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INTERFACIAL KINETIC SKI FRICTION

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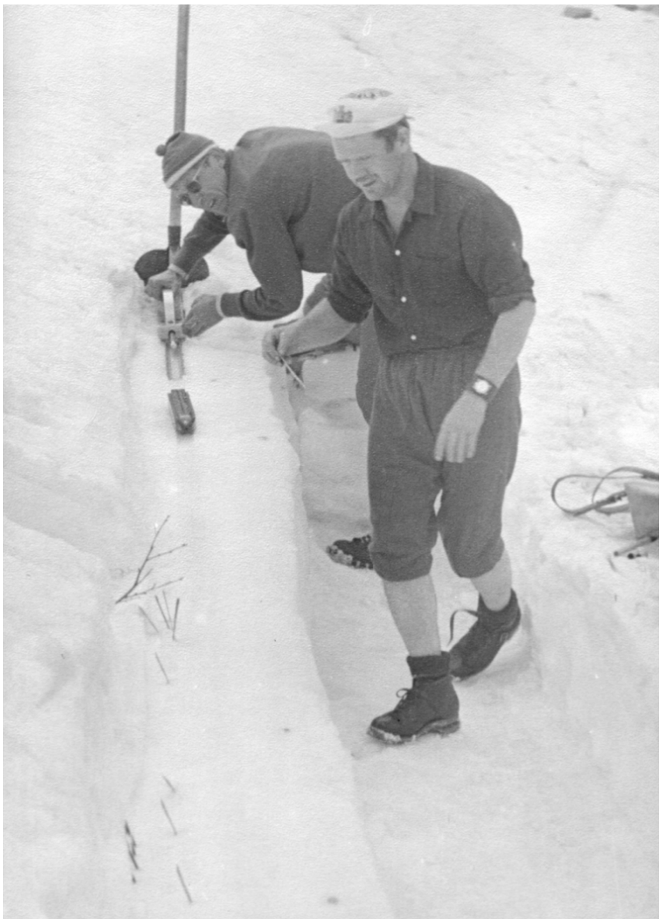
ABSTRACT

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.

First I would like to express my gratitude to my supervisor and promoter Professor Mats Tinnsten at Mid Sweden University for his support, inexhaustible patience, and his ideas reflected in the writing of this thesis. Secondly I would like to thank my remote vice-supervisor Professor Mikael Jonsson at Uppsala University for his contagious optimism.

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I would like to thank Östersund Municipality Culture and Recreation Board (Kultur- och fritidsnämnden) and Östersund Ski Stadium track grooming team for the help with the premises and a perfectly prepared ski track. Also, special thanks to their leaders Bertil Ericsson, Joakim Halvarsson and Bengt Ericsson.

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]:

$$\mu = \mu_{plough} + \mu_{dry} + \mu_{lub} + \mu_{cap} + \mu_{dirt} \tag{1}$$

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

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[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].

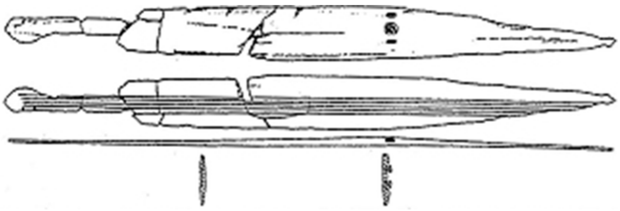

Figure 1. The Saija skis are over 5000 years old [10]

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 Ist 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.

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[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

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

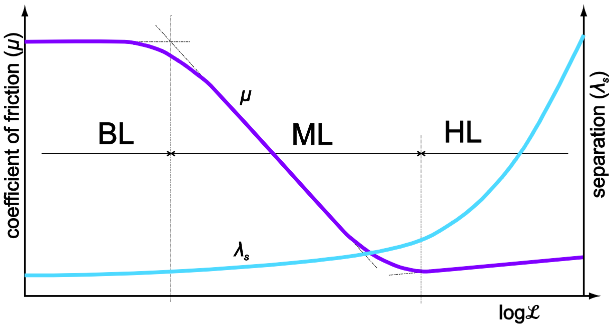
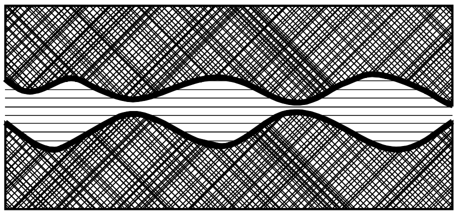
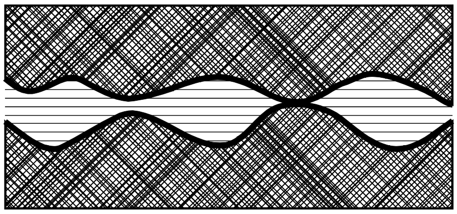


Figure 4. Generalized Stribeck curve and corresponding separation. HL: Full-film lubrication, ML: Mixed Lubrication, BL: Boundary Lubrication. Adopted from [34, 35]

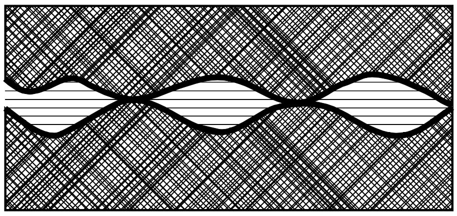
When the sliding velocity is high and the volume of a lubricant (melt water) is large enough, due to the hydrodynamic effects, the two surfaces are fully separated by the lubricant (Figure 5a). In this case the pressure of the fluid in contact is high enough to separate the surfaces. This called Hydrodynamic 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 $\lambda_{\max}$. 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].

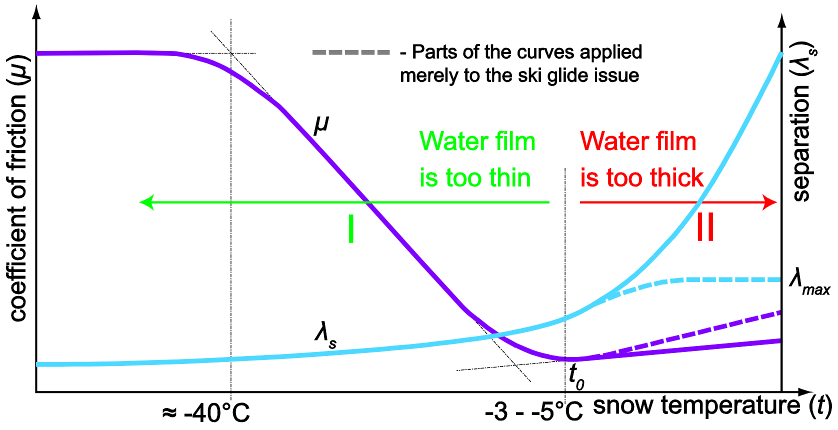


Figure 6. Generalized Stribeck curve applied and modified by the author to skiing issue, gliding velocity is constant. I: Snow temperature is lower than optimal, II: Snow temperature is higher than optimal.

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.

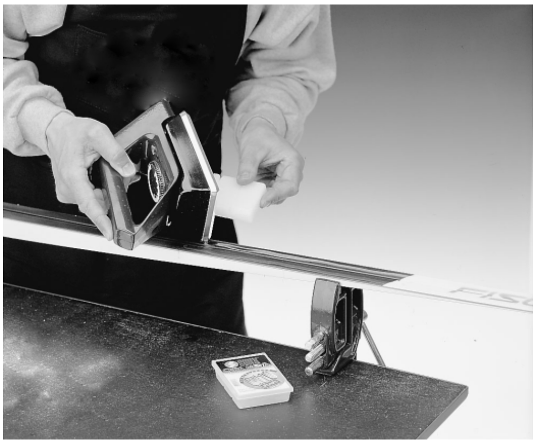


Figure 7. Hot glide waxing

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.

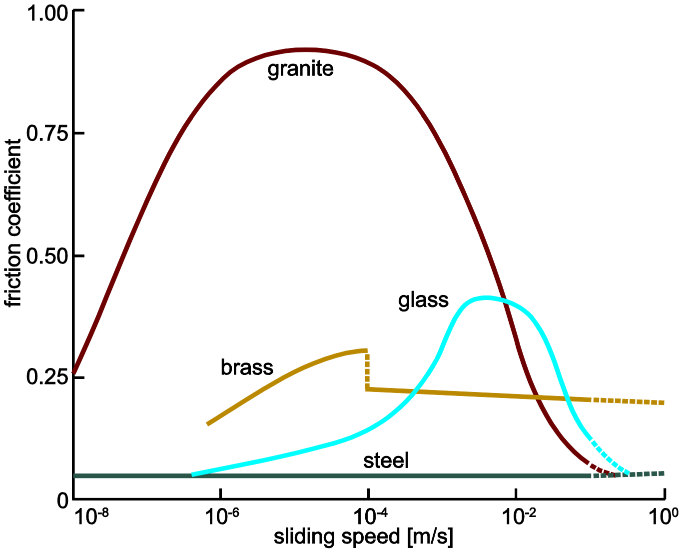


Figure 11. Friction of polycrystalline ice sliding on various smooth surfaces at -11.7°C [62]

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/cm^3]	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.

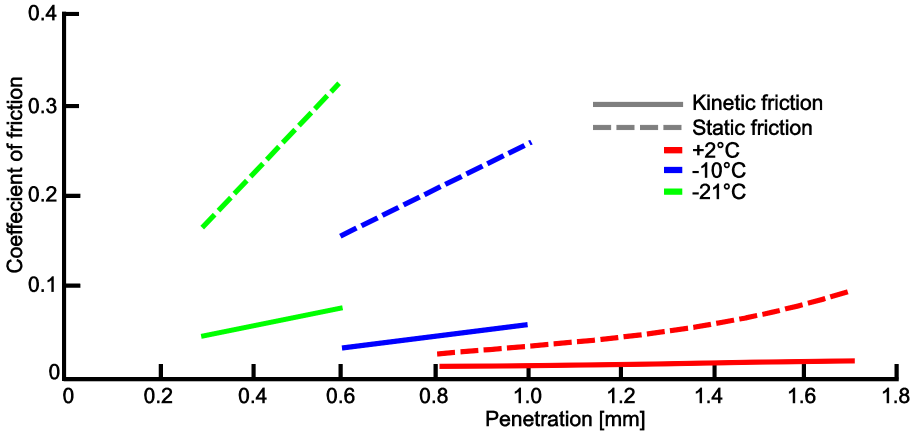


Figure 12. Friction of sliding surfaces coated with paraffins of various hardnesses at different temperatures. Hardness is given in penetration depth (mm) [18]

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.

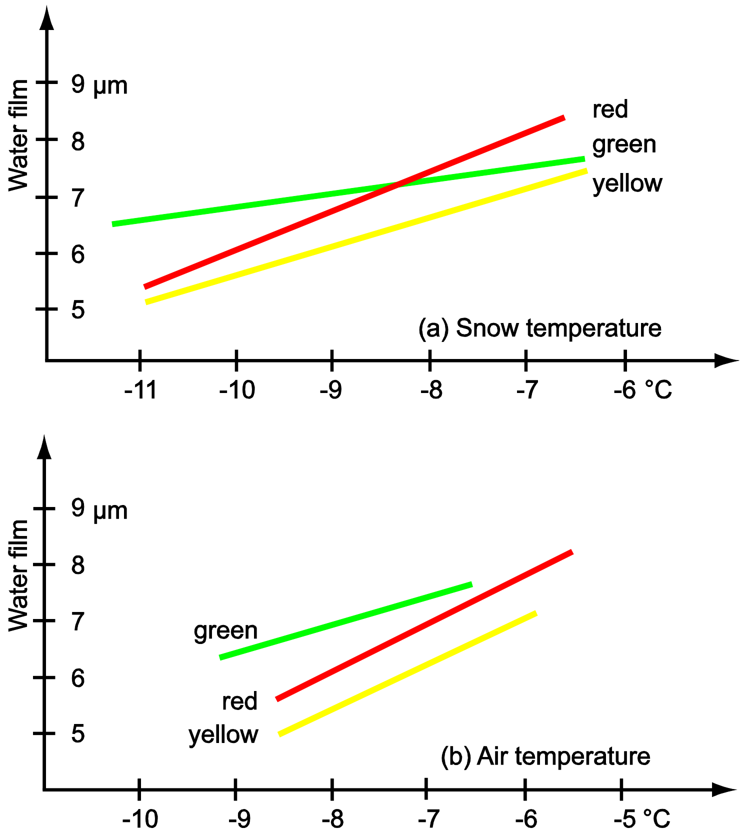


Figure 13. Dependence of the water film at different temperatures of snow (a) and air (b) and for skis prepared with different kinds of wax (Toko green, red and yellow) [23]

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.

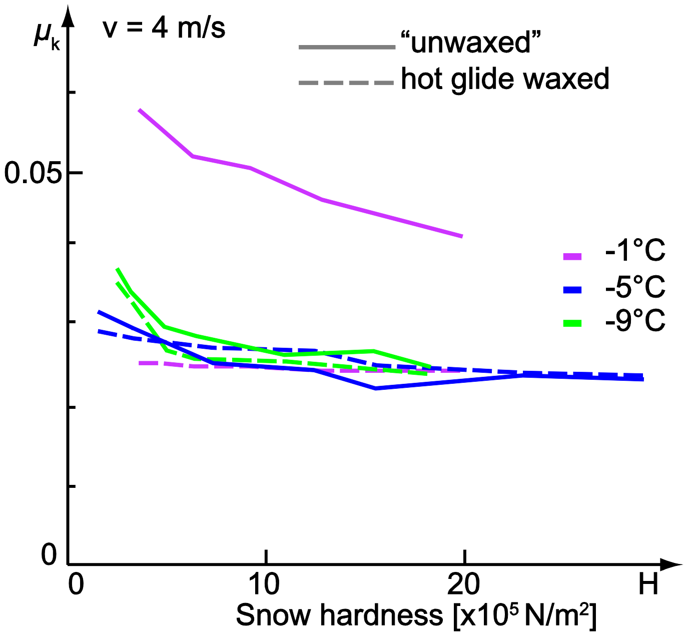


Figure 14. Kinetic coefficient of friction as a function of snow hardness [25]

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].

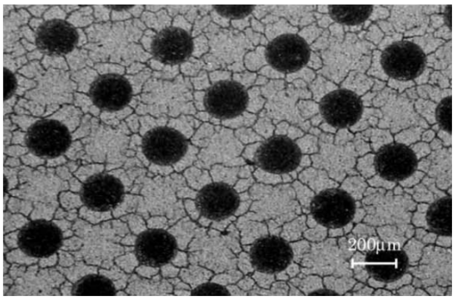


Figure 15. Optical micrographs of pores on the disk surface produced by the laser texturing [122]

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].

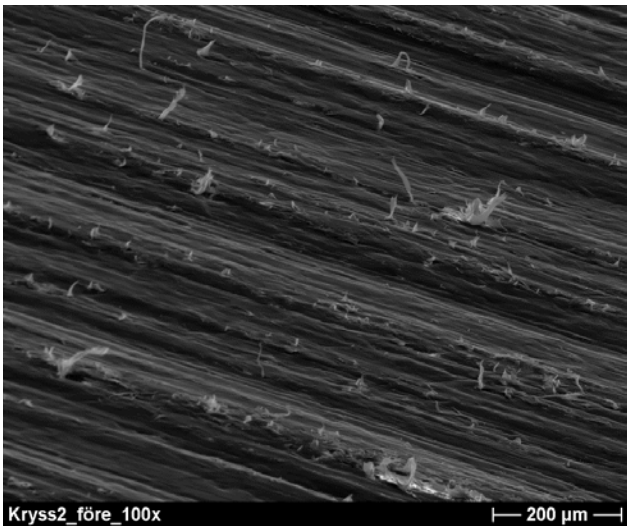


Figure 16. Typical stone ground surface [128]

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}:

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

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[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.

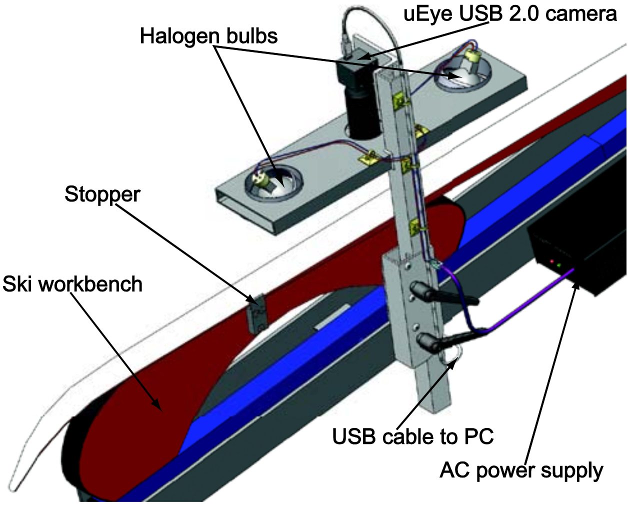

Figure 17. Dirt attraction measurement - Experimental setup

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].

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

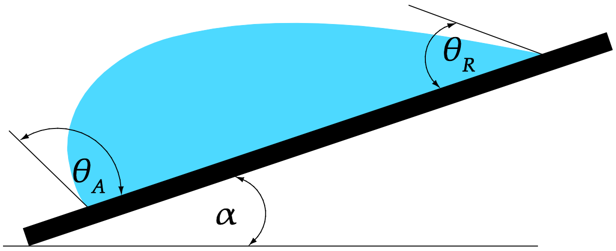

Figure 18. Dynamic wetting (sliding) of water droplet on a solid surface

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]:

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

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):

$$\cos\theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}} \tag{10}$$

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.

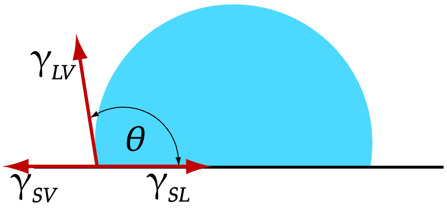

Figure 19. Young wettability model

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

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

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

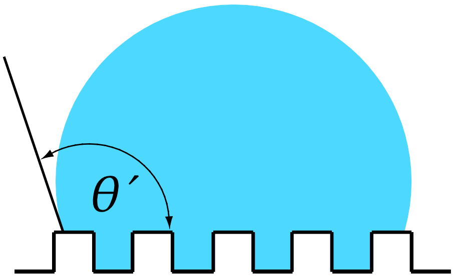

Figure 20. Wenzel wetting model

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

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

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.

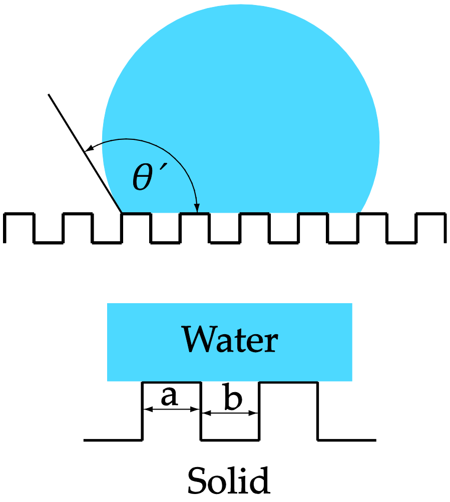

Figure 21. Cassie-Baxter wetting model

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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