Diss. ETH No. 18857

Polymers on snow
Towards skiing faster

A dissertation submitted to

ETH ZURICH

for the degree of
Doctor of Sciences

presented by

Jan Lukas Giesbrecht

Dipl. Werkstoff-Ing. ETH
born May 3, 1979
citizen of Bern, Switzerland

accepted on the recommendation of

Prof. Paul Smith, examiner
Prof. Nicholas D. Spencer, co-examiner
Dr. Leon E. Govaert, co-examiner
Dr. Theo A. Tervoort, co-examiner
Michael Jufer, co-examiner

2010

Contents

"It is not the critic who counts; not the man who points out how the strong man stumbles, or where the doer of deeds could have done them better. The credit belongs to the man who is actually in the arena, whose face is marred by dust and sweat and blood; who strives valiantly; who errs, who comes short again and again, because there is no effort without error and shortcoming; but who does actually strive to do the deeds; who knows great enthusiasms, the great devotions; who spends himself in a worthy cause; who at the best knows in the end the triumph of high achievement, and who at the worst, if he fails, at least fails while daring greatly, so that his place shall never be with those cold and timid souls who neither know victory nor defeat."

T. Roosevelt, *Citizenship in a republic: The Man in the arena*, *Speech at the Sorbonne*, Paris, April 23, **1910**.

To my parents

Summary

In the continued quest to reduce friction between mobile surfaces, that between the sole of a ski and snow stands out because of its long history of debate, the joy of skiing, as well as the notion that understanding of this complex issue may have broad, more general implications. For decades, a wide spectrum of parameters involved has been studied, and different theories advanced, that resulted, however, in only modestly successful guidelines for the creation of faster skis.

The work presented in this thesis was directed towards unvealing the influence of the surface chemistry and structure on the tribological properties of a slider sole gliding on snow.

Due to problems with existing techniques used to evaluate sliding surfaces on snow, a major effort was made to develop and validate a new experimental test method with scaled-down systems. Highly beneficial in the development of the new method was the introduction of a correction factor to the times of descent, t_e, which led to improvement of the accuracy of the measurements of t_e. This factor takes into account that t_e of a slider increases with repeated passes over a track. In addition, a dimensionless time of descent was introduced which permitted comparison of results obtained on tracks with the same slope angle but different track lengths and size of the slider and skis.

Using the method developed, we determined an optimum surface roughness range ($0.2\ \mu m < R_a < 1 \mu m$, R_a: arithmetical mean surface roughness), under the conditions experienced in an indoor ski hall in Germany (snow temperature -4 to -2 °C), for tribological properties that are virtually independent of the chemical composition of the slider soles and the orientation of the surface texture. However, if the surface roughness was of lower values, the influence of the chemical nature of the slider soles became substantial. Hydrophobic surfaces experienced lower frictional forces than their hydrophilic counterparts, of the same R_a. Furthermore, at R_a values above the optimum range, the experienced friction force was found to be governed by the orientation of the surface texture: the more a structure was aligned in the gliding direction, the less important was the increase in the friction.

The observed correlations may be explained by the interaction of the surfaces with the friction-induced water films, on which the skis glide. The thickness of those water films in our experimental conditions were estimated to be in the range of 0.1 to 0.2 µm. Advantageous

tribological characteristics were observed for R_a values from 0.2 to 1 µm, which is just above the thickness of the water film. These findings lead us to introduce the concept of an optimal microscopic contact area. In this approach we hypothesize that surfaces of the localized contact spots on which a ski glides with optimum roughness are not completely wetted by the water film and would effectively reduce the contact area between the water film and the ski sole and, hence, reduce the frictional force when compared with a fully water-covered surface which would lead to increased drag through capillary suction. Conversely at R_a values higher than the optimum range, the structure starts ploughing into the snow track resulting in an increase in the frictional force. The ploughing effect is consistent with the observed dependence on the orientation of the surface texture at higher R_a values, since the oriented surface structures minimize the total ploughing surface.

Furthermore, addition of only a few grooves (between 2 to 10) was found to further decrease the friction properties of a ski sole. One reason for this finding could be a guiding effect that these lines exert on the gliders.

Zusammenfassung

Das Phänomen des Gleitens eines Skis auf Schnee fasziniert Skifahrer und Wissenschaftler schon seit Jahrhunderten. Seit den frühsten Anfängen wurde versucht, Skis so herzustellen, dass sie möglichst wenig Reibung auf Schnee erzeugen. Auch von wissenschaftlicher Seite ist dieses Phänomen interessant, da die Reibung zwischen zwei Festkörpern oft durch einen Schmierfilm verringert wird, ähnlich dem Wasserfilm der zwischen Ski und Schnee zu finden ist. Entsprechend könnten die Erkenntnisse dieser Arbeit von grösserer Tragweite sein als „nur" für die Entwicklung zukünftiger Skibeläge. Seit Jahrzehnten wurden verschiedenste Parameter in diesem System untersucht und verschiedene Theorien aufgestellt wie ein optimaler Skibelag aussehen müsste. Alle Bemühungen resultierten bisher jedoch nur in allgemeinen Erkenntnissen, wie zum Beispiel, dass ein Skibelag hydrophob sein müsse.

Die hier präsentierte Arbeit untersucht den Einflusses von Oberflächenchemie und Oberflächenstruktur auf die Reibungseigenschaften auf Schnee.

Da bis anhin genutzte Messmethoden ungeeignet für unsere Messreihen waren, wurde eine grundsätzlich neue Testmethode entwickelt und validiert. Diese basiert auf der Verwendung von Modellversuchen mit kleinen Gleitern. Hierbei zeigte sich, dass sich bei wiederholten Fahrten über dieselbe Spur die Abfahrtzeit eines Gleiters kontinuierlich vergrösserte (linearer Trend). Durch die Anwendung eines Korrekturfaktors kann diese Abweichung kompensiert werden. Zusätzlich wurde eine dimensionslose Abfahrtszeit eingeführt, mit welcher der direkte Vergleich von Messungen auf Strecken mit unterschiedlicher Länge und unterschiedlichen Gleitern bei gleicher Steigung möglich wurde.

Mit der obengenannten Messmethode wurde ein optimaler Rauigkeitsbereich (0.2 µm < R_a < 1 µm, R_a: Mittenrauwert) für die Bedingungen, wie sie am Durchführungsort der Messungen (Indoor Skihalle, Schneetemperaturen von -4 bis -2 °C) vorgeherrscht haben, festgestellt. Hierbei war nur ein minimaler Einfluss der Oberflächenchemie oder der Orientierung der Struktur auszumachen.

Bei einer Reduktion der Oberflächenrauigkeit (R_a < 0.2 µm) des Gleiters erhöhten sich die Reibungseigenschaften der Gleiter drastisch und der Einfluss der Oberflächenchemie wurde beträchtlich: Hydrophobe Skibeläge zeigten deutlich geringere Reibungswerte als hydrophile bei gleicher Rauigkeit (R_a).

Besass der Skibelag eine grössere Oberflächenrauigkeit als im optimalen Fall (R_a > 1 µm), so konnte eine Abhängigkeit der Reibungseigenschaften von der Orientierung der Struktur festgestellt werden: Je mehr eine Struktur in Richtung der Gleitrichtung des Skis orientiert wurde, umso geringer war der Anstieg der Reibung.

Die hier beobachteten Abhängigkeiten lassen sich erklären, wenn man sich die Interaktion der Oberflächen mit dem reibungsinduzierten Wasserfilm, auf welchem ein Ski gleitet, vor Augen führt. Die Dicke dieser Wasserfilme lässt sich für die gegebenen Bedingungen auf 0.1 bis 0.2 µm abschätzen. Strukturen mit optimalen Reibungseigenschaften wurden im Bereich von 0.2 bis 1 µm R_a gefunden, was unmittelbar über dem Bereich der Wasserfilmdicke liegt. Diese Übereinstimmung veranlasste uns, das Konzept einer mikroskopischen Kontaktfläche einzuführen. Dieses Konzept beschreibt, dass die Fläche der einzelnen Kontaktpunkte, welcher der Ski mit der Piste hat, nicht vollständig benetzt werden, wenn die Oberfläche eine optimale Rauigkeit aufweist. Somit würde die effektive Kontaktfläche zwischen dem Ski und dem Wasserfilm verringert und damit die Reibung reduziert, indem die Kapillarkräfte reduziert werden.

Auf der anderen Seite kann das Ansteigen der Reibung bei hoher Rauigkeit mit einem „Pflügen“ der Struktur im Schnee erklärt werden. Diese Hypothese deckt sich mit der experimentellen Beobachtung, dass eine Struktur, die in der Gleitrichtung orientiert ist, den geringsten Widerstand bietet und somit den Anstieg der Reibungswiderstandes minimiert.

Im Weiteren wurde ein reibungsreduzierender Einfluss durch die Einbringung einer geringen Anzahl Rillen (zwischen 2 und 10) im Belag festgestellt. Der Grund für dieses Verhalten liegt höchstwahrscheinlich in einem Führungseffekt, den die Rillen herbeiführen.

Chapter I

Introduction

1. History of skiing

The use of skis dates back to pre-Christian times with the oldest evidence reported to be in 6300 BC.[1] Rock carvings reveal how skis were employed in earlier times[2] (cf. Figure 1) and how skiing evolved as an alternative to snow shoes as a means of transportation over snow.

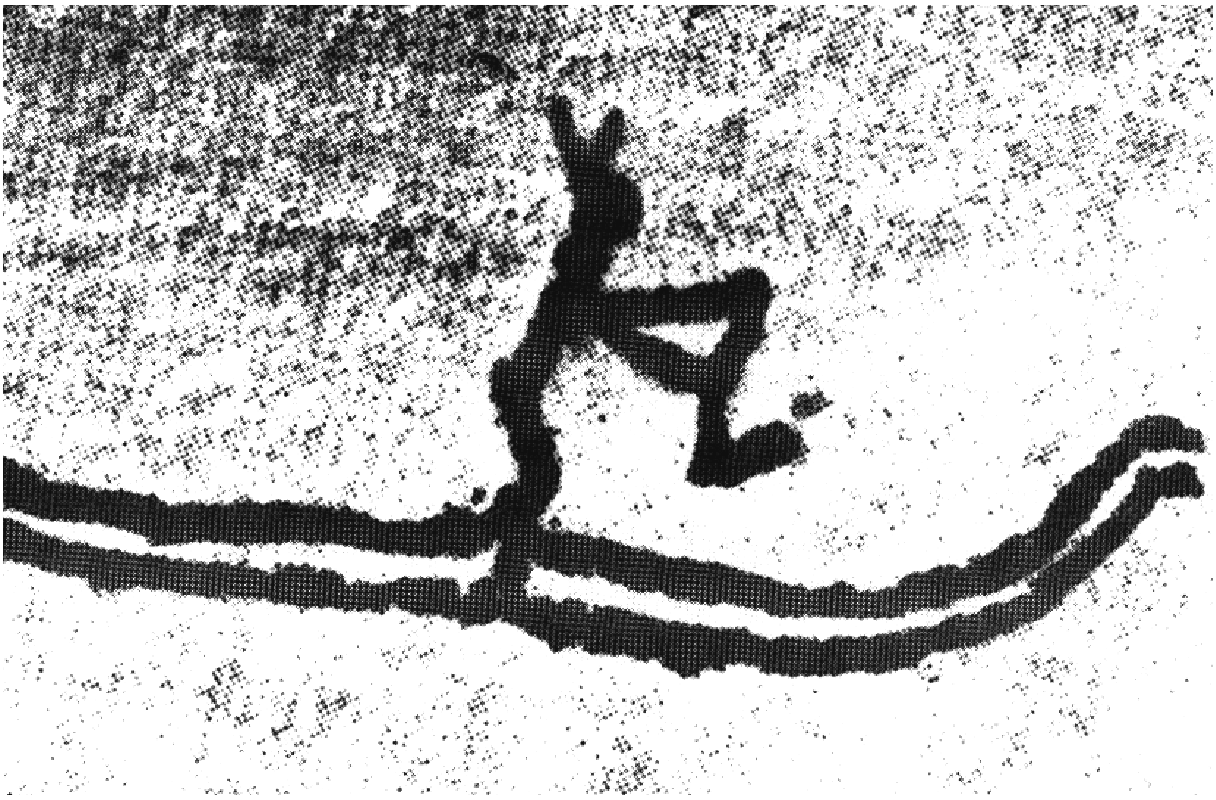


Figure 1: Image from Rødøy, Norway, symbolizing a hunter on skis, ca. 2500 BC (Norwegian Ski Museum, Oslo).

The earliest skis pairs were of uneven lengths consisting of a long ski which was used for sliding and a short one to brake and climb. The long ski measured up to 3 meters in length and had a smooth surface to promote sliding. By contrast, the small ski typically did not exceed 2 meters in length and was often covered with animal skin which allowed the ski to slide in only one direction[3] (Figure 2). By 1840 skis with equal lengths were common in Scandinavia.

The skiing technique as we know it today originated in the Telemark region, Norway, around the 1860's and takes its name from that region. The Telemark technique is characterized by the toes fixed onto the ski and a strap around the heel.

The skis were rather long and just a bit wider than the width of a foot. The sides of the skis had a curved shape which enabled easier turns. Skiing evolved increasingly into a recreational activity and soon afterwards competitions began to take place regularly.

Figure 2: Image from Johannes Schieffer in “The history of Lapland”, Norway in 1674.[3] The picture shows the uneven length of the skis used during that period of time.

Skiing was introduced as an Olympic sport at the winter Olympics in 1924 in Chamonix, France with events in ski jumping and Nordic combination, in which the results of jumping and cross-country skiing were combined. Alpine skiing followed at the Olympics in Innsbruck, Austria in 1936. The increased control over the ski required in Alpine skiing led to a new binding configuration in which the toes and the heel of the boots were both fixed onto the ski.

From a material science point of view, the shift of skiing from being a means of transportation to a sport dramatically accelerated the technological development of skis. Until the end of the 19th century, skis were still being made out of wood. Subsequently laminated wooden skis were produced, comprising a hickory bottom layer with a top layer of pine or ash. In addition, the use of steel edges became common. The sandwich construction of the skis was further refined by Howard Head in 1950; he constructed and sold the first ski which was build with aluminum and wood and had a phenolic running surface and steel edges. Around 1955 polyethylene was introduced commercially as a ski base by Kofler in Austria and soon later by InterMontana in Switzerland. It was sold under the brand name P-tex and rapidly replaced the other ski base materials on the market. In 1960 another revolution in the ski manufacturing took place with Franz Kneissel introducing a ski constructed with epoxy resin and glass fiber. The glass fiber based skis quickly replaced the wooden skis and by 1976 at the Nordic ski world championships in Falun, Sweden, the majority of the competitors used such fiberglass skis. At this event the world's first championship title was won on "plastic" skis (Thomas Magnusson, Sweden) and the world's last championship title on wooden skis was won by Magne Myrmo, Norway.[4]

Since polymers were first introduced as a ski base material, ultra-high molecular weight polyethylene (UHMW PE) has prevailed as the most widely used. This is mainly because of its high wear resistance, its high hydrophobicity and, relatively, affordable price.

2. Snow

The formation of snow starts in the atmosphere with a nucleating particle in a cloud. With the nucleation of an ice crystal a proto-snowflake is created upon which water vapor condenses, causing growth of the flake. Depending on the conditions (e.g. temperature and humidity of the surrounding air) ice crystals of different morphologies form (cf. Figure 3). While these crystals generally have a hexagonal structure, the classical snow crystal in the form of a star is only one of the possible conformations. Once the crystals reach a critical mass they are pulled towards the ground by gravity;[5] i.e. "it snows".

When the snowflakes reach the ground they accumulate into a cover and, as they often are at a temperature close to their melting point, rather quickly lose their atmospheric shape. The final structure of the snow grains depends on the temperature gradient in the cover. When there is no or only a small temperature gradient, the convex areas of the crystals tend to disappear by sublimation and the crystals become more and more evenly rounded particles (isothermal metamorphism), and the snow cover compacts and sinters together. If a large temperature gradient is present in the snow pack, the gradient metamorphism will dominate and transform the crystals into a prismatic form. This results in a loose snow cover which will not compact.[7] If the temperature in the course of the day is close or above the melting temperature of ice or the irradiation of the sun is intense, the snow crystals partly melt during the day. When the water then freezes over night, a solid ice-like snow cover is the result (melt-freeze metamorphism).

Hence, a snow cover can be built up of various different shapes of ice crystals and different layers, depending on the conditions under which they were formed.[8]

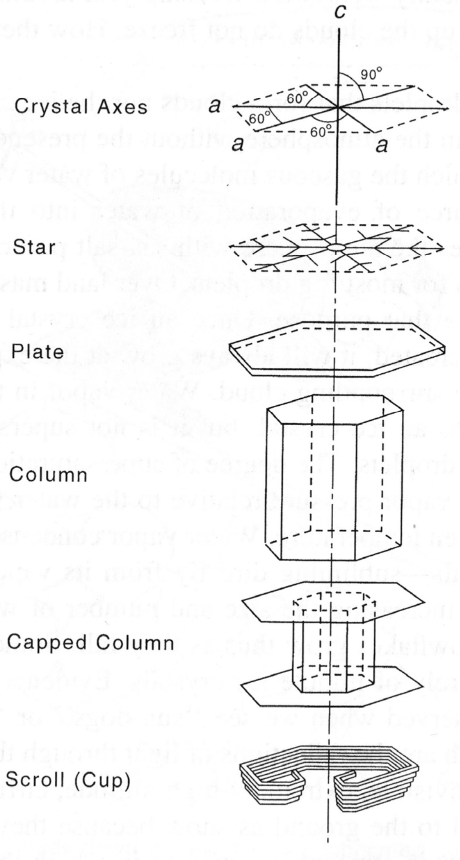


Figure 3: Principal types of atmospheric snow crystals.[6]

Artificial snow

During the past decades artificial snow increasingly contributes to the snow cover in all major skiing areas and is used extensively for the preparation of slopes for competitions. The technology of making artificial snow mimics the natural process of snow formation. The most common technique employed is the jet method, in which high pressure air guns are used to inject a mixture of small water droplets and air about 10 to 20 m above the snow cover. With the supercooling induced by the expansion of the air at the exit of the air gun and the surrounding temperature, the droplets freeze while falling to the ground. This process typically results in spherical particles with a diameter in the range of 100 to 800 μm.[5,6]

3. Processing of snow

In order to facilitate skiing, mechanical processing of the snow cover is applied to create and maintain ski slopes. This is initiated at the very beginning of the winter season with leveling and compacting of the snow. In later stages maintenance of an even track is needed and for races and Nordic ski tracks, hardening of the track surface is required.

Preparation of the snowpack is accomplished with grooming machines, as depicted in Figure 4. The grooming machine uses a snow tiller (a cylinder with spikes) attached to the back of the vehicle which breaks the snow into globular particles by fast rotation. The reduction in the size of the snow grains and the creation of a narrow granular distribution results in a more densely packed snow cover.

A secondary effect is warming up of the processed snow layer, which leads to faster sintering and, hence, solidification of the snow pack. The literature mentions that as a rule of rule of thumb a freshly processed slope needs about 8 hours after grooming to achieve its maximum hardness. Finally, for competitions, the preparation often involves an additional step in which water is injected a few centimeters deep into the snow pack to further enhance the hardness of the top layer.[6] Typically, ski tracks feature hardness values between 10^4 to 10^5 Pa.[10]

Figure 4: Grooming machine with front blade and lowered snow tiller (brochure Pistenbully 600[9]).

4. Sliding

Since medieval times glide enhancing coatings have been applied to skis to improve their performance. Johannes Scheffer mentions in his book in 1674 the application of pitch and rosin,[3] and until the 1950's, when the first plastic ski bases were introduced, (wooden) ski bases were coated to render them more wear resistant and less hydrophilic. Various coatings were employed; for example, Skigliss (consisting of natural resin) produced by TOKO (introduced in 1933).[11] After the Second World War paraffinic waxes were introduced; the latest development was that of fluorinated waxes since the 1990's.

Despite the wide use of coatings to enhance the performance of skis, the mechanism causing friction between runners and snow was the object of guesswork. First attempts to put this phenomenon on a more scientific base were made in the late 1930's by Bowden and Hughes who advanced the fundamental ideas of the melt-water lubrication theory.[12] They argued that the low friction experienced between a ski and snow is due the presence of a thin film of water which is caused by frictional heat – a concept that is widely accepted today.

However, a number of authors have demonstrated that the water film separating the sliders and the snow is thin,[13-16] hence, the assumption that all contact spots between a slider and snow are separated by water is not likely to be correct.

Detailed analysis by a multitude of authors of the friction between a slider and snow resulted in the identification of a number of contributions to the friction coefficient, μ, summarized as:

$$\mu = f(\mu_{dry}, \mu_{lub}, \mu_{plough}, \mu_{cap}, \mu_{el}, \mu_{dirt})$$

$\boldsymbol{\mu_{dry}}$: Dry friction occurs when the melt-water lubrication is absent or insufficient; this is the case at low temperatures (< -20 °C) or at low sliding speeds. In addition, dry friction is believed to take place at the tip of a ski.[17] Thus μ_{dry} represents the contribution of deformation and fracture of snow particles.[18]

$\boldsymbol{\mu_{lub}}$: Lubricated friction accounts for the hydrodynamic forces associated with shearing the water film between the slider and the snow. Model calculations showed that this contribution passes through a minimum with increasing speed, and that it increases with an increase in contact area and thickness of the water film.[14,19]

μ_{plough}: Ploughing and compaction of the snow by the slider can constitute a significant fraction of the total friction coefficient, especially if the snow track is not sufficiently compacted. It also accounts for the pushing snow aside by the slider. This contribution is drastically reduced on groomed slopes.[20]

μ_{cap}: Capillary attraction (capillary suction) occurs between the surface of the slider and the snow through liquid bridges,[14] which exert a resistive force on the slider due to contact angle hysteresis.

μ_{el}: Electrostatic forces result from charging of the ski sole which causes friction with the snow cover.[21-23]

μ_{dirt}: Resistive forces resulting from accumulation of dirt particles onto the ski sole, which can be caused, for example, by electrostatic charging of the sole.[10]

The present understanding, regarding the friction between skis and snow is a combination of the above factors. The influence of the various processes and phenomena depends strongly on the conditions present during sliding. For instance, as noted above, dry friction dominates at low temperatures and is less critical at higher temperatures. On a groomed slope the importance of ploughing is small, which is most often the case of interest. At ordinary temperatures, the main contributions are the dry and lubricated friction while capillary suction becomes important with a thicker water film, which occurs at higher temperatures. The influence of accumulation of dirt is highly dependent on the dirt concentration on the track. Finally, the contribution of electrostatic charging is not clear yet, but is believed to increase at lower temperatures and higher speeds.[22,24]

The actual friction that a ski experiences on snow at different temperatures resulting in different thicknesses of the friction-induced water layer is schematically shown in Figure 5. At low temperatures, below -30 °C, the ski experiences essentially dry friction as the frictional heat is not sufficient to melt the snow. When moving to intermediate temperatures (-10 to -1 °C) the friction is gradually reduced due to the creation of a melt-water film. A further increase in temperature yields again an increase in friction of the slider as the melt-water film thickens and initiates an increase in contact area resulting in capillary drag.

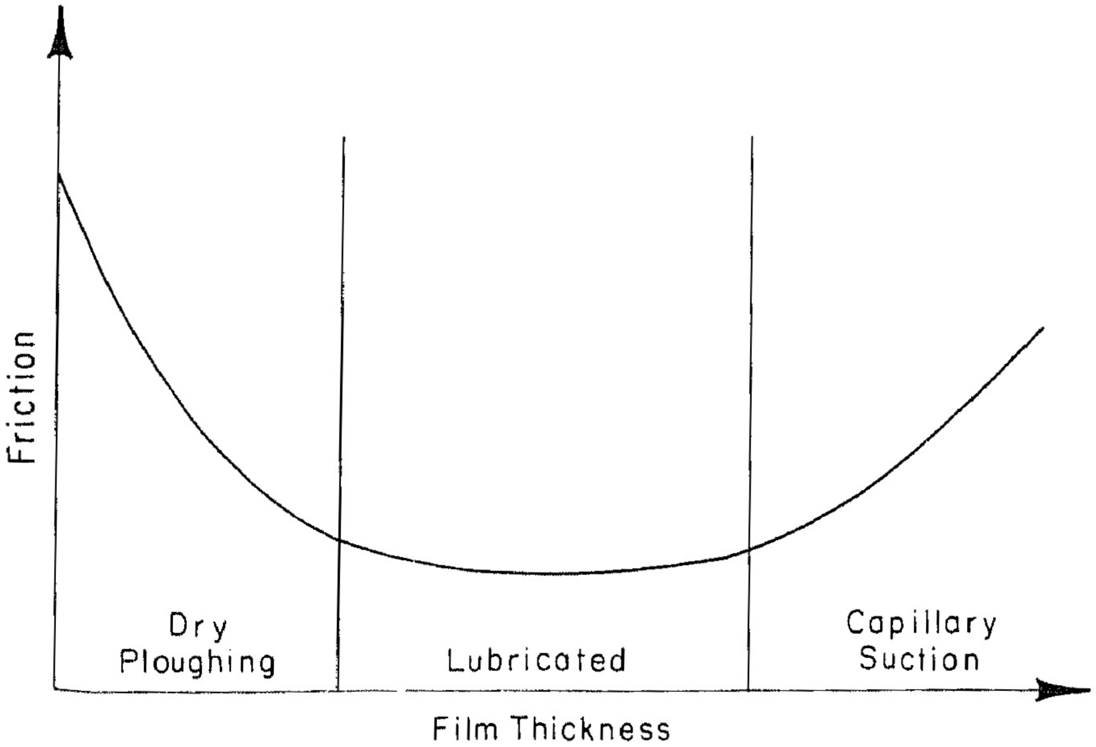


Figure 5: Schematic of the tribological phenomena of a ski on snow with increasing water film thickness. The figure was reprinted from a publication of Colbeck.[14]

5. Experimental observations

In the following a short summary is given of various findings reported in studies of sliding on snow or ice. The sections are structured so that - where possible - the influence of a single experimental parameter on friction is addressed.

Speed

At low temperatures the coefficient of friction decreases with increasing speed (v) on snow and ice tracks.[12,25] Evans *et al.* and other authors concluded from their experiments that the friction coefficient in this temperature range is proportional to $v^{-0.5}$.[26,27]

At temperatures close to the melting point of snow the friction coefficient passes a minimum at low speeds and increases with higher velocities.[28]

Pressure

At intermediate temperatures (-10 to -1 °C) the friction coefficient, μ, remains approximately constant when the surface pressure to a slider is altered[12,16,29-33] (in the range up to about 100 g/cm^2), while at higher pressures a decrease in the friction coefficient has been observed.[19,26,33,34] At lower temperatures (T < -10 °C), the friction coefficient decreases with increasing pressure in the full range of surface pressures.[17,19,32]

Temperature

The effect of temperature on the fiction of a slider on ice and snow can be summarized as follows: At very low temperature (around -40 °C) the friction coefficient of slider on snow and ice is essentially as high as on sand or concrete.[35] With increasing in temperature the friction coefficient continuously decreases until a minimum close to just below 0 °C is reached.[12,17,35] Thereafter, the friction coefficient increases again at increasing temperature.[32]

Snow surface

The friction coefficient decreases with increasing grain size of the snow track with the effect leveling off at grain sizes in the range of 3 mm.[17,34] This concurs with the generally accepted notion that newly fallen snow is more “aggressive” (corresponding to the higher friction experienced) than old and dense snow. An explanation for this is the metamorphosis of the snow in which the ice crystals transform to larger and more globular shapes.[6]

Slider chacteristics

***Thermal conductivity*:** At low temperatures a slider with lower heat conductivity experiences a lower friction coefficient. However at temperatures around 0 °C the influence of thermal conductivity becomes marginal.[12,34]

***Aspect ratio*:** The higher the aspect ratio of a ski, the lower is the friction experienced; however, at aspect ratios in excess of 6 the gain in performance is very little.[17]

***Surface chemistry*:** Different authors noted a decrease in the friction coefficient with hydrophobic surfaces compared to those with hydrophilic surface chemistries.[17,24,35] This effect was less pronounced at low temperatures. The application of waxes was found to improve the sliding properties of sliders[12,35] although it has to be mentioned that there exist experimental data that indicates that if a waxed ski slides on snow for a prolonged time, the accumulation of dirt increases friction above that of a slider with no wax treatment.[36]

***Surface roughness*:** A slider with a phenolic resin ski-sole of a peak to valley surface roughness in the range of 15 to 35 µm experiences *lower* friction than a "completely smooth" ski sole.[29] However, in work conducted on ice an *increase* in the kinetic and static friction of steel was observed when the arithmetical mean surface roughness, R_a, was increased from 1 to 6.1 µm at -22 °C.[37] Similar effects were also observed by other authors.[33] Regarding this apparent discrepancies, it should be noted however that the latter results were obtained on ice. Typically R_a values measured perpendicular to the sliding direction of structures as applied in Nordic skiing competitions are in the range of between 2.5 and 12 µm.[10] In work conducted on polished ice it was found that a slider with a roughness of R_a = 1.15 µm experiences higher friction at low speeds than a slider with a roughness of R_a = 0.6 µm and that this trend reverses for higher velocities. In addition, a similar effect was detected with the orientation of the applied roughness; a slider with a roughness of R_a = 0.6 µm experiences less friction at low speeds if the orientation is applied parallel to the sliding direction. This trend disappears again at higher speeds (v > 0.5 m/s).[38]

***Contact area*:** Investigations on the effect of contact area between a slider and snow on the friction coefficient yielded contradictory results. Lethovaara and Bäurle measured an increase of μ with an increase of the contact area which levels off at high values (at constant normal force).[16,31] Bowden, by contrast, observed in his experiments that the friction coefficient did not vary upon alteration of the area of the slider.[12] Colbeck explained this independence of μ on pressure with the assumption that the load bearing area increases proportional to the applied pressure,[14] corresponding to the well-known first law of Amonton in tribology.[39]

Other

***Apparent contact area*:** To describe the friction phenomena of skis gliding on snow several authors employed the concept of an "apparent" contact area. This takes into account that a ski-sole is not in full contact with the snow track over its entire surface, but is sliding on localized contact spots.[34,35] This, of course, applies at temperatures below 0 °C, as at temperatures close to or above the melting point of snow the water film will spread over the whole sole of the slider. Experimental data showed that the apparent contact area between a slider and snow can be as little as a fraction of a percent of the surface of the slider and that this value can increase up to 100 % for snow containing a high percentage of free water.[18,20,41] The individual contact spots have been determined to be of an average size of 100 to 200 μm (assuming a circular shaped spot).[18,20,41]

Water film thickness**:** Results reported for the thickness of the friction-induced water film cover a range from a few nanometers[15] to hundreds of micrometers.[13] More accurate estimates on the water film thickness have been obtained in more recent work which modeled a ski sliding on snow. At intermediate temperatures a range of 0.1 to 1.2 μm was advanced and an increase up to a few micro meters under wet conditions at ~0 °C was predicted.[14,16]

Interface temperature**:** An increase in the interface temperature has been observed when a slider is set in motion reaching a steady state when the time of motion is sufficiently long and it increased with speed and pressure.[35,42] However, the interface temperature was never reported to exceed the melting temperature of ice.

6. Objectives and scope of this thesis

As is evident from the above review, considerable efforts have been made to clarify the influence of various parameters on the friction between sliders and ice and snow, in particular, surface pressure, contact area and temperature. Remarkably, however, the surface chemistry and structure of the ski-soles have received relatively little attention and consistent results have not been reported to the present day.

Hence, the principal objective of this work is to re-address friction on snow in a comprehensive study - more specifically to determine how surface-chemistry and -structure influence the tribological properties of a ski-sole. For this purpose, different polymer materials chosen with chemical compositions ranging from ultra-hydrophilic to ultra-hydrophobic so that the extremes between adhesive, friction enhancing interactions and repulsive friction-reducing phenomena between snow and the ski-sole could be investigated. Furthermore, surface structures of different length scales were introduced onto the polymer films to systematically explore the relevance of these features on the friction.

In Chapter II a new experimental ski test method is introduced and validated. In the test, the approach of Bowden was adopted and small-scale (1:20 by weight) sliders were constructed. Special attention was paid to develop a method to conduct experiments at constant conditions. In the process a correction factor was found to improve the accuracy of the measurements and a dimensionless time of descent is introduced which permits comparing results obtained on different track lengths, and model and full-sized sliders.

The influence of surface chemistry on the friction on snow is described in Chapter III for a wide spectrum of polymer ski-soles. In addition, a correlation between contact angle and the frictional properties of the surfaces is addressed.

Chapter IV describes the influence of surface roughness (microscopic contact area) on the tribological properties of a slider on snow. Textures of different dimensions, patterns and orientations were introduced onto the ski-soles and their influence explored.

In Chapter V the influence of the macroscopic contact area between sliders and snow is investigated. For that purpose a step-shaped groove structures were introduced to the ski sole and the influence of total contact area and number of grooves was investigated.

Finally, general conclusions and an outlook are presented in Chapter VI.

7. References and notes

[1] Burov, G. M. in *Some mesolithic wooden artefacts from the site of Vis I in the European North-east of the USSR*, The Mesolithic in Europe. Papers presented at the Third International Symposium, Edinburgh, **1985**.

[2] International Ski Federation, History of skiing, http://history.fis-ski.com, **2009**.

[3] Scheffer, J., *The history of Lapland* **1674**, Oxford, p. 226.

[4] Fry, J., *The story of modern skiing* **2006**, University Press of New England, Hanover.

[5] Lind, D.; Sanders, S. P., *The physics of skiing: Skiing at the triple point* **1996**, Springer-Verlag, New York.

[6] Perla, R.; Martinelli, M., *Avalanche handbook***,** USDA Forest Service, Washington D.C. **1979**.

[7] Fauve, M.; Rhyner, H.; Schneebeli, M., *Preparation and maintenance of pistes* **2002**, Swiss Federal Institute for Snow and Avalanche Research SLF, Davos.

[8] Colbeck, S.; Akitaya, E.; Armstrong, R.; Gubler, H.; Lafeuille, J.; Lied, K.; McClung, D.; Morris, E., *The international classification for seasonal snow on the ground***,** The International Commission on Snow and Ice of the International Association of Scientific Hydrology, **1985**.

[9] Pistenbully 600 brochure, http://www.pistenbully.com/uploads/tx_z7simpledownloads/KGF_20S_PB600_2007_GB.pdf, **2009**.

[10] Moldestad, D. A., *Some aspects of ski base sliding and ski base structure*, PhD thesis, Norwegian University of Science and Technology, **1999**.

[11] TOKO AG, company history, http://www.toko.ch/de/history.html, **2009**.

[12] Bowden, F. P.; Hughes, T. P., *Proc. R. Soc. London* **1939**, *172*, 280-298.

[13] Ambach, W.; Mayr, B., *Cold Reg. Sci. Tech.* **1981**, *5*, 59-65.

[14] Colbeck, S. C., *J. Glaciol.* **1988**, *34*, 78-86.

[15] Strausky, H.; Krenn, J. R.; Leitner, A.; Aussenegg, F. R., *Appl. Phys. B* **1998**, *66*, 599-602.

[16] Bäurle, L.; Szabó, D.; Fauve, M.; Rhyner, H.; Spencer, N. D., *Tribol. Lett.* **2006**, *24*, 77-84.

[17] Klein, G. J., *The snow characteristics of aircraft skis*; AR-2, National Research Council of Canada, **1947**.

[18] Kuroiwa, D., *J. Glaciol.* **1977**, *19*, 141-152.

[19] Lehtovaara, A., *Kinetic friction between ski and snow*, PhD thesis, Tampere University of Technology, Finnland, **1989**.

[20] Theile, T.; Szabó, D.; Luthi, A.; Rhyner, H.; Schneebeli, M., *Tribol. Lett.* **2009**, *36*, 223-231.

[21] Petrenko, V. F., *J. Appl. Phys.* **1994**, *76*, 1216-1219.

[22] Petrenko, V. F.; Colbeck, S. C., *J. Appl. Phys.* **1995**, *77*, 4518-4521.

[23] Arakawa, M.; Petrenko, V. F.; Chen, C., *Can. J. Phys.* **2003**, *81*, 209-216.

[24] Colbeck, S. C., *Med. Sci. Sports Exerc.* **1995**, *27*, 136-141.

[25] Shimbo, M. in *The mechanism of sliding on snow*, International Association of Hydrology Commission of Snow and Ice, Helsinki, **1960**.

[26] Evans, D. C. B.; Nye, J. F.; Cheeseman, K. J., *Proc. R. Soc. London Ser. A-Math. Phys. Eng. Sci.* **1976**, *347*, 493-512.

[27] Oksanen, P.; Keinonen, J., *Wear* **1982**, *78*, 315-324.

[28] Kuroiwa, D., *J. Glaciol.* **1977**, *19*, 141-152.

[29] Shimbo, M., *Friction on snow of ski soles, unwaxed and waxed* in Scientific Study of Skiing in Japan, The Society of Ski Science: Tokyo, **1971**, 99-112.

[30] Calabrese, S. J.; Buxton, R.; Marsh, G., *Lubric. Eng.* **1980**, *36*, 283-289.

[31] Lehtovaara, A., *Tribologia* **1985**, *4*, 14-26.

[32] Buhl, D.; Fauve, M.; Rhyner, H., *Cold Reg. Sci. Tech.* **2001**, *33*, 133-140.

[33] Albracht, F.; Reichel, S.; Winkler, V.; Kern, H., *Materialwiss. Werkstofftech.* **2004**, *35*, 620-625.

[34] Ericksson, R., *Friction of runners on snow and ice*, SIPRE TL 44; U.S. Army Cold Regions Research and Engineering, **1955**.

[35] Bowden, F. P., *Proc. R. Soc. London Ser.* **1953**, *217*, 462-478.

[36] Kuzmin, L., *Investigation of the most essential factors influencing ski glide*, Licentiate thesis, Luleå, University of Technology, Sweden, **2006**.

[37] Calabrese, S. J.; Buxton, R.; Marsh, G., *Lubric. Eng.* **1980**, *36*, 283-289.

[38] Kietzig, A. M.; Hatzikiriakos, S. G.; Englezos, P., *J. Appl. Phys.* **2009**, *106*, 024303.

[39] Bowden, F. P.; Tabor, D., *The friction and lubrication of solids* **1954**, Oxford University Press: New York, p 98.

[40] Pihkala, P.; Spring, E., *Determination of the contact area between ski and snow using a simple thermal conductivity meter* in Report Series in Geophysics, University of Helsinki: Helsinki, **1986**, p 1-15.

[41] Bäurle, L.; Kaempfer, U.; Szabó, D.; Spencer, N. D., *Cold Reg. Sci. Technol.* **2007**, *47*, 276-289.

[42] Colbeck, S. C.; Warren, G. C., *J. Glaciol.* **1991**, *37*, 228-235.

Chapter II

New method for testing ski-soles

1. Introduction

Since the early 1940's a number of techniques have been developed to investigate friction between different surfaces and snow and ice. For this purpose, experiments have been conducted both in the laboratory and outdoor environments using scale models, or, alternatively, full-sized skis. Design setups developed for outdoor experimentation include vehicle-pulled sleds,[1-3] catapult launched sliders[4] and weighted skis,[5-9] or simple sleds, which are all conveyed down snow or ice tracks. In addition, laboratory experiments have been performed in temperature-controlled refrigerator chambers, which consisted either of small skis sliding down short inclined snow- or ice tracks,[3] or tribometer-type experiments such as: slider(s)-on-disc,[10-20] ring-on-disc,[4,21,22] pin-on-disc,[23,24] disc-on-disc[25] and slider-on-roll.[26]

Of the existing methods, the slider-on-disc technique, as introduced by Bowden,[10] yielded the best results and, therefore, is the preferred method for investigating friction on snow and ice in a laboratory environment. Even so, this design has several disadvantages. First, due to the difficulty in preparing good tracks (in terms of reproducibility and mechanical stability), measurements are conducted mostly on ice. Second, the rotating disk is susceptible to vibrations and centrifugal forces, resulting in a limitation of the measurable velocities to about 10 m/s.[18,27] Third, the specimens run in the same tracks for an entire series of experiments. As a consequence heating, compaction and flattening of the track leads to deviations from the real situation as experienced outdoors. Furthermore, as the disc track is limited in size and is curved, the size of the measured samples is confined to a few centimetres. In addition, sample size and, especially, the aspect ratio and the length of the specimens employed, complicate, if not prohibit, a correlation with real skiing;[28] consequently, a good correlation of the results obtained with this type of tribometers has failed to emerge. Moreover, the specimen design for current tribometers is not well suited for testing of large sets of samples, as they often require sliders of very specific shape, preparation of which requires substantial time and resources. Finally, in general, such equipment is rather capital intensive.

The current evaluation method that is used today by ski producers and their suppliers is "full scale" testing, in which a professional skier slides down a given straight track, and the time of descent is measured. During these tests speeds over 120 km/h are achieved.[29] Although obviously realistic, these tests have some disadvantages. As it is difficult to manufacture identical skis, several skis need to be prepared to examine one specific sole, which requires large quantities of material and resources. The deviations that occur in the positioning and the reaction of the athlete from series to series are also sources of errors. In addition, outdoor experimental conditions, such as temperature, wind, and irradiation of the track by the sun, are difficult, if not impossible, to control and, as they have a significant influence on the time of descent, severely hamper collection of consistent results. It should also be noted that in this testing method, the friction between the ski and snow has only a modest influence on the measured time of descent, since, at these high speeds, air drag is a major contributor.

Here we present an alternative small-slider-based test method for skis that fulfils the following requirements:

- Test conducted on snow (not on ice)
- Small-scale (because of limited availability of certain materials)
- Possibility to explore a large set of specimens in a short time frame
- Mimic actual skiing, i.e. no disc-like design
- Simple

2. General procedures

We adopted the approach of Bowden[10] and constructed small-scale (about 1:20 by weight) sliders (cf. Figure 1A). The weight of the slider is such that it resembles the pressure that a typical skier exerts on snow. A slider is send downhill, guided by a Nordic ski track and its time of descent is measured. In the following the term “series” denominates one descent of all the tested specimens in one experiment.

2.1. Specifications of the small skis

The model sliders have a length of 25 cm and a width of 6 cm to match the width of a Nordic ski track. They were built with aluminium (alloy AlMg4,5MnZn) and a reflective flag was mounted for rate-detection purposes. Brass weights were attached in a central position on the ski; the average weight of a complete ski with flag was 1.69 kg so that the surface pressure (about 1.3 kPa) is comparable to the surface pressure during actual skiing. It has to be mentioned, that, beneficially, at the temperatures where most experiments were conducted (about -3 °C), the influence of surface pressure has been reported to be negligible.[30]

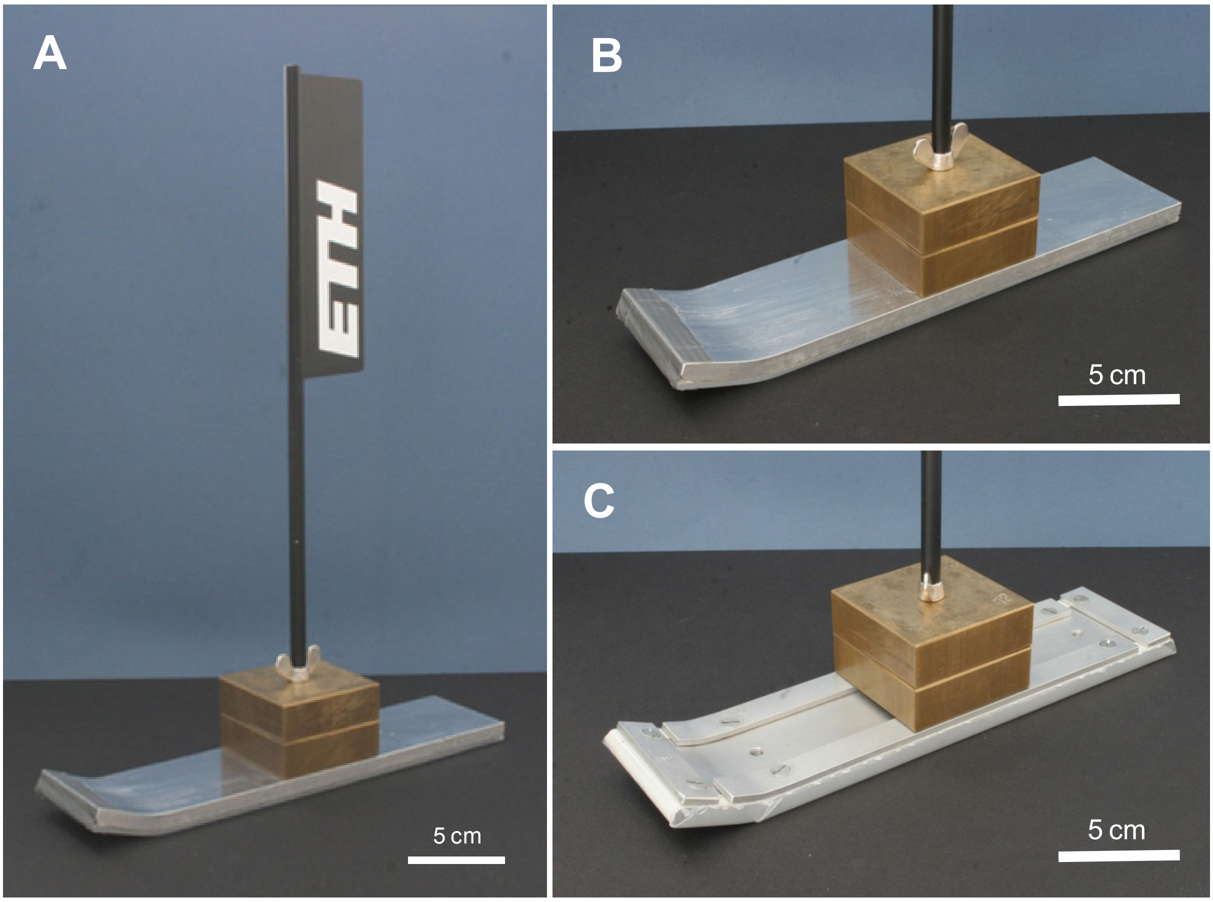


Figure 1: Newly developed small test ski. **A.** The ski with detection flag as used during the experiments. **B.** Ski fitted with aluminium strips to clamp thin films around the ski base and **C.** with a 2 mm thick ETFE layer glued onto the ski base for selected experiments with structured ski soles.

In order to evaluate various ski-sole materials and structures, two methods for attaching them to the sliders were selected. To fit thin polymer films, the base of the aluminium ski was coated with double-sided adhesive tape, to which the film was attached and then clamped all around the ski with aluminium strips as shown in Figure 1B. The latter approach was adopted to prevent snow from penetrating between film and adhesive tape. In a selected series of structured ski bases (see Chapters 4 and 5 for details), a 2 mm thick ethylene tetrafluoroethylene copolymer layer (ETFE, Symalit, Switzerland) with a glass mesh imprinted on its backside was glued to the ski base with a commercial epoxy glue (Agomet P 79, Angst & Pfister, Switzlerland) as shown in Figure 1C.

2.2. Track preparation

In order to create reproducible Nordic ski tracks (Figure 2), snow was prepared with conventional grooming machines (Pistenbully 100, Kässbohrer Geländefahrzeuge AG, Germany), as illustrated in Figure 3, operated by professionals and complying with world-cup regulations. This allows experiments to be conducted on a realistic snow surface, as experienced by ski athletes. The grooming operations commenced several days before the experiments were conducted. To obtain a compact and homogenous snow cover, the snow is first processed with a snow tiller, a fast rotating (about 2000 rpm) cylinder with spikes (Figure 3A). The various snow crystals in the snow cover are crushed to more or less spherical particles, resulting in a densely packed cover. A secondary effect is the heating up of the snow, which enhances sintering (solidifying) of the processed snow.

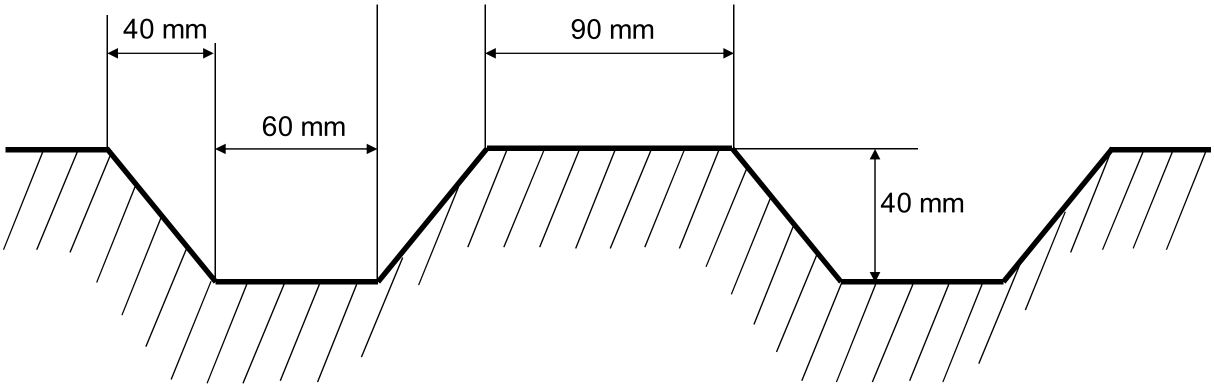


Figure 2: Cross-section of a typical Nordic skiing track.

On the day before the experiments, the grooming machine is pulling track plates (cf. Figure 3B) behind the snow tiller and forms the Nordic ski tracks with them. Track surfaces prepared by the grooming machines according to the above preparation procedure are expected to vary only slightly at the different test locations.[31,32]

The final grooming of the tracks was performed at least 6 hours before the measurements were started. This rest period was necessary for the track to solidify and to gain mechanical strength. (When a fresh track is used immediately after the grooming, the tracks deteriorate very quickly as the track gets carved out after only a few trials.)

2.3. Time of descent

The time of descent was measured with a light barrier timing system Timy (Alge, Austria) with a precision of 1/1’000 of a second. The sensors operated with reflectors and employed infrared light (Alge RLS1n).

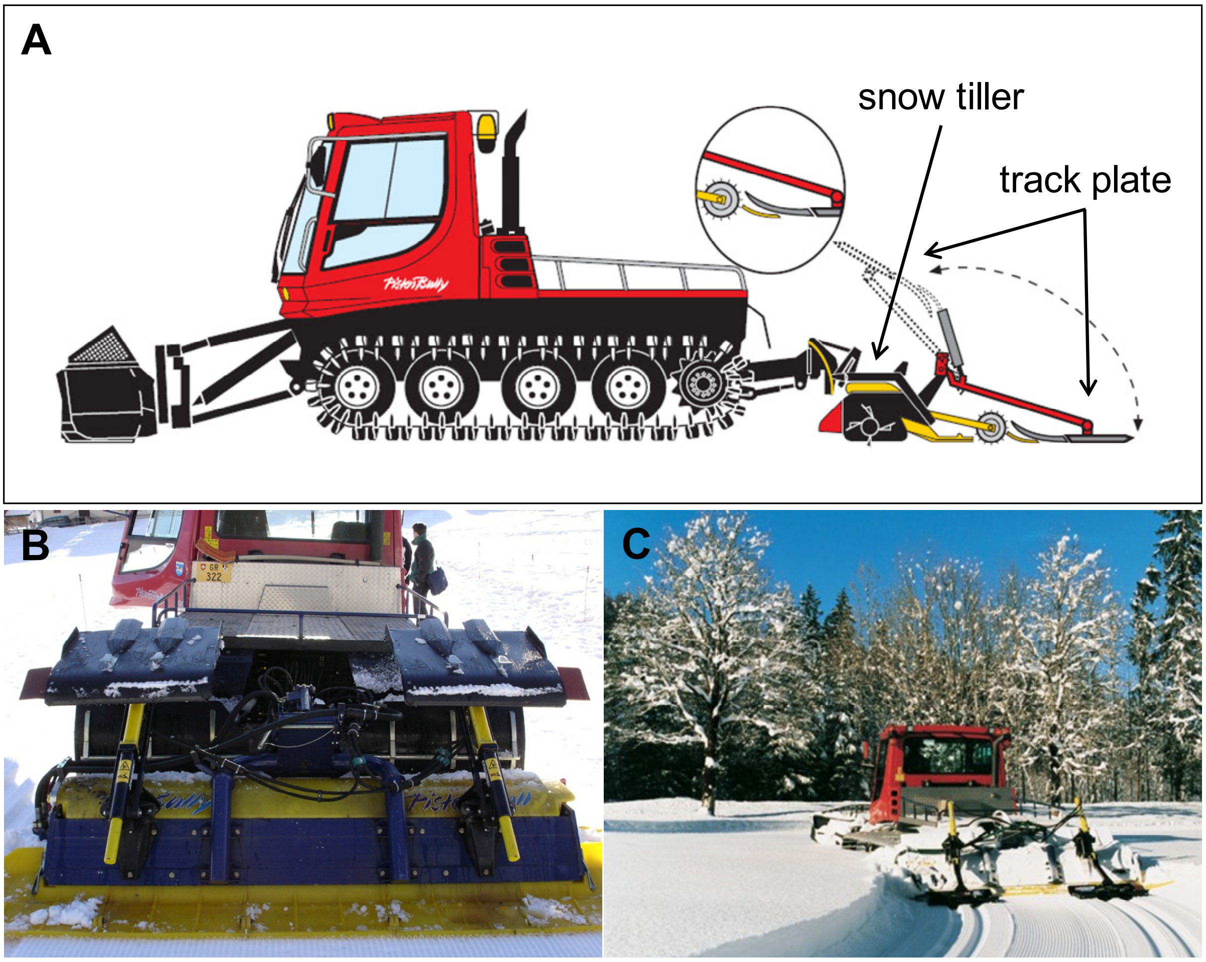


Figure 3: Grooming machine PistenBully 100. **A**. Schematic drawing, **B**. with pulled up track plates and, **C**. with lowered snow tiller and two track plates.

2.4. Location and setup

Experiments were executed both indoors and outdoors. The outdoor experiments were performed at different locations in Switzerland (Lenz, Davos and St. Moritz) and the indoor experiments were conducted in an indoor ski hall in Neuss, Germany. For all experiments, straight tracks were prepared in the direction of steepest descent. The slope angle in all experiments was gentle (approx. 10 to 12 °) and comparable for all places; the track lengths were between 35 to 40 m. In the indoor experimental setup, the snow was artificially produced without the use of nucleating agents. To provide constant starting conditions for the small-scale ski tests, a starter mark was used. The ski was positioned in the track and pulled back to the mark before it was released. The distance between the mark and the first light barrier was about 0.5 m. Typical experimental setups are shown in Figures 4 and 5.

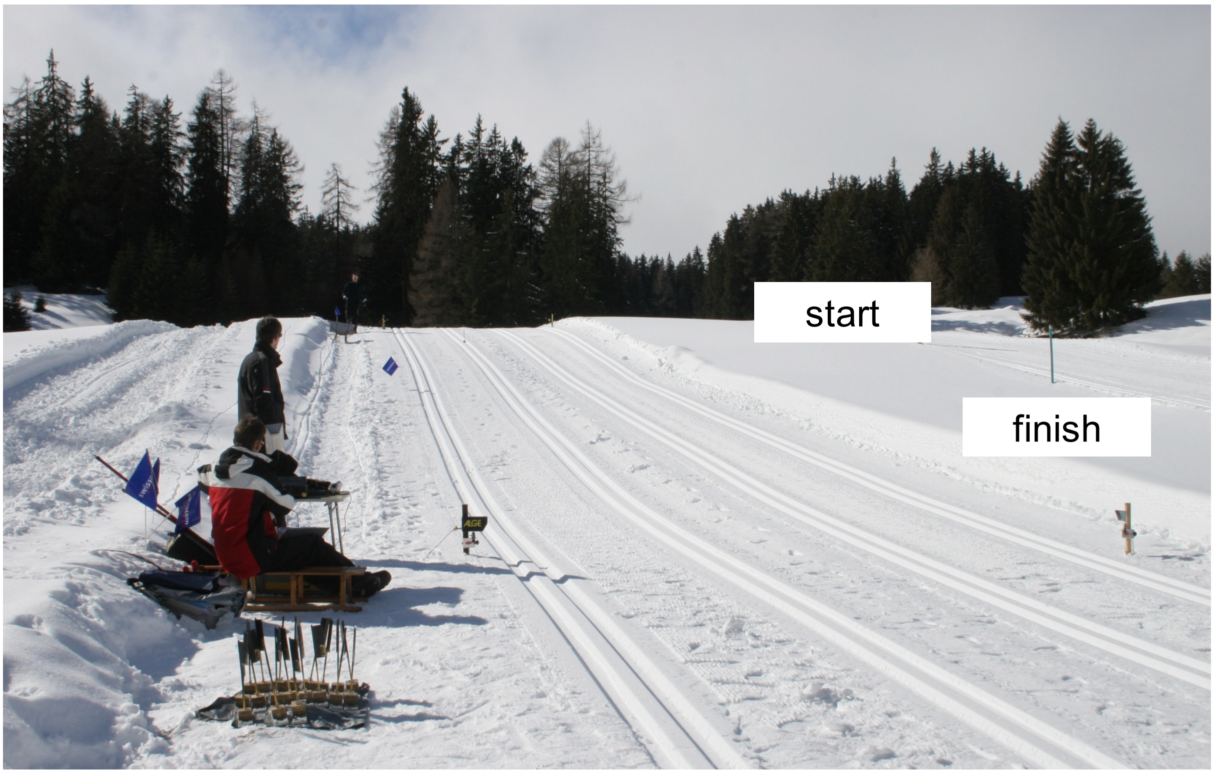


Figure 4: Typical outdoor test setup for small-scale ski experiments in Lenz, Switzerland.

Figure 5: Typical indoor test setup for small-scale ski experiments in Neuss, Germany.

2.5. Environmental influences

A weather station (provided by TOKO, Switzerland) was employed to monitor environmental conditions during the outdoor experiments. With this device the following parameters could be logged: air- and snow temperature, air humidity, wind speed and direction, irradiation from the sun and reflectance from the snow.

Due to near constant environmental conditions during the indoor experiments in Neuss, Germany, only the temperature of the snow and the air were recorded in the later stages of this work.

The temperature was determined with a Type K thermocouple. Snow temperature measurements with values higher than 0 °C were taken to be 0 °C, as it is physically not reasonable that snow is warmer than 0 °C. The misleading readouts were attributed to the fact that the snow is a three dimensional network with air inclusions which can be warmer than 0 °C. The sensor was, therefore, measuring a combined temperature of snow and air.

2.6. Presentation of results

The acquired data are presented in the form of a box-whisker plot[33] (Figure 6). Based on this method, different datasets can be compared without making assumptions about the statistical distribution of its values. It contains information about the asymmetry of the distribution and allows display of the complete collection of measurements. Alternatively, where stated, the shortest times of descent are presented.

3. Preliminary experiments

In preliminary experiments it was noted that when extremely smooth ski soles were tested the time of descent varied significantly, up to a factor 3. Therefore, an experiment with five sliders equipped with “flat” ETFE-soles (arithmetical mean surface roughness $R_a < 0.1$ µm; details about R_a can be found in Chapter 4) was conducted.

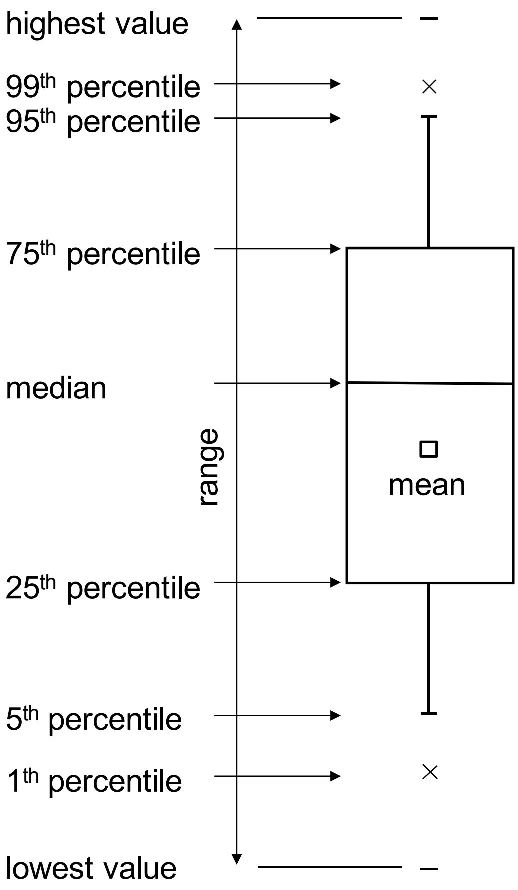


Figure 6: Representation of data in a box-whisker plot.

These small skis were run down the same track for repeated series and the development in their time of descent with the number of runs was analyzed. The time between each run in a series was typically about 30 seconds and the time between different series was about 5 minutes. In this study, a marked increase in the time of descent was noted for subsequent series in the same track, as shown in Figure 7. Remarkably, in the first series, the time of descent increased for every ski running down the same track. However, in the third and fourth series, the first ski of that series was always the slowest and the time of descent decreased for every following slider. When changing to a pristine track this behavior was reproduced, but only with sliders with extremely smooth soles.

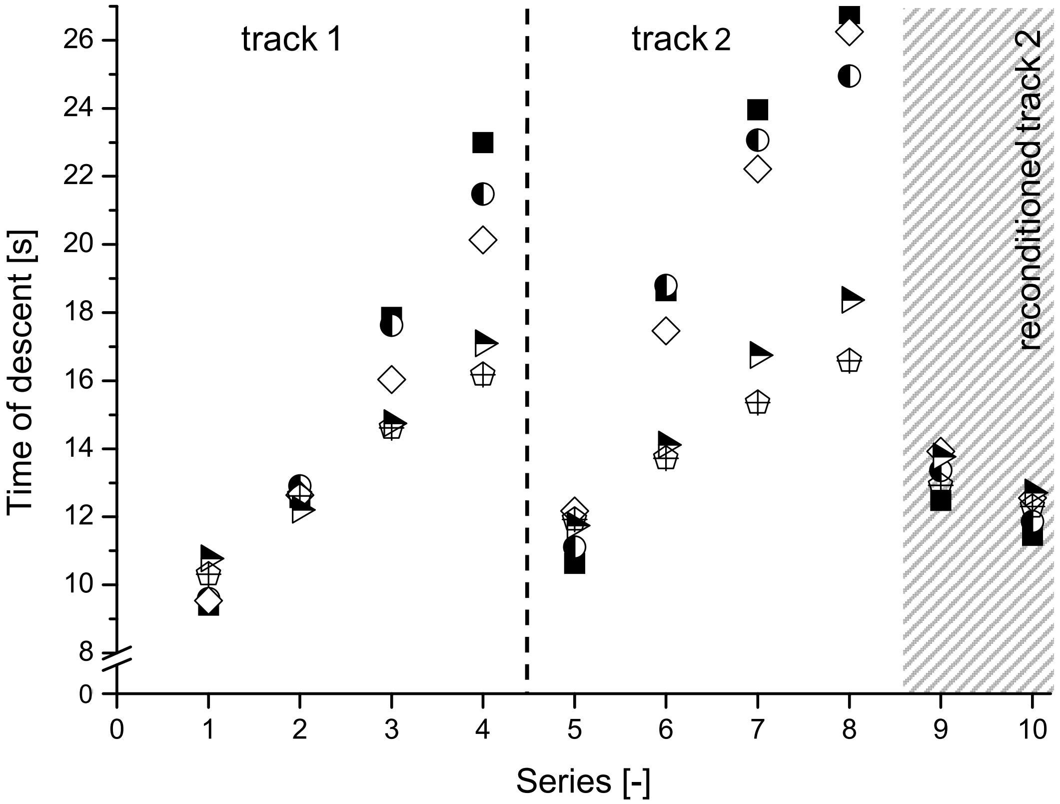


Figure 7: Time of descent recorded in successive series. Series 1 to 4 were conducted in track 1, series 5 to 10 in track 2, and between series 8 and 9 a slider equipped with sandpaper (grain size 200 µm) was pulled down the track. Five identical skis with smooth ETFE soles (R_a < 0.1 µm) were run down the track in ascending order: ■ : ski 1, ◐ : ski 2, ◇ : ski 3, ⧐ : ski 4 and ⬠ : ski 5. The test field was the indoor ski hall located in Neuss, Germany. The snow temperature was -3.3 °C, the air temperature was - 4 °C and track length was 40 m.

The recorded *increasing* time of descent between subsequent *series* could be due to the flattening of the snow track during runs, which would increase the size of the contact area with the ski soles. This effect will be discussed in detail in the next section.

The *decrease* in the time of descent for *sliders* within a given series, on the other hand, might be due the thin layer of melt water produced by a preceding ski, which has not solidified completely yet, allowing the following ski to experience less friction, as it can glide on the still existing water film. In an additional experiment it was established that with increasing time interval between descending skis (up to 5 minutes), the decrease in the time of descent within one series considerably diminished, corroborating the above thesis.

Another strong indication that the observed effects originate in changes of the snow surface is given by series 8, 9 and 10 in Figure 7. After test series 8 was completed, a ski equipped with sandpaper on its sole (grain size 200 µm) was pulled down to roughen the used track. As the data in the graph shows, the time of descent of the skis in the following series 9 and 10 is reduced close to the level of a pristine track in the previous series. This experiment indeed indicates that the influence of the surface structure of the snow track can be of considerable influence, and should be taken into consideration in experimental set ups in which a slider runs in a given track for a prolonged time, as for example with most tribometer type of experiments. (NB The above findings also put into question the fairness of ski competitions that are run on non-pristine tracks…).

It is of utmost importance to note that the here discussed dramatic increase in the time of descent for repeated runs of slider in a given track was only observed for soles of extremely smooth surfaces.

4. Validation of the method

4.1. Reproducibility

In order to determine the reproducibility of our test method, 20 small skis were equipped with linear low density polyethylene (LLDPE, The Dow Chemical Co., USA) foils cut from a single sheet. Results obtained in consecutive series are shown in Figure 8. Weather conditions during the series changed from light snowfall at the beginning of the measurements, to dry conditions after series 3. The data reveals that the spread in the time of descent, t_e, decreased by about a factor of three with the diminishing snowfall. This experiment indicates that the measurements are highly sensitive to changes in environmental conditions such as snowfall, wind, sun and temperature.

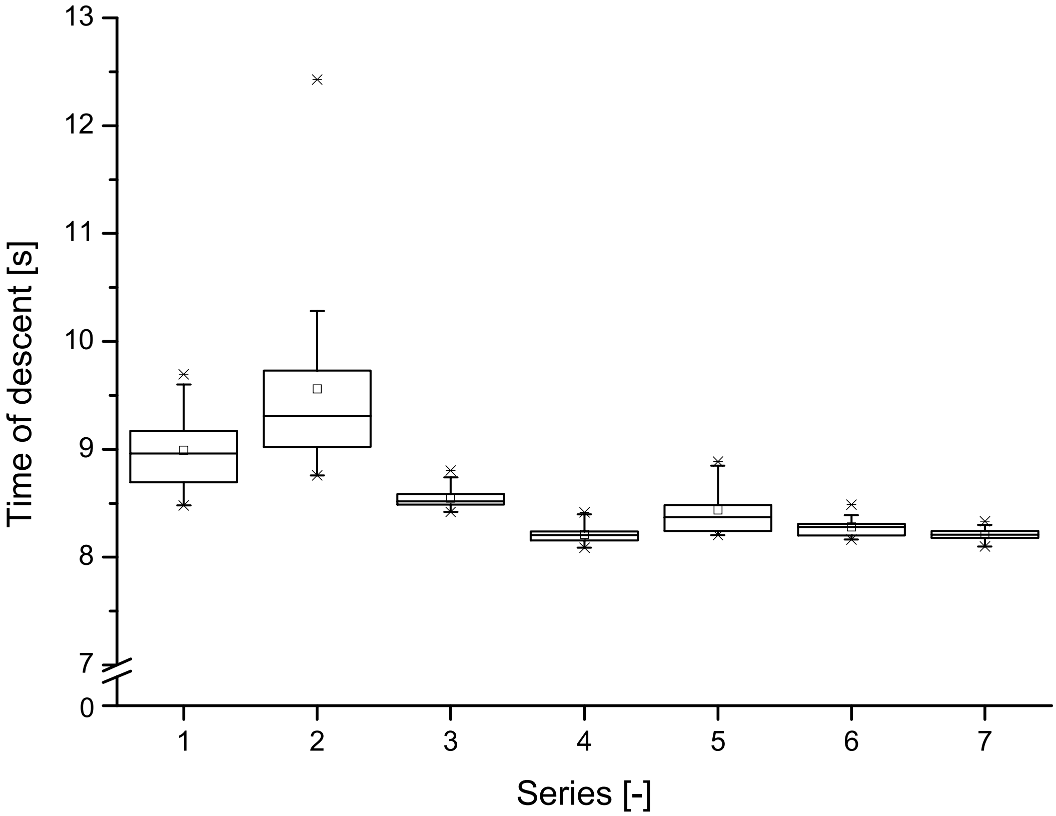


Figure 8: Box-whisker plot of the time of descent per series. All 20 skis were equipped with LLDPE foils. The test field was located in Lenz, Switzerland. The snow temperature was 0 °C, air temperature varied from 0.4 to 0.9 °C and track length was 40 m.

Therefore, to have approximately constant conditions, subsequent experiments were conducted in a time frame as narrow as possible and, simultaneously, the environmental conditions were monitored carefully, especially the temperature.

4.2. Statistical distribution

When the data from the previous (reproducibility) experiment is plotted as a frequency plot, the distribution is skewed towards shorter time of descent and, hence, assumption of a normal distribution of the measured times of descent is not appropriate. Consequently, the statistical parameters of a normal distribution, like the standard deviation, are not applicable for the time of descent in our experiments. If the above times of descent are plotted for the individual skis in the form of a box-whisker plot, however, significantly less spread is observed for the *shortest* times of descent of each ski than for the *average* times of descent (cf. Figure 10).

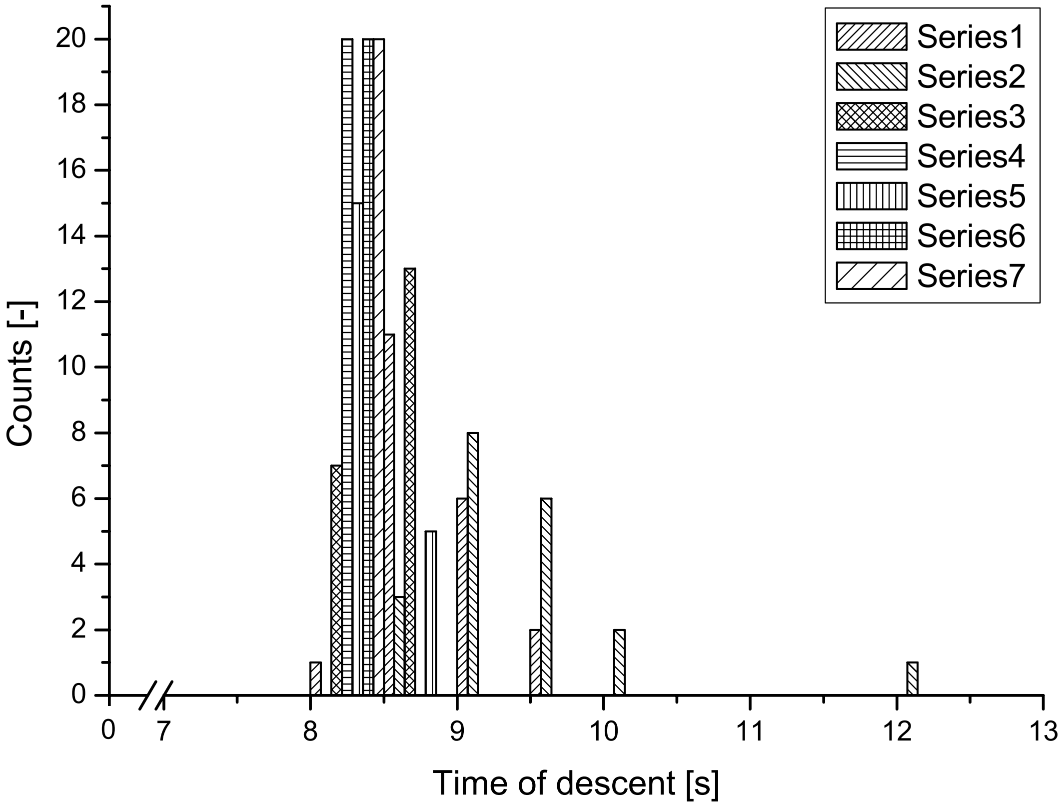


Figure 9: Frequency plot of all the time of descent data in Figure 8 (interval size 0.5 s). Patterns indicate different series.

For this reason, when hereafter reducing the box-whisker plots to single data points, the shortest time of descent of a dataset is employed.

4.3. Experimental errors

In the raw data of the first sets of experiments, a small, approximately linear increase in the time of descent of the skis in subsequent series could be observed. However, the time of descent of the slider was reduced to its initial value when a new track was employed (see Figure 11). In the preliminary experiments it was shown, that a used track can be refreshed (indicating that the time of descent is reduced to its initial value), if a slider equipped with a sandpaper was conveyed down the track.

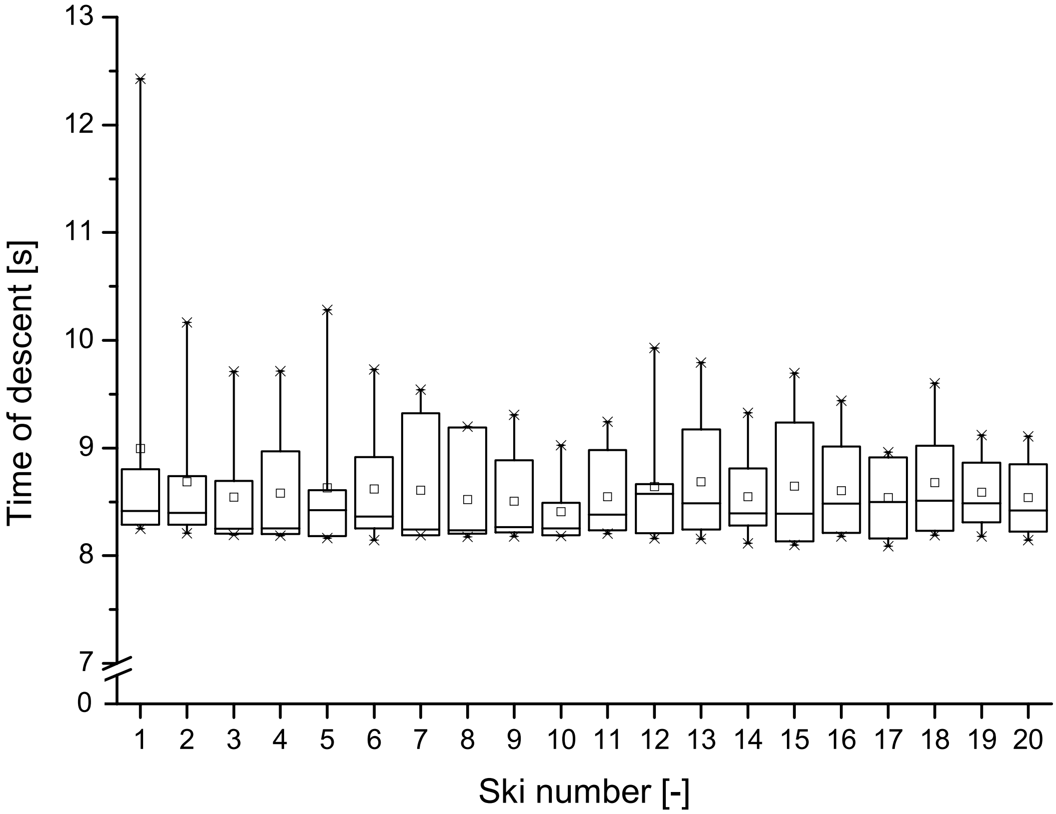


Figure 10: Box-whisker plot of the time of descent for each ski. All skis were equipped with LLDPE foils. The test field was located in Lenz, Switzerland. The snow temperature was 0 °C, the air temperature varied from 0.4 to 0.9 °C, track length was 40 m and 7 measurements were performed with each slider.

One possible cause for the increase in time of descent could be the slow erosion of the walls of the Nordic ski track. (Although necessary to guide the small skis, the walls of the Nordic ski tracks do introduce additional friction.) Indeed it was observed that the grooves of the track wore out with every subsequent run of a ski, resulting in a slightly extended effective track length due to the increasingly wavy path for the next ski to run down the track. In addition, the small amount of snow debris that was carved out in the process and was deposited in the track had to be compacted by the next ski.

A second observation was that due to erosion of the track, the track walls became slightly higher, further increasing the friction between the sides of the ski and the track in each subsequent run (Figure 12).

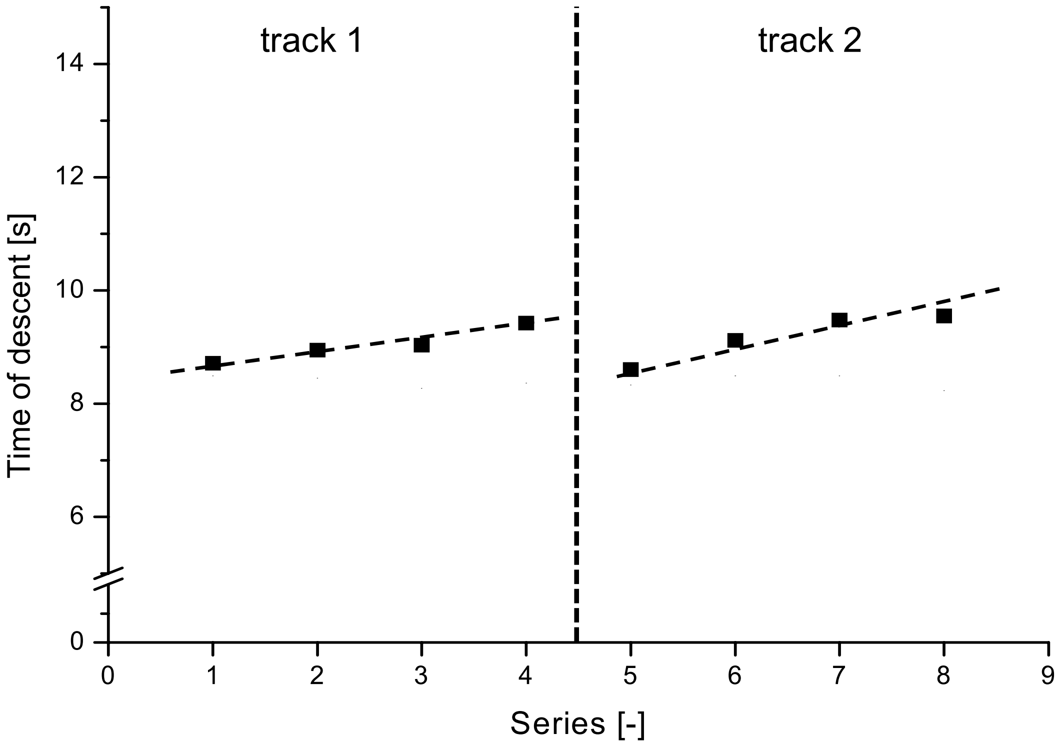


Figure 11: Times of decent of a typical slider during successive series. The vertical dashed line indicates a change back to a pristine track. The test field was the indoor ski hall located in Neuss, Germany. The snow temperature was -3.3 °C, the air temperature -4 °C and track length was 40 m (lines are drawn as a guide to the eye only).

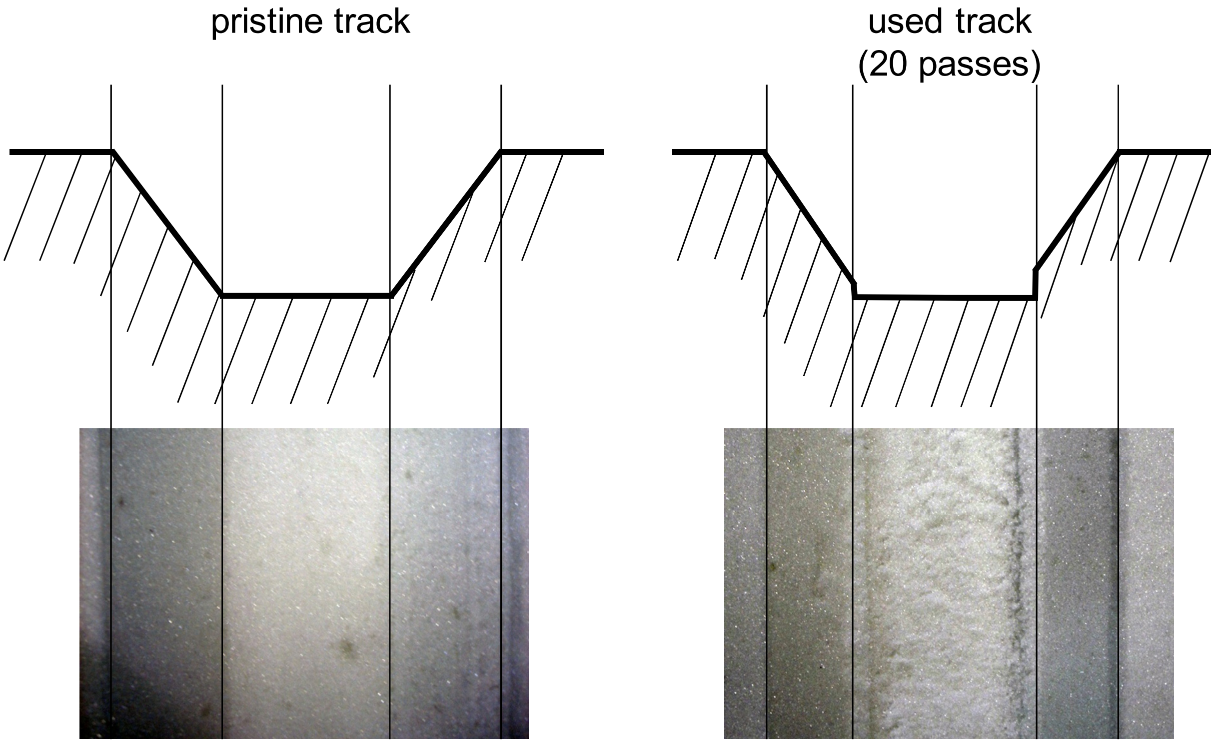


Figure 12: Schematic and top view of track erosion during testing resulting in widening and deteriorating of the track.

It was also observed that with repeated runs of the skis over the snow surface, the snow grains in the track surface were flattened, leading to an increase in contact area and, therewith, increasing friction of the ski base with the snow. This was confirmed by examination of microscopic images taken from replicas of the snow surface in the Nordic ski track. The "replicas" of the snow surface were obtained using a dimethyl siloxane resin (PROVIL novo Light C.D.2 fast set, Heraeus Kulzer GmbH, Germany), which has a curing time of about one hour at -3 °C. To obtain an imprint of the actual surface topology of the snow surface, the negative replica, which was taken from the snow, was plasma treated for 2 minutes, after which a positive imprint of this treated surface was made with the same resin. The sub-micrometer accuracy of this imprinting technique was shown by Schuler *et al.*.[34] Optical micrographs of the replicas of a pristine track and a track after 20 passes of a ski are shown in Figure 13.

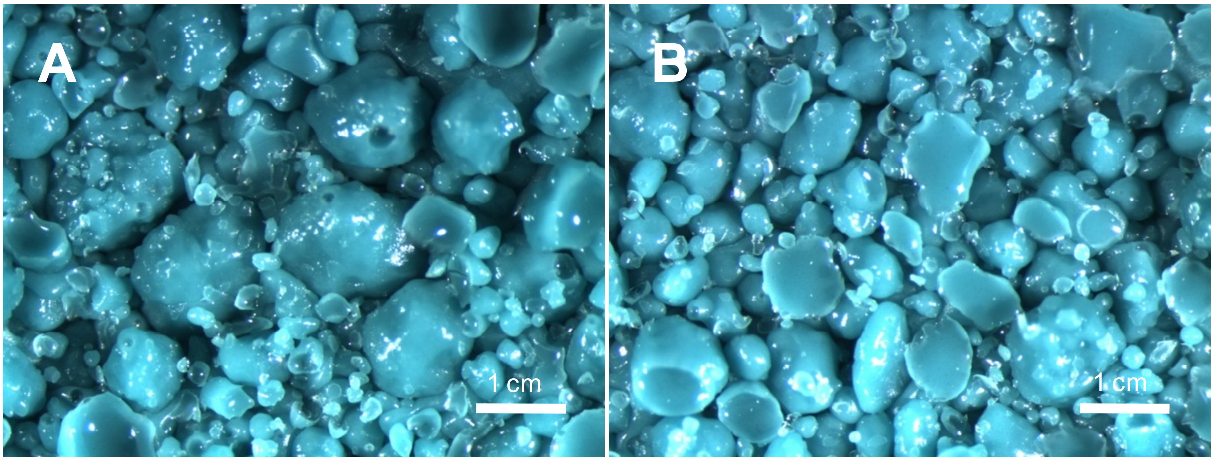


Figure 13: Replicas of snow surface, **A.** pristine track and, **B**. track after 20 passes of skis, revealing flattening of the snow grains.

Furthermore, it was noticed that in consecutive passes, the snow in the track became compacted, which leads to an increase in the hardness of the snow. This phenomenon was analyzed with a "ramsonde"-type[35] of instrument designed for our specific needs (cf. Figure 14). It consists of a stamp with a defined surface area and an attached pole along which a weight can be dropped from a given height. The measured quantity was the indentation depth into the snow, which is proportional to the reciprocal snow hardness.

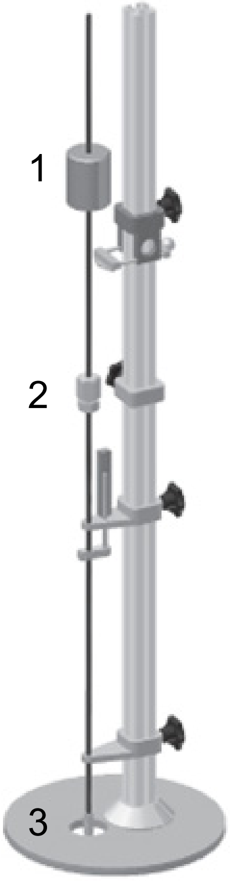


Figure 14: Tool used for measurement of track compaction: **1.** weight (250 g), **2.** stopping bolt and, **3.** stamp (200 mm^2).

The surface area of the stamp was 200 mm^2 and of a circular shape. Compaction of the track was determined by dropping a 250 g weight from 10 cm height onto a stopping bolt. The unused track typically was penetrated to a depth of 3.2 mm, whereas the track after 20 descents of skis had an indentation depth of only 2.5 mm (both numbers are an average of three measurements), indicative of compaction of the snow during the experiments due to the weight of the small skis.

Despite the above mentioned experimental errors, nonetheless a highly consistent, approximately linear increase could be observed during subsequent measurements of the time of descent of identical skis. This was, therefore, corrected for, by assuming a monotonous linear trend superposed on the experimental data.

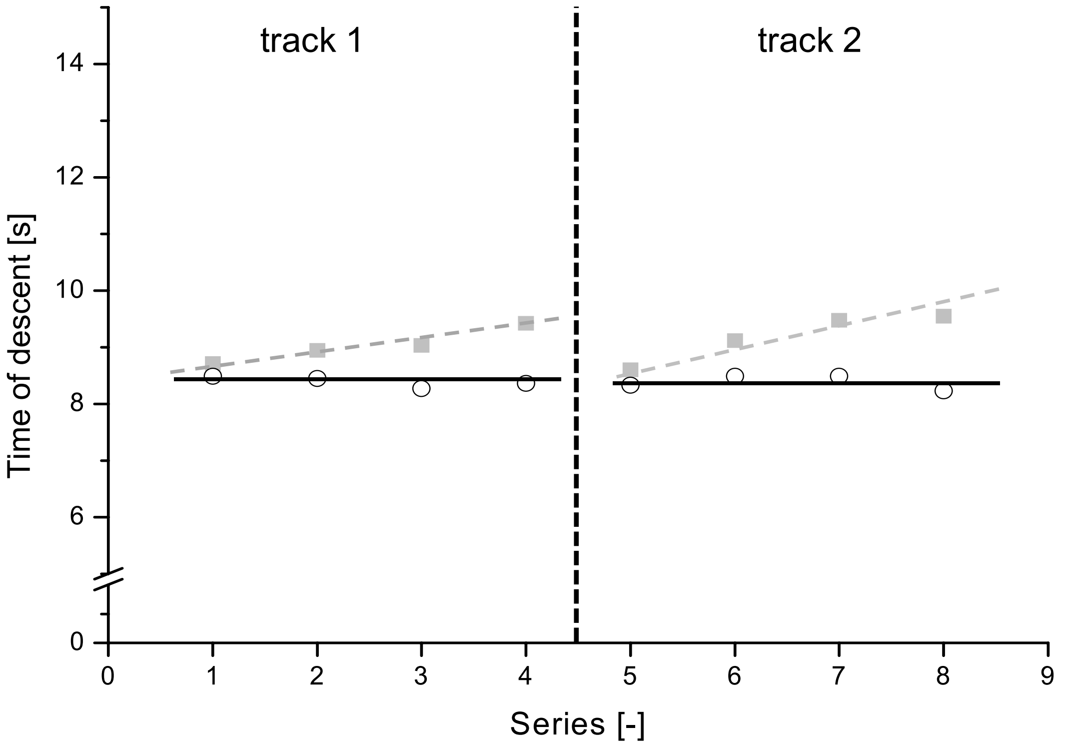


Figure 15: Times of descent of a typical slider during successive series uncorrected (■) and corrected (○). The vertical dashed line indicates a change back to a pristine track. The test field was the indoor ski hall located in Neuss, Germany. The snow temperature was -3.3 °C, the air temperature -4 °C and track length was 40 m (lines are drawn as a guide to the eye only).

An example of such a linear fit and the trend-adjusted data is shown in Figure 15. A detailed derivation of the correction factor can be found in Appendix A1.

The corrected data display a considerably reduced spread and a higher accuracy; therefore, this correction was applied to all subsequent measurements, unless stated differently.

4.4. Time of descent and correlation with Nordic skis

In order to account for differences in, among other things, track length and size of the sliders, in the following the concept of a "dimensionless time of descent" is introduced. Figure 16 schematically depicts a slider with mass *m* moving down a distance *s* along a track of total length s_0 and slope *α*. The gravitational force $F = mg$ is decomposed in a normal force perpendicular to the slope $F_N = mg\cos\alpha$, and a component parallel to the slope $F_s = mg\sin\alpha$.

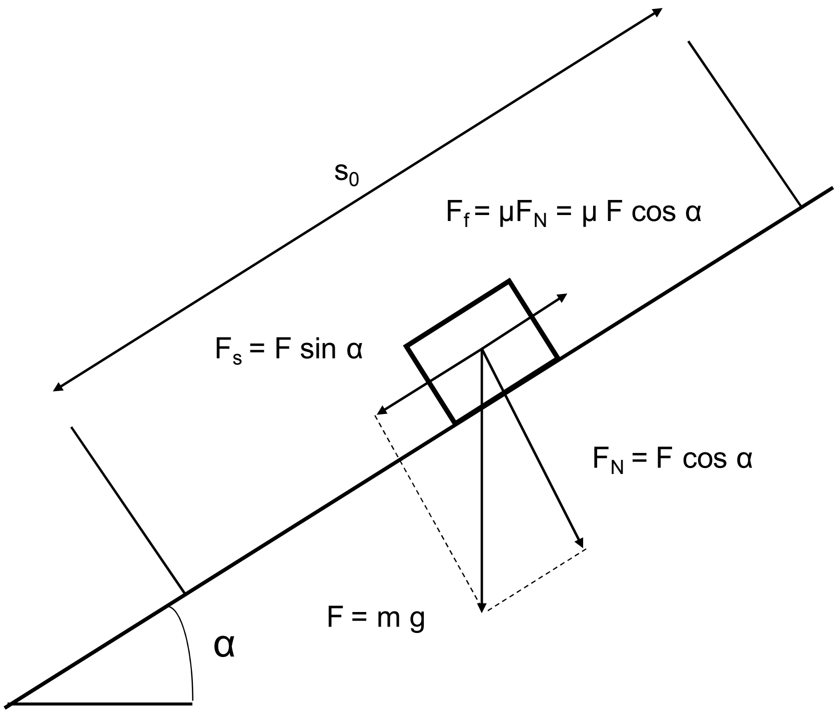


Figure 16: Schematic of definitions.

Assuming Coulomb friction and neglecting air drag (deemed justified in view of the compact size of the slider and the relative low speeds involved), the frictional force F_f is proportional to the normal force F_N, assuming a constant friction coefficient μ: $F_s = \mu mg\cos\alpha$. The equation of motion for the slider then follows from the force balance parallel to the slope:

$$F_s - F_f = mg\sin\alpha - \mu mg\cos\alpha = m\frac{d^2s}{dt^2} \qquad (1)$$

Selecting the track length s_0 as a characteristic distance and $t_0 = \sqrt{s_0/g}$ as a characteristic time, and defining a dimensionless time and distance as $t^* = t/t_0$, and $s^* = s/s_0$, respectively, lead to the following dimensionless equation of motion:

$$\frac{d^2s^*}{dt^{*2}} = \sin\alpha - \mu\cos\alpha \qquad (2)$$

Expressed in dimensionless quantities, the equation of motion of the experiment now only depends on the slope α, and the quantity of interest, i.e. the friction coefficient μ. Therefore, experimental times of descent, t_e, measured on tracks of different track length but of similar slope, can be compared using the dimensionless time of descent t_e^* defined as:

$$t_e^* = \frac{t_e}{t_0} = \frac{t_e}{\sqrt{\frac{s_0}{g}}} = \sqrt{\frac{g t_e^2}{s_0}} \qquad (3)$$

The benefit of this approach is shown in Table 1 in which results are presented that were obtained with a small slider and a Nordic ski both equipped with the same base material LLDPE on vastly different track lengths expressed in the dimensionless time of descent.

LLDPE sole	small ski	Nordic ski
track length [m]	35	142
time of descent t_e [s]	10.529	22.403
dimensionless time of descent t_e^* [-]	5.606	5.888

Table 1: Comparison of the actual time of descent, t_e, and the dimensionless time of descent, t_e^*. For the small sliders the average time is comprised of 12 measurements and that of the Nordic ski of 3. The test field was in Davos, Switzerland. The snow temperature varied from -11 to -9 ºC and the air temperature from -12 to -7 ºC.

Figure 17: Typical test setup for Nordic skis. The additional light barriers at the start and finish of the track are used for the determination of the start and final velocity.

To further validate correlation of results obtained with small sliders on Nordic ski tracks with those obtained in real ski experiments, a more elaborate set of references with Nordic skis was conducted (cf. Figure 17). A selected subset of materials (poly(tetrafluoroethylene) (PTFE), ultra-high molecular weight PE (UHMW PE), LLDPE and ETFE) was glued to the base of Nordic skis (World cup skate, Atomic GmbH Austria). The same set of materials was used also as the sole of the small-scale sliders, and both sets were tested on the same day in Davos, Switzerland. The experiments with the Nordic skis were carried out by TOKO with professional athletes, according to industry standards.

Due to the large difference in track length (small sliders 35 m, Nordic skis 142 m), the absolute times of descent in the two tests are, of course, vastly different. Gratifyingly, however, when expressed in the dimensionless time of descent a meaningful comparison of the two testing methods is obtained, and similar trends observed, for instance regarding the influence of the different nature of the ski-soles and t_e^*; see Figure 18.

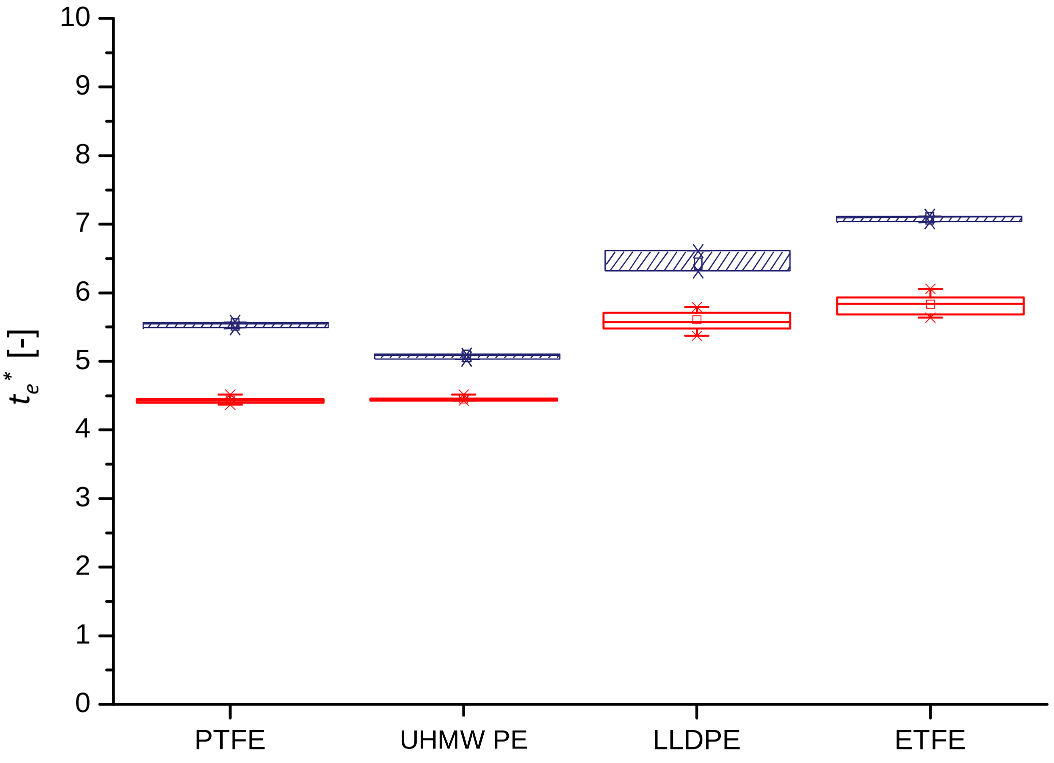


Figure 18: Correlation of results obtained with small sliders (red) and Nordic skis (patterned blue) fitted with the same soles (polymers indicated) on different tracks with different track lengths, expressed in dimensionless time of descent. The box-whisker plot for the small skis includes 12 measurements and those of the Nordic skis 3. The test field was located in Davos, Switzerland. The snow temperature varied from -11 to -9 ºC, the air temperature from -12 to -7 ºC and track length was 35 m for the small skis and 142 m for the Nordic skis.

5. Conclusions

A testing method is proposed and evaluated that is based on the time of descent of small skis sliding down a track of approximately constant slope to compare the frictional properties of materials on snow. It is shown that use of a dimensionless time of descent allows comparison of absolute times of descent, recorded on tracks of vastly different length. Furthermore, it is demonstrated that results obtained with the small model sliders, despite their reduced size and different aspect ratio, compare well with those recorded for actual Nordic skis. This is a non-trivial result as the small ski length could change the ratio of dry friction, which is experienced at the tip of the ski and the lubricated friction further back at the ski, when compared to actual skiing.[26] As Nordic skis have an aspect ratio of about 40 and our model sliders of about 3.6 only, it seems reasonable to expect that the results obtained in the following chapters should be relevant also for Alpine skis (aspect ratio of about 25).

Furthermore, it was also established that skiing deforms and flattens a snow track, which adversely influences the performance of following skis that run down the same track; this effect is dramatically more pronounced for sliders with relatively smooth soles. This experimental error, however, could be corrected for by advancing a linear trend superimposed on the actual time of descent.

The aforementioned increase in the time of descent with repeated passes on a track is contradicting the results of model calculations that assume only a lubricated friction component and a constant contact area of a ski gliding on snow.[28,36] This difference, in our opinion, points to the fact that a second friction mechanism must play a role in the system at hand, which could be capillary suction, as advanced by Colbeck.[28]

Remaining (minor) differences observed between the results obtained with the proposed method and actual Nordic skis can be attributed to the fact that the dimensionless time of descent is, of course, not strictly a function of the friction coefficient and the slope of the track only, but also of other experimental factors, most notably the temperature differences during the measurements and air drag.

6. References and notes

[1] Klein, G. J., *The snow characteristics of aircraft skis*; AR-2, National research council of Canada, **1947**.

[2] Kuzmin, L., *Investigation of the most essential factors influencing ski glide*, Licentiate thesis, Luleå University of Technology, Sweden, **2006**.

[3] Ericksson, R., *Friction of runners on snow and ice*, SIPRE TL 44, U.S. Army Cold Regions Research and Engineering, **1955**.

[4] Kuroiwa, D., *J. Glaciol.* **1977**, *19*, 141-152.

[5] Bowden, F. P., *Proc. R. Soc. London Ser.* **1953**, *217*, 462-478.

[6] Ambach, W.; Mayr, B., *Cold Reg. Sci. Tech.* **1981**, *5*, 59-65.

[7] Spring, E., *Tribologia* **1988**, *7*, 9-14.

[8] Colbeck, S. C.; Warren, G. C., *J. Glaciol.* **1991**, *37*, 228-235.

[9] Nachbauer, W.; Schröcksnadel, P.; Lackinger, B. in *Effects of snow and air conditions on ski friction*, Skiing Trauma and Safety, **1996**.

[10] Bowden, F. P.; Hughes, T. P., *Proc. R. Soc. London* **1939**, *172*, 280-298.

[11] Keinonen, J., *Acta Polytech. Scand., Appl. Phys. Ser* **1978**, *123*, 1-10.

[12] Oksanen, P.; Keinonen, J., *Wear* **1982**, *78*, 315-324.

[13] Lehtovaara, A., *Tribologia* **1985**, *4*, 14-26.

[14] Spring, E.; Pihkala, P.; Leino, M. A. H., *Acta Polytech. Scand., Appl. Phys. Ser* **1985**, *148*, 1-12.

[15] Hämäläinen, T.; Spring, E., *Commentationes Physico-Mathematicae* **1986**, *76*, 1-17.

[16] Akkok, M.; Ettles, C. M. M.; Calabrese, S. J., *J. Tribol.-Trans. ASME* **1987**, *109*, 552-561.

[17] Buhl, D.; Fauve, M.; Rhyner, H., *Cold Reg. Sci. Tech.* **2001**, *33*, 133-140.

[18] Bäurle, L.; Szabó, D.; Fauve, M.; Rhyner, H.; Spencer, N. D., *Tribol. Lett.* **2006**, *24*, 77-84.

[19] Hainzlmaier, C., *A tribologically optimized bobsleigh runner*, , PhD thesis, TU München, Germany, **2005**.

[20] Lehtovaara, A., *Kinetic friction between ski and snow*, PhD thesis, Tampere University of Technology, Finnland, **1989**.

[21] Calabrese, S. J.; Buxton, R.; Marsh, G., *Lubric. Eng.* **1980**, *36*, 283-289.

[22] Kietzig, A. M.; Hatzikiriakos, S. G.; Englezos, P., *J. Appl. Phys.* **2009**, *106*, 024303.

[23] Strausky, H.; Krenn, J. R.; Leitner, A.; Aussenegg, F. R., *Appl. Phys. B* **1998**, *66*, 599-602.

[24] Albracht, F.; Reichel, S.; Winkler, V.; Kern, H., *Materialwiss. Werkstofftech.* **2004**, *35*, 620-625.

[25] Shimbo, M. in *The mechanism of sliding on snow*, International Association of Hydrology Commission of Snow and Ice, Helsinki, **1960**.

[26] Evans, D. C. B.; Nye, J. F.; Cheeseman, K. J., *Proc. R. Soc. London Ser. A-Math. Phys. Eng. Sci.* **1976**, *347*, 493-512.

[27] Bäurle, L., *Sliding friction of polyethylene on snow and ice*, PhD thesis, ETH Zurich, Switzerland, **2006**.

[28] Colbeck, S. C., *J. Glaciol.* **1988**, *34*, 78-86.

[29] Personal communication, Udo Raunjak, TOKO AG, Switzerland, **2006**.

[30] Buhl, D.; Fauve, M.; Rhyner, H., *Cold Reg. Sci. Tech.* **2001**, *33*, 133-140.

[31] Fauve, M.; Rhyner, H.; Schneebeli, M., *Preparation and maintenance of pistes* **2002**, Swiss Federal Institute for Snow and Avalanche Research SLF, Davos.

[32] Lind, D.; Sanders, S. P., *The physics of skiing: Skiing at the triple point* **1996**, Springer-Verlag, New York.

[33] McGill, R.; Tukey, J. W.; Larsen, W. A., *Am. Stat.* **1978**, 32, 12-16.

[34] Schuler, M.; Kunzler, T. P.; de Wild, M.; Sprecher, C. M.; Trentin, D.; Brunette, D. M.; Textor, M.; Tosatti, S. G. P., *J. Biomed. Mater. Res. Part A* **2009**, *88A*, 12-22.

[35] Bader, H.; Haefeli, R.; Bucher, E.; Neher, J.; Eckel, O.; Thams, C., *Der Schnee und seine Methamorphose* **1939**, Kommissionsverlag Kümmerly & Frey, Bern.

[36] Colbeck, S., *A review of the processes that control snow friction*, in Cold Regions Science and Technology, **1992**; p 1-40.

Chapter III

Influence of chemical composition

1. Introduction

The base of a ski is one of its most important parts, as it has to fulfill a rather specific combination of requirements such as a high abrasion resistance and a low friction coefficient. Since medieval times, waxes and similar materials have been applied as coating to ski surfaces to decrease friction between skis and snow. Nowadays, in order to enhance the tribological properties of the commonly employed polyethylene ski-soles, a wide variety of wax coatings are used, ranging from high-melting paraffins for skiing at temperatures far below zero, to low-melting perfluorinated waxes at temperatures close to the melting point of snow.[1] Selection of the wax for optimum performance at a particular temperature range, unfortunately, is guided by empirical testing, although it is commonly assumed that the hardness of the wax should correlate with the hardness of the snow.[2,3] As the latter increases at lower temperatures, waxes for skiing at those temperatures should have enhanced mechanical properties, as provided by waxes with a higher melting point.

The first systematic scientific investigations of the tribological properties of different materials on snow were performed by Bowden and co-workers.[4,5] These authors concluded that a low friction coefficient between a slider and ice or snow originates in the formation of a very thin lubricating layer of water, generated by frictional heat. Based on this, Bowden *et al.* deduced that hydrophobic ski base materials having a low heat conductivity, should experience lower friction. To verify this prediction, the authors conducted contact angle measurements with a captive air-bubble method and found a good correlation of the contact angle and the friction properties of the surfaces investigated. For most materials, the contact angle decreased for prolonged exposure to water, and even more so if the materials were rubbed with a towel under water.[5] In another set of experiments, Bowden *et al.* reported that metal sliders having a high heat conductivity, allowing for rapid dissipation of the frictional heat before it can produce a lubricating water layer, experience higher friction on cold snow than sliders with a poor thermal conductivity. On the basis of these studies, Bowden concluded that poly(tetrafluoroethylene) (PTFE, better known as Teflon®) should be the superior material for ski bases, as this polymer exhibits the highest contact angle, combined with a low heat conductivity.

However, in part due to its poor abrasion resistance, PTFE ski-soles proved to be disappointing,[6,7] and, nowadays, the material of choice for ski-soles is ultra-high molecular weight polyethylene (UHMW PE). This material offers an attractive compromise between good physical properties, such as hydrophobicity and a high abrasion resistance, combined with a low density and relatively low price.[8,9] Typically, a few weight percent of carbon black is incorporated to render the ski base electrically conductive, in order to avoid tribo-electric static charging of the ski base.[10] Since the seminal work by Bowden in the 1940-1950's, many new polymers have been developed, including the above-mentioned UHMW PE, and notably in the area of copolymers of polyethylene and PTFE. Some of these materials have been explored as coatings for ice breakers[10] or for their tribological properties on ice[11,12] or snow.[2,13] However, a systematic study of the influence of the surface chemical composition of modern materials on their friction properties on snow is still lacking. It is, therefore, the objective of the work described in this chapter to evaluate a selection of polymers that exhibit a wide spectrum of chemical compositions, for their use as ski base materials.

2. Experimental

2.1. Materials

Six polymers of different chemical composition were selected, listed in Table 1, to cover a wide range of polarity, thus allowing for friction-increasing- and repulsive, friction-reducing interactions.

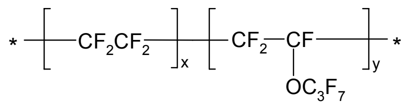
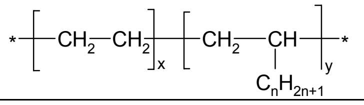
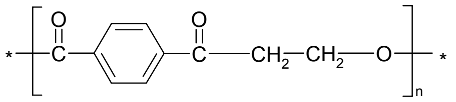
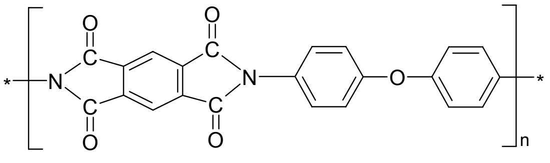
symbol	polymer	structure
●	Perfluoroalkoxy copolymer: PFA	 $*-\left[CF_2CF_2\right]_x-\left[CF_2-\underset{OC_3F_7}{CF}\right]_y-*$
▼	Linear-low density polyethylene: LLDPE	 $*-\left[CH_2-CH_2\right]_x-\left[CH_2-\underset{C_nH_{2n+1}}{CH}\right]_y-*$
■	Ethylene tetrafluoroethylene copolymer: ETFE	$*-\left[CH_2CH_2-CF_2CF_2\right]_n-*$
⬠	Poly(vinylidene fluoride): PVDF	$*-\left[CH_2-CF_2\right]_n-*$
◆	Poly(ethylene terephthalate): PET	
⬖	Polyimide: PI	

Table 1: Polymers employed in this chapter.

The relevant physical properties of these polymers are listed in Table 2.

polymer	thermal conductivity W (m K)$^{-1}$	surface tension mN m^{-1}	supplier	refs.
PFA	0.20	(23.9)	Goodfellow	14
LLDPE	0.34	34.3, 34.8, 35.3	Dow Chemical	15-18
ETFE	0.24	(27.6)	Goodfellow	19
PVDF	0.13	33.2, 36.5	Goodfellow	20-22
PET	0.15	44.6	Angst+Pfister	21,23
PI	0.11	37.7	UBE	23,24

Table 2: Selected physical properties of polymers used; values in brackets are estimates.

As the thermal conductivity of polymers is generally very low compared to other materials, especially metals, this characteristic is not considered in this work. However, in this chapter particular attention will be paid to their surface tension, more specifically their contact angle with water, which is directly associated with it (in the case of ideal flat surfaces).

2.2. Contact angle

As it is well known that surface roughness has a significant influence on contact angle measurements,[25-28] and that processing techniques considerably affect the surface roughness of polymer films, contact angle values were determined of the actual films employed, and not simply adopted from literature.

A dynamic contact angle measurement was chosen over a static method to obtain results of higher accuracy. (In static measurements the results can vary between the values of the advancing and the receding contact angles obtained in the dynamic measurements.[25]) The dynamic experiments were conducted employing an optical drop shape analyzing system (G2/G40 2.05-D, Kruess GmbH, Germany). Distilled water was used and applied at a rate of 15 µl/min. A video camera recorded the growth and shrinkage of a drop with 40 images per measurement. Two measurements were performed, one for the advancing contact angle and one for the receding. The measurements were always carried out both parallel and perpendicular to the ski axis. In order to examine effects due to the sliding tests, the samples were analyzed before and after sliding on snow (see Table 3 and 4).

Analysis of the data acquired was performed using the *tangent method 2* routine of the Krüss Drop Shape Analysis program (DSA version 1.80.0.2 for Windows 9x/NT/2000, 1997-2002 Krüss). This program utilizes a fourth-order polynomial function to fit both sides of the drop shape and calculates its angle with the base line. To avoid interference of pinning effects, the measured angle values were analyzed only after the border of the water droplet moved in a steady manner. If one side of the drop remained pinned, the values of that side were rejected.

In general, the contact angle determined in the perpendicular direction of the ski axis was found to be a few degrees higher than in the parallel direction in the measurements *before* the sliding experiments. A possible explanation for this effect could be that with the application of the film on the slider a texture is induced to the film which runs along the axis of the ski. This texture would pin the water droplet used in the contact-angle measurement, increasing the average value of the contact angle. It is worth to note that that pattern was no longer observed in contact-angle measurements performed *after* the experiment.

polymer	contact angle *parallel* to sliding direction		contact angle *perpendicular* to sliding direction	
	advancing °	receding °	advancing °	receding °
PFA	109 (±2)	90 (±3)	114 (±2)	94 (±2)
LLDPE	99 (±1)	83 (±2)	103 (±1)	86 (±2)
ETFE	81 (±1)	79 (±2)	99 (±2)	75 (±6)
PVDF	80 (±2)	53 (±2)	93 (±1)	62 (±1)
PET	87 (±1)	48 (±2)	88 (±1)	46 (±2)
PI	78 (±2)	40 (±3)	87 (±2)	30 (±2)

Table 3: Contact angles of distilled water both parallel and perpendicular to the ski axis, measured ***prior to*** sliding on snow (values in brackets indicate the standard deviation).

polymer	contact angle *parallel* to sliding direction		contact angle *perpendicular* to sliding direction	
	advancing °	receding °	advancing °	receding °
PFA	100 (±3)	76 (±3)	94 (±4)	80 (±3)
LLDPE	100 (±1)	20 (±4)	100 (±2)	30 (±6)
ETFE	95 (±2)	75 (±2)	96 (±3)	71 (±1)
PVDF	94 (±2)	14 (±3)	91 (±2)	25 (±9)
PET	89 (±1)	29 (±2)	94 (±1)	29 (±2)
PI	83 (±3)	13 (±6)	92 (±2)	18 (±3)

Table 4: Contact angles of distilled water both parallel and perpendicular to the ski axis, measured ***after*** sliding on snow (values in brackets indicate the standard deviation).

For a subset of the materials tested, e.g. PFA and LLDPE, the contact angle decreased after the polymer film slid on snow, concurring with Bowden's laboratory-scale experiments.[5] However, following these experiments, the majority of the materials, namely ETFE, PVDF, PI and PET, depict an increase in the advancing contact angle in the parallel direction. This may originate from an increase in surface roughness, as these films initially exhibit an extremely low surface roughness and, in addition, these polymers are known for their low wear resistance.

3. Results and discussion

In a first set of experiments, friction between snow and miniature skis equipped with films with a thickness of 100 µm to 250 µm of the selected polymeric materials was investigated according to the procedures presented in Chapter 2. The films were relatively flat, without visible texture on their surface and used as-received. The experiments of descending the sliders were conducted in an indoor ski-hall in Neuss, Germany, allowing for constant conditions at intermediate temperatures (-3 to -4 °C). This temperature range has been reported by other authors to be the range where the lowest friction between snow and sliders is experienced.[29] Figure 1 displays the obtained results.

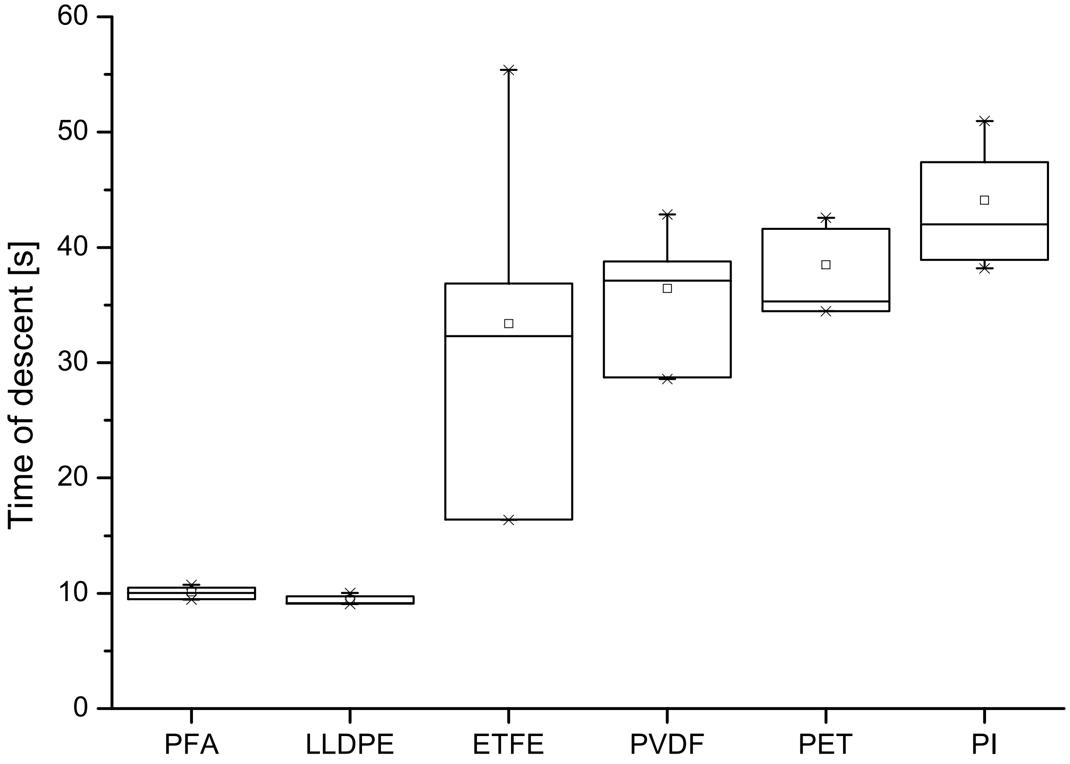


Figure 1: Box-whisker plot of the time of descent for all polymer ski-soles, arranged according to decreasing (approximate) contact angle (cf. Tables 3, 4). The snow temperature varied from -3.4 to -4 °C, the air temperature was -3 °C, track length was 40 m and 8 measurements per material were recorded (PET: 4).

Upon cursory examination of the data presented, there appears –not unexpectedly– to be some correlation between the contact angle, or polarity, of the material of the ski-sole and the time of descent; i.e. the more polar material exhibits higher friction with snow.

Further it was found that sliders equipped with polymers containing polar moieties (e.g. ETFE, PVDF, PI, PET) exhibited a significantly larger spread in the time of descent than their counterparts comprising only apolar groups. A possible explanation could be that small molecular segments reorient themselves gradually during the experiments and thus cause a change in the surface energy. This behavior has been observed with a range of polymers like polydimethylsiloxane (PDMS),[30] polyurethanes,[31] PET and polyamides,[32] and appears to be consistent with data presented in Tables 3 and 4. Another cause, however, might be that polar materials are more sensitive to small differences in surface roughness, as will be explored in more detail in Chapter 4.

3.1. Influence of temperature

In a second series, outdoor experiments were performed with a selected subset of ski-soles at a lower temperature (-10 °C) and at warmer conditions (0 °C). The data shows similar trends as observed in the previous (medium range temperature, -3 to -4 °C) measurements; i.e. hydrophobic materials display lower friction than more hydrophilic polymers.

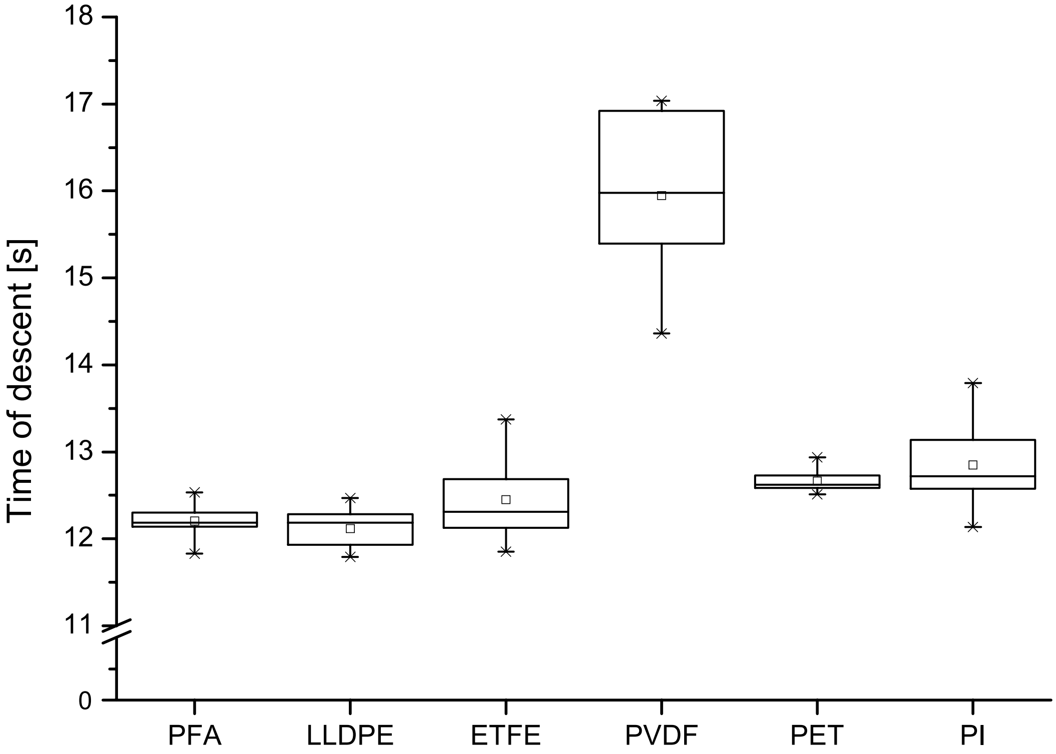


Figure 2: Box-whisker plot of the time of descent for various polymer ski-soles. The test field was located in Lenz, Switzerland. The snow temperature was 0 °C, the air temperature varied from -0.3 to 1.8 °C, track length was 80 m and 9 measurements were performed with each material.

For the experiments at the elevated temperature, it was observed that the time of descent for skis with soles of PET, PI and ETFE, reduced to the level of sliders with apolar soles, i.e. PTFE and LLDPE. In general, the data of the two experiments shows less distinction between skis with different sole-materials than the experiments performed in the ski hall. Therefore, all subsequent measurements were conducted in the indoor ski hall, since this location provides constant experimental conditions that, in addition, unvealed the clearest distinction between the different materials.

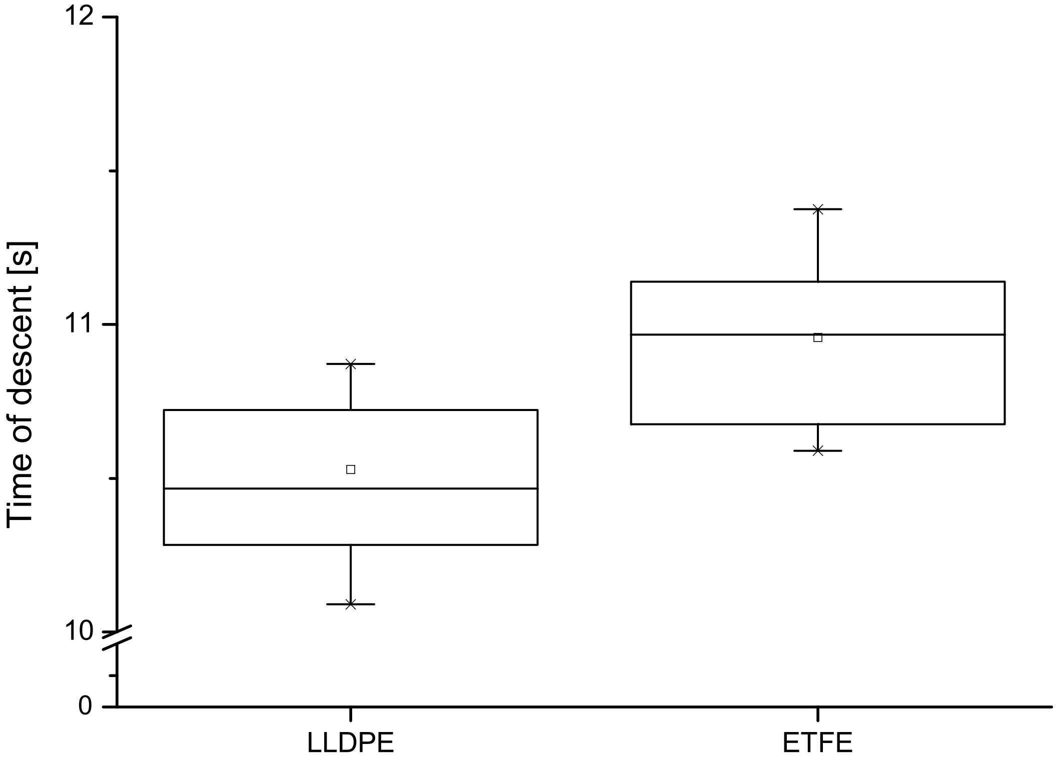


Figure 3: Box-whisker plot of the time of descent for ski-soles of LLDPE and ETFE. The test field was located in Davos, Switzerland. The snow temperature varied from -10.9 to -8.9 °C, the air temperature from -10.9 to -5.5 °C, track length was 34.6 m and 12 measurements were performed for each material.

3.2. Dependence on contact angle

To investigate in more detail a possible correlation between contact angle and frictional behavior, as suggested by several authors,[5,33,34] the times of descent of the small-scale slider equipped with different polymer films were plotted against their advancing and receding contact angles (Figures 4 to 7). Indeed, a correlation between the receding contact angle and the time of descent can be observed with contact angles measured *before* the sliding experiment was conducted (Figure 4 and 5). However, there was no distinct correlation between the receding contact angle and the time of descent measured *after* sliding on snow,(cf. Figure 6 and 7), possibly due to wear-induced surface roughness and dirt accumulation during the experiment.

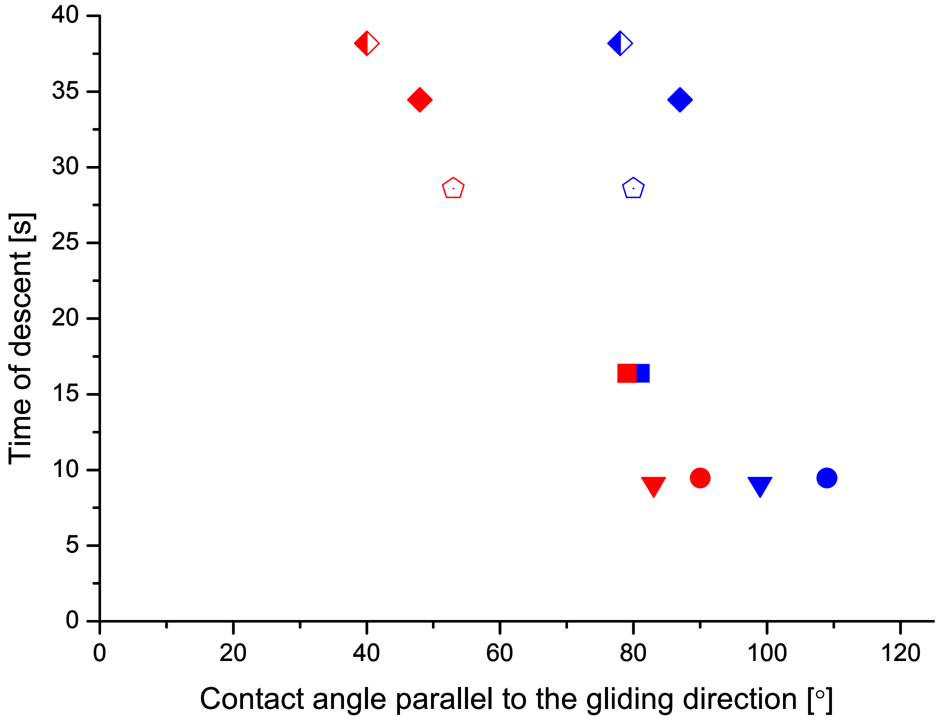


Figure 4: Shortest time of descent for all polymer ski-soles, plotted against dynamic contact angle measured *parallel* to the sliding direction ***prior to*** gliding on snow (data from Figure 1). The blue symbols indicate the advancing contact angles and the red symbols correspond to the receding contact angles. ● : PFA, ▼ : LLDPE, ■ : ETFE, ⬠ : PVDF, ◐ : PI and ◆ : PET.

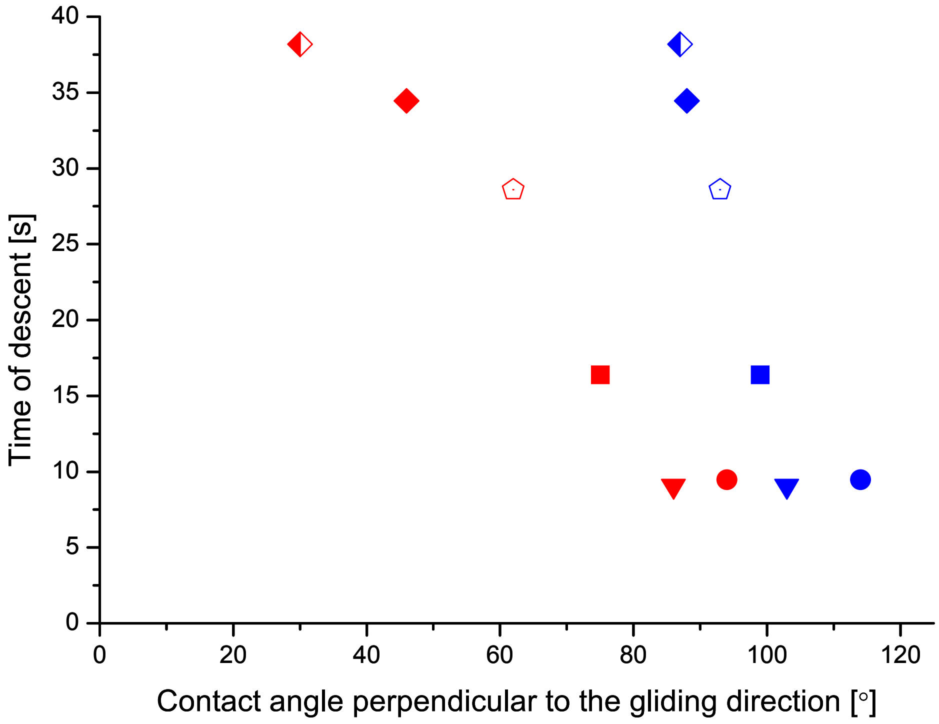


Figure 5: Shortest time of descent for all polymer ski-soles, plotted against dynamic contact angle measured *perpendicular* to the sliding direction ***prior to*** gliding on snow (data from Figure 1). The blue symbols indicate the advancing contact angles and the red symbols correspond to the receding contact angles. ● : PFA, ▼ : LLDPE, ■ : ETFE, ⬠ : PVDF, ⬖ : PI and ◆ : PET.

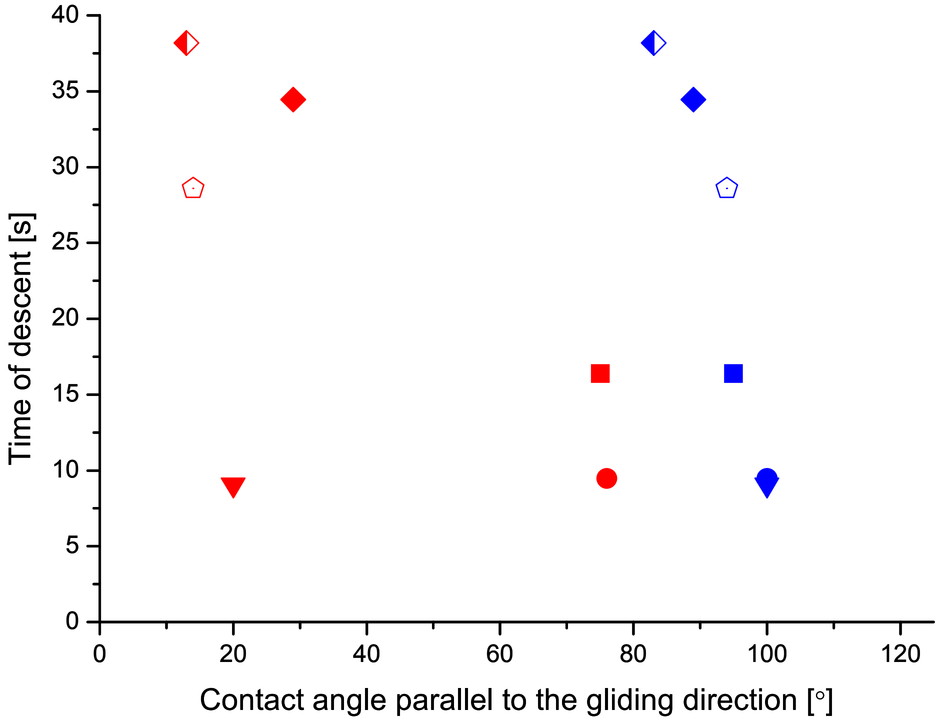


Figure 6: Shortest time of descent for all polymer ski-soles plotted against dynamic contact angle measured *parallel* to the sliding direction ***after*** gliding on snow *parallel* to the sliding direction. The blue symbols indicate the advancing contact angles and the red symbols correspond to the receding contact angles. ● : PFA, ▼ : LLDPE, ■ : ETFE, ⬠ : PVDF, ⬖ : PI and ◆ : PET.

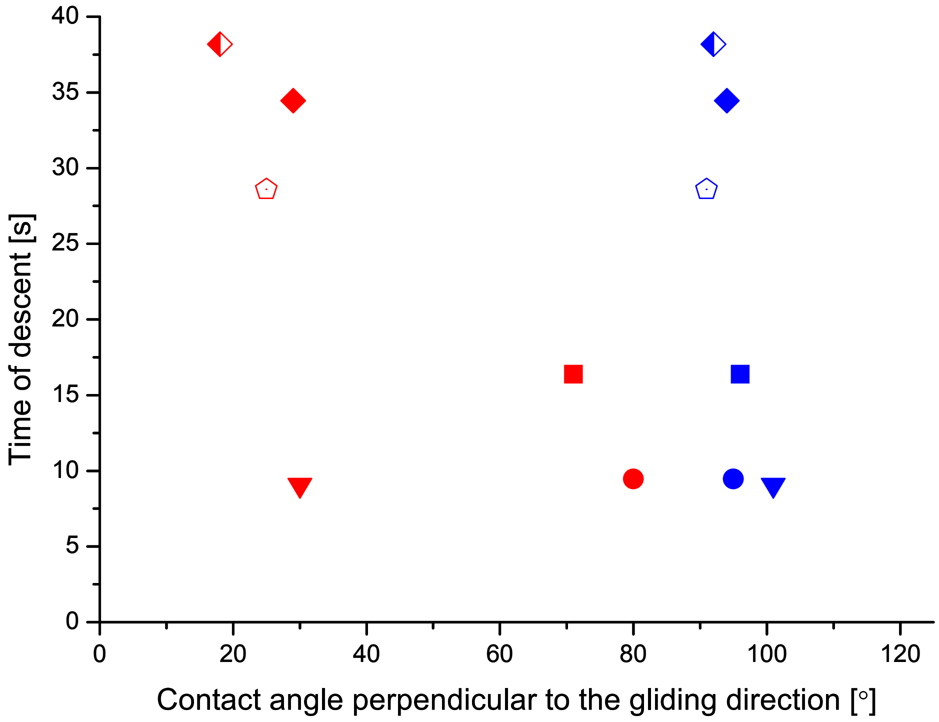


Figure 7: Shortest time of descent for all polymer ski-soles, plotted against dynamic contact angle measured *perpendicular* to the sliding direction ***after*** gliding on snow *perpendicular* to the sliding direction. The blue symbols indicate the advancing contact angles and the red symbols correspond to the receding contact angles. ● : PFA, ▼ : LLDPE, ■ : ETFE, ⬠ : PVDF, ⬖ : PI and ◆ : PET.

4. Conclusions

The data presented in this study, indeed appear to confirm the well-known rule of thumb that hydrophobic polymers glide faster over snow than their hydrophilic counterparts, despite the rather high standard deviation of contact-angle measurements (up to 9 °). It has to be mentioned, though, that the results obtained in this chapter were obtained with slider soles of relatively smooth polymer films with no visible surface texture. As will be demonstrated in the next Chapter 4, introduction of surface structures on the ski-sole dramatically alters their frictional properties and the simple concept of a correlation between time of descent and polarity and contact-angle arguments no longer holds.

5. References and notes

[1] TOKO Waxmanual, http://www.toko.ch/medias/sys_master/8451220103565056.pdf, **2009**.

[2] Shimbo, M., *Friction on snow of ski soles, unwaxed and waxed* in Scientific Study of Skiing in Japan, The Society of Ski Science: Tokyo, **1971**, 99-112.

[3] Colbeck, S., *A Review of the processes that control snow friction* in Cold Regions Science and Technology, **1992**; p 1-40.

[4] Bowden, F. P.; Hughes, T. P., *Proc. R. Soc. London* **1939**, *172*, 280-298.

[5] Bowden, F. P., *Proc. R. Soc. London Ser.* **1953**, *217*, 462-478.

[6] Personal communication, Urs Geissbühler, IMS Kunststoff AG, Switzerland, **2005**.

[7] Personal communication, Michael Jufer, TOKO AG, Switzerland, **2006**.

[8] Lind, D.; Sanders, S. P., *The physics of skiing: Skiing at the triple point* **1996**, Springer-Verlag, New York.

[9] Wikipedia ski, http://en.wikipedia.org/wiki/Ski, **2009**.

[10] Calabrese, S. J.; Buxton, R.; Marsh, G., *Lubric. Eng.* **1980**, *36*, 283-289.

[11] Albracht, F.; Reichel, S.; Winkler, V.; Kern, H., *Materialwiss. Werkstofftech.* **2004**, *35*, 620-625.

[12] Gnörich, W.; Grosch, K. A., *J. Inst. of the Rubber Ind.* **1972**, *6*, 192-196.

[13] Shimbo, M., in *The mechanism of sliding on snow*, International Association of Hydrology Commission of Snow and Ice, Helsinki, **1960**.

[14] DuPont Teflon® PFA: Properties bulletin, DuPont Fluoroproducts, Wilmington.

[15] McGraw-Hill, *Guide to Plastics: Property and specification charts* **1987**, McGraw-Hill, New York.

[16] Dettre, R. H.; Johnson, R. E., *J. Colloid Interface Sci.* **1966**, *21*, 367-377.

[17] Roe, R. J., *J. Phys. Chem.* **1968**, *72*, 2013-2017.

[18] Wu, S., *J. Polym. Sci. C.* **1971**, 19-30.

[19] DuPont Tefzel®, Properties handbook, DuPont Fluoroproducts, Wilmington.

[20] KF Polymer® Polyvinylidene Fluoride, Products bulletin, Kureha Chemical, Iwari.

[21] Wu, S., *Polymer interface and adhesion* **1982**, Marcel Dekker, New York.

[22] Wu, S., *J. Colloid Interface Sci.* **1979**, *71*, 605-609.

[23] Thompson, E. V., *Encyclopedia of polymer science and engineering* **1985**, Wiley-Interscience, New York.

[24] Sacher, E., *J. Appl. Polym. Sci.* **1978**, *22*, 2137-2139.

[25] Degennes, P. G., *Rev. Mod. Phys.* **1985**, *57*, 827-863.

[26] Dettre, R. H.; Johnson, R. E., *Adv. Chem.* **1964**, *43*, 136-144.

[27] Genzer, J.; Efimenko, K., *Biofouling* **2006**, *22*, 339-360.

[28] Quere, D., *Physica A* **2002**, *313*, 32-46.

[29] Buhl, D.; Fauve, M.; Rhyner, H., *Cold Reg. Sci. Tech.* **2001**, *33*, 133-140.

[30] Chen, C. Y.; Wang, J.; Chen, Z., *Langmuir* **2004**, *20*, 10186-10193.

[31] Tingey, K. G.; Andrade, J. D., *Langmuir* **1991**, *7*, 2471-2478.

[32] Tretinnikov, O. N.; Ikada, Y., *Langmuir* **1994**, *10*, 1606-1614.

[33] Colbeck, S. C., *J. Glaciol.* **1988**, *34*, 78-86.

[34] Kietzig, A. M.; Hatzikiriakos, S. G.; Englezos, P., *J. Appl. Phys.* **2009**, *106*, 024303.

Chapter IV

Surface structures

1. Introduction

Surprisingly, relatively little literature addresses the influence of the surface structure of ski bases on their tribological properties. Among early reports is that of Ericksson[1] who observed that the roughness of steel runners has a significant influence on their friction on snow. He found, to his surprise, that runners with the smoothest surface did not exhibit the lowest friction. Furthermore, he observed a dependence between the static friction of a slider on snow and the grain size of the snow pack and reported that on smaller snow grains the friction of the runner increased.

A more systematic study of tribological properties of sliders of different roughness was conducted by Shimbo, [2] who measured the friction of phenolic resin ski soles with bump heights between 15 to 35 µm against ice at 0 °C using a tribometer. He reported that friction decreased slightly with increasing surface roughness, and that a ski base with a smooth surface featured considerably higher friction than all other specimens. In a related study, analyzing different materials for application on ice breakers, Calabrese *et al.* found, however, an increase in the kinetic and static friction between steel and ice when the arithmetical mean surface roughness, R_a, was increased from 1 to 6.1 µm at -22 °C.[3] Similar effects were also observed by other authors.[4]

A study of the effect of structuring ski soles on the performance of Nordic skis was presented by Moldestad,[5] who observed that the optimum roughness of the surface structure increased with snow humidity, which he presumed to be related to the thickness of the water film under the ski sole generated by frictional heat. In addition, he reported that ski soles with coarser structures displayed lower friction at higher speeds. The range of surface roughness (R_a perpendicular to the gliding direction) of the competition skis used in that study ranged from 2.5 to 12 µm.[5]

In a recent study Kietzig *et al.* found that a slider with a roughness of R_a = 1.15 µm experiences higher friction at low speeds than a slider with a roughness of R_a = 0.6 µm and that this trend reverses for higher velocities.[6] In addition they reported a similar effect with the orientation of the applied roughness; a slider with a roughness of R_a = 0.6 µm experiences less friction at low speeds if the orientation is applied parallel to the sliding direction. This trend disappears at higher speeds (v > 0.5 m/s). The effect of the influence of different roughnesses was attributed to the increased hydrophobicity of the rougher structure which reduces the number of capillary bridges of the slider at speeds were the water film is present. The effect of orientation was explained with the presence of interlocking asperities which are minimized with a structure oriented in the gliding direction.

Evidently, the thickness of the water film resulting from frictional heat referred to above is crucial for understanding friction of a ski sliding on snow, and several experimental and numerical studies have been devoted to it, unfortunately yielding vastly different results, covering a range from a few nanometers[7] to a few hundred micrometers.[8] Using a detailed heat balance, Colbeck estimated a range for the water film thickness of 0.2 to 1.2 µm,[9] while numerical simulations by Bäurle *et al.* resulted in a range of 0.1 to 0.2 µm at intermediate temperatures (-1 to -10 °C), increasing up to a few micrometers under wet conditions at 0 °C.[10]

Bowden, and later Ericksson, applied the concept of “apparent” contact area[1,11] to skiing, and suggested that the ski sole is only in partial contact with the snow track. This implies that the ski is sliding only on a number of contact spots, the size of which is then another important parameter for the determination of the friction properties. Measurement of the size of these contact spots by different authors and with various methods yielded consistent results with the average size determined to be in the range of 100 to 200 µm.[12-14]

Although some knowledge has been gained in the above summarized (somewhat “spotty”) studies, to our knowledge, no research directed to systematically investigate the combined influences of surface roughness *and* the chemical composition of a ski base on its friction on snow has been reported; this is, hence, the aim of the study presented in this chapter.

2. Experimental

All experiments with the small sliders were conducted in the indoor ski hall in Neuss, Germany. The snow temperature varied from -4 to -2.6 ºC, the air temperature from -3.4 to -4 ºC and track length was 40 m, if not stated otherwise.

2.1. Structuring

Typical means of introducing a structure to the surface of a ski sole involve band or stone grinding techniques, of which the latter apparently provides a superior pattern. The stone grinding technique employs a rotating cylinder of corundum that is structured with a small diamond. Pressing the ski sole onto the rotating corundum cylinder yields a relief structure into the ski base. In the band grinding method the ski surface is structured with a grinding band running between two rolls.

To produce a desired structure, several machining cycles are required. As the ski is always processed more or less parallel to the grinding direction of the band or roll, these techniques typically introduce linear structures parallel to the gliding direction of the skis. The stone grinding machines that are used today are rather sophisticated, allowing for the alternation of the surface structure along the ski in both parallel and perpendicular direction, enabling the creation of complex structures,[15] such as gradients over the length of the ski. In our experiments, fine surface structures were introduced by using a steel brush as it is practiced in traditional ski preparation.

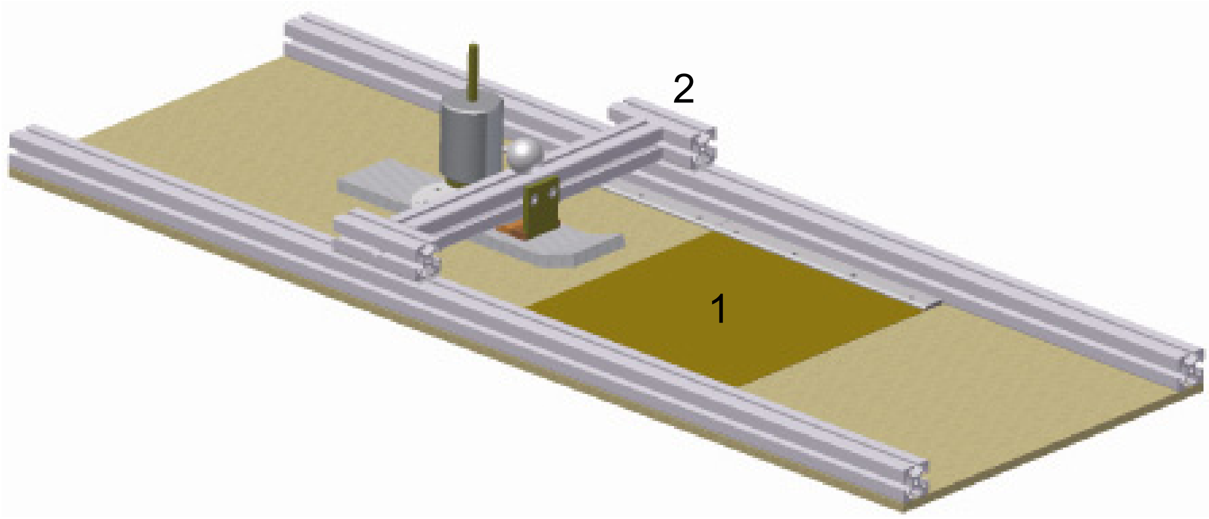


Figure 1: Ski structuring device: **1.** board with sand paper, **2.** holder to position the small skis at a given angle.

The steel brush was provided by TOKO, Switzerland and brush strokes were performed along the sliding direction of the ski.

For the introduction of coarser surface structures, an in-house-developed ski structuring device (see Figure 1) was employed to create structures on a slider surface in a well-defined manner. It consists of a board onto which sand paper of the desired grain size (purchased from Brütsch/Rüegger AG, Switzerland) was mounted, and a holder for the small skis to move them under a given load and angle over the sand paper. An elastomeric film was inserted between the grinding board and the sand paper, to ensure an even surface pressure distribution under the sliders. The surface pressure exerted on the skis was 12.75 g/cm^2 (1.25 kPa). The standard grinding procedure consisted of 10 strokes over the sand paper, whereby the latter was cleaned with an air gun after each stroke to remove wear particles.

2.2. Analysis of surface roughness

Topographic analysis of the surfaces of the slider soles was conducted with a white light optical profilometer FRT MicroProf® using the software Mark III (Fries Research & Technology GmbH, Germany). The resolution was 1 µm in the x- and y direction, and 10 nm in the z direction. To eliminate deviations due to differences in (UV-) light transparency of the polymers used (Table 1), the analysis was performed on replicas made with a dimethyl siloxane resin (PROVILnovo Light C.D.2 fast set, Heraeus Kulzer GmbH, Germany), instead of on the actual samples. The arithmetical mean roughness (R_a) was determined according to DIN EN ISO 4288.[16] The cut-off length (a filter that Fourier transforms the surface profile and rejects values larger than the cut-off length) was set to 0.8 mm and five measurements were recorded per sample. The slope of the overall surface profile was set to 0 ° with a linear correction factor prior to the analysis. The direction of the measurements was always perpendicular to the gliding direction of the skis.

Parameters for the characterization of the surface roughness

A range of surface roughness parameters were analyzed for correlation with the sliding results reported in this chapter. Among those two parameters showed particular promising correlations with the experimental times of descent and, therefore, will be described in more detail in the next section.

Arithmetical mean roughness

The arithmetical mean roughness R_a describes the mean deviation from the arithmetical average height of a surface profile. It is also known as the center line average (CLA).

$$R_a = \frac{1}{L}\int_0^L \left|y(x)\right| dx \qquad (1)$$

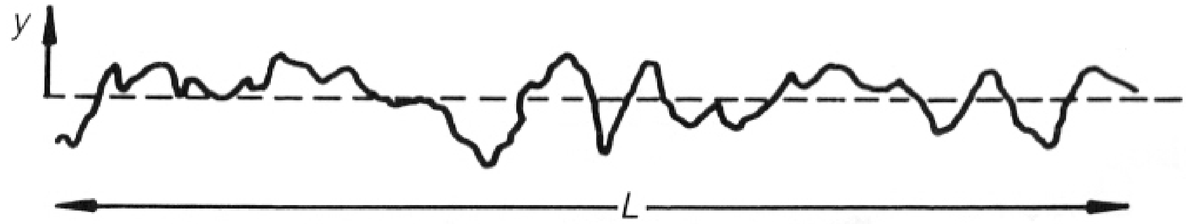


Figure 2: Surface roughness parameter: R_a describes the mean deviation of the average height. The figure was reprinted from the book Tribology written by Hutchings.[17]

Here, L is the scanning length in the x direction, and $y(x)$ is the height of the surface above the mean line at the distance x. As the height profile $y(x)$ is often fractal, as mentioned above, a filter that Fourier transforms the surface profile and rejects values larger than a cut-off length was used in this study.[18]

Core roughness depth

The core roughness depth R_k is used in industry for the description of the surface roughness of sliding surfaces in bearings. It is derived from the Abbott-Firestone curve (also called "bearing curve," see Figure 3) and is a measure of the core roughness (peak-to-valley) of the surface with the extreme peaks and valleys removed.

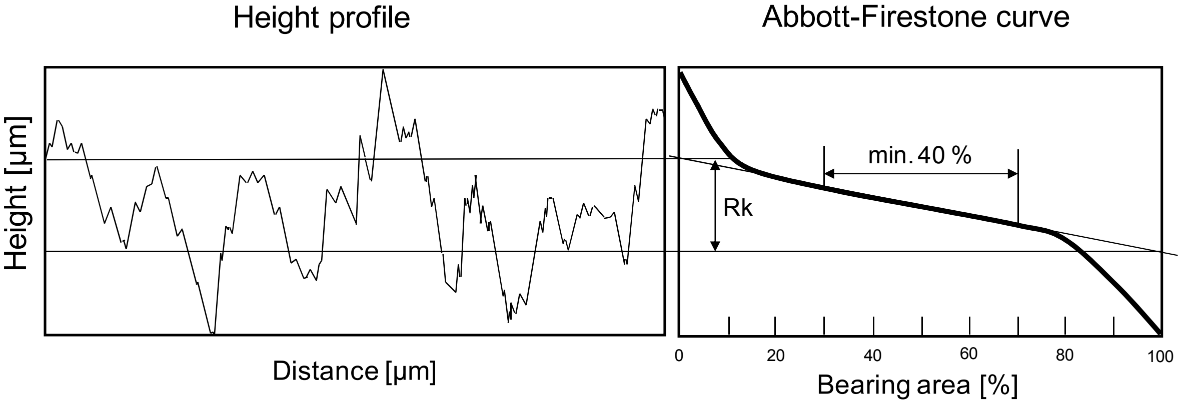


Figure 3: Surface roughness parameter: R_k describes the distance of the intersection of the tangent of the Abott-Firestone curve with the y-axis. The tangent is drawn in the middle of the curve and is covering 40 % of the curve.

The value is determined by fitting a secant with the least mean squares method to the middle 40 % segment of the curve. This segment typically shows the lowest slope in the Abbott-Firestone-curve and the R_k value is obtained by measuring the y-distance of the intersection points of the extended secant with the y-axis (cf. Figure 3).[19]

Both parameters, R_a and R_k are not sensitive to outliers; therefore, they can be considered as "robust" characteristics.

2.3. Materials

For the study of the influence of structure and chemical composition of ski soles on their friction with snow, seven polymers were selected that cover a wide range of polarities, thus allowing for friction enhancing- and repulsive, friction-reducing interactions. Table 1 lists the polymers used, as well as their thermal conductivity and surface tension.

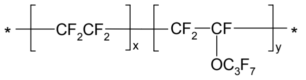
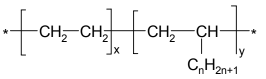
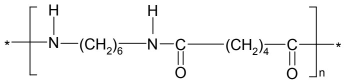
symbol	polymer	structure	thermal conductivity W (m K)$^{-1}$	surface tension m N m^{-1}	refs.
◓	Poly(tetrafluoroethylene): PTFE	$* \left[CF_2 - CF_2 \right]_n *$	0.25	23.9	20,21
●	Perfluoroalkoxy copolymer: PFA	 $* \left[CF_2CF_2 \right]_x \left[CF_2 - \underset{OC_3F_7}{\underset{\vert}{CF}} \right]_y *$	0.20	(23.9)	22
▲	Ultra-high molecular weight PE: UHMW PE	$* \left[CH_2 - CH_2 \right]_n *$	0.52	36.8	20,23
▼	Linear-low density PE: LLDPE	 $* \left[CH_2 - CH_2 \right]_x \left[CH_2 - \underset{C_nH_{2n+1}}{\underset{\vert}{CH}} \right]_y *$	0.34	34.3, 34.8, 35.3	24-27
⊳	Polyamide 6,6: PA 6,6	 $* \left[\overset{H}{\overset{\vert}{N}} - (CH_2)_6 - \overset{H}{\overset{\vert}{N}} - \underset{O}{\underset{\Vert}{C}} - (CH_2)_4 - \underset{O}{\underset{\Vert}{C}} \right]_n *$	0.23 - 0.43	44.7, 46.5	28,29
■	Ethylene tetrafluoro-ethylene copolymer: ETFE	$* \left[CH_2CH_2 - CF_2CF_2 \right]_n *$	0.24	(27.6)	30
⬠	Poly(vinylidene fluoride): PVDF	$* \left[CH_2 - CF_2 \right]_n *$	0.13	33.2, 36.5	28,31,32

Table 1: Selected physical properties of polymers used as slider soles; values in brackets are estimations. All polymeric films were obtained from Goodfellow, USA, with the exception of LLDPE which was processed in house from granulate purchased from Dow Chemical, USA.

3. Results and discussion

In a first set of experiments, polymer soles of different surface chemistry, ranging from hydrophilic to hydrophobic, were structured using a steel brush as it is practiced in traditional ski preparation and detailed in the above experimental section, resulting in a unidirectional structure along the axis of the slider (see insert Figure 4). The times of decent of these structured small skis were compared to those fitted with corresponding "flattened" films.

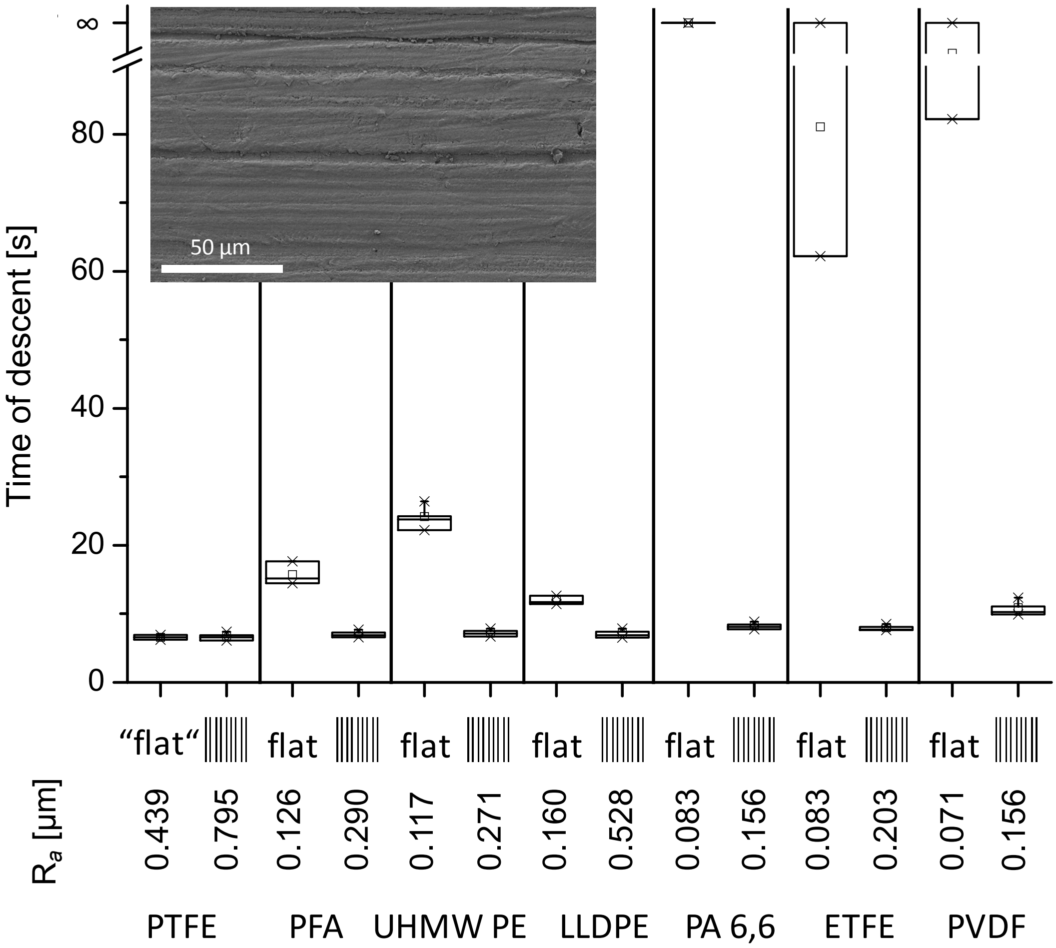


Figure 4: Box-whisker plot of the time of descent for all polymers. The notation "flat" corresponds to films that have no visible surface texture. PTFE, PFA, UHMW PE and PA 6,6 were pressed between two highly polished steel plates in a hot press. The structure was generated by repeated brushing the ski-sole with a steel brush along the ski-axis. ∞ indicates no sliding. The track length was 35 m and 4 measurements per slider were performed.

The latter were obtained by pressing the films between two highly polished steel plates with flat polyimide (PI) separators at elevated temperatures (about 20 °C below the melting temperature of the polymer film). The resulting arithmetical mean surface roughness values R_a of both the "flat" and the structured films were determined prior to the sliding tests on snow, and are indicated in Figure 3. The relatively high R_a-values of the "flat" hydrophobic PTFE, PFA, UHMW PE and LLDPE films probably stems from surface damage upon removal of the polyimide-film, and reduced flowability during hot-pressing of the ultra-high molar mass polymers PTFE and UHMW PE. The surface roughness after brushing the slider surface depends on the wear resistance of the polymer films and, hence, varied widely for the films used in this study.

Most interestingly, an initial comparison between the times of descent for sliders equiped with the structered and the flattend films reveals that the chemical nature of the ski-sole appears to be only of minor importance when compared to the influence of its surface structure (Figure 4). Indeed, a slider equipped with a smooth film of the hydrophilic polyamide 6,6 did not slide (*i.e.* infinite time of descent), but when brushed along the gliding direction, it performed virtually as well as skis fitted with structured hydrophobic polymers, such as polyethylene (!).

The influence of surface roughness of ski soles with a sole of a particular chemical composition was also demonstrated with actual Nordic skis, run by a professional athlete. The Nordic ski soles were structured using a stone grinding technique as commonly applied in the ski industry. The roughness values of the as-received sole films and the stone-ground soles are shown in Table 2.

A comparison between the performance of "flat" and structured Nordic skis, shown in Figure 5 - reassuringly - reveals a similar trend as observed for the small sliders (Figure 4), although the variations between the differently structured surfaces with identical chemistry were more pronounced for the latter.

polymer	arithmetical mean surface roughness, R_a		supplier
	as-received films µm	after stone grinding µm	
PTFE	0.255	0.984	Angst & Pfister
PFA	0.097	1.555	Quadrant
UHMW PE	0.835	1.622	Angst & Pfister
LLDPE	0.130	1.712	Dow Chemical
ETFE	0.090	1.443	Quadrant

Table 2: Surface roughness of Nordic skis, measured perpendicular to the ski axis ***prior to*** gliding on snow.

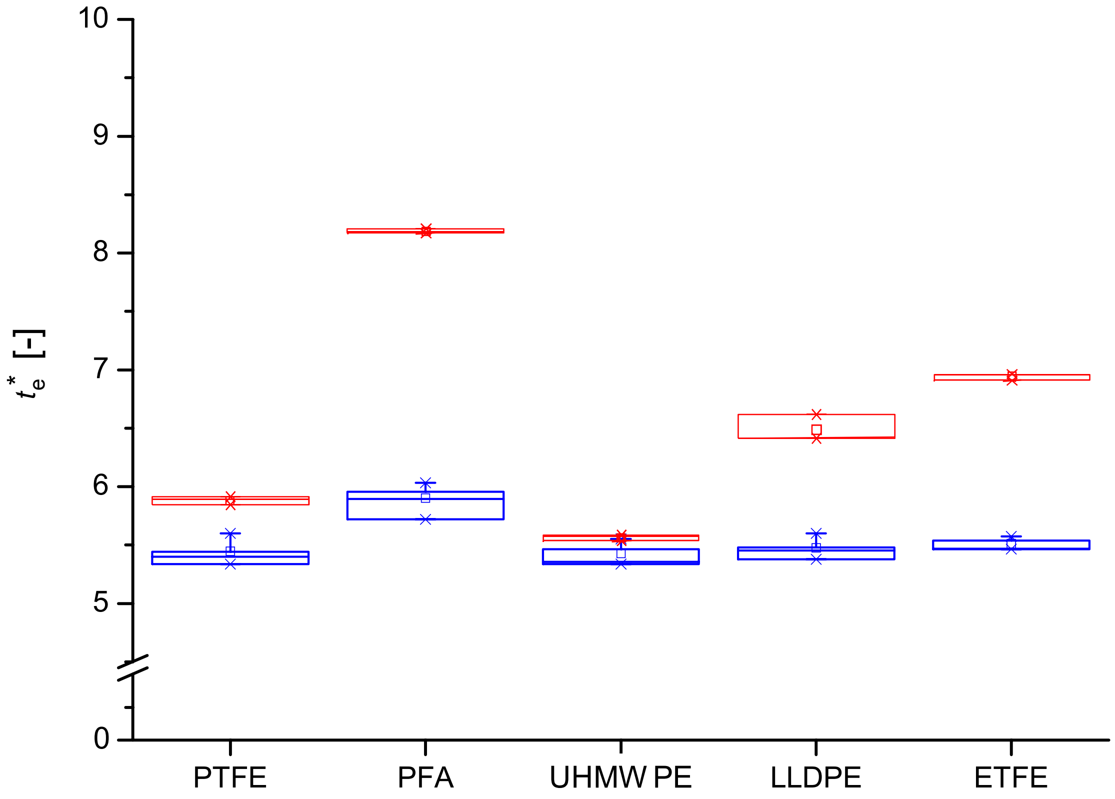


Figure 5: Box-whisker plot of the dimensionless time of descent, t_e^*, of **Nordic skis** with different polymer ski soles. The test field was located in Davos, Switzerland. The blue boxes represent measurements of Nordic skis with soles of conventionally structured polymers. The snow temperature varied from -12.4 to -11.7. °C, the air temperature varied from -10 to -8.5 °C, the track length was 140 m and 4 measurements per ski were performed. The red boxes are measurements of the same skis with ”flat” soles consisting of as-received films. The snow temperature varied from -10.9 to -8.9 °C, the air temperature varied from -10.9 to -5.5 °C, the track length was 142 m and 3 measurements per ski were performed.

This could be attributed on one hand to the technique of the stone grinding which yields a surface roughness that, in general, is higher than the one introduced with the steel brushing procedure. In addition, the wear resistance of the polymers is more crucial in this “structuring” technique since the grinding stone can be congested with wear particles during the structuring process, leading to different surface patterns. For example, in Table 2, it can be seen that the measured surface roughness of the structured PTFE ski is only about half the value of the structured UHMW PE ski. Finally, it cannot be excluded that the differences in snow and air temperature in the small-slider and Nordic ski experiments played a role.

A plot of the shortest time of descent for all small sliders versus the arithmetical mean surface roughness R_a of the different polymer soles is presented in Figure 6. (Additional data points originate from as-received polymeric films which exhibited a structure from processing, namely PA 6,6, PTFE and UHMW PE, which were also tested in this experiment. For the latter two this structure was also applied in the perpendicular direction.)

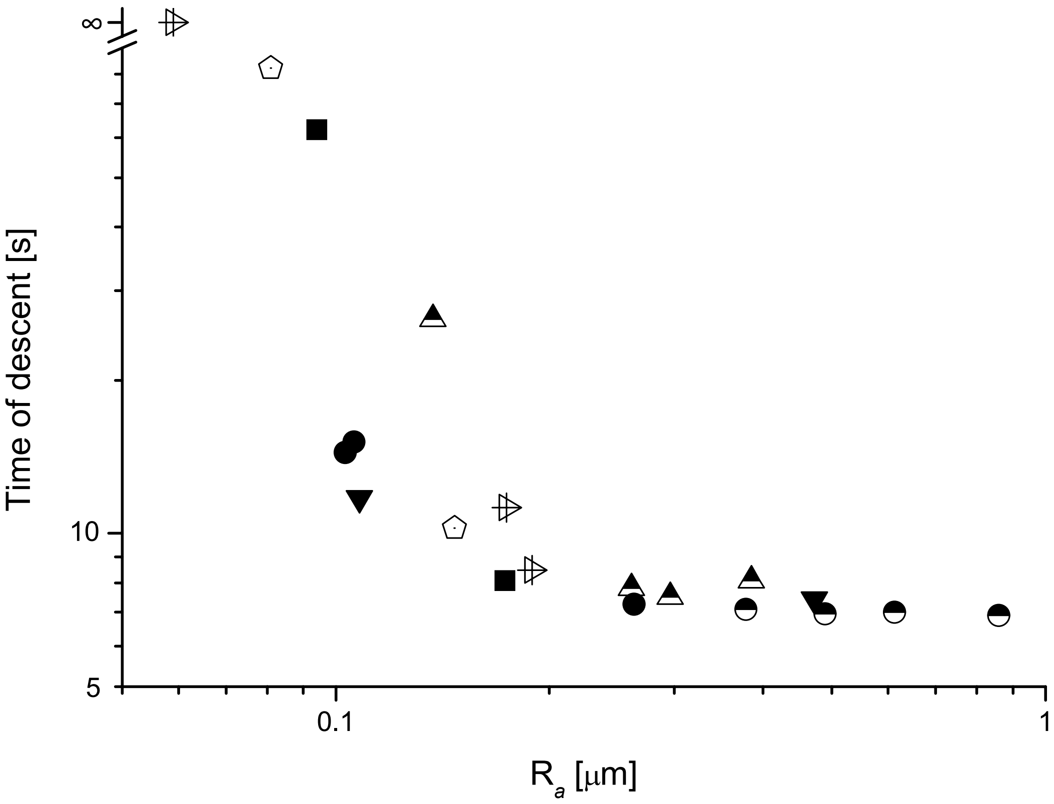


Figure 6: Shortest time of descent for all polymer ski soles, plotted against their arithmetical mean surface roughness *R*_a. ◓ : PTFE, ● : PFA, ▲ : UHMW PE, ▼ : LLDPE, ⊳ : PA 6,6, ■ : ETFE and ⬠ : PVDF. ∞ indicates no sliding. Four measurements per ski were performed.

The data in Figure 6 reveal a strong correlation of the time of descent with the surface roughness as characterized by R_a. Interestingly, for relatively flat surfaces, the time of descent strongly depends on the surface roughness, especially for ski soles made of hydrophilic polymers. However, at increasing roughness, $R_a > 0.2$ μm, the frictional properties of the sliders become increasingly *independent* of the chemical composition of the sole. It actually emerges that the optimum friction properties of all ski sole materials examined, leading to the shortest time of descent of the small skis on snow, are predominantly determined by the surface roughness of the soles and *not* by their chemical composition.

As ski soles used in Nordic skiing competitions typically have a relatively high surface roughness (R_a of 2.5 to 12.5 μm[5]), which exceeds the range of that introduced by a steel brush (cf. Figure 6), it was deemed desirable to extend the roughness range of our small slider soles to higher values. For these experiments, ETFE-based soles were chosen, since this material displayed a rather strong dependence of friction on surface roughness. The ETFE soles were structured using the device depicted in Figure 1, using sand paper of different grain sizes (25 to 200 μm). Two types of textures were selected. The first was a linear structure parallel to the ski-axis, similar to those in traditional ski preparation. The second structure was with no preferred orientation, which was created by circular grinding movements with the sand paper. In addition, the two structures that were used in the previous experiments with ETFE soles, i.e. the untreated- and steel-brushed surfaces were added to complete the experimental set. The results are shown in Figure 7.

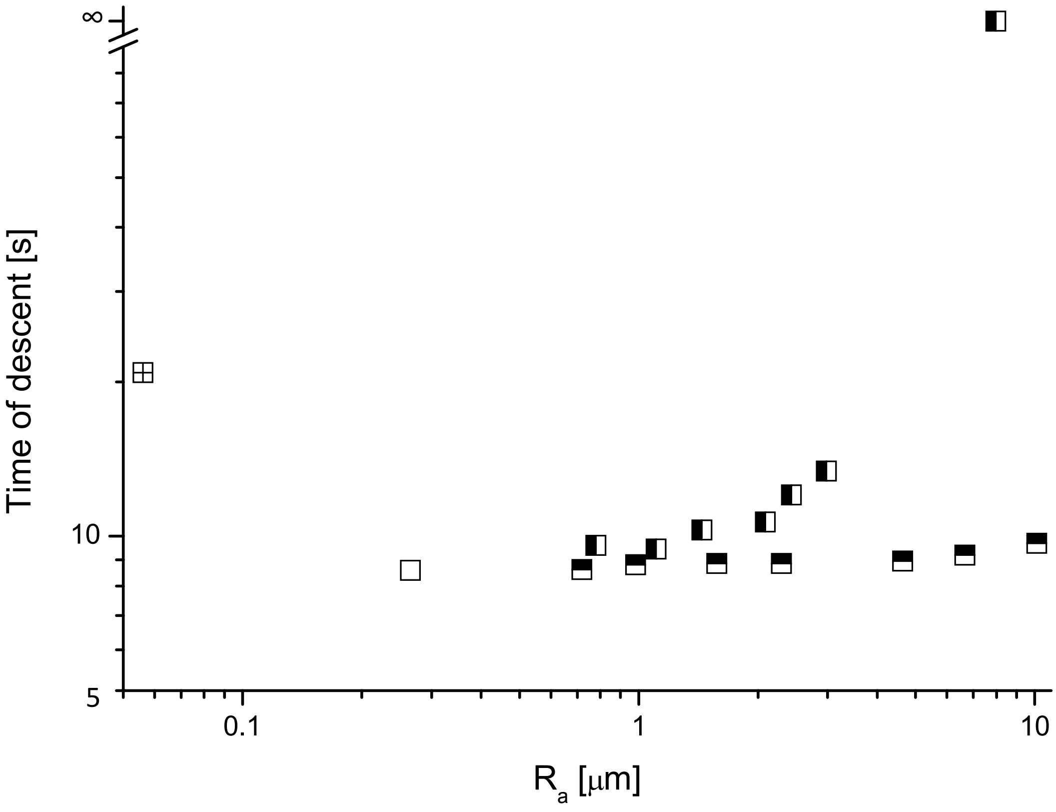


Figure 7: Shortest time of decent of small sliders fitted with differently structured ETFE soles, plotted against R_a. ⬒ : oriented structures and ◧ : unoriented structures, □ : oriented structure obtained with steel brush and ⊞ : untreated surface. ∞ indicates no sliding. Four measurements per ski were performed.

The data displayed in this figure reveal two distinct trends. For ski soles with *oriented* structures, a gentle increase of the time of descent with increasing surface roughness $R_a > 1$ μm is observed. By contrast, the time of descent for ski soles with *unoriented* structures exhibits a dramatically steeper increase with surface roughness, to the point that the ski-sole with the roughest unoriented structure (created with 200 µm grain size sand paper) did not glide at all, i.e. $t_e = \infty$.

As the preceding experiments were conducted at the same slope angle and under the same conditions, but on tracks of different length (35 m opposed to 40 m), the data presented in Figures 6 and 7 may be combined into one graph using the dimensionless time of descent t_e^*, introduced in Chapter 2.

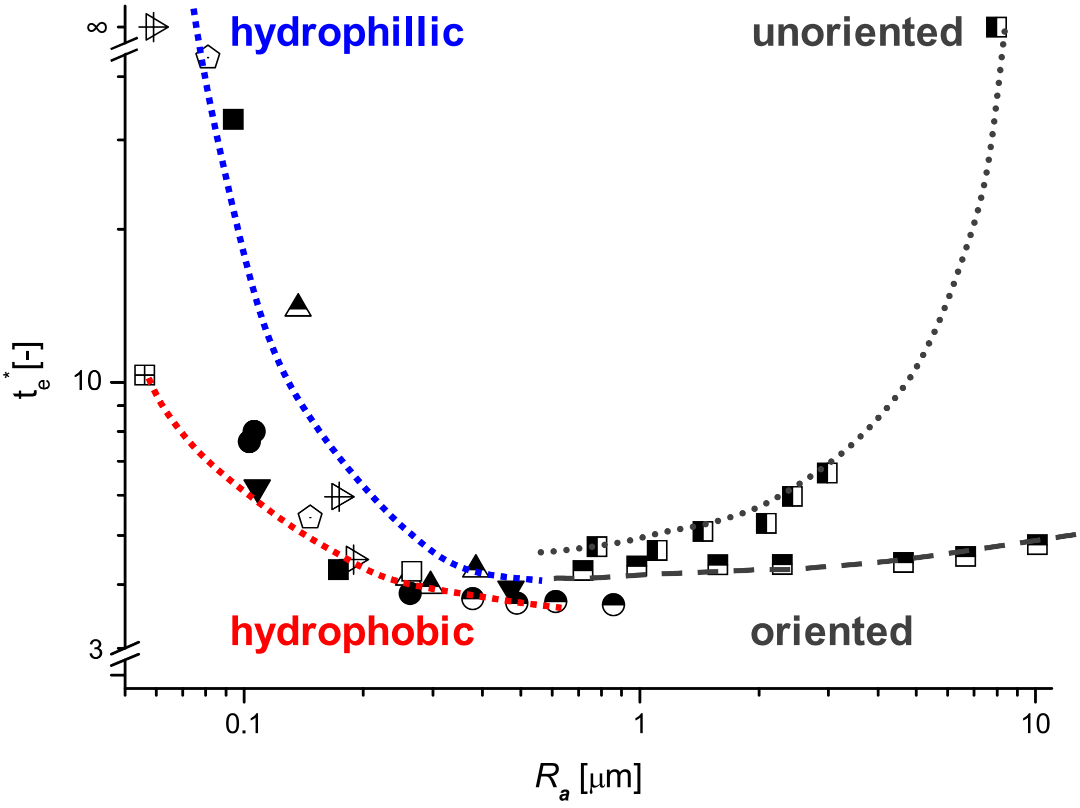


Figure 8: Shortest dimensionless time of decent, t_e^*, of small sliders fitted with differently structured soles of various polymers plotted against R_a. ◓ : PTFE, ● : PFA, ▲ : UHMW PE, ▼ : LLDPE, ⊳ : PA 6,6, ■ : ETFE, ⬠ : PVDF, ⬒ : oriented ETFE structures, ◧ : unoriented ETFE structures, □ : oriented ETFE structure obtained with steel brush and ◫ : untreated ETFE surface (data of Figure 6 and 7). ∞ indicates no sliding. The track length was 35 or 40 m and 4 measurements per ski were performed. The lines are drawn as a guide to the eye only.

A similar relationship between the time of descent and the arithmetical mean roughness (R_a) has been found between the time of descent and the core roughness depth (R_k) (see Appendix A2).

No clear trend emerges, when the data of Figure 8 are plotted against the contact angle of the corresponding structures prior to the skiing experiment and perpendicular to the ski-axis (cf. Figure 9). This is in contrast with the results obtained in Chapter 3 for flat films and those obtained in a study by Kietzig *et al.*[6] for structured sliders on ice.

Prior to discussing the results collected in Figure 8, it is important to recognize that the roughness range of the slider soles explored (R_a = 0.05 to 10 μm), is much smaller than the contact spot size between a ski sole and snow, which is in the order of 100-200 μm.[12-14] Therefore, for all sliders shown in Figure 8 the microscopic contact area (contact area inside a contact spot) between ski sole and snow is dominated by the roughness of the ski sole.

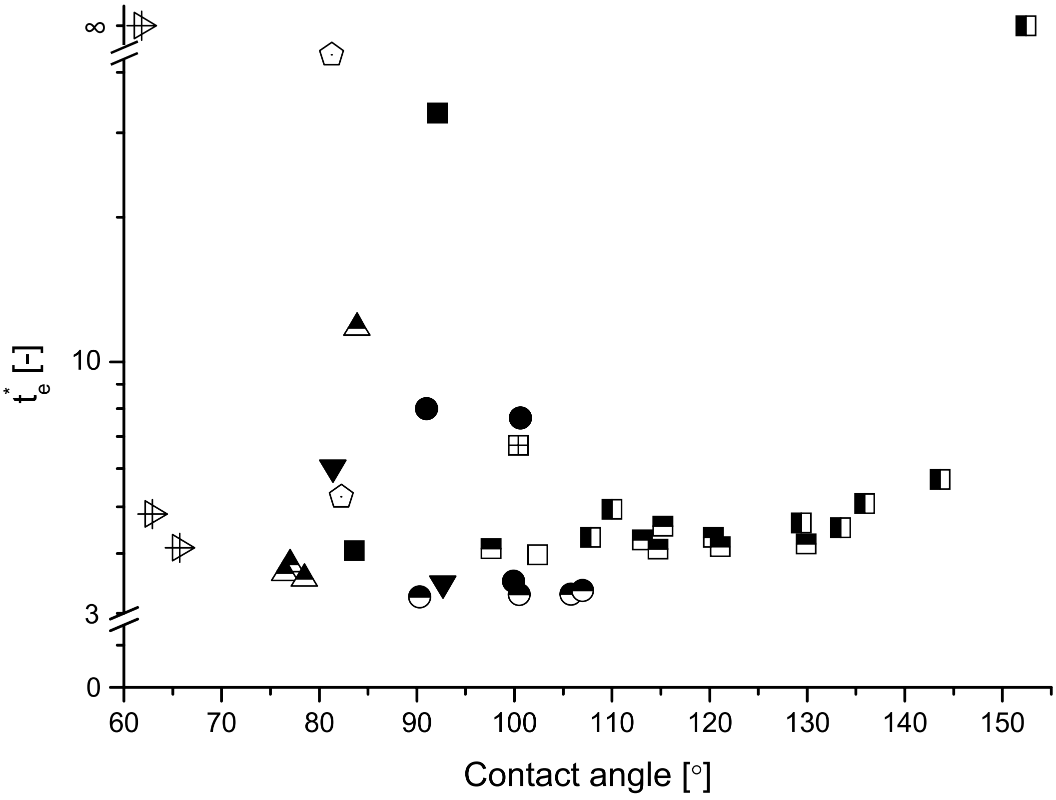


Figure 9: Shortest dimensionless time of decent, t_e^*, of small sliders fitted with differently structured soles of various polymers plotted against static contact angle measured perpendicular to the gliding direction (water drop of 6 to 8 μl distilled water gently placed on the surface). ◓ : PTFE, ● : PFA, ▲ : UHMW PE, ▼ : LLDPE, ⊳ : PA 6,6, ■ : ETFE, ⬠ : PVDF, ⬒ : oriented ETFE structures, ◧ : unoriented ETFE structures, □ : oriented ETFE structure obtained with steel brush and ⊞ : untreated ETFE surface (data of Figure 6 and 7). ∞ indicates no sliding. The track length was 35 or 40 m and 4 measurements per ski were performed.

Returning to the findings summarized in Figure 8, it seems reasonable to argue that for skis with a low surface roughness complete lubrication occurs in these localized contact spots as long as the thickness of the water layer generated by frictional heat is large compared to the surface roughness of the ski sole. In this roughness regime, the capillary suction effect, advanced by Colbeck,[9] applies, according to which capillary attraction exerts a frictional force due to "liquid bridging" between slider and snow grains. Capillary suction is more pronounced for polar surfaces. This explains the longer times of descent observed for flat hydrophilic- as opposed to flat hydrophobic surfaces. At increasing surface roughness the wetted contact area where capillary suction is active is reduced, and the friction coefficient becomes accordingly smaller. However, when the roughness of the ski sole becomes of the order of the thickness of the friction-induced water film, increased ploughing of the ski sole into the snow will occur, which, in turn, increases the friction coefficient.

It is to be expected that ploughing will be more severe when the relief structures are not aligned in the ski gliding direction, which is consistent with the large difference in performance between sliders with unoriented and oriented structured soles. A similar effect of orientation has been observed for the friction of metallic sliders on ice.[6]

According to the above reasoning, a ski should experience the lowest friction when the surface roughness is of the order of the lubricating water layer thickness. At this optimum surface roughness the "microscopic contact area" is favorably reduced, without having too many sole protrusions penetrating through the lubricating water film, thus minimizing the ploughing forces. For the prevailing experimental conditions in this work, the water layer thickness was estimated to be of the order of 0.1 to 1.2 µm,[9,10] which is in good agreement with the roughness of the slider soles at which minimum times of descent are observed (Figure 8). Interestingly, the here presented dependency of the friction properties of the slider on the surface roughness has also been observed in other fields, e.g. the friction properties of lubricated metal surfaces in the metal forming processes.[33]

Naturally, it is to be expected that the optimum surface roughness at which a ski sole experiences the lowest friction coefficient, depends on environmental conditions. At higher snow temperatures the water film generated by frictional heat will be thicker and, correspondingly, the optimum surface structure should be of a higher roughness. By contrast, at lower temperatures, the water layer will be thinner, which would suggest use of a smoother surface to prevent ploughing.

The experiments discussed so far revealed that if the surface roughness of the sole of sliders is in the optimum range, the difference between oriented and “random” surface textures is minimal. To further substantiate this finding, a set of experiments were performed, involving ski soles with surface structures that exhibited distinctly different orientations. For this purpose, soles were prepared in a two step process. First they were grinded with a milling cutter and, subsequently, structured with sand paper using the device in Figure 1. The initial grinding of the skis yielded a base structure with a wave-like pattern with a peak-to-valley distance of about 10 µm. The R_a values of these structures were in the range of 1 µm or lower (due to the filter applied in the determination of R_a). Structures with different orientations were then introduced on top of this base pattern. An image of the topography of a surface with a structure parallel to the sliding direction on top of the base structure is shown in Figure 10. The superimposed structure (lines) in the sliding direction on the peaks and valleys of the base pattern is distinctly visible.

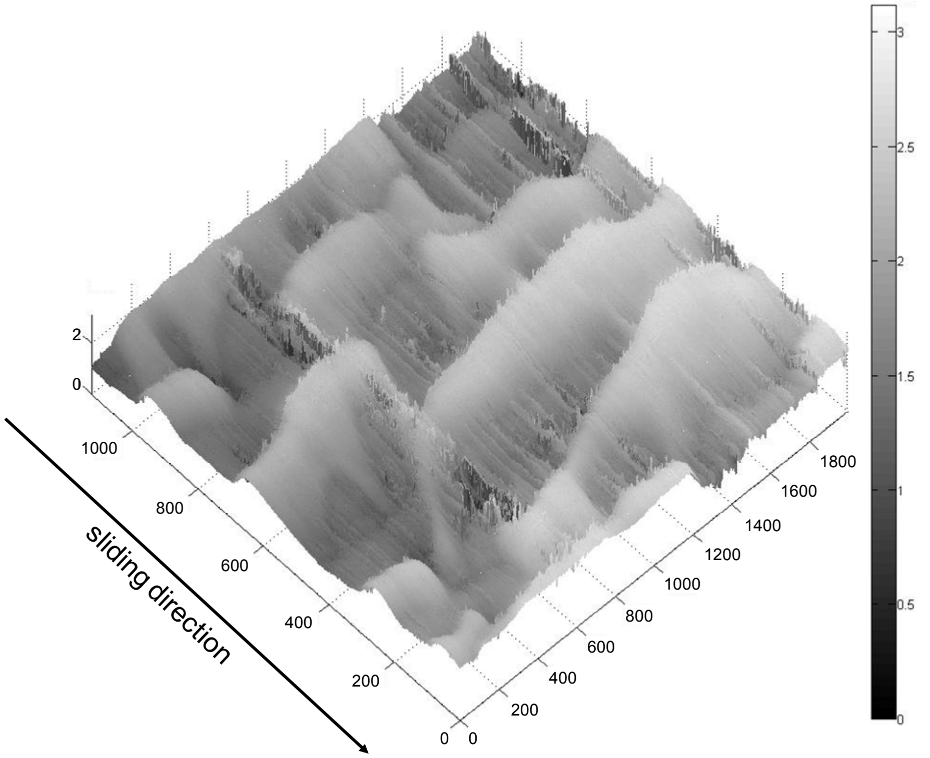


Figure 10: Surface profile recorded with an optical profilometer (units 10 µm). The ski sole was treated with a milling cutter, yielding a wave like base pattern, and, subsequently, grinded parallel to the sliding direction with sandpaper (grain size 35 µm). The profile shows a substructure resulting from the grinding over of the skis perpendicular to the sliding direction and a superimposed line structure in the sliding direction resulting from the sand paper treatment.

Five different "top" patterns were created: in addition to the above- mentioned parallel and unoriented structures, features perpendicular and at 45 ° to the sliding direction were applied, as well a cross-hatched structure alternating by 45 ° to the gliding direction. These surface structures were produced with sand papers of different grain sizes. Figure 11 shows the results obtained with them and are compared to a slider sole exhibiting only the base pattern. The grain sizes of the employed sandpaper are indicated on the x-axis and the open symbol on the right-hand side indicates the slider with only the base structure.

The data in this figure reveal that the effect of the orientation of the fine "top" structure is most pronounced for coarse structures (high surface roughness). Approaching the above discussed optimum surface roughness of about 1 µm, the differences due to orientation of the structure become less important, as was reported above. On the other hand, the results in Figure 11 also reaffirm the common knowledge, that gliding properties of ski soles with structures oriented parallel to the sliding direction invariably are superior.

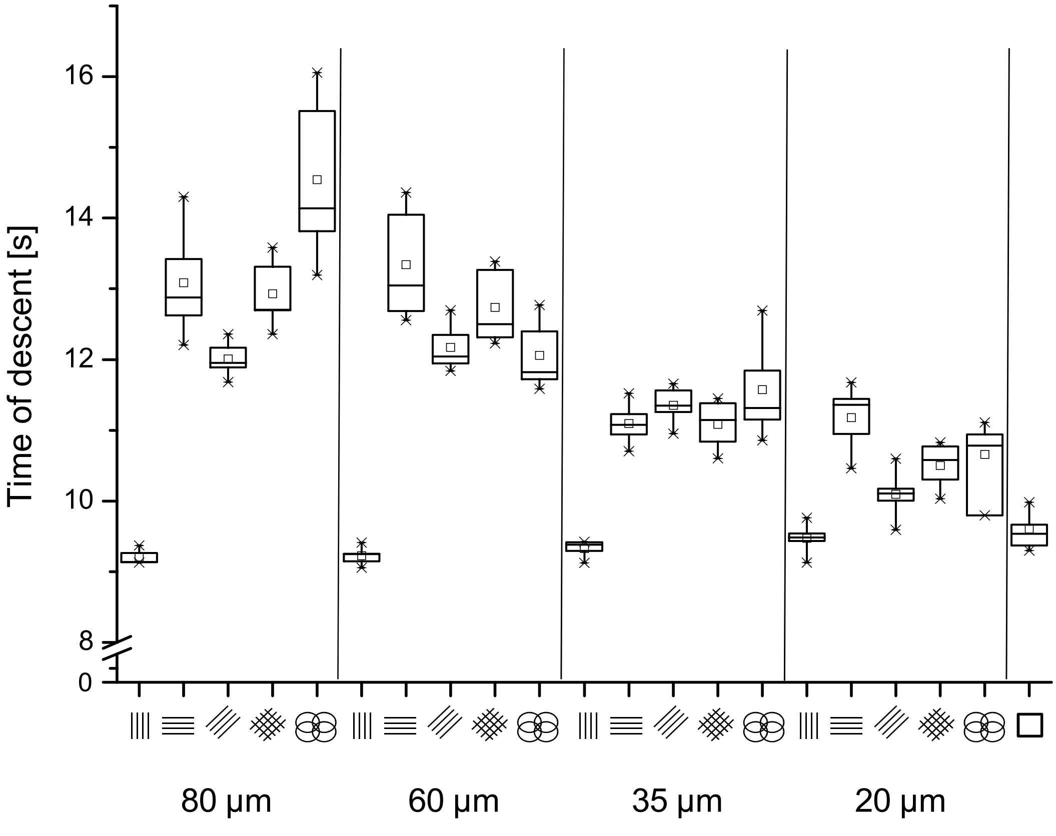


Figure 11: Box-whisker plot of the time of descent of small sliders with ETFE soles which were leveled with a grinder and subsequently structured with sand papers of different grain sizes (indicated). The symbols indicate the different patterns applied. The open square on the right hand side represents results obtained with soles featuring the base pattern only. Five measurements per structure were performed (except for the leveled structure which was measured in a different experiment at the same temperatures and distance and included 8 measurements).

4. Conclusions

In this study, polymer slider soles of a wide range of chemical compositions and surface structures were explored for their tribological properties on snow at near constant conditions (snow temperature -2.6 to -4 °C). An optimum surface roughness of the soles - in the range of 0.2 to 1 μm - is detected for which friction is minimal, essentially independent of the surface topology, and, most remarkably, for which the influence of the chemical composition of the sliding surface becomes virtually negligible. Outside this optimum range, two distinctly different trends are apparent. Reducing the surface roughness to lower values of R_a, i.e. smoother soles, the time of descent increases, most pronounced for hydrophilic materials. Indeed, ski soles made of relatively flat films of polar polymers such as PA 6,6, ETFE and PVDF do not glide at all, while they performed in a satisfactory fashion when featuring a roughness of the above-mentioned dimensions. On the other hand, upon increasing the roughness of the ski soles in excess of the optimum range, the time of descent again increases, now, however, strongly depending on the orientation of the surface structure. For instance, for ski soles made of ETFE, fitted with rough linear structures parallel to the gliding direction, the increase in time of descent is modest, but when a structure of the same roughness with no preferred orientation is applied, the sliders simply do not descend.

The above findings suggest that capillary suction is the dominant friction mechanism for "flat" ski soles and plastic deformation of the snow due to ploughing by protrusions on the slider base dominates the friction behavior for "rough" ski soles. Importantly, here, the terms "flat" and "rough" relate to the roughness of the ski sole relative to the thickness of the thin water layer that is generated by frictional heat, and that may assist in lubricating gliding of the ski. As the thickness of this water layer depends on the actual environmental conditions, it is expected that the optimal roughness for fast skiing varies with the temperature of the snow, such that optimal skiing at elevated temperatures requires ski soles with a high roughness, whilst under colder conditions smoother bottoms are more beneficial. Gratifyingly, the above predictions are in excellent accord with general experience in the skiing industry.[5,34]

5. References and notes

[1] Ericksson, R., *Friction of runners on snow and Ice* in SIPRE TL 44, U.S. Army Cold Regions Research and Engineering, **1955**.

[2] Shimbo, M., *Friction on snow of ski soles, unwaxed and waxed* in Scientific Study of Skiing in Japan, The Society of Ski Science: Tokyo, **1971**, p 99-112.

[3] Calabrese, S. J.; Buxton, R.; Marsh, G., *Lubric. Eng.* **1980**, *36*, 283-289.

[4] Albracht, F.; Reichel, S.; Winkler, V.; Kern, H., *Materialwiss. Werkstofftech.* **2004**, *35*, 620-625.

[5] Moldestad, D. A., *Some aspects of ski base sliding and ski base structure*, PhD thesis, Norwegian University of Science and Technology, **1999**.

[6] Kietzig, A. M.; Hatzikiriakos, S. G.; Englezos, P., *J. Appl. Phys.* **2009**, *106*, 024303.

[7] Strausky, H.; Krenn, J. R.; Leitner, A.; Aussenegg, F. R., *Appl. Phys. B* **1998**, *66*, 599-602.

[8] Ambach, W.; Mayr, B., *Cold Reg. Sci. Tech.* **1981**, *5*, 59-65.

[9] Colbeck, S. C., *J. Glaciol.* **1988**, *34*, 78-86.

[10] Bäurle, L.; Szabó, D.; Fauve, M.; Rhyner, H.; Spencer, N. D., *Tribol. Lett.* **2006**, *24*, 77-84.

[11] Bowden, F. P., *Proc. R. Soc. London Ser.* **1953**, *217*, 462-478.

[12] Bäurle, L.; Kaempfer, U.; Szabó, D.; Spencer, N. D., *Cold Reg. Sci. Technol.* **2007**, *47*, 276-289.

[13] Kuroiwa, D., *J. Glaciol.* **1977**, *19*, 141-152.

[14] Theile, T.; Szabó, D.; Luthi, A.; Rhyner, H.; Schneebeli, M., *Tribol. Lett.* **2009**, *36*, 223-231.

[15] Montana Sport International AG , http://www.ski-service.com, **2009**.

[16] Geometrical Product Specifications (GPS) - Surface texture: Profile method - Rules and procedures for the assessment of surface texture (ISO 4288:**1996**).

[17] Hutchings, I. M., *Tribology: Friction and wear of engineering materials* **1992**, Arnold, London.

[18] Wieland, M.; Hanggi, P.; Hotz, W.; Textor, M.; Keller, B. A.; Spencer, N. D., *Wear* **2000**, *237*, 231-252.

[19] Volk, R., *Rauhigkeitsmessung- Theorie und Praxis* **2005**, DIN Deutsches Institut für Normung.

[20] Wu, S., *J. Macromol. Sci.-Rev. Macromol. Chem. Phys.* **1974**, *C 10*, 1-73.

[21] Settlage, P. H.; Siegle, J. C., *Planet Space Sci.* **1961**, *3*, 73-81.

[22] DuPont Teflon® PFA: Properties bulletin, DuPont Fluoroproducts, Wilmington, DE, USA.

[23] Thompson, E. V., *Encyclopedia of polymer science and engineering* **1985**, Wiley-Interscience, New York.

[24] McGraw-Hill, *Guide to plastics: Property and specification charts* **1987**, McGraw-Hill, New York.

[25] Dettre, R. H.; Johnson, R. E., *J. Colloid Interface Sci.* **1966**, *21*, 367-377.

[26] Roe, R. J., *J. Phys. Chem.* **1968**, *72*, 2013-2017.

[27] Wu, S., *J. Polym. Sci. C.* **1971**, 19-30.

[28] Wu, S., *Polymer Interface and Adhesion* **1982**, Marcel Dekker, New York.

[29] Hellwege, K. H.; Hoffmann, R.; Knappe, W., *Z. für Polym.* **1968,** *226*, 109-115.

[30] DuPont Tefzel®, Properties handbook, DuPont Fluoroproducts, Wilmington, DE, USA.

[31] KF Polymer® Polyvinylidene Fluoride, Products bulletin, Kureha Chemical, Iwari, Japan.

[32] Wu, S., *J. Colloid Interface Sci.* **1979**, *71*, 605-609.

[33] Lee, B. H.; Keum, Y. T.; Wagoner, R. H., *J. Mater. Process. Technol.* **2002**, *130*, 60-63.

[34] TOKO Wax manual, http://www.toko.ch/medias/sys_master/8451220103565056.pdf, **2009**.

Chapter V

Macroscopic contact area

1. Introduction

While in the previous Chapter 4 attention was focused on the importance of *micro*scopic surface roughness of soles of sliders on snow, here systematic introduction of *additional macro*scopic features to them is explored. In that context, it is relevant to distinguish between the “global” macroscopic contact between the sole and snow, and the actual, local, more microscopic interaction loci. With respect to the latter, an important concept to describe friction of skis gliding on snow is the so-called “apparent contact area", that considers that a ski sole is not in full contact with the snow track over its entire surface, but - due to the relatively coarse morphology of snow - is sliding on localized contact spots that most often are lubricated with water.[1,2] This applies, of course, only at temperatures below 0 °C, as at temperatures close to or above the melting point of snow the water film will spread over the entire macroscopic surface of the slider. Kuroiwa[3] measured such an apparent contact area of a slider on snow by pressing and rotating a glass plate on snow to simulate repeated passes resulting in an apparent contact area of 3.8 % on fresh snow (density 0.34 g/cm^3 at -4 °C), and an average size of 200 µm of the contact spots (assuming a circular shape) with the individual snow grains. Bäurle *et al.*[4] measured the contact spot size with X-ray computer tomography (CT) and reported an average value in the same range (100 to 200 µm). Theile *et al.*[5] determined the contact spot size at -6 °C for a densely packed snow cover to be of a diameter of 110 µm using the same X-ray equipment as Bäurle *et al.* and additional modeling. The model also enabled them to estimate the contact area for which they found a value of 0.4 % of the total area of the slider. Pihkala and Spring determined the apparent contact area by means of thermal conductivity and found its value to range between 5 % to 15 % on an aged, cold snow pack, increasing up to 100 % close to 0 °C, with a high free water content.[6]

Turning now to *macro*scopic features, in particular the influence of macroscopic surface pressure on friction properties of a slider on snow and ice has been addressed by several authors. In these studies either the applied load onto a given slider of constant area, or the contact area at constant load were varied, and the influence on friction investigated. In laboratory experiments involving tribometer-type of measurements, different authors reported that at intermediate temperatures (-10 to -1 °C), the friction coefficient, μ, remains approximately constant when the surface pressure to a slider was varied[7-13] (up to about 100 g/cm^2), while at higher pressures a decrease in the friction coefficient with increasing pressure has been observed.[2,12,14,15] A lower temperatures (T < -10 °C), the friction coefficient was reported to decrease with increasing pressure in the full range of surface pressures applied.[11,15,16]

Investigations on the influence of a change in contact area at constant load on the friction coefficient yielded contradictory results. Lethovaara and Bäurle *et al.* observed an increase of μ at increasing contact area, which leveled off at high load values.[10,13] Bowden, by contrast, observed in his experiments that the friction coefficient did not vary upon alternation of the area of a slider.[7] Colbeck explained this independence of μ on (macroscopic) pressure with the assumption that the load bearing area increases proportional to the applied pressure,[17] which would correspond to Amontons's first law.[18]

Clearly, it appears that the influence of macroscopic contact area on friction of sliders on snow has not been fully resolved and that, for instance the influence of the addition of macroscopic features such as well-defined grooves - as often applied in the ski sport, to our knowledge, has not been systematically investigated; which is, hence, the aim of the work presented in this chapter. In this study, two main parameters will be varied, i.e. the macroscopic contact area, defined as the ratio between the macroscopic contact area of a structured ski and the total surface of the ski, A_0, and the number of (linear) features introduced onto the sole of a slider.

2. Experimental

All experiments were performed with ethylene tetrafluoroethylene copolymer (ETFE) soles, and according to procedures described in Chapter 2. The polymer films were used as received. The test field was located in the indoor ski hall in Neuss, Germany. The snow temperature varied from -5 to -3.3 ºC, the air temperature from -2.7 to -5 ºC and track length was 40 m.

2.1. Model structures

The surface topology selected for the experiments consists of a step-shaped, groove structure oriented in the gliding direction, as depicted in Figure 1, which permits modification of the macroscopic contact area of the surface in a well-defined manner. The grooves, leaving protruding ridges (hereinafter referred to as "lines") of a width ranging from 0.1 to 14.5 mm, were machined using side milling cutters. The diameter of the cutter tools was always 30 mm (cf. Figure 2). Due to the milling process, the grooves (surface B in Figure 1) invariably were of a surface roughness of $R_a = 0.6$ µm. The surface roughness of the top of the step structure, i.e. the lines, (surface A in Figure 1) was varied as described in the following.

As the skiing conditions of the experiments described in this chapter are identical to those in Chapter 4, it follows that the optimum roughness of the slider soles for fast skiing is about 0.5 µm ≤ R_a ≤1 µm. Therefore, for the surface that is in direct contact with the snow (line surface A in Figure 1), three different levels of roughness were selected that are below, inside and above this optimum roughness regime. "Flat" structures were produced simply by not grinding surface A, resulting in a surface roughness of the lines that is equal to that of the as-received ETFE film, i.e. $R_a < 0.1$ µm.

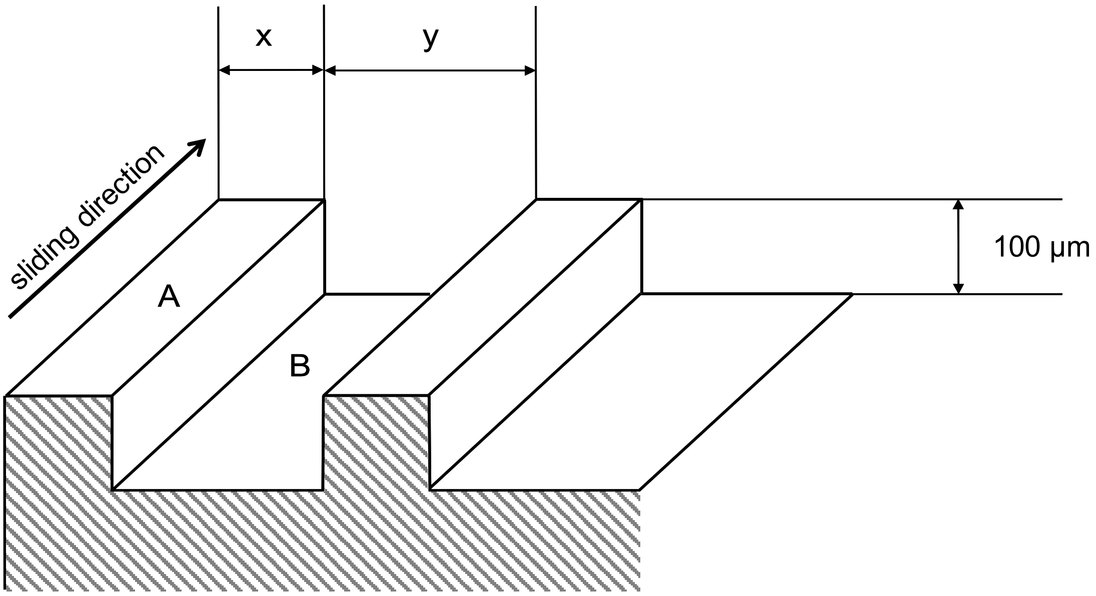


Figure 1: Sketch of the surface structure employed. The height of the ridges (lines) was 100 µm; x and y correspond to their width (A) and the spacing between them (B), respectively.

"Optimum" surfaces were produced by machining surface A with milling equipment with a carbide metal side milling cutter of a diameter of 30 mm (DMU 60T, Gildemeister GmbH, Germany), resulting in a roughness of $R_a = 0.6$ µm. "Rough" ski soles were created by grinding surface A with a carbide metal hob of a diameter of 20 mm, yielding a roughness of $R_a = 1.6$ µm (Table 1). All tools were operated at a speed of 1500 rpm.

machining -	surface roughness: R_a µm
none (virgin ETFE sole)	< 0.1
carbide metal side cutter	0.6
carbide metal hob	1.6

Table 1: Surface roughness produced by different means.

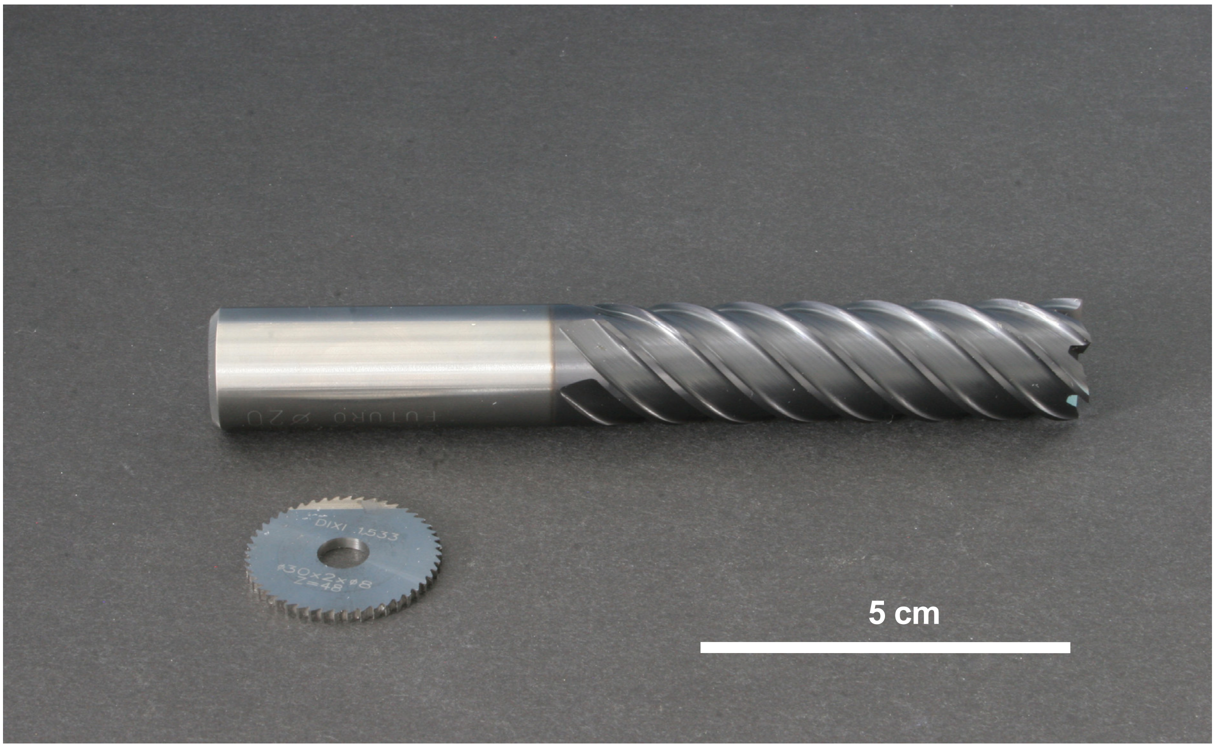


Figure 2: Machining tools: Top: Carbide metal hob with a diameter of 20 mm. Below: One of the side milling cutters employed to cut grooves into the slider base. Their width ranged from 0.1 to 3 mm (2 mm in figure) and the diameter of these tools was 30 mm.

2.2. Surface roughness analysis

The arithmetical mean roughness of the various surfaces (R_a) was determined according to DIN EN ISO 4288,[19] using a white light optical profilometer FRT MicroProf® with the software Mark III (Fries Research & Technology GmbH, Germany) of polymeric replicas of the soles, which were produced with a dimethyl siloxane resin (PROVILnovo Light C.D.2 fast set, Heraeus Kulzer GmbH, Germany).

3. Results and discussion

In the first set of experiments, the “flat” version of surface A (Figure 1) was selected ($R_a < 0.1$ µm). The results obtained with sliders equipped with these bases are presented in Figure 3. From the data collected in this figure, it is clear that sliders with relatively smooth soles with *no* grooves, i.e. of *full* macroscopic contact area, A_0, slide rather slow under the conditions employed, and feature a large spread in times of descent; which is consistent with results shown in Chapters 2 and 4. Remarkably, introduction of only a few grooves, creating only a few lines, causes a drastic decrease of this spread, as can already be seen for skis with 50 %

macroscopic contact area and only one groove (leaving 2 “lines”), and results in a drastic decrease in time of descent, t_e. This apparent trend levels off at 25 % macroscopic contact area. Nonetheless, the values of t_e recorded for all these structured “flat” skis never is significantly below that for a ski that has no step structure (full A_0), but features a surface roughness of R_a = 0.6 µm (included in Figure 3).

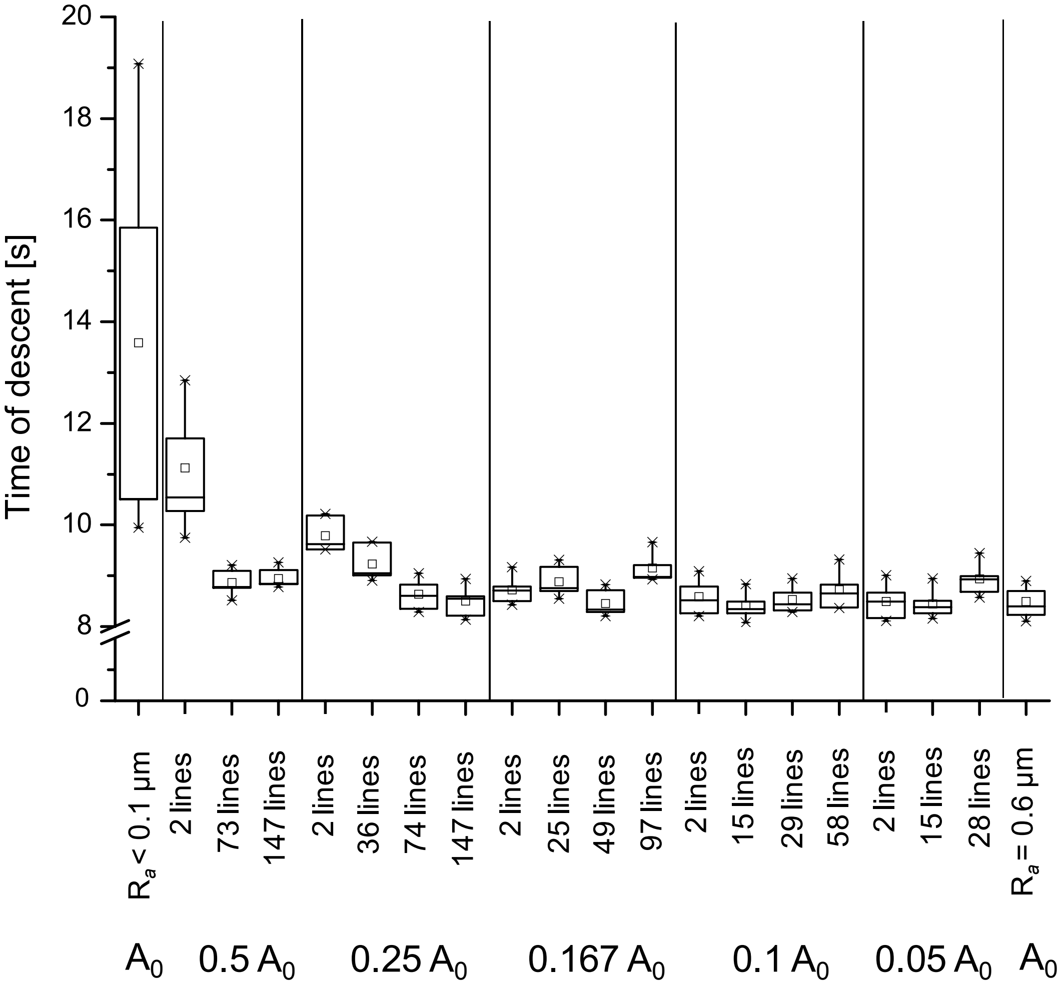


Figure 3: Box-whisker plot of the time of descent of sliders equipped with relatively flat ETFE soles (R_a < 0.1 µm). The results are ordered according to macroscopic contact area and number of lines. Also included is the result for a slider with full contact area A_0 and surface roughness R_a = 0.6 µm. Six measurements were performed with each slider.

In a second set of experiments the roughness of the top part of the step structure (line surface A in Figure 1) was R_a = 1.6 µm, i.e. exceeding the “optimum” roughness. In Chapter 4 it was shown that skis fitted with soles of a roughness in this range have a reduced microscopic contact area but, due to increased ploughing, experience higher friction than ski soles of a roughness in the optimum (lower) regime.

The results are presented in Figure 4, which clearly reveal that the change from a “flat” to a “rough” ski sole reduces the absolute value and spread in the time of descent, again in reassuring agreement with the results described in Chapter 4.

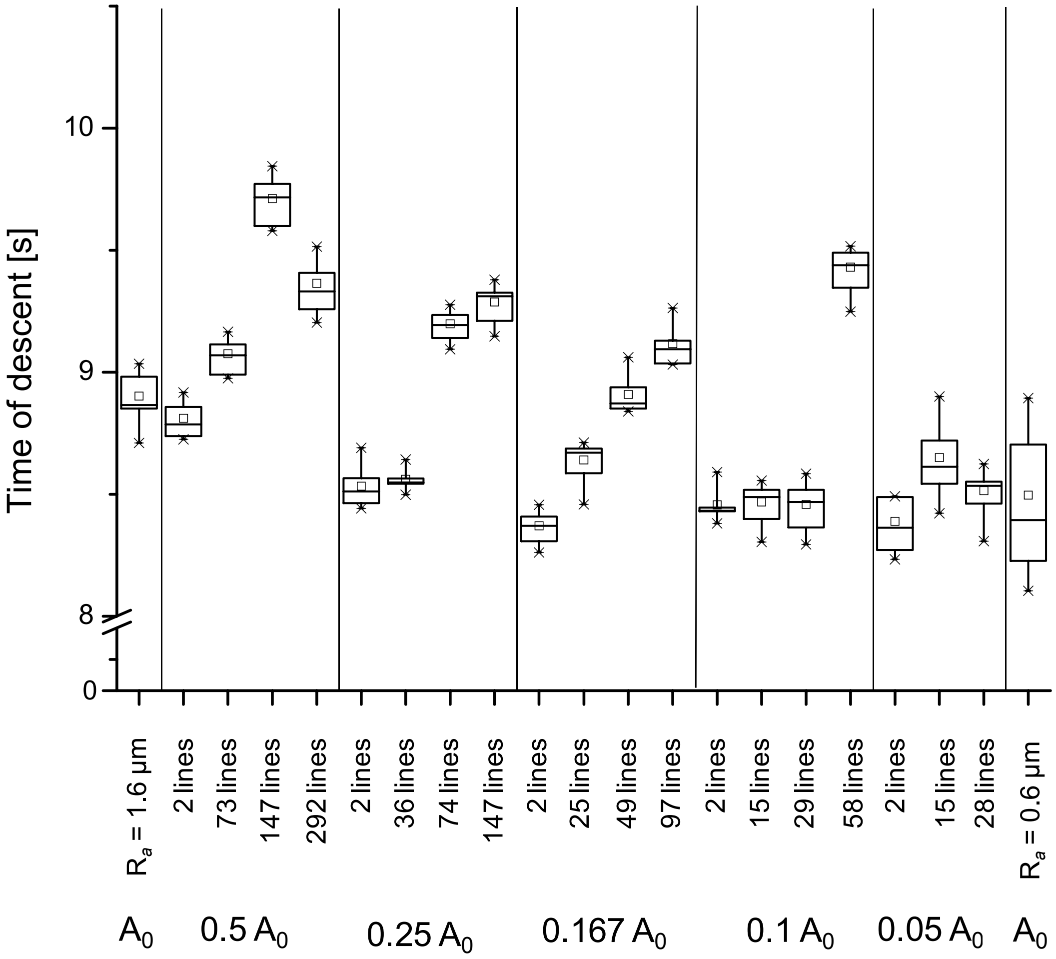


Figure 4: Box-whisker plot of the time of descent of sliders fitted with ETFE soles of a top surface roughness of R_a = 1.6 µm, ordered according to contact area and number of lines. Eight descents were performed.

Interestingly, comparing the results presented in Figures 3 and 4 at constant macroscopic contact area A_0, demonstrates that, at an equivalent number of lines, this parameter does not seem to have a significant influence on the time of descent, except for predominantly flat soles. To verify this, a third set of experiments was performed in which sliding was conducted with soles having a different macroscopic contact area but a constant number of lines. For these experiments, the “optimum” roughness of the top part of the step structure (surface A in Figure 1) was selected (R_a = 0.6 µm). All slider soles featured 10 equally spaced lines machined parallel to their gliding direction, while the macroscopic contact area of ski soles was varied over more than one order of magnitude. The results of these experiments are shown in Figure 5. As can be seen in this figure, indeed, no conspicuous influence of the macroscopic contact area is detected, indicating that the friction coefficient (at the speed, temperature and surface roughness employed) is independent of surface pressure. Only sliders with not-grooved soles (macroscopic contact area 100 % in Figure 5) appear to be slightly slower than their structured counterparts.

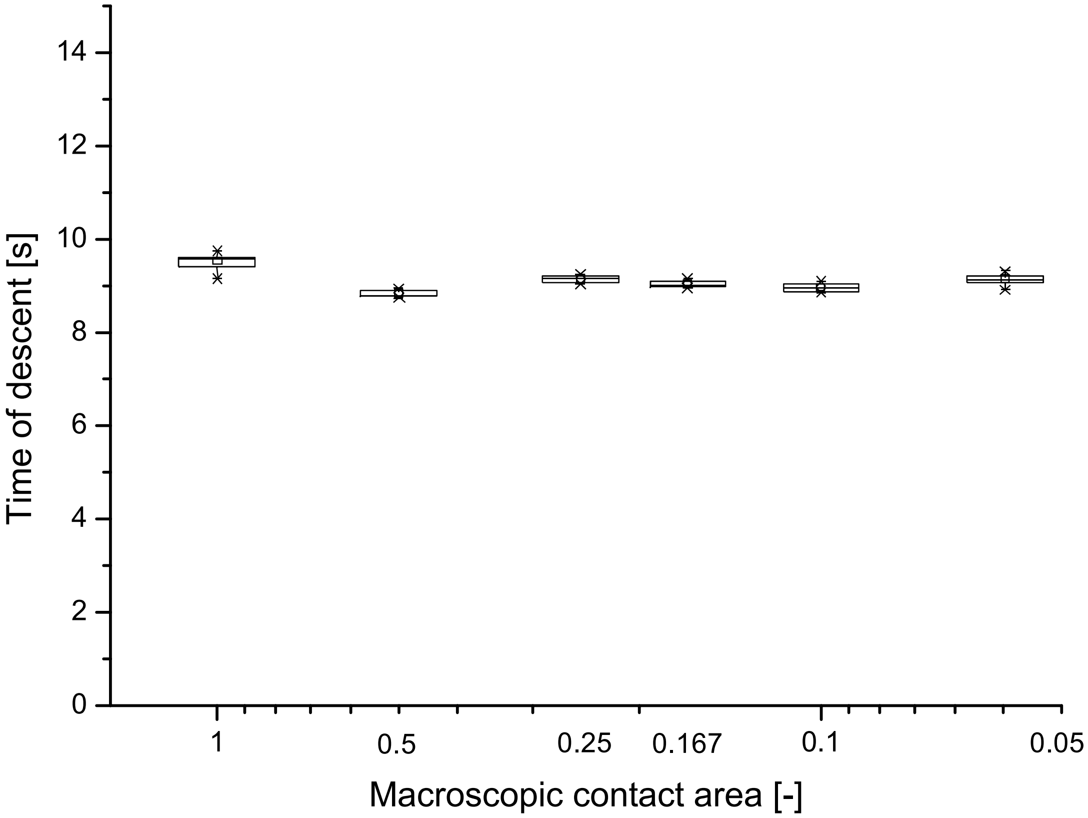


Figure 5: Box-whisker plot of the time of descent *vs.* macroscopic contact area of sliders with soles of a top surface roughness of R_a = 0.6 µm, machined to feature 10 evenly spaced lines along their axis, as well as that of the reference A_o (100 % macroscopic contact area). Eight measurements were performed with each slider.

As stated, the effect of a change in the macroscopic contact area, at least for the step height chosen (0.1 mm), is negligible, which is in contradiction to the findings of other authors.[10,13] An explanation of this result can be found when comparing the roughness of the snow track and the ski sole and the hardness of the snow track. The surface roughness of a snow track is several orders of magnitude larger than the roughness of a ski base (snow grains are in the order of millimeters, see Figure 13, Chapter 2). It is, therefore, reasonable to assume that the slider is contacting the snow only at localized spots and the contact area is reduced to a fraction of the area of the slider, as discussed in the introduction to this chapter. The surface pressure on these spots will, therefore, be large, possibly larger than the yield stress of the snow and, thus, the slider will deform the snow track until its contact surface is large enough to reduce the surface pressure below the yield stress of the snow track. The result is that the actual microscopic contact area depends only on the applied load and the yield strength of the snow asperities, *independent* of the macroscopic surface pressure. This corresponds to the well-known argument in tribology that leads to Amontons's first law, stating that the frictional force is independent of the apparent macroscopic areas of contact.[18]

An alternative, rather trivial, explanation of the surprising above result could be that already at 50 % macroscopic contact area (0.5 A_0), the 0.1 mm deep step structure ploughs into the snow, exposing the groove surface (surface B in Figure 1) to it. This would imply that the macroscopic contact area is in fact not influenced by the step structure applied and, therefore, no dependence is observed. As the surface roughness of the grooves was in the optimum roughness regime ($R_a = 0.6$ μm) and the same in all experiments, all sliders with the structured soles perform more or less equally well, especially for the second set of experiments, where the top surface was of a similar roughness ($R_a = 1.6$ μm) as the groove surface. In this case, it would be expected that a slider with 100 % contact area A_0 (see Figure 5) should have the lowest time of descent as it has no lines ploughing into the track increasing the friction force. However, the opposite is found: the data in Figures 3, 4 and 5 unequivocally show that the introduction of even a few lines *does* improve the performance of a ski. This is especially clear when the results in Figures 3 and 4 are plotted as time of descent against the number of lines, as shown in Figure 6 and 7, respectively.

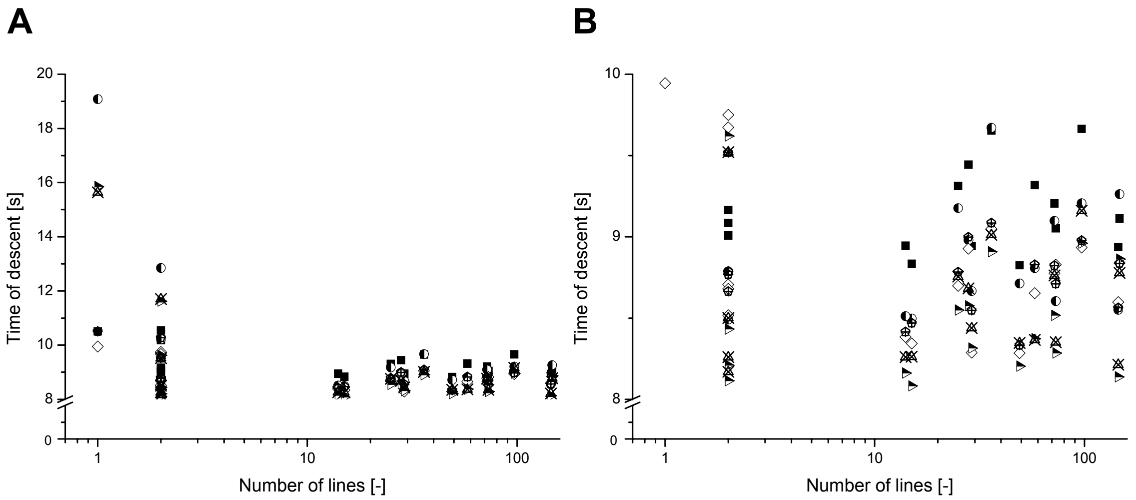


Figure 6: a) Shortest time of descent vs. number of lines on “flat” soles of surface roughness of $R_a < 0.1$ μm. The different symbols indicate different runs. b) Enlarged time scale.

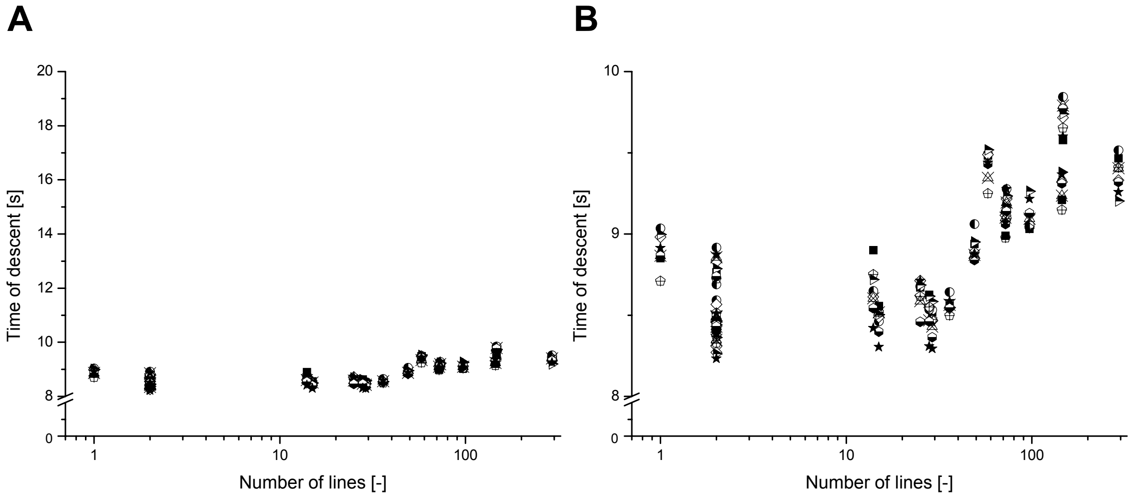


Figure 7: a) Shortest time of descent *vs.* number of lines on “rough” soles of surface roughness $R_a = 1.6$ μm. Different symbols indicate different runs. b) Enlarged time scale.

The data presented in these figures reveal that even at higher number of lines, the scatter in the time of descent is always larger for sliders with a structured sole of which the top part is relatively smooth (Figure 6) compared to skis with a rough uppermost surface (Figure 7).

This is especially clear upon more detailed inspection of the data (presented in Figures 6b, 7b) and, again, is indicative that excessive ploughing, exposing the entire contact area to snow as postulated above, does not occur, as the increased scatter is a signature of flat surface contact (see also Chapter 2, Figure 7).

Particularly for sliders with a flat top structure of their soles already the introduction of one groove (resulting in two “lines”, Figure 6) lowers the time of descent compared to a ski sole with no grooves (number of “lines” = 1), whereas adding more appears not to be beneficial. As a matter of fact, upon milling more than 50 grooves, the positive effect of the step structure vanishes and the sliders in fact become somewhat slower (Figure 7b).

As is evident from the data presented in Figure 5, the change in macroscopic contact area due to 0.1 mm deep grooves has little influence on the time of descent, the favorable effect of a few lines along the ski axis most likely being due to a guiding effect of these lines. By guiding the sliders in the Nordic track, the lines reduce the friction that they experience with the side walls of it. This trend reverses for a larger number of lines, i.e. above 10, possibly due to some ploughing of the increasing number of lines in the snow.

The small increase in time of descent for larger number of lines in Figure 7 might be explained as follows. The mean arithmetic surface roughness is defined as the integral of the surface profile along a line over the surface.[19] Therefore, in a strict mathematical sense, the roughness introduced by the step structure itself only depends on the macroscopic contact area and not on the number of lines if it is evaluated across the full ski width, as the groove depth was always constant. For example, at 50 % macroscopic contact area, dividing up the remaining 58 mm width into two lines of each 14.5 mm or in 290 lines of each 100 µm, results in the same arithmetic surface roughness, if the roughness is evaluated across the whole ski width. However, as the ski contacts the snow at spots of approximately 100 to 200 µm,[4-6] it seems more relevant to evaluate the roughness over the length of a contact spot. In this case, the roughness of a ski sole with two lines is simply the roughness of the top surface, but the roughness of a ski sole with 290 lines is now increased by 50 µm. This could explain the increase in time of descent for larger number of lines observed in Figure 7. The increasing roughness due to the lines on the length scale of contact spots increases the time of descent due to increased ploughing, as shown in Chapter 4. Gratifyingly, the decrease in friction of ski soles on snow due to the introduction of only a few lines is in agreement with empirically found improvements in, for instance, ski jumping, where typically three to four lines are created in a ski base to optimize their gliding performance[20] (see Figure 8).

Figure 8: Gregor Schlierenzauer takes flight during the third event of the four-hills ski jumping tournament in Innsbruck, Austria in 2009. Clearly visible are 3 distinct grooves in each ski sole (image: Kai Pfaffenbach, Reuters).

4. Conclusions

This chapter is concerned with the influence of *macro*scopic structures introduced to ski soles on their tribological properties on snow. The surface topology selected was a step structure of alternating grooves and lines, aligned parallel to the gliding direction, in which the number of steps, the macroscopic contact area, and also the surface roughness of that part that is in contact with the snow was varied. The effect of the structures was most pronounced if its top part -that is in contact with the snow-, was of the lowest roughness. Introduction of only 1 to 10 grooves, leaving 2-11 "lines" decreased the time of descent, while the addition of more caused the time of descent to increase again. The favorable decrease in time of descent is most likely due to a guiding effect of the lines, preventing the sliders from bumping against the side walls of the Nordic ski track. The observed increase upon introduction of a large number of lines is likely due to additional surface area and increased ploughing.

A dependence of the time of descent on the macroscopic contact area of the sliders reported by other authors,[10,13] could not be confirmed. This implies that the friction coefficient is independent of the surface pressure in the range studied here. The classical explanation for this is that the surface roughness of the snow track is by far higher that the surface roughness of the ski sole and that the surface pressure at the contact spots is higher than the yield stress of the snow track. In this case the load bearing contact area will increase proportionally to the applied load and is, therefore, mostly determined by the mechanical properties of the snow and its topological features, and less by the macroscopic contact area.

5. References and notes

[1] Bowden, F. P., *Proc. R. Soc. London Ser.* **1953**, *217*, 462-478.

[2] Ericksson, R., *Friction of runners on snow and ice* in SIPRE TL 44; U.S. Army Cold Regions Research and Engineering, **1955**.

[3] Kuroiwa, D., *J. Glaciol.* **1977**, *19*, 141-152.

[4] Bäurle, L.; Kaempfer, U.; Szabó, D.; Spencer, N. D., *Cold Reg. Sci. Technol.* **2007**, *47*, 276-289.

[5] Theile, T.; Szabó, D.; Luthi, A.; Rhyner, H.; Schneebeli, M., *Tribol. Lett.* **2009**, *36*, 223-231.

[6] Pihkala, P.; Spring, E., *Determination of the contact area between ski and snow using a simple thermal conductivity meter* in Report Series in Geophysics, University of Helsinki: Helsinki, **1986**, p 1-15.

[7] Bowden, F. P.; Hughes, T. P., *Proc. R. Soc. London* **1939**, *172*, 280-298.

[8] Shimbo, M., *Friction on snow of ski soles, unwaxed and waxed* in Scientific Study of Skiing in Japan, The Society of Ski Science: Tokyo, **1971**, p 99-112.

[9] Calabrese, S. J.; Buxton, R.; Marsh, G., *Lubric. Eng.* **1980**, *36*, 283-289.

[10] Lehtovaara, A., *Tribologia* **1985**, *4*, 14-26.

[11] Buhl, D.; Fauve, M.; Rhyner, H., *Cold Reg. Sci. Tech.* **2001**, *33*, 133-140.

[12] Albracht, F.; Reichel, S.; Winkler, V.; Kern, H., *Materialwiss. Werkstofftech.* **2004**, *35*, 620-625.

[13] Bäurle, L.; Szabó, D.; Fauve, M.; Rhyner, H.; Spencer, N. D., *Tribol. Lett.* **2006**, *24*, 77-84.

[14] Evans, D. C. B.; Nye, J. F.; Cheeseman, K. J., *Proc. R. Soc. London Ser. A-Math. Phys. Eng. Sci.* **1976**, *347*, 493-512.

[15] Lehtovaara, A. *Kinetic friction between ski and snow*, PhD thesis, Tampere University of Technology, Finnland, **1989**.

[16] Klein, G. J., *The snow characteristics of aircraft skis* in Aeronautical Report, AR-2; National Research Council of Canada, **1947**.

[17] Colbeck, S. C., *J. Glaciol.* **1988**, *34*, 78-86.

[18] Bowden, F. P.; Tabor, D., *The friction and lubrication of solids* **1954**, Oxford University Press: New York, p 98.

[19] Geometrical Product Specifications (GPS) - Surface texture: Profile method - Rules and procedures for the assessment of surface texture (ISO 4288:**1996**).

[20] Skispringen: Die Geheimschmiede in *Sport Aktuell*, SF DRS, Switzerland, **2009**.

Chapter VI

Conclusions and outlook

1. Conclusions

The work presented in this thesis was directed towards unvealing the influence of the surface chemistry and structure on the tribological properties of a polymer slider sole gliding on snow.

Due to problems with existing techniques used to evaluate sliding surfaces on snow, a major effort was made to develop and validate a new experimental test method with scaled-down systems. Concerns that the applied reduction of the slider size would have an effect on the correlations with real skis were shown to be unfounded. Highly beneficial in the development of the new method was the application of a correction factor to the times of descent, t_e, which led to improvement of the accuracy of the measurements of t_e. This factor takes into account that t_e of a slider increases with repeated passes over the track. In addition, a dimensionless time of descent, t_e^*, was introduced which permitted comparison of results obtained on tracks with the same slope angle but different track lengths and size of the slider and skis.

Using the method developed, we determined an optimum surface roughness region ($0.2\ \mu m < R_a < 1 \mu m$), under the conditions experienced in an indoor ski hall in Germany (snow temperature -2 to -4 °C), for tribological properties that are virtually independent of the chemical composition of the slider soles and the orientation of the surface texture. However, if the surface roughness was of lower values, the influence of the chemical nature of the slider soles became substantial. Hydrophobic surfaces experienced lower frictional forces than their hydrophilic counterparts of the same R_a. Furthermore, at R_a values above the optimum range, the experienced friction force was found to be governed by the orientation of the surface texture: the more a structure was aligned in the gliding direction, the less pronounced was the increase in friction.

The observed correlations may be explained by the interaction of the surfaces with the friction-induced water films and underlying snow, on which the skis glide. The thickness of those water films under the conditions in our experiments was estimated to be in the range of 0.1 to 0.2 µm.[1,2] Advantageous tribological characteristics were observed for R_a values from 0.2 to 1 µm, which is just above the thickness of the water film. These findings lead us to introduce the concept of an optimal microscopic contact area. In this approach we hypothesize that surfaces of the localized contact spots with optimum roughness on which a ski glides are not completely wetted by the water film. This would effectively reduce the contact area between the water film and the ski sole, hence, reduce the frictional force when compared with a fully water-covered surface, which would lead to increased drag through capillary suction. Conversely, at R_a values higher than the optimum range, the structure starts ploughing into the snow track resulting in an increase in the frictional force. The ploughing effect is consistent with the observed dependence on the orientation of the surface texture at higher R_a values, since the oriented surface structures minimize the total ploughing surface.

Finally it was found that addition of only a few macroscopic grooves (between 2 to 10) further enhances the friction properties of a ski sole. One reason for this observation could be a guiding effect that these lines exert on the gliders.

2. Outlook

The scope of this thesis is restricted to investigating the influence of the surface chemistry and structure of ski soles on the tribological properties between skis and snow in a common, but relatively narrow temperature range (-4 to -2 °C), at relatively low speeds (0 to 5 m/s), and surface structures that were limited to homogenous patterns over the area of the slider. Therefore, extension of the scope and applicability of the results presented to other conditions further research is recommended. In particular, investigations should be conducted into how the proposed relationship of friction between ski sole surface and snow apply at different speeds, temperatures, and surface structures, for instance gradients, as addressed in the following paragraphs.

Speed

The speed applied in our experiments corresponds well to Nordic skiing. However, in alpine skiing, much higher speeds are reached (in excess of 30 m/s). In this context, it should be noted that it has been observed, that skis with a higher surface roughness experience lower friction properties at higher speeds.[3] Therefore, additional experiments conducted at higher speeds are needed to determine the influence of those conditions on the water film thickness, and the deduced optimum surface roughness.

Temperature

Temperature undoubtedly affects the thickness of the film of water that forms between the ski and the snow surface, and, thus, if the presented concept of microscopic contact area applies, the optimum R_a value is predicted to change with temperature: under warmer conditions the water film will be thicker and, correspondingly, the optimum surface roughness should be higher; and *vice versa* at lower temperatures. Reassuringly, this is in good accordance with the actual experience in the skiing industry.[4]

As the thickness of the water film is a crucial parameter for the determination of the optimum surface roughness, investigations should be pursued to determine this thickness at different temperatures and rates of descent. This would allow manufacturers to design surface structures with optimal tribological properties, customized to prevailing conditions.

Surface gradient

Commercial and competitive skis are fitted with soles featuring superimposed structures of different length scales comprising complex structures and often pattern gradients. In the present work only simplified model structures were applied to the slider soles, and, consequently, further work needs to be conducted on more elaborate structures. This is of particular importance when considering that during a run, the interface between the ski sole and the snow changes, resulting in changes in the mechanisms from initially dry friction at the tip of the ski to lubricated friction at the back of the ski. Therefore, the surface structure along the ski should be modified accordingly.

Static charging

One other issue that has not been addressed in this work is static charging of ski soles generated during a descent, which can readily be observed by the attraction of snow grains to a neat ski base. In order to reduce the adverse effects of this phenomenon, ski soles which are employed to day comprise a few weight percent of carbon black. To further improve the performance of a ski base as suggested in this study, it would be of interest to incorporate carbon black in them.

Wear resistance

Finally, having proposed in this work optimum surface structures for the soles of sliders, it needs to be ensured that those structures actually remain mechanically intact - at least for the time of one competition run. This will also be important, of course, for the determination of the suitability of a ski sole for daily use. Hence, issues related to wear and tear of the (finely) tuned ski soles need to be considered in future studies.

Last but not least, the ultimate challenge in the preparation of a ski sole is, of course, that it performs well during the changing outdoor conditions experienced on a racing track. Considering the findings reported in Chapter 4 we can derive indications how to manufacture a ski sole that should be relatively insensitive to such changes. Use of a hydrophobic chemical composition of the sole surface reduces the sensitivity of friction at higher temperatures and application of a structure of proper roughness which is oriented in the gliding direction mitigates the generally observed increase in friction at lower temperatures.

Finally, it should be stressed that the phenomenon of lubricated friction is also encountered in many other fields - for instance in boundary friction between lubricated surfaces[5,6] and friction of sliding surfaces under conditions where the temperature at the interface approaches the melting point of at least one of the sliding materials.[7] Therefore, the here reported dependencies may have broader implications than only for the friction of polymer surfaces on snow addressed in this thesis.

3. References and notes

[1] Bäurle, L.; Szabó, D.; Fauve, M.; Rhyner, H.; Spencer, N. D., *Tribol. Lett.* **2006**, *24*, 77-84.

[2] Colbeck, S. C., *J. Glaciol.* **1988**, *34*, 78-86.

[3] Moldestad, D. A. *Some aspects of ski base sliding and ski base structure*, PhD thesis, Norwegian University of Science and Technology, **1999**.

[4] Toko, Wax manual, http://www.toko.ch/toko/manuals.asp?sid=2, **2005**.

[5] Bowden, F. P.; Tabor, D., *The friction and lubrication of solids* **1954**, Oxford University Press, New York.

[6] Lee, B. H.; Keum, Y. T.; Wagoner, R. H., *J. Mater. Process. Technol.* **2002**, *130*, 60-63.

[7] Bowden, F. P.; Freitag, E. H., *Nature* **1955**, *176*, 944-946.

Appendix

1. Correction factor

The correction factor, introduced in Chapter 2, is explained in the following paragraph. In a first step the fraction of skis that get slower in subsequent series is calculated and averaged over all skis runs in a given track. This factor is denominated *c1*:

$$\mathit{deceleration\ factor\ of\ subsequent\ series} = c1 = \frac{\mathit{time\ of\ descent\ of\ ski}\ X\ (\mathit{series}\ i-1)}{\mathit{time\ of\ descent\ of\ ski}\ X\ (\mathit{series}\ i)}\ (< 1)$$

As the above factor describes the deceleration effect in subsequent series, the factor of deceleration of a single descent of a ski needs to be calculated. Therefore, the factor *c1* needs to be divided by the number of skis in the experimental set

$$\mathit{deceleration\ factor\ of\ a\ single\ ski} = c2 = \frac{(1 - c1)}{\mathit{no.of\ skis\ in\ experimental\ set}}$$

The corrected time of descent (*corr.* t_e) for the skis is then determined by the multiplication of the deceleration factor of a single ski, *c2*, times the number of skis running before the measured ski, and the deceleration factor of complete series running beforehand in the same track, *c1* times the number of series.

$$\mathit{corr}.t_e\ \mathit{of\ ski}\ Y = t_e\ \mathit{of\ ski}\ Y * ((1 - (c2 * \mathit{no.of\ skis\ between\ first\ ski\ of\ the\ series\ and\ ski}\ Y)\ ) * \mathit{no.of\ completeted\ series\ in\ the\ track} * c1)$$

2. Chapter 4 Figure 8 plotted against R_k

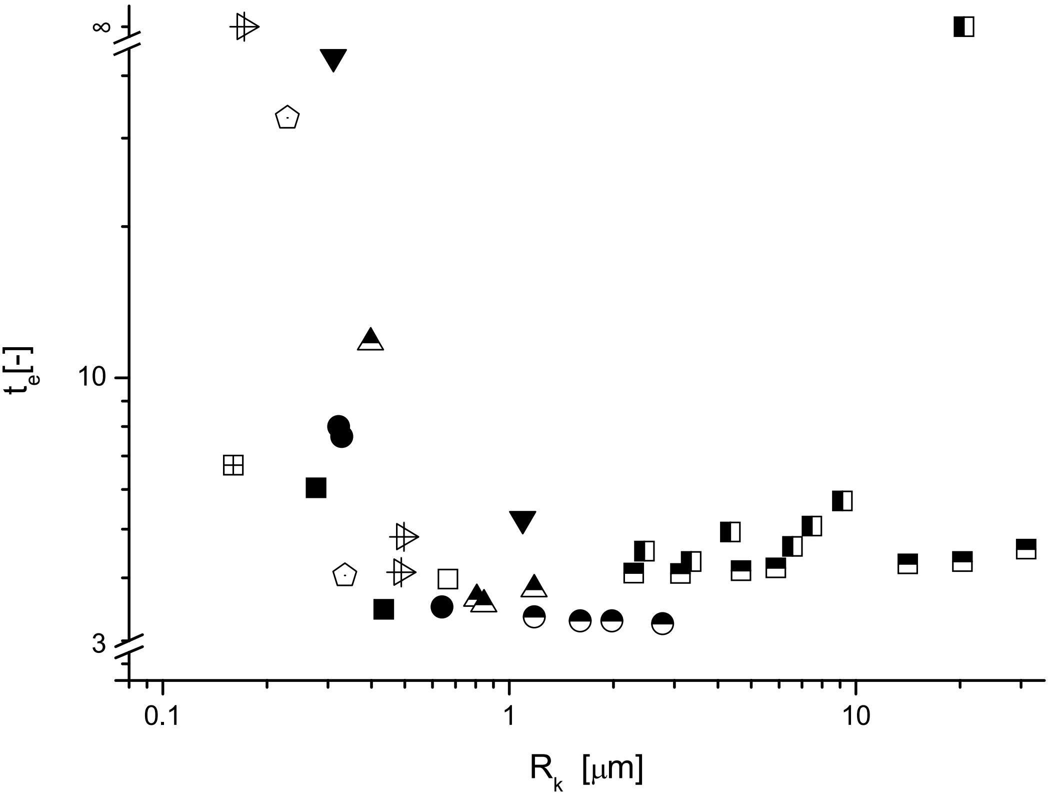


Figure 7: Shortest dimensionless time of decent, t_e^*, of small sliders fitted with differently structured soles of various polymers plotted against R_k. ◓ : PTFE, ● : PFA, ▲ : UHMW PE, ▼ : LLDPE, ⊳ : PA 6,6, ■ : ETFE, ⬠ : PVDF, ⬒ : oriented ETFE structures, ◧ : unoriented ETFE structures, □ : oriented ETFE structure obtained with steel brush and ⊞ : untreated ETFE surface (data of Figure 5 and 6). ∞ indicates no sliding. The track length was 35 or 40 m and 4 measurements per ski were performed.

Acknowledgments

The realization of the here presented work was only possible with the support and contribution of a multitude of people. Therefore, I would like to highlight all those who helped me during this time and made the past three years an unforgettable and enjoyable part of my life.

First of all, I wish to thank Paul Smith for giving me the opportunity being part of the polymer technology “family“ - it was a privilege being part of this unique group of people. I wish to express my gratitude especially for his encouragement to explore my own ideas, the inspiring and stimulating environment and the, at times, critical advice that brought me forward.

I am especially indebted to my supervisor Theo Tervoort, for his guidance, enthusiasm and his patience with my writing skills.

Nic Spencer, Leon Govaert and Michael Jufer are gratefully acknowledged for being co-examiners of the work presented in this thesis.

I wish to thank our industrial partner, TOKO AG, Switzerland, for financial and especially technical support, and the interesting collaboration. Special thanks are due to Michael Jufer (now with Fritz Keller AG, Switzerland), Judith Glück and Udo Raunjak.

As stated earlier, many people were involved with this work and in the following I like to mention some of their contributions. Joanna Wong, Karin Bernland and Pascal Wolfer are acknowledged for their efforts and patience with proof reading my drafts. I like to thank Doris Sporri for introducing me to the secrets of making replicas and the interesting discussions about surface science topics. I am grateful to Tobias Giesbrecht, Marc Simonet, Cyrill Kümin, Mischa Weder, Fabian Amstad, Christoph Bruhin, Jan Rys and Andreas Brunner for their experimental support during field experiments.

Special thanks goes also to the team of the mechanical workshop of the Department of Materials at ETH Zurich for their help with manufacturing essential equipment, in particular to Werner Schmidheiny, Christian Roth, Werner Blattman and Martin Elsener.

Ivo Dirix and Lorenz Brunner are acknowledged for making possible that I could conduct my surface topography measurements at Plus Orthopaedics AG, Switzerland (now part of Smith & Nephew, USA).

Furthermore, I would like thank all the members, associates and alumni of the polymer technology group, who made the time spent here so worthwhile. In particular Kirill Feldman, Walter Caseri, Matthias Gössi, Jérôme Lefèvre, Lorenz Brunner, Fabien Choffat, Andreas Brunner, Karin Bernland, Pascal Wolfer, Marc Simonet, Stefan Busato, Joanna Wong, Markus Trummer, Kurt Pernstich, Sara Fornera, Susanne Köppl, Vappu Hämmerli, Harald Lehmann, Ulrich Suter and Wolfgang Kaiser.

Sincere gratitude is due to my brother Tobias who supported the experimental work from day one, on whom I could always count, and whose critical, straightforward thoughts often advanced me. This work would not have been possible without you.

Last but not least I like to thank my parents and Simone for their patience, support and encouragement during all this time; without you I would never have gotten so far.

Curriculum Vitae

Jan Lukas Giesbrecht was born May 3, 1979 in Zurich, Switzerland. He attended the “Freies Gymnasium Zürich“ in Zürich, Switzerland and received the Matura in January 1999. After completing military service he started his studies in physics at the Swiss Federal Institute of Technology (ETH) Zürich in the fall of 2000. In 2001 he changed his major to Material Science at the same University, which he successfully completed with a “Diplom mit Auszeichnung“ (best of his major) in 2006 on the topic of “Solid high performance lubricates“ in the Polymer Technology Group of the Department of Materials, headed by Paul Smith. Within the scope of an exchange program he completed his last year of studies (2004-2005) at the University of Pennsylvania, Philadelphia, USA. In 2006, he again joined the Polymer Technology Group at ETH Zürich for his doctoral study described in this thesis.