Open Access Series ISSN 2509-9442

GLIDING

Article 4(2017) 19-23

source: www.team-snowstorm.de/Gliding

Ski preparation as a three-dimensional problem

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ARTICLE INFORMATION

Key Words:

snow condition
ski friction

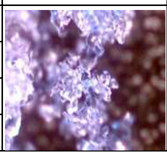
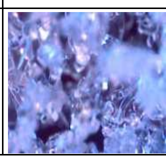
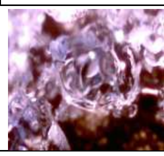
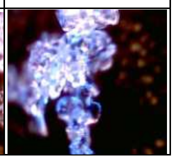
ABSTRACT

Everyone who skis knows that waxing at temperatures around the freezing point is a challenging task. It seems to exist no standard remedy to make the ski sliding on all types of snow. Waxing is much easier for conditions of low temperature or high humidity of the snow. Using a portable friction measuring device, a large variety of snow conditions was tested. The results prove that for either high snow humidities around the freezing point or dry snow at low snow temperatures the friction coefficient converges to a constant value. In the vicinity of the freezing point at low snow humidities, however, friction shows large scatter which is mainly influenced by the grain size of snow.

1. Introduction

Experiments with a portable tribometer were carried out over a time span of 4 years. During this time 100 data sets containing snow temperature, snow humidity, snow grain size and grain shape were recorded. Table 1 shows a small selection. More than 40 data sets additionally include static and dynamic friction coefficients. The measured friction values stretch over a range from 0.01 to 0.6 which corresponds to slipping on a fresh banana shell for the first case and walking on a carpet for the second case. The snow temperature ranged from 0°C to -18°C (for the friction tests from 0°C to -12°C) and the snow humidities from 10% to 100%. Thus, a large range of conditions was covered. In addition to the measurements, snow was analyzed using an optical microscope. The insets of Tab. 1 show photos of snow of an area of 3 mm by 3 mm. For each photo an average grain size was determined. The total range of grain sizes was 100 µm to 1,000 µm covering the most probable cases in the field.

Tab. 1: Selection of measurement data.

date		30.12.2010	02.01.2011	02.01.2011	03.01.2011	03.01.2011
air temperature	°C	0	0	0	-1	-1
air humidity	%	80	80	80	76	76
air pressure	hPa	-	1019	1019	1015	1015
snow temperature	°C	-2	-0,5	-0,5	-1,5	-1,5
snow humidity	%	13	13	10	13	13
static friction		0,25	0,4	0,6	0,35	0,4
dynamic friction		0,1	0,1	0,4	0,05	0,05
						

2. Experiments and Analysis

Experiments were performed using a portable tribometer with a sliding body made of ultra-high molecular weight polyethylene (uhmwpe). The sliding body was untreated. No ski wax was applied. Friction was measured against snow of varying grain size at different temperatures and humidities of both snow and air.

2.1 Tribometer

A tribometer is a device which applies a defined normal force F_n to a sliding body and determines the lateral force F_l, necessary to move this body. The output of such a measurement is the coefficient μ as defined by:

$$\mu = \frac{F_l}{F_n} \quad (1)$$

The coefficient of friction is dimensionless and can adopt values between 1.0 and 0.001 for snow and ice [1, 2, 3, 4]. Static friction μ_s refers to the state when the system starts to move, whereas dynamic friction μ_d describes the state of sliding. The coefficient of friction is a function of temperature, humidity, snow grain size and shape and properties of wax and polymer. In addition, the topography of the ski sole plays an important role.

The tribometer consists of a body containing a spiral spring to generate a spinning motion of a sliding body made of a metal cylinder that holds a foil of ultra-high molecular weight polyethylene (= specimen) on its flat side, see Fig. 1. Similar to a ground ski sole, the specimen carries grooves. The normal force is generated by the weight of the tribometer, resulting in a contact pressure similar to the contact pressure exerted by a skier on a pair of cross country skis. To determine the static coefficient of friction, the device was placed with its flat circular sliding area on snow. Then, using a handle, the device was turned around its vertical axis until the spiral spring in the body of the device reached a point where the spring force equaled the static lateral force. At this point the device locked and displayed the static coefficient of friction. In order to determine the dynamic coefficient of friction, the spiral spring had to be charged first by turning the metal cylinder to a fix position. The spring was released by a manual trigger, setting the cylinder in motion until friction stopped the revolutions. This value was interpreted as dynamic friction. The lower friction is, the more revolutions the cylinder can carry out. The range of detectable coefficients of friction spans from 1.0 to 0.01. The average sliding velocity was 1 m/s.

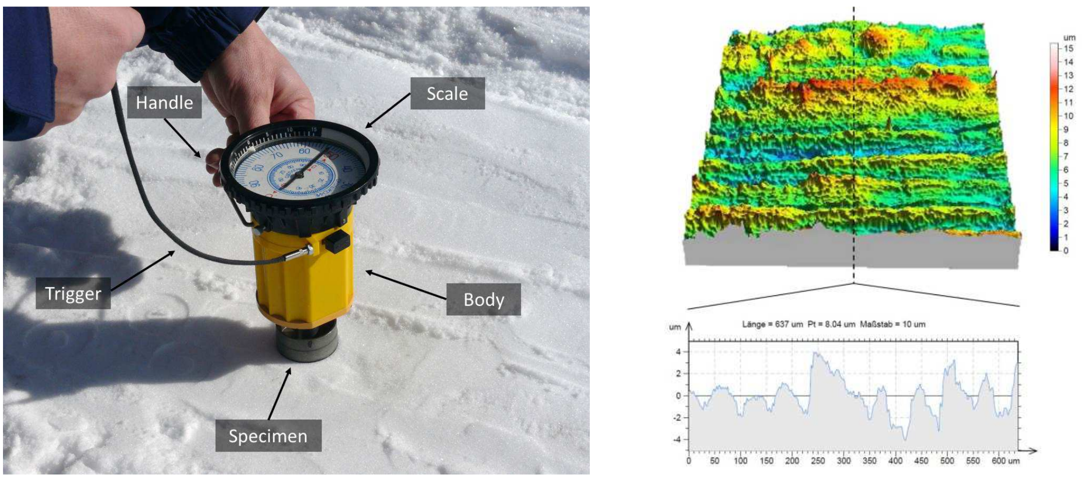


Fig. 1: Left: Portable tribometer. Right: Microscopy image of the polyethylene foil and cross section.

Before each friction test the sliding area was cleaned with alcohol. The whole device was given enough time to adjust to the local conditions. The tests were carried out on natural, artificial and combinations of both types of snow.

2.2 Analysis

Snow humidity was measured with a capacity stray field sensor (Typ 011, Doser Messtechnik GmbH & Co. KG, Germany). Air and snow temperature as well as air humidity were determined with a Testo 635 device (Testo AG, Germany). Air temperature and air humidity were measured close to the snow surface, whereas snow temperature was determined using a contact probe thermometer. The probe was placed in the same depth as the capacity stray field penetrates into the snow. To obtain images of the snow, a digital microscope with a magnification of 60 times was used. Snow was placed on a cooled plastic carrier and illuminated with cold LED light to obtain images with good contrast.

3. Results

3.1 Snow temperature and snow humidity

Each field test started with the measurement of snow temperature and snow humidity. The covered temperature range was 0°C to -18°C. Snow humidity ranged between 10% and 100%, see Fig. 2. The data show, that at small snow temperatures only small snow humidities occur. Close to the melting point humidity data fan out and cover a range between 10% and 100%. This behavior is caused by the fact that snow is not a homogeneous substance. Snow contains air in the space between the grains. Due to grains of different shape and size this space is unevenly distributed [5, 6, 7]. In addition, during the phase change of water from solid to liquid temperature remains at 0°C and the water content between the grains gradually increases. This behavior is underlined by the inset of Fig. 2 showing the coefficient of friction as function of snow temperature, measured with the help of a pin-on-disk snow tribometer [8]. Friction is high at low temperatures, decreases with increasing snow temperature and increases again for temperatures approaching 0°C. The minimum stretches over a range of about 5 K. As the water content gradually increases, friction increases as well. It is therefore important to determine whether friction is measured at the onset of melting or at the end of the phase change.

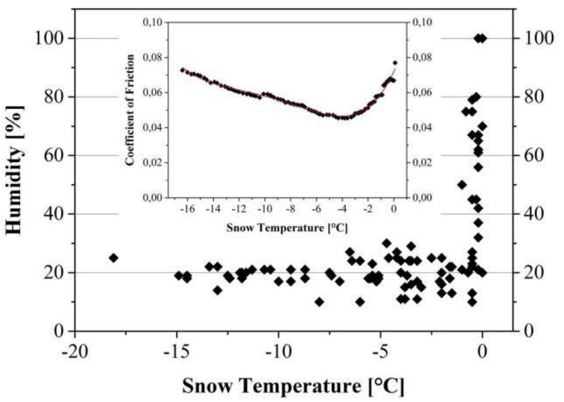


Fig. 2: Snow humidity as function of snow temperature.

It is interesting to note that between snow and air humidities no correlation was found. Whereas snow humidities increased with increasing snow temperatures, air humidity measured close to the snow surface kept constant. This is a characteristic of the local equilibrium between snow, air and water vapor. This equilibrium can be disturbed by air motion.

3.2 Friction tests

Static and dynamic coefficients of friction are displayed in Fig. 3. As common in tribology, static coefficients are higher than the dynamic ones. At the left hand side of the figure friction is shown as function of snow humidity. For low snow humidities the friction coefficients cover a range between 0.01 and 0.6. As snow humidity increases the scatter decreases and vanishes at about 75%. A similar behavior, however reversed, can be shown for increasing temperatures. Beginning at -7°C the scatter of the coefficients of friction intensifies and covers a range between 0.05 and 0.6.

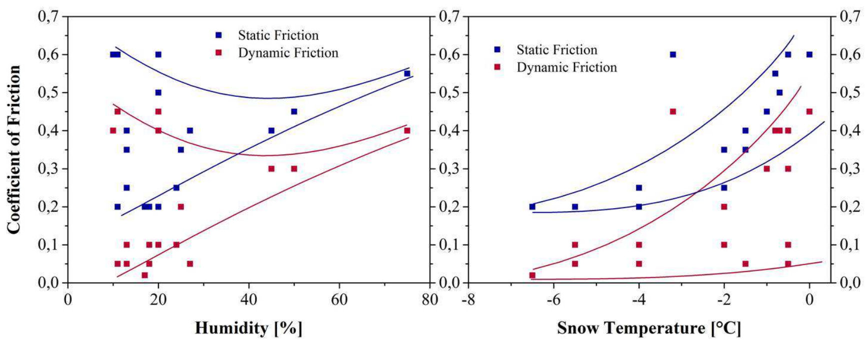


Fig. 3: Static and dynamic coefficients of friction as function of snow temperature and snow humidity.

To receive an overview, friction data were arranged as function of snow temperature and snow humidity, showing that the resulting cube is not completely filled with data points. For low temperatures and high snow humidities friction saturates at constant level, whereas close to the melting point a large variety of data points was measured. This effect does not exist when either snow humidity is high or snow temperature is low. At the end points the tribological system behaves quite stable whereas around 0°C the system is strongly influenced by a change in boundary conditions which have to be identified. To guide the eye a wire frame was introduced, see Fig. 4.

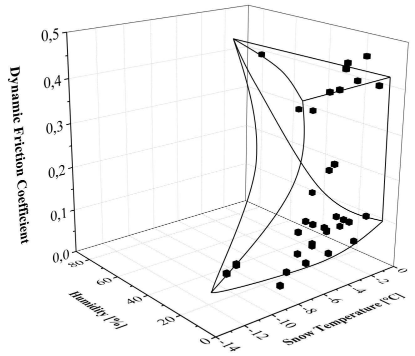


Fig. 4: Dynamic friction as function of snow temperature and snow humidity.

4. Discussion

In order to identify the reason for the data scatter between minimum and maximum friction, detailed analysis of the structure of snow was necessary. Since all data sets contain microscopy images of the snow grains, an average grain size was determined. Figure 5 shows the coefficient of friction as function of the snow grain size. According to this diagram low coefficients of friction are caused by large grains. The inserts show representative images of the snow leading to high friction – grain size 100 µm – and to low friction with grain sizes above 500 µm.

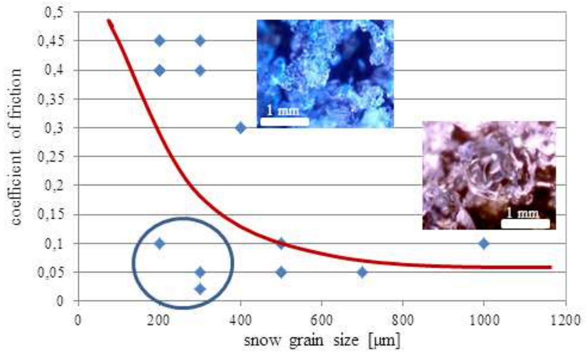


Fig. 5: Dynamic friction as function of snow temperature and snow humidity.

Despite the instructive dependence, the fit is not 100%, since at least 3 data points exhibit low friction although the grain size is small. This deviation points to the fact, that the coefficient of friction not only depends on the grain size, but on a wider range of parameters. First off all, the assumption of round grains only partly holds. Especially for small grains edges were detected, since this kind of snow did not have enough time to transform.
Another parameter neglected so far is the structure of the ski sole. It is assumed that there exists an optimal ratio between grain size and roughness parameters. However, these roughness parameters have not been identified yet and must be topic of further research.

5. Conclusions

The following conclusions can be drawn:
-Snow temperature and snow humidity create a three-dimensional space for the coefficient of friction that is partly filled with data.
-At low snow temperatures and high snow humidities friction aspires toward a constant value.
-Around the melting point friction coefficients cover a range from 0.01 to 0.1 depending on boundary conditions like grain size, grain shape and grinding structure.
-Intensive snow microscopy in needed in order to minimize waxing errors.

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Acknowlegment: The authors would like to thank Matthias Ahrens of Team Biathlon Canada for his comments!