

Investigation of the most essential factors influencing ski glide



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Abstract

There are many different parameters of a ski running surface (material, roughness, hydrophobicity, etc.). All the parameters have an influence on ski glide, some more and some less. Furthermore, some parameters with only minor relevance are commonly declared as critical, while truly critical parameters, as far as we know, never been investigated. In this thesis, we try to identify and structure the different stages of ski running surface preparation. In our experiments, we have applied well-established, commonly used treatments parallel with alternative preparations. The unexpected result of our experiments is that the treatments commonly used today are not as good as alternative treatments, namely; stone grinding and glide wax application are far from an optimal ski treatment if minimising friction over a given distance is the major goal.

Keywords: contamination, dirt, glide, hydrophobicity, ski, roughness, wax.

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List of Papers

A. Contact angles on the running surfaces of cross-country skis

Leonid Kuzmin and Mats Tinnsten

The Impact of Technology on Sport, A. Subic, S. Ujhashi (eds), ASTA, Proceedings of the Asia-Pacific Congress on Sports Technology, Tokyo Institute of Technology, September 2005, pp. 318 - 323, ISBN: 0-646-45025-5

B. Dirt absorption on the ski running surface - Quantification and influence on the gliding ability.

Leonid Kuzmin and Mats Tinnsten

submitted to *The Journal 'Sports Engineering'*

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1 Part I - Summary

1.1 Research Question

The major goal (major question) of our research is to come closer to discovering how we can minimise friction between the gliding (running) surface of skis and the snow.

As (Colbeck 1992) and (Langevin 1998) expressed it:

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

where μ is the friction coefficient, the subscripts *plough*, *dry*, *lub*, *cap* and *dirt* represent the friction due to ploughing, solid deformation, water lubrication, capillarity attraction, and surface contamination, respectively. Nevertheless, in this thesis we have concentrated on the two components of Equation 1: μ_{lub} and μ_{dirt} . Both Paper A and B are experimental research.

We examine the wettability of the ski running surface (Paper A) to see how different ski treatments influence the water droplet contact angle on the ski running surface. In this way, we could see how different treatments of the ski running surface may increase μ_{lub} , because μ_{lub} is directly dependent on the ski running surface wettability (hydrophobicity). In Paper B we investigate μ_{dirt} by observation, recording and analysing of such parameters as: ski glide, dirt accumulation on the ski running surface and the wettability of this surface.

1.2 Introduction

Snow friction has been the focus of much attention over the years, primarily because of the interest in recreational skiing.

There has been considerable uncertainty about the mechanisms of snow and ice friction. In particular, there has been controversy over the melt-lubrication theory, although there is a considerable body of evidence to support the idea, and lubrication

by melted water is widely accepted in other areas of frictional studies, or tribology. This water layer has been observed directly (Kuroiwa 1978) and measured by its capacitance (Ambach & Mayr 1981); its existence is further confirmed by the heat-dissipation calculations made by Samuel C. Colbeck in (Colbeck 1988).

Sliding over snow is necessarily more complicated than sliding over ice because of the large variety of possible snow conditions. This sliding process is extremely complicated and it is very hard to carry out research in this area. The number of scientific papers on the subject is limited, while the number of pseudo-scientific mantras from the wax industry and wax technicians is unlimited.

Here are a few examples of such mantras:

Mantra number 1 – *The ski base is porous, and we have to melt in glide waxes many times to impregnate the ski base.*

Let us examine this mantra with such simple tools as secondary school level Physics and Chemistry and elementary logic.

Firstly, we can estimate how big these pores and gaps in the ski base have to be to store at least one molecule of glide wax. Regular glide waxes are made from hydrocarbon compounds. Ski waxes are primarily made up of three types of hydrocarbons: paraffin, microcrystalline, and synthetic waxes. These three are combined to make a ski wax. All these waxes are polymers and have molecules which are chains of monomers (see Figure 1). Paraffin has the shortest unbranched carbon chain, and if we assume methane to be a monomer (Figure 2), we have the smallest possible glide wax molecule.

Secondly, we can compare the paraffin molecule and the water molecule. Even the smallest hydrocarbon molecule, methane (CH_4), is larger than a water (H_2O) molecule (see Figure 3). There is not much difference in size between a carbon atom and an oxygen atom, but the four hydrogen atoms make a methane molecule bigger than a water molecule by two hydrogen atoms. Moreover, there is no doubt that

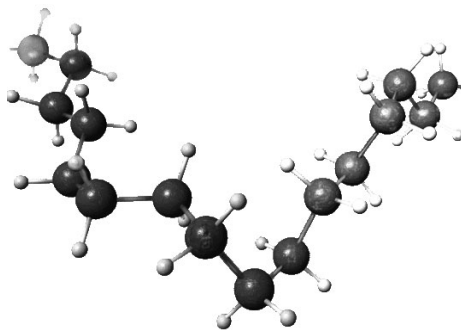


Figure 1: The chain of hydrocarbon monomers

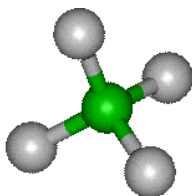


Figure 2: Methane (CH_4) molecule (source www.worldofmolecules.com)

the carbon chain of paraffin, consisting of at least 20 carbon atoms, is much larger than a water molecule.

Thirdly, we can use elementary logic. We have never ever observed any penetration of water into an unwaxed ski base. Such penetration would eliminate any glide, and the ski base would absorb water like a sponge. Consequently, if water is not able to penetrate into the ski base, the much larger paraffin molecules are certainly incapable of doing so.

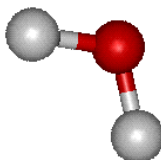


Figure 3: Water (H_2O) molecule (source www.worldofmolecules.com)

Conclusion 1 *There are no pores in the ski base, or these pores are smaller than 1 \AA (the approximate dimension of a water molecule). Hence, no penetration of glide wax into the ski base is possible. After scraping and brushing, only very small amounts of glide wax cover the ski running surface as an adhesion film.*

Mantra number 2 – *It is very important to use glide waxes to protect the ski base from abrasive wear.*

Usually a Sand Slurry Abrasion Test is used to examine the abrasive wear on a given material. The general concept of the Sand Slurry test is that it measures the abrasive effect on a given material when it is exposed to an abrasive solution made up of coarse sand and water. In the test, equal sized bars of the test material and steel are rotated at high speed in a 50% sand / 50% water mixture for several hours. The amount of abrasion of the test material is compared to the amount of abrasion of the steel control. The value of the test specimen will be a relative value compared to the steel. Steel is arbitrarily assigned a value of 100, so a product that suffers a 20% lower loss than steel would have a value of 20 in comparison to steel, which indicates an abrasion resistance $5\times$ that of steel. On the website of the polymer producer Dunone New Material CO., Ltd (www.dunone.com) we can read that UHMWPE is 7 times more abrasion resistant than carbon steel. In (Stein 1999), Figure 1 (see Figure 4) shows Sand Slurry test results for UHMWPE in comparison with other materials. On independent Wikipedia (en.wikipedia.org/wiki/Ultra_high_molecular_weight_polyethylene) we can read about UHMWPE that it: "...is highly resistant to abrasion (10 times more resistant to abrasion than Carbon Steel)".

Conclusion 2 *The ski base material UHMWPE is many times more abrasion resistant than any ski glide waxes available today. Accordingly, the idea that glide wax application protects the ski base from abrasion is clearly absurd.*

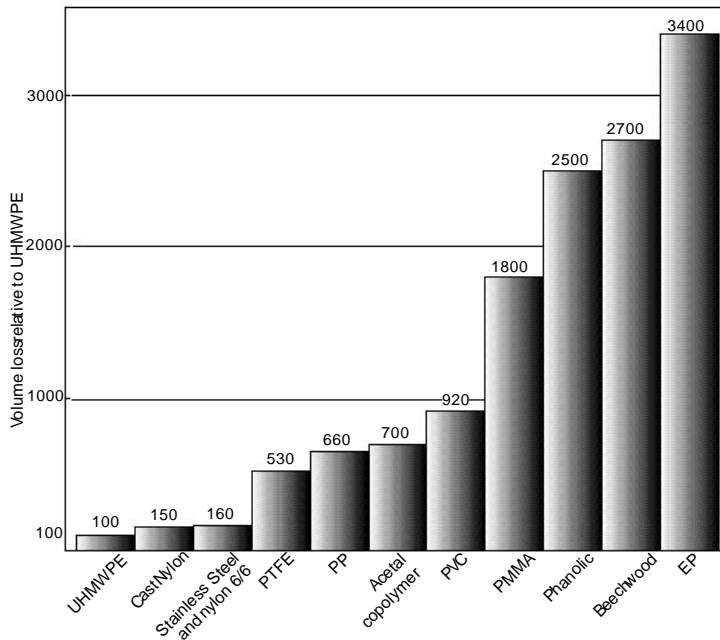


Figure 4: Comparative abrasion resistance of different engineering resins. PTFE, polytetrafluoroethylene; PVC, polyvinylchloride; PMMA, polymethyl methacrylate; EP, epoxy

Mantra number 3 - *Skis with a graphite ski base are much more advantageous than skis with a transparent base, because the graphite prevents the generation of an electrical field which has a negative influence on ski glide.*

The experiment in (Colbeck 1995) distinctly shows the presence of identical electrical fields on skis with a graphite base and skis with a transparent base. The field potential could have reached a value in excess of 3.0 kV. Even when metallic sliders glide on snow (Petrenko & Colbeck 1995) they are charged by strong electric fields of up to $2 \cdot 10^6$ V/m with potentials of up to 1.6 kV.

On the other hand the added graphite (carbon) decreases the hydrophobicity of the ski base (T. Werder & Koumoutsakos 2003), and noticeably impairs the mechanical properties of the ski base. Table 1 presents data from one of the biggest ski base makers, IMS Kunststoff AG (www.ims-plastics.com). The result of this

inexplicable development is that not a single property of the ski base has been improved, but many have deteriorated. We would like to draw attention to the fact that we believe that the "Wax absorption" in Table 1 is not a true absorption, but is in fact a film of wax bonded by adhesion to the ski running surface.

Type	Density [g/cm ³]	Modulus of elasticity [MPa]	Abrasion- resistance Sand slurry Steel = 100	Wax absorption [mg/cm ²]
P-Tex [®] 2000	0.935	500	20	1.9
P-Tex [®] 2000 Electra [®]	1.0	600	30	1.6

Table 1: Physical data on IMS press-sintered running bases ("Electra" is a trademark for the graphite base)

Conclusion 3 *Based on the above-mentioned research results, a transparent ski base is better as a ski running surface than a graphite ski base. Why ski makers only produce X-C skis with a graphite base is one of the biggest mysteries in the ski business.*

We could continue examining the ski waxing mantras in the light of the natural laws in force, but this is sufficient to understand how hard it is to find any grain of rationality in this matter.

Furthermore, someone who is not personally committed to X-C skiing can see the issues more clearly without becoming ensnared in the details. They see the problem from an altitude of abstraction. One suggested abstraction is: It is very difficult (probably impossible) to find any other activity in which technological progress has caused so much trouble as in X-C skiing.

The changeover from wooden equipment to composite and plastic equipment in canoeing and boat racing made the service and storing of boats and oars (paddles) much cheaper and simpler. The changeover from wooden equipment to composite and plastic equipment in X-C skiing made the current servicing of skis many times

more material- and labour-intensive than before. The preparation of one pair of skis at the Olympics 1972 took 15-30 minutes and cost about \$1, while the preparation of one pair of skis at the next Olympics 2006 will take several days and will cost a minimum of \$250 in materials alone, but if we include the service team salaries (which are quite predictable), the preparation will cost more than \$1000. As mentioned before, this development is very mysterious. The new ski base material (UHMWPE) outperforms the old one (wood) in all respects, but the after-sales service of new equipment is considerably more expensive.

1.2.1 The History of Cross-Country Skis

In countries with a snowy winter, different cultures have developed different means for travelling on foot across open country. While snowshoes became the most common equipment in northern USA and Canada, in northern Scandinavia and Finland it was skis.

There are two archaeological finds of skis that lay claim to being the oldest surviving skis in the world. The so-called "Kalvträskskidan", found in Västerbotten in Sweden in 1924, dates back to 3500 B.C. (Åström & Norberg 1984). The skis were made of wood and were 2040 mm long and 55 mm wide (see Figure 5). Other



Figure 5: The Kalvträsk ski

equally old skis (Yrjänheikki 2004) were found in the Saija region of Finland in 1938 (see Figure 6).

In modern history, the predecessor of the present-day ski made its debut in Telemark in Norway in the mid-19th century (Bryden 1998). Unlike many other styles of ski, the Telemark ski was long and thin and had sidecuts, which meant



Figure 6: The Saija skis

that the ski's tip and tail were broader than its waist (Figure 7). By the late 19th

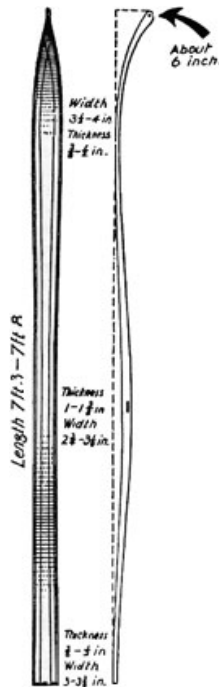


Figure 7: The Telemark ski

century, the Telemark ski had become the standard for the growing ski industry.

The next step in ski evolution was laminated skis. This was a layered ski that featured a hickory bottom with a top of ash or pine, and was introduced around 1932. This combination provided the advantages of lightness and durability with the added benefit of torsion strength. After the initial success of this two-ply ski, it

was only a matter of time before three- (or more) ply skis were developed. By 1951, laminated skis made up ninety percent of all ski production.

By the end of the 1960s and the beginning of the 1970s ski producers had begun to make skis with fiberglass laminate and with a glide-enhancing synthetic base. The development of the ski base was clearly moving towards an increase in durability and hydrophobicity. The step from a wooden ski base to a plastic ski base was very revolutionary, i.e. it was a step from a hydrophilic ski running surface to a hydrophobic ski running surface. In the time of wooden skis, skiers applied a pine tar pitch to increase the hydrophobicity of the wooden running surface (see Figure 8). The evolution of the ski base in chronological order was as follows: spruce →



Figure 8: Tin can with pine tar pitch from SWIX[®]

hickory → hickory with synthetic edges → Acrylonitrile Butadiene Styrene (ABS) → High Density Polyethylene (HDPE) → Ultra High Molecular Weight Polyethylene (UHMWPE).

The World Championship 1974 in Falun (Sweden) was a crucial moment in cross-country skiing history. Thomas Magnusson from Sweden became the first World Champion on plastic skis, the Norwegian Magne Myrmo became the last World Champion on wooden skis.

The evolution of ski construction and geometry followed the development in ski-track preparation. Harder ski-tracks demanded shorter, narrower skis with a

stiffer camber. The present-day skis would never have been invented if ski-tracks had continued to be naturally soft. Modern cross-country (X-C) skis are only an advantage on hard-packed snow on a machine groomed track. For instance, the skating-technique pioneer, American skier Bill Koch (Gotaas 2003) could never have developed such a technique if the ski-track had not been hard and wide enough.

All modern top-level X-C skis have an Ultra High Molecular Weight Polyethylene (UHMWPE) ski base. We therefore only consider this material as a ski running surface material in this thesis.

1.2.2 The History of Cross-Country Ski Wax

Johannes Scheffer in *Argentoratensis Lapponiae* (History of Lapland) in 1673 probably gave the first recorded instructions for ski wax application (Vaage 1977). He advised skiers to use pine tar pitch and rosin.

In the mid-1930s the production of ski-wax was an obscure industry. Ski competitors, retired or still active, ran the business in cellars and backyards. The raw materials were even more obscure, giving rise to strange blends, often with a strong smell. X-C ski waxes were not divided into a kick wax group and a glide wax group at this stage. Ski waxes from this period and earlier are known as the first generation of waxes.

In early 1943 the former elite X-C skier, Martin Matsbo, and a small group of chemists from the pharmaceutical company Astra AB in Sweden got together to draw up general guidelines to create a new ski wax (Swix n.d.). Research projects together with the Royal Institute of Technology in Stockholm were initiated to provide a more scientific approach about the technical factors behind ski glide. They rejected all the traditional raw materials: wood tar, which varied in quality from one batch to the next and broke down during long-time storage, vegetable and animal waxes and oils, rubbers and primitive resins. The innovators understood that a certain number

of different waxes were necessary to give an acceptable coverage of all possible snow-conditions, and they came up with a line of three hard waxes and two klisters. In contrary to the traditional raw materials, which gave black or brown colours, all prototypes were mostly colourless (and odourless). Fat-soluble colour pigments were therefore added to the blends, and the "three-colour idea" was created. SWIX[®] was born in 1946 (see Figure 9). These waxes are known as the second generation

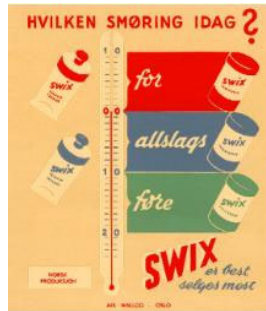


Figure 9: The SWIX[®] poster anno 1946

of waxes, though there was still no division into kick and glide waxes. Skiers used the same waxes as kick- and glide- waxes. Sometimes a softer wax was applied on the middle of the skis. From that time until the present all kick waxes have been and are instances of SWIX[®] à la 1946. Nothing revolutionary has happened since in this field.

Up to this point in time, ski and wax development was like a chain of logically related events, but with the advent of plastic skis in 1974, the chain became broken. The marketing (pseudo-scientific) activities gradually squeezed out the scientific activities.

The development from the first to the second generation is completely understandable: the aim was to get away from unpredictable raw materials, and by utilizing synthetic waxes, rubbers and resins produce a complete range of ski waxes. However, it is much harder to understand why the usage of fluorocarbon additives

and perfluorocarbon powders was hailed as a radical turning point, as a third generation of waxes. The principal unique property of perfluorocarbon powders such as a SWIX[®] FC8 is their high hydrophobicity. However, although it is high, it is not higher than a water drop contact angle of 120° (Blossey 2003). From our own measurements we know that old-fashioned glide hydrocarbon waxes (paraffin) have a water drop contact angle of about 108°, silicon gel more than 112°, and Polytetrafluoroethylene (PTFE) about 120°. It is hard to see it as a radical turning point, or that there is any reason to call Cera F the first wax in a new third generation of waxes. It all looks like an exemplary case of a promotional gimmick.

1.2.2.1 The History of Glide Wax At the beginning of the plastic ski epoch (1974), ski bases were treated at the ski factory with emery-paper. For this reason the ski running surface was very “hairy”, and this "hair" (pile) did not glide very well. In spite of this problem the switch from a wooden ski base to a High Density Polyethylene (HDPE) ski base was a great improvement. The hydrophilic HDPE ski base has a wettability with a contact angle of 110° and glides much better than the hygroscopic wooden ski base that has a wettability with a contact angle of 77° (Kalnins & Feist 1993).

To reduce the mechanical braking caused by the pile on HDPE ski running surfaces, skiers began to apply alpine glide waxes. Soon the wax companies began to produce “special” X-C glide waxes. It is uncertain why skiers stopped using a kick wax along the full length of the skis, but instead began to use glide wax on the front and back (“tips and tails”) of the ski. It was probably because the companies that produced the first plastic skis were Kneissl and Fischer, whose managers had much more experience of alpine skiing. The earliest X-C glide waxes were made of paraffin and a colouring agent. Figure 10 illustrates a typical current hydrocarbon wax.



Figure 10: Modern glide wax

From the very beginning, X-C glide waxes were a mixture of paraffin waxes (softer candle-like waxes) and microcrystalline waxes. Some additives such as graphite, silicon, PTFE, aluminium powder, etc. were utilised too. Paraffin and microcrystalline waxes are usually derived from petroleum.

In the early 1980s, glide wax producers began to use synthetic waxes. Synthetic waxes are very hard and brittle and are used as hardeners for paraffin waxes.

The “third” generation of X-C ski glide waxes arrived in 1987 with the entrance of SWIX[®] Cera F onto the ski wax market (Figure 11).

1.2.3 The Development of Cross-Country Ski Base Treatment

In this overview we will primarily focus on the mechanical aspects of ski running surface processing, beginning with the arrival of the plastic ski in 1974.

The ski running surface on early plastic skis was treated with sandpaper. Quite soon, skiers began to use steel scrapers for the treatment of the ski base. This practice was standard practice from the second half of the 1970s to the beginning of the 1990s.



Figure 11: SWIX[®] Cera F

Stone grinding (SG) treatment of the ski running surface was commonly used from the mid-1980s in alpine skiing. At the beginning of the 1990s, the stone grind-



Figure 12: Stone grinding machine

ing machine (see Figure 12) producers decided to enlarge their domain. The first impression of SG was not very pleasing; the ski did not glide at all. A very material- and labour-intensive processing was developed to get the skis to run acceptably after SG. Moreover, because the machine and wax makers made huge amounts of money by introducing the new equipment, they convinced the X-C skiing community and themselves of the superiority of SG machining. Today, SG (Figure 13) is the only commonly accepted method of ski base treatment.



Figure 13: Ski base stone grinding (source *www.ultratune.net*)

1.3 General approach

Our general research strategy in this thesis and in our future work is to always have a clear reference point. Many scientific papers and many practical manuals in the field of X-C ski waxing suffer from the lack of such a reference point. Our literature review discovered only one study that had investigated X-C ski glide by comparing steel scraped skis with stone ground skis (Hein Bergersen 1994). Even in such a broad paper as (Moldestad 1999) the author had investigated the X-C ski glide by comparing stone ground skis with stone ground skis, but each stone ground ski running surface has quite a complex machined pattern with an improbable repeatability. The results of such an investigation are difficult to compare with the results of future research in the same area. The same weakness has been found in a number of other essays on glide wax, i.e. that waxed skis are compared with waxed skis.

Therefore, we decided to use skis with a steel (HSS) scraped (see Figure 14) base. The ski running surface of all the reference skis was treated manually with an HSS scraper. This treatment is a very repeatable procedure, while stone grinding and waxing with the same glide wax brings in many unnecessary variables. There

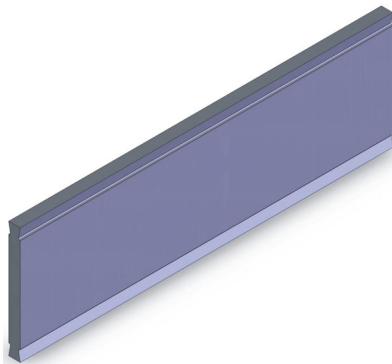


Figure 14: Steel (HSS) scraper

are many differing opinions about how the process of skis stone grinding should be carried out. Neither is it easy to decide which glide wax should be used on the reference skis.

In our opinion, the solution we have chosen is simple and clear – any measurements made on an HSS scraped ski running surface will give us a reliable reference point.

In **Paper A** (*Contact angles on the running surfaces of cross-country skis*) we examined the wettability of the ski running surface. As shown in (Colbeck 1992), a hydrophobic ski running surface would be advantageous under all snow (weather) conditions. In other words, the ski running surface has to be as hydrophobic as possible, or the contact angle with a water drop on this surface has to be as big as possible (180° is a maximum value, of course). We found a quite unexpected phenomenon: dry stone ground surfaces have a low contact angle, much lower than the scraped surface ($104, 83^\circ$ compared with $117, 26^\circ$). Our conclusion is: 1. The stone grinding procedure brushes out the amorphous phase of UHMWPE, the crystalline lamellae (crystalline phase of UHMWPE) rise up and make the running surface bristly and dry; 2. The grey coloured areas on the ski running surface have nothing to do with a “oxidized base”, but are a result of raised lamellae; 3. Glide wax cannot

penetrate into the ski base, glide wax is needed to bind up the lamellae and thereby increase hydrophobicity; 4. The roughness of stone ground and HSS scraped ski running surfaces is very similar;

The results of contact angle measurement in Paper A clarified the magnitude of the water droplet contact angle on the ski running surface and enables us to understand how great an improvement in glide we can get by the use of fluorocarbon additives. As an example, we took a picture (Figure 15) from <http://www.tokous.com/Chemical%20Makeup%20of%20Glide%20Wax.htm>. The picture shows that the con-

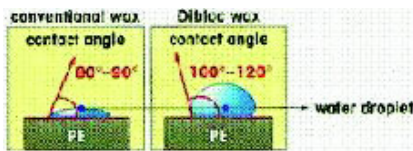


Figure 15: Contact angle on the PE ski running surface with conventional wax vs. Dibloc wax

tact angle on the PE ski running surface with "conventional wax" ($80^\circ - 90^\circ$) is much less than our measurements showed (115°). There is a great difference in the estimated improvement in glide: The results presented by Toko[®] show an improvement in the contact angle of $\approx 50\%$, compared with our measurements of $\approx 4\%$. Since, the planed untreated wooden surface has a water droplet contact angle of 77° (Kalnins & Feist 1993), it is hard to believe that a contact angle of $80^\circ - 90^\circ$ on the PE ski running surface with "conventional wax" is a correct result.

Let us analyse a typical stone grinding pattern (see Figure 16). The pattern parameters are shown in Figure 17. Modern SG machines grind the ski running surface with many different patterns, but these machines have a very important limitation: the minimum pattern element is always parallel to the long side of the ski, in other words the line C-D is always parallel to the line A-B (long side). Ski wax technicians are talking about \wedge -structure, V-structure and X-structure,

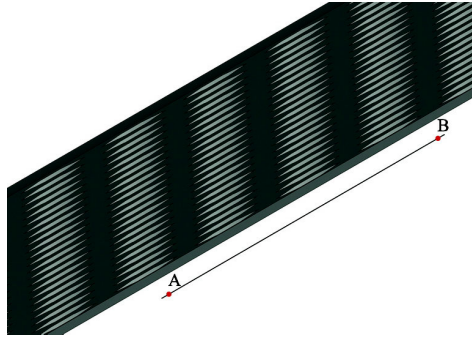


Figure 16: Simplified 3D model of stone ground (SG) ski running surface without bristles

but such structures (pattern) only exist as an optical illusion when many small elements follow line C-I, which is not parallel to A-B. This limitation makes SG processing as deteriorative ski glide procedure under cold weather conditions. As seen in (Colbeck 1994), when the elements are oriented longitudinally with the ski, the film of meltwater tends to be thinner. When the elements are oriented transversely across the ski, the water film thickness increases as the fluid pressure increases on the upstream sides of the asperities. Thus, a transverse structure should be beneficial at low temperatures, whereas a longitudinal structure should be better at high temperatures. The results of Paper A and the above-stated pattern analysis clearly show how important it is to find some other alternative to SG processing.

In **Paper B** (*Dirt absorption on the ski running surface - Quantification and influence on the gliding ability*), we examined the gliding ability of waxed and unwaxed skis, the sliding surface whiteness and the hydrophobicity. Our results were as follows: 1. Skis treated by any established waxing procedure lose their glide ability faster than the reference skis (dry skis); 2. Dirt absorption influences gliding ability negatively; 3. SG waxed running surfaces absorb more dirt than HSS scraped waxed running surfaces; 4. The peak pollution level (thickness) was higher on the waxed skis than on the reference skis; 5. Running surface darkening and skis slowing down

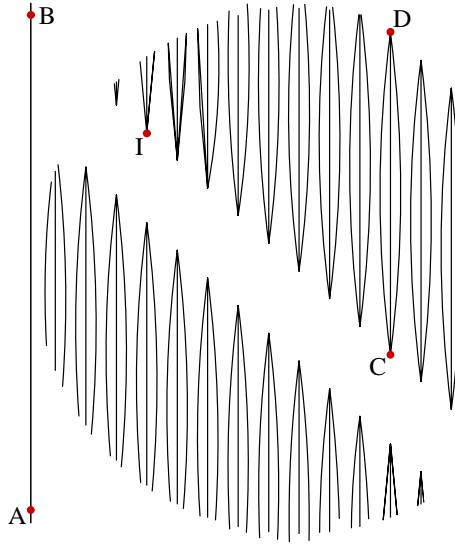


Figure 17: The view from above of the 3D model of stone ground (SG) ski running surface

correlate sufficiently closely;

General Conclusion: *The ski base material – UHMWPE has a high hydrophobicity after HSS scraper treatment (around 117°). This hydrophobicity is just slightly under the hydrophobicity of fluorocarbons (fluorocarbon polymers), which is around 120° . UHMWPE has an enormous abrasion resistance and does not need any glide wax protection. The step from a wooden ski base to a plastic ski base was a vast improvement: - water repellence increased by $\approx 53\%$, - abrasion resistance increased by $\approx 2700\%$. It seems that at the end of the 1970s the X-C community missed the opportunity to reconsider the value of glide waxing. Traditions and inertia resulted in the community retaining their old waxing principles, which were intended for wooden skis. However, 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.*

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2 Part II - Papers

Paper A

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

* This study is partly financed by the European Union.

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.

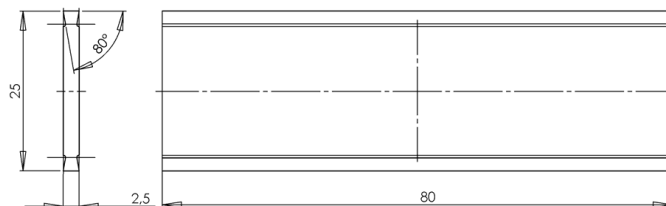


Figure 1. High Speed Steel (HSS) scraper.

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 1,5cm² area. An arithmetical mean value was then computed for each sample.

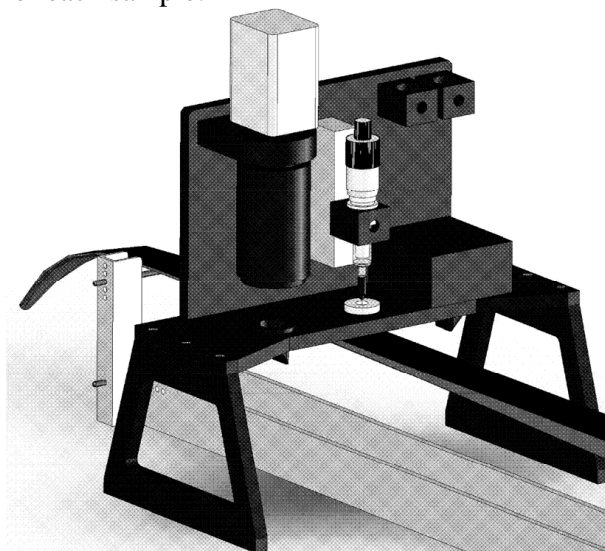


Figure 2. Ski under FTA125 goniometer.

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 1,5cm² 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.

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

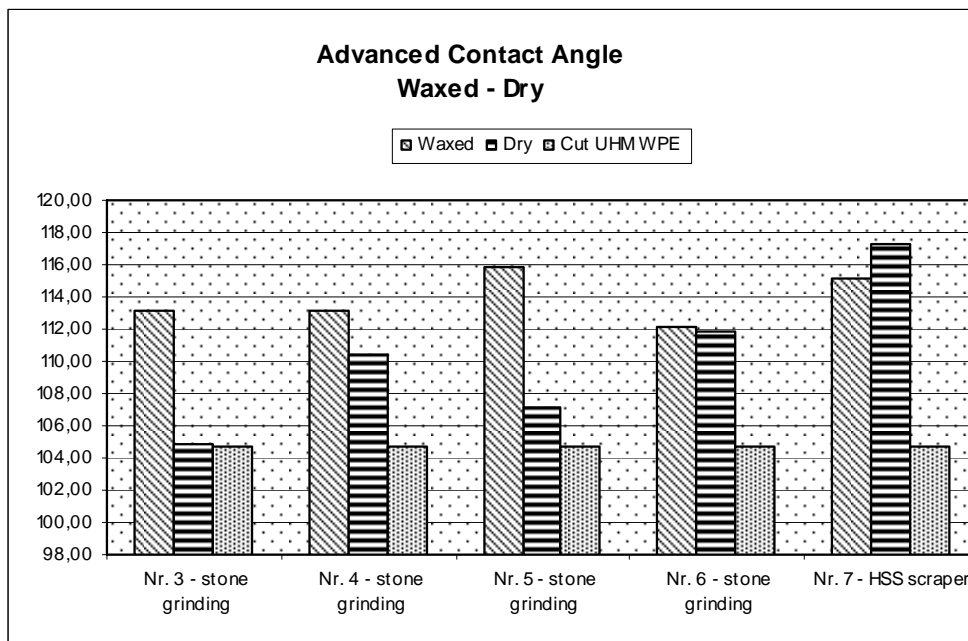


Figure 3. Contact angle comparison for differently treated surfaces.

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

The authors are grateful to their colleagues at the Tribology Laboratory at Luleå University of Technology for help with the 3D measurement of the ski running surfaces, to Klaus Krenn at ISOSPORT GmbH for the samples of running base and the fruitful discussions, and to Lars Svensson for the professional stone grinding of our samples.

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Paper B

Dirt absorption on the ski running surface - Quantification and influence on the gliding ability.

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- Sincere gratitude to Professor Mikael Jonsson (Luleå University) for the very fruitful discussions.
- In addition to the above we would like to mention that this study is partly financed by the European Union.

Abstract

It is common knowledge that minimizing 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 result all waxed skis lose their glide ability sooner then unwaxed (dry) skis. General conclusion: Stone grinding and glide wax application are far from an optimal treatment for skis if the primary goal is to minimise friction over a given distance.

Keywords: dirt, glide, ski, wax.

1 Introduction

For many, 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 overwhelming majority of research papers regarding sliding on snow have a direct connection to sport and to skiing competitions. And of course 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 μ is the friction coefficient, the subscripts *plough*, *dry*, *lub*, *cap* and *dirt* represent the friction due to ploughing, solid deformation, water lubrication, capillarity attraction, and surface contamination, respectively. In the real world such processes are not independent. For instance $\mu_{cap} = f(\mu_{dirt})$, because the optimum roughness of the ski running surface gradually becomes covered with dirt, and the capillarity drag increases, as shown in (Wenzel 1936) and (Cassie & Baxter 1944). But we have to simplify for the sake of the analysis.

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 overwhelming majority of ski technicians try very hard to decrease the electrostatic charge of the ski's running surface. Although Colbeck's (1992) wrote about the importance of using graphite waxes to minimize the electrostatic 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 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 treating the ski base in different ways affects the level of contamination of the ski base surface.

2 Apparatus and 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 (X-C) skiing. Our primary goal was to examine the relation 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 some 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.

2.2 Skis and their preparation

We used 5 pairs of identical Madshus skis (Appendix A.1) with a transparent base (P-Tex[®] 2000, Appendix A.1) and white background from the same batch. One pair was treated by stone grinding (SG) on a Tazzari RP13 by Lars Svensson, an internationally acclaimed expert (see Appendix A.1). The other skis were treated using an HSS scraper (Fig. 1).

For waxing we used the following SWIX[®] products: hydrocarbon wax - CH8, fluorocarbon wax - HF8, and perfluorocarbon powder - FC8. The hot waxes were

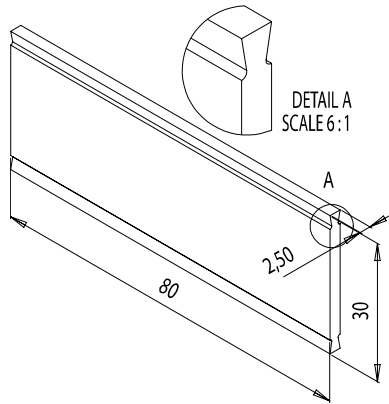


Figure 1: High Speed Steel (HSS) scraper

melted into the ski base 3 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 small special iron for applying the powder to ensure that good contact was made with the ski base. The very high initial water contact angle – 120.6° on the running surface prepared with the powder indicated satisfactory treatment. Before measurement the hot-waxed skis and dry skis were brushed with a Red Creek steel rotary (4000 r/min) brush. The skis treated with FC8 were brushed with a Red Creek horsehair rotary (4000 r/min) brush. A clean brush was used for the dry skis and another for the waxed skis.

2.3 Dirt attraction measurement

2.3.1 Theoretical principles

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 (1–4%). 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 10 years ago. Madshus AS kindly helped us by making a few pairs of such skis. 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. Such a small amount of graphite does not significantly affect the dirt attraction properties of the ski base. Therefore, 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 rate of the actual ski running surface. We assumed that the transparent base and white background reflect the greater part of the incident ray, so the light loss must be the result of absorbance of 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 2. The equation representing the Beer-Lambert Law is very straightforward: $A = \varepsilon bc$, where ε is the molar absorptivity, b is the pathlength 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 pathlength $b = h/\cos \alpha$ is a major influencing quantity, where h is the thickness of the dirt layer. The thicker the dirt layer \implies the greater the absorbance $A \implies$ and the larger the light loss.

In our real 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.

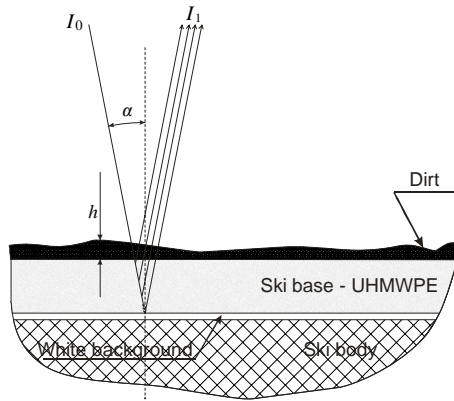


Figure 2: Beer-Lambert Law on the ski running surface

2.3.2 Hardware design and configuration

We chose a standard X-C ski workbench from STAR Ski Wax as a base stock, no. 4 in Figure 3. A uEye USB 2.0 camera (no. 2) acted as an image device (see Appendix A.2.1). Two halogen bulbs (no. 1) provided a powerful light source. Each halogen lamp was directed to a point on the ski running surface which was 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.) have a negligibly small influence on the total luminosity.

We used a direct current (DC) 12 V power supply with improved accuracy instead of using the standard alternating current (AC) 12 V power supply (see Appendix A.2.1). From the beginning we used the standard AC 12 V power supply, but only achieved about $\pm 6\%$ scattering in a test with a control sample, which is not acceptable. Probably the nature of the alternating current and the variability of commercial electricity mains supplies have an influence on the precision of measurement. With the Nordic Power DC 12 V power supply we achieved $\pm 0.4\%$ scattering

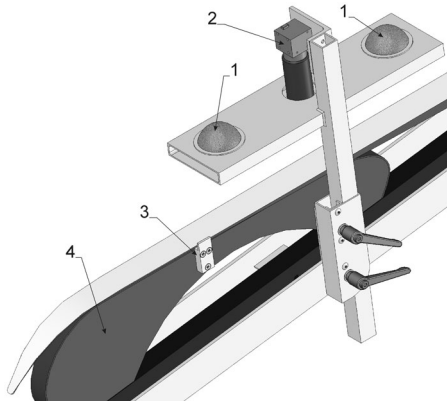


Figure 3: Experimental assembly

in a test with a control sample, which is high enough, because the real tests showed much larger differences.

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

2.3.3 Software and configuration

As an image capturing application we used "uEye Demo" (see Appendix A.2.2). uEye Demo was configured to capture a 8 bit monochrome image with no software correction. The processing line is presented in Figure 4. Each image is stored on the PC hard drive as a BMP 8-bit, grayscale mode file. In fact, this file is a matrix W (whiteness) with the size $m \times n$. Because the image is in a Grayscale mode, each matrix element $w_{ij} \in [0, 255]$, or in other words $0 \leq w_{ij} \leq 255$. As a whiteness value (w) we simple used the arithmetical mean of all the elements w_{ij} in the matrix W :

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

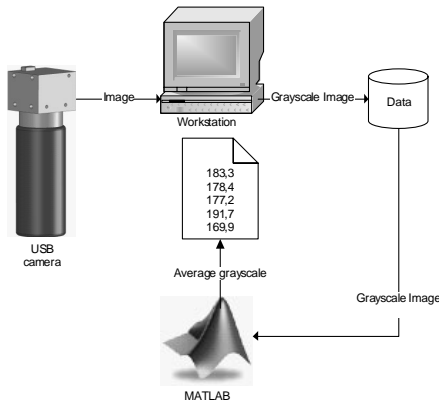


Figure 4: Processing line - from image capture to recording of average Grayscale

To realize Equation 1 we applied a MATLAB procedure `mean2` to our M-file script (see Appendix A.2.3) 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 (about $22.5 \times 17.5 \text{ mm}^2$) large, therefore in our case $m = 1013$, $n = 717$ and the total number of matrix elements is $[mn]_{m=1013, n=717} = 726\,321$.

2.4 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, θ'' is a right angle, as in Figure 5. The larger the angle, the higher the hydrophobicity. A goniometer FTA125 (presented in Figure 6 and in Appendix

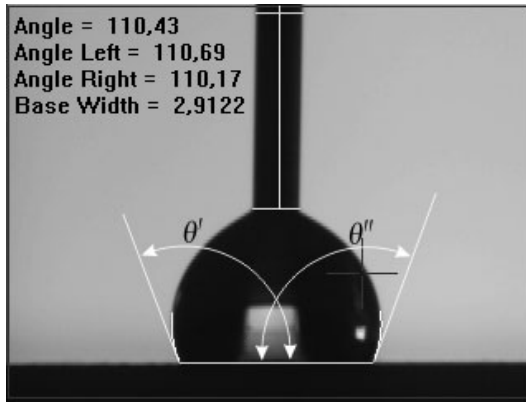


Figure 5: Contact angle presented by Fta32_Video

A.3.1) and the software Fta32_Video (see Appendix A.3.2) were used to measure this angle. The pump on the goniometer was driven manually. 31 images with rate 2 frames (images) per second were captured during each measurement. An arithmetical mean value was then computed for each sample: $\theta = \frac{1}{31} \sum_{i=1}^{31} \theta_i$.

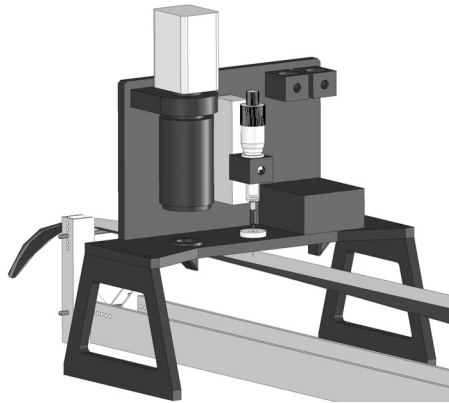


Figure 6: Ski under FTA125 goniometer

2.5 Gliding velocity measurement

Ski glide velocity was registered using a well-established procedure shown in Figure 7.



Figure 7: Glide test on a controll slope

A STAR Ski Wax digital chronometer with an infra-red sensor was used for time-taking (see Appendix A.4). This device has a resolution of 10^{-3} s. All the glide tests were performed on the same control slope. The slope is about 170 m. The first 70m are quite steep but the 100 m clocking zone is less steep. Our aim was to have about $10 \text{ m} \cdot \text{s}^{-1}$ average speed in the 100 m clocking zone. When the glide conditions were poor we started higher, under good glide conditions we started lower.

2.6 Realisation of the experiment

In this section we start by defining 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 Appendix B, Table 2), where 4 pair of skis were involved, two pairs as a 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.

The testing procedure was according to the following steps:

1. 4 pairs of skis are prepared for the experiment. 2 pairs are prepared with different well-established treatments, 2 pairs are prepared using well-established methods of treatment, 2 pairs are HSS scraped and remain dry;
2. Each new prepared pair is slid 5 – 10 m on the snow before taking the first measurements, to avoid choosing an unrepresentative basis for comparative measurements;
3. The skis are placed inside the wax cabin to get warm and dry;
4. Whiteness and hydrophobicity measurements of the ski running surface are performed;
5. 2 pairs of skis (one pair treated and one pair dry) are transported in a ski bag to the control slope. The glide test is performed. The same skier dressed in tight race suit performs all the glide tests during the whole test case;
6. Two skiers of similar weight and skill skate together an arbitrarily chosen distance, the path length is measured using a curvometer on the map afterwards;
7. The skiers return to the control slope. A glide test is performed;
8. These 2 pairs of skis are placed inside the wax cabin;
9. Another 2 pairs of skis (one pair treated and one pair dry) are transported in a ski bag to the control slope. The glide test is performed;
10. Steps 6-8 of the sequence are repeated with the new skis;

11. Whiteness and hydrophobicity measurements of the ski running surface of the first two pairs are performed. It takes more than 1 hour to perform steps 7-8, so the skis have enough time to become warm and dry;
12. Two skiers skate together an arbitrarily chosen distance on the two first pairs of skis;
13. Steps 7-8 of the sequence are repeated;
14. And so forth;

Usually we have had time to perform two such cycles (one cycle include steps 5-10) under stable conditions, sometimes only one. We performed 9 test cases (9 days) in total, but only 4 cases were successful and are presented in the paper. An icy ski track, unstable power supply, etc. made the work of 5 days inapplicable.

3 Results

3.1 Relation between distance covered and running surface hydrophobicity

Only one test case was performed under conditions below 0°C . With wet snow conditions grime covers the ski gliding surface extremely fast and contact angle measurement does not produce any useful values, because the thickness of the dirt film does not affect hydrophobicity much. For this reason we did not get any results that showed a significant dependence between the distance covered and the running surface hydrophobicity. We need to perform more tests under cold conditions.

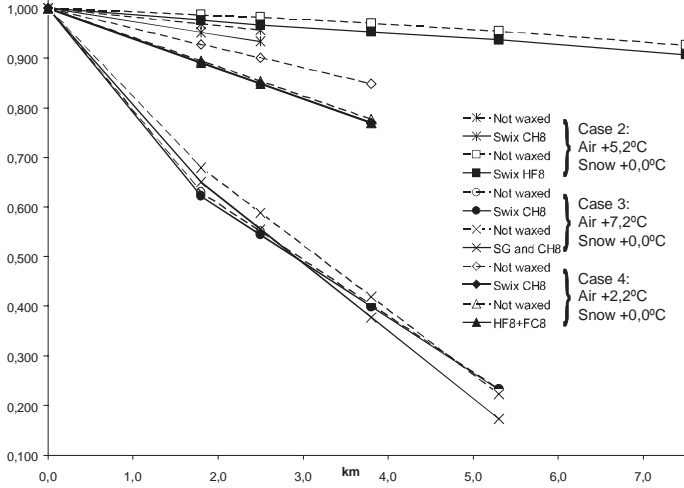


Figure 8: Comparative average grayscale of running surface sample area and distance covered

3.2 Relation between distance covered and running surface contamination

In Figure 8 and in Appendix B, Table 3 we see how quickly the ski running surface became darker. Case 1 is absent 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 dotted lines correspond to the dry (control) pairs of skis, the solid lines correspond to the waxed skis. Our result is definite – waxed ski base surfaces always became dirty sooner than unwaxed (HSS scraped). So, the next step was to examine how consistently the gliding velocity of the skis conformed to this tendency.

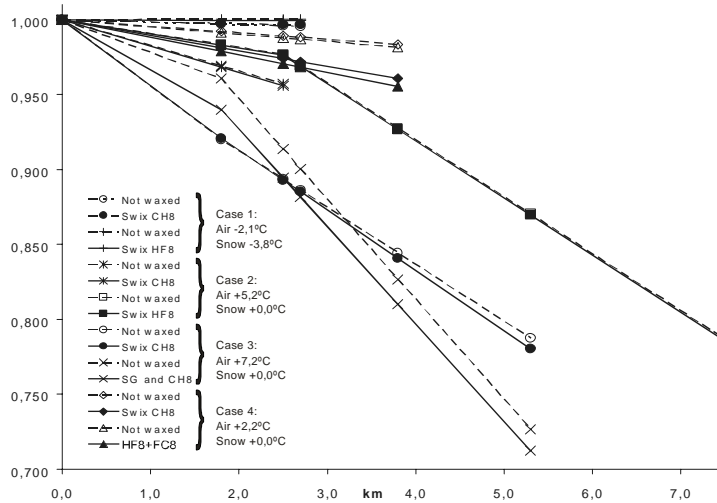


Figure 9: Comparative gliding velocity on the test slope and distance covered

Figure 9 shows that the tendency is the same - waxed skis lose their velocity sooner than unwaxed. 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 on a stretch of a realistic distance?

Let us examine Figure 10 (Appendix B, Table 4). Yes, 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 advantage longer (≈ 3.8 km) than (≈ 2.35 km) old-fashioned CH8 (-◆-), but still not for very long. In Figures 11 and 12 we can see a difference in contamination even with the naked eye.

Some types of ski treatment and certain snow conditions may shorten the advantage of the waxed skis considerably. In Table 1 the results of 3 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

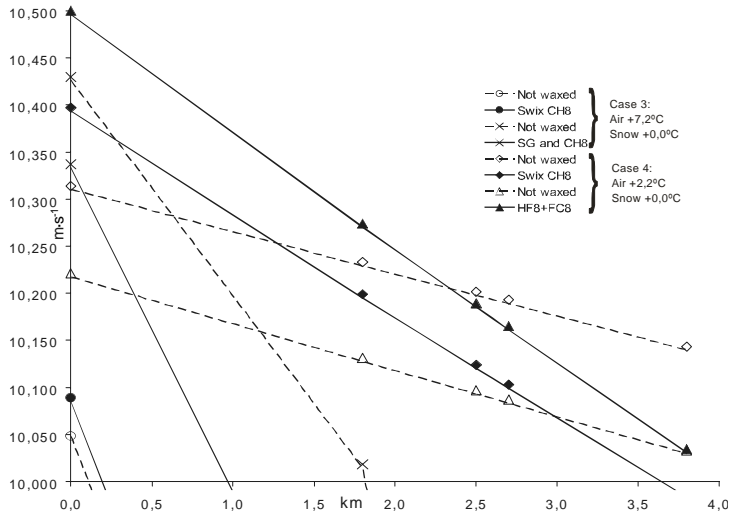


Figure 10: Average gliding velocity on the test slope and distance covered (close-up)

than the dry ones. The turning point lies around 200 m in this case.

Briefly:

- 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 sufficiently closely;



Figure 11: Unwaxed after 3.8 km (Case 4)



Figure 12: Waxed with Swix[®] CH8 after 3.8 km (Case4)

no. of descent	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

Table 1: Extreme example - turning point seen already during the second descent on a 100 m slope

4 Discussion and conclusions

4.1 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:

$$\int_0^l f_w(s) ds = \int_0^l f_d(s) ds \quad (2)$$

where l is the turning point at which the advantage of waxed skis changes into a disadvantage, $f_w(s)$ is the friction resistance force of the waxed skis, $f_d(s)$ is the friction resistance force of the dry (unwaxed) skis, 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 Figure 13 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. Undoubtedly, this is good news for millions of cross-country skiing amateurs, who may save both time and money. However, even for professional skiers, these results indicate that a new waxing philosophy is needed. Moreover, regarding the practical work in the field environment, technicians do not need complicated equipment for measuring friction. 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 as high as from 0.958 to 0.998 depending of the case. We can use it and predict increase of frictions as a function of darkening. Therefore, the

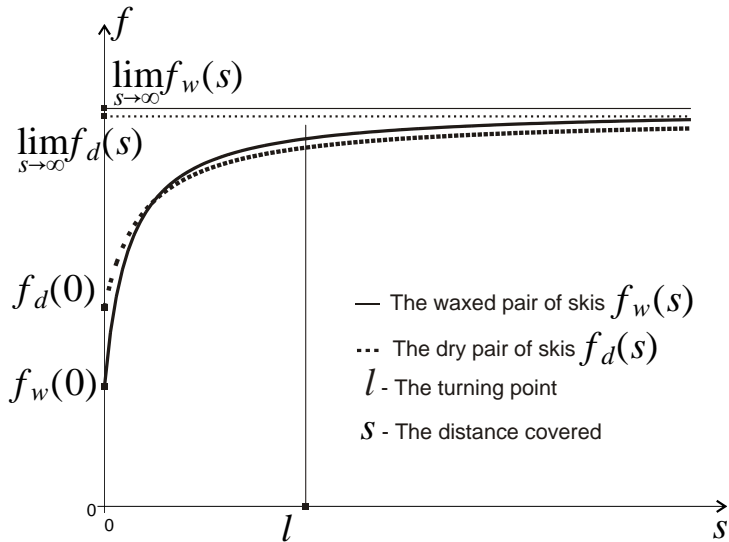


Figure 13: The graphic illustration of the general glide-distance problem

technicians only need to test the glide once to get 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 get $w_d(0)$, $w_w(0)$, $w_d(s_1)$, $w_w(s_1)$, $w_d(s_2)$, $w_w(s_2)$ (see Equation 1), where subscripts d and w represent unwaxed (dry) and waxed skis, s_1 and s_2 are suitable distances, $s_1 < s_2$. Next, they may define the actual instances of $f_w(s)$, $f_d(s)$ and find out the turning point l , and the magnitude of l indicates which races they should ski on unwaxed skis and which on waxed.

4.2 Running surface treatment

The situation regarding glide waxing in X-C skiing today is not acceptable. Waxing gurus tell terrifying stories, which scare away millions of potential skiers all over the world. Glide waxing procedures are grounded on unfeasible principles. The majority of all commonly accepted waxing postulates are pure mantras. Here is an extract from an interview with a Senior Research Scientist at the US Army Cold Regions Research and Engineering Laboratory, Dr. Samuel Colbeck (Rozell 1999): For all

the interest in gliding faster on snow and ice, Colbeck said there's been a remarkable lack of interest by ski companies in the physical processes that occur where ski meets snow. Most of the industry advances have been like genetic mutations, he said, where a company happens to select a new base material or color, it works, and everyone copies them. "The geometry of ski bases is not well understood," he said. "It's a science with a long way to go."

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

Stone grinding decrease 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 increase 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 are softer than the ski base. 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 incredible mechanical properties, etc. 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.

5 Future work

- To perform similar experiments under cold weather conditions (minus °C);
- To get skis produced with a transparent base with different molecular weight, and continue similar experiments to see 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 for the measurement of friction (glide) of skis without a skier, as aerodynamic resistance is a great source of inaccuracy;

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A Appendix - Experimental setup

A.1 Skis and their preparation

- Ski producer - Madshus AS, Norway, www.madshus.com;
- Base producer - IMS Kunststoff AG, Switzerland, www.ims-plastics.com;
- Grinding - Grinder RP13, Tazzari Sport Division, Italy, www.tazzarisportdivision.com;
- Stone grinding technician - Lars Svensson, MILEX, Sweden, www.milex.se;

A.2 Dirt attraction measurement

A.2.1 Hardware

- uEye USB2.0 camera - UI-1410-C from IDS Imaging Development Systems GmbH (www.ids-imaging.de/www/templates/uEye/uEye_e.htm), VGA with CMOS sensors. The aperture was adjusted to 16;
- Halogen lamp - OSRAM DECOSTAR[®] 51 IRC, 51 mm diameter, 45 mm length, GU5.3 base, with shield, 12 V, 35 W, 24 ° beam angle, 4400 cd luminous intensity;
- Power supply - Nordic Power primary switching power supply, type S014112C, 0.5% load regulation, 0.2% line regulation, ripple $\leq 100 \text{ mV}_{t-t}$;

A.2.2 Software

- uEye camera driver and capture application - uEye Demo Version 1.12.0012, grayscale mode, 8 bits colour depth;
- Statistical treatment of a grayscale image file - MATLAB[®] Version 7.0.1.24704 (R14) Service Pack 1;

A.2.3 MATLAB script (M-file)

```
%%_This M-file calculate an arithmetical
%% mean of an grayscale image._____%%
clear;
format compact;
disp(['XXXXX-----' date '-----XXXXX']);
M=ls;
MS=size(M);
```

```

RS=MS(1);
CS=MS(2);
n=1;
ActMap=pwd;
GrFile=fullfile(ActMap,'GrayScale03.xls');
for i=1:RS,
    RST=M(i,1:CS);
    if strfind(RST,'.bmp')
        IMG= imread(RST);
        IMG2=IMG(12:1024,4:720);
        MRES(n,1:CS)=RST;
        mean_IMG(n,1)=mean2(IMG2);
        disp(['mean gray scale of ' RST]);
        disp(mean_IMG(n,1));
        n=n+1;
    end
end
cd MatLab;
xlswrite5(MRES, GrFile, 0,2);
Write2Excel(GrFile, 0, '[1,1]',mean_IMG);
cd ..
%%%%__END__%%

```

A.3 Contact angle measurement

A.3.1 Hardware

Goniometer - goniometer FTA125, First Ten Ångstroms, USA, www.firsttenangstroms.com;

A.3.2 Software

Software for frame grabber - Fta32_Video build 211, First Ten Ångströms, USA, www.firsttenangstroms.com;

A.4 Gliding velocity measurement

Digital Chronometer - Crono Test PC2005, STAR SKI WAX, Italy, www.starwax.com;

B Appendix - Tables with the experimental data

Case no.	air [°C]	snow [°C]	Relative air humidity [%]	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

Table 2: Air and snow conditions under the test cases

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		

Table 3: Comparative average grayscale of running surface sample area and distance covered (NW is 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		

Table 4: Average gliding velocity [m/s] on the test slope and distance covered (NW is 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		

Table 5: Additional Table - Average grayscale of running surface sample area and distance covered, separately for the left (L) and for the right (R) skis (NW is 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		

Table 6: Additional Table - All gliding velocity measurements [m/s] on the test slope and distance covered (NW is abbreviation for "Not Waxed")

