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# Sliding of UHMWPE on ice: Experiment vs. modeling

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ABSTRACT

Systematic measurements of the coefficient of friction were performed in a model system consisting of intentionally patterned polyethylene blocks moving on ice surfaces (PE-ice system). All experiments were carried out under well controlled conditions (air temperature, ice temperature, surface topography, etc.). Three temperatures of − 10, − 6 and − 2 °C and three normal loads in the range between 40 and 80 N were applied at a constant speed of 1 m/s. It was found that the coefficient of friction $\mu$ strongly depends on relevant tribological factors as well as on the surface topography of the slider (embossment). In particular the dependency on the ice temperature $T_{\mathrm{Ice}}$ and the contact area $A_r$ (as predefined by the embossment chosen) appear to be the most decisive factors. The striking $\mu(T_{\mathrm{ice}})$ relationship revealed the unique role of the interfacial water layer connecting the patterned PE-block with the ice surface. We examined the applicability of a recently proposed model describing the tribology of the solid-ice system in terms of gliding-conditioned formation of an interfacial water layer: Makkonen and Tikanmäki, 2014 (M-T-model). The experimental data set has been fully reconstructed after extending the M-T-model by including the temperature dependency of the material hardness, $H_{\mathrm{PE}}$ and $H_{\mathrm{Ice}}$, as well as by calculating the load-dependent real contact area $A_r$ through an adaptation of the Hertzian contact model.

## 1. Introduction

Bowden and Hughes were the first to investigate the tribology of ice and snow in a systematic and scientifically relevant approach (Bowden and Hughes, 1939). The experiments resulted in the concept of frictional melting with the heat released in a frictional pathway liquefying a thin topmost ice layer. The resulting water film acts as an excellent lubricant in the slider-ice system. Until the present day this approach has been fundamental for the tribology on ice. Ambach and Mayr finally succeeded in proving the existence of a water film by measuring its thickness during the actual friction process of downhill skiing (Ambach and Mayr, 1981). Since then, the focus of research has been laid on the estimation of the contribution of several postulated elementary processes to the general gliding situation. The decisive factor influencing friction turned out to be the ice temperature (Bäurle et al., 2006; Bowden and Hughes, 1939; Buhl et al., 2001; Ducret et al., 2005; Marmo et al., 2005). An increasing temperature increases the water film thickness, resulting in lower coefficients of friction until just below the melting point. Accompanying ice hardness is reduced, which additionally supports the friction reduction (Ducret et al., 2005). Also the normal force $F_N$ on the contact and the relative sliding speed $v$ distinctly affect the formation of the water film. Bowden and Hughes (1939), Buhl et al. (2001), Scherge et al. (2013), Albracht et al. (2004) and Bäurle (2006) investigated the reduction of $\mu$ as induced by increasing normal force. This effect has been explained by attributing the increased power input to the formation of a thicker water layer. Evans et al. (1976), Oksanen and Keinonen (1982) and Bäurle et al. (Bäurle, 2006; Bäurle et al., 2006) studied the role of sliding speed on the frictional behavior. In the low temperature range the friction can decay with increasing velocity. However at elevated temperatures close to the melting point, when further raising the sliding speed, a significant increase of the coefficient of friction can be observed. Thus, the forming water film can act as an efficient lubricant as well as a medium raising the frictional resistance. The latter originates from an increased viscous shearing resistance of the fluid.

Accompanying the experimental research, modeling of ice friction evolved. Evans et al. set the basis for modeling the friction behavior with their consideration of the heat balance of the tribological contact: The frictional heat is produced in the contact zone and conducted into both tribological partners (Evans et al., 1976). The resulting equation relates the coefficient of friction to the temperature gradients, the normal force, sliding speed as well as to the thermal conductivities of the slider and ice. Unfortunately, the ice melting in the slider-ice interface was not explicitly designated by Evans. Oksanen and Keinonen renewed the topic of modeling ice friction through their approach of locating the origin of the frictional resistance in the viscous shearing of

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the produced water film (Oksanen and Keinonen, 1982). They further assumed that the heat conducted into the single tribological partners equals the amount of the stored energy of the heated body. Regarding the thermal balance of the system and including the previous assumption, an explicit equation for the coefficient of friction was achieved. Makkonen and Tikanmäki improved the work from Oksanen and Keinonen further by integrating the material hardness in the friction calculation. The resulting unified model is applicable for slider-ice systems operating in a very broad range of relevant frictional parameters (Makkonen and Tikanmäki, 2014).

For the low temperature range in which the formation of a lubricating water layer can be intuitively excluded the so called "dry-sliding mode" was also considered (Makkonen, 1994, 2012). In this case the energy required for moving the slider on an ice surface equals the work necessary for forming a new ice surface. Consequently, the coefficient of friction is governed by the surface energy of the interfaces formed when the slider contacts the ice.

It is obvious that the tribology in the slider-ice interface is of practical relevance for several Olympic winter disciplines (e.g. bobsleigh, cross-country skiing, ski jumping). Thus, one could expect that the modeling of such a system should be able to reconstruct the sport achievements and provide some hints towards future reduction of the $\mu$ values (material choice, optimized slider geometry, etc.). The model proposed by Lozowski et al. fits exactly these needs (Lozowski et al., 2013, 2014; Lozowski and Szilder, 2013; Penny et al., 2007). The L-model is tailored for real speed skating and bobsledding predominantly. It benefits from already established thermodynamics of the slider-ice interface and furthermore it precisely includes interface properties of relevance under practical conditions: (1) The geometry of a real slider and the slider-ice interface; (2) the ploughing through the ice surface; (3) the squeeze-out of the lubricating water layer. The L-model thereby assigns ploughing through the ice and the shearing of a lubricated water layer to be the decisive processes governing the frictional behavior. In spite of neglecting the heat conduction into the runner the L-model fits well the frictional data collected for speed skating and bobsledding.

In this study we created a tribological model system consisting of an UHMWPE-slider on an ice surface and tried to find the sliding conditions which minimize the coefficient of friction. For this purpose the surface of the PE-slider was intentionally patterned and consequently the role of the real contact area in the gliding performance became accessible. Moreover, in contrast to theoretical models which solely assume some surface roughness parameters, the patterning procedure applied here enabled us to directly determine the real effective contact area, a property fundamental for the evaluation of the theoretical models. We report here on the applicability of the M-T-model to describe the PE-ice system (as a model tribological system). The focus is placed on the analysis of the coefficient of friction $\mu$ and its dependency on the temperature $\mu(T_{\text{Ice}})$ and on contact parameters $\mu(Ar)$.

## 2. Experimental procedure

### 2.1. Sample preparation

PerGlide UHMWPE from PerLaTech GmbH (Germany) was chosen as ski sole material. The polymer type consists of GUR 4150 basic granulate from Ticona GmbH with graphite content. The sole is provided in rolls of 300 mm width and with a thickness of 1 mm. Using a cutting tool, samples were cut out from the sole to a sample size of 40 mm 110 mm before further processing. For the application of linear structures on the sole the method of embossing was chosen.

For the applicability of contact mechanics and comparability of measured and calculated coefficients of friction, a defined contact situation between ski sole and ice surface is necessary. This is not the case for grinded ski soles, which is the standard preparation technique for skis. A surface topography produced in this way consists of ridges showing a ragged rough topography. In addition, the ridges are not oriented parallel to the sliding direction. Based on the production process a slight skew is present. A sliding contact of a grinded structure should therefore be influenced by the statistical roughness of the ridges plus the shear forces produced by the skewness of the structure. In order to exclude these effects, we suggest a flat linear structure for our experiments to produce the best defined contact. The application of such structures to a UHMWPE-surface is not easily possible without influencing the basic material through e.g. heat input. After preliminary studies with the laser ablation technique we gained best results with the embossment technique. In addition to the smooth and parallel structures generated, a remarkable friction reduction was observed, which will be discussed in a subsequent publication.

For the application of embossment in the present study, a steel plate was machined using laser ablation technique. The resulting linear structures on the steel surface show a triangular shape in cross section. Four versions were produced, differing only in the gap distance of the structures ranging from 100 to 400 μm. For embossing the linear pattern into the ski base, the ski sole and the steel plate were put into a hydraulic press. Exerting a high force of 90,000 N a homogenous linear pattern parallel to the sliding direction was produced on the ski base surface. The structured ski sole was finally glued onto a special aluminum specimen, resulting in a flat contact area of 40 mm 65 mm with rounded outlet geometry on both sides to ensure smooth gliding (Fig. 1).

The geometrical contact area of the specimen is also the apparent contact area of 2600 mm$^2$.

### 2.2. Tribometer measurements

Measurements were carried out under strictly controlled conditions on a linear tribometer. The device was located in a box-shaped freezer, which could only be accessed from the top, to ensure a maximum in temperature stability. The tribometer consisted of a linear axis, which was connected to a massive aluminum frame. The axis runner held the measuring head, which included an actuating element, the force sensor and the specimen holder (Fig. 2).

The ski base sample was fixed in the sample holder and the appropriate normal force was applied. This was done manually by extending a torsion spring, which deflects a parallelogram actuation, pushing the sample against the counter body. The initial tribometer setup was supplemented by the installation of elastomeric damping units which would guarantee an alignment and a flat contact between the ski base sample and the counter body. The force sensor consisted of a solid joint with applied strain gauges, allowing the detection of forces up to 100 N in normal and up to 20 N in tangential direction. Below the measurement unit a rectangular aluminum tub was located, enabling the preparation of ice and snow surfaces as a counter body. A controller guarantees to maintain the inside temperature with an accuracy of ± 0.1 °C down to − 20 °C. A Pt-100 thermocouple, situated at the height of the tribological contact, served as a reference for the

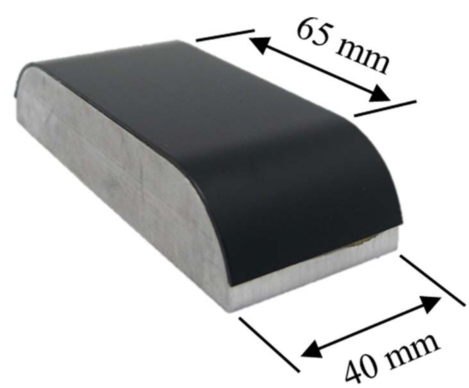


**Fig. 1.** Ski sole sample on an aluminum body.