Friction

Review Article

Ice friction: A brief review of the influencing factors and experimental methods

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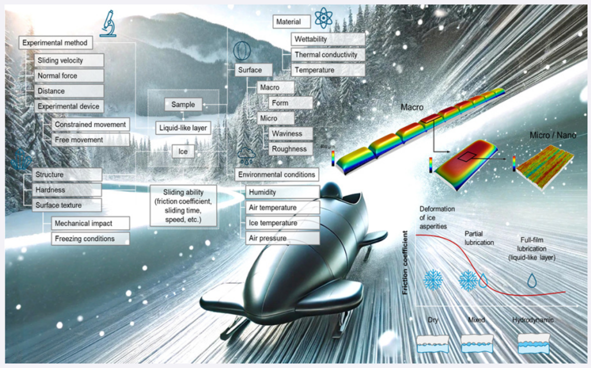
ABSTRACT: Ice friction is influenced by multiple interconnected parameters between the sliding body and ice, making it a challenging research area in tribology. The motivation for this review lies in the need to understand the parameters affecting ice friction and its relevance to the fields of sport, safety, and various industrial applications. The existing literature on ice friction only partially describes the test methods used. Thus, the comparability of the results and the drawing of conclusions are more challenging. This review addresses this issue by analyzing factors affecting ice friction, including properties of the ice, liquid-like layer, sliding body, and experimental methods. Small-scale rotary, linear, and large-scale laboratory and on-field setups are reviewed, and advantages and limitations are highlighted. The main results indicate that laboratory setups tend to provide more precise control over measurements but may not replicate real-world conditions. On the other hand, large-scale and on-field setups are closer to the actual conditions, but the control over experiments, reproducibility, and implementation is more challenging. The review concludes that future research should focus on comparing different test methods with the possibility of developing standardized protocols and improving large-scale experimental setups. The study aims to enhance the reliability of ice friction research and its practical applications, which should lead to improved safety and performance in the fields where ice friction plays a crucial role.



KEYWORDS: ice friction; test methods; sub-zero temperatures; on-field experiments

1 Introduction

Friction studies on ice can be considered one of the most complex friction systems due to several interacting parameters. Starting with the ice, its mechanical [1–3] and frictional properties [3–5] change significantly depending on the temperature. Therefore, it is essential to ensure stable experimental conditions. In this regard, the question of the heterogeneity of the ice surface, as well as the formation of micro-cracks, grains, and inclusions, which also change from experiment to experiment, remains relevant [1, 2]. Furthermore, depending on the friction system (sliding speed, applied load, contact area, etc.) and environmental factors, a liquid-like layer forms on the surface of the ice [3, 4], which significantly affects the friction on the ice but not linearly. Therefore, to reduce friction, the optimal conditions must be sought [5–7]. The next aspect is the specifics of the friction data acquisition equipment, which must have sufficiently high sensitivity because the friction coefficient approaches zero in ice friction studies. At the same time, the test setup must be insulated from external influences, as every additional noise affects the results. For fundamental research, a tribometer of relatively small size [8–10], which can be placed on a table in the laboratory, can be sufficient. However, by moving research closer to real-life applications, the need for equipment of a specific design and size increases, which accordingly requires the creation of relatively large rooms with climate control [11–13]. The question of sample size arises as well—smaller friction equipment condition limitations in sample size, but microscopical changes, e.g., in the texture of the sample surface or the material properties, can be detected more easily. On the other hand, using samples close to real-life dimensions, it is possible to more comprehensively analyze which parameters affect friction and to what extent—macrogeometry, microgeometry, material properties, experimental settings, environmental conditions, etc. Therefore, it is essential to understand what kind of ice friction research will be carried out to adapt the friction equipment according to the needs and possibilities.

Knowledge about ice friction is mainly applied in two fields—sport and safety. In ice sports such as ice hockey, speed skating [14, 15], luge, bobsleigh, and skeleton [16–19], reducing the friction coefficient allows faster movement on ice, which can

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contribute to athletes' competitive performance. On the safety side, an increase in the friction coefficient may even be vital under certain conditions, e.g., in tire manufacturing or shoe sole development [20–22]. This knowledge can also be helpful, for example, to prevent frost formation on aircraft wings, wind turbines, ships, etc. [23–26].

Although there are many theoretical and practical studies related to ice friction, each is unique in its own way, adapting the experimental conditions to a specific research object. The purpose of this review is to emphasize the influencing factors of the ice friction system and, by summarising the various experimental methods used in the known literature, compare and evaluate them to provide a framework for enhanced reliability of ice friction research.

2 Factors influencing ice friction

Ice friction can be described as the interaction of three variables—the sample sliding on ice, the ice, and the liquid-like layer that forms between the sample and ice. The sliding sample is affected by material properties and geometry. On the other hand, the properties of ice depend on the surrounding environmental conditions. The liquid-like layer formed between the sample and the ice is the most complex variable of this system. The thickness of the layer and, accordingly, the frictional properties are affected by the sliding sample, the ice, and environmental or ambient conditions, as well as the experimental parameters that define the tribological system. In Fig. 1, the ice friction influencing factors are schematically presented.

2.1 Ice

Ice crystals can form in one of 18 known water crystal structures depending on the freezing conditions (pressure, temperature, and freezing rate) or in an amorphous state. Amorphous ice is divided into three states depending on density and can be obtained by freezing ice quickly or under high pressure. Ice is mainly found in nature in the form of hexagonal crystals, or the hexagonal crystal form of ordinary ice, or frozen water (I_h) [28].

2.1.1 Ice composition

In the known literature, studies are mainly carried out with frozen saltwater [29–32] or freshwater [9, 33], depending on the objective. Saline water is characterized by its salt concentration or, depending on the location, where it is extracted. In the case of fresh water, tap or distilled water with a small admixture of tap water is used without characterizing the composition.

Sukhorukov and Marchenko [34] studied the sliding characteristics of steel and ice in the laboratory using a piston-type blank to which the ice was frozen. With a crushing machine, it was forced out of the cylinder. The study focused primarily on cylinders and pistons of different surface roughness but was carried out in salt and fresh water. The equipment did not give a precise value for the friction coefficient, but the force required to force the piston with ice out of the cylinder was observed to be higher for freshwater ice. The author explained that adding salt could work as an additional lubricant, reducing drag.

2.1.2 Ice texture

The texture of ice can affect the results of ice friction experiments. In most cases, ice replicas are used to analyze the texture of ice, and their two-dimensional (2D) roughness profiles are measured.

Bäurle et al. [35] made ice replicas to measure the roughness of the ice. A dimethyl siloxane polymer was used. Accordingly, the roughness of the replica was measured with a 2D profilometer. The average roughness (R_a) (arithmetic mean deviation of the profile), according to Baurle, was about 0.07 μm for smooth ice but about 0.3 μm for ice used, for example, in a bobsleigh track. Spagni et al. [9], similarly, made replicas of ice samples using a vinyl poly siloxane-based liquid thermo polymer. The roughness was measured with a 2D profilometer (Stylus), and an average R_a value of 0.1 μm was observed.

Ducret et al. [36] studied the wear of a polymer (ultra high molecular weight polyethylene (UHWMPE)) when sliding on ice. A more unconventional method was used to make silicone moulds with different topography in which the ice used in the experiments was frozen. The moulds were then surface-measured with an interferometer, and the average angle between the ice

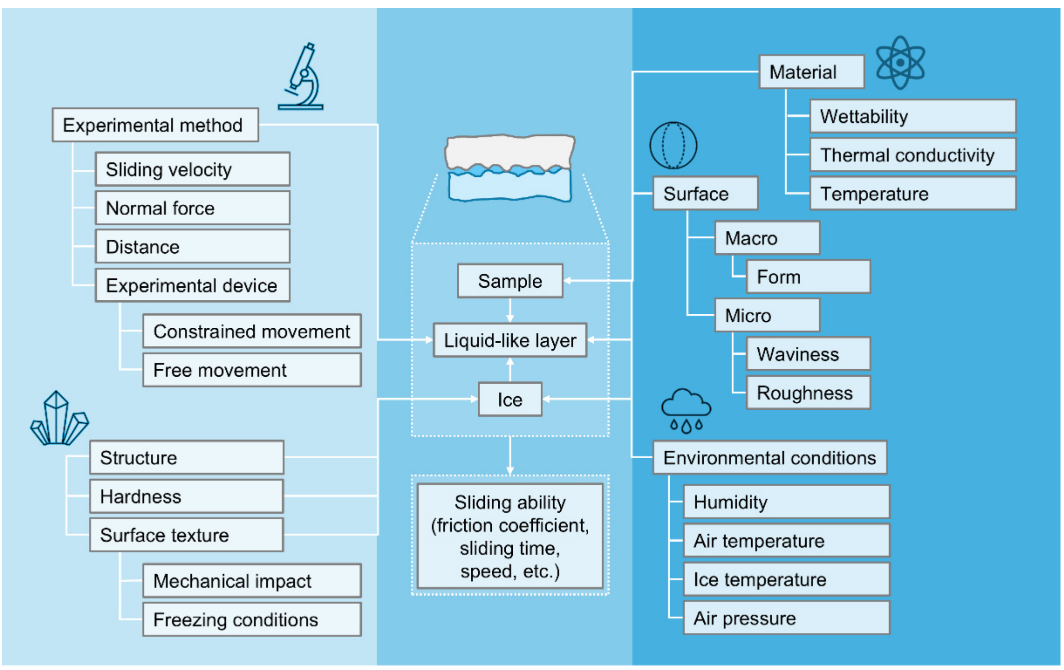

Fig. 1 Ice friction influencing factors [27].

roughness peaks and the sample on top was measured using three-dimensional (3D) surface texture measurement software. The measured angle was used as a roughness describing parameter—the smaller the angle, the smoother the surface.

Jansons et al. [37] used a different approach using a direct measurement method with a portable microscope to describe the ice surfaces and concluded that surface texture significantly impacts friction properties in laboratory and real-life conditions. It was emphasized that the experimental settings are essential; that is, if the weight of the sample is small (67 g) and no additional load is applied, the sample slides over the ice irregularities, and by reducing the ice contact surface, a lower friction coefficient can be obtained. However, if the weight of the sample is significant (95 kg), the opposite effect is observed because the sample is mechanically plowing in the unevenness of the ice.

2.1.3 Ice hardness

Barnes et al. [38] measured the hardness of ice on the ice surface in a climate simulation chamber. A compression apparatus was used where a metal ball was pressed on the ice surface for a specific time until it started to crack. The machine showed the pressure at the time of cracking. As a result, the authors proposed a model where the hardness of the ice depends on the contact time and temperature.

Poirier et al. [39] analyzed the Barnes model and concluded that it did not work under dynamic ice loads, so a different experiment was performed. Metal spheres of various sizes and weights were thrown from a height of 0.3 to 1.2 m onto the ice surface. The diameter of the footprint, or crater, left behind was measured to calculate the hardness of the ice. The ice hardness analysis was based on two assumptions: That the metal sphere is not deformed during the experiment and that the volume of the crater formed on the ice is proportional to the sphere's energy. The experiments were performed on three ice surfaces at the Canadian Olympic Park and the Calgary Olympic Oval. The obtained data show the dependence of ice hardness on ice temperature. In their work, Döppenschmidt and Butt [3] used a similar approach to confirm the data obtained by Poirier et al. [39].

2.2 Liquid-like layer

A water layer forms on the top of ice, making it slippery and playing an essential role in the processes associated with sliding on ice. Although there is still no consensus on what constitutes and how to define the water layer on the ice surface properly, several researchers have tried to describe it mainly using the concept of a liquid-like layer [5, 40, 41] or quasi-liquid layer [42–44], but generally, it is clear that a lubrication layer exists on the ice surface [3, 4]. Historically, three main theories have been distinguished as to how the water layer appears on the ice surface [5, 45]:

1) Pressure melting

For many years, the melting of the ice surface under pressure was thought to explain the low friction coefficient for ice. Water in liquid form is denser than ice and occupies about 10% less volume per mole. Consequently, based on Le Chatelier's principle, or the law of equilibrium, as the pressure increases, the ice begins to melt [4]. The melted water generates a slippery layer on top of the ice.

Bowden was the first to point out the flaws in this explanation [46], namely, pressure melting cannot be responsible for forming a thin film of water on the ice and making it slippery as this occurs even at very low pressures, e.g., under the shoes during walking. Colbeck [47] explained in his research why pressure melting would not be the cause of the low friction coefficient of ice. One of the main reasons is the high pressure required to melt the ice surface, which would lead the ice surface to crack. Furthermore, if the ice temperature is below −20 °C, based on the water phase diagram, a liquid-like layer theoretically cannot exist on the ice surface even at high pressures.

2) Surface melting

The melting of the ice surface, or the formation of a liquid-like layer from free water molecules on the ice surface, was described as early as Faraday's observations in the 19th century [5, 16, 48]. The layer exists on the ice independently of contact with another sample. Colbeck [49] and Makkonen [50] offered more evidence for the existence of this layer. The theoretical model for forming the liquid-like layer is based on the idea that ice molecules have free energy at the ice surface, hence creating a "transition layer" in the form of liquid water. The lowest temperatures at which the formation of the liquid-like layer was observed are between −30 and −40 °C, which consequently contradicts the theory discussed above [3, 4].

Several researchers have measured the thickness of the liquid-like layer on the ice surface using different methods. Still, the measured thickness has varied from 1 nm using X-ray scattering and a silicon surface to 100 nm using an atomic force microscope (Multimode NanoScope III, Digital Instruments, USA) at −5 °C ice temperature [3, 4]. Although it has been demonstrated that a liquid-like layer is present on the ice surface, the significant variation in thickness indicates that it is not appropriate to use a specific value.

3) Frictional heating

Bowden, as an alternative to pressure melting of ice [4–5, 48], proposed that ice heating during friction is the main reason for the low friction coefficient of ice. The heat generated by friction heats up the ice surface at the contact points. As the ice surface at the contact points melts, a thin film of water is formed which improves the sliding characteristics of the ice and the slider. Indeed, the heat is not fully utilized to melt the ice, heat is partly lost to the environment, surface deformation, etc., as well. Bowden points out that a slippery layer can become continuous if the ambient temperature is close to the melting temperature of the ice.

To prove experimentally that ice heats up by friction rather than pressure, Colbeck et al. [51] carried out a practical experiment using a thermocouple to measure the temperature of an ice skate. The temperature increased when the person in the experiment skated but decreased when they stopped. This way, it was experimentally proven that friction, not pressure, is the primary mechanism that heats the ice.

Following the generally accepted physical principles, friction regimes can be applied to ice friction based on the Stribeck curve principle [5, 6] by considering the liquid-like layer as the lubricating medium between the sliding surfaces (Fig. 2).

The graph can be divided into three friction regimes [5, 7]:

1) Dry or boundary friction

The liquid-like layer between the slider and the ice is very thin or non-existent. The temperature in the contact zone must be below the melting point, and the boundary layer must be less than the roughness of the sliding surface. The friction coefficient is very high, comparable to dry sliding on solid surfaces. This type of friction can be observed mainly at very low ice temperatures.

2) Mixed friction

At some contact points, the temperature of the ice surface is higher than the melting temperature, but the sliding surface's roughness is higher than the thickness of the liquid-like layer. In this case, the sample is partially supported by the ice surface asperities and partially by the liquid-like layer.

3) Hydrodynamic friction

The ice surface temperature in the contact zones is above the melting temperature, and the liquid-like layer is thicker than the height of the asperities. In this case, the sample is supported by the liquid-like layer only.

The thickness of the liquid-like layer affects the friction coefficient between the slider and the ice. As the layer thickness increases, the friction coefficient decreases, shifting the friction regime from boundary to mixed and hydrodynamic until an optimum liquid-like layer thickness is reached (Fig. 2). The transition between mixed and hydrodynamic friction regimes is considered to provide the optimum conditions [5, 7, 9, 36] to ensure the lowest friction coefficient. The thickness of the liquid-like layer is sufficient to ensure a low friction coefficient but, at the same time, not too thick to create additional drag. In hydrodynamic friction, where contact is only supported by the layer, the friction coefficient increases due to viscous friction [2, 5, 7].

2.3 Ice friction models

Many different parameters affect the ice friction process. Moreover, the mutual dependence of parameters on each other in different ice friction regimes, as well as the inclusion of parameters that cannot be measured or determined experimentally, makes creating a theory a very demanding task. Several authors [8–9, 52–59] have tried to develop and model the theory of ice friction with varying success.

One of the most well-known and practically applicable theories of ice friction nowadays was presented by Makkonen and Tikanmäki [53]. The ice friction model is derived from the theories of Evans et al. [52] and Oksanen and Keinonen [57]. By using modern technologies and conducting experimental research on ice with greater accuracy, Makkonen created a mathematical model that very accurately describes the experimentally observed phenomena in the study of ice friction.

Makkonen offers three regimes (Fig. 3) in the friction model:

(1) Friction, which is mainly controlled by the surface energy production at the nanoscale. This option is offered when the ice temperature is far below the melting temperature, at least −20 °C. The friction coefficient is assumed to be independent of the sliding velocity.

(2) Friction, which is mainly controlled by thermal conductivity. In this case, there is a minimal difference between the melting and the ice temperatures (up to −2 °C). In such a regime, it is proposed that the friction coefficient μ is approximately proportional to $1/\sqrt{V}$.

(3) Friction, controlled mainly by ice melting and water viscosity. In this case, there is a more significant difference between the melting and the ice temperatures than in the abovementioned regime, but less than in regime No. 1 (−2 to −20 °C). In this regime, the friction coefficient μ is approximately proportional to $\sqrt{V}$.

Böttcher et al. [54] using the Makkonen ice friction model, offered a solution to calculate the contact between the sample and the ice using the principles of the Hertz [60] contact model. They compared the calculated values of the friction coefficient with the measured ones and concluded that the trends are similar, but the values differ by a factor of about 2.5.

Lozowski et al. [18, 55, 56] developed separate models for calculating the friction coefficient, considering the contact geometry's peculiarities, for such sports as skeleton, bobsled, and speed skating. In the models, it was assumed that the contact is in the hydrodynamic regime. The surface of the sliding sample and the ice roughness are not considered. In the model proposed by Lozowski, macro geometry plays a significant role in the contact length and width, and even though the models are similar, each one is adapted to a specific sport, including particular parameters. Experimentally, the geometry of the contact, as well as the thickness of the liquid-like layer, are practically impossible to measure.

By comparing the theories of Makkonen and Tikanmäki [53] and Lozowski et al. [55] at a sliding speed of 10 m/s and three different ice temperatures (−40, −20, and −10 °C), the friction coefficient values varied up to two times at one setting.

Considering that the friction between the sample and the ice is affected by many different factors and the interrelationships are challenging to define, analytical models can be used. Statistical methods of correlation detection can be used to determine

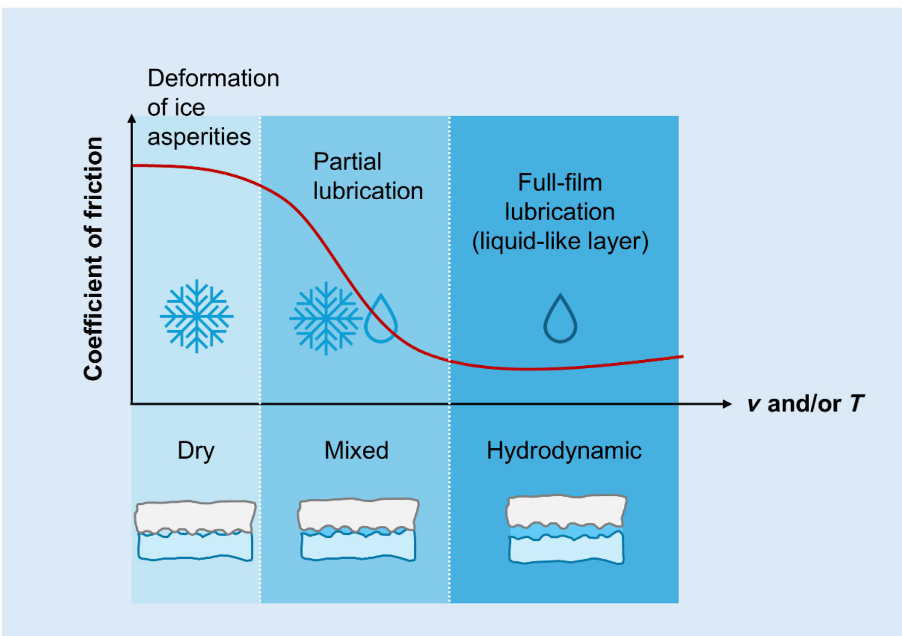

Fig. 2 Effect of liquid-like layer thickness on friction coefficient. Reproduced with permission from Ref. [6], © the authors 2019.

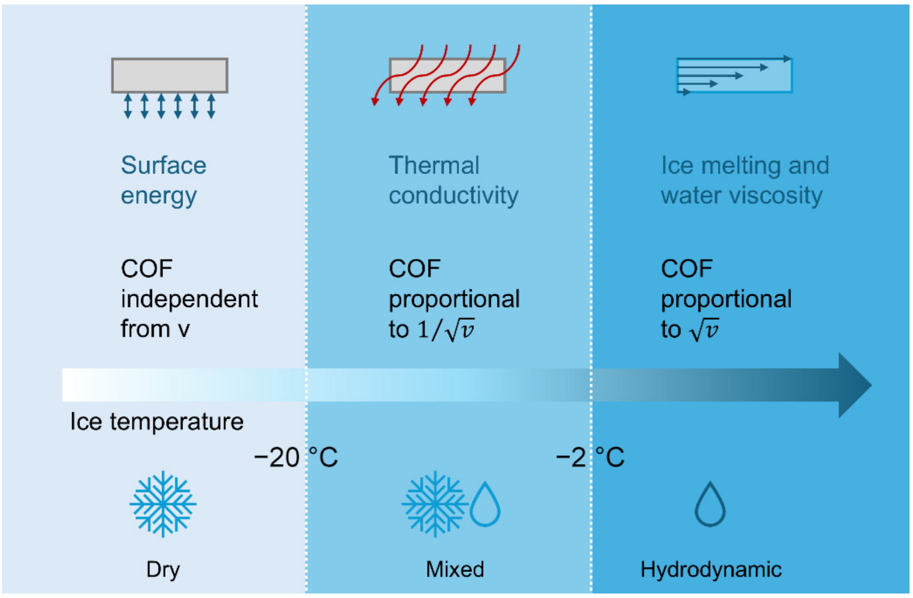

Fig. 3 Makkonen and Tikanmäki [53] proposed friction regimes.

regularities between the parameters. Thus, to study the quantitative relationships between variables [61–63], regression analysis was used in the work of Akkok et al. [64]. The parameters affecting the friction between metal, glass, nylon, and ice were determined and analyzed. The experiments were performed at a temperature of −20 °C with a rotary tribometer in the speed range from 0.05 to 5 m/s under three different loads (30, 75, and 150 N). Akkok described the obtained results with a multivariate regression analysis, thereby obtaining relationships between the influencing factors (sliding speed, load, thermal conductivity, density, heat capacity, and the difference between the maximum allowable surface temperature of the sample in contact with ice and the temperature of the sample before contact). Using the regression model, Akkok concluded that the material properties, in this case, have little influence on the friction coefficient. The most considerable effect was observed for the temperature difference. Applied load and sliding speed showed similar effects on the friction coefficient.

2.4 Experimental sample or slider

Experimental samples in different ice friction pairs can mainly vary in terms of material properties and geometry.

1) Material properties

If different materials are compared, the properties of the selected material should be considered. Researchers in the known literature associated with ice friction generally use thermal conductivity, hydrophobicity, or wettability properties to describe the material properties.

The influence of the material's thermal conductivity on sliding on ice is difficult to analyze due to other differences in the properties of such materials, e.g., hydrophobicity, hardness, etc. Although Akkok et al. [64] concluded that material properties have relatively little effect on the friction coefficient, the thermal conductivity of the material is mainly included as one of the influencing parameters in mathematical models [5, 53, 56]. Kietzig et al. [65] tested 14 different materials to analyze how thermal conductivity affects sliding on ice, concluding that as speed increases, the effect of material thermal conductivity on sliding properties decreases. Low thermal conductivity in the dry friction regime and at low speeds showed the most significant impact on the reduction of friction coefficient. This could be explained by the fact that in the dry or boundary friction regime, the temperature of the material is higher than that of the ice surface. Materials with low thermal conductivity do not cool down as quickly as materials with higher thermal conductivity. Therefore, when a warmer material slides over the ice surface, it tends to generate a thicker liquid-like layer, reducing the friction coefficient. However, to verify this effect, the influence of other material properties should be considered as well.

Material hydrophobicity or wettability properties were analyzed in experiments by Kietzig et al. [66]. The sample surface was treated with a laser, to obtain hydrophobic properties (contact angle before treatment (84°), after (128°)). The results showed differences in the friction coefficient at relatively warm ice temperatures of (−1.5 °C) conditions. As the sliding speed increased above 0.5 m/s, the surface of the laser-treated hydrophobic sample showed a lower friction coefficient than the surface before laser treatment. This was explained by the lower effect of capillary forces under warm conditions on the laser-treated sample compared to the untreated sample. Maggiore et al. [10] treated stainless steel samples with a laser, increasing the contact angle from about 80° to 130°. In friction tests against snow, a significant decrease in the friction coefficient was observed for the laser-treated samples as well.

2) Macro and microgeometry

Although in ice friction studies, slider surfaces are typically characterized by surface texture amplitude parameters [8, 9, 67]. Recently, the sample surfaces have been also analyzed at the macroscopic level [36, 54, 68] or using texture parameters characterizing the entire surface [69, 70]. Thus, the information is obtained not just for a specific surface area, but the entire surface (Fig. 4).

Gross et al. [68] emphasized that ice friction is affected by the macroscopic and microscopic characteristics of the slider surface. Using grooved stainless steel samples, it was proven that reducing the macroscopic contact area within certain limits can result in a lower friction coefficient. However, microscopic pileups, although in theory reduce the contact area, have the opposite effect on the friction properties due to the plowing inside the ice surface.

Kietzig et al. [66] created samples with similar roughness but different processing traces—concentric and random. The experimental results showed that the samples with concentric

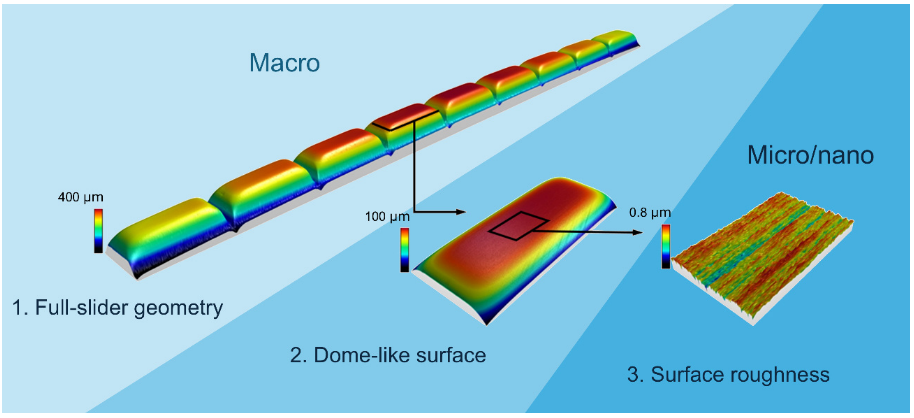

Fig. 4 Surface texture analysis on three levels.

machining in the sliding direction have a lower friction coefficient at low speeds (up to 0.1 m/s) than those with random machining traces. Böttcher et al. [54] produced specimens with grooves parallel to the sliding direction. A lower friction coefficient was obtained for specimens with fewer grooves (greater distance between grooves). Kim et al. [71] experimented with silicone samples, creating a rectilinear texture with spacings between them. Similar to Böttcher's work, the experiments showed a lower friction coefficient for samples with more considerable distances between the formations on the surface. Experiments were carried out using the same samples with the formations perpendicular and parallel to the sliding direction. At warmer ice temperatures (−8 to −2 °C), the samples with surface texture perpendicular to the sliding direction showed a lower friction coefficient.

A study comparing samples with different surface textures using shot blasting, sandpaper scratching, milling, and polishing was carried out in the work of Jansons et al. [69]. The results showed that the bearing ratio between the slider and the ice significantly influences the sliding parameters: Friction decreases with a decrease in the bearing ratio. However, two critical factors have to be taken into account: (1) relatively light samples (~68 g) were tested without any imposed motion, which means that the surface texture of the samples was not in close contact with the ice surface, causing no additional friction; (2) the direction of the milled grooves and scratches on the samples was parallel to the sliding direction, therefore creating samples with the same processing technology but perpendicular to the sliding direction, could increase friction.

2.5 Environmental conditions

To adequately describe the friction process between steel and ice, environmental conditions must also be considered. Jansons et al. [72] emphasized a critical issue related to describing the experiment's environmental conditions. They noticed that in the works of various authors, ice temperature was predominantly used as a descriptor of environmental or ambient conditions (88% of viewed papers) due to its direct effect on the ice hardness. Air temperature was predominantly used as a secondary descriptor of the environmental conditions (in 50% of the reviewed papers). Humidity was rarely considered or mentioned in publications (only in 19% of viewed papers). Jansons emphasized that the interplay between air temperature, ice temperature, and air humidity determines the friction properties on ice and should, therefore, always be considered in the experiments.

Kietzig et al. [5] and Calabrese et al. [73] studied the effect of humidity on the friction coefficient of a stainless steel-ice friction pair at −29 °C and found that higher humidity reduces the friction coefficient. Humidity is the concentration of water vapour in the air, therefore water vapour in the air increases with humidity. Since air is in contact with the sample surfaces and the liquid-like layer, water vapour molecules in the air tend to mix with water molecules in the liquid-like layer due to intermolecular hydrogen bonding [74]. Given this aspect and the study by Calabrese, air humidity should influence the thickness of the liquid-like layer and thus, the sliding of the sample on the ice.

Kietzig et al. [5] summarized the friction coefficient measurements performed at different ice temperatures by different authors and concluded that the optimum friction coefficient values occur in correspondence with the Stribeck curve (Fig. 2). Kim et al. [71] observed a similar trend, i.e., that the friction coefficient decreases until the optimum value is reached (depending on the surface texture of the samples (−10 to −4 °C)) and then increases again.

3 Experimental methods for measuring ice friction

Ice friction experiments have been conducted under controlled laboratory conditions and in real-life or on-field experiments. The most common friction pairs are steel–ice, polymer–ice, and rubber–ice.

In laboratories, different equipment is used—rotational [8–10, 20, 35, 75, 76] or linear tribometers [6, 22, 36, 69, 72, 77, 78, 78–80], rheometers [66, 80–81], large-scale tribometers [11–13, 33, 82]. In on-field experiments [14, 16–17, 47, 72, 83, 84], the experimental samples are usually real-sized, and the experiments are conducted under real-life conditions.

Table 1 contains information on the use of the ice friction equipment described in this chapter, along with the friction pairs, the environmental conditions and the results obtained.

3.1 Small-scale test methods

In laboratories, rotating or linear-type tribometers are mainly used (Fig. 5). Usually, the experiment stage is enclosed in a sealed housing, which enables a variety of stable and controlled ambient conditions.

3.1.1 Rotary-type tribometers

Spagni et al. [9] used a rotating tribometer enclosed in a thermally insulated chamber with an applied constant load (15 N) to analyze the friction coefficient at low velocities (0.025–1 m/s, or 80–800 r/min). Sand-blasted and polished stainless steel discs with different R_a (0.1, 1.4, and 2.6 μm) were used as isotropic experimental samples. The experiments were conducted at five

Table 1 Overview of experimental setups, applied parameters, and outcome of various ice friction studies

Experimental setup	Sliding speed (m/s)	Applied load (N)	Used samples	Environmental condition control	Outcome	Reported friction coefficient (COF) range
Experiments under laboratory conditions: rotary-type						
Pin-on-disc UMT3-CETR tribometer (Spagni et al. [9])	0.03–1	15	Sandblasted stainless steel pins with different roughness	Thermally insulated chamber. Air temperature −17 to −2° C (min. −25 °C) controlled by a cold, dry airflow. No information about ice temperature and humidity.	Surface texture influences the tribological friction regime. Results are comparable to the Stribeck curve. Roughness has a lower influence on the friction coefficient at higher velocity.	0.02–0.11
Custom made Pin-on-disc tribometer (Scherge et al. [8])	1–65	0.5	ϕ3 mm stainless steel pins with R_a 34 nm	Tribometer chamber. Ice temperature −17 to −6 °C. No information about air temperature and humidity.	An endoscopic camera is used to record the friction process. Data comparable to the Stribeck curve. Measured data have a reasonable correlation with the Makkonen model.	0.01–0.09
Custom made Pin-on-disc tribometer (Higgins et al. [75])	0.003–2.6	2	Rubber substrate	The tribometer was placed in a cold chamber. Air temperature ranges from −33 to −1 °C. No information about ice temperature and humidity.	Ice-rubber friction map produced, depending on velocities and temperature. High velocities, lower friction. At high temperatures and velocities, the ice, rather than the rubber, is dominant in determining the friction.	0.1–0.9
Custom made ϕ1.8 m tribometer (Bäurle et al. [35, 76])	0.5–20	20–100	Polyethylene samples 40 mm × 40 mm × 9 mm	Cold chamber with air temperature range (−20)–1 °C. Thermocouples and IR are used to measure ice temperature. No information about humidity.	IR is used to measure the ice temperature. The main factors influencing friction are the thickness of the liquid-like layer and the actual contact area. Dry friction and hydrodynamic approach are used to explain friction and contact temperatures.	0.04–0.11
Custom made Tribometer with a styrofoam container (Maggiore et al. [10])	1–9	7	Laser-treated 50 mm × 50 mm steel samples and UHMWPE as a reference	Tests were performed at +15 °C ambient temperature and a relative humidity of 50%. Snow temperature (−15)–(−5) °C. Air temperature above track 0.2 °C.	Laser-treated samples showed a lower friction coefficient than bare stainless steel samples. Contact angle increased by laser treatment.	0.04–0.11
Rheometer Physica MCR 501 using a modified parallel-plate geometry (Kietzig et al. [66])	0.005–1.4	3	Steel alloy samples in the shape of rings with an outside and inside diameter of 25.4 and 23.4, respectively, and 1 mm thickness with different surface roughness	Parallel plates are enclosed in an environmental chamber. Air temperature −15 to −1 °C (min. −150 °C). No information about ice temperature and humidity.	3D plot of temperature and velocity dependence of the friction coefficient. Hydrophobicity reduces friction. Capillary bridges play an important role in the friction force. Orientation of the scratches and grooves in the sliding direction decreases friction under boundary conditions. Results are comparable to the Stribeck curve.	0.01–0.15
Rheometer Anton Paar, DSR 502, with clamped spherical sliders (Liefferink et al. [80])	0–1	0–5	Different material, roughness spheres with radius varying from 0.75 to 22 mm	Thermally isolated setup. Air temperature (−110)–0 °C. No information about ice temperature and humidity.	Friction depends on the contact regime and elastic or plastic deformation. If the contact is elastic, friction is linked to a liquid-like layer. If the contact is plastic, friction is set by the amount of plowing. Temperature, pressure, and velocity have an important impact on friction.	0.01–0.7
Custom-made rotating tribometer with control of both sample and ice (Hemette [20])	0–1	0–50	Rubber sphere (R = 15.5 mm) against ice disk	Thermally isolated tribometer. Air temperature sensors were placed in the chamber. Tests at −25 to −2.5 °C. No information about ice temperature and humidity.	Simultaneous evolution of the contact during the friction process. Ice disk and rubber sphere rotate separately. Typical bell-shaped curve for velocity-dependent friction behavior.	0.1–1.5
Rheometer Anton Paar MCR 302 with a pin on disk fixture and three points of contact (Martinsen et al. [81])	0–1	1	Polymeric coatings	Ice disk cooled with Peltier cooling plate. Cooling hood to maintain conditions. Ice and air temperature −10 °C. No information about humidity.	Friction as a function of sliding velocity. Comparability with the Stribeck curve. Different coatings were analyzed.	0.01–0.4
Experiments under laboratory conditions: linear-type						
Custom-made 1.6 m long linear tribometer (Böttcher et al. [54])	1	40–80	UHMWPE Ski base sample 65 mm × 40 mm with different textures	Box-shaped freezer. Air temperature −10 to −2 ° C (min. −20 °C). Thermocouples are used to measure ice temperature. No information about humidity.	Measured data correlate well with the improved Makkonen and Tikanmäki [53] model in relation to the contact area.	0.02–0.05

(Continued)

Experimental setup	Sliding speed (m/s)	Applied load (N)	Used samples	Environmental condition control	Outcome	Reported friction coefficient (COF) range
Custom-made 0.1 m long liner tribometer (Ducret et al. [36])	0.003	10	UHMWPE samples 13 mm × 13 mm with different roughness	Friction test in hermetic enclosure air temperature 20–+30 °C. No information about ice temperature and humidity.	Friction measurements are made on ice surfaces with different textures. Analyzed wear behavior of UHMWPE on ice.	0.04–0.18
Custom-made 1 m long reciprocating linear tribometer (Marmo et al. [77])	0.008–0.37	2.1–4.2	Steel sheet 1000 mm × 100 mm × 2 mm	The tribometer located in the chest freezer is −27 to −0.5 °C. Ice temperature is the same as air temperature. The temperature was set to −27 °C, and the freezer was turned off during the experiments. No information about humidity.	Ice hemispheres were tested on the steel substrate. Friction and wear data were observed, and an ice-on-steel friction map and observation method using LT-SEM were developed.	0.05–0.15
Linear-type friction tester MXD-02, Labthink (Kim et al. [71])	0.003	0–5	Micro-line patterned square silicon wafers 35 mm × 35 mm	Experiments were performed inside a temperature control chamber. Ice temperature of −17.7 to −2.5 °C. No information about air temperature and humidity.	Line-patterned surfaces were investigated. Longer gaps lead to smaller COF. Opposite trends were observed for parallel and perpendicular patterned surfaces at different ice friction regimes.	0.02–0.08
In-house built linear friction tester (Tuononen et al. [78])	0.5	1.3	Rubber block 25 mm × 25 mm	Tribometer located in a climate chamber. Air temperature of −5 °C. No information about ice temperature and humidity.	After each test run, ice surface topography was measured. Rubber scratched the ice surface. Short sliding distances can convert high-friction ice to slippery ice.	0.1–1
Custom made Linear friction tester (Tada et al. [79])	0–0.01	240	Tire tread rubber block 60 mm × 20 mm	Tribometer is located in the freezer. Air temperature of −38 to −2 °C. No information about ice temperature and humidity.	Ice friction is divided into two friction regimes: where a liquid-like layer occurs and where it does not.	0.05–1
Custom made Linear friction tester (Lahayne et al. [22])	0.65	0.15–0.45 MPa	Different rubber tread compound blocks	Air temperature from −13 to −5 °C.	Different rubber compounds lead to varying dependencies on the friction coefficient.	0.05–0.25
Modular oscillating tribometer RVM1000 (Velkavrh et al. [6])	0–0.38	52	Stainless steel samples (35 mm × 18 mm × 14 mm) with different roughness	A modular oscillating tribometer is equipped with an insulated test chamber. Control and measurements of air temperature (4–8 °C), ice temperature (−8 °C), and relative humidity (25%–75%).	Isotropic steel samples with higher roughness provided lower friction. Proposed explanation based on friction regimes.	0.02–0.25
Custom-made belt-type tribometer (Lutz et al. [90])	0–28	40–140	Ice samples (160 mm × 100 mm; 330 mm × 100 mm) against UHMWPE ski base	The tribometer is located in the cooling cell. Ambient temperature (−19 to −4 °C) and humidity recorded.	Custom-made tribometer validated and used for ski materials testing.	0.03–0.04
Custom-made 3 m long inclined track tribometer (Jansons et al. [69])	0–3.7	0.7	Stainless steel samples (35 mm × 18 mm × 14 mm) with differently prepared surfaces	The tribometer was installed in the climate simulation chamber with an additional microclimate chamber. Control and measurements of air temperature ((−2.5)–1 °C), ice temperature (−9 to −4 °C), and relative humidity (60%–80%).	Sliding speed is used as friction describing parameter. Under low-pressure conditions, the bearing ratio was used to describe the surface texture parameters.	—
Experiments under laboratory conditions: large-scale						
Custom made ϕ3.8 m tribometer (Scherge et al. [33])	2.8–28	100– 500	Stainless steel runners 150 mm × 20 mm × 8 mm with two different radii	Test cell with air temperature control. Air temperature was set to −5 °C at the cooling stage. No information about ice temperature and humidity.	High-speed tribometer was used, and an ultra-low friction coefficient was observed. Friction depends on the contact pressure.	0.01–0.03
4 m long linear tribometer. No information about producer (Klapproth et al. [82])	1–5	0.1–0.5	Rubber blocks with a nominal area of 1 mm^2	Ice temperature (−8 to −1 °C).	The theoretical model compared to experimental results—qualitative agreement.	0.05–0.6
Custom-made 24 m long linear type tribometer (Rohm et al. [67])	0.1–12	50–150	Steel skis with different roughness 487.5 mm × 30 mm × 30 mm	The tribometer is located inside a cold room with additional ice/snow surface cooling. Snow temperature (−12 to −3 °C); air temperature (−10 to −2 °C); relative humidity (~80%).	Each test was conducted on freshly produced snow. Close to the melting point, friction increased for smoother surfaces.	0.05–0.4

(Continued)

Experimental setup	Sliding speed (m/s)	Applied load (N)	Used samples	Environmental condition control	Outcome	Reported friction coefficient (COF) range
Custom-made 120 m long free gliding tribometer (Sandberg et al. [13])	0–12.5	300–1,275	Skis	The tribometer is mainly located inside the indoor snow test facility. Snow temperature (−8 °C); air temperature (−12 to −3 °C); relative humidity (~50%–90%).	Analysis of the constructed tribometer. A tribometer can be used outside. A run-in effect was observed as runs increased.	0.02
On-field experiments						
Frame with bobsled runners pushed on a flat and inclined surface (Poirier et al. [17])	1–10	1,200–1,900	Frame with 4 bobsled runners	Ice surface temperature (−5 to −2 °C). No information about air temperature and humidity.	Experiments were conducted at the hockey rink and bobsleigh push training facility. The sliding speed was measured with a radar gun.	0.004
Sled with skate blades launched on a hockey ice rink (Federolf et al. [83])	1–2	950–2,200	Constructed aluminum sled with mounted skate blades	A device installed in an ice hockey rink. Air temperature 14–16 °C; ice temperature −6 to −5 °C; relative humidity 17%–26%.	The sled was launched from the propulsion unit, and the timing gates were fixed at a fixed distance. Different skate blades compared.	0.004–0.01
Speed skater on skates (de Koning et al. [14])	4–11	710	Instrumented skates with built-in transducers	Speed skating ice rinks. Air temperature 12 °C; ice temperature (−11)–1.8 °C; relative humidity 55%.	Experiments were carried out on three speed-skating ice rinks. Friction coefficient increases with speed.	0.003–0.007
Speed skater on skates (Colbeck et al. [51])	0.4–1.2	?	Skate with a thermocouple	Tests were performed indoors and outdoors. Ice temperature −13.5 to −2.5 °C. No information about air temperature and humidity.	Direct skate temperature measurements showed that the dominant mechanism in ice friction is frictional heating.	—
24 m long ice-track (Jansons et al. [72])	0–9	932	Skeleton with different runners' surface roughness	Tests were performed in an enclosed ice track. Air temperature (−11)–10 °C; ice temperature −11 to −2 °C; relative humidity 60%–95%.	Ice temperature influences ice friction more than the applied load and surface roughness. Sliding speed is used as a friction-describing parameter.	—

different air temperatures controlled by a cold, dry airflow, assuming that the ice temperature corresponds to the air temperature (−17, −13, −10, −6, and −2 °C). As a result, it was found that the friction coefficient decreases with increasing velocity (friction coefficient lower than 0.02 at 1 m/s). Furthermore, at −6 °C, the rougher samples showed a similar friction coefficient (~0.02) as the smoothest sample. This phenomenon was explained by the influence of surface morphology on the ice friction regime of the system: In the dry friction regime, higher roughness leads to a higher friction coefficient, but at higher velocities where a thicker liquid-like layer forms, the influence of surface roughness on the friction coefficient is not as pronounced anymore. The effect of temperature in the experiments showed a negligible impact on the friction coefficient. The authors suggest this could be because, in the experiments, the sample slid along the same path. Thus, due to heating by friction, the ice surface and the sample warmed up until equilibrium was reached.

Scherge et al. [8] analyzed the friction coefficient of a disc-shaped sample (ϕ3 mm; R_a 0.03 μm) at three different ice temperatures (−17, −10, and −6 °C) with a custom-made micro-tribometer (ϕ30 mm) and compared the results with calculated values using the Makkonen and Tikanmäki [53] theoretical ice friction model. The experiments were carried out at sliding velocities between 1 and 65 m/s with an applied load of 500 mN. It was shown that at all three ice temperatures, the friction coefficient decreased with increasing sliding velocity up to ~25 m/s (friction coefficient ~0.01). An exception was observed at the ice temperature of −6 °C: As the velocity increased further, the friction coefficient started to increase reaching values above 0.02. This could be due to the hydrodynamic friction regime, i.e., at ~45 m/s, the liquid-like layer between the ice and the sample is so thick that the friction coefficient tends to increase due to viscous drag [5].

The experiments of Kietzig et al. [66] were carried out with a commercial rheometer using a modified parallel-plate geometry enclosed in an environmental chamber. Different stainless steel samples with an outside diameter of ϕ25.4 mm and an inside diameter of ϕ23.4 mm were used in the experiments. The surfaces were randomly polished, ensuring R_a 0.6 μm. The applied force was kept constant at 3 N, and the velocity ranged between 0.2 and 1.4 m/s. As a result, a 3D plot was obtained showing the dependence of the friction coefficient on the sliding velocity and temperature. It was observed that the friction coefficient decreases with increasing sliding velocity. The lowest friction coefficient (~0.02) was achieved at an ice temperature of −4 °C. The friction coefficient increases with decreasing temperature, which the authors attribute to a decrease in the liquid-like layer. For temperatures above −4 °C, an increase in the friction coefficient was also observed, which could be due to the formation of capillary bridges between the sample and the ice. Kietzig et al. [66] also investigated the hydrophobicity and orientation of scratches on the surface and concluded that the hydrophobicity of the slider material reduces friction in mixed and hydrodynamic friction regimes. The scratches or grooves in the sliding direction can also reduce friction, especially in dry friction regime.

Liefferink et al. [80] studied how temperature, contact pressure, and sliding velocity affect friction between spherical sliders of

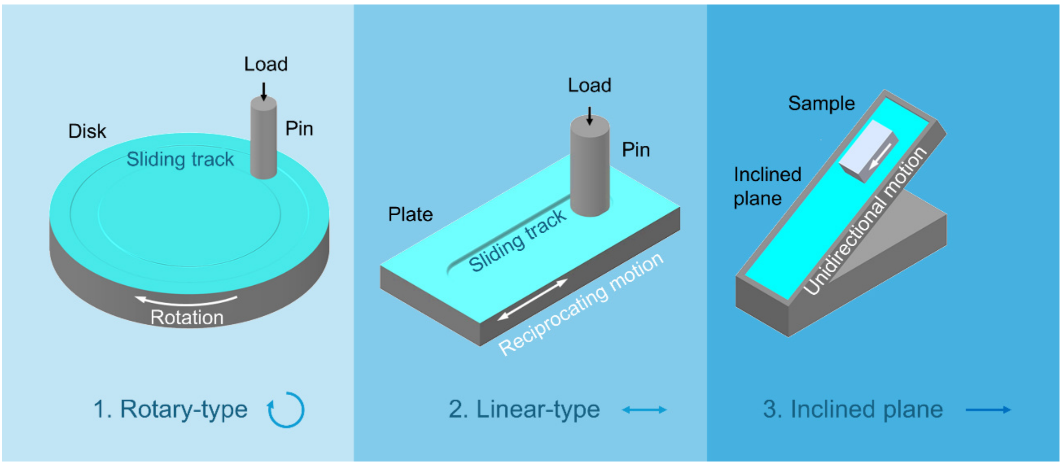

Fig. 5 Sketch of (a) rotary-type tribometers, (b) linear-type tribometers, and (c) inclined plane tribometers.

different materials and ice using a commercial rheometer. The setup was thermally isolated and cooled down to −110 °C with liquid nitrogen or a coolant liquid. It was concluded that temperature, pressure, and sliding velocity each play a crucial role in ice friction, primarily affecting the hardness of ice. The geometry and texture of the slider determine the contact pressure. If the contact of the slider and ice is mainly elastic, friction can be linked to the liquid-like layer, but if the contact is primarily plastic, then as the contact pressure approaches ice hardness, plowing friction dominates. If friction coefficient as a function of the ice temperature is analyzed, it was observed that for different slider materials (silicon carbide; stainless steel) and geometry (radius 0.75; 6 mm, R_a 0.14 μm; dimensions 22 mm × 1.7 mm × 5 mm, R_a 0.9 μm), the trend remains similar over the temperature range of −110–0 °C at the same sliding velocity (0.38 m/s) and applied load (2.5 N). Far from the melting point, the friction coefficient follows the Arrhenius temperature behavior. Still, as the temperature approaches the melting point, the friction coefficient rises rapidly due to the plowing through the ice.

Bäurle et al. [76] experimented with sliding ski-base polyethene block samples (40 mm × 40 mm × 9 mm) on ice using a ϕ1.8 m rotating tribometer placed in a climate simulation chamber within an accessible temperature range from −20 to +1 °C. The ice temperature was measured with infrared (IR) sensors, and an IR camera was used to take images of the track behind the slider. The velocity varied from 0.5 to 20 m/s, and the applied load ranged from 20 to 100 N. In the experiments, Baurle showed that the contact area influences the friction coefficient: The smaller the contact area, the lower the friction coefficient. It was concluded that the main factors influencing ice friction are the real contact area and liquid-like layer varying over more than an order of magnitude, depending mostly on temperature and velocity. Theoretical models at low temperatures (air temperature ⩽ −10 °C), intermediate temperatures (−10 °C < air temperature ⩽ −1 °C), and temperatures close to the melting point (air temperature > −1 °C) as well as the experimental part and liquid-like layer dependence from several interrelated factors indicated a significant effect of real contact area and liquid-like layer on the friction coefficient on ice.

Maggiore et al. [10] modified 50 mm × 50 mm stainless steel samples using a commercial Yb:KGW laser system and compared them to stone-grinded ultra-high molecular weight polyethylene (UHMWPE) as a reference. The friction experiments were carried out with a custom-built tribometer, and instead of ice, a snow surface was used. All tests were performed at +15 °C air temperature, relative humidity 50%, and initial snow temperature was set to −15 or −10 °C depending on the duration of the test. The applied load was 7 N, and the sliding velocity changed from 1 to 9 m/s. Contact angle measurements for laser-treated laser-induced periodic surface structures (LIPSS) surfaces showed an increase in values similar to the UHMWPE reference (~130°) if compared to the bare stainless steel sample (~80°). A decrease in friction for laser-treated or hydrophobic samples was observed as well, which corresponds to the results of Rohm et al. [67], although the UHMWPE reference sample showed the lowest friction values. Friction coefficient values increased as the sliding velocity increased, especially for bare stainless steel samples. This could be explained by the fact that the tribometer was in relatively warm ambient conditions, and during the experiments, the thickness of the liquid-like layer increased significantly, especially for high sliding velocities.

Rubber-ice friction tests were conducted by Higgins et al. [75]. The pin-on-disc tribometer was placed in a cold chamber, and measurements were performed at the air temperature range from −33 to −1 °C. Ice hemispheres were used as pins and tested against the tire rubber substrate. The applied load was set to 2 N. As a result, a rubber/ice friction coefficient dependence on velocity (0–2.5 m/s) and a temperature map plot were created. It was concluded that low friction is observed at high velocities due to the increase in the liquid-like layer. However, a statement that at warmer ice temperatures (> −7 °C), sliding velocity does not influence the friction coefficient was made as well.

Hemmete [20] used a thermally insulated custom-built tribometer to analyze point contact between a rubber sphere and an ice disc, controlling velocities independently and simultaneously while measuring the contact forces and visualizing the contact area. The steady-state friction coefficient was measured at different sliding velocities (50 μm/s–1 m/s), the air temperature was set to −10 °C, and an applied load of 10 N was used. As a result, a bell-shaped curve evolution as a function of the sliding velocity was established. The results are in coincidence with the data from Grosch [85] and Heinz and Grosch [86] and can be related to the real contact area and high adhesion between the smooth ice surface and rubber at low sliding velocities [79, 87].

3.1.2 Linear-type tribometers

Marmo et al. [77] performed stainless steel/ice friction experiments with a linear reciprocating tribometer at low velocities (0.008–0.37 m/s) with the aim of investigating the effect of ice wear and "debris" on the friction coefficient in the air temperature region of −27 to −0.5 °C. The tribometer was placed on the floor of a chest freezer on granite blocks that acted as a heat sink. A dry-polished stainless steel sheet (1 m × 0.1 m × 2 mm) was used as a substrate. The applied load was set at 2.1–4.2 N. The result was a stainless steel/ice friction map. The map shows that the friction coefficient is the highest at low velocity (~0.05 m/s) and low temperature (−20 to −25 °C) and lowest at high temperature (−3 °C) and increasing velocity (~0.3 m/s).

Lungevics et al. [70] analyzed macro and micro geometry of shot-blasted and polished stainless steel samples (dimensions: 35 mm × 18 mm × 14 mm; arithmetic mean height (S_a): 0.8, 2, and 2.9 μm) on two different test setups: (1) inclined plane tribometer (more information and experiments with different samples in Ref. [69]) and (2) linear tribometer (more information and experiments with different samples in Refs. [6, 88]).

Inclined plane tests were conducted at ice temperature −7 °C, air temperature −4 °C, and relative humidity 60%, obtaining sliding velocities along a 3-m-long ice track as samples were slid down from a steady state. The inclined plane tribometer was located in a climate simulation chamber with an additional microclimate chamber around the ice track to ensure the stability of the ambient conditions. Sliding velocity was measured at different positions on the ice track and was used as an indicator of friction (higher velocity represents lower friction coefficient). No additional load was applied to the sliding samples. As a result, only the sample weight contributed to the normal load of 0.65. A linear relationship between S_a and sliding velocity was observed at higher sliding velocity values (2–3.5 m/s). At the beginning of sliding (~0.5 m/s), the rougher sample (S_a 2.9 μm) showed higher sliding velocity than the smoother sample (S_a 2 μm). This was explained by the fact that due to the smaller contact area, the rougher sample might be more prone to breaking capillary bridges during the start of the sample movement.

The linear tribometer tests were conducted under similar ambient conditions (ice temperature −8 °C, air temperature 7 °C, and relative humidity 55%) with an applied load of 52 N and average sliding velocities from 0.02 to 0.38 m/s. A microclimate chamber was built around the testing stage. The logical trend remained the same as observed on the inclined plane setup—the rougher sample showed a lower friction coefficient. For smoother samples, the friction coefficient remained independent of sliding velocity (S_a 0.8 μm resulted in a friction coefficient of ~0.016; S_a 2 μm resulted in a friction coefficient of ~0.023), but for the roughest sample (S_a 2.9 μm), as the velocity increased, the friction coefficient decreased (from 0.08 to 0.04).

Ducret et al. [36] used a linear tribometer (sliding velocity of 0.003 m/s) placed in a hermetic enclosure to study the tribological properties of a polyethylene (UHMWPE) sample on ice. In this case, Ducret focused on the ice topography and its influence on the results, observing that for different ice topographies, at the same applied load (10 N) and air temperature −5 °C, the friction coefficient can vary up to 4 times (0.04 and 0.16). A decrease in the friction coefficient was observed as the ambient temperature increased from −15 to +5 °C (from 0.1 to near 0).

Böttcher et al. [54] used the same material (UHMWPE) to measure and calculate the friction coefficient on ice for samples (ski base sample 40 mm × 65 mm) with different surface topography and grooves in the sliding direction (ridges with a width from 100 to 400 μm), thus changing the nominal contact area. A linear tribometer located in a box-shaped freezer with a constant sliding velocity of 1 m/s was used. The experiments were conducted at ice temperatures from −10 to −2 °C and applied loads from 40 to 86 N. The influence of the applied load on the friction coefficient in the considered range was negligible (within standard deviation), but as the ice temperature increased, the friction coefficient decreased (from 0.05 to 0.025) for all samples. A friction coefficient 3D map was created as a function of the surface topography and ice temperature, and samples with wider ridges showed lower friction coefficient values. Thus, a larger contact area resulted in lower friction. The authors explained that the result can be impacted by plowing of samples into the ice.

In the work of Tada et al. [79], friction of a rectangular tire tread rubber block (2 cm × 6 cm × 1 cm) on ice was investigated in the air temperature range from −38 to −2 °C and sliding velocity ranging from 3 μm/s to 0.01 m/s. A linear friction tester was placed in the freezer, and the load was applied to 240 N. The results indicated a bell-shaped function of the sliding velocity at temperatures below −10 °C, which coincides with the results of Hemmete [20]. In a warmer temperature range, an increase in sliding velocity resulted in a slight increase in the friction coefficient. Authors suggested that at low temperatures (< −15 °C) and low sliding velocity, an essential contribution to the rubber-ice friction is a slip between the ice surface and ice fragments attached to the rubber surface, but at temperatures above −10 °C, a thin liquid-like film of pre-melted ice occurs at the interface.

Tuononen et al. [78] used an in-house linear ice friction tester located in a climate chamber. White light interferometry was used to analyze the ice surface topography during friction testing with a rubber slider (25 mm × 25 mm). The friction coefficient for different sliding velocities (0.002, 0.015, 0.1, and 0.9 m/s) and for different applied loads (85, 141, 229, 331, and 423 N) at an air temperature of −5 °C was measured. The lowest friction coefficient, ~0.2, was observed for the highest velocity and load. Similar results were observed in the work of Lahayne et al. [22] using a linear-type friction tester. There, the friction coefficient decreased as the applied load increased and temperature decreased at a constant sliding velocity (0.65 m/s). The friction coefficient was measured in dependence on the traveled distance, and the shape of the friction curve was consistent with other ice/rubber friction results [20, 79, 85].

3.2 Large-scale test methods

To bring the experiment conditions closer to reality, Scherge et al. [33] carried out research using a high-speed tribometer set up in a ϕ3.8 m tire test bench situated in a cooled cell (air temperature in experiments was maintained constant at −5 °C). As a slider, two stainless steel bobsled-style runners were prepared (150 mm × 20 mm × 8 mm), and the cross-sectional radius of the curvature of the sliding surface varied between 4 and 8 mm. The runners were polished to R_a 0.009 μm. The friction coefficient was analyzed as a function of the sliding velocity (from 2.8 to 28 m/s) and the applied load (from 100 to 500 N). As the sliding velocity increased, the friction coefficient of both runners decreased (from ~0.016 to ~0.006). The authors suggested that two distinct friction regimes occur: (1) up to a sliding velocity of about 3 m/s, where there is a steep decrease of friction coefficient as the sliding velocity increases; and (2) above a sliding velocity of 3 m/s, where the reduction of friction is constant but with a significantly smaller slope. From load experiments, differences in friction coefficient between runners were observed at lower applied loads (100 and 200 N). Above 300 N, the friction coefficient for both runners stabilized and remained constant at ~0.012. The authors calculated the compressive failure stress of ice in dependence of temperature and used Hertzian contact mechanics to analyze at which applied load the compressive failure stress is achieved at constant pressure. For runners with a 4 mm cross-sectional radius, the compressive failure stress was calculated to be at an applied load of 200 N, and for runners with an 8 mm cross-sectional radius at 400 N.

A 24 m long tribometer (previously described in Hasler et al.

[11]) was used under controlled laboratory conditions by Rohm et al. [67]. The tribometer can be used for compressed snow and ice experiments. Rohm studied the friction coefficient of grinded metal skis (487.5 mm × 30 mm × 30 mm) with different surface roughness (S_a = 0.16, 0.28, 0.92, and 6.63 μm) on compressed snow. The experiments were performed at four different ambient conditions (from −3 to −12 °C snow temperature, from −2 to −10 air temperature, and relative humidity remained ~80%) and at three different applied loads (56, 98, and 140 N).

The rougher skis showed the lowest friction coefficient at all ambient conditions, with the most significant differences at the warmest conditions. The authors attributed this result to the smaller contact area of the rougher skis, which reduces the adhesive forces between the slider and the snow. Experiments on the effect of the applied force are not of sufficient significance to analyze its impact. A similar 12 m long custom-made linear tribometer under controlled laboratory conditions was used in the research of Lemmettylä et al. [12]. The authors emphasized that the relevance of conducting practical experiments with real-scale skis under controlled environmental conditions is significant. This type of linear tribometer provides a more extended snow/ice surface, so in theory, each time the ski slides over the same track, the snow/ice manages to regenerate [1] and there is no almost continuous contact with it, as is the case with most rotary and linear laboratory tribometers.

Sandberg et al. [13] used a free-gliding ski tribometer with a ski launched and accelerated by an electric winch or released to slide freely down the slope. The deceleration of the sled is determined by air resistance and friction. The applied load can be increased up to 130 kg, and a real-size ski or another slider can be used. Although the tribometer can be used at different locations, in this case, it was located in an indoor snow test facility, providing a 120 m long test track. The air temperature and humidity were controlled from −3 to −12 °C and from 50% to 90%, respectively. The sled was launched at a target sliding velocity of 5.8 m/s and then decelerated to a full stop. The highest friction coefficient of 0.021 was observed at the highest sliding velocity of 5 m/s, with similar results (~0.19) observed for other studied sliding velocities. Interestingly, with each subsequent test run on the same snow surface, an upward trend could be observed for the friction coefficient curve. The authors suggested that the increasing trend might be explained by the increase in the contact area and related to the interaction between the ski base and the liquid-like layer, similarly as observed by Rohm et al. [67] and described in the work of Almqvist et al. [89] well.

3.3 On-field test methods

On-field experiments are as close as possible to real-life conditions. This means that the data obtained will be more representative for a given friction process. On the other hand, in some cases, it is impossible to control factors such as human impact and ambient conditions.

Colbeck et al. [51] experimented with the temperature of the ice skates, proving that ice melting due to friction is the leading cause of the low friction coefficient. A thermocouple was attached to the skates to measure the temperature. The skate temperature was observed to be higher at fast skating, but as the skates stopped and remained in contact with the ice, the skate temperature dropped. De Koning et al. [14] experimented with ice skates in a similar fashion. Ice friction was investigated in the case of speed skating, with custom skates fitted with sensors that measured forces in horizontal and vertical directions. The results showed that the friction coefficient is optimal at an ice temperature of around −7 °C when skating in a straight line at 8 m/s. The optimum point is the result of the liquid-like layer thickness and ice hardness, i.e., the liquid-like layer thickness increases with increasing ice temperature, but at the same time the ice hardness decreases, leading to the skates cutting into ice more efficiently and increasing the friction coefficient. The friction coefficient increased by about 28% when skating in curves. This was attributed to the more significant ice deformation as the blades of the skates cut more pronounced into the ice.

Federolf et al. [83] used a variety of customized experimental hockey skates to determine whether they reduce the friction coefficient compared to standard hockey skates. A sledge with skates was fabricated, and a mass (53 kg) was applied to each skate. The sledge was launched at a constant speed of 1.8 m/s by a starting mechanism and passed through several timing points (at most 14 m from the start) on the hockey rink. Accordingly, the friction coefficient was calculated from the time data. It was concluded that the experimental skates showed a lower friction coefficient than the standard skates: The standard skates' mean friction coefficient was 0.007; the experimental skates' mean friction was below 0.006. It was concluded that a changing blade angle and a higher applied load provided lower friction, but friction was independent of sliding velocity in the test range. One of the disadvantages of this experimental method was a fixed straight sledge motion, as the authors highlighted that in some measurements the sledge slipped.

Poirier et al. [17] carried out experiments with bobsled to determine the dependence of the friction coefficient on the sliding velocity (1–10 m/s). The athlete pushed the sled to a certain velocity and allowed it to slide freely. The sliding velocity was recorded by a radar. No change in the friction coefficient (0.004) was observed using this experimental method. The Poirier experimental results largely depended on the sliding path of the athlete who pushed the sledge.

Hainzlmaier [16] in his doctoral thesis, designed tribologically improved bobsled sleds. Seven different sets of sleds were produced. Different pilots (total 6) with different sleds made runs on the Königsee bobsleigh track and the sliding time was recorded. The experiments were carried out on different days under various ambient conditions. It was found that there is an optimum pressure where the friction coefficient is a minimum, but it significantly changes from straights to curves on the ice track.

Jansons et al. [72] used a 24 m long bobsled push-start training ice track equipped with optical sensors. The sliding time or velocity was detected as a describing factor. A groove along the sliding direction was embedded into the ice track to ensure a straight movement down the track. A skeleton with standard runners and an additional weight with a total of 95 kg was used. Scratched (S_a 0.11 μm) and polished (S_a 0.02 μm) runners were used. Experiments were conducted at different ambient conditions (air temperature from −4 to 10 °C; ice temperature from −6 to −1 °C; relative humidity from 55% to 95%). Overall, polished runners reached a higher sliding velocity, depending on ambient conditions. From more than 20 experiments, it was concluded that ambient conditions and especially the interplay between the above-mentioned characteristics contributed to the friction results more significantly than the surface roughness.

4 Discussion

In ice friction, it is common to distinguish between three different friction regimes: boundary or dry friction, mixed friction, and hydrodynamic friction [5, 7, 49]. The theoretical friction regime depends on the thickness of the liquid-like layer between the sample and the ice surface [3, 5, 40–41]. The thickness of the liquid-like layer, in turn, depends on the environmental conditions and the experimental setup (Fig. 1).

Since 1990, several researchers have made significant contributions to the study of ice friction (Fig. 6). Considering the time schedule of the last twenty years, it can be observed that ice friction studies are mostly based on small-sized laboratory equipment. It can also be observed that there is a gap in research after 2008, which could be explained by the global financial crisis. Since 2015, research on ice friction has been published quite regularly, and in the last ten years, experiments have also been carried out on large-scale laboratory equipment. This emphasizes both the technical and financial development of the field and the need to conduct experiments with experimental samples and settings closer to real life.

As mentioned above, from Fig. 6, it can be concluded that the majority of ice friction experiments have been carried out under laboratory conditions, which provide stable and controllable environmental conditions, but, at the same time, impose size limitations. The small-scale tribometers are generally designed so that the sample continuously slides over the same relatively short sliding track. Furthermore, although, in theory, for small-scale friction testers, the environmental conditions should be relatively easy to control in a laboratory setting, this is often not the case. Authors often limit themselves to controlling the temperature of air or ice, assuming they have the same value. In most cases, air humidity is not analyzed, although it has a significant effect on the friction process. In laboratory, the experimental parameters, i.e., the applied force and the sliding speed, are limited and can significantly differ from real life.

An alternative to small-scale tribometers is the construction of large-sized tribometers, which requires both the construction or adaptation of existing infrastructure and significant financial investments. However, if research is focused on an industrial application or a consumer end-product, this equipment provides results closer to real-life conditions. So far, on-field experiments have been mostly carried out with human participation. In some experiments, this is permissible, but to ensure reliable results, a maximum control/overview over the experimental settings and influencing parameters must be ensured.

Table 1 summarizes various experimental studies on ice friction, listing the test method, experimental setup, samples, environmental control conditions, outcomes, and the obtained friction coefficient range. The number of experimental studies of ice friction is more significant than that listed in the table, especially those performed under laboratory conditions. Table 1 focuses on relatively recent studies and covers as much different experimental equipment as possible. Experimental samples are primarily metal, rubber, and polymer.

Practically, the classification of experimental test methods can be linked with the categorization of tribological systems (Fig. 7) proposed by Czichos and Habig [91]. If the experiments are carried out in the on-field mode with a real experimental object, then they could be included in the first category. Accordingly, if a real experimental object is tested in laboratory conditions, then it can be included in the second and third categories. On the other hand, if experiments are carried out with original parts of a real object, for example, a bobsled runner, then tribological tests can be included in category four. By reducing original parts and elements and simplifying surfaces, tribology tests can be categorized into categories five and six.

To compare and evaluate the ice friction test methods described in Table 1, the following criteria were set: control over experimental variables, measurement range and resolution, repeatability and reproducibility, relevance to real conditions, cost and practicality, safety and ease of use (Fig. 8).

The ability to precisely control and measure critical variables such as temperature, humidity, applied load, and sliding speed ensures reliable and reproducible results. Laboratory settings typically offer better control, allowing researchers to isolate specific factors that affect ice friction. However, this must be balanced with the need to simulate real-world conditions.

The experimental method should be able to measure the coefficient of friction and other relevant parameters over a wide range of conditions (e.g., different temperatures, loads, and speeds) with high sensitivity, especially when the coefficient of friction approaches zero. Small-sized laboratory equipment often allows experiments to be performed with a higher sensitivity, and thus, the effects of small changes in surface roughness, texture, and material properties can be accurately recorded. However, the experimental conditions have significant limitations.

Consistent results are critical for reliability and reproducibility across studies or laboratories when repeated under the same conditions. Standardized methods with clear protocols are known to provide higher repeatability and reproducibility. However, since

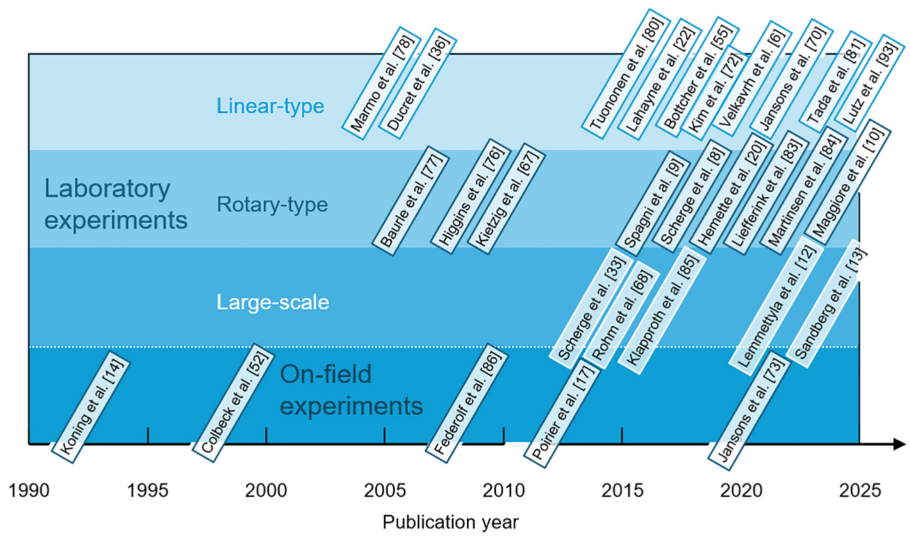

Fig. 6 Test methods used for ice friction experiments arranged according to the year of publication and type of the test setup.

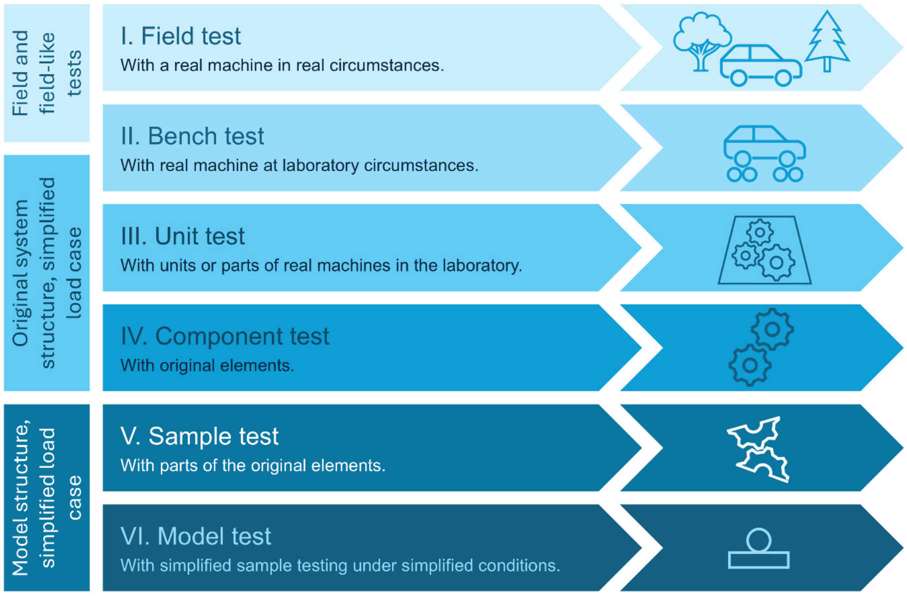

Fig. 7 Categories of tribological testing. Reproduced with permission from Ref. [91], Springer Fachmedien Wiesbaden GmbH, ein Teil von Springer Nature 2020.

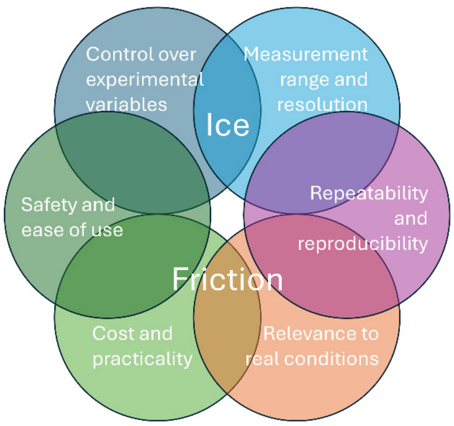

Fig. 8 Criteria for the ice friction test methods.

no standardized methods exist for ice friction, it is important to describe the experimental conditions in as much detail as possible.

The test method must closely replicate the real conditions under which the ice friction phenomenon occurs, which is especially important in applied research such as sports, safety, or transportation.

Methods that simulate real-life scenarios (large-scale tests or field experiments) generally provide more appropriate results compared to strictly controlled but less realistic laboratory conditions.

Large-scale or highly specialized facilities may offer a better simulation of real-world conditions but are often more expensive and more difficult to maintain. Ideally, the experimental method should be cost-effective and practical. Thus, it is important to understand the purpose of ice friction research.

The safety of researchers and the ease of setting up and conducting experiments, especially in extreme conditions such as low temperatures are crucial. Thus, methods that minimize risks and are simple to use are preferred, especially for long-term or field-based studies.

In relation to the above described, in Table 2, an evaluation of the benefits and drawbacks of the discussed methods is provided.

5 Summary

Research of ice friction is a multifaceted challenge due to the interplay of variables. The present literature review highlights the factors influencing ice friction, including the properties of the ice, the liquid-like layer, and the geometry as well as the material properties of the sliding body. The most common experimental methods used to study ice friction are summarized and analyzed, starting from small-scale laboratory tribometers to large-scale and on-field experiments. Several conclusions can be drawn:

(1) Interdependence of parameters. The frictional properties of ice are not determined by a single factor but by a complicated interplay, including the interaction between the sliding body and the ice surface, the liquid-like layer, and the experimental conditions. Such complexity outlines the need for precise control

Table 2 Comparison of test methods used in ice friction experiments, based on the set criteria

Test method criteria	Rotary-type tribometer	Linear-type tribometer	Large-scale tribometer	On-field experiment
Control over experimental variables	●●●●○	●●●●○	●●●○○	◐○○○○
Measurement range and resolution	●●●○○	●●●◐○	●●●●○	●●○○○
Repeatability and reproducibility	●●●●○	●●●●◐	●●●●○	●●◐○○
Relevance to real conditions	●●○○○	●●●○○	●●●●◐	●●●●◐
Cost and practicality	●●●●◐	●●●●◐	●●●○○	●●◐○○
Safety and ease of use	●●●●◐	●●●●◐	●●●◐○	●●◐○○

and recording of all experimental variables to ensure reproducibility and comparability.

(2) Limitations of the experimental setups. Although small-scale laboratory experimental setups provide high-level control and resolution, these methods tend to not be effective in simulating real-life conditions. However, there are significant challenges in terms of cost and practicality, as well as environmental control if large-scale tribometers or on-field experimental methods are used.

(3) Lack of standardization. Although ice friction is a complicated tribological system, the development of universally accepted experimental protocols or guidelines could improve the repeatability and reproducibility of results, which would lead to a reduced gap between the controlled laboratory conditions and practical, real-life applications.

Given the current state of the ice friction research, future fields of study can be addressed:

(1) Development of standardized protocols. The establishment of universally accepted experimental protocols or guidelines for conducting and describing ice friction experiments would improve the comparability and reliability between different studies.

(2) Large-scale testing. Further investments in large-scale tribometers to improve control over experimental variables, would provide closer to real-life experimental conditions, thus providing a more appropriate insight into the practical implications of ice friction in fields such as sports, safety, and transportation.

(3) Research of advanced materials. Continuity to study advanced materials with different properties and surface texture modifications under various environmental conditions will lead to improved tribological properties for specific applications.

(4) Control of environmental conditions. Improved monitoring and reporting of environmental conditions, especially for ice temperature, air temperature, and air humidity. Understanding how these parameters affect friction on ice, will lead to an improvement in the accuracy of ice friction models.

Although over the last decades, considerable progress has been made in understanding the phenomenon of ice friction, a large unexplored field remains open for future studies. Considering the mentioned challenges, it would be possible in the near future to improve the existing theoretical models and experimental methods for ice friction, which would ultimately lead to improved performance and safety in cases where ice friction plays a crucial role.

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Author contributions

Idea for the article: Ernests Jansons; literature research and data analysis: Ernests Jansons, Jānis Lungevics, Igor Velkavrh, and Thomas Wright; Writing—original draft preparation: Ernests Jansons; Writing—review and editing: Ernests Jansons, Jānis Lungevics, Igor Velkavrh, and Thomas Wright.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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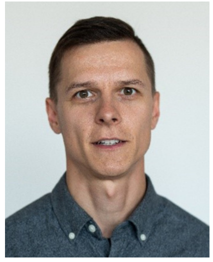
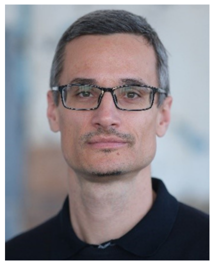
Ernests Jansons is a leading researcher who obtained a Ph.D. degree in 2022 and focuses on dimensional metrology and tribology, with a particular emphasis on ice friction. His research investigates the interaction between the surface texture and ice, along with the impact of various factors on the sliding behavior of the friction pairs. Additionally, leveraging expertise in Mechanical Engineering, both 3D CAD models and physical equipment are designed and developed for conducting ice friction experiments. Additionally, as an assistant professor, he teaches courses related to machine design. To date, has been involved in six international and national research projects, serving as the lead participant in two of them. In 2022, he received an award from the Latvian Academy of Sciences for significant contributions to ice tribology research.



Janis Lungevics is a leading researcher who has over ten years of experience in ice tribology and dimensional metrology. He has participated in six scientific projects and multiple smaller studies related to surface engineering and tribology. Currently, he leads the RTU work package of the National Research Project. In February 2022, he received an award from the Latvian Academy of Sciences, Latvia, for his noteworthy achievements in ice tribology research. He works at Riga Technical University, Latvia, as a leading researcher, assistant professor, and head of the Mitutoyo Metrology Scientific Laboratory, Latvia. In 2019, he received an RTU annual Award in Valorisation for his great contribution to developing collaboration between RTU and the Latvian production industry. In the same year, he was elected to the Latvian Metrology Council.



Igor Velkavrh is a project manager with nearly 20 years of experience in the fields of tribology and surface engineering. He studied mechanical engineering at the University of Ljubljana, the Republic of Slovenia, where he obtained his Ph.D. degree and gained experience in an international R&D environment. Since 2013, he has been working at the V-Research Tribo Design department and is active in projects dealing with the optimization of friction and wear in high-tech applications bridging the gap between the industry and the academia. He has detailed know-how on various subfields of tribology such as coating-, polymer-, gas-, and low-temperature tribology, as well as snow and ice friction phenomena and is a co-author of various scientific articles in international journals and conferences, active as a reviewer and guest editor.

Thomas Wright is a business unit manager with over 10 years of experience in the R&D environment. He has a bachelor degree in materials science from the University of Leeds, UK, where he also carried out his doctoral thesis in the field of processing and degradation of aramid fibers. From 2013 to 2020, he was a research fellow at the University of Innsbruck, the Republic of Austria, working on numerous academic and industrial projects. Since December 2020, he has been working as the business unit manager of the V-Research Tribo Design department focusing on sustainable materials and promoting the research of special tribological systems such as fibre- and low-temperature tribology.