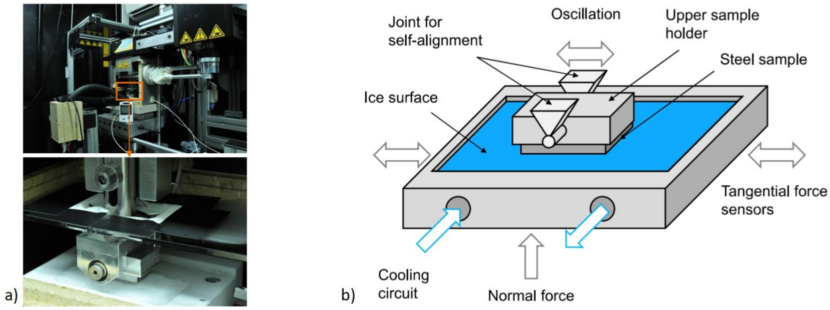

Fig. 10. a) Photo of an oscillating type tribometer *RVM1000*; b) a schematic sketch of an oscillating type tribometer [6].

Experimental sample 3D surface geometry measurements

Within the Doctoral Thesis, experimental sample surface geometry was measured and characterized with different instruments. The contact type profilometry was considered the most important and usable measurement tool to achieve the main goal, i.e., develop a new surface micro and macrogeometry measurement methodology. The 3D profilometry results were post-processed in *TalyMap Gold* software (Mountain Maps, France).

The following list shows which measurement tools were used in the publications of the Doctoral Thesis.

- Contact-type profilometer *Form Talysurf Intra 50* with standard stylus *112/2009* (Taylor Hobson, UK). **Publications 1**, **2**, **3**, **5**, **6**, and **7.**
- Confocal microscope *VK-X250/260* (Keyence International NV/SA, Belgium). **Publications 3**, **4**, and **6.**
- Optical microscope *Eclipse LV150* (Nikon, Japan). **Publication 1.**
- Scanning electron microscope *S-4800* (Hitachi, Japan). **Publication 1.**
- Atomic force microscope *Smena NT-MDT* (NT-MDT Spectrum Instruments, Russia). **Publication 1**.

4. New surface macrogeometry and microgeometry measurement methodology

A new methodology that defines a general strategy of surface texture measurements and results interpretation in this Doctoral Thesis is graphically shown in Fig. 11. This methodology and its advantages over previously used methods are described in more detail in **Publications 5**, **6**, and **7**. The main advantage of the new methodology is the possibility of calculating surface contact area containing the full surface complexity (form, waviness, and roughness), providing the missing data for contact pressure calculations between the sliding surface and ice. This information ensures a better explanation for surface texture's influence on friction on ice.

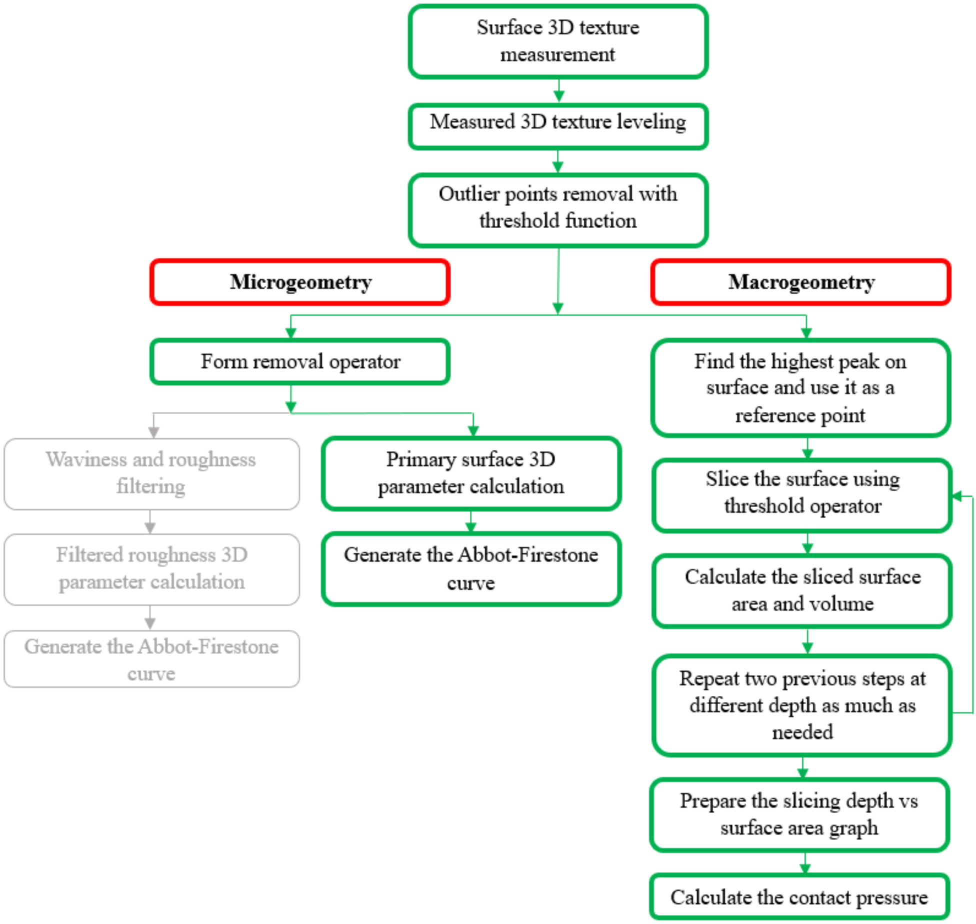

Fig. 11. A graphical interpretation of new surface macrogeometry and microgeometry measurements and result processing methodology. The block in grey shows the previously used approach, while the blocks in green show the new methodology steps.

The Thesis author proposes to perform surface virtual slicing using the "Threshold" operator in 3D surface analysis software. First, the measured 3D surface must be leveled, and the highest texture point must be used to define the virtual slicing plane reference. The highest point is used as a reference because this point will be the first one in contact with ice during the tribology experiments. An external force applied to the sample along with the heat transfer causes the ice to melt, resulting in the surface plowing into ice, increasing the contact area. By performing the proposed virtual slicing method, measuring the contact area at different sample plowing depths in the ice is possible, providing necessary information for contact pressure calculations. Figure 12 shows a schematic principle of surface virtual slicing.

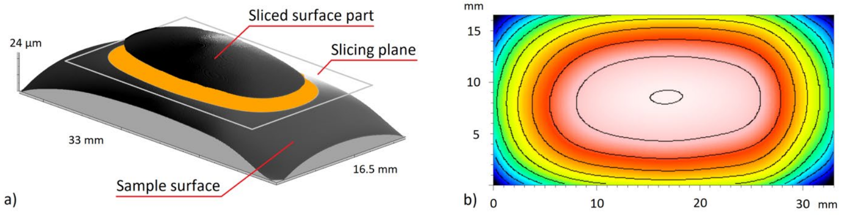

Fig. 12. a) Representation of the surface virtual slicing using the "Threshold" operator. Virtual slicing plane separates the surface segment from the entire surface, and its surface area and volume can be calculated. b) Contour map example of a sliced surface. A 3 µm step between the virtual planes was used in this example. The obtained contours show which parts of the entire surface would contact ice at various plowing depths. If the surface has curvature, as shown in this example, the actual contact area with ice is significantly smaller than the nominal surface area [15].

Calculated contact area values at different heights from the highest point can be used to calculate the contact pressure between the sliding body and the ice providing essential information for analyzing how significantly the sliding surface will plow in the relatively soft ice. Figure 13 shows how measured contact area is used to calculate contact pressures for tribometer setups used in this Doctoral Thesis.

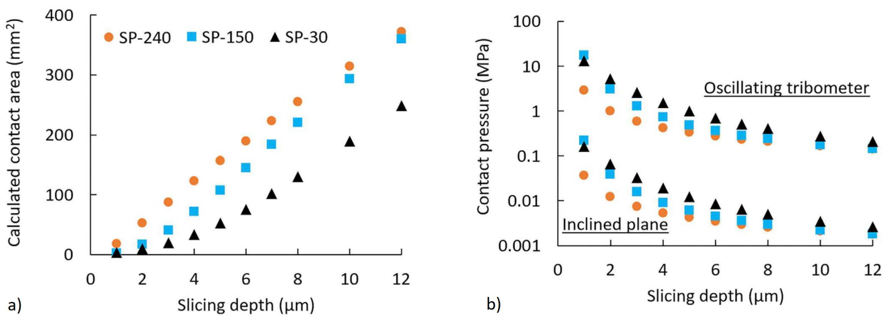

Fig. 13. a) Examples of measured surface contact area values at different slicing depths from the surface's highest point. Due to the sample surface curvature, the contact area increases at a lower slicing depth. The smoothest sample (SP-240) has the largest contact area and thus the lowest contact pressure, while the roughest sample (SP-30) has the highest contact pressure. b) Calculated contact pressure (shown in logarithmic scale) at various slicing depths for two experimental setups (oscillating tribometer and inclined plane tribometer). The most significant differences in contact pressure between the samples occur at smaller slicing depths, where surface asperities play a more prominent role. If the sample surface were sliced at 12 µm below the highest surface peak, the contact pressure evens for all samples [15].

Information about the actual contact area and the calculated contact pressure is a major improvement in the ice tribology research field because the results can be used in the theoretical coefficient of friction calculation models, which previously used only nominal values of the surface geometry. With the new methodology, the actual contact area is known and can be directly used in further calculations. A visual example of surface measurement post-processing according to the new methodology is shown in the Thesis Appendix 10.

5. Approbation of the new methodology

New surface macrogeometry and microgeometry measurement methodology was approbated comparing it with the previously used surface characterization methods. Experiments and comparisons are described in **Publications 5**, **6**, and **7**. The following chapters highlight the most important results of the methodology approbation experiments.

Comparison of surfaces produced with different manufacturing methods

The most significant benefit of the newly developed sliding surface macrogeometry and microgeometry measurement methodology is the possibility to reliably compare surfaces produced with different manufacturing methods, which was impossible using previously known methods.

For example, patterned surfaces with deep grooves can be manufactured, as shown in the Figure 14 section Milled surfaces. However, how to reliably characterize such surfaces using only surface roughness parameters is unclear.

One may try performing a surface measurement between the grooves, but there might not be enough space for 3D measurement if the grooves are tightly spaced. Another option would be the contact area theoretical calculations knowing the sample's initial surface and subtracting the grooved area. However, this approach could result in a significant error due to the imperfections of the surface, which caused the need for a new surface characterization method in the first place. Another issue is the potential material pile-ups on the edges of the grooves, as shown in Fig. 17. Without proper surface texture measurements, it is not possible to detect them. These issues raise many questions on how to measure such complex surfaces reliably. The solution is a newly developed surface macrogeometry and microgeometry measurement method that includes whole surface complexity (form, waviness, and roughness). This methodology removes none of the surface components during the comparison, providing a more realistic interpretation of the comparable surfaces. It does not matter if the surface is manufactured by milling, shot blasting, laser texturing, etc. The new methodology needs a complete 3D texture measurement that gets to be virtually sliced afterward and calculated contact areas or bearing ratios used as surface geometry characterizing parameters.

In **Publication 5,** eight differently manufactured surfaces (see Fig. 14) were, first, described using the bearing ratio curves, and to compare the new methodology with the previously used, surface roughness parameters Sa, Sdq, Ssk, and Sku were also measured for all surfaces.

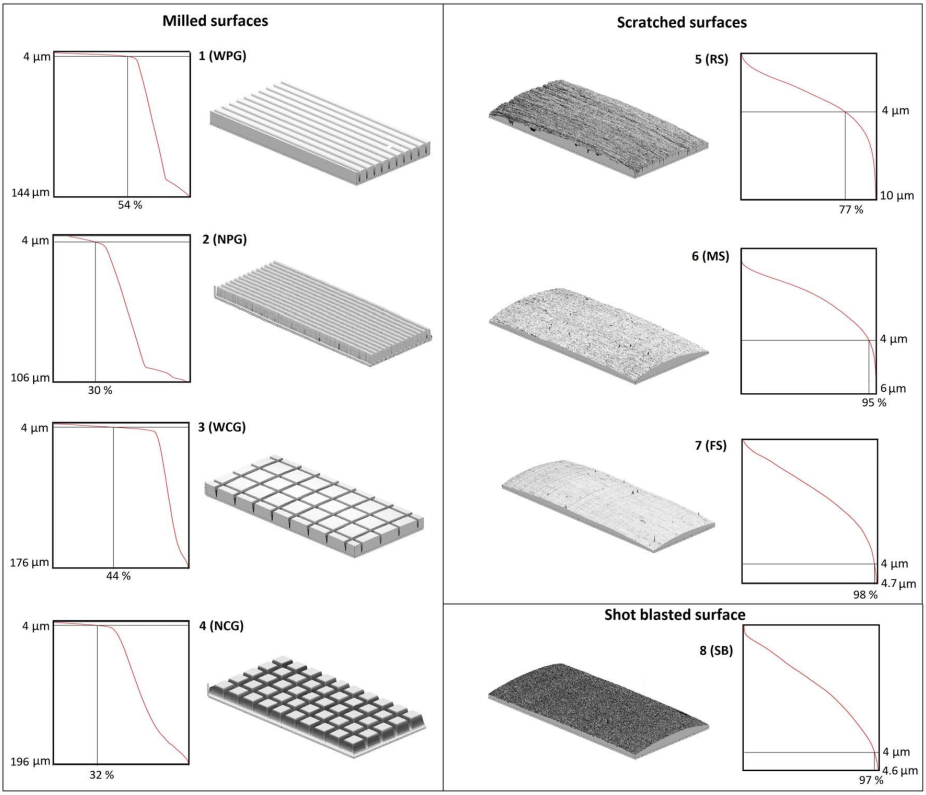

Fig. 14. Examples of differently manufactured surface 3D textures. Milling patterned samples WPG, NPG, WCG, NCG, scratched samples RS, MS, FS, and shot blasted sample SB. Graphs next to the 3D textures show the bearing ratios of these textures at 4 μm from the highest point. Obtained results show that differently produced surfaces can have significantly different contact areas at the same plowing depth in the ice, resulting in different contact pressures that influence the coefficient of friction on ice [7]. (Copyright ASME)

Then samples were tested on an inclined plane tribometer setup at different ambient conditions. Experiment No. 1 was conducted at 64 % air humidity, −2.5 °C air temperature, and −9 °C ice temperature, and Experiment No. 2 was conducted at 78 % air humidity, +1 °C air temperature, and −4 °C ice temperature. The obtained sample sliding speed results were used to compare sample tribological performance. A higher average speed means a lower coefficient of friction. Then, tribology experiment results were compared with sample texture parameters and bearing ratio values. The comparison results are shown in Fig. 15.

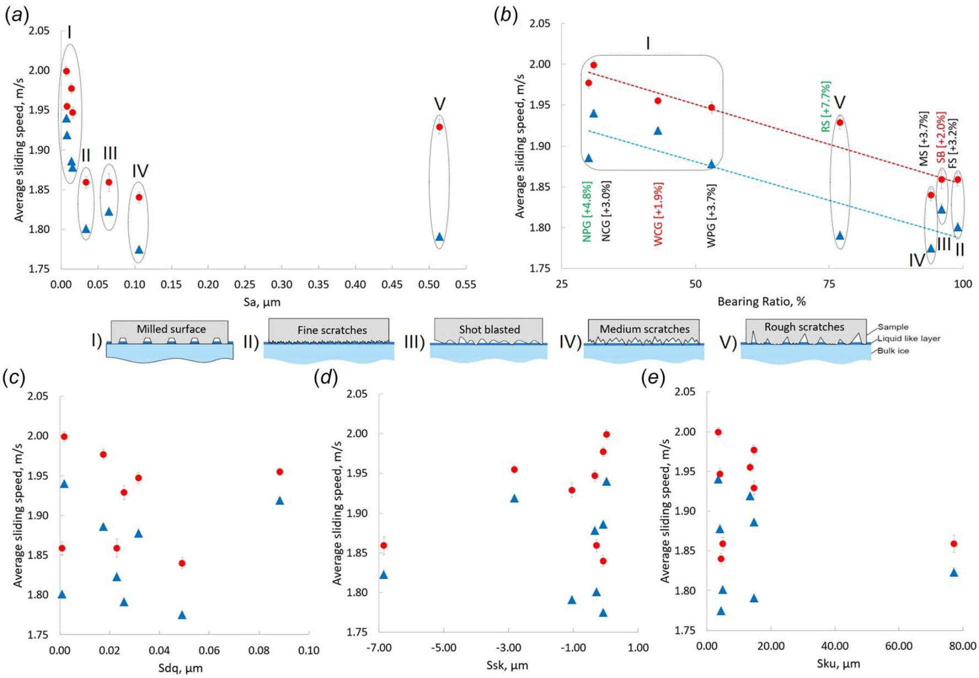

Fig. 15. Comparison between (a) average sliding speed and surface roughness parameter Sa, (b) average sliding speed and the bearing ratio at 4 micrometers from the highest surface point, (c) average sliding speed and surface roughness parameter Sdq, (d) average sliding speed and surface roughness parameter Ssk, and (e) average sliding speed and surface roughness parameter Sku. Triangles, Experiment No. 1 (64 %, −2.5 °C, −9 °C); Dots, Experiment No. 2 (78 %, +1 °C, −4 °C). Circled areas and Roman numbers represent different surface textures shown in sketches below the graphs [7]. (Copyright ASME)

The obtained results showed a linear trend between the bearing ratio and sliding speed in these experimental settings. Changes in the ambient conditions shifted the tribology experiments' overall values, but the trendline remained the same. In such experimental settings, smaller contact areas promoted better tribological performance. Remembering that the inclined plane tribometer setup has low contact pressure (<1 MPa), it is vital to remember that a significant contact pressure increase could result in different results due to the sample plowing in the ice.

The observed correlation between average sliding speed and surface roughness parameter Sa was not as good. The results proved that the surface roughness parameter Sa is not the best parameter for ice tribology research to describe the surface texture. Additionally, it was proven that there were no logical trends between average sliding speed and surface roughness parameters Sdq, Ssk, and Sku. The obtained results showed great potential to use the bearing ratio as a surface characterization parameter instead of Sa if the experimental sample surfaces have different surface textures. However, if the surface manufacturing method is the same and only manufacturing parameters are slightly changed, the surface roughness parameter Sa can also be used.

Comparison of surfaces produced with the same manufacturing process

After the differently manufactured surface comparison described above, the new surface macrogeometry and microgeometry measurement methodology was also approbated on samples produced with the same manufacturing method to see if also, in such cases, there are noticeable benefits compared to the previously known method. This study is fully described in **Publication 6**, but the following chapter will highlight the study's main results.

Experimental samples of this study were prepared by combining sandblasting and polishing to produce smooth surfaces with randomly distributed dimples. In Fig. 16, the prepared surfaces are shown.

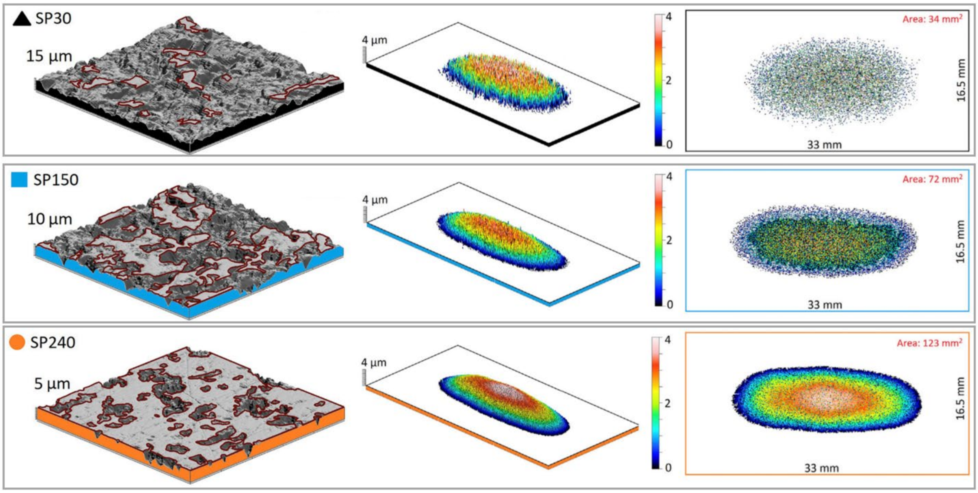

Fig. 16. Shotblasted samples. The 3D texture closeup (500 × 500 µm) is shown on the left. Sample virtually sliced surface parts at 4 µm from the highest point are shown in the middle. The projected surface areas of the sliced surface part are shown on the right [15].

Table 6 shows a calculated proportion of variance (RSQ) between the measured surface parameters and the coefficient of friction measurements from the oscillating tribometer. The closer the RSQ value gets to 1, the better the correlation between the compared parameters. For a graphic representation, RSQ values are prepared in a color scale, reaching from red (value 0) to yellow (value 0.5) and green (value 1). Red shades represent areas with low correlation, while green shades represent areas with high correlation. For more details, please see **Publication 6**.

Table 6 [15]

The proportion of variance (RSQ) between surface roughness/contact pressure and the measured coefficients of friction (COF) on the oscillating tribometer

Information about sample surface																			
Contact Pressure, [MPa]	Slicing depth, [μm]	SP30	SP150	SP240															
	1	13.18	17.57	2.93															
	2	5.27	3.10	0.99															
	3	2.64	1.29	0.60															
	4	1.55	0.73	0.43															
	5	0.99	0.49	0.34															
	6	0.69	0.36	0.28															
	7	0.52	0.29	0.24															
	8	0.41	0.24	0.21															
	10	0.28	0.18	0.17															
	12	0.21	0.15	0.14															
Texture parameters	Sa (R), μm	3.2	2.4	1.0															
	Sa (P), μm	1.7	1.1	0.4															
	Ssk (P)	-0.6	-1.2	-2.9															
	Sku (P)	3.0	3.8	12.0															
	Sds (P), pks/mm2	4272	5622	10881															
Oscillating tribometer tests																			
Velocity, [m/s]	incr./decr.	COF values			Contact Pressure VS COF, [RSQ]										Texture VS COF, [RSQ]				
0.02	Increase	0.079	0.028	0.014	0.18	0.91	0.98	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.76	0.89	0.70	0.52	0.64
0.04		0.057	0.023	0.014	0.17	0.90	0.98	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.75	0.88	0.70	0.52	0.63
0.10		0.045	0.024	0.015	0.25	0.95	1.00	0.99	0.99	0.99	0.98	0.98	0.96	0.95	0.83	0.94	0.78	0.61	0.72
0.15		0.041	0.023	0.016	0.23	0.94	1.00	1.00	1.00	0.99	0.99	0.98	0.97	0.95	0.81	0.93	0.76	0.59	0.70
0.19		0.043	0.028	0.023	0.20	0.93	0.99	1.00	1.00	1.00	0.99	0.99	0.98	0.97	0.79	0.91	0.74	0.56	0.67
0.29		0.029	0.019	0.017	0.14	0.88	0.97	0.99	1.00	1.00	1.00	1.00	1.00	0.99	0.71	0.85	0.66	0.47	0.59
0.39		0.033	0.020	0.016	0.19	0.92	0.99	1.00	1.00	1.00	1.00	0.99	0.98	0.97	0.78	0.90	0.72	0.54	0.66
0.29	Decrease	0.030	0.019	0.015	0.18	0.94	0.99	1.00	1.00	1.00	0.99	0.99	0.97	0.96	0.80	0.92	0.75	0.58	0.69
0.19		0.039	0.024	0.018	0.24	0.95	1.00	1.00	1.00	0.99	0.99	0.98	0.97	0.95	0.82	0.93	0.77	0.60	0.71
0.15		0.040	0.023	0.016	0.24	0.95	1.00	1.00	1.00	0.99	0.99	0.98	0.96	0.95	0.82	0.93	0.78	0.60	0.71
0.10		0.044	0.023	0.016	0.20	0.93	0.99	1.00	1.00	1.00	0.99	0.99	0.98	0.97	0.79	0.91	0.74	0.56	0.67
0.04		0.051	0.023	0.015	0.18	0.91	0.98	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.76	0.89	0.71	0.53	0.64
0.02		0.059	0.023	0.015	0.15	0.89	0.99	0.99	1.00	1.00	1.00	1.00	0.99	0.99	0.73	0.86	0.67	0.49	0.60

Obtained results proved that the new method of using the calculated contact area of the entire sliding body surface provides a better correlation between the surface geometry and friction on ice. A more detailed explanation of this can be found in **Publication 6** [15].

Microgeometry impact on coefficient of friction on ice

Experimental studies have proven that macrogeometry has a more significant role in the friction process, suggesting that optimizing this geometry component must be prioritized. However, the neglection of microgeometry components may cause a significant friction increase. This problem is explained in Publication 7. In this study, the sample surface area with ice was reduced by milling parallel grooves. During this machining process, material pile-ups formed on the edges of the grooves, as shown in Fig. 17 (top left). The pile-ups varied in height and were unsymmetrical on each ridge, extending 8 μm to 20 μm from the top surface. After milling the grooves, these samples were tested on an inclined plane tribometer, and their tribological performance was compared to a polished surface without grooves with a larger contact area with ice. From the previously discussed results, the grooved surface with a smaller contact area should slide faster, but experimental results showed that grooved surfaces had approximately 8 % slower sliding speed than the reference (see Fig. 17, bottom left). These results proved that focusing on macrogeometry without considering microgeometry will not provide the desired surface tribological performance.

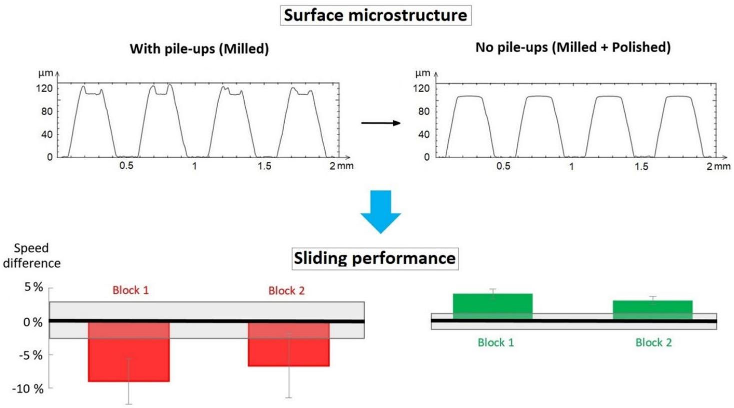

Fig. 17. The experimental sample profile directly after groove milling is shown in the top left side of the image, and the profile from the same surface location after additional repolishing is shown in the top right side. The sliding speed of the sample with pile-ups was slower relative to the polished, flat surface reference (a grey area in the graph) but faster when the pile-ups was removed by polishing [5].

After initial experiments, additional polishing was performed for the grooved samples. The polishing process removed the pile-ups, flattened, and rounded the edges. The groove width increased from about 0.175 mm to 0.190 mm, introducing a gentle rounding at the edge of each groove, as seen in Fig. 17 (top right). Polishing out the pile-ups removed the microscopic aspect and returned a nanoscopic roughness on the ridge surface to 13 nm.

Then these samples were tested one more time on the inclined plane tribometer. With the pile-ups removed, the sliding speed was approximately 4 % faster than the polished reference surface. Simply repolishing resulted in a 12 % difference in surface tribological performance. This significant sliding performance difference emphasized the influence of both microsized and macroscale contact areas on the sliding speed. A more detailed discussion of this can be found in **Publication 7** [5].

Sliding body surface temperature influence on friction on ice

It was already known that sliding body temperature significantly influences the sliding ability on the ice. Historically winter sports athletes used to heat their equipment before the competition to increase the ice surface melting, which in most cases resulted in better results. Because of the temperature's significant influence, preheating winter sports equipment in many sports is forbidden. For example, in bobsleigh, skeleton, and luge competitions, sleigh runner temperature is monitored before the start and cannot exceed the reference temperature.

What was not known was how specific changes in sliding object geometry at different temperatures influence friction properties. The question was whether one should increase the contact area with ice or reduce it depending on the ambient temperature and humidity, ice temperature, and sliding body temperature to improve sliding performance. Two practical experiments were conducted using samples with different contact areas at different temperatures. The ice temperature (–9 °C) was kept the same, but the sample temperature was first reduced to –18 °C, and during the second set of tests sample temperature was kept at +5 °C. See more details in **Publications 3, 4,** and **6** [4], [6], [15]. Figure 18 shows the coefficient of friction value differences at these test conditions.

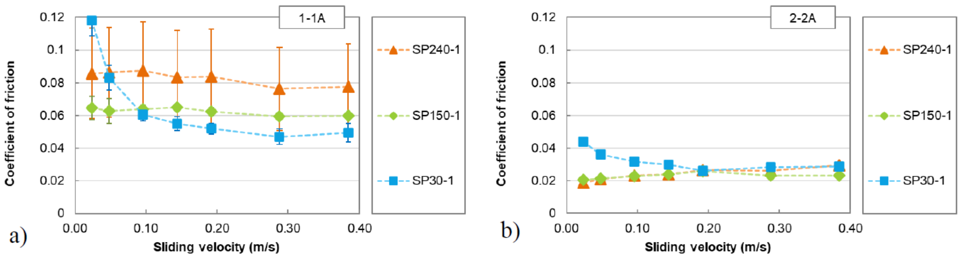

Fig. 18. Coefficient of friction measurements. a) For test setup 1-1A, where the sample temperature was –18 °C, the coefficient of friction decreased with sliding velocity increase, and friction was higher for samples with a larger contact area with ice. Also, it was noticed that the surface contact area significantly impacts the measured friction value. b) For test setup 2-2A, where the sample temperature was +5 °C, the overall friction value significantly decreased compared to test setup 1-1A, as logically predicted, but the influence of surface contact area is not as pronounced. However, it has an inverse effect on friction, as in test setup 1-1A, i.e., in this case, friction was higher for surfaces with smaller contact areas [4].

Obtained results highlight the overall surface temperature influence on sliding on ice and show that surface preparation might have an inverse effect on the process, so both parameters should be considered as a system to improve sliding on ice. These observations and the possibilities of new surface area measurements and thermal image recordings of the friction process might provide proof for surface temperature and contact area interaction explanation. Such a study is planned for the future.

CONCLUSIONS AND FUTURE OUTLOOK

The objective of the Doctoral Thesis was to develop a new methodology of sliding body surface macrogeometry and microgeometry measurements. The scientific literature review revealed that ice tribology studies never simultaneously considered sliding body surface macrogeometry (form) and microgeometry (waviness and roughness). According to previously known surface measurement methodologies, which considered only microgeometry, experimental sample surface area measurements included less than 2 % of the entire sliding body surface. Besides, sliding body surface macrogeometry was only considered in purely theoretical studies, which consider surface microgeometry ideally smooth. As a result, the sliding body surface contact area with ice cannot be determined. See **Publication 6**.

The objective of the Doctoral Thesis was achieved, and the main findings are the following:

1. A new methodology of sliding body surface macrogeometry and microgeometry measurements was developed. The new methodology contains measurements of sliding body surface form, waviness, and roughness components, which are further used in the sliding body surface and ice contact area determination. It was proved that the sliding body contact area with ice and coefficient of friction have a strong correlation (proportion of variance from 0.9 to 1). See **Publications 5**, **6**, and **7**.
2. The newly developed methodology of sliding body surface macrogeometry and microgeometry measurements allows for comparing the tribological performance of sliding body surfaces produced with various manufacturing methods, including abrasion, shot blasting, patterning with a milling or laser, chemical etching, and others. With the previously known methodology, tribological performance could be compared only for the samples manufactured with the same manufacturing method. See **Publication 5**.
3. It was proved that sliding body surface macrogeometry and microgeometry must be considered to ensure the previously specified coefficient of friction on ice. It was observed that sliding body surface macrogeometry (form) influences the contact area between the sliding body and ice. A study discussed in **Publication 5** proved that a 60 % increase in contact area reduced the sample average sliding speed by 7 %. However, microgeometry imperfections (high micro spikes and sharp edges) also influence the contact area. A study discussed in **Publication 7** proved that simple micro asperity removal from the sliding body surface could improve its average sliding speed by 12 %.
4. It was concluded that sliding body surface temperature must be considered during the coefficient of friction on ice determination. Experiments reported in **Publications 3** and **4**, with contact pressure between the sliding body surface and ice higher than 1 MPa, proved that for sliding body surfaces with temperature 9 °C below ice temperature, a reduction of contact area between the body and ice by 30 % reduced the coefficient of friction two times. However, if the sliding body surface temperature was 14 °C higher than the ice temperature, the same 30 % contact area reduction resulted in a two times higher coefficient of friction, inverting the surface texture influence trend. See **Publications 3** and **4.**

Considering the findings of the Doctoral Thesis, future research on surface texture influence on the coefficient of friction on ice should implement the new methodology of sliding body surface macrogeometry and microgeometry measurements along with thermal imaging recordings of the friction experiments. The combination of the sliding body surface geometry and thermal observations contains information for a better explanation of sliding surface interaction with ice. The developed methodology should be tested on different size and shape samples in various experimental settings not included in this Doctoral Thesis.

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