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How to glide well on wet snow? Can roughness and hydrophobicity lower friction of polymers on snow?

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ABSTRACT

To maximize performance in elite winter sports, considerable effort has been made to find gliding surfaces, which decrease snow friction to a minimum. Shifting away the focus from elite sport to mass winter sport equipment, this study aimed to evaluate materials providing acceptable gliding performance and in the same time high structural strength. Therefore, we investigated wet and dry snow friction of known engineering polymers with different surface configurations. Static and kinetic friction coefficients (COF) on snow of twelve gliders made of different polymers were measured on a linear friction tester placed in a cold chamber. Of each polymer, two gliders were built and tested: one with a smooth surface, another one with a stone grinded surface. Roughness parameters and dynamic contact angles were measured to characterize the surfaces. Dry and wet snow samples were prepared by grinding ice into powder followed by sieving, compressing and natural snow sintering. The snow surface temperature was measured before each experiment with a pyrometer. Liquid water content was generated directly before each experiment by applying infrared light. COF on wet and dry snow were correlated with mean R_a-values and mean contact angles. Mean static COF ranged from 0.05 to 0.375 on dry, and from 0.133 to 0.674 on wet snow. On dry snow, only a moderate negative relationship between static COF and contact angle was found ($r_{pearson}$ = -0.6), whereas on wet snow a strong negative relationship was found ($r_{pearson}$ = -0.92). Static COF and R_a showed a moderate relationship only on dry snow ($r_{pearson}$ = 0.62). Excluding HDPE and ABS, smooth samples showed distinctly lower static friction than structured samples. The study showed that snow friction is a complex interplay of surface topography, hydrophobicity and mechanical properties, especially on wet snow. The typical texture for HDPE ski bases did not sufficiently decrease snow friction of the tested engineering polymers. On wet snow, hydrophobicity was the most important factor for good gliding. On dry snow, surface roughness had a stronger influence than hydrophobicity. Snow had clearly the strongest influence on the polymer - snow friction because it is a highly variable material with quickly changing physical properties.

1. Introduction

Snow and ice friction has been studied frequently until today due to diverse reasons [1 - 25]. Whether to develop faster skis or winter tires with improved grip, or to calculate runout distances of avalanches, there are many applications where the interaction of snow with a surface is relevant. COF on snow can vary more than one order of magnitude and depend on many interdependent and non-stationary variables. The complexity of snow friction is mainly caused by the strong variability of the physical properties of snow. In nature, snow occurs at high homologous temperatures and is therefore very sensitive to thermal energy inputs. Only slight changes of the ambient conditions therefore provoke distinct changes of the snow properties. In consequence, quick and strong changes in snow friction can appear [26]. This study compares dry and wet snow friction by quantifying the relationship of the polymers' hydrophobicity, surface roughness and friction coefficients.

As known to authors, most studies on snow friction were focused to find materials and surfaces, which decrease snow friction to a minimum aiming to maximize performance in elite winter sports, especially in skiing and snowboarding disciplines. Since decades, state-of-the-art technology for fast ski gliding consist of the optimal combination of four components: (1) Ski mechanical, dynamical and geometrical properties adapted to snow, terrain and the athlete. (2) Base material with its chemical and mechanical properties providing low friction as well as machinability for further surface modification besides being compatible to the manufacturing processes, e.g. glueing systems, press temperatures etc. (3) Modification of the gliding base topography, mostly by grinding, cutting or swaging, and (4) mechanical, chemical and sub micro-topographical surface modifications, adapted to the existing thermal and structural snow properties as well as to the gliding process parameters speed and pressure of the specific snow sport discipline (e.g. by waxing). The desired functionalities as exemplarily described for a ski are usually realized using a compound of different materials, each of it selected to fulfill a specific functionality, but costly and work-intensive manufactured.

In contrast, this study was motivated by the development of snow sport equipment for mass sports where gliding performance is less important, but cost efficiency, robustness and freedom of maintenance are more relevant, like for low price skis, sledges or other types of snow gliders for rather low speeds. From an engineering point of view, such equipment should have a low product complexity as well as a simple and automatic manufacturing, e.g. single polymer injection molding. Using just one single material to satisfy the various requirements of a snow gliding sport equipment is challenging, though. To select polymers which provide high structural strength, acceptable gliding performance, while enabling cost efficient manufacturability is not straightforward. Therefore, this study aimed to quantify the friction of various engineering polymers on dry and wet snow, and tried to explain the found frictional behavior with the roughness and hydrophobicity of the tested material samples.

2. Methods

2.1 Snow Friction Measurements

The experiments were performed on a linear friction tester placed in a cold chamber where air temperature was kept at -2 °C. The device consists of two position or force controlled linear drives. A vertical drive was programmed to press the glider onto the snow sample with a constant force of $F_{vertical} = 53.3 \pm 0.5$ N corresponding to $p = 43.3 \pm 0.4$ kN/m^2, followed by a horizontal movement of 120 mm with a constant velocity of $v_{horizontal} = 0.1$ m/s to induce friction between polymer glider and snow sample. A new snow sample was used in every measurement. Vertical and horizontal forces were measured with 100 kHz sampling rate and 0.1 N resolution by a force plate, placed under the snow sample (Kistler Model 9254, Switzerland). The displacement was measured with the same sampling rate with 1 µm resolution by a linear encoder (Renishaw, UK). The snow surface temperature of the snow samples was measured with an infrared thermometer (Optris LS, E2006-01-A).

Static and kinetic friction coefficients (COF) of 12 gliders (90 × 60 mm) made of six different polymers (HDPE; PA; POM; PA/Glass fiber (GF); PA/GF/Additive; PA/PP/GF) were measured on dry snow with close to zero snow temperatures and on wet snow. Of each polymer, two gliders were built and tested: one with a smooth surface, another one with a stone grinded surface resulted from identical grinding machine settings. For every glider five measurements were planned. During the study some polymers were already excluded due to excessively high friction values or due to too high costs. These were not measured in all configurations or the sample numbers were reduced.

Mean static and kinetic COF and standard deviations were calculated. Static friction coefficients on wet and dry snow of all measurements of both smooth and structured gliders were linearly correlated with their mean R_a-values and mean contact angles. The slope, its 95%- confidence interval, p-values and the Pearson correlation coefficient were calculated.

2.2 Snow Sample Preparation

Cylindrical snow samples with a diameter of 39.6 mm, and a height of 14.7 ± 1 mm were prepared according to the following steps (Fig. 1 right): Ice was grinded into powder, sieved (710 µm) and stored at -25°C for one to four days to promote natural sintering and rounding of the sharp ice particles by isothermal metamorphism. After storage snow density of 256 kg/m^3 and a snow specific surface area of 25.7 mm^{-1} was revealed from micro-CT measurements (Fig. 1a) [27]. The produced snow was then sieved (1.4 mm) into the cylindrical sample holders, followed by compression (s = 7 mm; v = 1 mm/min) and sintering for another 12 to 20 hours at -5 °C. Two hours before the experiments, the samples were taken out to adapt to the air temperature of the laboratory of -2 °C. Liquid water content of approximately 8 % to 15 % (water visible / funicular regime) was generated directly before each friction experiment by applying infrared light for 60 s (OSRAM THERA RD 150 W 240 V E27) [28]. The mean density of the snow samples was 490 ± 24 kg/m^3 (n = 30). The mean specific surface area, quantified by its near infrared reflectivity was 19.1 ± 1.0 mm^{-1} that corresponds to an optical equivalent grain size (OED) of 0.315 ± 0.015 mm [29].

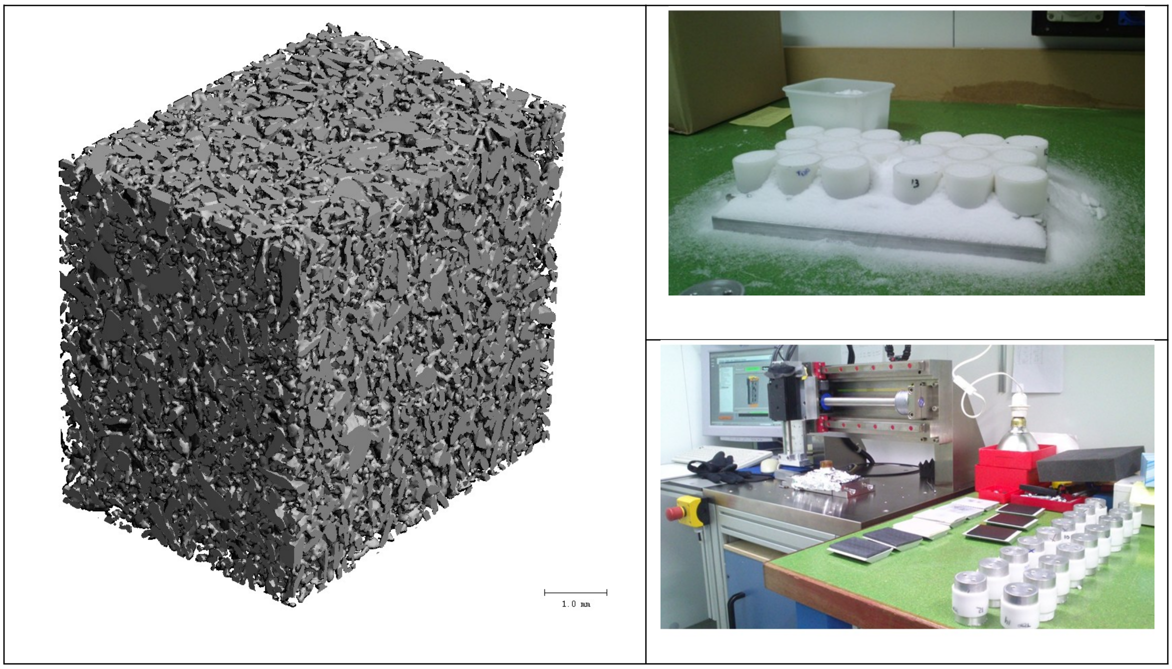

Figure 1. Left: Grinded and sieved ice powder after sintering to a snow similar material. Right top: friction experiment setup with snow samples and gliders. Right bottom: snow sample preparation: sieved and flatted snow in sample holder.

2.3 Dynamic Contact Angle Measurements

The apparatus consists of a macroscopic camera (Sony; 25 Hz; 640p x 480p), a backlight and an automatic syringe. The image analysis as well as the syringe control was programmed with LabVIEW. For every smooth sample as well as for three structured samples (HDPE; PA/GF; PA/PP/GF) 5 to 10 measurements were done. Deionized water was used. Advancing (α_a) and receding (α_r) angles (if occurred) were determined and mean and standard deviations were calculated (Fig. 2).

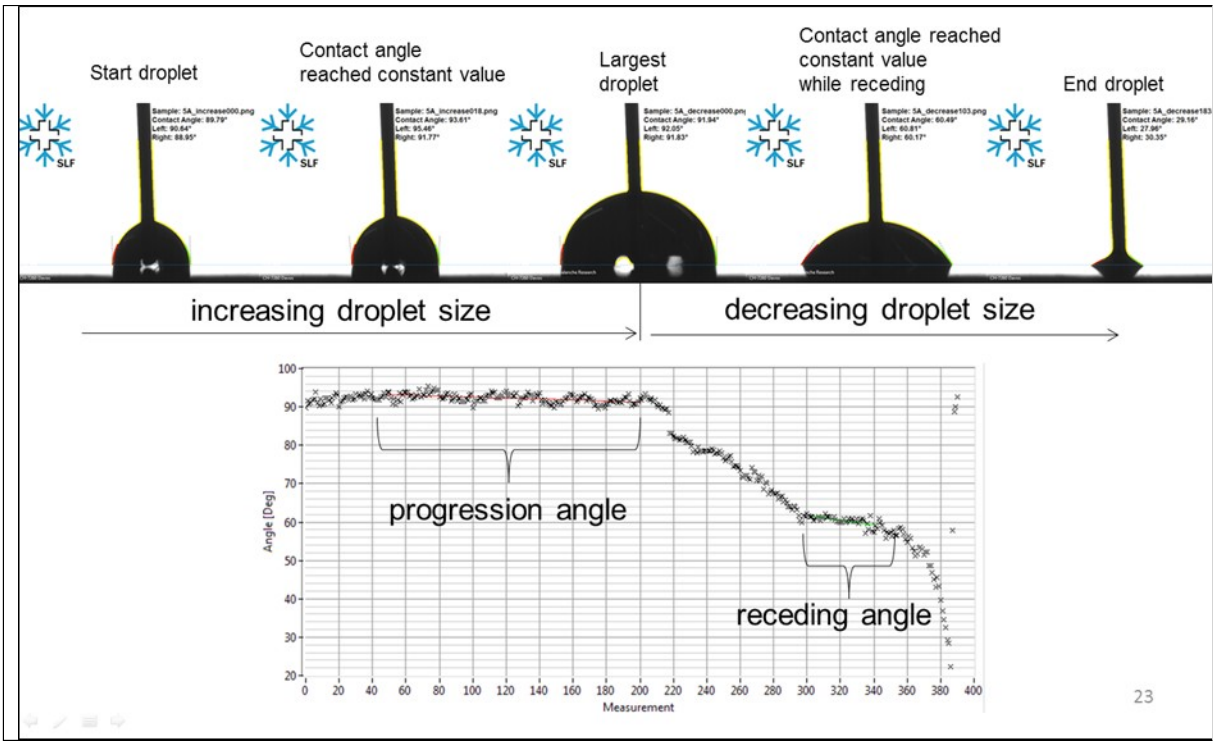

Figure 2. Exemplary data of a dynamic contact angle measurement of POM showing an advancing and receding angle. Each data point on the graph represents the mean of two contact angles (left & right) taken from one picture.

2.4 Roughness Measurements

Roughness profiles were captured over a length of 17.5 mm with a portable roughness measurement apparatus (MarSurf PS1; Mahr GmbH, Germany) perpendicular to the texture or running direction of the samples. Three to five profiles were taken for every sample. Mean R_a-values (arithmetic roughness) and standard deviations of the measured profiles were used to characterize surface roughness.

3 Results

Wet snow friction was found distinctively higher than dry snow friction for most of the tested gliders (Fig. 2). For the static regime the increase of friction from dry to wet snow was unexpectedly large with factors from 1.5 (HDPE) to 4.8 (PA/GF/Add.). Whereas the kinetic friction increased less up to a factor of 1.6 (ABS), keeping dry and wet snow friction in the same order of magnitude. Exceptions were smooth HDPE and ABS gliders, for which the kinetic COF were slightly reduced from dry to wet snow (Tab. 1).

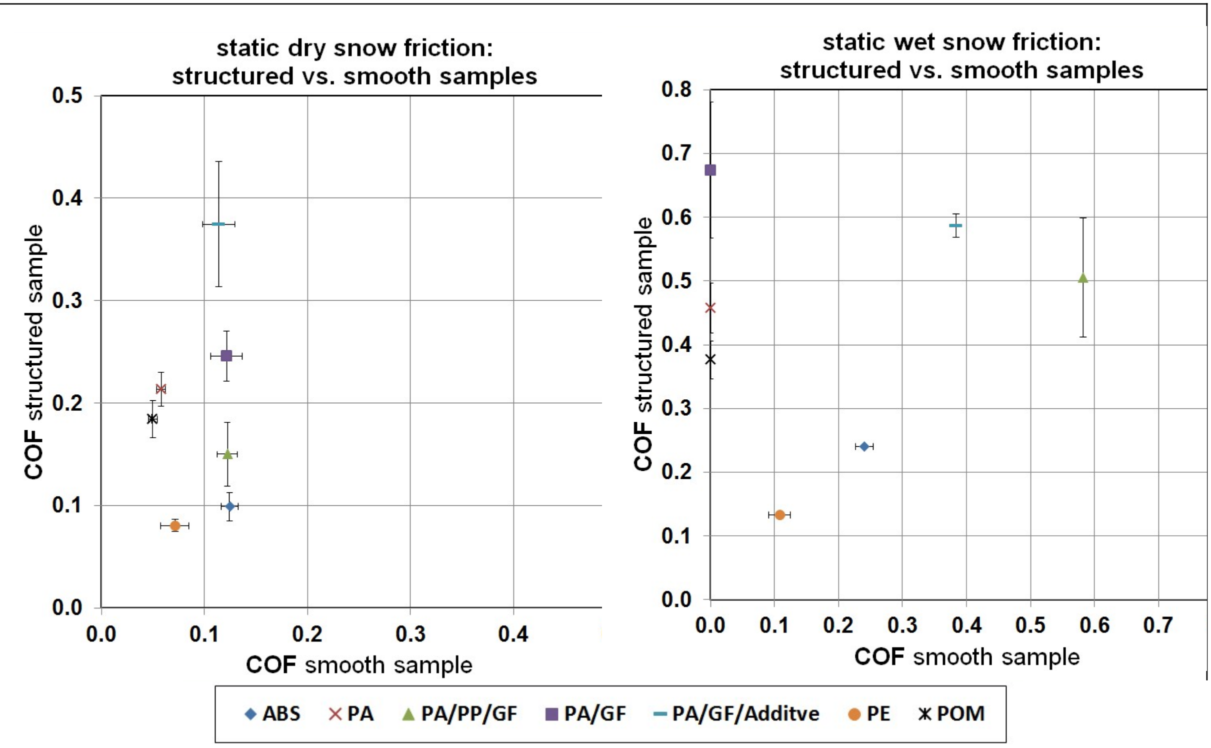

Figure 2. Left: mean static friction coefficients (± s) on dry snow for smooth and structured polymer gliders. Right: mean static friction coefficients (± s) on wet snow for smooth and structured polymer gliders. Smooth gliders of PA/GF, PA and POM were not measured.

Considering the slider's surface properties, Figure 2 (left) shows that structuring had a strong negative effect on dry snow static friction for 5 out of 7 gliders. The roughness of the structured samples ranged from 3 to 6 µm testifying the strong impact of material properties on the grinding outcome (Tab. 2). Gliders with a smooth surface instead, had a relatively low COF on dry snow (Fig. 2, left). Within the smooth gliders roughness varied strongly up to a factor of 40, contrasting two groups: (1) The glass fiber reinforced samples, HDPE and ABS with roughness's from 0.5 to 1.6 µm, and (2) POM and PA with a distinctly lower roughness of 0.04 µm. The latter showed the lowest static friction on dry snow. In the kinetic regime, HDPE reached a similar COF as PA, whereas the extraordinary low kinetic COF of POM (0.033) was unreached. The importance of small roughness for low static friction at dry snow conditions was shown by the calculated Pearson correlations, which were significant on dry snow but not on wet snow (Fig. 3, Tab. 2).

Wet snow friction was much more influenced by the gliders' hydrophobicity and clearly less by its roughness (Fig. 2 right). For example, static friction of the smooth hydrophilic PA/PP/GF gliders (α_a = 77.4°) more than quadrupled from dry to wet snow (0.12 to 0.58), whereas the friction of the hydrophobic HDPE gliders (α_a = 92.4°) increased only from 0.07 to 0.11 (Tab. 2). The general importance of hydrophobicity for low friction on wet snow was shown by the strong correlation of advancing angles and static COF (Fig. 4, Tab. 3). The measured advancing angles of the smooth gliders ranged from 75° to 97° and were differently affected by stone grinding depending on the polymer.

Table 1. Mean (± s) static and kinetic friction coefficients of smooth and structured polymer surfaces on dry snow (n = 5…13) and on wet snow (n = 1…5).

	smooth samples				structured samples			
	dry snow		wet snow		dry snow		wet snow	
polymer	COF stat	COF kin	COF stat	COF kin	COF stat	COF kin	COF stat	COF kin
HDPE	0.072 ± 0.006	0.055 ± 0.005	0.108	0.050	0.081 ± 0.014	0.054 ± 0.010	0.133 ± 0.017	0.070 ± 0.002
PA	0.058 ± 0.005	0.057 ± 0.010	not measured		0.205 ± 0.029	0.177 ± 0.018	0.458 ± 0.039	0.212 ± 0.017
POM	0.050 ± 0.004	0.033 ± 0.005	not measured		0.184 ± 0.018	0.116 ± 0.020	0.376 ± 0.030	0.137 ± 0.013
PA/GF	0.122 ± 0.016	0.123 ± 0.021	not measured		0.246 ± 0.025	0.177 ± 0.014	0.674 ± 0.107	0.204 ± 0.060
PA/GF/Add.	0.114 ± 0.016	0.099 ±0.016	0.383	0.112	0.375 ± 0.061	0.172 ± 0.014	0.586 ± 0.018	0.173 ± 0.000
PA/PP/GF	0.122 ± 0.010	0.075 ± 0.008	0.582	0.163	0.150 ± 0.031	0.103 ± 0.028	0.505 ± 0.093	0.129 ± 0.039
ABS	0.125 ± 0.008	0.087 ± 0.011	0.240 ± 0.013	0.081± 0.005	0.099 ± 0.014	0.062 ± 0.001	0.186 ± 0.002	0.098 ± 0.005

HDPE showed an increase of advancing angle after grinding, whereas for PA/GF a decrease was found compared to the values of the smooth gliders. Interestingly, the PA/GF polymer compound with the hydrophobic additive PP also showed an increase of advancing angles after grinding. Receding angles occurred only for HDPE and POM. For HDPE and PA/GF/Additive structuring seemed to cause an increase in static friction. In contrast, for PA/PP/GF a decrease in static friction was found. In the kinetic friction regime on wet snow, structuring was advantageous for some polymers: The structured gliders of PA/PP/GF had lower kinetic friction than the smooth ones.

Table 2. Mean (± s) R_a –values (n = 5…10) and mean contact angles (n = 3…22) of smooth and structured polymer surfaces.

	smooth samples			structured samples		
polymer	R_a [µm]	advancing angle [º]	receding angle [º]	R_a [µm]	advancing angle [º]	receding angle [º]
HDPE	0.75 ± 0.09	92.4 ± 2.5	62.0 ± 10.0	2.77 ± 0.23	97.0 ± 4.3	61.0 ± 3
PA	0.04 ± 0.01	74.7 ± 1.9	not found	3.65 ± 0.69	not measured	not measured
POM	0.04 ± 0.01	88.3 ± 2.6	52.6 ± 4.9	4.75 ± 0.50	not measured	not measured
PA/GF	0.83 ± 0.21	76.9 ± 2.2	not found	6.06 ± 0.55	73.1 ± 2.5	not found
PA/GF/Additive	0.59 ± 0.06	82.1 ± 3.4	not found	4.44 ± 0.96	not measured	not measured
PA/PP/GF	1.64 ± 0.40	77.4 ± 6.4	not found	5.43 ± 0.44	93.3 ± 9.8	not found
ABS	0.60 ± 0.02	90.7 ± 4.4	not found	3.94 ± 1.21	not measured	not measured

Table 3. Correlation coefficients, slope with 95% - confidence interval of linear fit and p-values.

correlation	**snow condition**	$r_{pearson}$ **[-]**	**slope ± CI**	**p [-]**
COF stat vs. advancing angle	dry	- 0.60	- 0.004 ± 0.001 [1/°]	< 0.001
COF stat vs. advancing angle	wet	- 0.92	- 0.020 ± 0.005 [1/°]	< 0.001
COF stat vs. R_a	dry	0.62	0.029 ± 0.008 [1/µm]	< 0.001
COF stat vs. R_a	wet	0.58	0.055 ± 0.031 [1/µm]	0.015

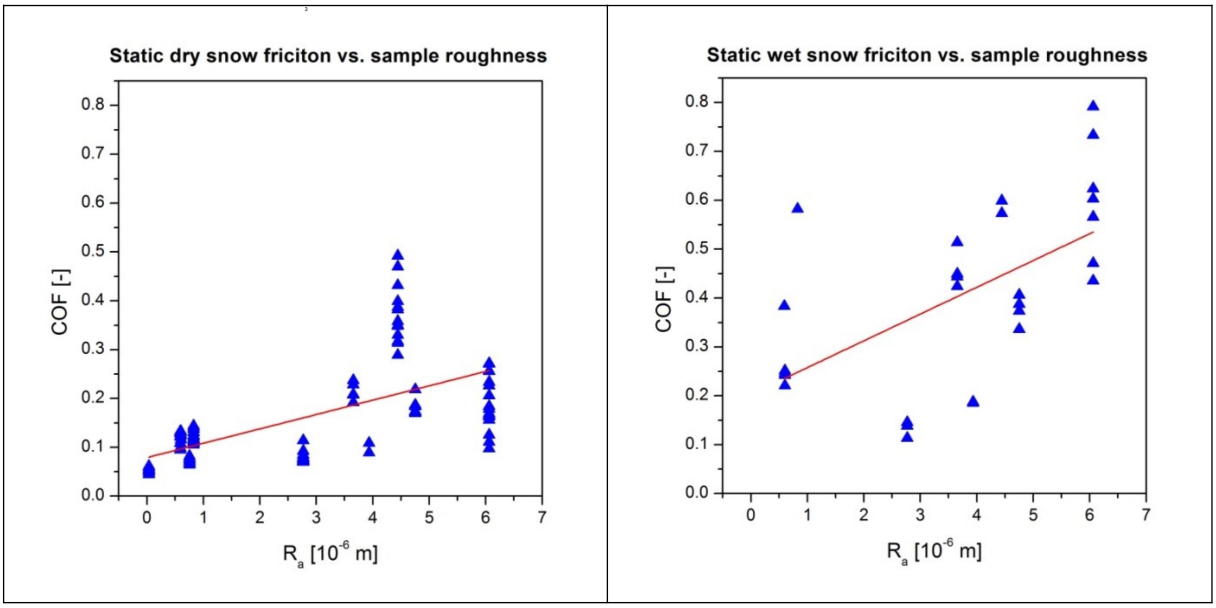

Figure 3. Linear correlation of static COF and arithmetic roughness R_a (a) on dry snow and (b) on wet snow.

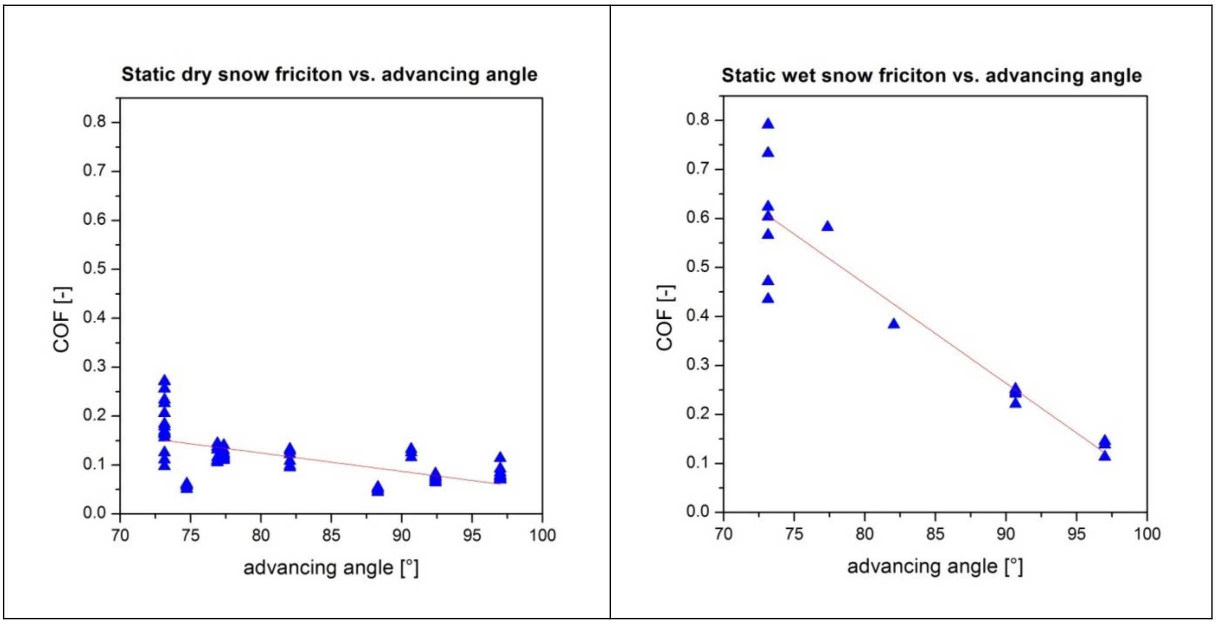

Figure 4. Linear correlation of static COF and advancing angle (a) on dry snow and (b) on wet snow.

4 Discussion

4.1 Results & Processes

The general advantage of smooth gliders on dry snow found in this study could be explained by less penetration and interlocking of the structure with the snow surface. This also explained why kinetic friction coefficients were less negatively influenced by structuring. On wet snow, the advantage of smooth gliders vanished due to different effects mainly related to the prevalence of liquid water at the interface and due to the changing snow mechanics when snow reaches the melting point and liquid water starts to accumulate within the snow pores. We consider the following process as the most relevant while changing from dry to wet snow friction, which in sum leads to an increase in friction:

(1) A reduction of cohesion strength due to weakened grain bonds by melting limits the buildup of static friction forces between a rough glider and the snow surface by interlocking. This effect actually decreases friction and contributes weakening the correlation of glider roughness and static friction on wet snow.

(2) An additional effect of the changing snow mechanics is assumed by an increased solid-solid contact area due to increased creep of the wet snow under load (Fig. 5 left), which increases friction [14]. Moreover, the low strength of wet snow can promote water accumulation at the polymer-snow interface if the top snow volume is strongly compressed. The near surface liquid water content then is likely to increases beyond the actual liquid water content at an unloaded state.

(3) The smoother and more hydrophilic the glider surface is, the more water connects the snow surface pores and grains with large areas of the glider. This is assumed to distinctively contribute to the observed high wet snow friction. The smoother and more hydrophilic the glider surface is, the more water connects the snow surface grains and pores with large areas of the glider. This is assumed to distinctively contribute to the observed high wet snow friction as additional forces are required to shear off the interfacial water and de-wet the sliders' surface.

The last point explains well why the friction of the different polymers diverged on wet snow, whereas the reasons given in (1) partly explain why the differences between smooth and structured samples were smaller on wet snow. Interestingly, structuring did lower wet snow friction of most hydrophobic gliders (ABS and PA/PP/GF but not HDPE), while for hydrophilic gliders, structuring caused always an increase in wet snow friction. A complementary explanation is that structuring also increases the surface area of a glider. An enlarged hydrophilic surface might amplify its disadvantageous property, increasing wetting and by that, wet snow friction.

In addition, the material's mechanical properties strongly affect the structuring process, its topographical result, and the final frictional behavior due to the geometry and stiffness of the microscopic ice-polymer contacts (especially in the dry and mixed lubrication friction regimes). Moreover, it has to be kept in mind that the R_a-value is a very simplified description of a surface. Many important topographical characteristics, which are known to influence snow friction were not analyzed within this study like the bearing curve [30], the occurrence of the excessive peaks or parameters quantifying the micro roughness. For some of the found results clear explanations stay open, as for structured ABS which was reducing kinetic friction on dry snow, contrary to all the other gliders. We assume that whether optimal wideness of the plateaus of the stone grind texture lead to minimal interlocking, advantageous geometry of the microscopic polymer-snow contacts (low micro roughness) or enhanced melt water generation by increased pressure at the contact points could explain the measured low friction (Fig. 5 left).

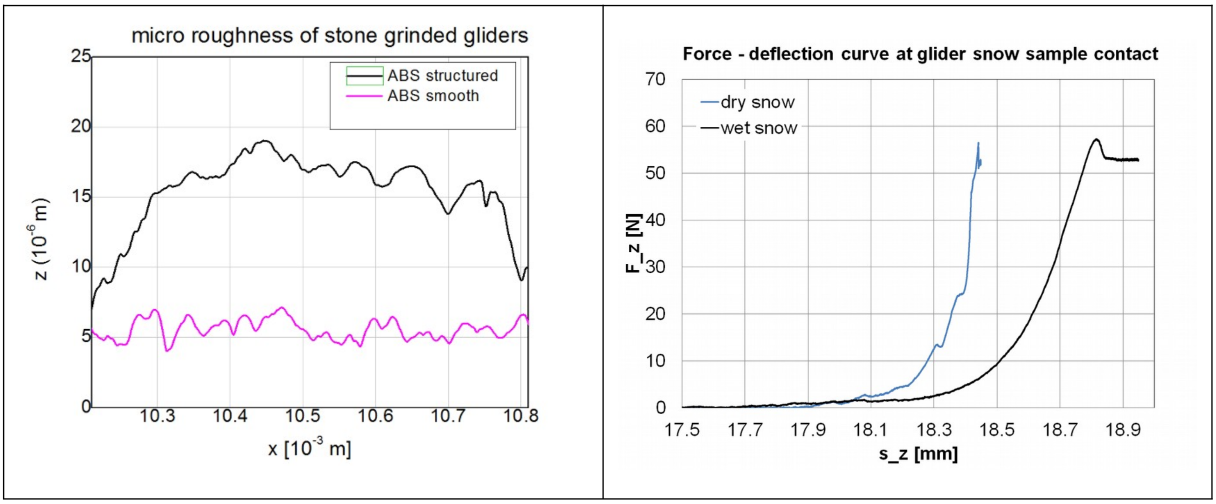

Fig. 5. Left: micro roughness of three stone grinded gliders of different polymers. Right: force – deflection at glider-snow contact.

4.2 Test Design & Samples

The presented snow friction test design proved a high sensitivity on material properties and surface structure parameters, especially for the wet snow configuration. Both snow sample preparation and friction measurements showed good reproducibility. Although the amount of wet snow friction data was rather small, statistical significant and strong dependencies were found. Subjective comparisons with real scale gliders on the field proved the test design as valid for the desired low speed application focusing on the stick-slip transition while starting to glide. Processes connected to larger amounts of generated melt water occurring at higher speeds are not considered by this test design. Some missing data and the low number of tests have to be considered critically from a scientific point of view, but the method and the study presented were adequate for the aimed polymer selection for snow friction related product development.

Due to the different mechanical properties of the polymers (viscosity, stiffness) the same grinding procedure obviously led to variations in the resulting surface roughness of the gliders up to a factor of 2. The smooth samples had even larger differences of roughness due to different manufacturing processes and material properties. As known from XC-ski grinding, R_a-values range from approximately 1 to 5 µm for coldest to warm and wet snow conditions [31]. The differences among the analyzed samples have therefore been considered as relevant and made the evaluation of the polymers' snow gliding performance more difficult.

The differences in roughness, the suspected heterogeneity of the glass fiber reinforced samples as well as the glass fibers sticking out of the surface, limited the dynamic contact angle measurement's validity. Nevertheless, measured advancing angles largely corresponded to values found in the literature. POM and PA both showed slightly higher values, whereas for HDPE slightly smaller values were measured [32 - 35].

5 Conclusions

Whereas on dry snow most of the tested engineering polymers revealed low friction, comparable to HDPE, none of the tested polymers showed the desired low friction coefficients on wet snow. Structured ABS gliders came closest with friction coefficients of 15 to 40% higher than HDPE. Applying typical ski base surface textures by stone grinding did not reduce the friction values sufficiently. To the contrary, on dry snow structuring was even increasing the friction coefficients. Especially the glass fiber content of the tested PA compounds, which is used to provide the desired structural engineering properties, caused the extraordinary high friction values. The application of hydrophobic additives reduced wet snow friction, but were not able to realize the desired benchmark performance. Although POM showed promising low friction on dry snow, it was excluded from the wet snow measurements, as it was clear that POM would not meet the desired low material costs for the aimed mass winter sport products.

The study showed that snow friction is a complex interplay of surface topography, hydrophobicity and mechanical properties, especially on wet snow. Therefore, structuring procedures and topographies for optimal gliding altered for a specific material is not necessarily applicable for another material. The correlation of COF and contact angle measurements showed that hydrophobicity is the key factor for good gliding properties on wet snow. On dry snow, surface roughness has a stronger influence than hydrophobicity. Nevertheless, other material properties should not be neglected. Snow has clearly the strongest influence on the polymer - snow friction because it is a highly variably material with quickly changing physical properties.

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