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Interfacial Kinetic Ski Friction

Leonid Kuzmin

DEPARTMENT OF
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INTERFACIAL KINETIC SKI FRICTION

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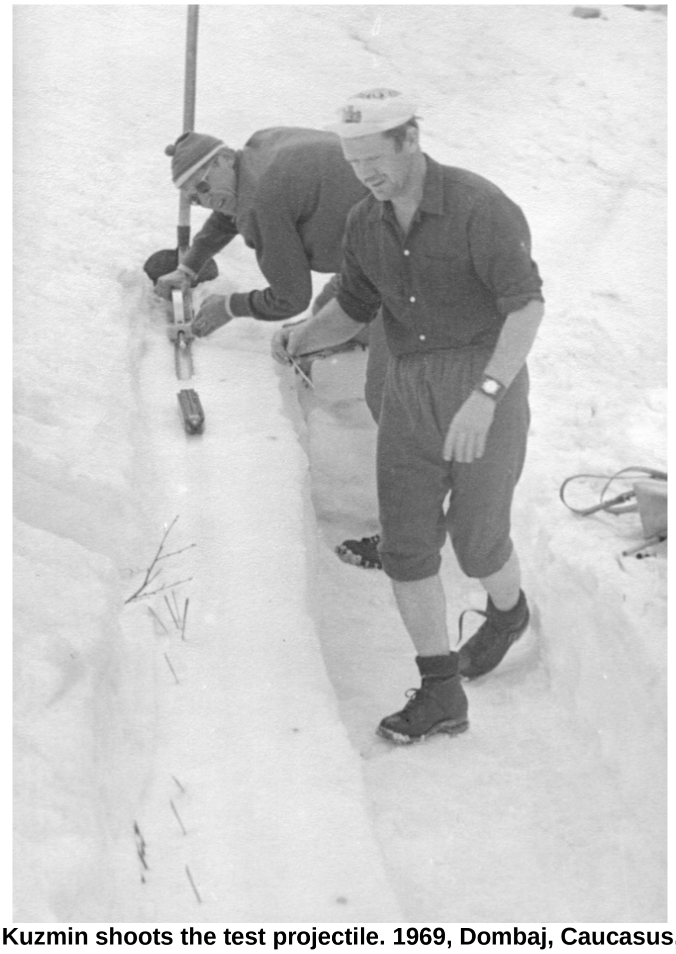
ABSTRACT

It is no doubt, that the ski glide over the snow is a very complicated object of research. However, ski glide is just a one area of many other areas of human knowledge. As a rule, the scientists and practitioners, who work in these areas, operate with some publicly expressed more or less solid hypotheses. These researchers work with one hypothesis until another and a better one comes up. Our literature studies and our own observations regarding modern skis preparations, did not give us any solid hypotheses, which are able to explain the actual form and content of this procedure. The present work is an attempt to reveal such hypotheses.

Conclusion: To achieve an optimal glide on skis with the base (the ski sole) made of some high hydrophobic durable polymer, e.g. UHMWPE, PTFE; we only have to create an adequate topography (texture) on the ski running surface, adequate to the actual snow conditions.

Keywords: ski glide, ski base, ski wax, hydrophobicity, UHMWPE, PTFE, topography.

In memory of my father, Nikolaj I. Kuzmin (Николай Иванович Кузьмин)
pioneer in ski science in the Soviet Union.



N. Kuzmin shoots the test projectile. 1969, Dombaj, Caucasus, USSR;

ACKNOWLEDGEMENT

Many people contributed to this thesis by their physical or intellectual support. The present work was implemented at the Department of Engineering and Sustainable Development at Mid Sweden University, Östersund. The financial support for this work was provided by the European Union and by Mid Sweden University.

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Many thanks to our equipment and material suppliers: Madshus AS (Gunnar Bjertnæs, Lars Hanstad), Rottefella AS (Torbjørn Ragg), Backcountry Equipment AB (Sven-Gunnar Johansson), Milex (Lars Svensson), Sportmarket AB (Lasse Jonsson).

For the past six years I have enjoyed the pleasant working environment in the Department of Engineering and Sustainable Development at Mid Sweden University. Thank you everybody.

Finally, I want to express my deep gratitude and love to my wife Antonina for her care, patience and her never-ending support in my work.

TABLE OF CONTENTS

LIST OF PAPERS

This thesis is mainly based on the following seven papers, herein referred to by their Roman numerals:

Paper I KUZMIN, L. & TINNSTEN, M. 2005. Contact angles on the running surfaces of cross-country skis. *In:* SUBIC, A. & UJIHASHI, S. (eds.) *The Impact of Technology on Sport.* Melbourne, Australia: Australasian Sports Technology Alliance Pty Ltd.

Paper II KUZMIN, L. & TINNSTEN, M. 2006. Dirt absorption on the ski running surface - quantification and influence on the gliding ability. *Sports Engineering,* 9**,** 137-146.

Paper III KUZMIN, L. & TINNSTEN, M. 2007. The contamination, wettability and gliding ability of ski running surfaces. *In:* LINNAMO, V., KOMI, P. V. & MÜLLER, E. (eds.) *Science and Nordic Skiing.* London, UK: Meyer & Meyer Sport.

Paper IV KUZMIN, L. & TINNSTEN, M. 2007. Estimation of dirt attraction on running surfaces of cross-country skis. *In:* SUBIC, A., UJIHASHI, S. & FUSS, F. K. (eds.) *The Impact of Technology on Sport II.* London, UK: Taylor & Francis Group.

Paper V KUZMIN, L. & TINNSTEN, M. 2008. Hot Glide Wax Treatment and the Hardness of the Ski Running Surface. *In:* ESTIVALET, M. & BRISSON, P. (eds.) *The Engineering of Sport 7, Vol. 2.* Paris: Springer-Verlag France.

Paper VI KUZMIN, L., DANVIND, J., CARLSSON, P. & TINNSTEN, M. 2010. Estimating surface hydrophobicity by introducing a wettability factor based on contact angles. *Submitted for publication*.

Paper VII KUZMIN, L., CARLSSON, P. & TINNSTEN, M. 2010. General relationship between machining of the ski running surface and its water capillary drag. *Submitted for publication*.

"Are you not ashamed, then, as a man of science, that is, an explorer and pursuer of nature, to seek a testimony to truth in minds imbued with habit?"[1]
Marcus Tullius Cicero

1 GOAL OF THE STUDY

The primary goal of this research is to determine topographical, physical, and chemical properties of the ski running surface that are significant for the glide on the snow and to discover, whether we can modify, or in which manner we have to modify these properties to improve the ski glide.

The secondary goal is to develop the practice-relevant methods to implement the discovered positive modifications.

1.1 Domain of the study

The friction (both static and kinetic) between the ski running surface and the snow is an extremely complicated process. However, as always in scientific cognition we have to sacrifice the real life complexity to get some foreseeable structure. For this reason, we will assume that the overall ski friction results from independent components. If different friction processes operate independently, the total friction could be expressed, as the sum of terms that represent each mechanism [1]:

$$\mu = \mu_{plough} + \mu_{dry} + \mu_{lub} + \mu_{cap} + \mu_{dirt} \quad (1)$$

where μ is the kinetic friction between the ski running surface and the snow, μ_{plough} - friction due to ploughing, μ_{dry} - due to solid deformation, μ_{lub} - due to water lubrication, μ_{cap} - due to capillary attraction and μ_{dirt} - due to surface contamination. No doubt, it is possible to introduce even more components of total friction, e.g. the friction associated with moving charges can be defined as the electrostatic friction. However, from our point of view, the Equation (1) is sufficient to formulate the process of the ski glide.

Both compact and impact resistance of piste under the stable weather conditions are very strongly related to the plasto-elastic (weight distribution over a ski) [2, 3] and the vibro-resonance characteristics of skis [4, 5]. In our experiments

[1] Cicero, M.T., *De Natura Deorum (On the Nature of the Gods)*. 1896, London: Methuen & Co.

we neither tested, nor measured the compact and impact resistance of the snow track under the gliding ski. Therefore we did not take into account this factor. We just tried to make this component, as constant as possible, by choosing very similar skis (from one batch) and using a well groomed ski track. Therefore, the component μ_{plough} (friction due to ploughing) includes only the sliding surfaces asperities ploughing [6], but not a ski track deformation. Thus, we can call our object of study an interfacial kinetic friction between the ski running surface and the snow.

All experiments were carried out on cross-country (XC) skis. However, it does not mean that the obtained results are applicable only to XC skiing. The ski glide in the alpine skiing, ski jumping, and XC skiing have the same nature: the ski running surface slides on a groomed ski track.

1.2 General approach

Our choice of tools, wax, skis, and the procedure for the ski preparation were based on the direct application to XC skiing. The general research strategy in the present work is to always have a clear reference point. Absence of clear reference point in ski glide research is like absence of control group with placebo in medical research. In some articles an undefined term "unwaxed" can be found, which is not a satisfactory reference point in our opinion. In other articles the authors mention the skis with the stone ground base, which is not reliable enough: - wearing the stone grinding machine's diamante does not permit to make the same pattern time after time, - skis have to be glide waxed for an acceptable glide ability [7]. Therefore, we consider the scraping of the ski running surface [7, 8] to be the most reliable kind of the ski base mechanical treatment today. The scrapers have been grounded on the same factory of the same material, and the scraping has been performed by the same expert. Hence, we believe the scraping gives a more reproducible texturing.

2 INTRODUCTION

Skiing has a centuries-old history [9, 10]. From the beginning it was a way to move in the winter time, when the ground is covered with the loose snow. At the same time, skiing has always been a kind of sport and recreation [11]. The ski equipment development follows this trend [12].

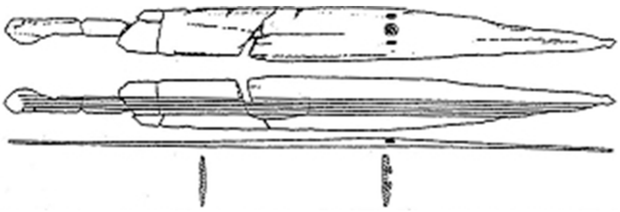


Figure 1. The Saija skis are over 5000 years old [10]

The first ski competitions took place in Norway as early as 1767 [13]. The first Olympic Winter Games were in 1924 in Chamonix, France. The International Ski Federation known by the name in French, Fédération Internationale de Ski (FIS) was also founded in 1924 and also in Chamonix, France. FIS Nordic World Ski Championships have been held since 1925, and the first FIS World Championships in the alpine skiing took place in 1931.

Figure 2. Norwegian skier Thorleif Haug in action under the I[st] Olympic Winter Games 1924. Photo: Unknown /Scanpix

As we can see, skiing, in general, has a very long history of development, while skiing competitions do not have such a long way. This probably explains why a solid, well structured, logical and practically useful theory was not built around the subject. If one attempts to delve deeply into the subject by studying the information on Internet, the confusion would just increase, if he wishes to prepare his or her skis in the best possible way. We will try to describe the nature of such a situation.

2.1 Why is the today's ski preparation doctrine so inconsistent?

One of the several illustrations of such inconsistency is a discussion pertaining to the ski base wear. The majority of the ski waxing manuals, the majority of the established glide wax experts, the majority of well recognised ski wax technicians, and skiers keep talking about a positive influence of the glide waxing on the ski base wear.

On the other hand, the polymer tribologists disapprove the use of lubricants and polymers together from a dirt accumulation point of view [14]: "...polymers are not used in general in the presence of any lubricant, this subject has nevertheless attracted interest from polymer tribologists. One obvious reason is that polymers, intentionally or unintentionally, do become subjected to lubricant contamination". Authors of [15, 16] did not find any positive impact of a hot waxing on the ski base wear. A well known ski glide researcher Masaki Shimbo [17, 18] is very determined about his conclusion: "Paraffins were found to come off almost completely from the sliding surfaces after running several hundred meters over granular summer snow". Even the authors near to big ski wax producer [19] are somewhat sceptical about the glide wax treatment: "Det er imidlertid viktig å merke seg at hvis man i stor grad smelter materialet og "fyller det" med parafinvoks, vil de mekaniske egenskapene (slitestyrke o.a.) bli drastisk redusert = However, it is important to note that if one melts the material (the ski base material – UHMWPE)[1] at a large degree and "fills it" with paraffin wax, the mechanical properties (wear resistance, etc.) will be drastically degraded".

How can such diametrically opposed opinions be possible? It looks as if the scientific researches and the following scientific publications exist in one universe, while the practice of skiing and the practice of the ski preparation are in another. Here are some examples of such inconsequence (majority of the examples are from author's own 35 years experience in XC skiing branch as an athlete, as a technician, as a coach and scientist):

- Strong and persistent wish to see the ski preparation as an art and magic, but not as a technological process and science.
- Extensive character of a higher-level sport. Political prestige and chauvinism have always been able to generate huge (even immense) resources. The existence of such resources kills all inducement to be effective.
- By reason of profits or by reason of incompetence (or by both) the glide wax producers maintain delusions (porosity of the ski base [20, 21], drying of the ski base, etc.) which circulate in the ski community.

[1] Author's note

- Very big weight of such pseudo arguments as "everybody does", "nobody does", "always did" and "never did" among skiers and ski technicians.
- Insufficient interest of physicists and engineers to support the ski science [22].
- Overdependence (affective fixation) on practice prevents the ski technicians from involving scientific methods in their work.
- Insufficient knowledge about the competitive skiing does not allow scientists to conduct experiments, which can give the answers to the vital questions.
- Snow groomed ski track is a very complicated medium, which changes every minute.
- Despite of the technical progress, the ski companies cannot produce skis precisely, as they have been designed; random fluctuations significantly influence the plasto-elastic and vibro-resonance characteristics of the manufactured skis, and such unstable "background" does not help to reveal the friction mechanisms in an interface ski running surface – snow.
- Lack of a "control group" and a departing point in the majority of the ski glide tests. Stone ground and waxed in a different way skis are compared with each other in an attempt to find some tendency. But any kind of a "control group", worthy of its name, does not exist.
- Common use of the expressions "unwaxed skis"/"no wax" in a number of scientific papers without any further explanation. For example: [18], [23], [24], [25], [26], [27], etc.
- Ignoring of the simple glide test rules formulated in [28] and in [29]. For example, the majority of the ski technicians tests the ski glide under a very low velocity: much lower than the race average speed (Figure 3).

Figure 3. Glide tests at IBU World Championship 2008 in Östersund

The clear goal-setting and the structurization can help avoid the above mentioned inconsistencies. Thus, we are going to present a structured analysis of the ski glide problem.

3 STRUCTURED ANALYSIS OF THE SKI GLIDE PROBLEM

In spite of a complex nature of the snow, we will employ the classical tribological methods to analyse the ski running surface glide on the snow, based on a general assumption of the acceptance of heat melting theory [30-33] for the ski friction. In Figure 4 we present the classical illustration of a lubricated glide issue. On the horizontal axis of the generalized Stribeck curve the lubrication number [34] has been plotted. This number is defined as:

$$\mathcal{L} = \frac{\eta u_s}{p_{av} R_a} \tag{2}$$

with η the viscosity of the lubricant (water in our case), u_s the relative velocity, p_{av} the average pressure in the contact and R_a the combined Centre Line Average (CLA) surface roughness, defined by

$$R_a = \sqrt{R_{a_1}^{\ 2} + R_{a_2}^{\ 2}} \tag{3}$$

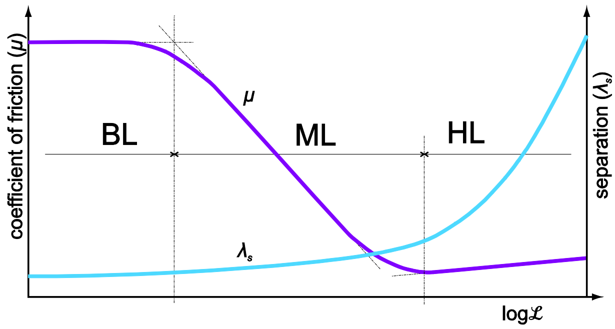
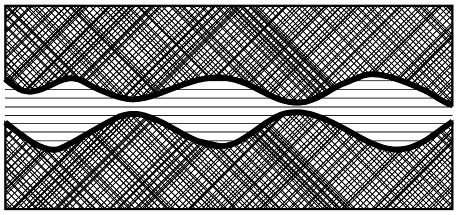
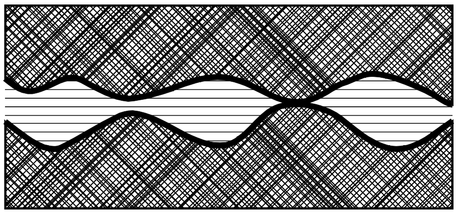


Figure 4. Generalized Stribeck curve and corresponding separation. HL: Full-film lubrication, ML: Mixed Lubrication, BL: Boundary Lubrication. Adopted from [34, 35]

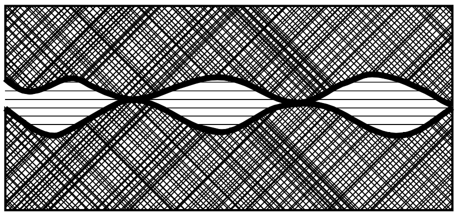
When the sliding velocity is high and the volume of a lubricant (melt water) is large enough, due to the hydrodynamic effects, the two surfaces are fully separated by the lubricant (Figure 5a). In this case the pressure of the fluid in contact is high enough to separate the surfaces. This called Hydrodynamic Lubrication regime (HL). When the velocity or the lubricant (melt water) volume (or both) decrease, the pressure of the fluid in contact decreases (less hydrodynamic action) too, and, as a result, the asperities of the surfaces start touching each other, and a part of the load is carried by the asperities. This leads to an increase of friction. In this case the friction is given by the shear between the interacting asperities, as well as by the shear of the lubricant. This is a transition regime and it is called Mixed Lubrication (ML), see Figure 5b. By decreasing the velocity or/and the melt water volume further, the pressure of the lubricant in contact becomes equal to the ambient pressure, and as a result, more asperities are in contact and the total normal load is carried by the interacting asperities. This regime is called Boundary Lubrication (BL), see Figure 5c. In the BL regime the friction is controlled by the shear stress of the boundary layers built on the surfaces of the solid bodies (the ski running surface and the snow crystals).



a) HL



b) ML



c) BL

Figure 5. The three lubrication regimes: a) hydrodynamic lubrication regime (HL), b) mixed lubrication regime (ML) and c) boundary lubrication regime (BL). Adopted from [36]

Normally, the classical tribology serves the industry and the design of different machines. The machines are designed in the manner to ensure the optimal volume of a lubricant. In case of the ski glide, the volume of a lubricant (volume of melt water) depends on the ambient temperature and humidity, the snow temperature and humidity, skis velocity, and on other uncontrollable parameters. Another essential difference between the ski glide and the industrial application is a travelling locus of the sliding surfaces. Mechanical engineers have to deal with a circular and back-and-forth motion. In such case lubricants are reused all the time. Skiers have to deal with a one-way movement and the lubricant (melt water) cannot be reused. The ski friction has to generate a new amount of a lubricant along the full length of the skiing distance. Thereby, the Equation (2) is not very useful, if we wish to plot the Stribeck curve against the snow temperature. However, because the snow temperature affects the volume of melt water, and, as a consequence, has an impact on the separation film, according to λ_s in Figure 4, we can approximately employ generalized Stribeck curve to the ski glide problem.

On Figure 6 the interpretation of Stribeck curve applied to the ski glide issue is introduced. We approximately defined the transition point from the boundary lubrication (BL) to the mixed lubrication (ML) as a -40°C according to [1, 30, 37], and a point with a minimum ski glide friction t_0 as a -3 - -5°C according to [30, 38-41]. The locations of these points also depend on other parameters, not just the temperature (of skis velocity, for instance). However, these points illustrate the practical problem for anyone who will get the perfect ski glide very well. In addition, it is necessary to identify and explain some contingencies, which are differed from the classical Stribeck curve: We assumed that skier's velocity and weight are constant. For this reason it is likely that the maximum separation is a finite quantity λ_{max}. Coefficient of friction in zone II increases not just according to the hydrodynamic lubrication theory, but also because of the increase of the contact area between the snow and the ski running surface through the water film [42-47].

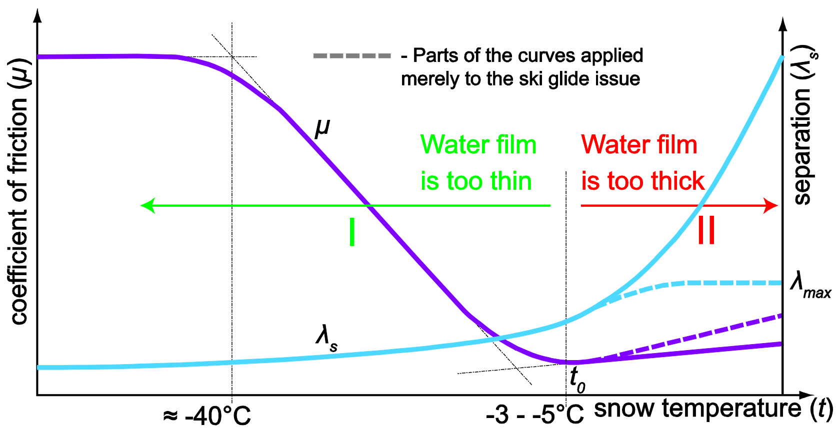


Figure 6. Generalized Stribeck curve applied and modified by the author to skiing issue, gliding velocity is constant. I: Snow temperature is lower than optimal, II: Snow temperature is higher than optimal.

By this illustration (Figure 6) we attempt to generalize the ski glide problem. This generalisation has a pronounced qualitative character. The area around the point of minimal friction is not very interesting: ski running surface friction is already small. Therefore, below we will pay attention to zone I and zone II, and will analyse the present situation, and will suggest some directions of development.

3.1 Zone I (Water film is too thin)

The boundary lubrication regime is not an actual area of the ski glide. According to FIS rules (303.2.2) it is not allowed to compete when the air temperature is below -20°C. Thus, we have to consider a mixed lubrication regime. It is the lubricant deficit: a thin water film is not able to separate the snow and the ski running surface asperities. Thus, we may simplify the Equation (1) by the elimination of variables μ_{cap} (too dry) and μ_{dirt} (according to [48], dirt attraction is insignificant on cold dry snow):

$$\mu = \mu_{plough} + \mu_{dry} + \mu_{lub} \tag{4}$$

3.1.1 State of the art

Here we will summarize materials and technical resources to reduce a ski-snow friction under the cold dry snow conditions. We consider only materials and technical resources which are generally accessible for skiers today.

3.1.1.1 Ski base material

Polyethylene has been used as a ski base material in the alpine skis construction from the end of 1950s [49]. It is difficult to say what kind of polyethylene was used at that time, whether it was a high-density polyethylene (HDPE) or an ultra high molecular weight polyethylene (UHMWPE). The old classification was not clear enough [50]. However, since 1974 and until now, the cross-country skis with UHMWPE ski base (ski sole) have been widespread.

There are two general varieties of the modern UHMWPE ski base: the pure UHMWPE transparent base and the “graphite” black base with the carbon-black (amorphous carbon) additive. Different transparent bases have molecular weight between 3×10^6 – 12×10^6 g/mol [51]. The carbon bases are very similar to transparent ones and differ by the molecular weight and contain the carbon-black additive.

At the beginning of 1974 there was only a transparent base. Certainly, there were no recommendations from the ski manufactures regarding the ski base alternative. From the beginning of 1980s it was possible to choose between the carbon and the transparent ski base. However, from that time and until now the recommendations of ski manufacturers have been varying over time. In some years the transparent base was recommended only for the cold dry snow, in other years only for the wet snow. There is a similar situation with the carbon additive contain. At the beginning of 1990s one can read about the superiority of their skis with the low carbon contain base for the cold and dry snow in the product catalogue of company "M". At the same time, company "N" wrote about the superiority of their skis with the high carbon contain base for the same snow conditions. Today almost all XC skis have a carbon ski base.

3.1.1.2 Physicochemical treatment of the ski running surface

There is a one generally accepted way of physicochemical treatment of the ski running surface for the cold and dry snow conditions: a hot glide waxing. The glide waxes (perfluorocarbon powders) are applied to the ski running surface by melting (Figure 7). All the glide waxes, which are presented on the market today, are very similar, according to [52]: "…the strategy in wax development by the various manufacturers follows the same general rules concerning the hydrocarbon composition (long to short alkanes)". Even worse [53]: "The compositional analysis showed that one company's three lines of Alpine and Nordic glide waxes to be compositionally equivalent". The glide wax producers' recommendations are similar to each other: lower temperature – harder glide wax.

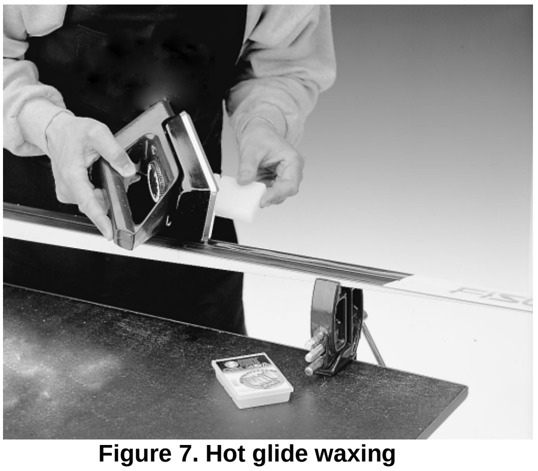


Figure 7. Hot glide waxing

3.1.1.3 Topography of ski running surface, initial creation and tuning

Generally, the initial ski base mechanical treatment can be divided into the stone grinding and the steel scraping. The stone grinding [16, 54-57] is an accepted method of a ski-base treatment; ski factories commonly apply this method to the newly produced skis. The steel scraping method has a number of promising features [7, 8, 58], but today it is mainly employed by a few enthusiasts.

Figure 8. Stone grinding (from www.wintersteiger.com)

The recommendations of the ski manufacturers and the stone grinding suppliers are very straightforward: colder snow – finer grinding pattern.

After the initial mechanical treatment, the topography of the ski running surface can be tuned by one of many kinds of manual riller, see Figure 9 and Figure 10.

Figure 9. Manual riller

Figure 10. Use of the manual riller

There is a common practise to use a very fine riller for the cold and dry snow or no riller at all.

Another method to tune (smooth) the ski running surface topography is a hot glide waxing; it does fill the pattern's valleys and smoothes the topography of the surface.

3.1.2 Analysis and directions of development

Below comes the analysis of the existing materials and the technical resources. We will present some rationalization proposals to reduce the ski-snow friction under the cold dry snow conditions.

3.1.2.1 Ski base material

Hardness – To minimize the coefficients μ_{plough} and μ_{dry} from the Equation (4), the ski base material has to be harder than the snow crystals. Unfortunately, the actual ski base material – UHMWPE already below -15°C is softer than the ice [59-65]. Thus, we have to consider even harder material for the ski base. Moreover, if the ski base is harder than the snow crystals, its movement over the snow will generate more melt water, because in this case the ski running surface will deform and melt the snow crystals, not otherwise. Hence, the ski base hardness furthers the melt water generation [23, 43], melt water distribution [66], and, consequently, reduces variables μ_{dry} and μ_{lub} from Equation (4) [42]. In spite of another material and quite low velocities, Figure 11 could give an indication of the ski base material hardness importance.

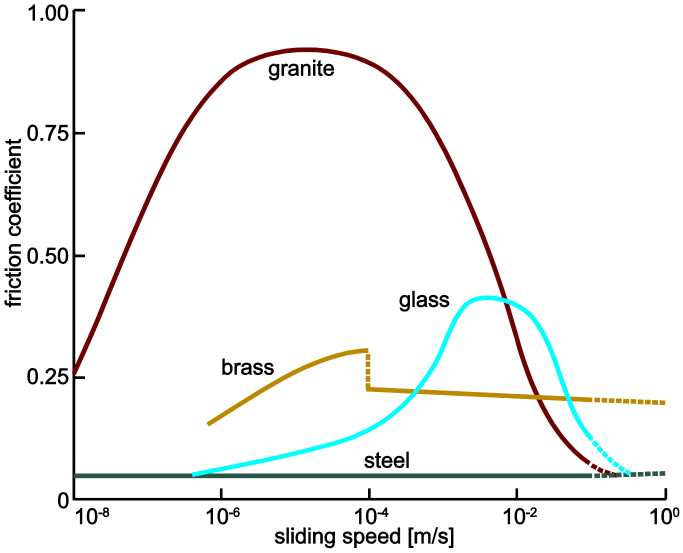


Figure 11. Friction of polycrystalline ice sliding on various smooth surfaces at -11.7°C [62]

Wear resistance – The cold and dry snow is a very abrasive medium and can easily degrade metals [67] and even rocks [68]. Therefore, a high wear resistance is a necessary criterion for the ski base material. UHMWPE is an extremely wear-resistant material [69] and has a straightforward direction in its development: the increase of the molecular weight decreases a coefficient of dry friction (μ_{dry}) and increases wear resistance [70-72]. Another way to improve the ski base wear resistance is filling (reinforcement) it with an appropriate substance. However, very often such a reinforcement degrades the gliding properties of the material [73]. In case with the ski base, the reason for similar reinforcement is unclear. There are no data regarding the dry friction coefficient of a carbon filled UHMWPE ski base, but there is no wear resistance increase according to the Table 1 . Our literature study did not find any acceptable explanation of the carbon ski base popularity. From the beginning, there was an antistatic role of carbon additive (electricity-conductive additive) as a legitimate reason for the carbon ski base appearance. But the American scientists did not find any relationship between the electrical conductance of the gliding surface and the static electric field strength [74-77]. Thus, we found only one expedient property of the carbon ski base: the black colour. This colour favours the increasing of the ski running surface temperature by the absorption of the ambient sunlight [78-80]. But it is possible to avoid the negative property of the carbon additive (degradation of wear resistance and degradation of hydrophobicity [81]) and keep the sunlight absorption ability, if we just add some intensive liposoluble black dye instead of carbon.

Table 1. Ski base properties, Electra = UHMWPE with carbon additives (data by Gurit (Ittigen) AG)

	P-Tex® 2000	P-Tex® 2000 Electra®
Molecular weight (Visk. ISO/R1191) [g/mol]	$5 \cdot 10^6$	$5 \cdot 10^6$
Density (DIN 53479) [g/cm³]	0.935	1.0
Abrasion resistance (Sand-slurry Steel 37 = 100)	20	30
Modulus of elasticity (DIN 53457) [MPa]	500	600

However, by the employment of such high technology reinforcing material, as quasicrystals, we may get a new very promising ski base for the cold dry snow conditions. Quasicrystals have a very low coefficient of dry friction [82] and very hydrophobic [83]. UHMWPE reinforced with quasicrystal particles exhibits a higher wear resistance rate than a pure UHMWPE [84, 85].

Wettability – We are in Zone I (Figure 6), and we have the melt water deficit. Nevertheless, the hydrophobic ski base (hydrophobic sliding surface) is able to distribute the available thin melt water film more effectively [17, 43, 59, 86]. The adhesion between the ski running surface and the snow is even lower, if the ski base is made of the hydrophobic material [87]. Our own [48] and others' [88] test results show a lower friction on the ski running surfaces with a higher water repellence. Thus, we have to employ a material with the highest possible hydrophobicity. In connection to this, such substance, as polytetrafluoroethylene (PTFE), is a first-priority candidate. For a long time ago (in 1953) [59, 89, 90] PTFE was found to be a very promising ski base material. However, the ski manufacturers consider the low wear resistance of PTFE and the difficulties of glueing such a ski base to be the reason for the lack of skis with PTFE base. Nevertheless, the glueing of PTFE is not very difficult today [91, 92]. The standard PTFE, evidently, has a poor wear resistance [73], but it can be easily replaced by the cross-linked PTFE [93], which has a much higher wear resistance rate [94, 95], as it is needed under the cold dry snow conditions. The PTFE ski base is advantageous even from the point of view of health. There is no need to use health hazard perfluoroalkanes to improve water repellents of the ski running surface.

Thermal conductivity – Following the melt water lubrication hypothesis, it is possible to state the positive role of low thermal conductivity of the ski base material [30, 32, 40, 66, 96-98]. A lower thermal conductivity spares the friction heat, which promotes the melt water generation. Therefore, it is difficult to understand the presence of comparatively very thermal conductive carbon additives (24.0 $W \cdot m^{-1} \cdot K^{-1}$) in conventional modern ski base (0.4 $W \cdot m^{-1} \cdot K^{-1}$) [64].

Hence, such additives make the ski base a more thermal conductive, which is not advisable for the cold dry snow conditions.

3.1.2.2 Physicochemical treatment of ski running surface

At this time it is very important to clarify our standpoint and the use of terms regarding a ski glide lubricant. It is very common in the ski society to believe that the glide waxes can act as a lubricant under the melt water deficit conditions. Yes, they can, but only within a very short distance of a few hundred meters [17, 18, 99]. After that we will see gray/white areas on a previously shiny black ski running surface. This delusion is based on perception of the ski glide as some kind of industrial application, but it is not. As it was mentioned above in section 3, skiing is a one-way movement, and if the glide wax or any kind of dry lubricants (inorganic layered lattice systems) additives [100] present on the sliding surfaces asperities separation, such waxes or additives have to be left on the ski track and cannot be reused.

Another delusion is a belief that the glide wax which is dissolved in amorphous phase [101, 102] "sweats" and separates asperities by that. From [103]: "During sliding, first the thin wax layer at the surface wears off, then the "stored" wax in the base is "sweating" due to a reversed diffusion process and supplies the gliding interface with lubricating material". All said looks very attractive, because it should be an effective solution for the ski glide on aggressive snow. But if we assume a need of a just 1 μm (which is obviously scanty) thick glide wax film to partially separate sliding surfaces asperities under a running distance of 10 km, by the following estimation (ski wide is a 4 cm):

$$10^4 \times 4 \cdot 10^{-2} \times 10^{-6} = 4 \cdot 10^{-4} \ [\mathrm{m}^3] \tag{5}$$

We will get a need of 0.4 litre glide wax per one ski. It does not seem to be reasonable. Moreover, the authors of [19] are very sceptical about the "sweating" mechanism, and the authors of [102, 104] are even more resolute. They decidedly disclaim the existence of such a mechanism. In spite of the above, the habit to "saturate" the ski base many times with a hot glide wax is very popular among the skiers and the ski technicians. However, we do not find any evidence which proves any positive influence of such "saturation". On the contrary, the authors of [19] point out the significant degradation of the essential mechanical properties after such treatment. Our own tests prove this statement quite well [105]. Fortunately, the conventional hot wax treatment with iron is not long-continued enough to damage the ski base (but it can be too hot and it will cause damage anyway). Treatment with "Thermo Bag" ("Thermo Box") [106] is not hot enough, otherwise the ski base should be "saturated", swollen and hereupon should come unstuck. Another interesting question is if it is so good for the ski glide to get the ski base “saturated” with the glide wax, why do not the ski base manufacturers do it? It should be much more logical and efficient than today’s practice.

Another durable affirmation is a necessity to adjust the hardness of the ski to be similar to the snow crystals actual hardness. It supposedly should reduce the ski friction. From [103]: “...one of the purposes of wax is to adjust the hardness of the sliding surface to match the hardness of the snow”. However, our study of literature of the classical tribology did not bring any evidence of such a common rule. It is hard to understand why it is possible to produce more melt water and to reduce the friction, if the ski running surface has the same hardness as the snow crystals. The ski running surface has to deform and abrade the snow crystals for the melt water generation, and therefore should be, as hard as possible, to thaw more water under the same snow conditions. A number of authors confirm this [1, 18, 23, 43, 59, 62, 66, 98, 107, 108]. A famous Japanese ski scientist Masaki Shimbo gave us a very good illustration of what was going on (Figure 12) [18]. One can see that a hard ski running surface is advantageous for any snow conditions. Moreover, our own experiment shows the impossibility of an appropriate hardness adjustment for the cold and dry snow [105] with the one of hardest glide wax on the market.

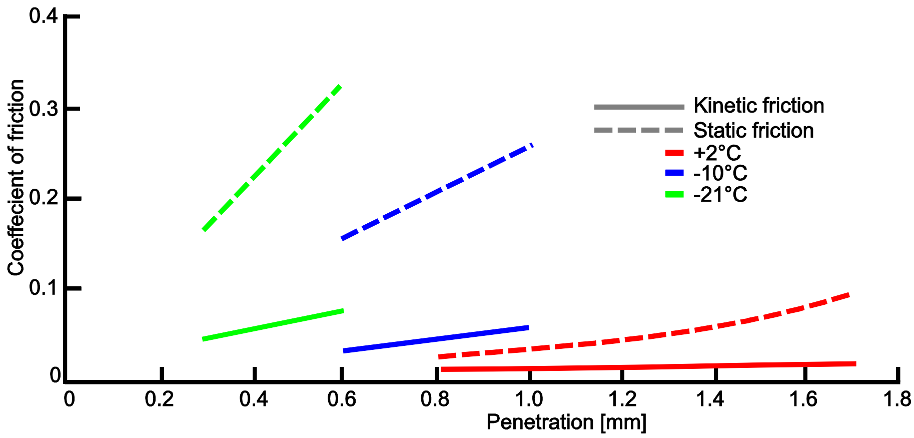


Figure 12. Friction of sliding surfaces coated with paraffins of various hardnesses at different temperatures. Hardness is given in penetration depth (mm) [18]

Another popular assertion is that the optimum melt water film thickness can be achieved only with the wax that is recommended by the manufacturer for the given temperature range [103]. Usually, as the support of this assertion, one almost classic paper is cited [23]. However, if one unprejudicedly looks at the most important key points of this paper (Figure 13), he will see the same tendency as the above: the harder ski running surface generates more melt water.

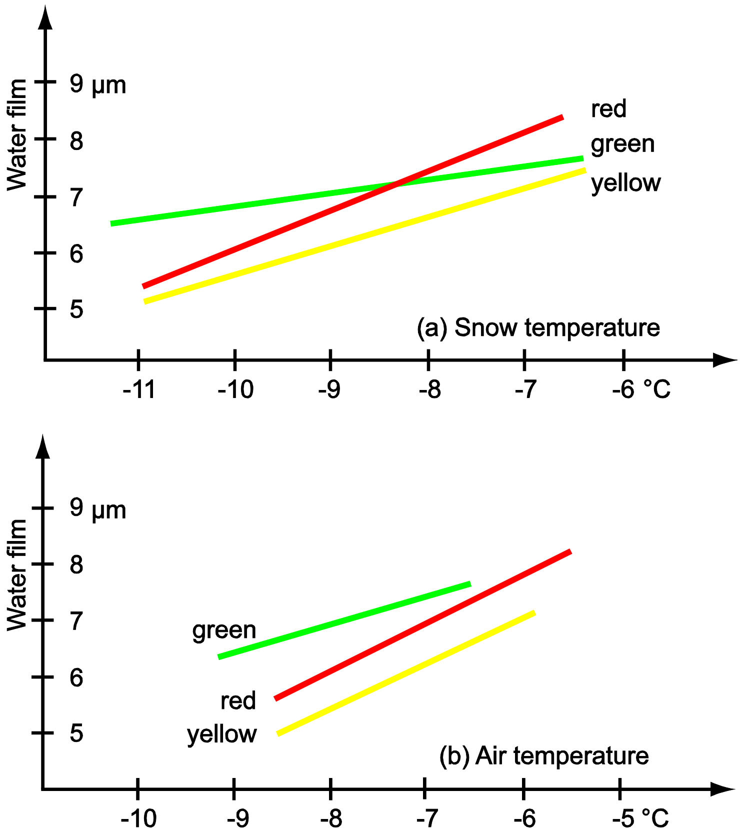


Figure 13. Dependence of the water film at different temperatures of snow (a) and air (b) and for skis prepared with different kinds of wax (Toko green, red and yellow) [23]

Here comes the time when it is appropriate to exhibit plots 6 and 8 from one Finnish work [25]. This work was carried out with the use of the modern ski base and the suitable glide waxes. We superimposed the plots for the highest used velocity, and the result is shown in Figure 14. If we ignore the presence of the undefined term "unwaxed" (however, we can exclude the stone grinding, because the paper was written before this technique appeared in XC skiing), these plots support our own results from [48] (except for plots for -1°C) quite well.

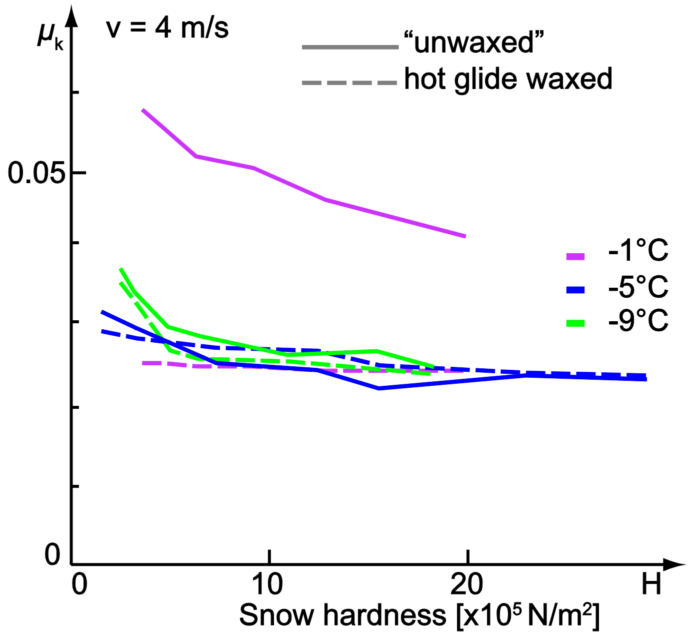


Figure 14. Kinetic coefficient of friction as a function of snow hardness [25]

Therefore, according to the mentioned above, to the measurements taken (Table 2), the experiments carried out [48], and the test results from [25], we found no reason to perform the hot glide wax treatment for the cold aggressive snow. Perhaps, it can be used just for the temporal smoothing of the ski running surface. Also, the use of the glide waxes because of high environmental [109-111] and health risks [112-117] might have to be re-considered.

Table 2. Hardness at room temperature of ski base materials and of some glide waxes intended for the cold and dry snow conditions

Material	Hardness [Shore D]
P-Tex® 2000 Electra®	65.7
P-Tex® 2000	64.2
P-Tex® 4000	67.3
P-Tex® 5000	68.6
Star glide wax NA8 (-8°/-20°C)	50.4
Swix® LF4 -10°C/-20°C	47.8
Toko® Dibloc LF -10°C to -30°C	46.9
Vauhti graphite antistatic Hard -7°…-25°C	46.7

3.1.2.3 *Topography of ski running surface, initial creation and tuning*

As it has been already mentioned in 3.1.1.3, the stone grinding and the manual rillers are the most common methods and tools to create and tune the ski base topography. However, because we already have a very thin water film, these methods make the situation (and ski glide) even worse. The direction of the minimal elements of the stone grinding patterns and the majority of rillers patterns are always longitudinal to the course [55-57]. Because of this, the actual ski running surface structure makes melt water film even thinner [118-120], which leads to the increased friction. Therefore, anyone who wants to utilise the melt water film more effectively, has to find a new method for the ski base machining to produce a more transversal structure [43, 121]. A positive effect of such a structure under the cold and dry snow (ice) conditions has been already demonstrated by a few authors [40, 66]. Another very promising method that has never been used in skiing, is to create a crater-formed structure on the ski running surface. Such an adequately made pattern (Figure 15) moves ML region and point t_0 to the left (Figure 6) and reduces friction because of that [122].

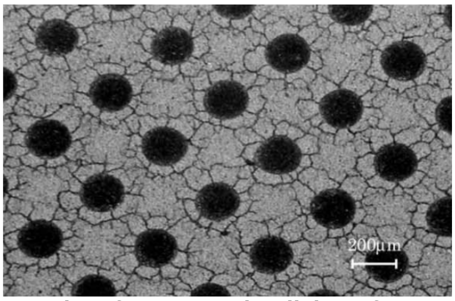


Figure 15. Optical micrographs of pores on the disk surface produced by the laser texturing [122]

As fairly stated in [123], the ski running surface roughness after the stone grinding is too coarse (R_a is about 10 – 150 μm) for the effective utilization of a very thin (from 50 nm [124] up to 13.5 μm [23] and to 10 – 50 μm [31]) melt water film. Thus, we can assert that even the hot glide waxing can help to smooth the ski running surface for quite a short distance, but the direct mechanical smoothing of the surface [125] is obviously preferable.

Another drawback of the stone grinding are the micro hairs on the ski running surface (Figure 16) [126]. The skis with the stone ground base have to be treated with the hot glide wax, otherwise such skis exhibit a very poor performance [7, 26]. Even the wettability of the ski base material can be influenced undesirably by the penetration of the high-energy abrasive particles from the grinding stone into the ski base [127].

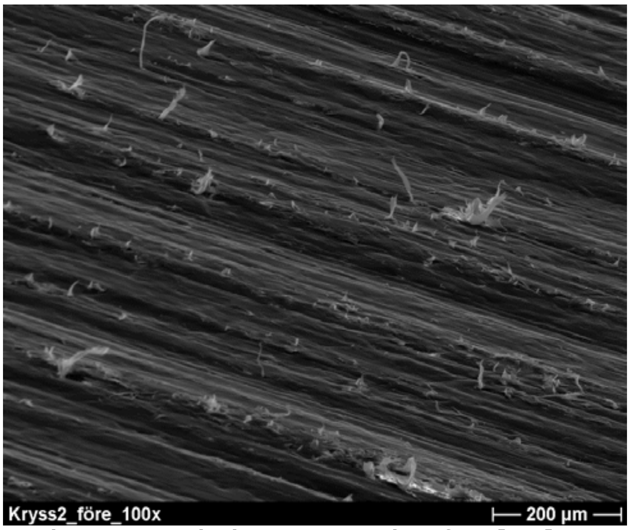


Figure 16. Typical stone ground surface [128]

As it was described above, the hydrophobic (low-free-energy [129, 130]) ski running surface is a preferred alternative. However, even the material with the lowest surface energy (6.7 mJ/m^2 for a surface with the regularly aligned closest-hexagonal-packed –CF_3 groups)[1] gives a water contact angle of only around 120° [131, 132]. Thus, if we wish to increase the hydrophobicity of the ski running surface even more, we have to perform an appropriate optimization of the surface structure [133]. There are a few methods to make the super-hydrophobic surfaces, e.g. fractal surfaces [134], hierarchical micro- and nanostructures [135], and even methods to measure fractality of the ski running surface structure [136], but the fractal surfaces and many other kinds of super-hydrophobic surfaces are very vulnerable to damage [137, 138]. From this point of view, it seems very promising to employ a surface with a random structure [139]. Such structure can be made by CNC mill or by the simple air blast roughening [140]. Also, the treatment with plasma [141, 142] is quite promising from a durability point of view [143].

3.2 Zone II (Water film is too thick)

The excess of a lubricant takes place. A melt water film fully separates the snow and the ski running surface asperities. Hence, we may simplify the Equation (1) by the elimination of variables μ_{plough} and μ_{dry}:

$$\mu = \mu_{lub} + \mu_{cap} + \mu_{dirt} \tag{6}$$

[1] This value is much smaller than that (22 mJ/m^2) of polytetrafluoroethylene (PTFE)

3.2.1 State of the art

We will summarize materials and technical resources to reduce the ski-snow friction under the wet snow conditions. We consider only materials and technical resources which are generally accessible for the skiers today.

3.2.1.1 Ski base material

See 3.1.1.1.

3.2.1.2 Physicochemical treatment of ski running surface

There are two generally accepted ways of the physicochemical treatment of the ski running surface for the wet snow conditions: that is a hot glide waxing (manual- or roto-corking rubbing are included) and the application of the perfluorocarbon comprising fluids. However, the expected results are not guaranteed. For example, as we can read in [53]: "In response to the study, one of the wax manufacturers contended that additives were present in their waxes and that the trace chemicals were critical to the waxes' performances. The subsequent chemical analyses were unable to confirm the presence of additives". The glide wax producers' recommendations are similar to each other: a higher temperature – a softer glide wax and higher contains of the perfluorocarbon additives.

3.2.1.3 Topography of ski running surface, initial creation and tuning

Please refer to 3.1.1.3. The recommendations of the ski manufacturers and the stone grinding suppliers are straightforward: as more free water is contained in the snow, as coarser (deeper) grinding pattern and coarser (widely spaced) manual riller pattern should be used.

3.2.2 The analysis and directions of development

Here we will analyse the existing materials and technical resources and present some rationalization proposals to reduce the ski-snow friction under the wet snow conditions.

3.2.2.1 Ski base material

Hardness – According to (6), the hardness influences only the third variable μ_{dirt}, because a hard and resilient material is more dirt-repellent than a soft and tenacious material [48, 58]. The standard PTFE should work very well.

Wear resistance – We analyze the ski glide under the wet snow conditions - the HL regime. In this case the wear resistance of the ski base is an inessential property.

Wettability – By the low wettability (by high hydrophobicity) of the ski base material we can easily attain the high hydrophobicity of the ski running surface and reduce the ski friction [86], mostly by reducing variable μ_{cap} from Equation (6). From this point of view, it is hard to understand the presence of carbon additives in the ski base, which reduce the hydrophobicity and increase contact angles hysteresis [144]. Some ski companies produce skis using the ski base with perfluoroalkanes [145], as additives to decrease the ski running surface free energy. However, such additives are very volatile and their presence in the ski base significantly degrades the mechanical properties of the base [104]. Thus, PTFE (Teflon®) seems to be the best ski base material for the wet snow conditions in terms of today's available substances.

Thermal conductivity – It is an inessential parameter of the ski base material, because the melt water volume is already big enough.

3.2.2.2 Physicochemical treatment of the ski running surface

The purpose of the physicochemical treatment (waxing) under the condition of the excess of melt water is merely the following: to increase hydrophobicity of the ski running surface. However, our own [7] and some other authors' [130] measurements have exhibited very similar wettability for the fresh machined UHMWPE ski base and for perfluoroalkanes. Moreover, due to the fact that the current glide waxes for such conditions are quite soft and tenacious, in comparison with the UHMWPE ski base, these glide waxes (hydrofluorocarbons, perfluoroalkanes) increase the dirt absorption and accumulation on the ski running surface [48, 58, 146]. The experiment described in [58] has not been carried out just as an isolated glide test. The designing and the performing of a reliable outdoor glide test is quite a challenging task and has been criticised by some researches, e.g. [147]. The glide test has been accompanied by the hardware-controlled unbiased estimation of the dirt attraction to the ski running surface. This method is described in detail in [146]. A specially made device used for the estimation is presented in Figure 17.

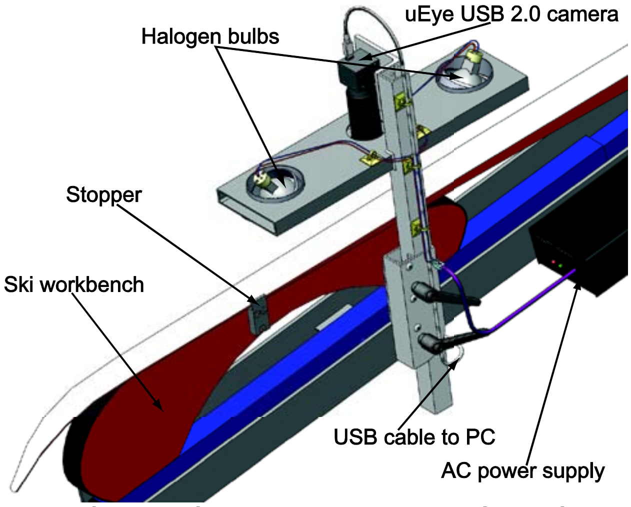


Figure 17. Dirt attraction measurement - Experimental setup

The measurements performed by this device show a clear relationship between the glide wax existence and the contamination of the ski running surface under the wet snow conditions. It is hard to believe, that the dirt attraction can promote a certain reduction of the ski friction, most likely the opposite.

On the other hand, a hot glide wax treatment makes some kind of mixture on and in the upper layer of the ski base. Consequently, as a result of such treatment, we get some mixture of hydrocarbons and fluorocarbons on the ski running surface. It is important to consider an uncontrollable character of the mixture. Any glide waxing adherent has the habit of performing the hot waxing procedure repeatedly with many different waxes. After that it is impossible to know for sure how high the concentration of fluorocarbons is in the upper layer of the ski base. It is an unknown quantity. But according to [52, 148-150], the wettability (hydrophobicity) of a fluorine-based additive/paraffinic-based wax mixture does not follow a linear subjection to the fluorocarbon concentration. Thus, we cannot predict the result of such treatment accurately enough. Maybe, we have gotten a highly hydrophobic ski running surface, maybe otherwise. According to stated above, there is no reason for wax treatment under the wet snow conditions.

Even the literature study regarding the use of lubricants on the polymer sliding surfaces in industry did not give any illustration of such practice. Only in [14] we found a statement about the undesirability of such combination, because of the contamination of the lubricant and the sliding surfaces.

3.2.2.3 *Topography of the ski running surface, initial creation, and tuning*

It is a very complicated field with a lot of subjects of implicit beliefs. One such belief consists in the dewatering (draining) role of different structures (patterns) on the ski running surface and the reduction of the ski friction in case of using such structures. Common practice and some researches [54, 151] support the idea that friction decreases in this case. However, according to the classical tribology theory it is incorrect: any structure (longitudinal, transversal and isotropic) increases friction under the HL regime [118, 119, 152]. It is clearly stated in [119]: "For almost all combinations of correlation lengths, roughness effects increase the load capacity, increase the friction, and decrease the flow rate". Therefore, the ideal ski running surface for the wet snow is an absolutely smooth surface, if we assume a constant contact with the melt water [153, 154]. However (and fortunately), it is not the case in the real life skiing.

Moreover, the solitary range of wettability of surface [155] and of ski base material [156] is not such important for a fast ski sliding over the water film. Another parameter is much more important, namely contact angles hysteresis (CAH), which is illustrated on Figure 18. Since the degree of wettability (capillary attachment) affects directly the movement of water droplets on an inclining plane, we may find the state of equilibrium by an equation from [157, 158]:

$$\frac{mg(\sin\alpha)}{w} = \gamma_{LV}(\cos\theta_R - \cos\theta_A) \qquad (7)$$

Where the advanced contact angle (ACA) θ_A, receding contact angle (RCA) θ_R and the surface tension parameter are related to the angle α at which the droplet starts to slide along the inclined plate. Here m is the drop mass, g is the gravitational acceleration, w is the width of the droplet along the line parallel to the plane and perpendicular to its maximum inclination direction, and γ_{LV} is the surface tension of the liquid (water-air). Hence, we need to get $\Delta\cos$ from Equation (8) to be equal to zero, and in this case the solitary value of θ_A is quite insignificant [159-161].

$$\Delta\cos = \cos\theta_R - \cos\theta_A \qquad (8)$$

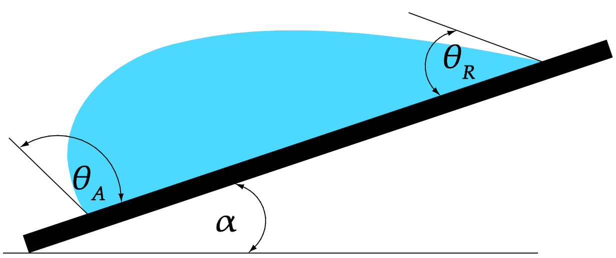


Figure 18. Dynamic wetting (sliding) of water droplet on a solid surface

To estimate the surface wettability with a higher accuracy than $\Delta\cos$, we introduced a dimensionless wettability factor, as a function of experimentally measured contact angles (ACA and RCA) [162]:

$$F_w = (\cos\theta_R - \cos\theta_A)\sqrt[3]{(\cos\theta_A + \cos\theta_R + 2)\frac{\sqrt{8 - 2(\cos\theta_A + \cos\theta_R)^2}}{9 - (\cos\theta_A + \cos\theta_R + 1)^2}} \quad (9)$$

Therefore, almost all known patterns needed to obtain the super-hydrophobicity [134, 140, 163] are not applicable for skiing under the wet snow conditions. They have rather high roughness, which consequently increases CAH [160] and equilibrium angle α, and as the result increases value of μ_{cap} from Equation (6) [125, 162, 164]. The "hairy" nature of such structure should increase the dirt adhesion [19] and consequently the value of variable μ_{dirt} from the same equation.

On an absolutely smooth flat surface the classic Young wettability model operates (Figure 19):

$$\cos\theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}} \quad (10)$$

where γ_{SL}, γ_{SV}, and γ_{LV} are the interfacial free energies per unit area of the solid-liquid, solid-gas, and liquid-gas interfaces, respectively.

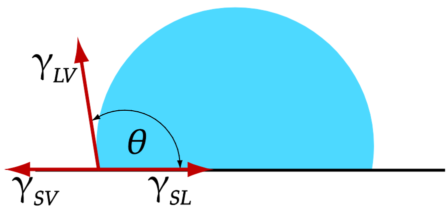


Figure 19. Young wettability model

On a rough surface it is possible to be under Wenzel wetting model [165] (Figure 20):

$$\cos\theta' = \frac{r(\gamma_{SV} - \gamma_{SL})}{\gamma_{LV}} = r\cos\theta \quad (11)$$

where $r = \frac{\text{Real Surface area}}{\text{Apparent Surface area}}$.

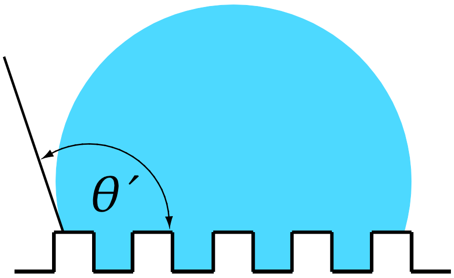


Figure 20. Wenzel wetting model

Or to be under Cassie-Baxter wetting model [166] (Figure 21):

$$\cos\theta' = f\cos\theta + (1-f)\cos 180^{\circ} = f\cos\theta + f - 1 \quad (12)$$

where f is the area fraction of solid surface and $f = \frac{\sum a}{\sum(a+b)}$, cos 180° is the water contact angle for air.

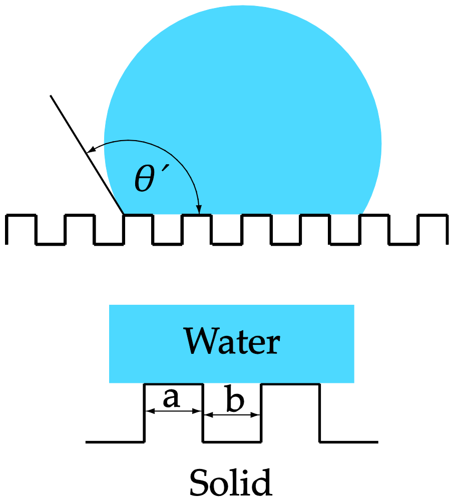


Figure 21. Cassie-Baxter wetting model

Unfortunately, high roughness of the ski running surface (Wenzel regime) is not very promising method to reduce the capillary drag. The authors of [160, 167] clearly assert the relationship between Wenzel state and CAH: Wenzel state leads to larger CAH, and larger CAH leads to the increased slide friction [151, 155, 168-172]. Thus, if we wish to reduce the ski friction under the wet snow conditions, we have to achieve Cassie-Baxter state [173] for the contact between the ski running surface and the snow, or in, other words, the heterogeneous wetting contact [174-176]. Even a specific shape of the roughness have to be well thought-out [177].

In real life we have to consider a not ideally flat ski track and melt water with the air bubbles and dissolved air. Hence, the ski running surface is not always in contact with melt water and it is possible to get water out of the ski running surface cavitations and substitute the water with the air. This can create the heterogeneous wetting contact and reduce friction by reducing capillary drag. Therefore, we have to create the ski running surface topography in the way to achieve the quickest possible empting of the cavitations. So, the interior of the cavitations (ski base material) has to be high hydrophobic, because empting is influenced by both shear and tensile hydrophobicity [125, 139, 162]. Although the shear hydrophobicity depends on both ACA and RCA, the tensile hydrophobicity depends only on RCA [178]:

$$W_{adh} = \gamma_{LV}(1 + \cos\theta_R) \tag{13}$$

The cavitations should have steep interior faces [138, 151, 179], should be for the most part close to the longitudinal direction to avoid a water film increasing [152] and have to be long enough (should have shape of grooves) to minimize the contact between the melt water and the ski base material inside of the cavitations.

To cut a long story short, to minimize the capillary drag under the wet snow conditions, we have to create a pattern, which is very smooth on a micro level (R_a is below 50 nm according to [124]) and coarse enough on a macro level to provide the heterogeneous wetting contact.

4 CONCLUSION

In our opinion, there is certain stagnation in the ski glide research area during the last 35 years. We can give an outstanding example of a purposeful research work: early Swix® (Astra AB) development of a new wax generation, making wax based on the scientific methods [180]. In 1942-1946 the company performed an extensive work. They designed the new unprecedented research devices, carried out thousands of tests, and the result speaks for itself: in the 1948 Olympics, all of the Swedish gold medal winners skied using the new Swix wax. It is hard to see anything similar today.

Another remarkable fact, that the ski preparation did not change much after the substitution of wood by plastic. The porous and hydrophilic wood was impregnated for a better glide. The non-porous and highly hydrophobic UHMWPE ski base has to be impregnated as well.

On the base of the literature study and the experiments performed, we will reveal some reasonable dependences and yield directions of the future development.

4.1 Ski base material

As we found out that the hardness (more melt water on the cold snow, less dirt absorption on the wet snow), the wear resistance (in the first place for the cold and dry snow) and the hydrophobicity are the most important features for one good ski base and can be improved in the nearest future as following:

- Pure UHMWPE with as high as possible molecular weight;
- UHMWPE reinforced with quasicrystals;
- Cross-linked PTFE for all snow conditions;
- Standard PTFE (Teflon®) for the wet snow;
- To add an intensive liposoluble dye to the ski base for the cold and dry snow conditions instead of carbon to reduce the thermal conductivity and increase the sun radiation absorption.

4.2 Physicochemical treatment of ski running surface

If in the future we are able to create the adequate structures on the ski running surface, we do not need any forms of the glide wax treatment, especially for the PTFE ski base. Here are some observations regarding the subject:

- Glide waxes can be applied on the ski running surface merely with the purpose to correct the not optimal surface topography (texture);
- Perfluoroalkanes can be applied directly on not recently machined (not fresh enough) ski running surface to improve the surface chemistry, especially for the short skiing distances. This method is applicable only for the wet and very clean snow, otherwise the dirt adsorption could degrade the ski glide;
- It is worth to re-consider the use of the glide waxes in connection with the high environmental and health risks.

4.3 Topography of ski running surface, initial creation and tuning

The topography (structure, pattern) is an essential parameter, which influences the ski glide to the great extent. By the appropriate topography we may move the plot on Figure 6 to the left, if we are in Zone I (melt water deficit) and to the right, if we are in Zone II (melt water excess). We have to develop some new methods, machines, and tools in order to control this factor:

- Development of new machines and manual tools, capable of producing the micro hair-free adequate structures (patterns) on the ski running surface;
- New machines and manual tools, capable of producing the true X-shaped and other non longitudinal structures (and even longitudinal if needed);
- New methods for the creation of a partly controllable random structure. Deep random structure with, for the most part, close to the longitudinal direction for the wet snow. The shallow random structure with, for the most part, close to transversal direction for the cold and dry snow;
- New methods, machines, and manual tools, which should be able to produce the crater-formed structures for the cold and dry snow.

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Paper I

CONTACT ANGLES ON THE RUNNING SURFACES OF CROSS-COUNTRY SKIS*

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The importance of high hydrophobicity for minimising snow-ski friction has been discussed in a number of scientific papers. The chemical modification of surface forces using fluoropolymeric coatings can result in water contact angles of up to 120°, but not more. To reach extreme values of the contact angle, a second factor has to be modified, namely surface structure. In this study a number of cross-country skis were treated with a modern method of stone grinding and with old-fashioned steel scraping. The surface roughness (3D) and the surface (solid-liquid) contact angle were then measured. After this, the skis were treated with a hot glide wax and new measurements were made. This study also examines the contact angles (solid-liquid) of the flowed surface of a sample of glide wax and the surface of a sample of solid press-sintered running base (UHMWPE). Unexpectedly low hydrophobicity was observed after stone grinding.

Keywords: Hydrophobicity, skis, roughness.

1. Introduction

Skiers have always been interested in attaining a better glide on skis, but there has been considerable uncertainty about the basic model to be used. Today there is much evidence to support the idea of meltwater lubrication.

Colbeck [1] considered two different mechanisms for removing water from the ski-snow contact surface. Using the squeeze mechanism, the thickness (h) of the film would be in balance: $h^4 = 3cr^2\eta^2u^2 / 2L\rho_i$ where c is the ratio of area to load, r is the contact radius between the snow and the ski, η is the viscosity of water, u is speed, L is the latent heat of fusion and ρ_i is the density of ice. Using the shear mechanism, the thickness would be much less: $h^2 = \eta u \pi r / L\rho_i$

Obviously, a smooth, hydrophobic ski base would make a shear water-removal mechanism less effective. Water slides more readily on hydrophobic

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surfaces. In a case with excess lubrication, capillary forces would be higher on the less hydrophobic ski base. In view of this, we can see that a hydrophobic surface would be advantageous in all snow (weather) conditions [2].

All leading cross-country (X-C) ski manufacturers use an Ultra High Molecular Weight Polyethylene (UHMWPE) as the ski base. Running surface treatment consists of a mechanical base treatment and waxing. Modern glide waxes repel water very well. Nevertheless, even an extremely hydrophobic wax, such as perfluorocarbon, has a water contact angle limited to 120°. On the other hand, using the optimal mechanical running surface treatment we may attain a water contact angle of up to 180° [5].

The water contact angle is governed by the forces exerted at the three phase contact line of the drop in the plane of the solid, which is where the solid/liquid, liquid/gas and solid/gas interfaces meet. The forces acting at this line are the surface tensions, and their balance gives the Young's equation: $\cos\theta_Y = \gamma_{sv} - \gamma_{sl} / \gamma_{lv}$ where γ_{ij} denotes the surface tension (energy per unit surface) of the interface *ij* and where *s*, *l* and *v* designate the solid, liquid and vapour phases respectively. Classical studies by Wenzel [3] and Cassie and Baxter [4] established that roughness as well as surface energy are the factors that determine wettability. Wenzel proposed a model describing the contact angle on a rough surface as: $\cos\theta_W = r\cos\theta_Y$ where *r* is the roughness factor, defined as the ratio of the actual area of a rough surface to the projected geometric area. Since *r* is always larger than one, the surface roughness enhances both the hydrophilicity of hydrophilic surfaces and the hydrophobicity of hydrophobic ones. Cassie and Baxter proposed an equation describing the contact angle on a surface composed of a solid and air, assuming the water contact angle for air to be 180°: $\cos\theta_C = \varphi_S \cos\theta_Y + \varphi_S - 1$ with φ_S being the area fraction of the solid-liquid interface. So, regardless of the approach, the contact angle is always larger or equal on a rough surface, so giving the running surface a structure is the most effective way to increase hydrophobicity.

2. Apparatus and procedures

2.1. *General approach*

Our choice of tools, wax, skis and the procedure for ski preparation was based on direct application to X-C skiing. Our primary goal was to examine the relation between surface roughness and hydrophobicity. Our secondary goal was to estimate the magnitude of the water drop contact angle on the running surface of the ski.

2.2. *Skis and their preparation*

We used 5 similar Karhu skis from the same batch. 4 skis were treated with 4 different patterns of stone grinding on Tazzari RP13.2. One ski was treated with an HSS scraper (Figure 1). For waxing we used Swix CH8. Paraffin was melted into the ski base 3 times, and they were then scraped with the plastic scraper. Before measurement the skis were brushed with a Red Creek steel rotary (4000 r/min) brush. A clean brush was used for the dry skis and another for the waxed skis.

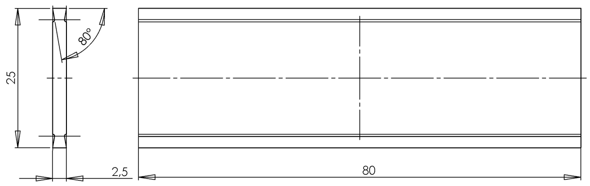

Figure 1. High Speed Steel (HSS) scraper.

2.3. *Contact angle measurement*

The running surface hydrophobicity of the ski was measured as the advanced contact angle of a water drop. The larger the angle, the higher the hydrophobicity. A goniometer FTA125 and the software Fta32_Video build 185 from "First Ten Ångstroms" were used to measure this angle. The pump on the goniometer was driven manually. 15 images with 2 f/sec were captured during each measurement. For each ski base sample we made 3 measurements at 3 different points within the marked 1,5cm^2 area. An arithmetical mean value was then computed for each sample.

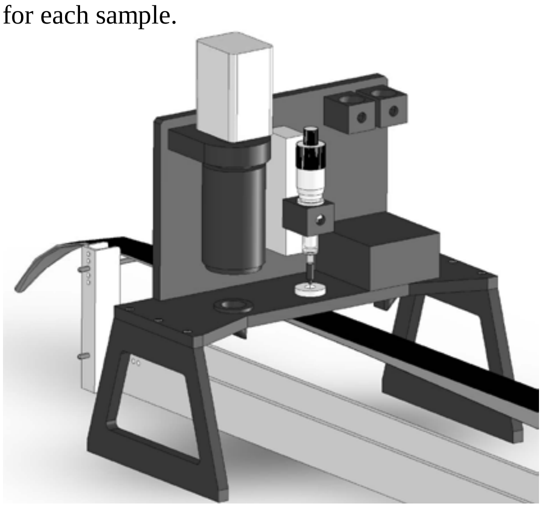
Figure 2. Ski under FTA125 goniometer.

2.4. *3D ski running surface measurement*

Surface measurements were taken using a Wyko NT1100 Optical Profiler and the software Vision32 for NT-1100 (version 2.303 SMU4 build 5). Standard indexes such as Ra, Rq, Rt and Rz were recorded. For each new ski base sample we made 2 measurements at 2 different points within the marked 1,5cm^2 area. An arithmetical mean value was then computed for each sample.

3. Results

3.1. *Relation between running surface roughness and hydrophobicity*

We did not find any significant relation between the roughness of the samples and hydrophobicity. Pearson's correlation between each of the indexes and the contact angle lies in the range: -0,07 ÷ 0,19.

Table 1. Contact angle and surface standard indexes.

Ski and kind of treatment	*Contact Angle*	*Ra*	*Rq*	*Rz*	*Rt*
Nr. 3 Stone grinding - pattern 1A. Dry.	104,83	3,66	4,52	31,69	41,33
Nr. 3 Stone grinding - pattern 1A, CH8.	113,14	3,19	4,13	28,79	33,80
Nr. 4 Stone grinding - pattern 1B. Dry.	110,48	4,75	5,72	31,46	35,26
Nr. 4 Stone grinding - pattern 1B, CH8.	113,14	4,78	6,08	35,08	36,84
Nr. 5 Stone grinding - pattern 2A. Dry.	107,18	2,76	3,51	26,10	31,62
Nr. 5 Stone grinding - pattern 2A, CH8.	115,88	2,73	3,49	23,94	26,50
Nr. 6 Stone grinding - pattern 2B. Dry.	111,92	3,12	4,02	27,48	30,14
Nr. 6 Stone grinding - pattern 2B CH8.	112,15	3,07	3,89	24,78	29,63
Nr. 7 Treated with HSS scraper. Dry.	117,26	4,60	5,71	32,11	34,69
Nr. 7 Treated with HSS scraper, CH8.	115,17	3,75	4,64	28,91	33,03

Where Ra is the average roughness, Rq is the root-mean-squared roughness, Rt is the peak-to-valley difference, and Rz is the average of the ten greatest peak-to-valley separations on the sample. For more details see ISO and DIN standards.

3.2. *The magnitude of the water drop contact angle*

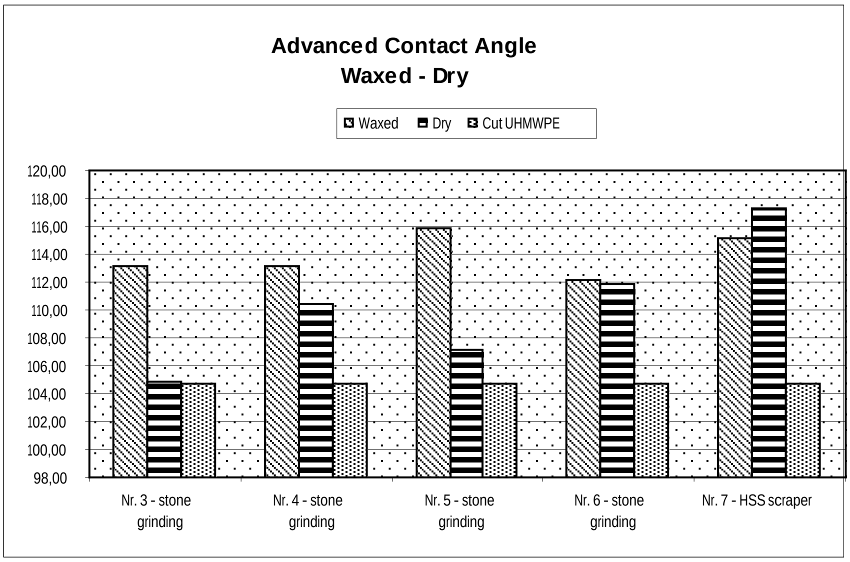

Figure 3. Contact angle comparison for differently treated surfaces.

In addition, we measured the contact angle of the flowed surface of a sample of glide wax Swix CH8 – 108,01°, and on a solid sample of graphite UHMWPE – 104,67°. This solid sample represents similar material to the ski base.

4. Discussion and conclusions

4.1. *Roughness and hydrophobicity*

From our results we can draw the conclusion that the above-mentioned surface standard indexes are unsuitable for measuring hydrophobicity. These indexes do not help us to estimate the fractal structure of the surface [5]. We have to find other methods to measure the fractality of the surface.

4.2. *Running surface hydrophobicity*

Figure 3 (or Table 1) shows a quite unexpected phenomenon: dry stone ground surfaces have a low contact angle, much lower than the scraped surface (104,83° compared with 117,26°). After applying hot wax to the skis with a stone ground base, the contact angle increased dramatically. We can assume that stone grinding reduced the hydrophobicity of UHMWPE as a material (by temperature, by interaction with coolant fluid, etc.), but scraping did not. And we may suppose that the manual scraping resulted in some kind of randomly rough surface [5], with quite high hydrophobicity. However, stone grinding increases the contact angle, because both the flowed surface of the sample of glide wax and the solid sample have lower contact angles. The disadvantage of the stone grinding procedure is that wax has to be applied to the surface, which increases the attraction of polluting substances to the ski base. The degree of pollution adhesion depends on the hardness of the ski running surface.

Acknowledgments

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Paper II

Dirt absorption on the ski running surface – quantification and influence on the gliding ability

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Abstract

We propose a thesis that minimising dirt on the running surface of skis improves the surface glide. Waxing usually improves the gliding ability of skis in the short term. But how does waxing affect pollution absorption in the long term? In this study a number of skis with a transparent base and a white background were treated by steel scraping and with different glide waxes. The gliding ability of waxed and unwaxed skis, the sliding surface whiteness and the hydrophobicity were tested and documented. Tests were performed before and after the skis had been used for different distances. It was observed that all the waxed skis (regardless of the wax used) absorbed more dirt than unwaxed, and as a result all waxed skis lose their glide ability sooner than unwaxed (freshly scraped) skis in wet snow conditions.

Keywords: dirt, glide, ski, wax

Introduction

For many centuries skis have been used as a means of winter transport, but in the last 80 years skis have mainly been used as recreation equipment. Therefore the majority of research papers about sliding on snow have a direct connection to sport and to skiing competitions, and the focus of attention has been on minimising friction between the ski gliding (running) surface and the snow.

As Colbeck (1992) and Langevin (1998) expressed it: $\mu = \mu_{plough} + \mu_{dry} + \mu_{lub} + \mu_{cap} + \mu_{dirt}$, where the subscripts *plough*, *dry*, *lub*, *cap* and *dirt* represent the friction due to ploughing, solid deformation, water lubrication, capilliary attraction, and surface contamination, respectively. In the real world such processes are not independent. For instance $\mu_{cap} = f(\mu_{dirt})$, because the ski running surface gradually becomes covered with dirt, and the initial optimum roughness of the surface vanishes, so the capillarity drag increases, as shown by Wenzel (1936) and Cassie & Baxter (1994). But in our experiment we have to simplify for the sake of the analysis.

We believe that surface contamination μ_{dirt} is a very important parameter. Dirt accumulation influences all the other gliding mechanisms. However, our literature review discovered no studies that had investigated the relationship between the ski base material, the treatment of the ski base and the contamination factor of the ski base.

The majority of ski technicians try to decrease the electrostatic charge of the ski's running surface. Although Colbeck (1992) wrote about the importance of using graphite waxes to minimise the electrostatic

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drag of dirt, in a later study (Colbeck, 1995) he writes that: 'The rate of charging on wet snow increased with speed but was not affected by the use of a "graphite, antistatic" wax. Use of another "antistatic" wax on dry, soft snow actually increased the measured voltage over that of the bare base'. Even if contamination by dirt particles attracted by the charges is important (Colbeck, 1994), we may suppose that the softness and tenacity (viscosity) of the ski sliding surface will have a major influence on the attraction of dirt. We cannot decrease the electrostatic charge by any known ski base treatment, but we can change the hardness and tenacity of the ski base surface in many different ways.

The purpose of this study is to examine how treatment of the ski base in different ways affects the level of contamination of the ski base surface.

Apparatus and methods

General approach

Our choice of tools, wax, skis and the procedure for ski preparation was based on direct application to cross-country (X-C) skiing. Our primary goal was to examine the relationship between ski base treatment and dirt absorption. Our secondary goal was to estimate the magnitude of the water drop contact angle on the running surface of the ski after skiing for a defined distance.

Our primary experimental method is to monitor the glide variation of treated skis and dry (HSS scraped) skis, respectively. The absolute values of glide, surface whiteness and surface hydrophobicity are of secondary importance.

Skis and their preparation

We used five pairs of identical Madshus skis (www.madshus.com) with a transparent base (P-Tex® 2000, www.ims-plastics.com) and white background from the same batch. One pair was treated by stone grinding (SG) on a Tazzari RP13 (www.tazzarisport division.com). The other skis were treated using an HSS scraper.

For waxing we used the following SWIX® products: hydrocarbon wax CH8, fluorocarbon wax HF8, and perfluorocarbon powder FC8. The hot waxes were melted into the ski base three times, and they were then scraped with the plastic scraper. All the skis were prepared in the same way with a hot wax, including those that were later given a perfluorocarbon powder finish. The FC8 powder was melted on top of the scraped and brushed HF8 wax. We used a special small iron for applying the powder to ensure that good contact was made with the ski base. The high initial water contact angle (120.6°) on the running surface prepared with the powder indicated satisfactory treatment. Before measurement all skis were brushed with a Red Creek steel rotary (4000 rev min^{-1}) brush. The skis treated with FC8 were brushed with a Red Creek horsehair rotary (4000 rev min^{-1}) brush. A clean brush was used for the dry skis and another for the waxed skis.

Dirt attraction measurement

Theoretical principles

Almost all commercially produced top level X-C skis have a graphite base. Generally, the graphite base is a mixture of UHMWPE (ultra-high molecular weight polyethylene) and amorphous graphite (about 5% for the X-C skis). It is very difficult to measure the amount of dirt on the graphite base. Optically, it is not possible to see dark pollution on a black surface. Mechanically, it is hard to separate the pollution from shavings of the base material. Chemically, normal organic solvents (hydrocarbon) dissolve both the dirt and the amorphous graphite from the ski base. Therefore we have used skis with a transparent base. As mentioned above, the most common type of ski base is a mixture of UHMWPE and amorphous graphite, while the transparent base in our experiments is a pure UHMWPE. We believe that the relatively small amount of such a hydrophilic substance as amorphous graphite (Werder & Koumoutsakos, 2003) added into the ski base is hardly able to reverse the tendency of the ski running surface to attract dirt. Therefore the results of our experiments on skis with a transparent base also apply unconditionally to skis with a graphite base.

As a measurement of the rate of surface contamination build-up we chose a whiteness of the actual ski running surface. We assumed that the transparent base and white background reflect the greater part of the incident light, so that light loss must be the result of absorbance by the film of dirt. Our measurement method was grounded on the Beer–Lambert law. *The law says that the fraction of light absorbed by each layer of solution is the same.*

The absorbance A is defined as $A = \log_{10}(I_0/I_1)$, where I_0 is the intensity of the incident light, and I_1 is the intensity of the light after it has passed through the material (Fig. 1). The equation representing the Beer–Lambert law is very straightforward: $A = \varepsilon bc$, where ε is the molar absorptivity, b is the path length of the sample, and c is the concentration of the compound in solution. In our case, ε is quite constant, c is stable too, so the path length $b = h/\cos\alpha$ is a major influencing quantity, where h is the thickness of the dirt layer. The thicker dirt layer h causes greater absorbance A, and greater absorbance causes larger light loss.

In our case we observed the whiteness changing on a finite area, where the light absorption varied, depending on both the grime thickness and the grime surface scattering.

Hardware design and configuration

We chose a standard X-C ski workbench from STAR Ski Wax as a base stock (no. 4 in Fig. 2). A uEye USB 2.0 camera (no. 2) acted as an image device (www.ids-imaging.de). Two halogen bulbs (no. 1) provided a powerful light source. Each halogen lamp was directed to a point on the ski running surface that was under the camera, giving us a very strong spotlight on the observed area. Moreover, the powerful lighting allowed us to keep the lens aperture small. Furthermore, such strong collimated light considerably improved the measurement accuracy, because the surrounding sources of light (windows, etc.) have a negligibly small influence on the total luminosity.

With the Nordic Power DC 12 V power supply we achieved ±0.4% scattering in a test with a control sample, which is high enough, because the real tests showed much larger differences.

The ski was fixed to the workbench by an already mounted binding and tightly abutted on to the stopper (no. 3). Such anchoring guaranteed very accurate and repeatable positioning.

Software and configuration

As an image capturing application, we used ‘uEye Demo’, configured to capture an 8 bit monochrome image with no software correction. Each image is stored on a PC hard drive as a BMP 8 bit, grayscale file. In fact, this file is a matrix W (whiteness) with the size $m \times n$. Because the image is in grayscale mode, each matrix element $w_{ij} \in [0, 255]$, or in other words $0 \le w_{ij} \le 255$. As a whiteness value ($\overline{w}$) we simply used the arithmetical mean of all the elements in the matrix W:

$$\overline{w} = \frac{1}{mn}\sum_{i=1}^{m}\sum_{j=1}^{n} w_{ij} \qquad (1)$$

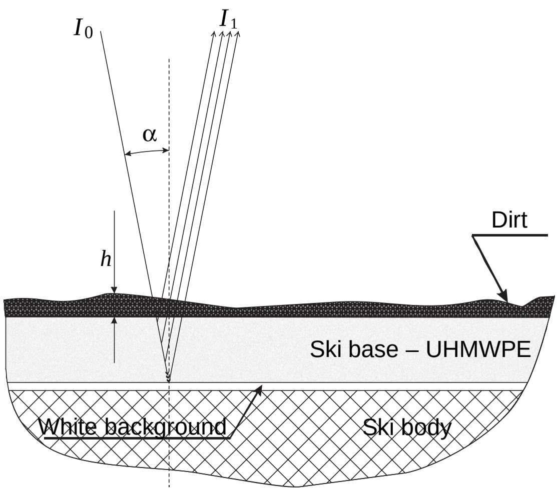

Figure 1 Beer–Lambert Law on the ski running surface

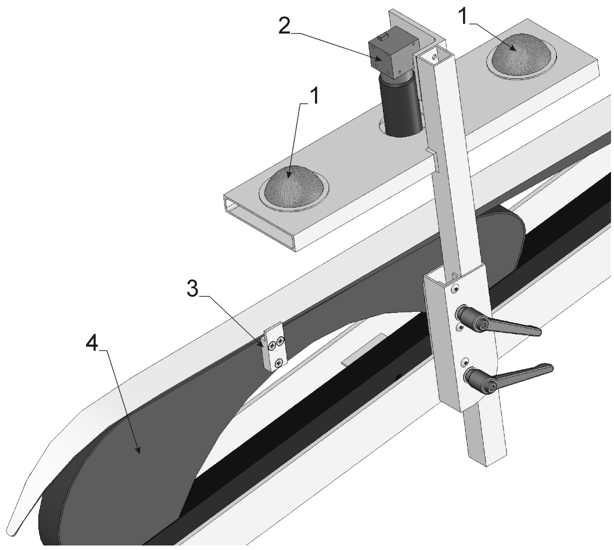

Figure 2 Experimental assembly

The processed area of the ski running surface is 1013×717 pixels (about 22.5×17.5 mm^2); therefore in our case $m = 1013$, $n = 717$ and the total number of matrix elements is $[mn]_{m=1013,\ n=717} = 726{,}321$.

Contact angle measurement

Drop-shape analysis is a convenient way to measure contact angles and thereby determine surface energy. Contact angles are measured by fitting a mathematical expression to the shape of the drop and then calculating the slope of the tangent to the drop at the liquid–solid–vapour interface line.

The running surface hydrophobicity of the ski was measured by measuring the advanced contact angle of a water drop $\theta_i = (\theta'_i + \theta''_i)/2$ where i is a frame number, θ' is a left angle, and θ'' is a right angle, as in Fig. 3. The larger the angle, the higher the hydrophobicity. A goniometer FTA125 (Fig. 4) was used to measure this angle. The pump on the goniometer was driven manually. Thirty-one images were captured during each measurement at a frame rate of 2 images per second . An arithmetical mean value was then computed for each sample:

$$\theta = \frac{1}{31}\sum_{i=1}^{31}\theta_i \,.$$

Each time we made two such measurements within the processed area of the ski running surface.

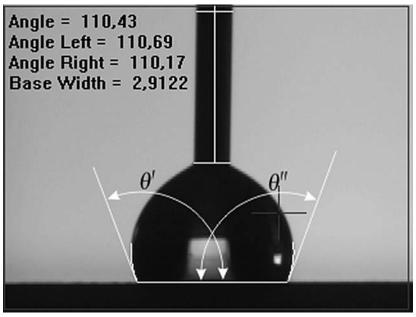

Figure 3 Contact angle measurement

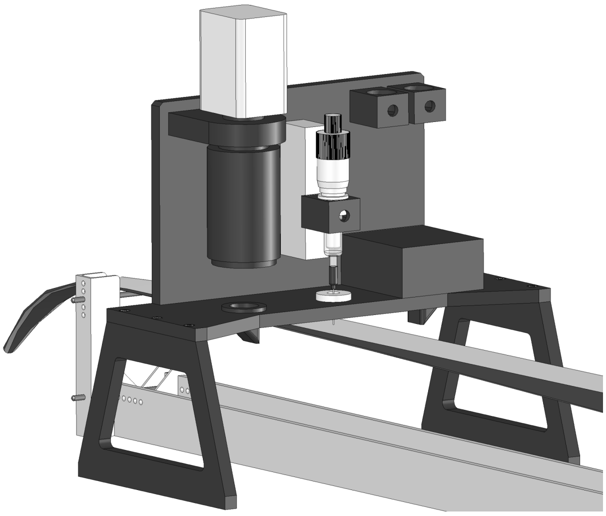

Figure 4 Ski under FTA125 goniometer for contact angle measurement (www.firsttenangstroms.com)

Field tests

The ski glide velocity was measured on a defined slope as shown in Fig. 5.

The slope is about 170 m. The first 70 m are quite steep but the 100 m clocking zone is less steep. A STAR Ski Wax digital chronometer with an infra-red sensor was used for timekeeping (www.starwax.com). This device has an accuracy of 10^{-3} s.

Here we have to define the terms used in this paper.

- *Case (test case)* – a test carried out under similar weather and snow conditions, usually on the same day (see Table 2), where four pairs of skis were involved, two pairs as reference pairs and two that were treated in a different way.
- *Glide test* – two pairs of skis were tested, a reference pair and a treated pair. Each pair of skis was tested three times and an average value was calculated. To achieve as stable results as possible, we tested the skis in the following sequence: 1–2–2–1–2–1, where 1 is a first pair in the glide test. The first pair to be tested was chosen randomly.

Figure 5 Glide test on a control slope

The testing procedure had the following steps.

1 Four pairs of skis were prepared for the experiment. Two pairs were prepared using well established methods, and two pairs were HSS scraped and remained dry.
2 Each new prepared pair was slid 5–10 m on the snow before taking the first measurements, to avoid choosing an unrepresentative basis for comparative measurements.
3 The skis were placed inside the wax cabin to become warm and dry.
4 Whiteness and hydrophobicity measurements of the ski running surface were carried out.
5 Two pairs of skis (one pair treated and one pair dry) were transported in a ski bag to the control slope. The glide test was performed. The same skier dressed in a tight race suit performed all the glide tests during the whole test case.
6 Two skiers of similar weight and skill skated together an arbitrarily chosen distance; the path length was measured using a curvometer on the map afterwards.
7 The skiers returned to the control slope. A glide test was performed.
8 These two pairs of skis were placed inside the wax cabin.
9 Another two pairs of skis (one pair treated and one pair dry) were transported in a ski bag to the control slope. The glide test was performed.
10 Steps 6–8 of the sequence were repeated with the new skis.
11 Whiteness and hydrophobicity measurements of the ski running surface of the first two pairs were carried out. It took more than an hour to perform steps 7–8, so the skis had enough time to become warm and dry.
12 Two skiers skated together an arbitrarily chosen distance on the two first pairs of skis.
13 Steps 7–8 of the sequence were repeated.

Table 1 Air and snow conditions in the test cases

Case no.	Air (0ºC)	Snow (0ºC)	Relative air humidity (%)	Snow crystal
1	–2.1	–3.8	75	Fine
2	+5.2	+0.0	63	Wet corn
3	+7.2	+0.0	59	Wet fine
4	+2.2	+0.0	73	Wet corn

Usually we had time to perform two such cycles (one cycle included steps 5–10) under stable conditions, but sometimes there was time for only one cycle. We performed nine test cases (nine days) in total, but only the last four cases were successful and are presented in this paper. An icy ski track, an unstable power supply, etc. made the work of five days inapplicable. Nevertheless, because the tests were performed as a direct concurrence between a treated pair and a reference pair, we believe that the results are reliable enough.

Results and discussion

Relationship between distance covered and running surface hydrophobicity

Only one test was carried out at a temperature below 0°C. On wet snow, grime covers the ski gliding surface extremely quickly and contact angle measurement does not produce any useful values. When the ski running surface is completely covered by grime, the thickness of the film has little effect on hydrophobicity. For this reason none of the results showed a significant dependence between the distance covered and the running surface hydrophobicity. We need to perform more tests under cold conditions.

Relationship between distance covered and running surface contamination

In Fig. 6 and in Table 2, we see how quickly the ski running surface became darker. Case 1 is not shown

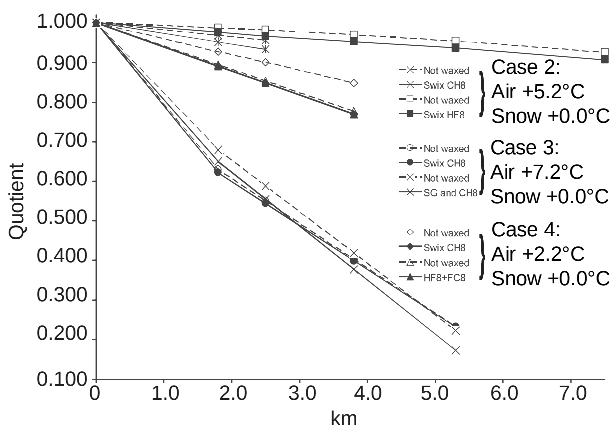

Figure 6 Comparative average grayscale of running surface sample area and distance covered

Table 2 Comparative average grayscale of running surface sample area and distance covered (NW is an abbreviation for 'not waxed')

Case and wax	Distance covered (km)					
	0.0	1.8	2.5	3.8	5.3	7.5
2 NW	1.000		0.957			
2 CH8	1.000		0.933			
2 NW	1.000		0.983			0.926
2 HF8	1.000		0.966			0.907
3 NW	1.000	0.630			0.233	
3 CH8	1.000	0.623			0.232	
3 NW	1.000	0.679			0.223	
3 SG + CH8	1.000	0.650			0.172	
4 NW	1.000			0.848		
4 CH8	1.000			0.770		
4 NW	1.000			0.777		
4 HF8 + FC8	1.000			0.770		

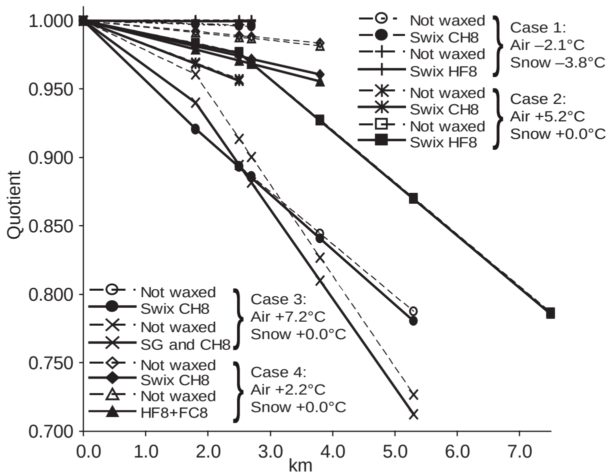

Figure 7 Comparative gliding velocity on the test slope and distance covered

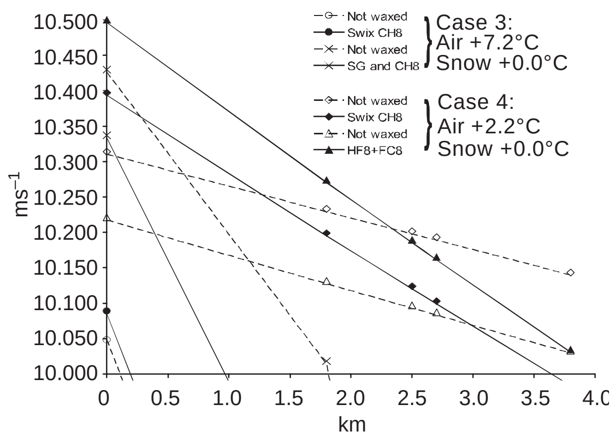

Figure 8 Average gliding velocity on the test slope and distance covered (close-up)

here, because the grayscale measurement was not reliable (AC power supply). In this paper the comparative value is presented as a ratio between a new absolute value and an initial absolute value $D_{comp}(s_i) = D(s_i)/D(0)$ where $D_{comp}(s_i)$ is a comparative value of a parameter of a certain pair of skis, $D(0)$ is an initial absolute value of the parameter (initial grayscale or initial velocity), $D(s_i)$ is the next measured value of the parameter (grayscale or velocity), s_i is the distance covered, and therefore the initial comparative value $D_{comp}(0) = 1$. The dashed lines correspond to the dry (control) pairs of skis; the solid lines correspond to the waxed skis. Our result showed that waxed ski base surfaces always became dirty sooner than unwaxed ones; the next step was to examine how consistently the gliding velocity of the skis conformed to this tendency.

Fig. 7 shows that waxed skis lose their velocity sooner than unwaxed ones. Even skis prepared with high-tech perfluorocarbon powder FC8 (–▲–) lose their gliding ability sooner than dry skis (–△–). But is it possible that the initial glide of waxed skis is so much greater that the unwaxed skis cannot catch up with them within a realistic distance?

We see in Fig. 8 and Table 3 that waxed skis have a higher initial velocity (except case 2 CH8), but after quite a short distance this advantage disappears. Perfluorocarbon powder FC8 (–▲–) keeps its

Table 3 Average gliding velocity (m s^{-1}) on the test slope and distance covered (NW is an abbreviation for 'not waxed')

Case and wax	Distance covered (km)						
	0.0	1.8	2.5	2.7	3.8	5.3	7.5
1 NW	9.664			9.623			
1 CH8	9.696			9.664			
1 NW	9.673			9.675			
1 HF8	9.679			9.673			
2 NW	12.814		12.265				
2 CH8	12.747		12.186				
2 NW	13.274		12.967				10.445
2 HF8	13.274		12.960				10.427
3 NW	10.052	9.250				7.916	
3 CH8	10.089	9.292				7.876	
3 NW	10.430	10.018				7.579	
3 SG+CH8	10.337	9.717				7.366	
4 NW	10.314				10.144		
4 CH8	10.397				9.987		
4 NW	10.221				10.033		
4 HF8+ FC8	10.500				10.034		

Figure 9 Unwaxed ski base after 3.8 km (case 4)

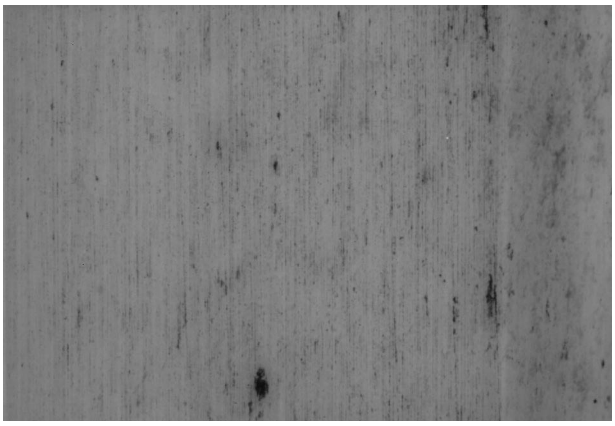

Figure 10 Waxed with Swix® CH8 ski base after 3.8 km (case 4)

advantage longer (≈ 3.8 km) than CH8 (–♦–) (≈ 2.35 km), but still not for very long. In Figs. 9 and 10 we can see a difference in contamination.

Some types of ski treatment and certain snow conditions may reduce the advantage of the waxed skis considerably. In Table 4 the results of three glide tests are presented that compare stone ground skis (SG) treated with CH8 and dry skis (case 3).

Each test run there and back involves skiing about 250 m, and already during the second descent we could see that the waxed skis had started to glide more slowly than the dry ones. The turning point lies around 200 m in this case.

Running surface contamination

Because all our tests were performed under quite unabrasive snow conditions, the impairment of gliding ability cannot be explained by ski running surface deterioration, but it can be explained by ski running surface contamination. Obviously, the distance (turning point) when waxed skis lose their advantage over unwaxed is not a constant, but is influenced by many variables. Here is a theoretical solution to the problem:

Table 4 Extreme example – turning point seen during the second descent on a 100 m slope

Descent no.	Time of descent (s)	
	No. 60 unwaxed	No. 59 SG and CH8
1	9.567	9.529
2	9.573	9.716
3	9.623	9.778

$$\int_0^l f_w(s)\,\mathrm{d}s = \int_0^l f_d(s)\,\mathrm{d}s \qquad (2)$$

where l is the turning point at which the advantage of waxed skis changes into a disadvantage, $f_w(s)$ is the frictional resistance force of the waxed skis, $f_d(s)$ is the frictional resistance force of the dry (unwaxed) skis, and s is the distance covered. It would be possible to find a general expression for $f_w(s)$ and $f_d(s)$ based on a larger amount of similar experiments and then approximately solve equation 2. In Fig. 11 we present a graphic illustration of the general problem.

In spite of the fact that perfluorocarbon powder is commonly described as a dirt repellent wax, our experiment shows that a fresh HSS scraped running surface is more dirt repellent; these results indicate that a new waxing philosophy is needed. Moreover, for

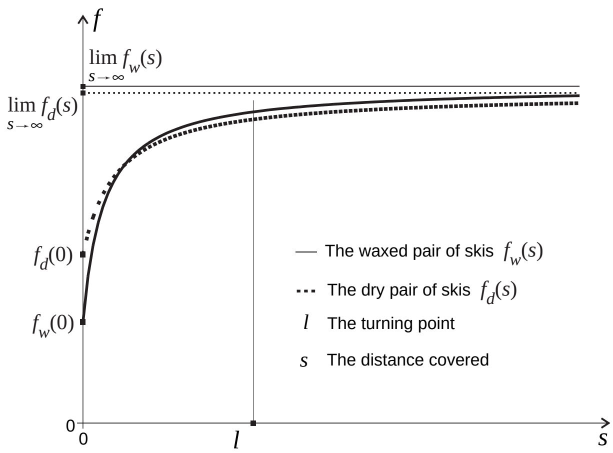

Figure 11 Graphic illustration of the general glide–distance problem

Table 5 Average grayscale of running surface sample area and distance covered, separately for the left (L) and for the right (R) skis (NW is an abbreviation for 'not waxed')

Case and wax		Distance covered (km)						
		0.0	1.8	2.5	2.7	3.8	5.3	7.5
2 NW	L	196.01		185.35				
	R	192.77		186.57				
2 CH8	L	192.03		177.44				
	R	184.75		174.19				
2 NW	L	188.49		182.68				172.28
	R	192.41		191.57				180.46
2 HF8	L	197.71		190.39				178.60
	R	195.18		189.25				177.58
3 NW	L	188.38	130.36				68.71	
	R	186.22	123.95				14.97	
3 CH8	L	182.84	122.24				66.39	
	R	177.42	102.04				17.11	
3 NW	L	183.28	131.52				69.76	
	R	188.33	102.43				16.90	
3 SG+CH8	L	186.28	124.21				49.78	
	R	178.64	113.01				13.16	
4 NW	L	179.90				146.60		
	R	176.16				148.65		
4 CH8	L	173.94				135.46		
	R	168.60				122.31		
4 NW	L	170.20				135.48		
	R	175.34				126.85		
4 HF8+ FC8	L	181.29				140.66		
	R	178.55				130.14		

practical work in a real competition environment, technicians do not need complicated equipment for measuring friction to define point l.

In our experiment, there is a Pearson's correlation (Weisstein, 1994) between the darkening of the ski running surface and the slowing of the skis from as high as 0.958 to 0.998, depending on the case. We can use it to predict an increase in friction as a function of darkening. Therefore the technicians need only to test the glide once to obtain the initial glide velocity $V_d(0)$, $V_w(0)$, and the whiteness of the running surfaces of the waxed and unwaxed skis three times to obtain $w_d(0)$, $w_w(0)$, $w_d(s_1)$, $w_w(s_1)$, $w_d(s_2)$ and $w_w(s_2)$ (see equation 1), where subscripts d and w represent unwaxed (dry) and waxed skis, and s_1 and s_2 are suitable distances, with $s_1 < s_2$. Next, they can define the actual instances of $f_w(s)$, $f_d(s)$ and find out the turning point l; the magnitude of l indicates which races they should ski on unwaxed skis and which on waxed.

Running surface treatment

It is important to understand that the two interacting surfaces, the base and the snow, do not need any additional lubricant other than that which is always present – namely water. The optimal roughness, high hydrophobicity and dirt-repellent capacity are sufficient for a perfect glide.

Stone grinding decreases the hydrophobicity of the ski running surface and contributes significantly to grime attraction as explained by Kuzmin & Tinnsten (2005), which is not a good way to create roughness on the ski running surface. Perfluorocarbon increased the hydrophobicity of the ski running surface, but perfluorocarbon is much softer than UHMWPE and has high tenacity. Obviously, the augmentation of softness and tenacity of the outer layer of the ski base increases dirt absorption on the ski running surface. All the waxes in our experiment were softer than the ski base.

Table 6 All gliding velocity measurements (m s^{-1}) on the test slope and distance covered (NW is an abbreviation for 'not waxed')

Case and wax	**Distance covered (km)**						
	0.0	**1.8**	**2.5**	**2.7**	**3.8**	**5.3**	**7.5**
1 NW	9.671			9.675			
	9.699			9.591			
	9.654			9.623			
	9.656						
1 CH8	9.658			9.651			
	9.701			9.664			
	9.731			9.682			
	9.692						
1 NW	9.679			9.682			
	9.656			9.660			
	9.673			9.675			
1 HF8	9.630			9.615			
	9.679			9.677			
	9.690			9.673			
2 NW	13.116		13.116				
	12.561		12.561				
	12.776		12.776				
2 CH8	12.765		12.297				
	12.744		12.268				
	12.732		11.996				
2 NW	13.289		13.243				10.479
	13.339		12.867				10.453
	13.194		12.801				10.403
2 HF8	13.270		13.055				10.484
	13.321		12.985				10.381
	13.233		12.842				10.417
3 NW	10.149	9.271				7.419	
	10.003	9.198				7.993	
	10.004	9.282				8.398	
3 CH8	10.289	9.308				7.603	
	10.040	9.321				7.955	
	9.943	9.248				8.087	
3 NW	10.453	10.012				7.398	
	10.446	10.007				7.600	
	10.392	10.034				7.748	
3 SG+CH8	10.494	9.799				7.014	
	10.292	9.799				7.510	
	10.227	9.556				7.602	
4 NW	10.200				10.216		
	10.333				10.115		
	10.412				10.101		
4 CH8	10.370				10.052		
	10.417				10.003		
	10.405				9.908		
4 NW	10.178				10.078		
	10.251				10.005		
	10.233				10.017		
4 HF8+ FC8	10.501				10.107		
	10.511				10.007		
	10.489				9.990		

Perfluorocarbon powders do not increase hardness and do not decrease tenacity (probably the contrary) of the outer layer of the ski running surface. Therefore, such glide waxes do not increase the dirt-repellent properties. As shown in Kurtz (2004), the ski base material, UHMWPE, is a material with a great potential. UHMWPE has a low friction coefficient and good mechanical properties. Therefore we believe that the development of new ski bases made of UHMWPE with hard hydrophobic additives (e.g. fluoroplastics) and the development of a bristle-free alternative to stone grinding is the most promising way to improve ski glide. The development of a heterogeneous ski running surface with microparticles of hard hydrophobic additives is especially interesting. The surface created by such a mixture may considerably reduce capillarity drag.

Conclusion

- Skis treated by any established waxing procedure lose their glide ability faster than the reference skis (dry skis).
- Dirt absorption influences gliding ability negatively.
- Stone ground waxed running surfaces absorb more dirt than HSS scraped waxed running surfaces.
- The peak pollution level (thickness) was higher on the waxed skis than on the reference skis;
- Running surface darkening and skis slowing down correlate (Pearson product moment correlation) sufficiently closely.

Future work

- To perform similar experiments under cold weather conditions (below 0°C).
- To obtain skis produced with a transparent base with a different molecular weight, and continue similar experiments to test the relationship between the hardness of the ski base, the hardness of the glide wax and the running surface contamination.
- To design a new experimental setup to meassure the friction (glide) of skis without a skier, as aerodynamic resistance is a great source of inaccuracy.

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Paper III

The contamination, wettability and gliding ability of ski running surfaces

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1 Introduction

The ski running surface (ski base) of the overwhelming majority of modern skis is made using ultra high molecular weight polyethylene (UHMWPE). This material ($C_{2n}H_{4n}$) is very similar to ski glide waxes (acyclic saturated hydrocarbons - C_nH_{2n+2}). The essential distinction between these two substances lies in the length of the molecular chain. In view of this, it is interesting to examine how great an advantage in long distance skiing is obtained by preparing the running surface of skis with glide wax.

It is common knowledge that minimizing dirt on the running surface of skis improves the ski glide under all snow conditions. Under cold conditions (when there is a lack of lubrication) water slides more readily on hydrophobic surfaces, while in the case of excess lubrication, there is less capillary force on a hydrophobic ski base. In view of this, it is clear that a hydrophobic surface would be advantageous in all snow conditions (Colbeck, 1992). We have therefore chosen to examine the interdependence of the following factors: the ski glide, dirt accumulation and wettability of the ski running surface in relation to the distance covered.

2 Methods

The skis and their preparation – Our general research strategy in this study is to always have a clear reference point. Many scientific papers and many practical manuals in the field of XC ski waxing suffer from the lack of such a reference point. Our literature review discovered only one study that had investigated XC ski glide by comparing steel scraped skis with stone ground skis (Bergersen et al., 1994). Each stone ground ski running surface has quite a complex machined pattern with improbable repeatability. A number of hot wax treatments and the softness of the wax (waxes) result in a ski running surface with unpredictable characteristics. It is therefore difficult to compare the results of an investigation involving only stone ground skis are difficult to compare with the results of further tests in the same area. We therefore decided to use skis treated (scraped / peeled) with a tool that we designed especially for this purpose.

The reference skis were always fresh scraped, while the other skis were treated with various suitable glide waxes. Before the tests all the skis were brushed with a Red Creek steel rotary (3000 r/min) brush. The skis treated with SWIX® FC8 were brushed with a Red Creek horsehair rotary (3000 r/min) brush. One clean brush was used for the dry skis and another for the waxed skis.

Almost all commercially produced top level XC skis have a “graphite” base. Generally, the “graphite” base is a mixture of UHMWPE and one of the allotropes of carbon – amorphous carbon (about 5% for the XC skis). It is very difficult to measure the amount of dirt on a “graphite” base. We therefore used 4 pairs of identical Madshus skis from the same batch with a transparent base (a pure IMS P-Tex® 2000) glued onto a white background. We believe that the relatively small amount of such hydrophilic (Werder et al., 2003) and weakening additives (www3.gurit.com/pdfs/running_bases/ Extruded_and_press-sintered_running_bases.pdf, page 10, Table 2. Electra® ≡ carbon addition), as amorphous graphite, is hardly likely to reverse the tendencies observed. The results of our experiments on skis with a transparent base therefore also apply unconditionally to skis with a “graphite” base.

Field tests - The slope was about 170 m long. The first 70 m were quite steep but the 100 m clocking zone was less steep. A STAR Ski Wax (www.starwax.com) digital chronometer with an infra-red sensor was used for time-taking. This device has a resolution of 10^{-3} s. Our comparative glide test was performed as follows: Two pairs of skis were tested, a reference pair and a waxed pair. Each pair of skis was tested three times and an average value was calculated. To achieve as stable results as possible, we tested the skis in the following sequence: 1-2-2-1-2-1, where 1 is a first pair in the glide test. By this procedure we could ensure a short time gap (100 m slope + braking distance + U-turn + uphill + pair change ≈ 150 s) between the tests of two different pairs, so we could assume that there would not be any significant changes in the snow properties during such a short time period. The first pair to be tested was chosen randomly. The glide test was repeated after simultaneous skiing on both pairs of skis. The distance covered was measured using a GPS receiver Garmin Forerunner® 201. Twenty-seven such tests were performed, which involved 162 descents of the slope.

Tests were performed in March-April 2005 under wet snow conditions. The average air temperature was 5.5°C, varying from 2.2 to 7.2°C. Tests were performed under dry snow conditions in March 2006. The average snow temperature was -7.6°C, varying from -3.8 to -10.8°C.

Dirt attraction measurement - We chose a whiteness test of the actual ski running surface as a measurement of the rate of surface contamination build-up (Fig. 1). We used "uEye Demo" (www.ids-imaging.de) as an image capturing application. The application was configured to capture an 8-bit monochrome image with no software correction. Each image was stored on the PC hard drive as a BMP 8-bit, greyscale mode file. In fact, this file is a matrix $W = (w)_{ij}$ (whiteness) with the size $m \times n$. Because it is a greyscale image, each matrix element $0 \le w_{ij} \le 255$. As a whiteness value ($\bar{w}$) we simply used the arithmetical mean of all the elements in the matrix W: $\bar{w} = \frac{1}{mn}\sum_{i=1}^{m}\sum_{j=1}^{n} w_{ij}$. The size of the area of the ski running surface under observation is 1013×717 pixels (about $22{,}5 \times 17{,}5$ mm²).

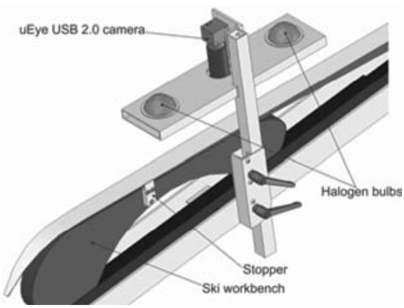

Fig. 1: Dirt attraction measurement - Experimental assembly

Wettability measurement - The running surface hydrophobicity of the ski was measured by measuring the advanced contact angle of a water drop $\theta = (\theta_i' + \theta_i'')/2$ where *i* is a frame number, *θ′* is a left angle, and *θ″* is a right angle, as in Fig. 2.

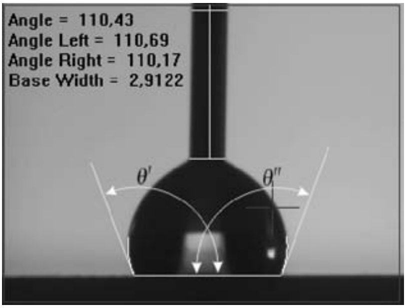

Fig. 2: Contact angle measurement

A goniometer FTA125 (www.firsttenangstroms.com) was used to measure this angle. 31 images at a rate of 2 frames (images) per second were captured during each measurement. An arithmetical mean value was then computed for each sample: $\theta = \frac{1}{31}\sum_{i=1}^{31}\theta_i$. We made two such measurements within the observed area of the ski running surface on each test.

3 Results

The gliding abilities of the skis tested were very similar, but not identical. We therefore calculated comparative values for the waxed skis $C(s_i) = A_w(s_i)/A_r(s_i)$, where $A_w\,(s_i)$ is an absolute value of a parameter of a waxed ($A_r\,(s_i)$ - reference) pair of skis, and s_i is the distance covered. Later on we normalized the comparative values $N(s_i) = C(s_i)/C(0)$, therefore $N(0) = 1$. If $N(s_i) < 1$, waxed skis lose a certain (*N*) quality faster than the reference skis after s_i km skiing, and vice versa. By linear interpolation, flat (constant) extrapolation and averaging all the normalized comparative values we can present the principal trend much more clearly: $\bar{N}(s_i) = \frac{1}{m}\sum_{j=1}^{m} N_j(s_i)$, where j is a test series number, and m is the total amount of series.

Under wet snow conditions, grime covers the ski gliding surface extremely quickly and the contact angle measurement does not produce any useful values. On the other hand, under dry snow conditions, grime covers the ski gliding surface insignificantly and the greyscale measurement lies within the margin of error. Consequently, we have focused on the relation between dirt/glide (Fig. 3) under wet snow conditions and wettability/glide (Fig. 4) under cold dry snow conditions.

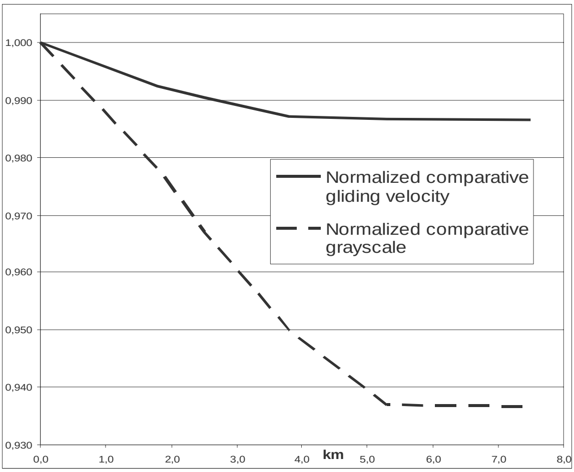

Fig. 3: Velocity and whiteness relative to distance on wet snow

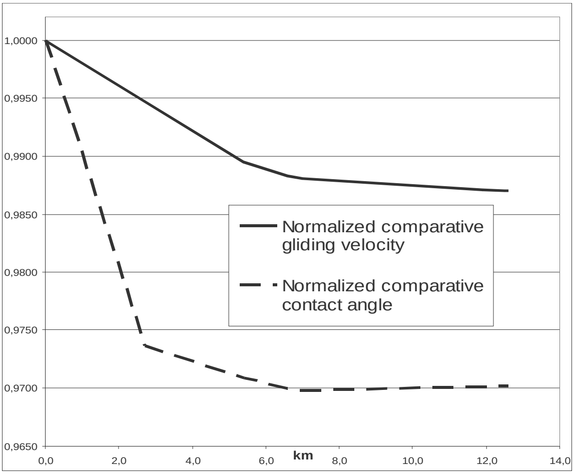

Fig. 4: Velocity and contact angle relative to distance on dry snow

4 Discussion

From our results we can draw the conclusion that the waxed skis lose their glide ability faster than the reference skis (unwaxed scraped skis).

Wet snow - The softness and tenacity of the outer layer of the waxed ski base increases dirt absorption on the ski running surface. On the other hand fresh scraped UHMWPE is a very hydrophobic (Kuzmin and Tinnsten, 2005) hard, resilient material (Kurtz, 2004) which has excellent glide and stain-repellent properties.

Dry snow - (D.C. Sun, 1996) described the accelerated ageing of UHMWPE at a heating rate of 0.6°C/min to 80°C for either 11 or 23 days. This was considered to be the equivalent of 4 to 6 or 7 to 9 years of ageing, respectively. (Widmer, 2002) showed a significant decrease in the surface hydrophobicity of UHMWPE after oxygen plasma treatment. From the above we can see that heat impairs useful properties of the ski base.

Our hypothesis is the following: that the glide wax quickly (300-500 m) wears out on the cold dry snow, and subsequently the ski running surface which has been damaged by the waxing iron (150-160°C) then comes into contact with the snow.

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Paper IV

ESTIMATION OF DIRT ATTRACTION ON RUNNING SURFACES OF CROSS-COUNTRY SKIS.

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Methods for analysing impurities in snow are used in glaciology and ecological studies. However, the relationship between the dirt accumulation on the ski running surface and the concentration of pollution in the snow is not straightforward, since the interaction between the top layer of snow in the ski track and the ski running surface is responsible for the dirt accumulation on the running surface. In this paper the dirt film accumulated on the gliding surface is studied. A number of XC skis with a transparent base and a white background were examined after undergoing different treatments. Measurements of the whiteness of the running surface of the skis were carried out and glide tests were performed. The measurements and tests were repeated after skiing various distances on a ski track under varying snow conditions. The following observations were made during the study: - The experimental setup could deliver a reliable value of the whiteness of the ski running surface. We achieved 0,3% standard deviation in a test on a control sample; - The correlation between the ski glide and the amount of dirt is obvious and significant.

1 Introduction

The importance of keeping the ski running surface clean from any pollution in order to minimize snow-ski friction is mentioned in a number of scientific papers. Evidently, the amount of dirt that accumulates on the ski running surface is heavily dependent on the concentration of pollution in the snow.

However, our literature review discovered no studies that had investigated the contamination factor of the ski base. The lack of such an investigation may, for instance, explain a conclusion regarding the ski glide on wet snow in (Slotfeldt-Ellingsen and Torgersen, 1982). The authors believe that glide wax wears down much faster on wet snow, than on cold, dry snow.

2 Methods

2.1 General approach

Our choice of tools, wax, skis and the procedure for ski preparation was based on direct application to cross-country (XC) skiing. Our primary experimental method was to monitor the glide variation in the case of treated skis and dry (HSS scraped) skis respectively. The absolute values of glide and surface whiteness are of secondary importance.

Theory

Almost all commercially produced top level skis have a graphite base. Generally, the graphite base is a mixture of UHMWPE (ultra-high molecular weight polyethylene) and amorphous graphite (about 5%). It is very difficult (perhaps impossible) to measure the amount of dirt on the graphite base. Optically, it is not possible to see dark pollution on a black surface. Mechanically, it is hard to separate the pollution from shavings of the base material. Chemically, normal organic solvents (hydrocarbon) dissolve both the dirt and the amorphous graphite from the ski base. Therefore, we have used skis with a transparent base. Such skis were usual 15 years ago. As mentioned above, the most common type of ski base is a mixture of UHMWPE and amorphous graphite, while the transparent base in our experiments is made of pure UHMWPE. We believe, such a small amount of graphite does not significantly affect the dirt attraction pattern. Therefore, the results of our experiments on skis with a transparent base may also be applied to skis with a graphite base.

As a measurement of the rate of surface contamination build-up, we chose the whiteness rate of the ski running surface. We assumed that the transparent base and white background reflect the greater part of the incident ray, so any light loss must be the result of absorbance by the film of dirt. Our measurement method was grounded on the Beer-Lambert Law. *The Law says that the fraction of light absorbed by each layer of solution is the same.*

The absorbance A is defined as $A = \log_{10}(I_0 / I_1)$, where I_0 is the intensity of the incident light, and I_1 is the intensity after passing through the material. This is shown in (Figure 1).

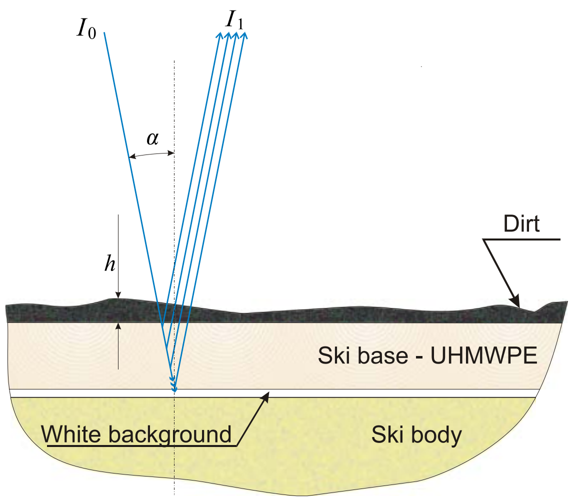

Figure 1. Beer-Lambert Law and the ski running surface

The equation representing the Beer-Lambert Law is very straightforward: $A = \varepsilon bc$, where ε is the molar absorptivity, b is the path length of the sample, c is the concentration of the compound in solution. In our case, ε is quite constant, c is stable too, so the path length $b = h / \cos\alpha$ is the major influencing factor, where h is the thickness of the dirt layer. The thicker the dirt layer, the greater the absorbance A, and the larger the light loss. In our real case we observed the whiteness change on a finite area, where the light absorption varied depending on both the grime thickness and the grime surface scattering.

Experimental setup

As illustrated in (Figure 2) a uEye USB 2.0 camera acted as an image-capturing device. Two halogen bulbs provided a powerful light source. Each halogen lamp was directed to a point on the ski running surface under the camera, which gave us a very strong spotlight on the observed area. Moreover, the powerful lighting allowed us to keep the lens aperture small. Furthermore, such strong collimated light considerably improved the measurement accuracy, because the surrounding sources of light (windows, etc.) had a negligibly small influence on the total luminosity.

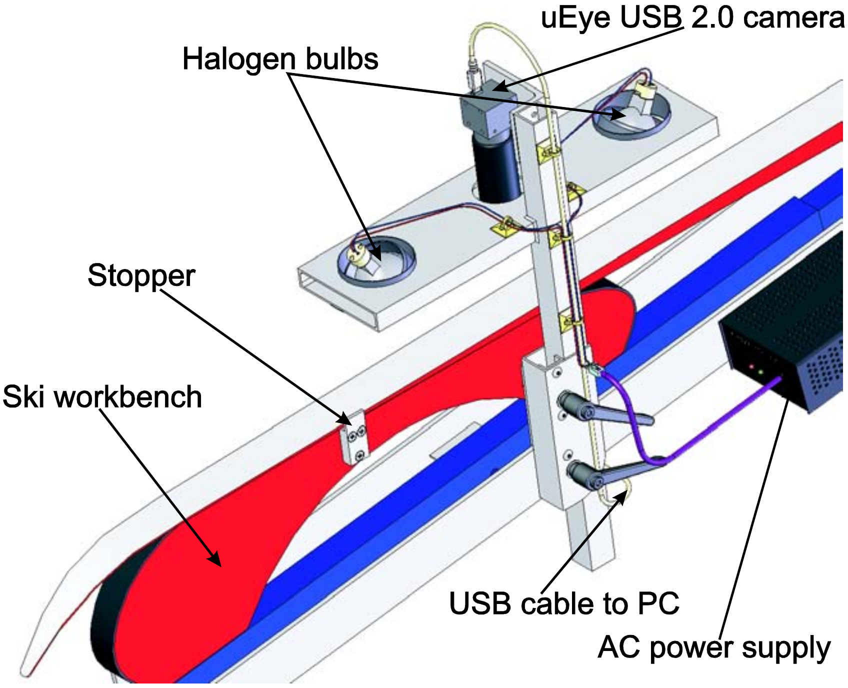

Figure 2. Dirt attraction measurement - Experimental setup

We used a direct current (DC) 12 V power supply with improved accuracy to eliminate the instability that may occur when using the standard alternating current (AC) 12 V from the mains power supply.

The ski was fastened to the workbench by a pivot joint in the binding, which had been mounted in advance. In addition the ski was tightly abutted on to the stopper. Such anchoring guaranteed a very accurate and repeatable positioning.

We used an "uEye Demo" as an image-capturing application The uEye Demo was configured to capture a 8 bit monochrome image with no software correction. The processing line is presented in (Figure 3). Each image was stored on the PC hard drive as a BMP 8-bit, grayscale mode file. In fact, this file is a *W* (whiteness) matrix of the size $m \times n$. Because the image is in a grayscale mode, each matrix element $w_{ij} \in [0, 255]$.

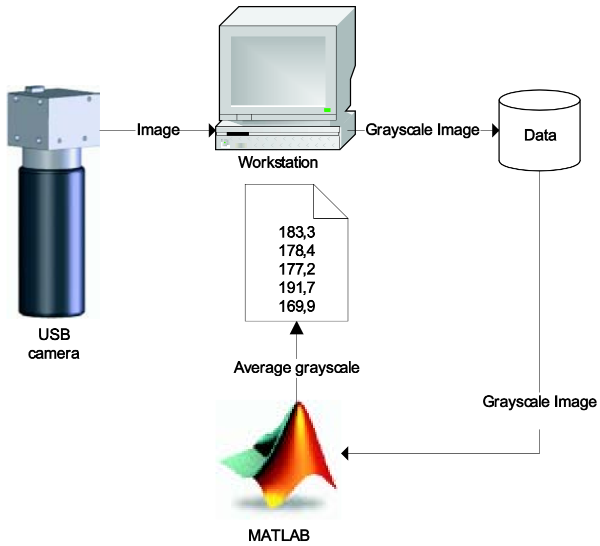

Figure 3. Analysis of observations

As a whiteness value (*w*) we simple used the arithmetical mean of all the elements w_{ij} in the matrix *W*, $w = \frac{1}{mn}\sum_{i=1}^{m}\sum_{j=1}^{n} w_{ij}$. To realize this equation we applied a MATLAB procedure `mean2` to our M-file for statistical treatment of the experimental data. We only processed the flat area of the image, which does not include the ski groove. The processed area of the ski running surface is 1013 × 717 pixels large (about 22,5 × 17,5 mm²) (Figure 4). The area is located just in front of the pressure peak. To minimize the wearing-off effect on the inside half of ski, we marked all the skis as either left (*l*) or right (*r*) in all the pairs, and the whiteness value was calculated as $w = 1/2(w_l + w_r)$.

Figure 4. The processed area of the ski running surface

3 Results

If the ski was placed in the experimental setup for a long time, the processed area became warmer and warmer, and *w* increased. However, when we measured the whiteness of all the skis, we measured the skis at regular intervals so that all the skis were kept at a similar temperature. In this way we obtained a quite stable measurement. In (Figure 5) the results of 40 measurements of the same sample are presented with a two-minute interval between measurements to avoid warming-up the sample. The mean whiteness was 132,8, and the standard deviation was 0,412.

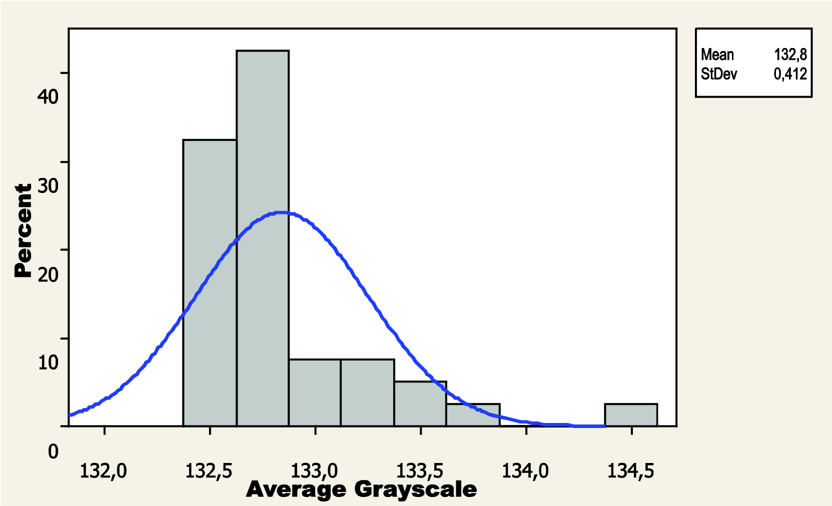

Figure 5. Distribution of the average grayscale fitted as a Gaussian Distribution

The gliding abilities of used skis are very similar, but not, however, exactly equal. We therefore calculated comparative values for the waxed skis $C(s_i) = A_w(s_i) / A_r(s_i)$, where $A_w(s_i)$ is the absolute value of the parameter of a pair of treated skis, $A_r(s_i)$ of a pair of reference skis, and s_i is the distance covered.

Later on we normalized the comparative values $N(s_i) = C(s_i) / C(0)$. Therefore $N(0) = 1$, and if $N(s_i) < 1$, then the waxed skis lose some (N) quality faster than the reference skis after s_i km skiing, and vice versa. By linear interpolation, flat (constant) extrapolation and averaging of all the normalized comparative values we may present the principal trend much more visually as follows: $\bar{N}(s_i) = \frac{1}{m}\sum_{j=1}^{m} N_j(s_i)$, where j is a test series number, and m is the total amount of series.

The results of the comparative glide test on wet snow (for a complete description of a test procedure see (Kuzmin and Tinnsten, 2006) shows a good correlation between whiteness and velocity (Figure 6). On the other hand, on cold, dry snow grime covers the ski gliding surface utterly insignificantly, and the grayscale measurement lies inside the margin of error in the test results.

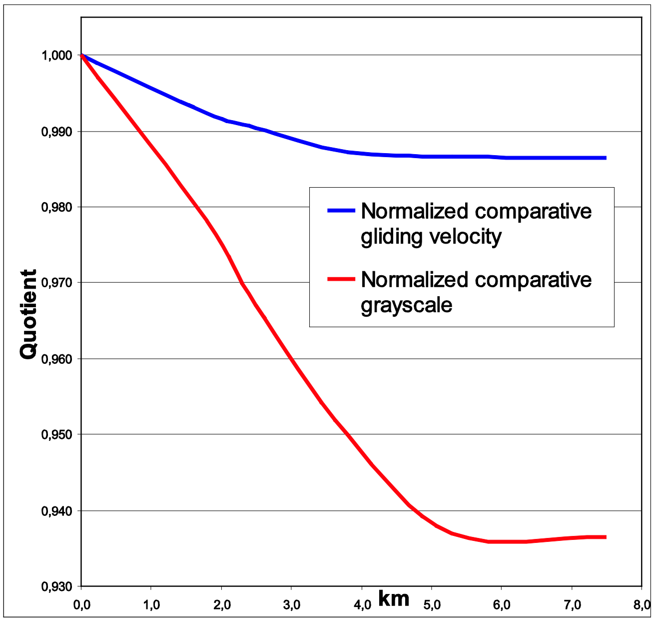

Figure 6. Velocity and whiteness relative to distance on wet snow

4 Discussion

From our results we can draw the conclusion that the above-stated method to estimate the dirt attraction on the running surface of XC skis works precisely enough under wet snow conditions, but not under cold snow conditions.

Acknowledgements

The authors are grateful to Gunnar Bjertnæs and Svein Inge Holtesmo from Madshus AS for the sample skis with a transparent base and for the fruitful discussions we have had, to Sven-Gunnar Johansson - Backcountry Equipment AB for the comfortable ski boots, to Torbjørn Ragg - Rottefella AS for the high-tech ski bindings and to the staff at Östersund's Ski Stadium for always preparing the ski track perfectly.

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Paper V

Hot glide wax treatment and the hardness of the ski running surface.

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TOPICS: Ski & other Winter Sports; Materials; Performance Sports;

Abstract: In the cross country skiing community, hot wax treatment of the ski running surface (SRS) is used in order to influence the surface hardness of the skis in relation to the hardness of the snow crystals. This is discussed in a number of scientific papers and recommended in almost every ski waxing manual. The general idea is to decrease (soften) the surface hardness by the use of a soft glide wax treatment for wet snow conditions and to increase (harden) the hardness of the surface by a hard (synthetic) glide wax treatment for cold, dry snow conditions. The question is; does the hot glide wax treatment of the ski running surface influence the surface hardness? And if so, in what way?
In our experiment, ski base specimens of UHMWPE (transparent and "graphite") were treated with ski glide wax. Half of the specimens were treated with soft yellow glide wax, and half with hard green glide wax. After the wax treatment, the surface hardness (Shore D) was measured with a durometer. The study revealed that: both soft glide wax and hard glide wax treatment make the SRS softer; after a long immersion (12 hours) in the bath of melted glide wax, both the hardness of the specimens treated with soft glide wax and of those treated with hard glide wax decreased significant. Conclusion: The hot wax treatment of the SRS with available glide waxes cannot make the SRS harder than it was initially (unwaxed).

Key words: ski base, glide wax, hardness.

1- Introduction

The application of glide wax is still an art. Skiers and technicians have enormous collections of glide waxes. Through years of experience, skiers and technicians have tried to learn which products work best for specific snow conditions. However, very often (too often) there is only a weak correlation between the effort expended and the result.

In our opinion, the huge number of unproved theories regarding ski glide preparation is a primary obstacle to achieving the optimum ski glide. In (Karlöf et al., 2005) we can read that: "The purpose of ski wax is to reduce adhesion forces, to reduce surface tension, and to prevent ploughing by adjusting the slider base hardness to the hardness of the snow. For example, by applying harder waxes the slider surface hardness is increased…", but this paper does not include any comparative data regarding the hardness of the ski base and the glide waxes. Another work that examines the effects of the hardness of glide wax is (Rogowski et al., 2005). However, this paper does not either present the comparative hardness of waxed and unwaxed ski bases.

The general opinion, which we agree with, is that the hardness of the ski running surface (SRS) appreciably influences the ski glide properties on the snow surface. However, our literature review discovered no studies that had investigated the effects of hot wax treatment on SRS hardness. Moreover, in our literature review of another winter sport event, speed skating, we did not find similar arguments regarding "various running surface hardnesses for various ice hardnesses". The development of skate blade material consists in achieving a steady increase in hardness, regardless of the hardness of the ice, see for instance (Yang, 1988) and (Kuehmann et al., 2002).

2- Methods

2.1 – General approach

The choice of tools, wax, ski base material and the procedure for SRS preparation was based on direct application to cross-country (XC) skiing. Our primary aim with the study was to monitor the changes in the hardness of the SRS in relation to different periods of test specimens treating (dipping) in molten glide wax.

2.2 – Materials

The ski base material we used is made by Gurit (Ittigen) AG (former IMS Kunststoff AG). For our samples we used both transparent base (TB) and “graphite base” (GB). The transparent base samples were made from P-Tex® 2000; a pure ultra-high molecular weight polyethylene (UHMWPE). The “graphite base” samples were made from P-Tex® 2000 Electra®. The “graphite base” is a mixture of UHMWPE and amorphous graphite (black). The specimens were machined as shown in Figure 1.

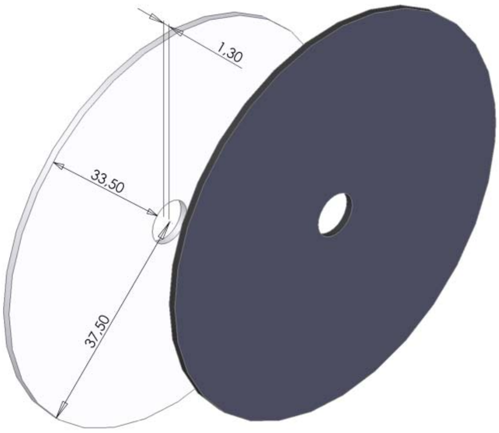

Figure 1: ski base specimens

The glide waxes used in our experiment were made by STAR SKI WAX (Italy). We employed only two waxes: NA2 (0°/-4°C), which is the softest, and NA8 (-8°/-20°C), which is the hardest in the NA range.

2.3 – Apparatus

To melt the glide waxes and to keep them at a temperature of 119° ± 2°C during the treatment we used a Serenit® Electric burner. To control and record the temperature we employed a CENTER 306 Data Logger Thermometer, which has 0,1°C resolution ± 0,3% accuracy. To measure the hardness we employed a Shore® S1 Portable Digital Durometer (Instron) with 0,1 resolution.

2.4 – Experimental setup and carrying out

1) The initial hardness of the transparent base and the “graphite base” were measured; 2) We melted two glide waxes (NA2 and NA8) in two separate stainless steel vessels on two electric burners. Both burners were adjusted to sustain a temperature of 119°C; 3) The specimens were immersed (soaked) in the molten glide waxes for the p_n period [min], where $p_n = 3^n$, n $\in$ [1, 6] except for $p_0 = 0$ which is a starting point; 4) Directly, after the molten glide wax bath, the specimens were placed between two PTFE plates under a 40 kg weight to press out the excess wax and flatten the specimens; 5) After the specimens had cooled, we scraped away any remaining excess wax with a plastic scraper; 4) We waited for five days before measuring the hardness, to allow time for the wax to solidify. We consider this ample time for solidification, as nobody would normally wax their skis five days before a race; 5) Hardness measurements were performed, recorded and treated statistically.

3- Results

3.1 – Visual observations

Even with the naked eye, it was possible to see how the specimens changed after treatment (dipping) in the molten glide wax baths. Figure 2 shows the specimens after three minutes (p_1) of treatment, and Figure 3 after four hours and three minutes (p_6) of hot wax treatment. The difference between these two pictures can be clearly observed.

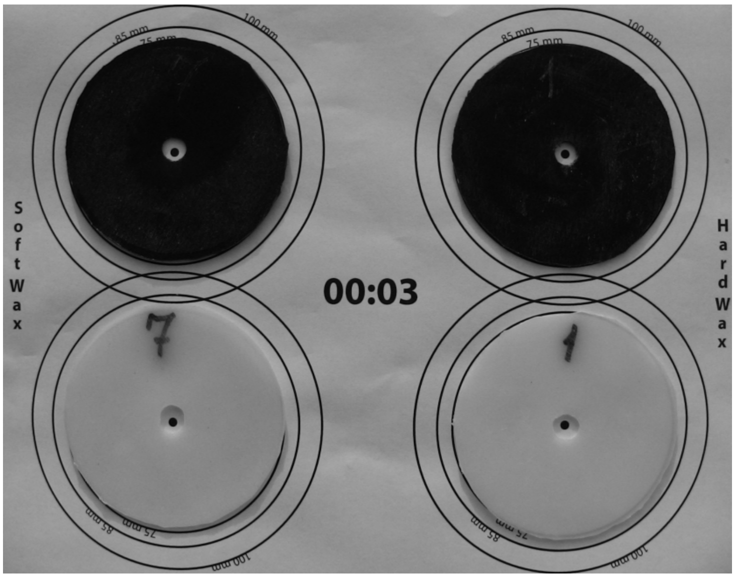

Figure 2: specimens after three minutes in the molten glide wax bath

The specimens in Figure 3 are significantly swollen in comparison with the specimens in Figure 2.

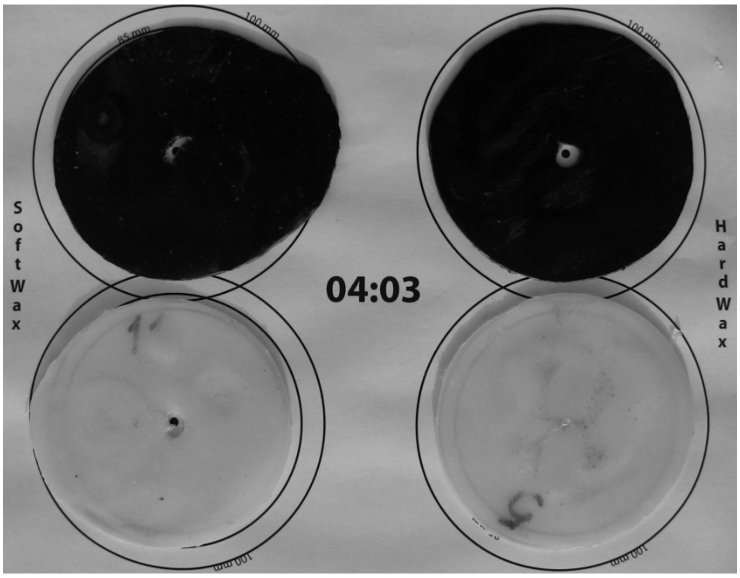

Figure 3: specimens after four hours and three minutes in the molten glide wax bath

3.2 – Hardness measurements

Five hardness tests (Shore D) was performed on each specimen. In Figure 4 the results of the measurements are presented as an arithmetical mean of the five hardness tests. The sample standard deviation $s=\sqrt{\frac{1}{4}\sum_{i=1}^{5}(H_i-\overline{H})^2}$ is presented as error bars on the chart in Figure 4.

From the chart in Figure 4 it is clear that all the specimens, regardless of the ski base material and glide wax, become softer and softer after treatment. It is especially interesting that even the specimens treated with hard glide wax (NA8) also become softer. This observation is in strong contrast to the universally recognised purpose of hard glide wax application. Table 1, which shows our measurements, confirms this observation:

Material	Hardness (Shore D)
P-Tex® 2000 Electra®	65,7 ± 0,7
P-Tex® 2000	64,8 ± 0,6
Glide wax NA2 (0°/-4°C)	12,9 ± 0,8
Glide wax NA8 (-8°/-20°C)	50,4 ± 3,3

Table 1: hardness of utilised materials

To avoid speculation that our result validation only applies to STAR glide waxes, we made hardness tests using a number of other major glide wax brands. The measurement values of tests with similar glide waxes were comparable, which agrees very well with conclusions from (Rogowski et al., 2005).

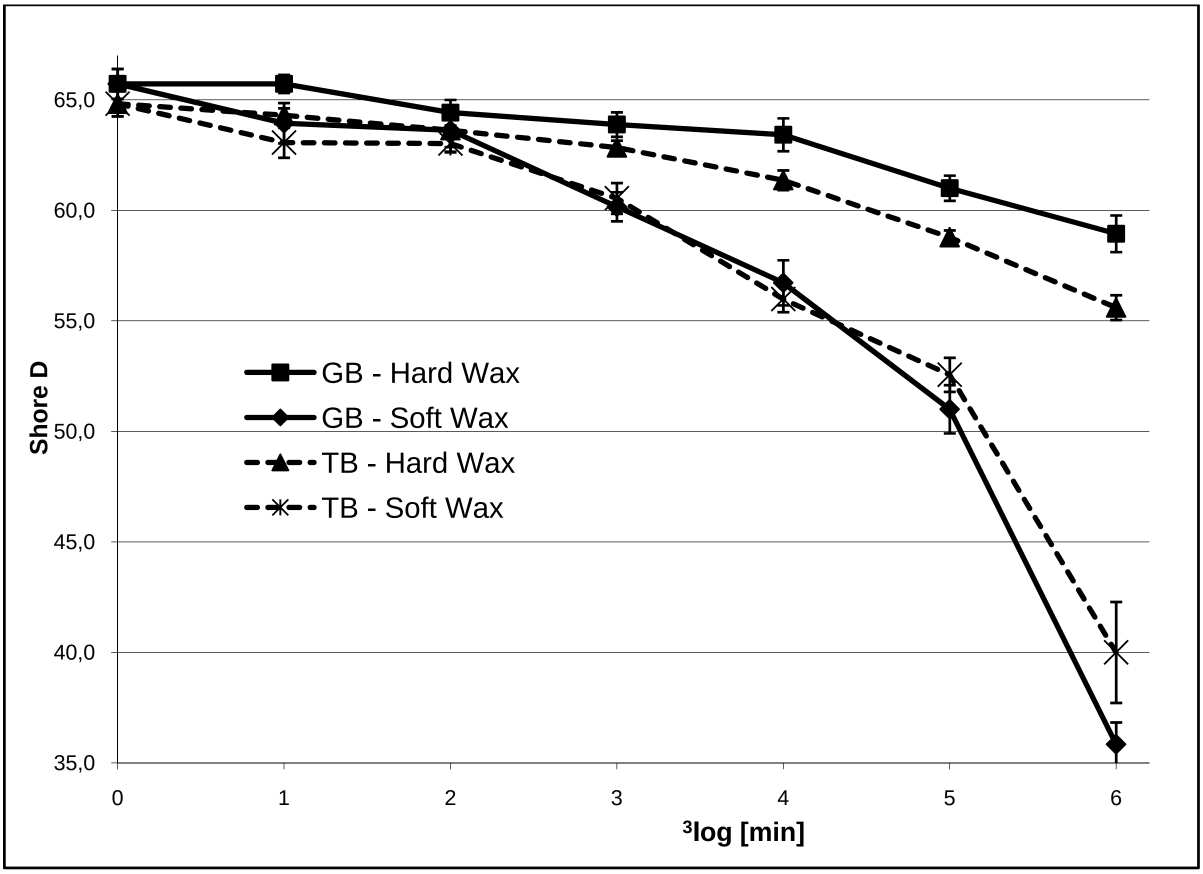

Figure 4: SRS hardness in relation to period of dipping in the molten glide wax bath

4- Discussion

Obviously hot wax treatment influences the SRS hardness and the observed results are due to a dilution process. We would not describe this process as “impregnation”, “penetration”, “absorption” or “saturation”. All such terms imply some kind of ski base porosity, in which we don’t believe. To quote from e-mail correspondence with Urs Geissbühler (Research & Development Manager, Gurit (Ittigen) AG): “There are no "pores" in press sintered UHMWPE as some wax manufacturers have been telling people over the last 40 years.”

In ours believe, it is a pure dilution process, as we observed in this experiment, as in the old alchemist maxim: “similia similibus solvuntur”. The behaviour of this process could be described in (Oral et al., 2007) by Fick’s second law of diffusion, where the concentration of the solute as a function of depth and time is

$$C(x,t) = C_0 \operatorname{erfc}(\frac{x}{2\sqrt{Dt}}) \quad (1)$$

where C_0 is the saturation concentration of the material, x is the depth, D is the diffusion coefficient, and t is the time. The complementary error function, erfc(z), is simply [1-erf(z)]. The variables D and C_0 are very dependent on the melting temperature. Since the diffusion of molten glide wax is believed to be limited to the amorphous regions of the polymer, soaking with molten glide wax should have no effect on the crystallinity of the UHMWPE (ski base) below the melting point (Oral et al., 2007). On this assumption, it is easy to understand why the softer material (hard glide wax NA8, see Table 1) is not able to make the harder material (ski base, see Table 1) even harder.

From our results we can draw the conclusion that the hot wax treatment of the SRS with available glide waxes cannot make the SRS harder than it was initially (unwaxed). Our results and conclusion are in agreement with the summary regarding microcrystalline wax from (Mathia et al., 1989).

In the light of our results, it seems to be more effective to use a completely unwaxed ski base for cold dry snow conditions (aggressive snow). At the same time, in practice it will be necessary to treat the ski base with hard glide wax if the ski base has previously been treated with a soft glide wax. In this case treatment with a hard ski wax will succeed in making the SRS harder than before.

5- Acknowledgements

The authors are grateful to Urs Geissbühler from Gurit (Ittigen) AG for the ski base material and for the fruitful discussions regarding optimal SRS treatment

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Paper VI

Estimating surface hydrophobicity by introducing a wettability factor based on contact angles

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A new approach to calculating the degree of hydrophobicity.

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Estimating the magnitude of hydrophobicity by measuring advancing and receding contact angles has long been discussed. A new approach to deal with the problem, presented in this paper, is to introduce a wettability factor. This factor is dependent only on the above-mentioned, experimentally measured contact angles.

Wettability, hydrophobicity, contact angle.

Introduction

The term "hydrophobicity" has been used over many decades. Nevertheless, the meaning of the term is still discussed.[1] For example, there is disagreement over the question of which parameters should be employed to characterise the degree of hydrophobicity. Many industrial representatives and a number of scientists[2-4] use a single "stationary" or advancing contact angle (ACA or θ_A) as a measure of hydrophobicity. The higher ACA, the higher the hydrophobicity. However, this approach has been criticized by several authors,[5-7] who point out the necessity of taking the receding contact angle (RCA or θ_R) into account.

From a pragmatic point of view, in the case of the majority of tribological applications, with an almost constant distance between the two sliding surfaces, e.g. sliding bearings, ski glide, human synovial joints and so forth, we may employ a different approach that only takes into account shear hydrophobicity[1] (shear wettability) and excludes tensile hydrophobicity. Therefore, by taking into consideration only the shear wettability, we may use a model with moving (sliding) droplets on an inclining surface,[8-10] in which the contact-angle hysteresis (CAH) has to be taken into account in order to estimate the shear wettability of the surface.[11-17] Dussan and Chow[11] describe the role of CAH as follows: “It is shown that from both a physical and mathematical point of view *contact-angle hysteresis*, i.e. the ability of the position of the contact line to remain fixed as long as the value of the contact angle θ lies within the interval $\theta_R \le \theta \le \theta_A$, where $\theta_A \ne \theta_R$, emerges as the single most important characteristic of the system”. However, it is not sufficient to take CAH into account as an isolated variable (which, nevertheless, is much better than merely θ_A), as it done in $\Delta\cos = \cos\theta_R - \cos\theta_A$ [6], because this method assumes that the droplet width (w) is a constant. This approach has been criticized[18] (page 1444): “…greater forces present in the case of hydrophilic surfaces “push” the drop onto the surface and increase their reciprocal contact area, modifying the parameter w, the lateral size of the drop. This greater interfacial contact simply increases the number of total “hindrances” intrinsic of the interface, thus increasing the plane tilting necessary to move the drop”. In view of this, we have introduced a wettability factor, which means that we also take w into account.

This paper presents a method of estimating the degree of hydrophobicity of any hydrophobic surface by measuring the advancing (ACA) and receding (RCA) contact angles. Values of the ACA and RCA can be determined, either by using the commonly used captive-drop goniometry method (also referred to as the “sessile drop method”)[15, 19] or by using the Wilhelmy balance method.[20, 21] The reliability of these methods is not discussed in this paper.

Acknowledgment

The authors would like to express sincere gratitude to Professor Thomas J. McCarthy (University of Massachusetts) for the fruitful discussion of how to define the term “hydrophobic”.

Theory

To avoid any confusion in the definition of ACA and RCA[22], we have adopted the following definition taken from Leger and Joanny[23]: “If the liquid-vapour interface has been obtained by advancing the liquid, (after spreading of a drop for example) the contact angle has a value θ_A larger than the equilibrium value; if on the contrary the liquid-vapour interface has been obtained by receding the liquid (by retraction or aspiration of a drop) the measured contact angle θ_R is smaller than the equilibrium contact angle”. The contact angles described in Figure 1 are simply and solely based on this definition.

Since the degree of wettability (capillary attachment) directly affects the movement of water droplets on an inclining plane, the equation (1)[24, 25] is used

$$\frac{mg\left(\sin\alpha\right)}{w} = \gamma_{LV}(\cos\theta_R - \cos\theta_A) \qquad (1)$$

where θ_R, θ_A and the surface tension parameter are related to the angle α at which the droplet starts to slide along the inclined plate, where m is the drop mass, g is the gravitational acceleration, w is the width of the droplet along a line parallel to the plane and perpendicular to its maximum inclination direction and γ_{LV} is the surface tension of the liquid (water-air).

In view of the criticism given in Della Volpe, Siboni and Morra[18], one cannot assume that w in the equation (1) is a constant, even though the drop volume is a constant (provided by the hardware), as w is actually dependent on θ_A and θ_R. However, for a hydrophobic surface it can be assumed, that the droplet is a spherical cap and that the droplet volume is constant, as illustrated in Figure 1.

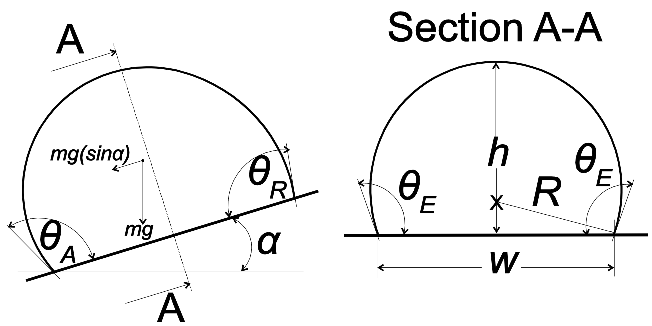

Figure 1. Profile and plan view of drop during sliding without acceleration.

In addition, the advancing and receding contact angles are unaffected by the maximum drop volume.[9] The equilibrium value of the contact angle θ_E can be obtained from the literature[26, 27] as an empirical equation $\cos\theta_E = 0.5\cos\theta_A + 0.5\cos\theta_R$, and one can derive the width of the drop, value w, by solving the combined equations:

$$\begin{cases} V = \pi \int_{R-h}^{R} \left(R^2 - x^2\right) dx \\ h = R + R\sin\left(\theta_E - \frac{\pi}{2}\right) \\ R = \dfrac{w}{2\cos\left(\theta_E - \frac{\pi}{2}\right)} \\ \cos\theta_E = \dfrac{\cos\theta_A + \cos\theta_R}{2} \\ \theta_A \in (0,\pi) \\ \theta_R \in (0,\pi) \end{cases} \qquad (2)$$

where V is the droplet volume, R is the droplet radius and h is the droplet height, see Figure 1.

This results in:

$$w = 2^{\frac{5}{6}} \sqrt[3]{\frac{3V}{\pi}} \sqrt[3]{-\left(\cos\theta_A + \cos\theta_R + 2\right) \frac{\sqrt{8 - 2\left(\cos\theta_A + \cos\theta_R\right)^2}}{\left(\cos\theta_A + \cos\theta_R + 1\right)^2 - 9}} \qquad (3)$$

Substituting the solution results for w from (3) into (1) gives:

$$2^{-\frac{5}{6}}\sqrt[3]{\frac{\pi}{3}}\gamma_{LV}{}^{-1}g\rho V^{\frac{2}{3}}\sin\alpha =$$

$$=\left(\cos\theta_R-\cos\theta_A\right)\sqrt[3]{\left(\cos\theta_A+\cos\theta_R+2\right)\frac{\sqrt{8-2\left(\cos\theta_A+\cos\theta_R\right)^2}}{9-\left(\cos\theta_A+\cos\theta_R+1\right)^2}} \qquad (4)$$

In equation (4) all the terms dependent on θ_A and θ_R (that are experimentally available) are combined on the right side of the equation. Thus, one can introduce a dimensionless wettability factor F_w as a function of our experimentally measured contact angles (ACA and RCA) as suggested below:

$$F_w=\left(\cos\theta_R-\cos\theta_A\right)\sqrt[3]{\left(\cos\theta_A+\cos\theta_R+2\right)\frac{\sqrt{8-2\left(\cos\theta_A+\cos\theta_R\right)^2}}{9-\left(\cos\theta_A+\cos\theta_R+1\right)^2}} \qquad (5)$$

We may take equations (3) and (5), substitute them into (1) and get:

$$mg\sin\alpha = 2^{\frac{5}{6}}\sqrt[3]{\frac{3V}{\pi}}\gamma_{LV}F_w \qquad (6)$$

From the transformed equilibrium condition equation (6) it follows that the smaller the wettability factor defined in (5), the lower will be the equilibrium angle α, and as a result the lower the shear wettability of the tested surface.

So, we may use F_w as a comparative index of the wettability of different surfaces by calculating it from the measurements of the advanced and receding contact angles.

Results and Discussion

The results presented below in Table 1 refer to the wettability of three hypothetical hydrophobic surfaces. However, these results are very close to our own measurements on polyethylene surfaces.

Table 1. Comparison $\Delta\cos$ vs. F_w

Case No		$\Delta\cos$	F_w
1	$\theta_A=119.00^{\circ};\ \theta_R=90.00^{\circ};$	0.485	0.378
2	$\theta_A=110.00^{\circ};\ \theta_R=81.79^{\circ};$	0.485	0.410
3	$\theta_A=101.00^{\circ};\ \theta_R=72.90^{\circ};$	0.485	0.443

To compare the methods of calculating the magnitude of the surface wettability by calculating $\Delta\cos = \cos\theta_R - \cos\theta_A$ [6] with the proposed method of calculating F_w from equation (5), we found pairs of θ_A and θ_R, which give an equal value of $\Delta\cos$ (Table 1). Thus, the calculation of $\Delta\cos$ does not give sufficient information to indicate a difference in wettability (hydrophobicity) on all three hypothetical surfaces, which has been pointed out by Della Volpe, Siboni and Morra[18]: "As a conclusion it is not possible to consider "only the hysteresis as important to hydrophobicity" in the case of sliding drops or in every other case…".

On the other hand, F_w indicates the lowest magnitude of wettability (Table 1) in case No 1, higher in case No 2, and even higher in case No 3, which agrees with the statement by Della Volpe, Siboni and Morra[18]: "…greater forces present in the case of hydrophilic surfaces "push" the drop onto the surface and increase their reciprocal contact area, modifying the parameter w, the lateral size of the drop". **QED**

In conclusion, the introduction of a dimensionless wettability factor F_w provides a new approach to solving a major theoretical problem, and enables a comparison of the wettability of different surfaces based on given advanced and receding contact angles, which is more reliable than previous methods.

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Paper VII

The relationship between the type of machining of the ski running surface and its capillary drag

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The difference in the capillary drag of ski running surfaces treated using different types of machining was studied by measuring the advanced and receding contact angles on two different ski base materials. The study found that ski running surfaces flattened by a steel drum have a lower wettability factor and are more effective in reducing capillary drag under homogenous wetting conditions.

Ski base, stone grinding, capillary drag, contact angle.

Introduction

For many centuries skis have been used as a means of winter transport, but in the last 80 years skis have mainly been used as recreational equipment. Therefore, the majority of research papers regarding sliding on snow have a direct connection to sport and to skiing competitions and the focus of attention has been on minimizing the friction between the ski gliding (running) surface and the snow. On the other hand, there has been considerable uncertainty about the basic model of interaction involved. Today there is much evidence to support the idea of a meltwater lubrication model.

The current established procedure of ski preparation for optimal glide includes two major aspects: mechanical treatment (machining) and hot glide wax treatment. In this paper we will primarily focus on the mechanical aspects of the processing of the ski running surface. It is also important to investigate ski-running-surface properties without any glide wax, because there is an accumulated body of evidence indicating that glide wax may be unnecessary: glide wax wears out after a few hundred meters [1], and in some cases its application does not improve (or even impairs) the ski glide [2-6].

Generally, ski base machining can be subdivided into stone grinding and steel scraping. Stone grinding [7-11] is an accepted method of ski-base treatment: ski factories commonly apply this method to newly produced skis. The steel scraping method [11-13] has a number of promising features [4, 12, 13], but is today only employed by a few enthusiasts.

Ski-snow friction is a very complicated process involving several aspects. Assuming that an optimal thickness of water film exists, conditions can range from almost dry sliding, in which too little meltwater is available, to very wet sliding, in which too much meltwater is available. Because of this, Colbeck's [14, 15] empirical model takes into account the thickness of the water film. Colbeck describes the friction between the ski running surface and the snow as:

$$\mu = \mu_{cap} + \frac{\mu_{dry}\mu_{lub}}{\mu_{dry} + \mu_{lub}} \qquad (1)$$

$$\mu_{dry} = \varepsilon \exp(-\xi h) \qquad (2)$$

$$\mu_{cap} = \beta h^3 \qquad (3)$$

where μ is the friction coefficient between the ski running surface and the snow, μ_{dry} - due to solid deformation, μ_{lub} - due to water lubrication, μ_{cap} - due to capillary attraction, h – water film thickness, β, ε and ξ are constants that can be determined experimentally but that vary according to the prevailing conditions. Fig. 1 shows the relationship between three of the above components and the thickness of the water film. These friction components are not completely independent. However, in order to understand the major effects examined in this paper, we will concentrate only upon the effect of friction due to capillary attraction μ_{cap}.

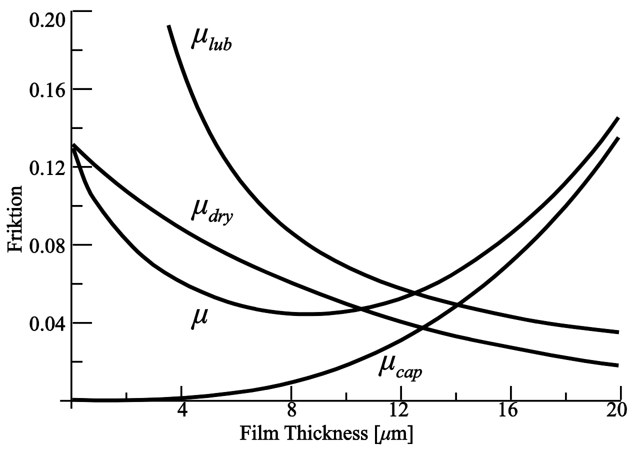

Fig. 1 Example of total friction vs. film thickness from the empirical model by Colbeck (1988, 1992). The total friction is the sum of three components due to dry friction, melt-film shearing, and capillary attraction.

That the effect of capillary attraction is the most significant variable is not indisputable. In spite of the fact that a water film exists under all snow and ice conditions above -73°C [16] and not just exists – affects the snow crystal's morphology [17], some authors [18-20] do not take the role of capillary forces into account when studying ski glide. However, we believe that existing knowledge [15, 21-26] indicates that capillary forces are a very important component of total ski friction, and this paper therefore focuses on how different types of mechanical treatment of the ski base influences capillary forces.

We also discuss methods to estimate the well-known phenomenon of capillary attraction (capillary drag), using the concept of a wettability factor (WF) from [27], which seems to satisfy the main requirements.

Our objective is not to find out which kind of surface machining is the most advantageous, but to identify a general trend. Furthermore, we question the commonly accepted thesis that increased roughness of the ski running surface reduces the capillary drag [8]. We therefore examine the relationship between the mechanical treatment of the ski base and capillary drag.

Theoretical Basis

Measuring capillary drag directly is a very difficult task: we therefore employ the accepted analytical relationship between the capillary adhesive force and the contact angle hysteresis (CAH) [21, 28-31], which is expressed as $(\theta_A - \theta_R)$, where θ_A is the advancing contact angle (ACA) and θ_R is the receding contact angle (RCA). The total capillary drag is comprised of the tensile capillary drag and the shear capillary drag, which is described in [32, 33]. Fig. 2 illustrates the difference between tensile and shear hydrophobicity, which are responsible for the tensile and the shear capillary drag respectively [33].

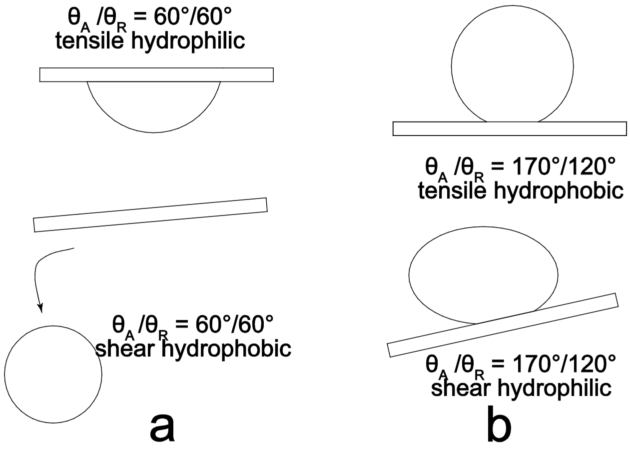

Fig. 2 Differences between shear and tensile hydrophobicity. (a) A surface with θ_A/θ_R = 60°/60° supports a small droplet of water when held perfectly horizontal but does not if the surface is slightly tilted. (b) A droplet needs to distort from a section of a sphere in order to slide on a surface with θ_A/θ_R = 170°/120°. (Gao and McCarthy, 2008)

However, the tensile capillary drag is not representative for the ski glide on snow because the ski base is commonly made of ultra high molecular weight polyethylene (UHMWPE), which is a highly hydrophobic material. The tensile capillary drag therefore appears to only be responsible for a negligibly small part of the total capillary drag [34, 35]. In this study we, therefore, assume that the shear capillary drag is responsible for the major part of the total capillary drag. As we did not use tilting-plate goniometry (TPG) [36], we were not able to measure α directly. Instead we used captive-drop goniometry (CDG) to directly measure θ_A and θ_R, and then used a calculation method to obtain the wettability factor (F_w) as a comparative index for differently machined ski running surfaces [27].

$$F_w = \left(\cos\theta_R - \cos\theta_A\right)\sqrt[3]{\left(\cos\theta_A + \cos\theta_R + 2\right)\frac{\sqrt{8-2\left(\cos\theta_A+\cos\theta_R\right)^2}}{9-\left(\cos\theta_A+\cos\theta_R+1\right)^2}} \quad (4)$$

Materials and Methods

General approach

Our choice of tools, skis and procedures for ski preparation were based on a direct application to cross-country skiing.

Our primary experimental method was monitoring the variation of the hysteresis between the advanced contact angle and the receding contact angle of water on skis treated with different types (and subtypes) of mechanical process. A case-based comparative analysis is of primary importance here, while the absolute values of the contact angle hysteresis and surface hydrophobicity are not as important in this study.

Preparation of the test samples

We used six pairs of identical skis (from the same batch) manufactured by Madshus (www.madshus.com), three pairs with a transparent (clear) ski base P-Tex® 2000 (a former trade mark of Gurit (Ittigen) AG, sold to CPS GmbH) and three pairs with a black (graphite) ski base P-Tex® 2000 Electra® (referred to hereafter as "transparent" and "black" ski base material). The ski base properties are presented in Table 1, as formerly published by Gurit (Ittigen) AG on www.gurit.com.

Table 1 Ski base (running base) properties

	P-Tex® 2000	P-Tex® 2000 Electra®
Molecular weight (Visk. ISO/R1191) [g/mol]	$5 \cdot 10^6$	$5 \cdot 10^6$
Density (DIN 53479) [g/cm^3]	0.935	1.0
Abrasion resistance (Sand-slurry Steel 37 = 100)	20	30
Modulus of elasticity (DIN 53457) [MPa]	500	600

Three skis with a transparent base and three skis with a black base were professionally stone ground using a Wintersteiger machine (www.wintersteiger.com). The two types of ski base were ground with three different patterns, which resulted in six different patterns. Although there is a lack of unified standards for stone-ground ski base patterns [10] we will follow the accepted practice here and refer to the patterns (traceries) symbolically as I, II and III. The other skis were treated using three high speed steel (HSS) scrapers [13] with different edge sharpening, and three different sized burrs, as illustrated in Fig. 3.

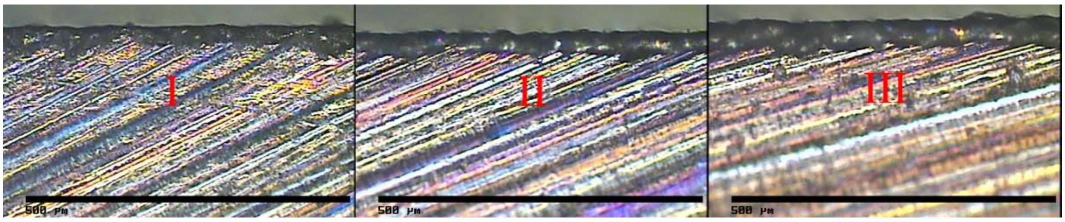

Fig. 3 Scraper edges with burrs of three different heights (I – short, II – medium, III – large) shown under an optical microscope. The black bars are each 500 μm long.

After initial measurements, the ski running surfaces were smoothed (Sm), to flatten asperities, using a stainless steel drum of our own design (Fig. 4), with a lathe-turned working face (the arithmetic average roughness (R_a) was about 20 μm).

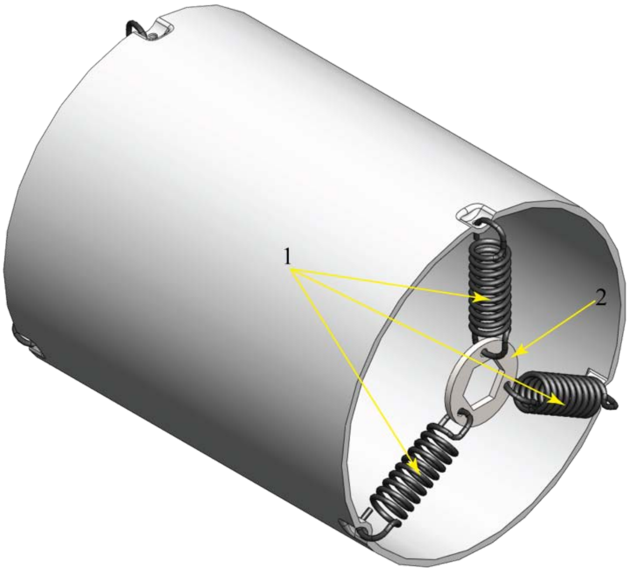

Fig. 4 Stainless steel drum for smoothing the ski running surface (1 - spring hanger, 2 - mounting washer)

The drum was used in the same way (Fig. 5) as a common rotary brush made by Red Creek (www.redcreek.se). Smoothing (flattening) in this way can be considered a mechanical treatment without material loss. Before any measurements were made, all the ski base surfaces were brushed with a Red Creek steel rotary brush rotating at 2800 rpm, and were wiped down with a lint-free non-woven cloth.

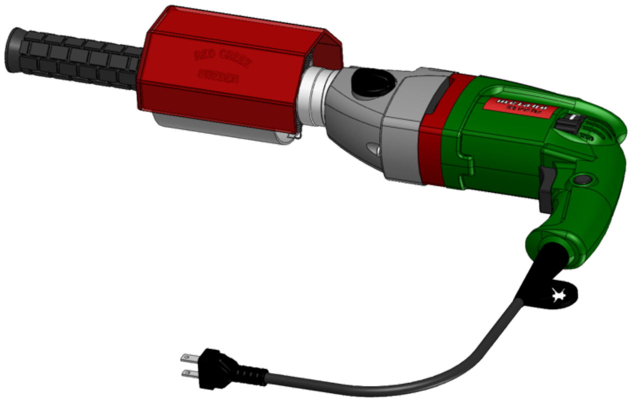

Fig. 5 The drum, handle and drill

To attain a benchmark reference for our comparisons, we prepared two samples of ski-base material (one transparent, one black) by cutting (Cut) a piece of ski-base material with a very sharp blade. These samples had minimal roughness in our experiment.

Roughness measurement

Surface measurements were taken using the Dektak® 6M stylus profiler (www.veeco.com) and the software "Dektak 32". Standard indexes such as R_a, R_q and R_t were recorded.

Estimation of the magnitude of the capillary drag

Drop-shape analysis is a convenient way to determine surface energy, through measuring contact angles. Contact angles are measured by fitting a mathematical expression to the shape of the drop and then calculating the slope of the tangent to the drop at the liquid-solid-vapour interface line.
An FTA125 goniometer with a homemade ski holder and the Fta32_Video build 300 analysis software produced by First Ten Ångstroms (www.firsttenangstroms.com) were used to measure the ACA and the RCA. The pump on the goniometer was driven manually, and special glass capillary needles with small tips (inner diameter of 5 μm at the tip) were used. About 15 images were captured during the ACA measurement (using 2 frames per second) and 15 images were taken immediately after for the RCA measurement (as described in [37]). For each ski, three measurements were made at three different points of the ski running surface at the front of the ski. An arithmetical mean value was then computed for each ski.

Results

Roughness of the ski running surface

The results of the measurement of the roughness of the ski running surface are presented in Table 2. R_a is the average roughness, R_q is the root-mean-squared roughness, and R_t is the peak-to-valley difference on the sample. For more details see ISO and DIN standards.

Table 2 Ski running surface roughness in surface standard indexes (Sm – smoothed/flattened)

	Stone Ground						Steel Scraped						Cut
	III		II		I		III		II		I		
Transparent		Sm		Sm		Sm		Sm		Sm		Sm	
R_a [μm]	7.35	7.03	5.35	4.56	3.26	2.84	3.72	3.27	3.46	3.08	3.48	3.47	1.16
R_q [μm]	9.13	8.64	6.33	5.62	4.05	3.60	4.63	4.05	4.17	3.73	4.40	4.30	1.43
R_t [μm]	40.41	34.11	26.99	26.37	19.18	18.29	24.92	19.37	22.43	17.85	24.56	20.55	5.95
Black													
R_a [μm]	6.02	5.70	5.90	5.87	3.28	3.28	2.36	2.27	2.85	2.81	3.01	2.94	1.59
R_q [μm]	7.60	7.07	7.00	7.09	4.19	4.14	3.08	2.98	3.55	3.39	3.69	3.62	1.87
R_t [μm]	38.83	31.20	27.80	37.98	23.30	24.44	18.81	16.07	17.94	15.92	17.79	17.39	7.37

Wettability factor

The results of the WF for each of the ski base types are presented in Fig. 6 and Fig. 7.

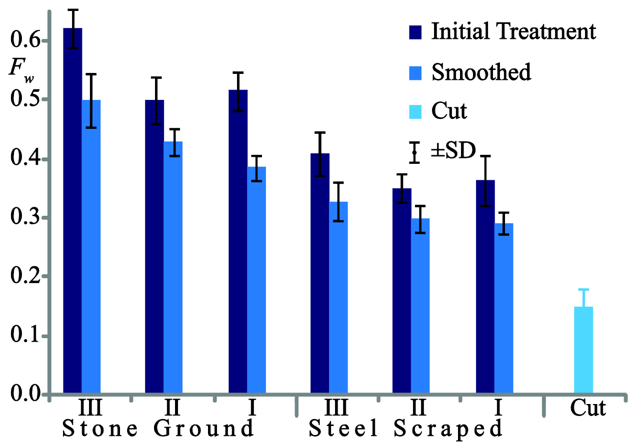

Fig. 6 Wettability factor (F_w) for the P-Tex® 2000 ski base (transparent). SD - Standard Deviation.

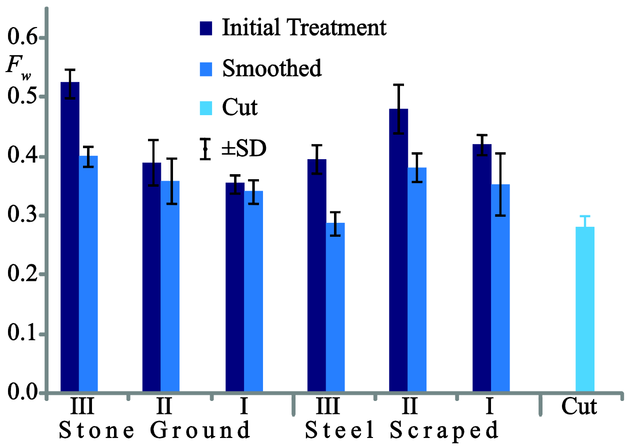

Fig. 7 Wettability factor (F_w) for the P-Tex® 2000 Electra® ski base (black). SD - Standard Deviation.

N.B. the horizontal axes in Fig. 6 and Fig. 7 do not contain any formal roughness parameters. The formal roughness parameters are shown in Table 2.

Correlation ACA - WF

Our calculation of a Pearson product-moment correlation coefficient between ACA and WF gave -0.09 for the black base and 0.02 for the transparent. The Spearman rank correlation is therefore 0.10 and 0.18 respectively. Both methods show a weak correlation between ACA and shear wettability.

Discussion

Reliability of the method

A number of researchers criticise the captive-drop goniometry (CDG) method (also referred to as the "sessile drop method") of ACA and RCA measurements when used to estimate the capillary drag [36, 38-40]. On the other hand, some authors [29, 37] advocate the employment of CDG to measure ACA and RCA. Unfortunately it was not possible to employ the most recognized Wilhelmy balance method [41] in our experiment, because the whole ski is composed of many materials, not only UHMWPE.

However, it is necessary to emphasize that in our case CDG was used under strictly controlled conditions, i.e. under the same environmental conditions, with the same liquid (distilled water) and with two similar materials. We believe that under such circumstances the employment of CDG for comparative studies is acceptable.

Smoothness and WF

We have not found any earlier research that demonstrates the relationship between standard surface roughness parameters and wettability; on the other hand we have discovered a few studies that demonstrate zero correlation between roughness and wettability [13, 42, 43]. Standard surface roughness parameters provide incomplete data for an adequate characterisation of patterns [44]. Therefore, a comparison of the WF of two different patterns (traceries), even when the patterns have a similar roughness (see Table 2), does not make sense. By combining the machining factors and types of ski base we attained twelve different initial patterns.

We therefore only compared surfaces with the same patterns (initial treatment and smoothed) and the surfaces of the cut samples. From the data presented in Fig. 6 and Fig. 7 one can identify a clear tendency: smoother (flattened with the steel drum) surfaces have a lower WF (F_w). We did not observe a similar effect to the Lotus-Effect [45-47] in our experiment. Probably, a nonlinear relation between roughness and CAH [48] is one of reasons to absence of the Lotus-Effect.

On the other hand, our observations agree with what is early reported [25, 49, 50], namely: calculating the WF from the data presented in [25, 49, 50] results in lower WF values for smooth surfaces, which indicates a lower capillary drag and higher shear hydrophobicity. In other words, smoother surfaces require a lower tilting angle for the droplet to start to slide along the inclined plane.

However, in the real life environment, the ski running surface has periodic contact with the air. It is therefore advantageous to make broad (about 1.0 mm wide, long grooves. The presence of air in these grooves makes a heterogeneous wetting regime [48, 51, 52] of the ski running surface, which results in a much lower capillary drag. In other words, under wet snow conditions the ski running surface has to be very smooth on a micro level to reduce capillary drag when it is exposed to homogenous wetting. Coarse grooves along the ski running surface will, however, create heterogeneous wetting contact and a lower capillary drag.

Marked differences between the two types of ski bases

Different response to the same machining

Our results indicate that the WF is generally lower (beneficial) in the case of the stone-ground P-Tex® 2000 Electra® ski base than in the case of the stone-ground P-Tex® 2000 (transparent) ski base. However steel-scraped machining gave the opposite effect, in which the transparent ski base had a lower WF. At the moment we have no definitive evidence of why this is so; more detailed investigations of the properties of the machined ski bases are needed to answer this question in full. However, the following factors may provide part of the explanation.

In general, rotary emery stone treatment (stone grinding) produces more and longer "hair" on the surface treated, in the more tensile P-Tex® 2000 ski base (see Table 1), compared to the less tensile P-Tex® 2000 Electra® (Table 1). On the other hand, the purely translational movement of a steel scraper along the surface only generates a negligible amount of rather short "hair" on both the materials tested. Clear P-Tex® 2000, which is free from hydrophilic [53] carbon additives, should therefore exhibit a lower WF.

Inconsistent data on the cut sample of P Tex® 2000 Electra®

The data relating to the cut sample of P-Tex® 2000 Electra® (see Fig. 6 and Fig. 7) differ from the clear tendency towards a correlation between smoothness and WF described above. The lowest values of the WF of skis and of a cut sample of transparent P-Tex® 2000 ski base respectively are 0.29 (ACA is 100.7°) and 0.15 (ACA is 93.4°) (about 100 % difference). On the other hand, the lowest values of the WF of the black P-Tex® 2000 Electra® ski base are 0.29 (ACA is 110.5°) and 0.28 (ACA is 111.7°) respectively, which is basically the same, taking into account the standard deviation values. An explanation to such inconsistent results can be found by studying the scanning electron microscope (SEM) images of both samples, as illustrated in Fig. 8. The images show that the P-Tex® 2000 Electra® sample appears to be covered with a kind of "fish scales" and is much less smooth than the P-Tex® 2000 sample, which could explain the high WF of the black ski base cut sample. The dimension of one such scale is about 100 x 70 μm, while the droplet diameter is about 1.7 – 2.5 mm (goniometric data). It would appear that the conditions for the Cassie-Baxter mechanism [54] or for the Wenzel mechanism [55] are satisfied, which could explain the high ACA “anomaly”. Moreover, if we consider WF increase in this case, we can assume effect of just Wenzel model in this case [56, 57].

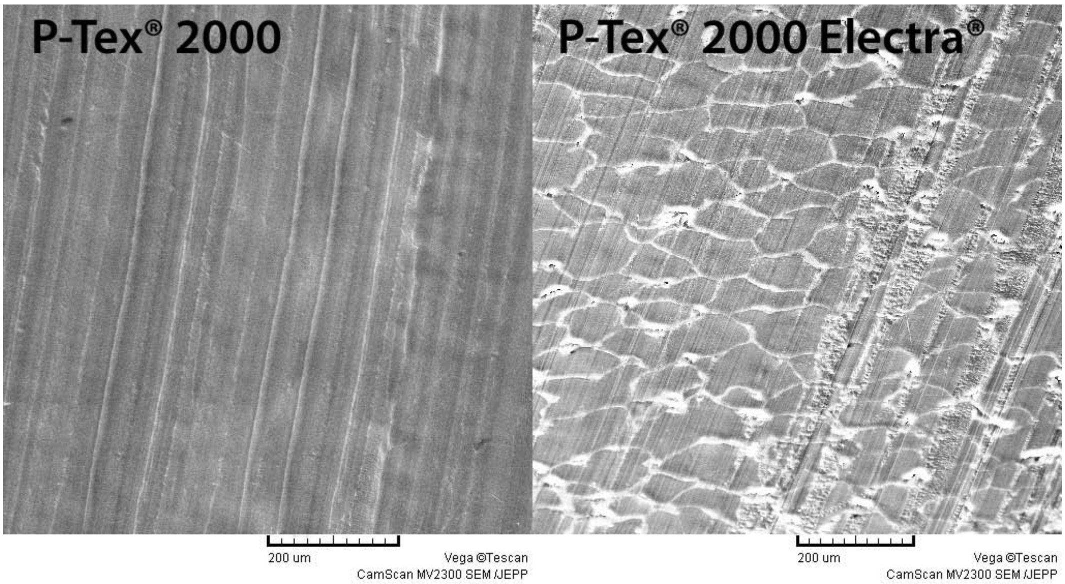

Fig. 8 The ski base material samples examined through an SEM. The lengthwise scratches are a knife edge trace

It should be noted here, that such differences in the surfaces produced by the “knife-in-the-bulk” cut and “surface scratching” could have been anticipated, in view of the very different material deformation mechanisms involved. However, at present we cannot make such a prediction without first studying the surfaces microscopically.

Conclusions

- By measuring the ACA and RCA and calculating the WF we can see that the method of machining the ski running surface strongly affects the capillary drag against the water film.
- The same patterns exhibit lower WF values after smoothing (flattening), which indicates a lower capillary drag and higher shear hydrophobicity.
- Neither the stone grinding nor the steel scraping is an optimal kind of machining for the ski-running surface regarding the capillary drag, as the cut samples have a very low WF. The algorithm suggested in [51] may provide a first step in finding better mechanical treatment for improving ski glide in the future.
- An isolated value of ACA is not enough to predict the magnitude of capillary drag.

- The P-Tex® 2000 ski base (transparent, pure UHMWPE) seems to be preferable to P-Tex® 2000 Electra® (black, “graphite”) ski base, as the cut sample of the former has a lower capillary drag (see Fig. 6 and Fig. 7).

Future work

In the future we would like to design and construct an experimental set-up for tilting-plate goniometry applicable to ski surface measurements. There are indications that TGP may provide more reliable results than captive-drop goniometry. A comparison of the TPG results with the existing experimental data would provide a better understanding of the processes involved in relation to ski glide.

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