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Nano ski wax, effects and benefits

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FOR
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Nano ski waxes, effects and benefits

Enthusiastic skiers spend much time and money in order to optimize their gliding performance. The traditional way to wax skis includes several steps starting from various hydrocarbon waxes to advanced treatments with high flour content waxes. In recent years liquid gliding products have offered a further possibility.

The effects of ski waxes are often discussed but rarely studied. Ski bases consist of ultra-high molecular weight polyethylene (UHMWPE) in semi crystalline state. Diffusion of ski wax into the base material as a function of time and temperature should be studied. This master thesis will focus on the material changes due to the waxing process: how do liquid gliding products interact with the ski base and which influence have the process parameters (i.e. snow conditions, speed, weather, etc.) on the tribo-system?

Liquid gliding products will form a thin coating on top the ski base material. The characteristics of these coatings and its contribution to a reduced coefficient of friction should be studied.

Methodology: During the project thesis, relevant methods to characterize the ski base were found and used (Raman Spectroscopy, DMTA, XPS). However, there are some results that need to be further developed due to their complexity (i.e. XPS).
A methodology on how to measure wear of the gliding product should be found and defined during this master thesis (material loss, contact angle, chemical analysis, topographical changes of the surface, etc.).

The experiments will be as follows:
A) Ski base characteristics.
B) Gliding product characteristics.
C) Application methods.
D) Field and/or lab experiments.
F) Analysis of the results.

The project will be in cooperation with Olympiatoppen and the Norwegian ski team.
The thesis should include the signed problem text, and be written as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is appreciated.

Three weeks after start of the thesis work, an A3 sheet illustrating the work is to be handed in. A template for this presentation is available on the IPM's web site under the menu "Masteroppgave" (http://www.ntnu.no/ipm/masteroppgave). This sheet should be updated one week before the Master's thesis is submitted.

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ABSTRACT

The effects of the gliding properties of ski waxes are often discussed and many speculations and assumptions are made. However there are not many studies and documented results in this field. This project is carried out in cooperation with Olympiatoppen and the Norwegian ski team to research and document the effects and benefits of gliding waxes. Ski base material consists of ultra-high molecular weight polyethylene (UHMWPE) in semicrystalline state. The focus will be on the material changes caused by the waxing process. This project examines two different types of ski base material with three different gliding waxes. Essential factors of the friction and the effects of gliding wax on skis were studied. The Fluor content, both in the base material and in the wax, and the Gallium content in one of the gliding waxes, was, given special attention. Experiments on the ski base materials, with and without waxes, were conducted. Material characterisation has been evaluated by using XPS, ICP and contact angle measurement of water droplets on the ski base materials. The friction properties have been tested with outdoor gliding field tests where the two ski bases have been compared with each other and also a reference ski. A tribometer was used in the lab to measure the coefficient of friction. The content of the ski base material were unknown, there is found that both type of bases tested contains Fluor. It was also found that the Fluor content on the top surface is not directly comparable with the surface energy and the contact angle.

SAMMENDRAG

Det er enorm interesse for ski i Norge, spesielt langrennski. Det er mye synsing og meninger om hva som gir best glid, men det er veldig lite vitenskapelig forskning som har blitt gjort på området. Dette prosjekte er et samarbeid med Olympiatoppen og det norske skilandslaget for å undersøke og dokumentere egenskaper og effekt av glider på langrennski. Skisålematerialet er laget av ekstremt lange kjeder med polyetylen, ultra-high molekular weigh polyethylene (UHMWPE). Dette materialet er semikrystallinsk, har lav friksjonskoeffisient og høy slitasjemotstand.

Målet med dette prosjekte var å undersøke materialegenskaper og friksjonsegenskaper til to skisålematerialer, samt å se på virkningen av tre forskjellige glidere på disse materialene. Materialanalyser ble gjennomført ved hjelp av et røntgen fotoelektron spektroskop, XPS, og ved å måle kontaktvinkelen av vanndråper på materialene. På denne måten vil man se hvor vannavstøtende materialet er. Dette har en sterk sammenheng med friksjonen til materialet. Det ble kjørt glidtest ute i skisporet, her ble de to sålematerialene målt opp mot hverandre og mot en referanseski. Det ble også kjørt friksjonstest i lab, der friksjonskoeffisienten til materialene ble målt. Et veldig interessant punkt var om det var mulig å sammenlikne labresultatene med de resultatene man fikk ute i feltet. Innholdet i sålematerialet var ukjent, ved hjelp av XPS analyse fant man ut at begge sålematerialene inneholdt fluor. Det ble også funnet ut at fluorinnholdet på overfalten av skisålen ikke er direkte sammenlignbar med overflateenergien og kontaktvinkelen sålematerialet lager i kontakt med snø og vann.

PREFACE AND ACKNOWLEDGEMENTS

This report was written as the master thesis curriculum for the master program for Mechanical Engineering, in the Department of Engineering Design and Materials. The master thesis is a 30 ECTS study as the subject TMM4911 Materials and has duration of 20 weeks.

I am amused to investigate and do technical research in one of my big hobbies and to get a deeper understanding of the material technology behind skiing. This has been a great opportunity to learn more about tribology and to do experiments in the lab.

I would like to thank my supervisor Nuria Espallargas for her guidance and help through the whole project and my co-supervisor Felix Breitschädel for sharing his knowledge of skis and the help with my experiments.

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DECLARATION OF AUTHORSHIP

I hereby declare that this document has been composed by myself and describes my own work, unless otherwise acknowledged in the text.

Date: 10.06.2013

Nora Holst Haaland

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols	Description
a	Acceleration
F_F	Friction force
F_N	Normal force
g	Gravity
m	Mass
R_a	Arithmetic mean roughness
R_q	Root mean square average roughness
T_g	Glass transition temperature
T_m	Melting temperature
v	Velocity
v_0	Start velocity
x	Distance
α	Contact angle
λ_c	Cut off length
μ	Coefficient of friction

Abbreviations	Description
COF	Coefficient of friction
DMTA	Dynamical mechanical thermal analysis
HDPE	High density polyethylene
HMWPE	High molecular weight polyethylene
ICP	Inductively coupled plasma
LDPE	Low density polyethylene
NTNU	Norwegian University of Science and Technology
PECVD	Plasma-enhanced chemical vapour deposition
ppm	Parts per million
PTFE	Polytetrafluorethylene
RSD	Relative standard deviation
SD	Standard deviation
UHMWPE	Ultra high molecular weight polyethylene
XPS	X-ray photoelectron spectroscopy

1 INTRODUCTION

Norway has a long and proud ski history, they say Norwegians are born with skis on their feet, but that alone is not enough to become world champion. In the biggest races where the skier not only wins a noble gold medal, but also the nations honour and the worlds respect, it is the small details that difference the winner from the loser, or second place. There is a lot of money to be made in the ski industry, neighbours competing for who have the best equipment and the fastest skis and top athletes who have a new pair of ski for every type of snow and temperature. The ski wax industry is no different. Leisure skiers have their own ski preparation room in the basement and the top athletes have hired their own personal ski waxer. Many enthusiastic skiers have done their own gliding tests and know what wax they prefer for the different snow and weather conditions, but very little is documented and proven in this area.

What we do know is the factors that affect friction. Low friction gives good glide. Some of the features that affect friction are the type of weather, snow, skis, the structure of the ski base, the ski base material and the type of wax. It is not easy to optimise friction as many aspects need to be considered. Various types of ski wax exist, both for gliding and kicking. With the right weather and snow information it should be possible to choose the best pair of skis and optimise them with wax.

The ski base material used today is mostly ultra-high molecule weight polyethylene (UHMWPE) or other types of polyethylene and polytetrafluorethylene (PTFE), better known as Teflon. Polyethylene has been the major ski base material since the 1970s. Polyethylene, especially UHMWPE, has very good characteristics; it has high hydrophobicity and low friction, good wear resistance and has relatively easy processability and is therefore a natural choice.

The Winter Olympics is one of the events that gather most Norwegian people in front of the TV screen. The pride in the ski history and the desire to be best in the ski track makes a grand interest for the Norwegian people. To fulfil the nation’s desire they need the best people and the best equipment, and also the best ski base and wax. This project aims to document the effects of nano ski wax in cooperation with Olympiatoppen and the Norwegian ski team.

2 GOAL

In a previous project work (performed in the fall semester of 2012), background information for eight ski base materials was found. The primary focus in this master thesis has been to investigate the factors that affect the friction in the ski base material, with and without gliding additives (e.g wax). Two ski base materials from the previous project were selected for thoroughly investigation of material characterisation and friction properties. Field and lab testing was performed to document the material and frictional properties and to analyse which elements that makes the friction lower so the ski glide better.

The aim of this project was to research and document the effects and benefits of nano ski wax on the ski base material. Ultra-high molecular weight polyethylene is the most common ski base material used by the elite. The effect on different additives in the friction and gliding properties of the ski base material was investigated and experiments were conducted. Special attention was paid to the Fluor and Gallium content in the materials and in the waxes. Characterisation of the ski base material was performed and the friction and wear properties was analysed towards skiing.

A modified tribometer for low temperature tests and other materials characterisation techniques will be used for material and frictional investigation. Both outdoor field tests and lab tests will be conducted with the aim to be able to see the feasibility of using lab tests for predicting field performance of ski materials. The Fluor content of two ski bases and in the waxes will be examined as the main elements providing with the best gliding. How the Fluor content and coefficient of friction goes together shall be evaluated.

3 THEORETICAL BACKGROUND

3.1 HISTORY

Skis have existed for centuries. The oldest skis in existence were found in Sweden and are dated all way back to 3200 BC [1]. Skis originate from Scandinavia and through time skis have mainly been used for hunting and transportation. In the 19th century skiing became an activity for enjoyment, and in 1924 the first winter Olympics were held in Chamonix, France, where Norway won the most medals. In Norway skiing is a big part of the history and the national identity, especially cross country skiing. One of the most famous historical incidents took place in the beginning of the 13th century when Norway was in a civil war. The biggest enemies were Birkebeinerne and Baglerne. King Sverre, the leader for Birkebeinerne, had gathered most of the Norwegian country under his dominion. Sverre was succeeded by his son Håkon Sverresson, but himself died 2 years later in 1204. Sverresson's new born son, Håkon Håkonsson, was thus strongly pursued by Baglerne. Figure 1 illustrates Håkonsson's escape over the mountains as a baby in the arms of Birkebeinerne. When he was brought to safety, the civil war ended and Håkon Håkonsson became king of a united medieval Norway. In 1932 a cross country ski competition started to honour Birkebeinerne, and today there are 16 000 participants annually in the 54 kilometre long race [2-4].

Figure 1 Good skiing skills saved the heir to the throne, illustrated by Knud Bergslien.

In newer history Sondre Norheim (1825-1897) from Telemark is said to be the founder of modern skiing. He developed slalom, introduced Telemark and gave the old ski a new shape, binding and technique, this made skiing much more than only a type of transportation [5].

Ski wax has existed for a very long time, both to preserve the skis and also as kicking wax, to get a grip. This was done by mixing resin, paraffin, animal tallow and tar and putting it underneath the ski. In 1943 the Swedish skier Martin Matsbo joined a pharmacy company, AB Astra, to develop new ski wax together with engineers and chemists. It resulted in SWIX. In 1946 SWIX launched three different kick waxes, red, blue and green, depending on the weather [6]. In the 1973-1974 season Blue Extra was put on the market. This was the same season as the Falun world championships (1974) which had the first world champion on fibreglass skis and the last one on wooden skis. Norway was not prepared for the new development in ski material and found that, especially on wet snow, the new plastic skis had a major benefit [7]. It turned out that the plastic skis were very easily able to combine with the old ski wax. After this season everyone was competing with ski soles made of polyethylene. The next big development in the ski industry was Cera F, a gliding wax powder containing Fluor. Some Italians did research using Fluor as additives or a processing chemical in the ski base, which gave them an advantage in the season 1986-1987 when only they had Fluor gliding wax. It was soon possible for everyone to get the new powder, the only problem was that it was very expensive. The advantages were a better glide, reduction in ice build-up and less accumulation of dirt [8].

3.2 SKI BASE MATERIAL

A ski consists of the bulk material and the sole, the ski base material in this project is synonymous with the ski sole material. It is this surface that is in contact with the snow therefore the focus in this project will be the properties of the boundary between the ski base and the snow.

3.2.1 POLYETHYLENE

After the breakthrough in 1974 the ski base material has been made mostly of the polymer *polyethylene*, which is the most common polymer material. Polyethylene is made of long chains of ethylene which transforms into polyethylene via polymerisation, see Figure 2. The double bond between the carbon atoms breaks and reacts with other ethylene monomers. In this way very long molecule chains of polyethylene can be produced. When the chain becomes longer, the molecule weight becomes higher. Extremely long chains are called Ultra-High Molecular Weight Polyethylene (UHMWPE) and are in many cases beneficial, especially when it comes to products that need very low friction, which is the case for skiing (both alpine and Nordic).

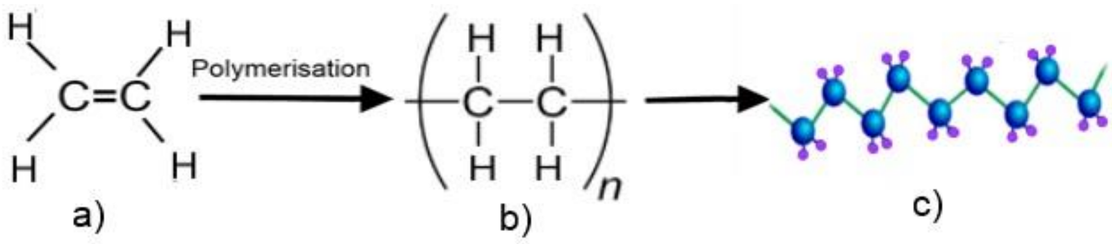


Figure 2 a) Ethylene molecule, **b)** ethylene monomer, **c)** polyethylene molecule.

There are many different types of polyethylene in the market, among them the low and high molecular weight and the low and high density polyethylene are the most well-known and used. The first type depends on how many monomers there are in the average molecule. The latter depends on the structure of the molecules, how they are oriented and whether the molecules have branches or not. If the polymers are in a straight line, they are able to crystallise and get a more compact structure, they become High Density Polyethylene (HDPE). If the density is low they are called Low Density Polyethylene (LDPE). Polyethylene is not able to crystallise completely due to the ends of the molecule chain, hence it is only semicrystalline, as shown in Figure 3. The polymers that do not crystallise are of amorphous character, these polymers are more affected by the temperature than the semicrystalline polymers are. They become very brittle below the glass transition temperature due to the low mobility of the molecules and have rubbery properties between the glass transition temperature and the crystalline melting temperature [9, 10].

The melting temperature, T_m, for semicrystalline polymers it is more accurately called the crystalline melting temperature. It is the temperature where the crystalline parts in the molecular morphology become amorphous and ductile.

The glass transition temperature, T_g, is the phase change where amorphous polymers transform from ductile to brittle. In semi-crystalline polymers it is only the amorphous parts that make the phase change [9].

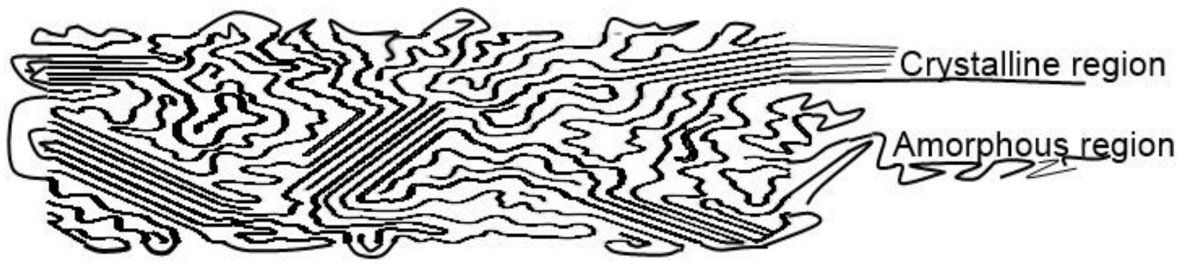


Figure 3 Semicrystalline structure of polymers.

The semicrystalline polyethylene has strong intermolecular forces that prevent softening above the glass transition temperature, and there is no visible phase change, that makes the semicrystalline polyethylene less temperature dependent. The crystalline structure makes the polymer stronger and harder than the amorphous structure, the intermolecular distance becomes smaller and the secondary forces, such as van der Waals, will hold the chain together more strongly. The properties of semicrystalline polyethylene rely on the amounts of amorphous and crystalline structure. The crystalline parts give the polymer strength and hardness, while the amorphous regions provide elasticity and impact resistance. Variations in microscopic structures can change the properties of the polyethylene. If the structure is linear, branched or cross-linked or if the molecule contains copolymers or additives, it will make the polymer properties change. Polyethylene is a thermoplastic, which means it reforms after heating. It is a recyclable plastic and the chemical structure does not break down during heating [9, 10]. Table 1 shows the difference between different types of polyethylene.

Table 1 The differences and similarities between LDPE, HDPE and UHMWPE [9-12].

	Density [g/cm^3]	Mol-weight [g/mol]	T_m [°C]	T_g [°C]	Properties, characteristics and user areas	Limitations
Linear-low density polyethylene LLDPE	0.915-0.25			-120	Similar to LDPE, but higher impact resistance and tensile strength. Use areas: Films, packaging	Not as easy to process
Low-density polyethylene LDPE	0.910-0.925		105-115	-110 to - 20	Soft, relatively high toughness, stress and crack resistance. Good chemical resistance. Partly transparent. Use areas: Transparent packaging	Low modulus and strength, UV-degradation
Medium density polyethylene MDPE	0.925-0.940		115-130	-118	Mix of LDPE and HDPE. Higher stress cracking resistance than HDPE Use areas: Packaging, bags	Lower strength than HDPE
High-density polyethylene HDPE	0.941 and higher (normally up to 0.960)		130-145	-200 to - 90	Hard. Improved chemical resistance, mechanical and permeation barrier properties can be used in large constructions. Use areas: Bottles and toys	Lower stress cracking resistance than MDPE
High-molecular weight polyethylene HMWPE	Medium high to high density	300 000 to 600 000	130-140		High impact strength, low friction, good wear and chemical resistance. Can be formed by extrusion. Use areas: Cheap ski bases, bearings, hard packaging	Not as good strength as UHMWPE and higher friction.
Ultra-High Molecular Weight Polyethylene UHMWPE	Typically 0.930-0.940 Lower due to crystals and difficult processing	3-12 million	135-150	n.a	Improved characteristics from HMWPE. Very high wear resistance and very low friction. Use areas: Ski base material, artificial joints, bearings	Difficult to process, sintered. Expensive

High molecular weight polyethylene types normally have a high density due to its capacity to crystallise. All polyethylene types are of low density when evaluated against other materials and they are all lighter than water. Notice that Table 1 is produced with information from several different sources [9-12] and the values have some variations and uncertainties, as they are only approximate values. For instance the value for the melting temperature to UHMWPE is in most journal articles for skiing sat to be between 140 °C and 150 °C and in the Material Handbook by Cardarelli [9] it is sat to be 125 °C to 135 °C. This can be due to additives in the ski base material, different molecular weights or the degree of crystallinity. The four lines above the bold line in Table 1 shows the densities that difference the polyethylene, while the two lines below the bold line shows the molecular weight that differs the polyethylene. Ski base materials are either of high molecular weight, HMWPE, or ultra-high molecular weight, UHMWPE. The latter is the most relevant material for this project. . There is not a given value for UHMWPE in the literature, which may be due to the high crystallinity.

ULTRA HIGH MOLECULAR WEIGHT POLYETHYLENE

UHMWPE is the polyethylene with the best properties considering it from a ski base point of view according to history and the previous years. The extremely long chains of polyethylene have crystallised and make a polymer of very high wear and abrasion resistance, very high hydrophobicity and low friction. UHMWPE is also able to absorb waxes that make the friction lower in the gliding zone and higher in the kicking zone.

PRODUCTION OF THE SKI BASE

UHMWPE is very difficult to produce due to the extremely long molecular chains and is therefore expensive. UHMWPE is sintered from powder under high pressure and heat. This is a very demanding process, illustrated in Figure 4. Almost all high quality skis today are made with UHMWPE ski base.

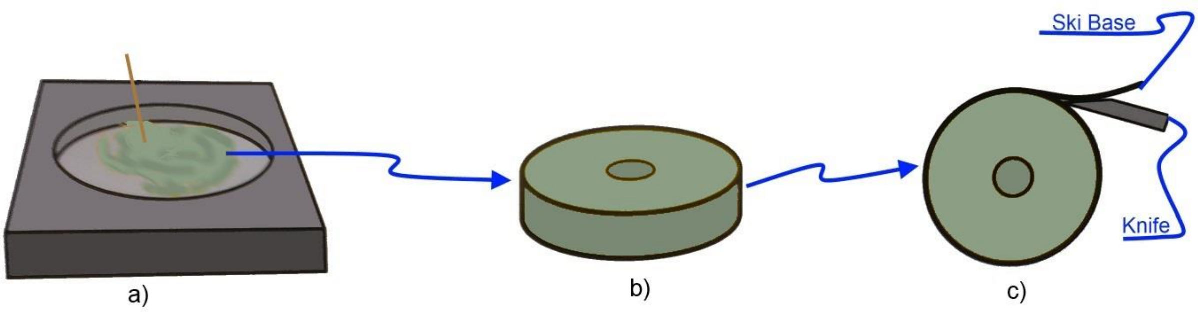


Figure 4 Production of ski base. **a)** UHMWPE granulate is sintered under high pressure and heat. **b)** Sintered plate. **c)** Peeled UHMWPE base, almost ready to use. Adapted from [13].

HMWPE has many of the same good properties as UHMWPE as described in Table 1, however the processing is much easier. Compared to UHMWPE HMWPE can be extruded and many of the good properties of HDPE are generated. From extrusion it is possible to get the wanted shape directly, shown in Figure 5. This is the kind of sole material and process method that is used for the average skis.

Extruded ski bases are anisotropic, the crystalline molecules have an align shape, while sintered soles have homogenous isotropic properties due to the production process, the ski base should have the same strength in all directions [10, 14].

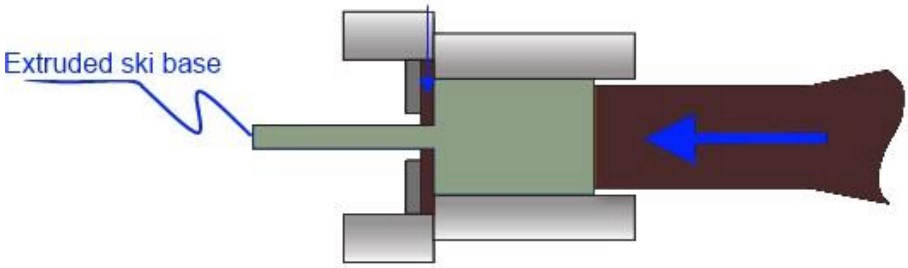


Figure 5 Extrusion of ski base.

3.2.2 POLYTETRAFLUORETHYLENE

If all the Hydrogen atoms in polyethylene are changed with Fluor, one gets polytetrafluorethylene, PTFE. Fluor atoms are larger than Hydrogen and are the most electronegative elements in the periodic table. Therefore, when the PTFE molecule is formed, it gets the form of a spiral due to repulsion forces between the Fluor atoms. The polymerisation for PTFE is shown in Figure 6. PTFE has a lower coefficient of friction compared to polyethylene and UHMWPE, but it lacks mechanical strength especially on cold snow. PTFE has a very high melting temperature of 340 °C and also a very high melting viscosity and is hence extremely difficult to process. Due to the high T_m and the high melting viscosity it very expensive and is mostly used as a thin coating. The glass transition temperature is around 130 °C. PTFE can be used as a ski base, or coating on a ski base, but it is more common to use it as an additive in UHMWPE to decrease the friction in the ski base [15, 16].

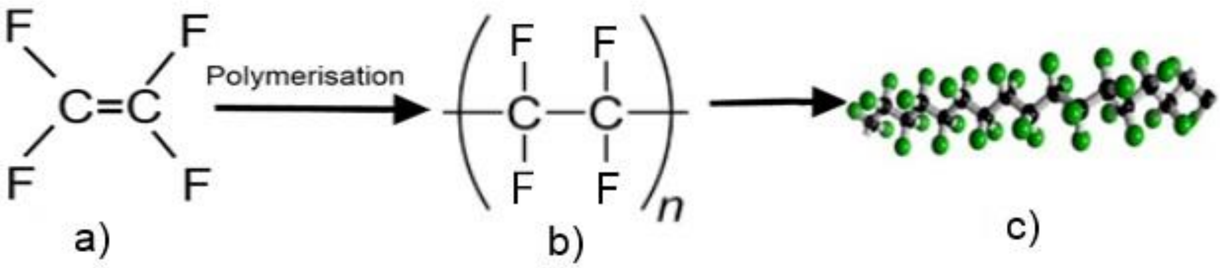


Figure 6 a) Tetrafluorethylene molecule **b)** PTFE monomer **C)** PTFE molecule.

3.2.3 ADDITIVES

Additives are used in polymers to change their properties. It is important that the additive improves the specific characteristic without making others worse. To improve the tribological behaviour for polymers different type of fillers are often used. Short fibres can be used to increase the mechanical strength while solid lubricants are used to decrease the coefficient of friction. Antioxidants can be used to avoid the aging of material or degradation from UV light [17, 18]. The features that need to be improved for ski bases are aging of the base and minimising the friction, which is the focus of this master thesis.

The solid lubricant fillers used in the polyethylene ski base are PTFE, graphite and molybdenum disulphide. Carbon black is normally added in the polyethylene to get better strength, lower friction and a black colour. Graphite as additive could change the colour, the hardness, the electrical-, thermal- and frictional characteristics [19]. Graphite is crystalline carbon and carbon black is amorphous carbon. Graphite strengthens the ski base material, the ski base becomes harder which can be beneficial in cold conditions. Close to zero degrees the graphite conducts frictional heat away from the interface, which may lower the friction. Most racing skis used today have black ski soles as a result of additives like carbon black and graphite, white ski bases becomes more common for conditions near zero degrees. One of the purposes of additives is to improve the lubricating water film thickness, the wear resistance and the hydrophobicity of the ski base. Furthermore ski bases also need to be able to absorb waxes. Waxes are used to excel the properties of the ski base considered the snow and weather conditions, further information about waxes is to be found in section 3.

SKI BASE MATERIAL TODAY

UHMWPE is used as the main component in the ski bases of all top model skis and different additives are applied to improve different properties, such as friction. It is the low friction, good wear resistance and the capacity to absorb wax that makes UHMWPE suitable as ski base nowadays. UHMWPE is also relatively cheap and easy to do surface treatments as different grindings.

3.3 WAX

In classic cross country skiing it is common to use both gliding wax and kicking wax, in other disciplines of skiing, including downhill and snowboard, only gliding waxes are used. Gliding wax is used to optimise the glide and prevent the oxidation of the ski base. Selected glide waxes are considered in this work and they will be described in detail later [20, 21].

3.3.1 BASIC WAX

Basic waxes are made of hydrocarbons that have a lower melting temperature than the ski base; the waxes are short chains of hydrocarbons while the ski base is made of extremely long chains. Typical numbers of carbon atoms in waxes can be 20 to 100, while for the base it can be many millions of carbon atoms. This way the wax will have a lower melting temperature than the base for an easy application [8, 10, 20].

To improve the gliding effect the wax should be melted into the ski base material. The semicrystalline polyethylene ski base will expand and the gaps and voids in the amorphous area will open up and letting the melted wax to fill them up, as illustrated in Figure 7.

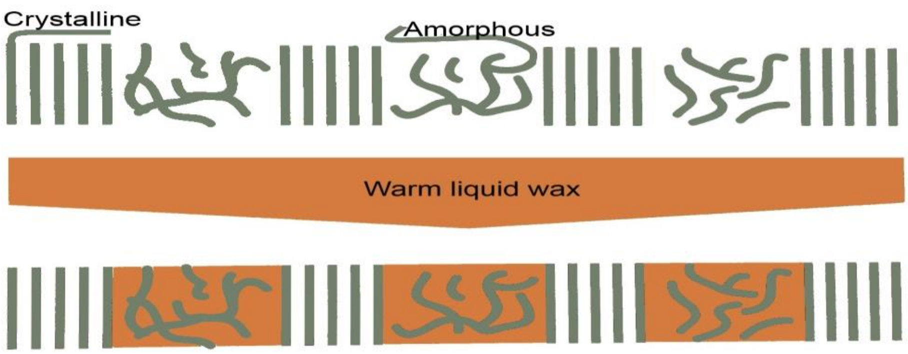


Figure 7 The heated wax is penetrated into the amorphous parts of the ski base material, adapted from [13].

After the wax is applied with a hot iron, it will lie as a thin coating on the ski base material, shown in Figure 8 b). It is desirable to keep the original surface topography of the sole, since it is designed to optimise the ski performance. The ski soles are scraped and brushed back to its original structure while the penetrated wax is left in the base material, as in Figure 8 c).

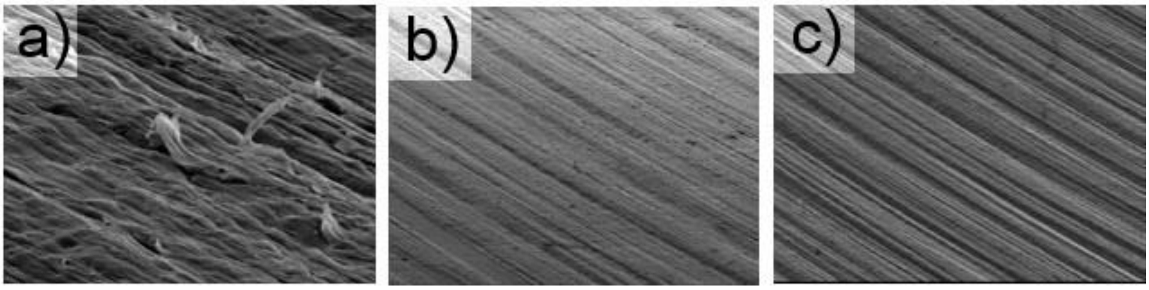


Figure 8 a) Untreated base after steel scraping, **b)** base with low fluorine wax, **c)** ski base topography after waxing and brushing, adapted from [21].

The ambient weather and snow conditions affect the wax selection. Air and snow surface temperature are two important parameters to consider [22]. If the temperature is low, the snow will be harder and so should the wax, if the temperature is mild the wax used should be softer [23]. New snow in cold weather has sharp edges, so if the wax is too soft the snowflakes will plough into the wax and create resistance and increase friction, as shown in Figure 9 a). However, it is the soft waxes that have the best water repellence and the lowest coefficient of friction on soft snow. If the wax is too hard the friction will not create the desired water layer between the ski base and the snow. The lubricating effect from the water layer will fail, and the friction force will increase, illustrated in Figure 9 b). Figure 9 c) shows optimal wax strength compared to the snow [13].

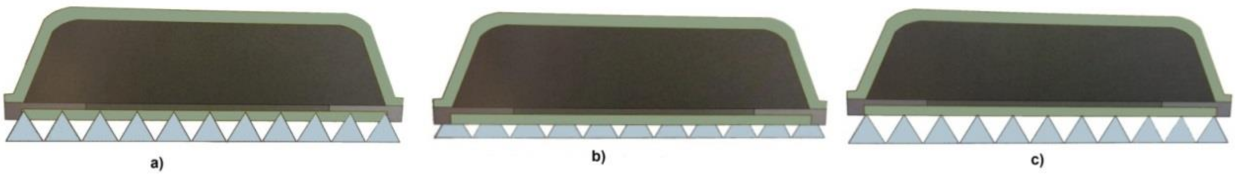


Figure 9 a) soft wax. **b)** hard wax. **c)** optimal hardness on wax relative to the snow, adapted from [13].

Hydrocarbon waxes are normally divided into three types; paraffin, microcrystalline and synthetic waxes. Paraffin is the softest type and has the best friction properties, but breaks easily under pressure, microcrystalline has a higher molecular weight and better resistance towards shear stresses. Synthetic waxes have longer chains than paraffin and microcrystalline, are harder and are used to harden the paraffin for use on cold snow [24].

FLUOR CONTAINING WAXES

Fluor containing waxes are commonly used underneath racing skis, especially when the weather is warm or humid. Ski waxes that contain Fluor can be found as basic paraffin wax, powder wax or as liquid wax. All or parts of the Hydrogen in the hydrocarbon waxes are changed with Fluor atoms, which is the same primary difference as between PE and PTFE (see section 3.2.2). The Fluor has exceptional physical and chemical properties, the Fluor-Carbon bonds are extremely strong and Fluor has the highest electronegativity value of all elements, not including noble gases. The high electronegativity means it does not attract other electrons towards itself and therefore has a capacity to not accumulate dirt and contaminants. Due to the stability of the Fluor-Carbon bonds the melting temperature is very high and the processability of fluorocarbons is challenging and therefore expensive. A ski wax should have a lower melting temperature than the ski base. The lower melting temperature the wax has, the deeper it can penetrate into the sole. The fluorocarbon waxes have very short chains which decrease their melting temperature. The mechanical strength for fluorocarbons is too low for the cold weather, so other additives are often put into the ski waxes so the wax will have a wider temperature range. Most wax companies have several waxes containing Fluor, each for different weather and snow conditions [15, 20, 21].

GALLIUM CONTAINING WAXES

Gallium has in the recent years become a part of the ski wax industry, but there was already made a patent considering "Synthetic Resin Composition Containing Gallium Particles and Use Thereof in the Glide Surfacing Materials of Skis and Other Applications" by Sugimura et al. [25] in 1991. Gallium containing waxes are made of the metallic gallium or gallium alloys and fluorocarbons. Gallium has several special characteristics that make it appropriate for ski wax. The melting temperature is 30 °C, so little or no heating is required. It is a very good semiconductor that prevents static electricity between the ski base and the snow surface, which avoids accumulation of dirt and dust. The element Gallium expands as it gets colder and has very good adhesive properties that makes the wax last longer on the base. Gallium is very water repellent and it also becomes harder the colder it gets, so it is very suitable when it is humid and on artificial snow [25, 26]. Sugimura et al. tested metallic gallium and gallium alloys and found out it was beneficial to have the particles in a size of 50 μm and below, at least no larger than 150 μm. The amount of gallium should comprise of 0,001 to 30 parts by weight of gallium mixed with 100 parts by weight of synthetic resin. The preferable amount should be from 0,01 to 10 wt% Gallium or even higher [25]. The glide, the water repellency and the wear resistance were tested by Sugimura on Gallium and Gallium alloys coated with paraffin, the results are shown in Table 2. Gallium with no alloy of other metals shows the best results.

Table 2 The effect of Gallium and Gallium alloy, adapted from [25].

Particles added	Glide	Water Repellency	Wear Resistance
Ga	Very Good	Very Good	Very Good
Ga-5 Zn	Good	Very Good	Good
Ga-15 Zn	Good	Very Good	Good
Ga-40 In	Very Good	Good	Very Good
Ga-5 Al	Good	Good	Good
Ga-15 Al	Good	Good	Good
no addition	Poor	Poor	Poor

● Very Good
● Good
● Poor

3.3.2 POWDER WAX

Powder waxes are hydrocarbon in a powder state often added solid lubricants and other particles. The powder waxes can include PTFE, boron nitride, molybdenum disulphide nano powder, tungsten disulphide nano powder, graphite nano powder among other nano particles. Fluorine powders are the most common used and have an applying temperature up to 180 °C. Figure 10 shows FC8X powder wax in a thin layer on the ski before it will be ironed into the base.

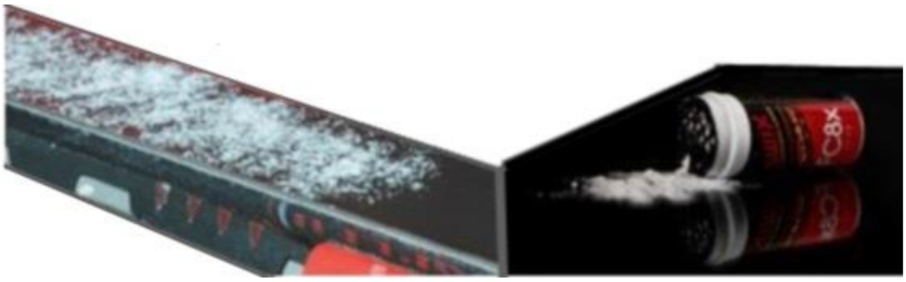


Figure 10 Swix FC8X powder wax is prepared to be ironed on the ski base [21] .

3.3.3 LIQUID WAX

A liquid wax may be put on the ski in the end of the waxing process to get the perfect finish on the ski base before a race. The wax stays on the ski base as a thin layer of coating and does not penetrate into the ski base. The wax can include fluorine, graphite and even some metals such as aluminium and gallium. This type of wax is not heated before use, it is used as a solvent that evaporates and is ready minutes after it is applied as a thin coating. Figure 11 illustrates the principles of the composition of the ski wax in and on the ski base.

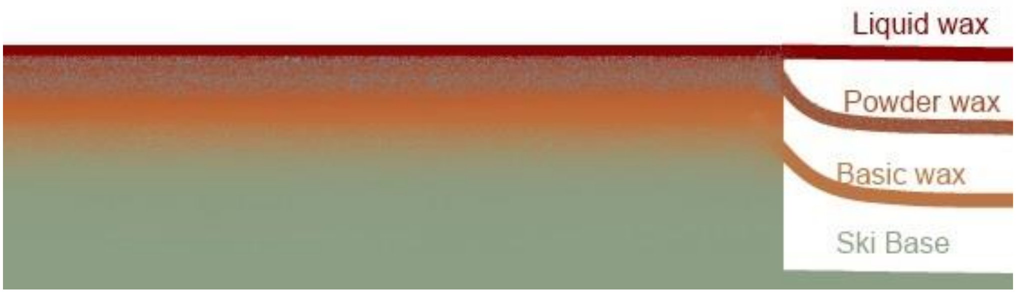


Figure 11 The basic wax fill most of the voids in the ski base, the powder wax fill remaining voids and liquid wax is put on top as a thin layer of coating.

3.4 SKI TRIBOLOGY

Tribology can be defined as ”the science and technology of interacting surfaces in relative motion” [27, 28]. This includes the study of friction, wear and lubrication. The study of lubrication in a ski base perspective is the gliding wax and the water layer between the ski base and the snow. Without a thin water layer the coefficient of friction will increase and so will the wear of the ski base. The thickness of the water layer between the skis and the snow depends on the structure of the ski base, its material properties and the condition of the snow, ambient temperature, speed and local contact pressure.

3.4.1 SURFACE TOPOGRAPHY

A perfect pair of skis fits the skier’s weight in size, flexibility and tension. These parameters are also strongly affected by the snow, track and weather conditions. The running surface needs a sufficient topography regarding the actual snow conditions.

SNOW

Snow is a very interesting material which is under constant change once it reaches the ground. There is a huge diversity of snow crystals which are a result of the processes during the crystallization phase. Air temperature and humidity, falling time, wind and contamination are some of the parameters which influence the snow crystal shape and size. Snow can be classified in several categories such as new snow, old (transformed) snow, natural or artificial snow.

New snow at low temperatures will have sharp edges, while for temperatures close to zero the crystals are losing its shape and the real contact area between the snow and the skis will increase. New snowflakes can be shaped as big or small crystals, the sharp edges get torn away by mechanical impacts (wind, ski track preparations etc.) as well as due to diffusion, so the old snowflakes are rounder. The small crystals have a bigger density and therefore a larger real contact area with the skis than lager crystals. Artificial snow differs from natural snow, mostly because it is frozen from the outside in, while natural snow is made from the inside out. The inside of artificial snow may not be completely frozen, when it freezes it can break and create sharp edges, this snow can be ten times smaller than natural snow. Artificial snow has a high density and a big contact area and sharp crystals which are essential when considering friction. A bigger contact area will lead to a stronger friction and can result in suction which will lower the speed of the skier significantly [13]. Swix, a company selling waxes, distinguish the type of snow on their waxes the way illustrated in Figure 12.

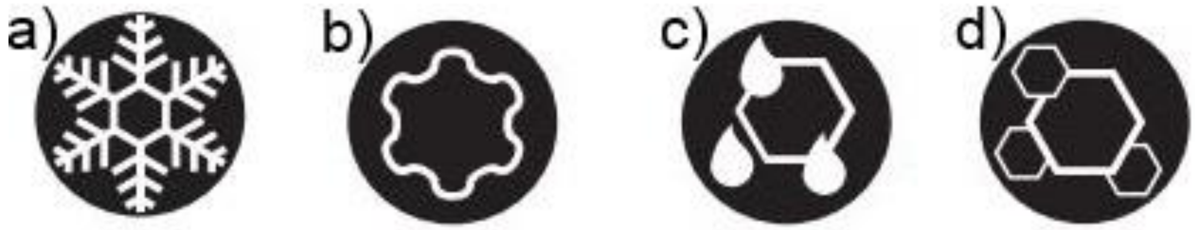


Figure 12 Characterisation of snow; **a)** new snow, **b)**old or transformed snow, **c**) wet and grained snow and **d)**grained and icy snow[29].

SKI BASE STRUCTURE

The surface topography of the ski base material is chosen out of the shape, temperature and humidity of the snow. If it is mild, the base needs grooves to channel the water out to avoid suction and if it is cold and dry the surface should be able to produce water so it will create a lubricating water film. The aim is normally to decrease the real contact area between the snow and the ski base. A smooth surface has a smaller contact area, but it is more likely to experience suction. A structure on the base can avoid the suction, but create more friction than necessary when it is cold [30, 31]. A basic rule is to have a fine structure when it is cold and dry and have a coarse structure for warm wet snow, as illustrated in Figure 13. The ski bases get usually stone grinded to achieve the desired surface topography.

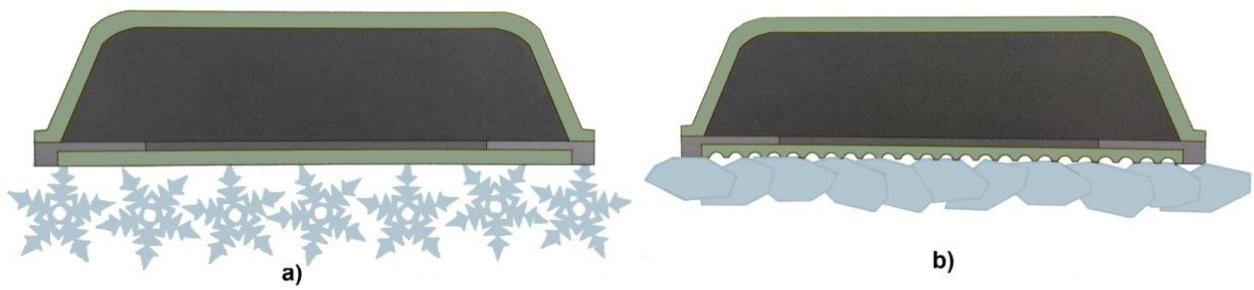


Figure 13 a) a smooth structure when the snowflakes are cold and have a crystal structure, **b)** a coarse structure when the snow is wet and grained. Adapted from [13].

ROUGHNESS

Many factors need to be considered when measuring the surface topography. It is normal to distinguish between roughness and waviness as shown in Figure 14. In this work only the roughness will be considered and it will be assumed that the waviness is not a factor influencing the friction performance of the ski. The skis are flattened before they get stone ground.

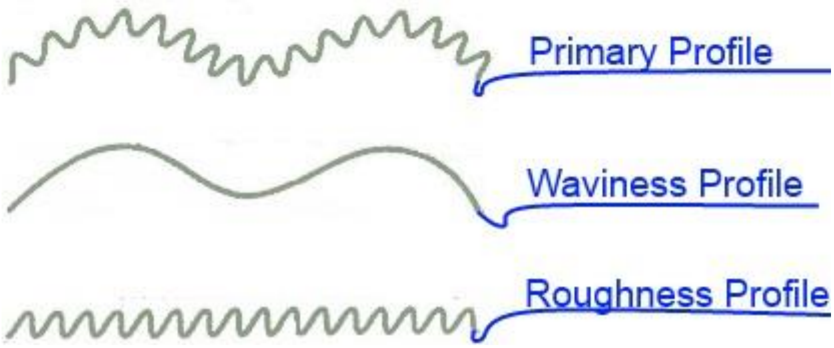


Figure 14 The difference between waviness and roughness.

Skis can have a great variety of patterns in the base structure, depending on the purpose for the skis. The cross country ski base has normally grooves aligned along the ski in the magnitude of 0,1 mm wide and a depth between 0,01 and 0,1 mm [30]. There is not a standard way to measure roughness of ski bases, however some of the most common ways to measure surface topography is by using arithmetic mean roughness (R_a) and root mean square average roughness (R_q). In this project both R_a and R_q will be measured.

Ra is the most used parameter to measure the surface roughness. Average Roughness and Center Line Average are other names for R_a. R_a is the area between the roughness profile and the mean line as illustrated in Figure 15 [32]. Ra is the integral of the absolute value of the height, r, of the surface roughness over the evaluation length, L:

Average height of profile $$R_a = \frac{1}{L}\int_0^L r(x)\,dx \quad (1)$$

The digital equivalent is normally:

Approximately average height $$R_a = \frac{1}{N}\sum_{n=1}^{N} r_n \quad (2)$$

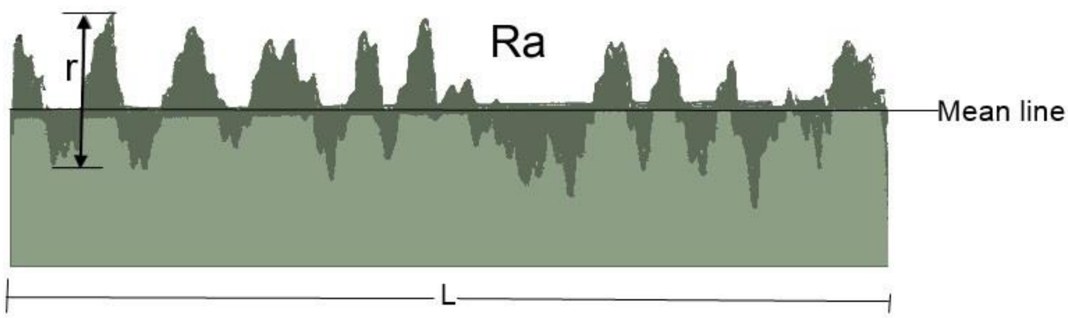


Figure 15 Arithmetic mean roughness R_a. The average height of the dark green area is R_a.

The effect from one scratch will give little impact on R_a because it is averaged out. The value of R_a is directly related to the area enclosed by the surface profile about the mean line and will therefore not give any information about how the roughness is shaped [33]. Figure 16 a), b) and c) shows three different surface roughnesses, all with the same R_a value.

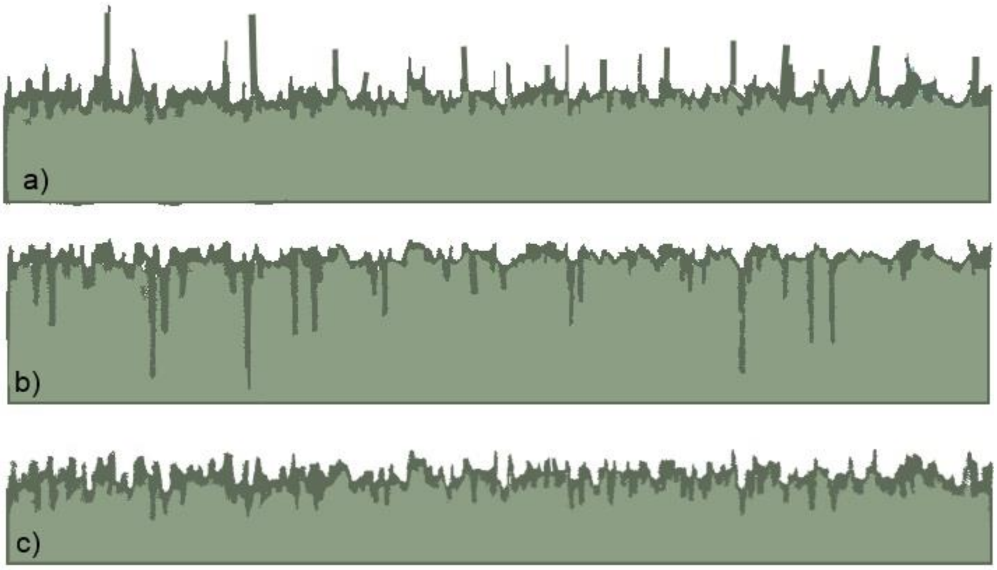


Figure 16 a) high peaks, **b**) low valleys and **C)** an even roughness, all have the same R_a value, adapted from [32].

For a more accurate measurement the root mean square average roughness is measured, R_q is more sensitive to the position of the peaks and valleys on a surface than R_a. The root mean square average roughness can be calculated from:

Root-mean-square height of profile $$R_q = \sqrt{\frac{1}{L}\int_0^L r^2(x)dx} \tag{3}$$

Evaluated by computer the approximation is normally:

Approximately R_q $$R_q = \sqrt{\frac{1}{L}\sum_{n=1}^{N} r_n^2} \tag{4}$$

For a pure sine wave-roughness profile R_q is proportional to Ra, then R_q is about 1,11 times larger [32]. Figure 17 shows R_a and R_q compared to each other and to the mean line.

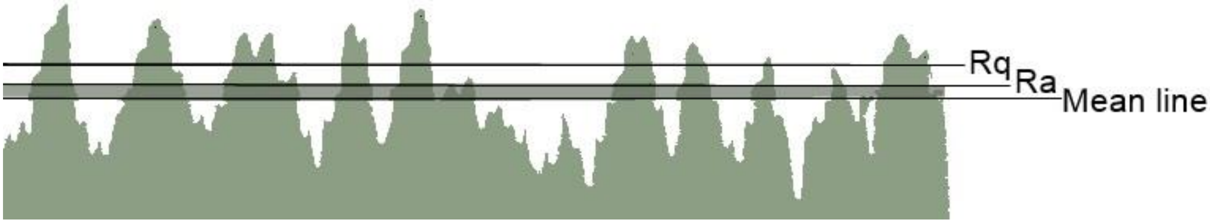


Figure 17 R_q takes the peaks into account and has therefore different value than R_a.

R_a and R_q describe the height of the peaks and valleys, to measure the spacing parameters in the roughness profile mean spacing of profile irregularities of primary profile (Rsm) is used, illustrated in Figure 18 [32]. Rsm is the mean value of the profile element width, Xs , over an evaluation length:

Mean spacing of profile irregularities $Rsm = \frac{1}{m}\sum_{i=m}^{m} Xs_i$ (5)

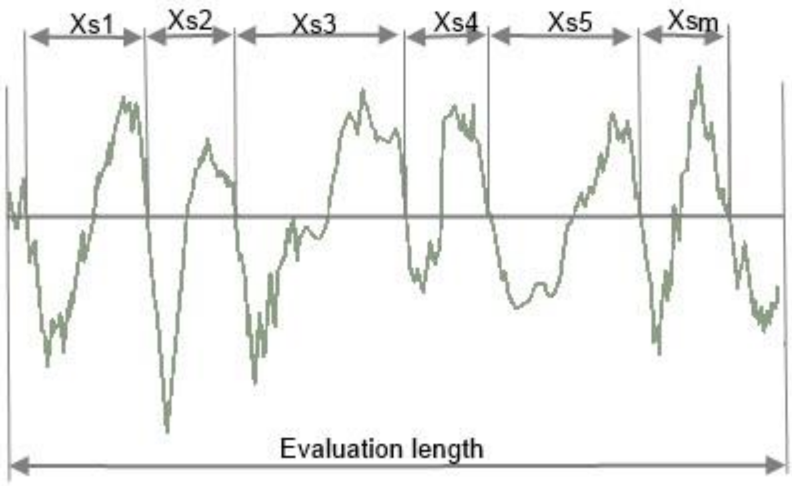


Figure 18 The mean spacing of the profile irregularities, Xsm is one spacing distance.

For cross country ski bases the surface roughness R_a normally has a value from 1-10 µm, the R_q will accordingly be a bit higher. Rsm values for ski bases are between 150 and 500 µm.

3.4.2 SCIENCE FRICTION

Friction can be defined as dissipation of energy between sliding bodies [33]. The energy loss can be transferred into heat or it can result in wear or deformation on the softest of the sliding surfaces. When skis are sliding on snow, the friction heat may result in a phase change, this is ice or snow transforming into water. The occurring water will be used as lubrication source that smooths the surface and lowers the coefficient of friction (COF). Low coefficient of friction will give low friction force and good glide. Friction can be calculated as follows:

Friction $F_F = \mu \cdot F_N$ (6)

Where F_F is the friction force, µ is the coefficient of friction and F_N is the normal force. The friction force is proportional to the normal force and dependent of the real contact area. The real contact area is the area where there is an actual contact between the two materials, where the ski base asperities are in contact with the snow asperities.

Asperities are the unevenness in a surface and it is the asperities that constitute the real contact area. Between the ski base and the snow the real contact area is approximately one thousand of the nominal contact area [34, 35]. The asperities support the normal load from the surface and generate the frictional force that acts between the surfaces. When the asperities are in contact they deform plastically, which will result in an increase of friction. To separate the snow and the ski base asperities a solid lubricant is introduced (wax), as shown in Figure 19. If the wax has a lower shear strength than the asperities, the deformation energy is reduced which results in lower friction [21] .

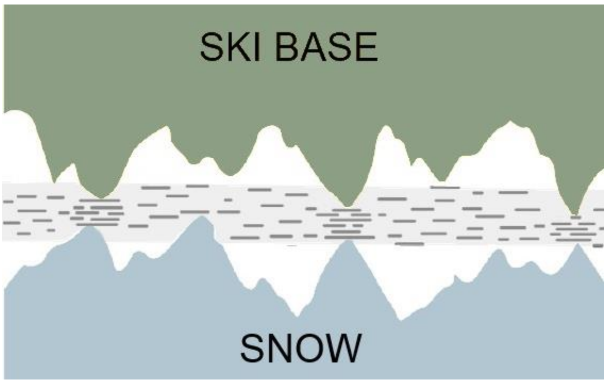


Figure 19 Separation of the asperities is achieved by introducing a solid lubricant (wax), adapted from [21].

THE LAWS OF FRICTION

There are three Laws of Friction, first described by Leonardo da Vinci (1452-1519), rediscovered by Guillaume Amontons (1663-1705) and then Charles August Coulomb (1736-1806) added a third law. The Laws of Friction can be described this way [18]:

1. The friction force is proportional to the normal load.
2. The friction force is independent of the real contact area.
3. The kinetic friction force is independent of the sliding velocity.

Equation 6 ($F_F=\mu \cdot F_N$) expresses the first and the second law. The three Laws of Friction are of varying reliability and especially polymer materials do not always obey these laws. This is because of large plastic deformations that occur on the tip of the asperities [28]. When considered skiing, the friction is dependent on the lubricating water film thickness that is mainly produced by the frictional heating. Nonetheless the two first laws are found to be approximately true considering skiing for both kinetic and static friction [35].

There are three regimes of friction for snow and polymers; dry friction, lubricated and capillary suction [36]. Dry friction does not have a water lubricating film between the snow and the ski base, which results in a higher coefficient of friction. This occurs mostly in very cold weather. Dry friction may give adhesive ploughing on the snow. The softest material is the one deforming most easily and will experience ploughing and decide the real contact area, as illustrated in Figure 20.

Figure 20 Adhesive ploughing, the hard base deforms the less hard snow and creates friction [37].

In the lubricating regime it is found that the coefficient of friction between ice or snow and the ski is depended on the speed and temperature, which decides the thickness of the water film [36]. When going fast on skis a lubricating water film will be created on the ski surface and when it is warm outside a water layer upon the snow can be created. The water layer will lower the contact between the asperities, the deformation will be less and the friction will be lower. If the snow is very wet, the third regime is found (suction). Upon suction the tension of the water surface film breaks and the coefficient of friction increases. Figure 21 shows the coefficient of friction as a function of the water film thickness and indicates the three different regimes of friction [36, 38].

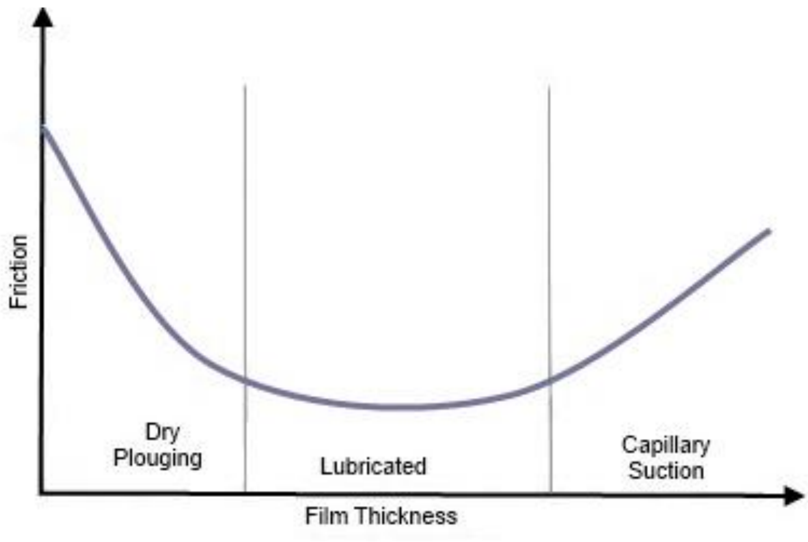


Figure 21 The three different friction mechanisms which are determined by the water film thickness [36].

There are two types of friction, kinetic and static. Kinetic friction slows down an already moving object and static friction stops a motionless object from moving. The coefficient of friction (COF) for static friction is higher than for kinetic friction. In this project a low kinetic friction for skis on snow is sought. The COF is very temperature dependent and tests have shown that minimal friction is found to be around -3 °C. At this temperature the friction heat will create the ultimate thickness of the water film, below -5 °C and above 0 °C the COF increases considerably. The kinetic coefficient of friction of polyethylene on snow is normally between 0.02 and 0.18 [38, 39].

The coefficient of friction is also dependent on how well the gliding wax fits the weather and temperature conditions. A simplified example, using equations (7-10), shows how the coefficient of friction can make a skier perform better with a small difference in COF. If two skiers both have a mass of 70 kilograms, going at a speed of 5 meter per second and one skier has skis with COF of 0.04, while the other skier has a COF of 0.06. When skier one stops without adding thrust he would glide 32 meters, while the other skier would only glide 21 meters. Even with the small difference in COF it would make a significant difference in the effort that the other skier has to make to slide at the same speed.

Friction $$F_F=\mu\cdot F_N \tag{7}$$

Normal force $$F_N=m\cdot g \tag{8}$$

Acceleration $$a= F_F/m \tag{9}$$

Velocity $$v^2=v_0^2+2ax \tag{10}$$

Where g=9,81 m/s^2, $v_0=0$, v=5 m/s, m=70 kg, for skier one $\mu=0.04$, skier two $\mu=0.06$ and x is the unknown distances, x_1=32 m and x_2=21 m.

3.4.3 WEAR OF WAX

A major problem with wax is that it tends to wear off. After a few kilometre of skiing the glide normally are lower than when the skis where newly glided. ASTM defines wear as damage to a solid surface that involves progressive loss of material due to relative motion between that surface and the contacting substance [40]. The material, in this case wax, can be removed from the base in three ways: by melting, by chemical dissolution and by physical separation of atoms from the surface [40]. When the skier is in the snow track, melting will not be an alternative and the chemical dissolution will be minimal, so physical separation of atoms from the surface is how the wax is worn off, this can be wear by particles, fluids or sliding. There is very little information in the literature about wear of wax on ski bases. The author of this thesis believes there are two main types of wear mechanisms that can influence the wear of wax; adhesive and abrasive wear. Adhesive wear may occur when it is mild and the wax is relatively soft while and when there is no lubricating water layer present. Adhesive wear will occur at low temperatures, when the wax and the snow are harder. In the different types of wax-on-snow wear, the results are that wax is worn off the ski base and left as dirt in the ski track.

Adhesive wear is caused by surfaces in direct contact, plastic deformation take place which creates wear debris and material transfer between the contacting substrates [41]. When the wax is soft and the lubricating water film is absent, or partly absent, there can be local bonding between the wax asperities and the snow asperities and the wax transfer to the substrate (the ski track) illustrated in Figure 22.

Figure 22 Adhesive wear, without a water layer material transfer from wax to snow may occur.

Abrasive wear is material loss or deformation due to hard particles that are forced against each other and moved along a solid surface [42]. Two body wear occurs when the snow is clean, then the hard snow will scrape the wax off, typically for artificial snow, shown in Figure 23.

Figure 23 Two body wear, hard snow particles scraping the wax off.

Hard particles can be caught in the snow and scratch the wax and base. Three body wear occurs when contaminations and ice lies in the track and goes between the snow and the base [42]. The hard contamination particles and the ice will wear on both surfaces, shown in Figure 24.

Figure 24 Two body wear, hard snow particles scraping the wax off.

4 EXPERIMENTAL

One of the goals for this project was to document the effect of nano ski wax (e.g. wax containing additives in nanosize) or other additives in the ski base material. To detect the effect of the nano ski wax, it was performed material characterisation and friction testing in the field and in the lab. Many methods and apparatus were evaluated to perform proper tests. After considering factors such as relevance, availability and price, the tests performed were X-ray photoelectron spectroscopy (XPS), Dynamical-mechanical thermal analysis (DMTA), contact angle, gliding outdoor field test and friction test in the lab. One aim was to be able to compare field testing with lab testing. If lab results gave a good fitting with the field tests, it might be possible to do more of the research and ski preparation inside in a lab where the thermal and wind conditions are stable. By doing the material characterisation tests before and after gliding on skis it was possible to find which element that gave good glide and which element in the ski wax that would stay on the ski base for the longest. The content of the ski base material and the ski wax used should also be found. XPS, ICP-MS and contact angle was used to characterise the materials while a gliding field test and friction lab test were performed to document the friction properties of the materials. DMTA was performed on the two ski bases, but there are many uncertainties in the results, more about DMTA is to be found in Appendix A. All the apparatus used for testing can be found at either NTNU or SINTEF.

4.1 MATERIALS DESCTIPTION AND CHARACTERISATION

In a previous project, eight different ski base materials were tested with Raman spectroscopy and DMTA, listed in Table 3 [43]. All materials are produced by the plastic producing company Isosport (Eisenstadt, Austria). The ski bases are made of extremely long chains of UHMWPE and are therefore sintered, they are of semi-crystalline character. There are different additives in the ski base materials, but exactly what each product contains is not certain due to industrial secrets. The previous project, it was focused on distinguishing the different materials from each other, mainly by looking at different additives such as carbon black and PTFE [43]. For a greater understanding of the ski base and the impact of waxes, two materials were chosen for further research; IS-4 and IS-5, the materials in the green frame in Table 3. IS-4 and IS-5 have the same content of carbon black, but different molecular weight and additives. It is also known that IS-4 contains PTFE, which is not expected to be the case for IS-5. There was also a visible difference in the IS-4 and the IS-5 base material, IS-5 contains small white particles in the whole base material visible with the naked eye.

Table 3 Eight different ski bases from Isosport, C is the various carbon types, X is the various types of additives and the numbers before C and X express the corresponding fraction in %. GGV is when the bases were grinded and flame treated.

Nr	Name	Material	Molecular weight	Carbon Black	Additives
IS-1	M IS CB 7515 C10 GGV 1,20/50	095097	9,20	15C10	-
IS-2	M IS CB 7515 R3051 GGV1,20/50	095096	9,20	20C6/C17	-
IS-3	M IS NCB R2964 GGV 1,20/50	095081	10,5	16C13	5X11
IS-4	M IS NCB R3041 2G2GV1,20/50	095080	5,00	10C9	2X2/3X8/5PTFE
IS-5	M IS NCB R3042 2G2GV1,20/50	095079	9,20	10C9	12X2
IS-6	M IS NHS GRAPH. RACE R2904 GGV 1,20/50	095114	5,00	12C1C9	3X9/1X7
IS-7	M IS NHS GRAPH. RACE R2991 GGV 1,20/50	095125	5,00	12C9	3X9/1X7
IS-8	M IS NHS GRAPH. RACE R3011 GGV 1,20/50	095116	5,00	15C9	5X9/1,5X7

The two types of ski material chosen for this master thesis (IS-4 and IS-5) were treated with three types of waxes, one basic wax, and two topping waxes. The basic was used, CH10 from Swix, is shown in Figure 25 a). CH sands for hydrocarbon, and this particular CH wax is designed for mild weather; 0 °C to +10 °C. As a topping, the liquid waxes Swix Cera F FC8L and Gallium FCG were used together with the basic wax. The liquid waxes are shown in Figure 25 b) and c). FC8L is a Swix Cera F 100 % fluorocarbon product and has a recommended temperature range from -4 °C to +4 °C. The FCG wax manufacturer is Gallium Wax and the FCG wax is of the type DOCTOR MAX FLUOR LIQUID, fluorocarbon wax containing Gallium. The recommended temperature range for FCG is -5 °C to +10 °C. The liquid waxes are put on top of the basic wax, CH10, and rubbed into the base according to the producers recommendations, some will evaporate and the rest will stay in the base.

Figure 25 The three waxes used, **a)** Swix CH10, **b)** Swix FC8L and **c)** Gallium FCG.

In all the tests conducted, the same type of grinding was used on the ski base. If there were exceptions it will be specified. The different ski bases used are listed in Table 4. IS-4 and IS-5 are the two types of ski material from Table 3, and the varieties of the ski bases at the end of the table have been skied on for 42,3 km before the tests were done. The skiing was performed using skate technique, without the use of kicking wax. The distances of 42,3 km was skied during the field tests.

Table 4 Varieties of ski base material tested.

Ski base material 1	Ski base material 2
IS-4 no wax	IS-5 no wax
IS-4 CH10	IS-5 CH10
IS-4 CH10 + FC8L	IS-5 CH10 + FC8L
IS-4 CH10 + FCG	IS-5 CH10 + FCG
IS-4 CH10 + FC8L 42,3km	IS-5 CH10 + FC8L 42,3km
IS-4 CH10 + FCG 42,3km	IS-5 CH10 + FCG 42,3km

4.1.1 XPS

X-ray photoelectron spectroscopy, XPS, is a surface analysis technique that can give information about a material composition up to a depth of several nanometres in the specimen tested [18]. X-ray light is sent on the specimen and the electrons are reflected with different intensity. The XPS measures the energy of the electrons emitted by the x-ray light. The result is a graph with the intensity on the y-axis and the binding energy on the x-axis. Each element has a characteristic binding energy. The intensity and the different peaks on the graph will also give information about the amount of elements and the chemical composition, since they are bound with different energy [44].

THE XPS EXPERIMENT

The XPS instrument used in this project was a Kratos Axis Ultra and located at NTNU. All the 12 materials in Table 4 were tested; the ski bases were cut into small samples, approximately 10 mm x 5 mm. The purpose of the XPS on the ski base materials was to verify the carbon black content and to detect if there were other additives. XPS works under high vacuum and hence the waxes were not possible to test alone. PTFE, fluorine, boron nitride, molybdenum disulphide, tungsten disulphide nano powder were additives searched specifically for on the ski base materials with wax in the XPS. It is also worth noting that the liquid waxes used in this work (FC8L and FCG) might suffer some kind of evaporation once in the vacuum chamber. This might lead to some uncertainties in the XPS measurements.

All the samples were put on a small plate, XPS is very sensitive and it was important not to touch the samples with the hands. The samples were first taken into one chamber, the Load Chamber, where the samples were introduced to vacuum. When a sufficient vacuum level was reached the samples were moved to the next chamber, the Standard Chamber, and then over to the last chamber, the Surface Analysis Chamber, where the actual testing was taking place. Figure 26 shows a picture of the XPS instrument at NTNU and the samples tested.

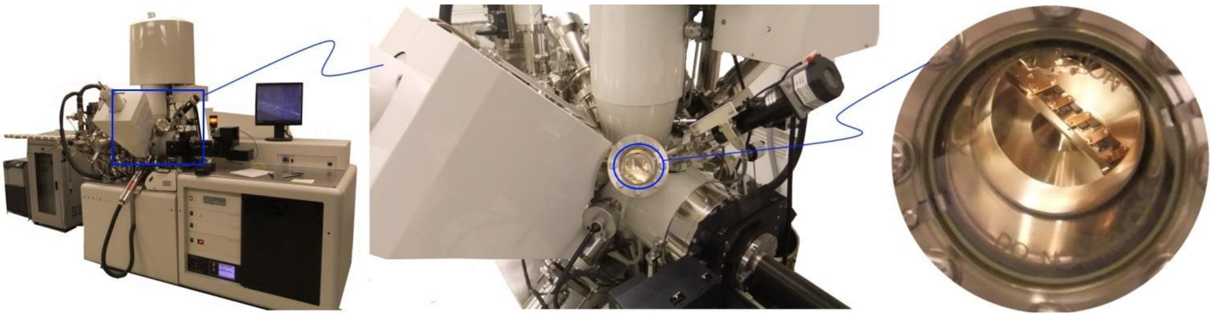


Figure 26 The XPS apparatus at NTNU, the picture to the right shows the 12 samples ready to be tested.

4.1.2 CONTACT ANGLE

The gliding speed is directly linked to the coefficient of friction (COF) which is related to the hydrophobicity level in the ski base. It is possible to determine the hydrophobicity of a material by measuring the contact angle of a water drop on the material surface. The bigger the contact angle, the more hydrophobic is the material and the less friction should be expected on snow or ice. If the contact angle is more than 90° the material is considered hydrophobic, if the contact angle is less than 90° the material is considered hydrophilic. Figure 27 shows four materials with different hydrophobicity grades.

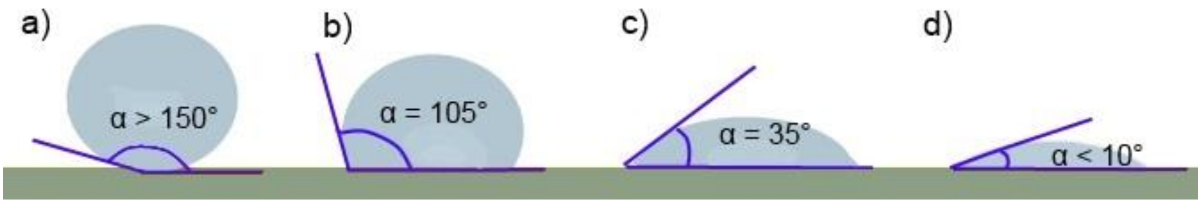


Figure 27 hydrophobic surfaces will give a higher contact angle than a less hydrophobic surface. High contact angle results in low real contact area. **a)** is the most hydrophobic material, while **d)** is the most hydrophilic.

THE CONTACT ANGLE EXPERIMENT

All the 12 materials from Table 4 were sent to SINTEF in Oslo to perform the contact angle test. The experiment was done with a sessile drop technique. All the samples had their roughness measured with a confocal microscope (see section 4.2.2) prior to the experiment to make sure all the tests were within the same roughness. All the samples were tested with ten drops each, the results were a contact angle and a standard deviation for each test.

4.1.3 ICP

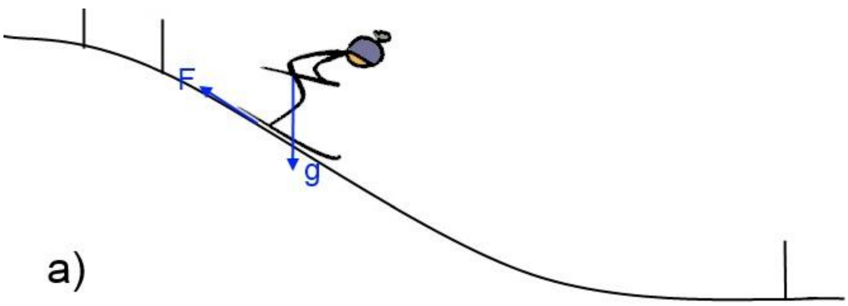
Inductively coupled plasma (ICP) is a technique that allows the precise determination of metallic ion concentration in liquid solutions. The liquid solutions are heated with a plasma torch at around 7000 °C and the metal ions are separated in a magnetic field chamber. The different species are detected by mass spectroscopy (MS). ICP was performed in order to measure the Gallium ion concentration in the liquid waxes. Prior to the ICP analyses, the liquid solutions are usually mixed with HNO3 20% v/v until reaching a concentration of 0.6M HNO3. The solutions are then injected in the Finnigan ELEMENT 2 high resolution ICP-MS equipment, available at NTNU.

4.2 FRICTION PROPERTIES

In addition to the materials characterisation, friction measurements of the ski base materials with and without wax and before and after field testing were carried out. The outdoor field tests are expected to give the closest results on how the skis and the waxes will work in a real situation such as the Olympics. However, the goal for this project is to evaluate field tests against lab tests and see if friction lab tests can be representative for outdoor field tests in the future. One of the main limitations of field tests is that friction values cannot be measured.

4.2.1 FIELD TEST

Outdoor field tests in the ski tracks are the most realistic type of testing for investigating the performance of materials for use in ski, but unfortunately these tests requires a lot of resources, such as a test-skier, multiple pairs of skis and time and distance measurement equipment among measurement equipment (Figure 29). Moreover there are many variables in the weather and snow conditions and human variances can occur that may influence the air drag and the friction, which by the way cannot be measured in field. To conduct a field gliding test a test field set up is established. This is normally performed in slightly downhill track that smooths over to be flat. The skier is standing still in a crouched position (hockey) and only getting speed by the gravity, as shown in Figure 28 [13]. It is assumed that drag force, gravity and other forces are working equality in each test and only friction is changing. Multiple series were done in this project to make the results more precise and reliable and the statistics were calculated and evaluated. Weather and snow conditions must be measured to make it possible to compare the results. As illustrated in Figure 28, there are three time-measurement sticks (photocells) that take the time. The two first ones start the time, while the last one stops the time. If there is a relatively large difference between the two start-photocells, the run is not valid. The times reported in the results are the time between the second and third photocell.



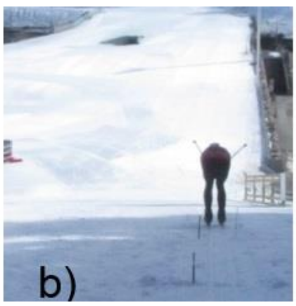


Figure 28 a) The principle for a gliding test, the skier only gains speed due to the gravitational force, photo cells measure the time of the run, snow friction is the major varying resistance while the skier stands still the whole way down. **b)** shows the skier in trucked position in a field gliding test in Holmenkollen (Oslo).

THE FIELD TEST EXPERIMENT

Three pairs of skis were tested in this work; one reference ski and two skis of the same model with IS-4 and IS-5 ski base sole. The test-skis were skating skis so the wear of the wax should be as even as possible over the whole ski and kicking wax was not a necessity. The first ski-test day was in Holmenkollen, Oslo, the track was 115 meters and two experienced ski-testers performed the tests. In each gliding test the three ski pairs were tested 6 times by both ski-testers, which means each round consisted of 36 runs. The skis were tested in a series with ski number 1-2-3-3-2-1-1-2-3-3-2-1-1-2-3-3-2-1. The test sequence was a follow:

1. Field gliding test of all three pairs, IS-4-base skis and IS-5-base skis without any wax
2. Field gliding test of all three pairs, IS-4 and IS-5 with CH10-wax and FC8 liquid-wax
3. 8 km skate-skiing with IS-4 and IS-5
4. Field gliding test of all three pairs
5. 8 km skate-skiing with IS-4 and IS-5
6. Field gliding test of all three pairs

There were changes in the temperature during the day in Holmenkollen, so a continuing of the gliding tests was completed in Granåsen, Trondheim, two days later. The skis were in the same condition as the last round in Holmenkollen and the test track in Granåsen was 82 meters long. This time it was only one ski-tester and the skis were tested 6 times for each gliding test. The continued test-sequence in Granåsen was as follow:

1. Field gliding test of all three pairs
2. 10,6 km skate-skiing with IS-4 and IS-5
3. Field gliding test of all three pairs

In all the gliding field tests the measured result is time.

Snow is a very difficult element to do scientific research on, it is therefore important to document the condition of the snow to be able to compare the results. A thermometer was used during the field tests to measure the temperature in the air and in the snow. A humidity measurement device was used to measure air and snow humidity. The snow was weighted to find the density. The snowflakes size and shape was characterised by being shuffled on a snow crystal card which is a plate that is ruled in millimetres and with classification system on the side, as shown in Figure 29. This was done during every round.

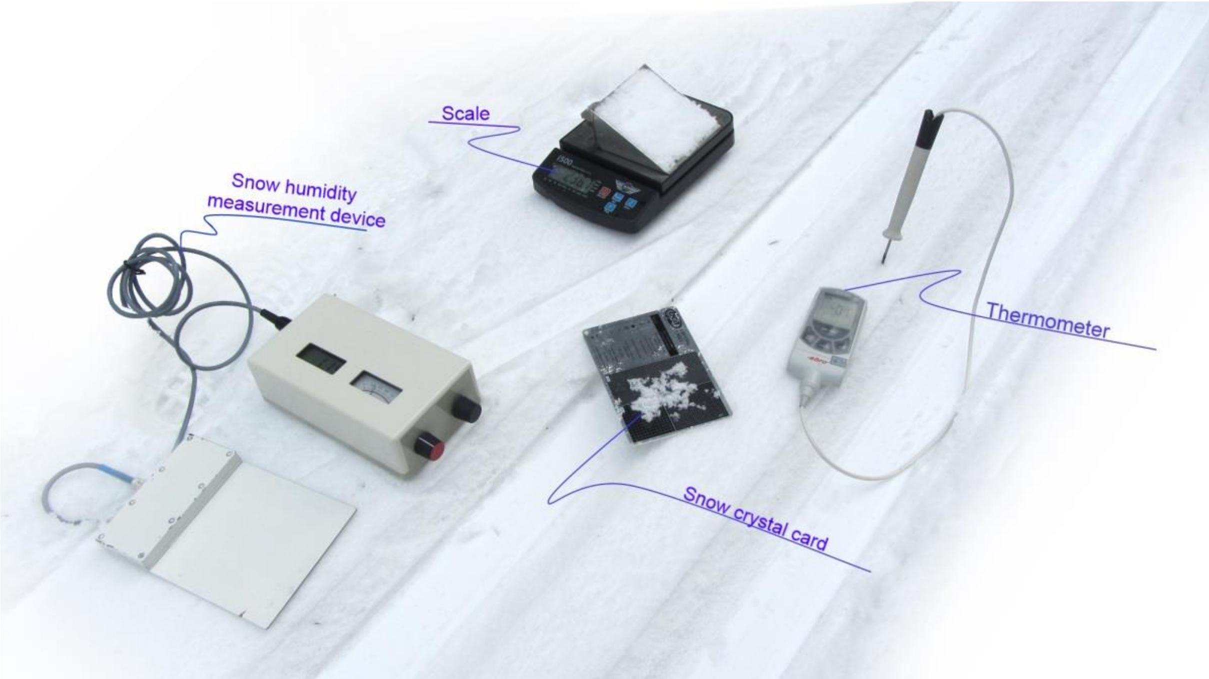


Figure 29 The equipment used to measure the weather and snow conditions during the field tests.

4.2.2 LAB TEST AND SURFACE CHARACTERISATION

TE 88

The coefficient of friction of the different ski base materials sliding against snow was measured using the friction and wear test machine TE88 from Phoenix Tribology (Figure 30). The equipment is a multi-station friction and wear test machine developed for testing materials under a variety of contact pressures and it is available at NTNU. TE 88 can be aligned with different modules; pin-on-plate, ball-on-plate, block-on-ring and ball-on-ring. In this project the pin-on-plate arrangement was used, where the pin was a small piece of ski base material and the plate was made of snow. The machine was modified in order to accommodate the snow and the ski materials on it for testing at temperatures below 0 °C. The TE 88 was connected to a computer and a data acquisition system able to record the coefficient of friction between the ski base material and snow, the sliding speed and the sliding distance, as well as the temperature of the substrate with high acquisition rates. The apparatus involves a variable speed gear-motor. The motor spins and generate a linear movement on the plate. The pin, which in this case is the ski base, get applied pressure form an hydraulic pump which is balanced with a counter weight and connected to an amplifier that makes the results more accurate[45, 46]. The main components of the TE 88 are shown in Figure 30.

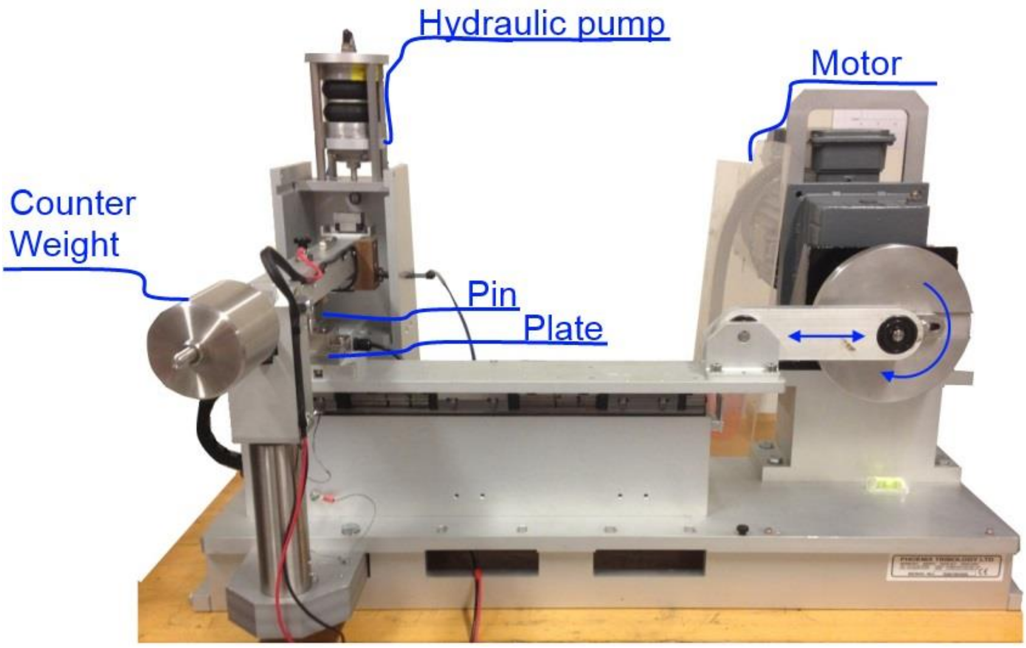


Figure 30 The TE 88 main components. There are a hydraulic pump and a counter weight that balance the load given to the pin. The plate is moved linearly by the motor to the right.

The modified set-up consists of a refrigerating system and a specially made snow-holder, shown in Figure 31 a) and b) respectively. Julabo FP 89-ME Ultra-Low Refrigerated-Heating Circulator was the refrigerating system used to cool down the snow-holder. Methanol is used as the coolant for controlling the temperature. The cooling system allows temperatures as low as -90 °C [47]. The snow-holder is made of brass and can be filled with snow or ice. The snow-holder is hollow inside and allows methanol from the refrigerating system to control the temperature.

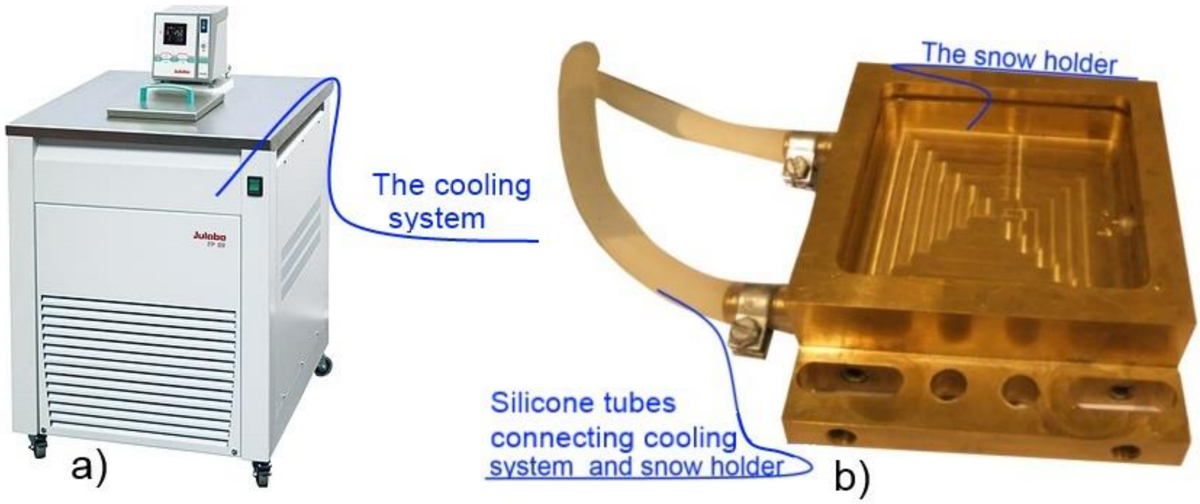


Figure 31 a) the Julabo FP 89 ME cooling system [47] . **b)** The special made snow-holder that are connected to a cooling system via silicon tubes.

CONFOCAL MICROSCOPE

A confocal microscope (Alicona InfiniteFocus Real3D) was used to investigate the surface topography of the ski base before and after friction testing. The microscope can analyse the surface and verify optical roughness measurements with the ISO standards ISO 4287 and ISO 4288 [32]. The vertical resolution of the equipment may be up to 10 nm. The microscope is a non-contact measurement tool and it is therefore possible to see if there are changes in the roughness before and after testing without damaging the materials. The microscope takes numerous pictures at different vertical focus distances and gathers them into a 3D image which can be further analysed. In this project the output was the microscope pictures and the roughness values R_a, R_q and Rsm, explained in section 3.4.1. Figure 32 shows a picture of the confocal microscope used in this project.

Figure 32 The confocal microscope is here used to find an approximate roughness on the ski bases used so the same grinding was used on all the material tested.

THE TE 88 AND CONFOCAL MICROSCOPE EXPERIMENT

To conduct the TE 88 friction test many factors needed to be considered. The ski base samples were cut to 20 mm x 20 mm and were glued on a wooden plate that was fastened to the TE88 sample holder, illustrated in Figure 33. The sliding direction was the same as the grindings in the ski base material. Based on calculations taking into account the weight of an average person skiing on cross country skis the normal load on the ski base material was set to 150 N. It was assumed ha the nominal contact pressure of a person skiing on cross country skis to be between 100 and 500 kPa, therefore a nominal contact pressure of 375 kPa was chosen for the tests. The area of the ski base material was 400 mm², if this is put into Equation 11 the normal force to be used in the TE88 will be 150 N.

Force $$F_n = P \cdot A \quad (11)$$

Where F_n is the normal force applied in the tribometer, P is the contact pressure and A is the nominal area of the ski base material on snow.

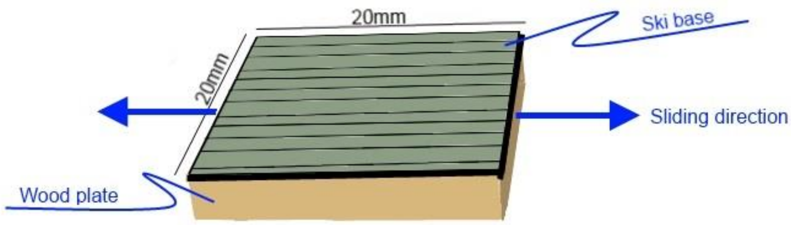


Figure 33 The sample specimen contains of ski base glued to a wooden plate. The sliding direction is in the same way as the grinding.

The snow holder is made of a special plate where a coolant can circulate inside as described above. The plate is 78 mm x 80 mm on the inside, since the ski base samples were 20 mm x 20 mm the chosen sliding distance were 50 mm. The silicone tubes from the cooling system and a thermometer that measures the snow temperature was fasten to the snow holder, shown in Figure 34. Snow was compressed into the plate before every test, as even as possible. The snow was fine grained new snow collected from Bymarka, Trondheim, February 2013, the temperature that day was -2 °C. The snow was kept in a freezer at -18 °C. In that way the snow was very similar for every test. The variances can be found in the way the snow was applied in the testing plate, which was very difficult to do the same way for every test. The tests were conducted in an open room with no cooling of the air, so the surface of the snow was warmer than the measured temperature inside the snow. The samples left a polished snow track, illustrated in Figure 34.

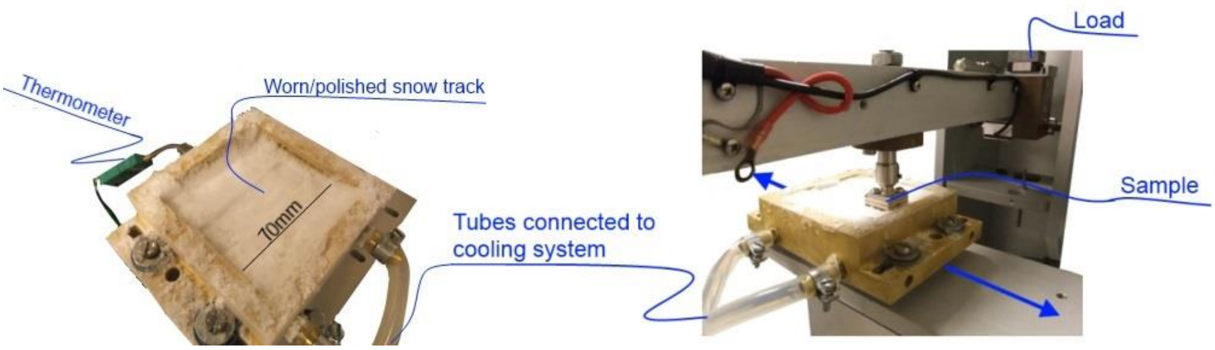


Figure 34 The snow had a 70 mm worn track after testing. To the right, the sample is standing still while the snow holder with snow moves.

The maximum sliding speed for a safe and reliable test at the TE 88 system is 2 Hz even though the machine can arrive to 10 Hz. The tests were run for half an hour. First the tests were run during ten minutes at a speed of 1 Hz, then ten minutes at 2 Hz and then ten minutes at 1 Hz again. The test setup for the TE 88 and the microscope is illustrated in Figure 35. With this test setup it was possible to see if there was a big difference in COF compared to speed and if it was a big polishing effect over time.

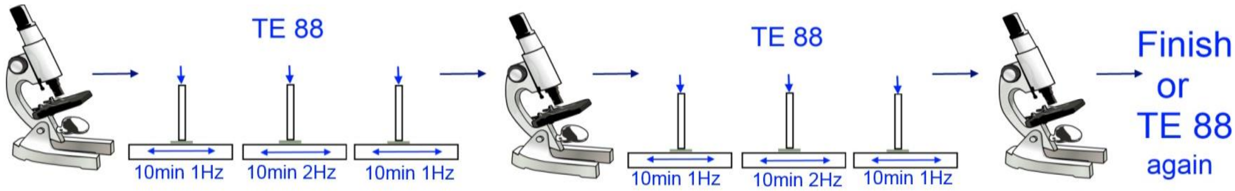


Figure 35 Each test material was tested in the microscope, then 30 minutes with TE 88, microscope, TE 88, microscope again and then TE 88 one last time if results were reliable.

A summary of the variable parameters in the experimental set up of TE 88 is listed in Table 5.

Table 5 The system parameters with values used with the TE 88 experiment.

System parameters	Value
Speed – cycles	1-2 Hz
Velocity	0,36 – 0,072 km/h
Normal Load and Contact Pressure	150 N and 375 kPa
Air temperature	23-25 °C
Snow temperature	-10 °C (and a few tests with -2 °C)

Before and after every sliding run with the TE 88 the samples were tested in the confocal microscope, the same area every time. This has been completed by using the same corner as starting point, illustrated in Figure 36. The cut off length (λ_c) defines the intersection between the roughness and waviness components and was chosen to be 800 µm [32]. This is the same cut off length used in previous projects by Olympiatoppen and the samples were measured according to the ISO-standards ISO 4287 and ISO 4288.

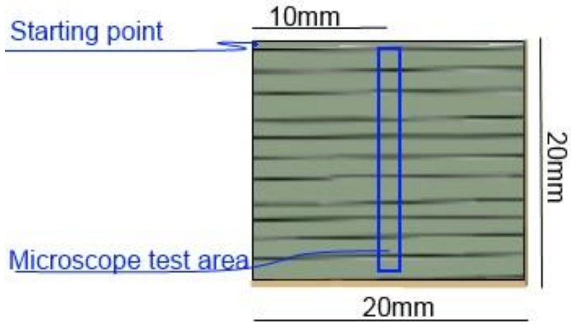


Figure 36 Area of the microscope pictures.

5 RESULTS AND DISCUSSION

A summary of the tests conducted on the materials from Table 4 is listed in Table 6. The microscope (M) the TE 88 (T), the XPS (X) and the contact angle tests (α) were conducted on all the materials. Note that only half of the materials were tested at the outdoor gliding field test (F).

Table 6 All the experiments conducted.

	No wax	CH10	CH10 +FC8L	CH10 +FCG	FC8L 42,3 km	FCG 42,3 km
IS-4	X α F M T	X α M T	X α F M T	X α M T	X α F M T	X α M T
IS-5	X α F M T	X α M T	X α F M T	X α M T	X α F M T	X α M T

X – XPS, α – contact angle, F – field test, M – confocal microscope, T – TE88

In addition to the materials in Table 4 a reference ski was included in the gliding field test and later tested with the TE 88. In the TE 88 the reference ski was tested without wax, so the materials from the gliding tests could be compared with the reference ski, both considered gliding time and COF. Also two materials with a different grinding were tested with the TE 88. However, the materials in Table 6 are the focus in this work.

5.1 XPS

XPS is able to do accurate analysis on the very top of a surface. Elements respond differently to different energy. The elements also respond differently depending on which element they are bounded to. The binding energy for Carbon-Carbon bonds are not the same as for Carbon-Fluor bonds. In this project the main focus has been to evaluate the content of specific elements, especially the fluorine content and not the different type of bonding. Figure 37 shows the survey spectra of all the 12 material tested with the XPS. At a first glance all the materials look very similar.

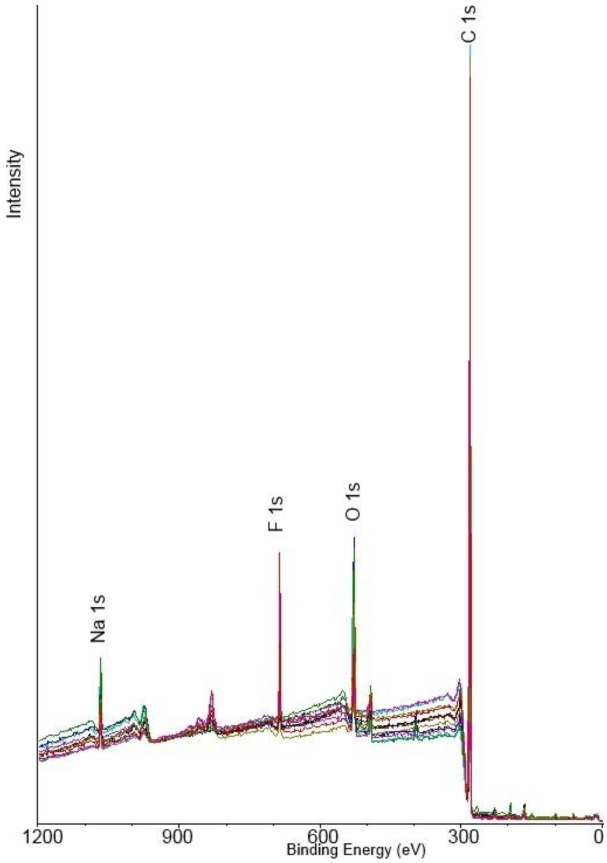


Figure 37 All the 12 materials show many similar peaks when tested with XPS.

Table 7 shows an approximately element composition for each material, based on the intensity and the area of the peaks as a function of the binding energy. The information from Table 7 is only a rough approximation. Further analysis is needed to draw any conclusions. All the materials were tested with XPS on two points and the results for every sample were very similar. Table 7 shows the results from the first test of each sample. There is one exception, the IS-5 FC8L 42,3 km material were tested on a white particle as well as the main black base, which responded differently. Both results for IS-5 FC8L 42,3 km are shown in Table 7. The area measured is based on the Shirley method which is commonly used with XPS. The element composition is measured as the atomic percentage. Note that the materials tested in the lab have not been analysed in this work. These XPS results are very preliminary and should be treated cautiously, a future deeper work on these analyses will be performed.

Table 7 XPS results from the first test of each sample. There is one exception, the IS-5 FC8L 42,3km material were tested on a white particle as well as the main black base, which responded differently. Both results for IS-5 FC8L 42,3 km are shown in the table. All values are in approximate atomic percentage [%].

Sample	C	O	F	N	Ga	B	Na	S	Al	Si
IS-4 no wax	92,68	3,06	2,68	-	-	0,09	0,61	0,58	-	-
IS-4 CH10	92,35	4,97	0,85	-	-	0,29	0,67	0,64	-	0,16
IS-4 FC8L	93,88	1,74	3,79	-	-	-	0,22	0,24	-	-
IS-4 FCG	94,38	2,28	2,37	-	-	-	0,38	0,38	-	-
IS-4 FC8L 42,3 km	83,10	10,59	0,44	1,91	-	0,15	1,38	0,80	-	0,72
IS-4 FCG 42,3 km	86,08	9,49	0,29	1,30	-	0,13	0,69	0,69	0,24	0,74
IS-5 no wax	89,15	5,11	2,64	-	-	0,60	0,99	0,99	-	-
IS-5 CH10	89,46	5,42	2,46	-	-	0,09	0,72	0,73	-	0,35
IS-5 FC8L	82,09	7,49	5,25	-	-	1,50	1,36	1,35	-	0,20
IS-5 FCG	90,48	3,20	4,75	-	-	0,06	0,56	0,58	-	0,06
IS-5 FC8L 42,3 km	87,76	6,72	2,33	1,60	-	0,17	0,36	0,37	-	0,51
IS-5 FC8L 42,3 km (white particle)	80,20	6,49	9,38	1,79	-	-	0,29	0,32	-	0,46
IS-5 FCG 42,3 km	86,61	7,44	2,64	0,51	-	0,10	0,81	0,83	-	0,62

Gallium could not be detected in any of the materials with the XPS. XPS is a very accurate measurement tool, but the concentration of Gallium in the materials, the liquid state and the vacuum system could be factors influencing the lack of detection for this element. In Sugimura et al. [25] it is mentioned that the Gallium particles added in the wax can be from a range of 0,01 to 10 wt% or even higher. If the wax has a low amount of Gallium (in the lowest range proposed by Sugimura) the XPS is not sensitive enough to detect this element. In addition, the wax was spread as liquid forming a thin layer on the base, making it difficult to be hold on the surface after introducing the sample in the XPS vacuum chamber. Since the concentration of Gallium was not provided by the producer of the wax and it is not possible to analyse liquids in the XPS, the liquid waxes were tested using ICP technique, the results can be found in section 5.3. Figure 38 show the binding energies of the spectra Ga 3d where a Gallium signal should have been when tested in the XPS. There are no signs of a peak, only background noise.

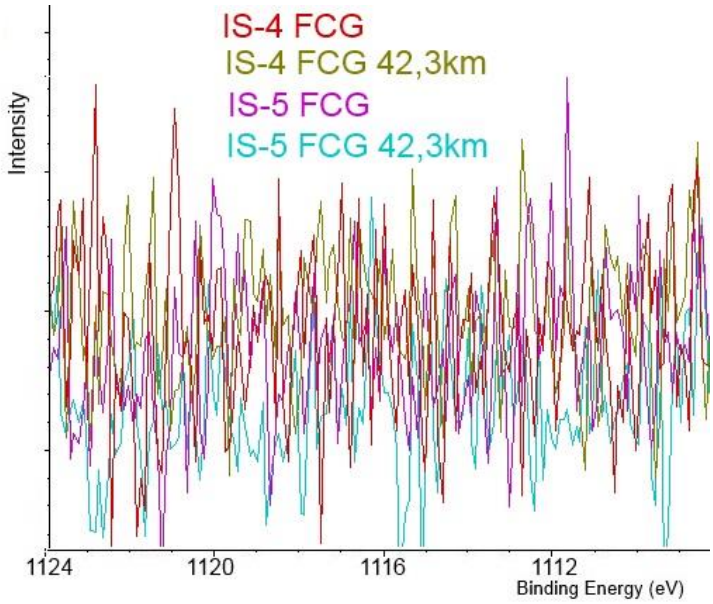


Figure 38 No Gallium is to be found with XPS.

All the graphs are normalised for allowing a comparison. The Fluor content in the IS-4 and IS-5 materials without any wax are compared in Figure 39. Table 7 indicates that IS-4 and IS- 5 have very similar fluorine content when no wax is added. Figure 39 shows that the intensity, and therefore the amount, of Fluor are greater for the IS-5 ski base material than for the IS-4 ski base material in the spectra F 1s. When applying CH10 wax, which is not expected to contain any fluorine, only IS-5 gives a much greater response to the Fluor than IS-4, shown in Figure 40. This can be because only the fluorine in the IS-5 is high enough to give response on the top layer of the surface after applying CH10. However, no quantification of the amounts of the different elements was performed in this work

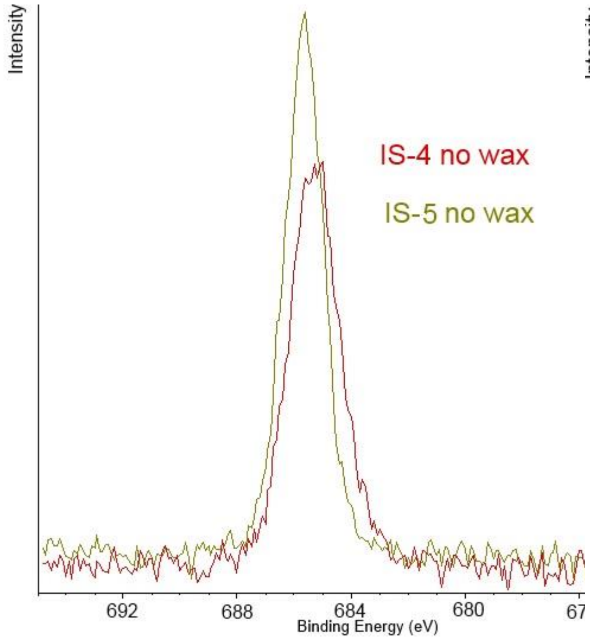


Figure 39 The Fluor content of the two ski base materials compared when no wax is added.

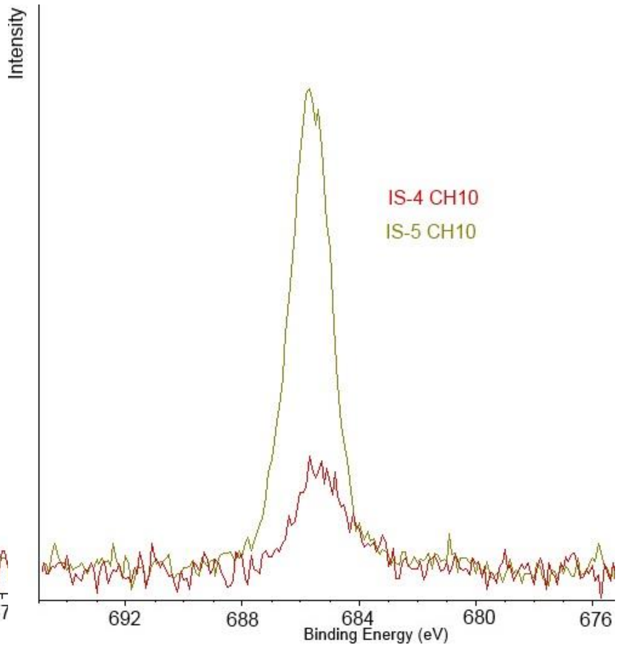


Figure 40 The Fluor content of the two ski base materials compared when CH10 wax is added.

When comparing the Fluor content of all the three waxes applied on material IS-4, Figure 41, and on IS-5, Figure 42, it is clearly that FC8L wax contains the most Fluor and the FCG wax also contains more Fluor than the main base. The CH10 wax is not expected to contain any Fluor according to the manufacturer. This is clear in the spectra of Figure 43, where the peak of Fluor for CH10 is much lower than the one found in the ski base material (IS-4). As mentioned earlier, the Fluor response in IS-4 CH10 is most probably from the Fluor in the base material.

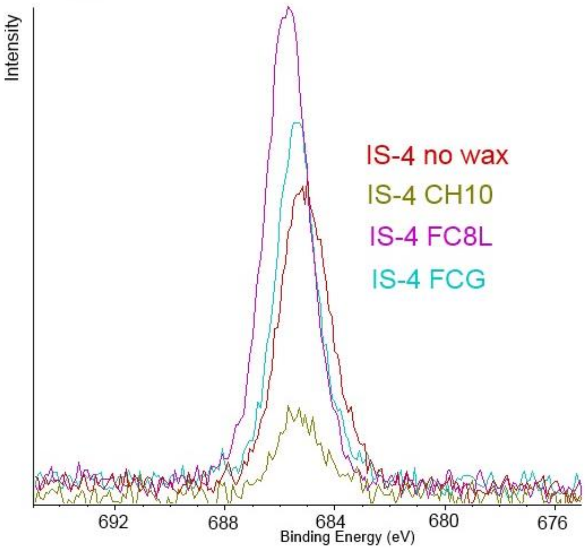


Figure 41 The Fluor content of IS-4 ski base material for no wax, CH10, FC8L and FCG.

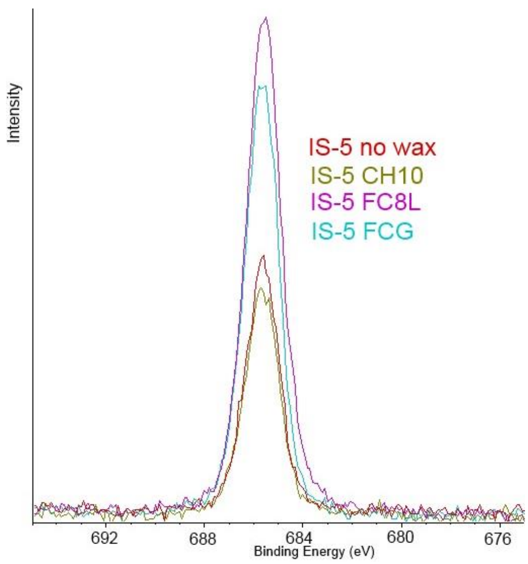


Figure 42 The Fluor content of IS-5 ski base material for no wax, CH10, FC8L and FCG.

When comparing the materials before and after skiing in, it is obvious that the Fluor content of the materials decreases, shown in Figure 43 to Figure 46. The white particle in the IS-5 material has the highest content of Fluor of them all, even after 42,3 km skiing, which means the white particles contain the largest amount of fluorine. It seems like the largest difference in the Fluor content is found between IS-4 and IS-5 after skiing 42,3 km. This can imply that the IS-5 base preserves the wax better than the IS-4 base. Another thing worth noting from Table 7 when comparing the Fluor content and comparing Figure 39 and Figure 46, is that the fluorine amount or intensity is much lower for IS-4 after 42,3 km than for IS-5. The differences are not so large before the base is skied on and worn (with no wax). A reason for this is that the IS- material has a thin layer with Fluor on top when there is no wax, that it later has been worn away or the IS-5 ski base preserve the fluorine in the waxes better than the IS-4 base.

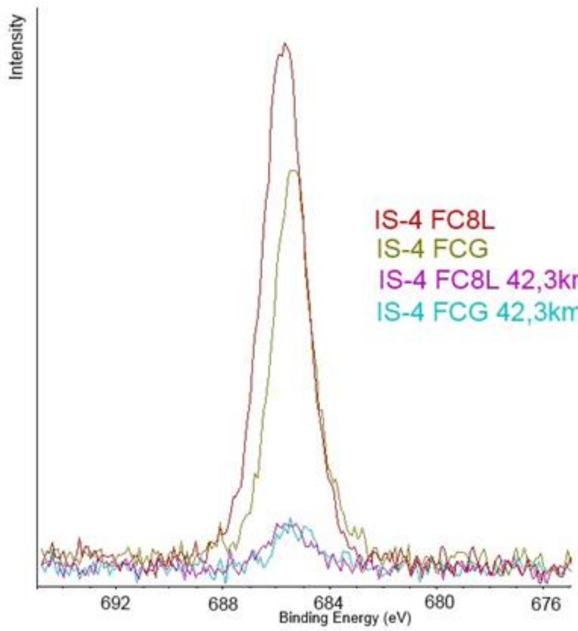


Figure 43 The Fluor content for the IS-4 ski base material before and after skiing 42,3 km.

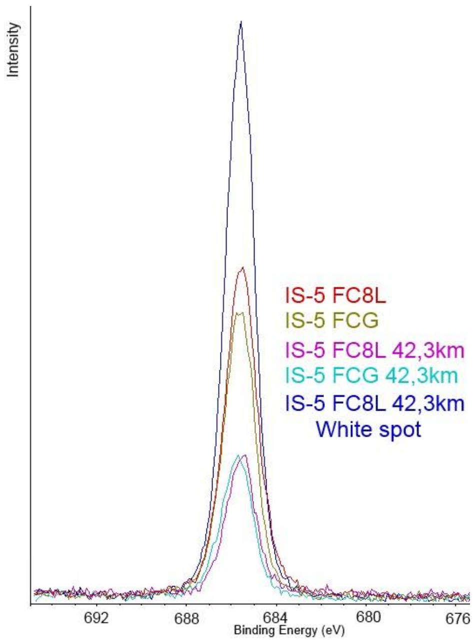


Figure 44 The Fluor content for the IS-5 ski base material before and after skiing 42,3 km, including the white particle in the ski base.

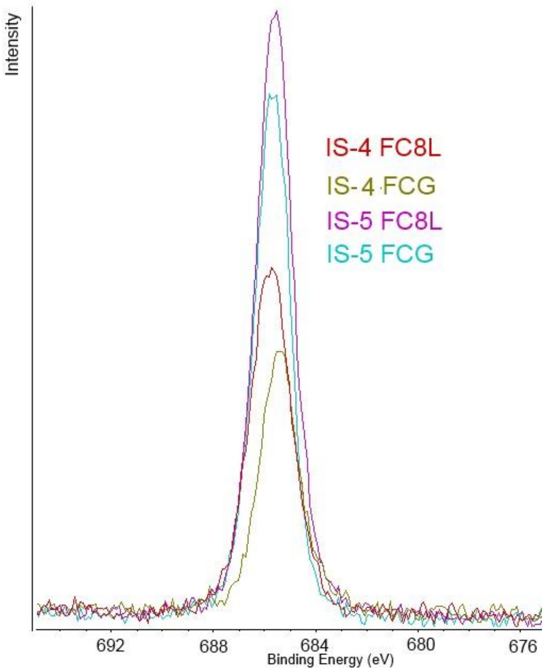


Figure 45 The two base material compared with FC8L and FCG wax, before skiing, in the spectra F 1s.

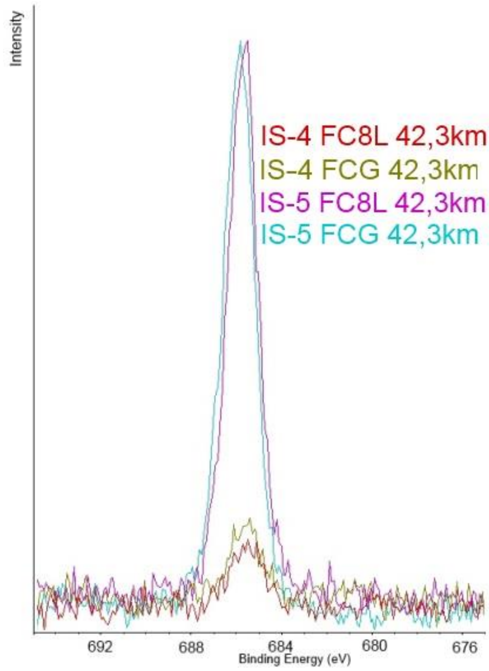


Figure 46 The two base material compared with FC8L and FCG wax, after skiing 42,3 km in the spectra F 1s.

Nitrogen appears after the skiing on both materials, shown in Figure 47 and Figure 48. The Nitrogen may be a contaminant found in the snow or due to the handling process of the skies during the field tests. For confirming the origin, a sample of liquid snow should be tested in ICP for identifying the elements. Figure 49 shows that IS-5 FCG shows the lowest Nitrogen content in the 1s spectra of all the materials that have been skied. According to Table 7 the IS-4 FCG 42,3 km also shows a lower atomic percentage of Nitrogen than IS-4 FC8L 42,3 km. This could imply that the FCG wax prevents accumulation of dirt and contamination better than the FC8L wax.

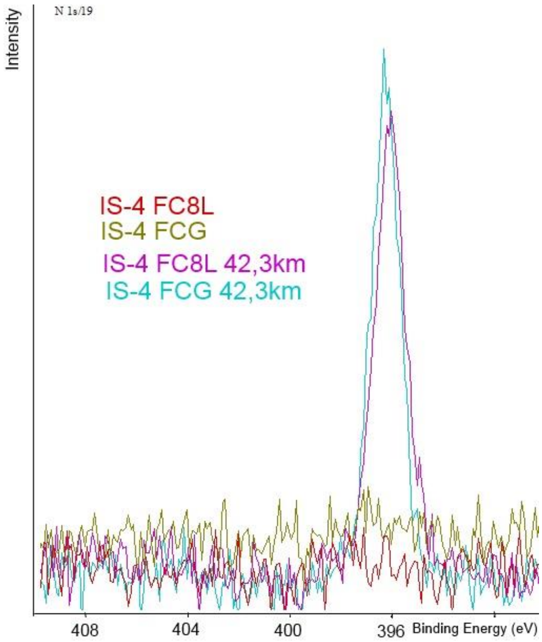


Figure 47 Nitrogen appears in the IS-4 ski base material after skiing 42,3 km.

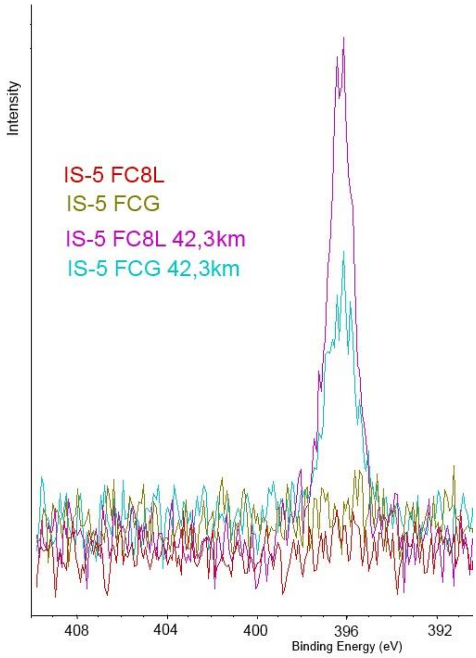


Figure 48 Nitrogen appears in the IS-5 ski base material after skiing 42,3 km.

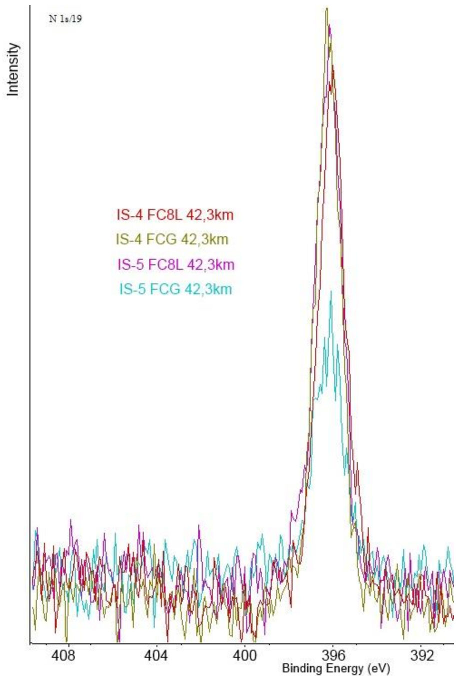


Figure 49 The intensity of Nitrogen in the spectra N 1s is lower for IS-5 FCG 42,3 km than for the rest of the skied materials.

The carbon content of the materials is very similar, they are difficult to distinguish and can be affected by contaminations. Figure 50 shows the IS-4 and IS-5 materials compared to each other. The intensity of the graphs is very similar which emphasise that the Carbon content is the same, as Isosport claimed. Further analysis of Carbon in the 1s spectra is in Appendix B.

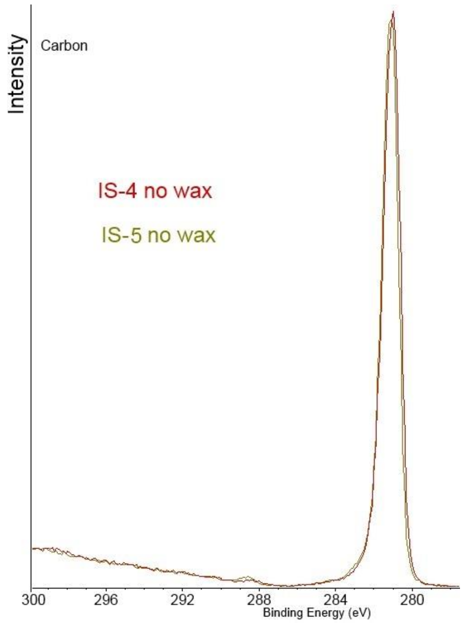


Figure 50 The Carbon content in the 1s spectra for IS-4 and IS-5 base materials with no wax added are very similar.

Oxygen content seems to increase after skiing. Both carbon and oxygen are difficult to analyse because they can have an origin in contaminations that contributes to the amount of the elements (e.g. in the field tests, the skis are handled with the hands or gloves and the snow used for the lab tests was collected from a public area with car traffic nearby).

Raman spectroscopy was conducted on the IS-4 and IS-5 material in the previous project work [43]. The results from Raman spectroscopy measurement performed on a white particle in the IS-5 material show great similarities with *Teflon* which means it most likely to contain fluorine, shown in Figure 51. When analysing the particle in XPS there is a great difference in the Fluor content between the white particle and the rest of the ski base material, as described in Table 7 and shown in Figure 52. The IS-4 material shows great similarities with a polymer chain (i.e. polyethylene) when tested with Raman Spectroscopy, which is much as expected. However, there are no similarities with *Teflon*. Table 3 states that IS-4 contains PTFE and it does contain some Fluor, but there are not as good match as with the white particle when tested in Raman Spectroscopy. The Raman spectrum of IS-4 is shown in Figure 53.

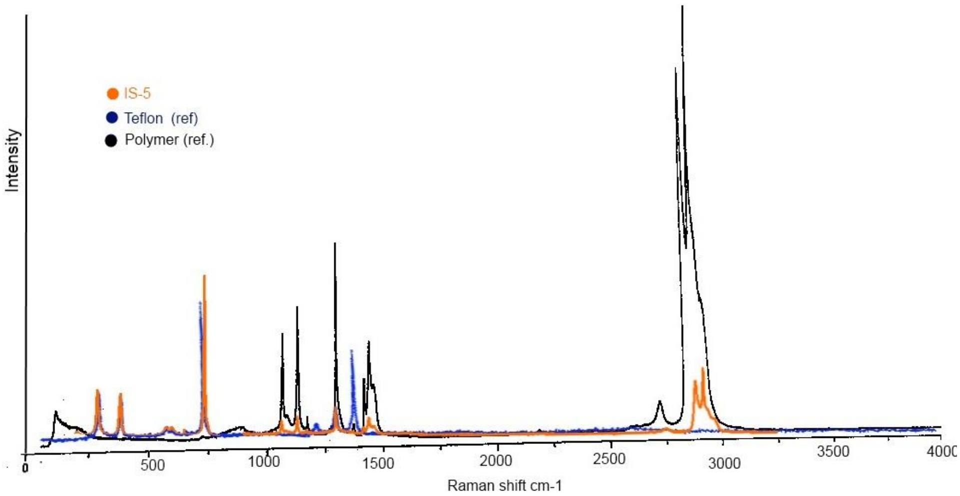


Figure 51 IS-5 white spot shows great similarities with Teflon.

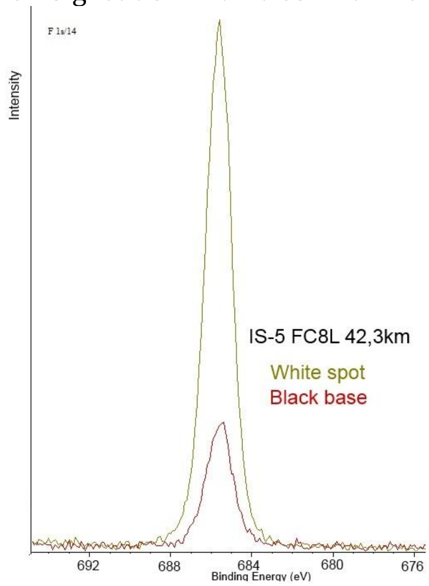


Figure 52 The intensity of the Fluor is much higher for the white spot than the black base for IS-5.

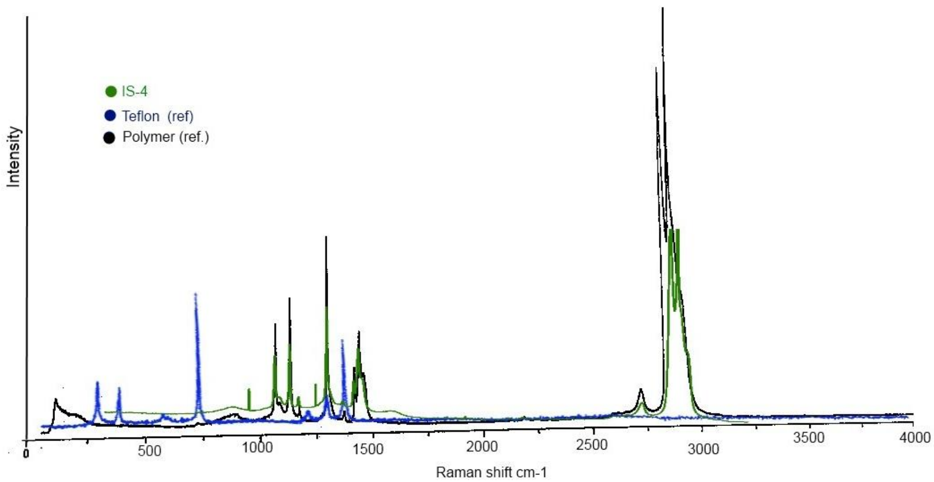


Figure 53 The IS-4 material show great similarities with polymer, but not with Teflon.

5.2 CONTACT ANGLE

The coefficient of friction and the hydrophobicity of a material are closely related. The hydrophobicity of the materials studied in this work was found by measuring the contact angle of a water drop on the surface of the materials. Each sample was tested with ten water droplets, the results are presented as one average contact angle with a resulting standard deviation. The roughness of the tested bases was also measured as it can affect the contact angle. However the roughness for the tests are designed to be equal and the area the roughness is measured represents only a part of the area where the contact angle test has been performed on. It is therefore assumed that the roughness here has very little effect. The contact angle and roughness results are shown in Table 8.

Table 8 The roughness and the static contact angle from the contact angle test.

Sample	Roughness	Average [µm]	Contact angle (α) [°]	STDEV (α) [°]
1 IS-4 no wax	Ra	2,26	**86,9**	1,2
	Rq	3,18		
	Rsm	237,27		
2 IS-4 CH10	Ra	2,23	**98,5**	1,2
	Rq	2,77		
	Rsm	214,00		
3 IS-4 FC8L	Ra	1,89	**93,6**	1,5
	Rq	2,45		
	Rsm	188,33		
4 IS-4 FCG	Ra	2,14	**106,8**	3,7
	Rq	2,83		
	Rsm	263,00		
5 IS-4 FC8L 42,3 km	Ra	2,21	**85,3**	1,9
	Rq	2,65		
	Rsm	332,00		
6 IS-4 FCG 42,3 km	Ra	1,87	**81,4**	1,1
	Rq	2,43		
	Rsm	236,67		
7 IS-5 no wax	Ra	2,61	**93,8**	0,9
	Rq	3,34		
	Rsm	230,67		
8 IS-5 CH10	Ra	2,22	**99,6**	1,5
	Rq	2,75		
	Rsm	213,67		
9 IS-5 FC8L	Ra	2,40	**97,4**	1,0
	Rq	3,10		
	Rsm	200,33		
10 IS-5 FCG	Ra	2,20	**121,3**	1,1
	Rq	2,71		
	Rsm	206,00		
11 IS-5 FC8L 42,3 km	Ra	2,56	**77,5**	1,3
	Rq	3,21		
	Rsm	287,33		
12 IS-5 FCG 42,3 km	Ra	2,58	**81,0**	1,2
	Rq	3,20		
	Rsm	291,00		

The standard deviation is large for the material IS-4 FCG, but there is no other material within the same area for the contact angle, so for the purpose of this project it will be assumed that this deviation will not affect the results. It is clearly the material with the second largest contact angle. The differences in roughness measured are not large enough to have an impact on the average contact angle, but worth noting if the results were not as predicted.

Table 9 shows the contact angle for the 12 materials from the highest to the lowest.

Table 9 Contact angle for the 12 tested materials.

No.	Material	Contact angle [°]
1	IS-5 FCG	121,3
2	IS-4 FCG	106,8
3	IS-5 CH10	99,6
4	IS-4 CH10	98,5
5	IS-5 FC8L	97,4
6	IS-5 no wax	93,8
7	IS-4 FC8L	93,6
8	IS-4 no wax	86,9
9	IS-4 FC8L 42,3 km	85,3
10	IS-4 FCG 42,3 km	81,4
11	IS-5 FCG 42,3 km	81,0
12	IS-5 FC8L 42,3 km	77,5

The FCG wax, before it is worn off by skiing, constitutes the materials with the largest contact angle. Secondly are the CH10 material, which is a very interesting result since it is expected that FC8L will provide with better friction properties than CH10 wax, since it contains Fluor. As expected the materials with the lowest contact angle are the ones used in the gliding field tests. This is due to contaminations and dirt in the track which makes the material more hydrophilic. The IS-5 materials have a much higher contact angle than the corresponding material of IS-4 before skiing, however after skiing the IS-5 materials have the lowest contact angle. This might mean that IS-5 materials have suffered a much more severe wear process or the contamination on the surface is larger.

5.3 ICP

ICP was conducted on the two liquid waxes, FC8L and FCG. After not getting an answer of the Gallium content with the XPS, the ICP was performed directly on the liquids. The main intention with the ICP was to confirm that the Gallium wax contained Gallium. However it was searched for several other metals in the waxes. Table 10 shows the results from the ICP with the amount in parts per million (ppm) and relative standard deviation (RSD).

Table 10 The results from the ICP.

Wax:	FC8L		FCG	
Isotope:	**Cons.** [ppm]	**RSD** [%]	**Cons.** [ppm]	**RSD** [%]
Pb208(LR)	0,09	6,0	0,40	10,0
Mg25(MR)	33,2	3,7	13,5	5,1
P31(MR)	142	7,0	91	5,3
S34(MR)	85	0,9	0	4,3
Ca43(MR)	102	24,0	205	18,4
Cr52(MR)	1,2	8,2	1,3	5,9
Fe56(MR)	38,4	3,2	6,6	7,6
Zn66(MR)	7,4	6,8	153,5	7,8
Ga69(MR)	0,103	114,6	17,6	8,0

There was not possible to determine the Fluor content with the ICP analysis, but the Gallium content was measured. FC8L do not contain any Gallium, while FCG wax contains 17,6 ppm. In Sugimura et al. the preferable amount of Gallium is 0,001 to 30 parts by weight mixed with 100 parts by weight of synthetic resin, or in a range from 0,01 to 10 wt% or even higher. These numbers are difficult to compare with the results from the ICP. 17,6 ppm is very little, and likely smaller than the amount purposed in Sugimura et al. The ICP analysis is very reliable. Which effect the small amount of Gallium can give the base, would be interesting to find out. There were also found a small amount of Zinc with the ICP analysis for the FCG wax.

5.4 FIELD TEST

A proper gliding field test requires many repetitions since there can be many variations in snow and weather conditions throughout the test period. Even though the output will only be the gliding time between two photo cells there is much information that must be written down and gathered to find out if the results are valid and which results can be compared. For the field test in this work, all the information was gathered into on a large excel-file including all weather and snow information as well as all the gliding times. One example of the results is shown in Appendix D.

At the first testing day in Holmenkollen it was sun, so the field test track became more humid during the second test run and dried up and froze towards the last test run. This was not ideal conditions for the ski wax used, which is why there were sat up another test day. The differences in weather conditions means that the different runs had different times, however this is one of the reasons a reference ski was included in the tests. All results were compared to the reference ski, and not only to each other. The second test day was in Granåsen, Trondheim. The track in Granåsen was a little shorter, but gave relatively similar gliding times as in Holmenkollen. The skis were tested first one time in the same condition as they left Holmenkollen, then the skis were skied on for 10,6 km and tested again. In Granåsen there was no wind, but a little snow on the first test, which increased the time. In the second test there were good weather conditions. More information about the snow and the weather during the field tests can be found in Appendix D.

The skis were skied for a total of 42,3 km. This includes the distance of the long distance skiing and for the skiing of the field tests, for more information see Appendix D, Table D-5. The long distance skiing was first one 8 km loop before the third gliding field test. Before the fourth gliding field test there were a new 8 km round. And then a last round of 10,6 km before the sixth and last gliding field test. To have long distance skiing between the tests are a common way to do field tests, so the variance of the skis over time can be evaluated. The results from the field tests are found in Figure 56.

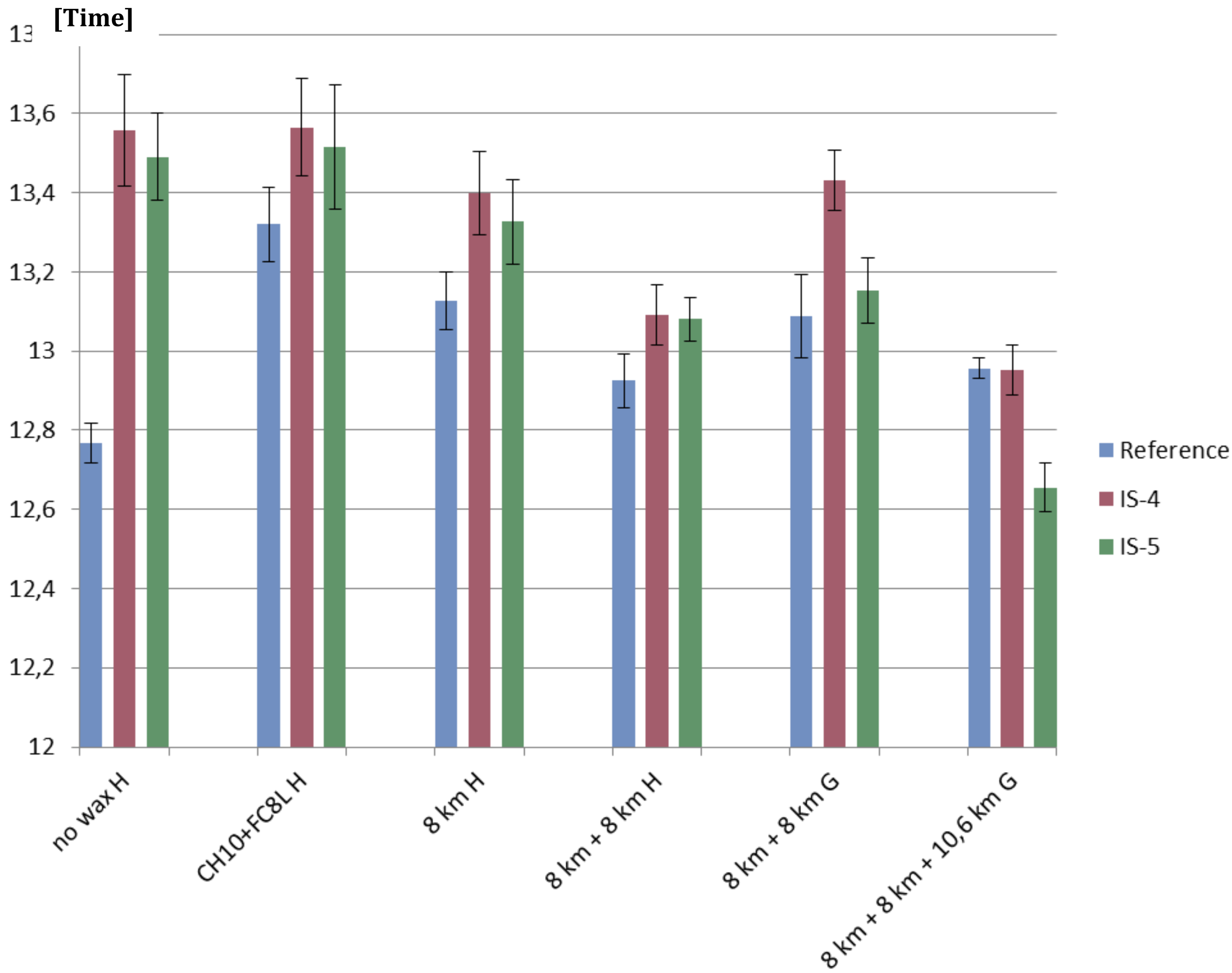


Figure 54 The results from the gliding field test. The H stands for Holmenkollen, while the G stands for Granåsen.

All the results in Figure 54 are the average time for each ski, while the black line on the top illustrates the standard deviation for each ski. All the four gliding tests in Holmenkollen consisted of six runs from two experienced test-skier, and the two tests from Granåsen are six runs from one test-skier, respectively. Figure 54 shows the results from 180 runs. The results from Holmenkollen are the average times from the two test-skiers put together, to see the individual rounds for the two test-skiers, see Appendix D, Figure D-6.

Table 11 shows the exact times from Figure 54. The materials with no wax, CH10+FC8L and 10,6 km has been tested with all the other apparatus. The three materials in the middle, 8 km , +8 km and 0 km, had no comparisons with other experiments.

Table 11 The average times for all the tests done during the gliding field test with percentage deviation compared to the reference ski.

	no wax	CH10+FC8L	8 km	+8 km	0 km	10,6 km	average
Ref [sec]	12,767	13,279	13,113	12,926	13,23	12,956	13,045
IS-4 [sec]	13,557	13,492	13,388	13,09	13,623	12,953	13,35
IS-5 [sec]	13,512	13,519	13,332	13,081	13,374	12,655	13,246
IS-4 [%]	**5,83**	**1,58**	**2,05**	**1,25**	**2,89**	**-0,02**	**2,285**
IS-5 [%]	**5,51**	**1,78**	**1,64**	**1,19**	**1,08**	**-2,38**	**1,517**

The total average shows that compared to all the runs the reference ski was fastest with an average time of 13,045 seconds each test. IS-5 followed with an average time of 13,246 s and at last IS-4 with an average time of 13,350 s. Negative percentage means the pair were faster than the reference ski.

It is important to notice that the reference ski is only used as a reference. It is another type of ski. The relative distance between the reference ski and the IS-4 ski and IS-5 ski is much more interesting. Nonetheless, the ski base of the reference ski was tested in the TE 88 to find a coefficient of friction for this material, but no material characterisation has been done on the reference ski. The IS-4 ski and IS-5 ski are of the same type of ski with identical ski characteristics. They were tested against each other earlier and confirmed equal, therefore they are directly comparable.

5.5 LAB FRICTION AND SURFACE CHARACTERISATION

The TE 88 was conducted on all the materials in Table 4 and on the reference ski from the gliding field test. The reference ski was tested in the same condition as in the gliding field test (with no wax). In addition TE 88 was carried out on two materials with another grinding to see if there were any remarkable differences in the results. However the main focus are the differences in the materials and the affection on friction, not the type of grinding. Since there is no material characterisation of the reference ski material, the materials in Table 6 will be most interesting. The TE 88 tests were performed at -10 °C on all the materials, but in an open room with no cooling. Four materials were tested with a temperature of -2 °C, but the results were not any good when there was no resistance in the snow. The snow got to wet and slushy. For more information about the tests at -2 °C see Appendix E.

Figure 55 shows the results from the material IS-5 FCG, test number 1. The COF decreases as increasing the testing time. This is not the case for all the tests done with the TE 88 and there is no clear decrease in COF as the speed increases. Therefore when evaluating the results it should be the total average value that are taken into account. For a visual inspection of all the results see Appendix E, Figure E-1. In Figure 55 one representative test result is shown.

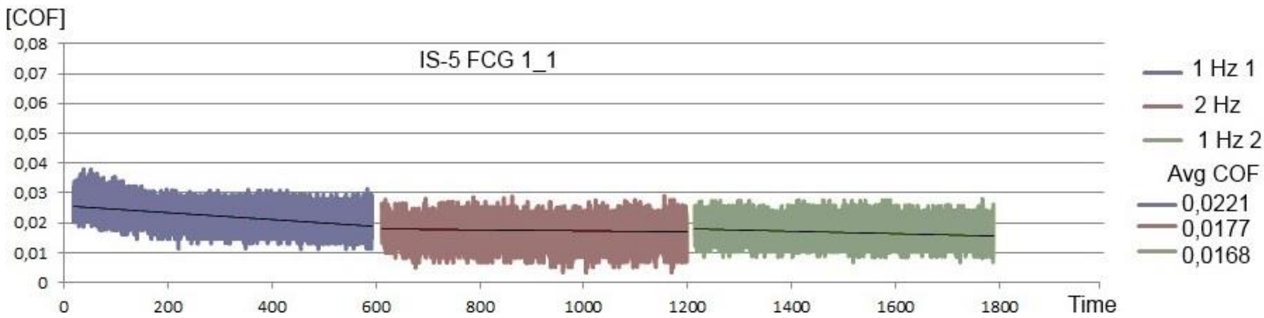


Figure 55 The result from the TE 88 test for the material IS-5 FCG, test number 1

All the materials in Table 4 were tested at least two times. If the difference in COF was too large, the materials were tested one more time (this happened with the materials IS-4 FC8L and IS-5 FC8L 42.3 km). Table 12 shows the final results from the TE 88 testing.

Table 12 The COF for all the material tested with the TE 88, as well as the average COF and the standard deviation of the COF.

	IS-4				IS-5			
	COF 1	COF 2	AVG COF	COF dev.	COF 1	COF 2	AVG COF	COF dev.
No wax	0,0284	0,0272	**0,0278**	0,0012	0,0304	0,0239	**0,0272**	0,0065
CH10	0,0187	0,0215	**0,0201**	0,0028	0,0163	0,0244	**0,0204**	0,0081
FC8L	0,0216*	0,0151	**0,0184**	0,0065	0,0123	0,0200	**0,0162**	0,0077
FCG	0,0164	0,0166	**0,0165**	0,0002	0,0189	0,0170	**0,0180**	0,0019
FC8L 42,3 km	0,0312	0,0259	**0,0286**	0,0053	0,0320*	0,0316	**0,0318**	0,0004
FCG 42,3 km	0,0284	0,0257	**0,0275**	0,0027	0,0182	0,0205	**0,0194**	0,0023
FC8L grinded	0,0262	0,0193	**0,0228**	0,0069	0,0209	0,0229	**0,0219**	0,002
	Reference ski							
	COF 1	COF 2	AVG COF	COF dev.				
No wax	0,0180	0,0125	**0,0153**	0,0055				

*The materials were tested again due to large differences in COF 1 and COF 2 and were replaced with the COF from the third run with TE 88. The COF less similar to the new COF was discarded.

The COF for the samples with a coarser grinding tested on – 10 °C with the TE 88 is higher than when a finer grinding is used for the materials waxed with FC8L. This can be due to the relative low test temperature. In Table 13 all the material from Table 4 tested with the TE 88 is listed from the lowest COF to the highest COF. In general the bases with no wax or that have been skied on for 42,3 km have the largest COF and the ski bases that are newly glided with wax has the lowest COF. This is much as expected, nevertheless all the tests are done on snow which is a very difficult medium to work with in the lab. None of the base materials (IS-4 or IS-4) stands out at the first glance in the results from the lab tests, which is also the case for the field test.

Table 13 List of the main materials from lowest to highest COF measured with TE 88.

COF No.	Material	AVG COF
1	IS-5 FC8L	**0,0162**
2	IS-4 FCG	**0,0165**
3	IS-5 FCG	**0,0180**
4	IS-4 FC8L	**0,0184**
5	IS-5 FCG 42,3 km	**0,0194**
6	IS-4 CH10	**0,0201**
7	IS-5 CH10	**0,0204**
8	IS-5 No wax	**0,0272**
9	IS-4 FCG 42,3 km	**0,0275**
10	IS-4 No wax	**0,0278**
11	IS-4FC8L 42, 3km	**0,0286**
12	IS-5 FC8L 42,3 km	**0,0318**

6 SUMMARY AND COMPARISON

Table 14 shows a summary of the most important results obtained in this work the values are average values. The table is explained in the list below:

- Col 1: The material tested
- Col 2: Roughness (R_q) measured during the TE 88 test
- Col 3: The average COF measured with TE 88
- Col 4: The ranking of the material sorted by Col. 3
- Col. 5: The roughness (R_q) measured during the contact angle test
- Col 6: The contact angle of the material
- Col 7: The ranking of the material sorted by Col 6.
- Col 8: The time for the field test compared to the reference ski. Note: negative percentage means the skis were faster than the reference ski
- Col 9: The approximate atomic composition of the Fluor content at the surface of the material measured with the XPS analysis

Table 14 Summary of various results after the lab and the field tests.

Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9
Material:	R_q TE 88 [µm]	COF	COF ranking number	R_q α [µm]	α [°]	α ranking number	time [%]	F [at%]
IS-4 No wax	3,09	0,0278	10	3,18	86,9	8	5,827	2,68
IS-4 CH10	2,83	0,0201	6	2,77	98,5	4	-	0,85
IS-4 FC8L	3,00	0,0184	4	2,45	93,6	7	2,054	3,79
IS-4 FCG	2,47	0,0165	2	2,83	106,8	2	-	2,37
IS-4 FC8L 42,3km	2,44	0,0286	11	2,65	85,3	9	0,023	0,44
IS-4 FCG 42,3km	2,54	0,0275	9	2,43	81,4	10	-	0,29
IS-5 No wax	3,24	0,0272	8	3,34	93,8	6	5,514	2,64
IS- CH10	3,33	0,0204	7	2,75	99,6	3	-	2,46
IS-5 FC8L	2,53	0,0162	1	3,10	97,4	5	1,643	5,25
IS-5 FCG	3,05	0,0180	3	2,71	121,3	1	-	4,75
IS-5 FC8L 42,3km	3,56	0,0318	12	3,21	77,5	12	-2,379	2,33
IS-5 FCG 42,3km	2,84	0,0194	5	3,20	81,0	11	-	2,64
Ref. ski	2,95	0,0155	-	-	-	-	0	-

6.1 COMPARISON OF IS-4 AND IS-5 SKI BASE MATERIAL

To characterise the properties for the two different ski base materials, IS-4 and IS-5, analysis and comparisons of how the three waxes affect the bases has been carried out. This is done by compare the two materials up against each other when the different waxes are applied, and also evaluate the condition of the materials after they are skied on.

NO WAX

In the field tests the IS-5 pair runs slightly faster than the IS-4 pair when no wax is applied, though not remarkably. IS-5 with no wax scores better than IS-4 with no wax in both lowest COF and highest contact angle. The COF's are quite similar, but when testing the contact angle, the IS-5 no wax material gets place number 6, which is good considering there is no wax enhancing the hydrophobicity. IS-5 gets a contact angle of 6,9 ° higher than IS-4 no wax material. The Fluor content is apparently almost the same according Table 7 (IS-4 is 0,04 atm% higher). When evaluating the peak intensity in the XPS results (Figure 39) against each other and considering the development of the Fluor content in the rest of the samples, it can be assumed that the Fluor content in IS-4 is lower than for IS-5.

CH10

Both materials with CH10 wax shows very large contact angles, third and fourth best of all the samples. On the other hand they have the lowest content of Fluor before the samples were tested in the field, IS-4 has a lower Fluor content than IS-5. IS-4 and IS-5, when added CH10 wax, behaved very similarly in the lab (unfortunately these materials were not tested in the field). The difference in the measured COF is only 0,0003 and the difference in the measured contact angle is less than 1 °.

FC8L

However, applying FC8L on top of the materials with CH10, it results in a small difference in performance for the two materials, favouring IS-5. IS-5 with FC8L wax is the material with the lowest COF tested in TE 88. The measured COF for IS-5 is 0,0022 lower than IS-4 and the contact angle is 3,8° larger. Also in the field tests IS-5 were faster than IS-4 when FC8L wax was applied to the skis. The Fluor content for IS-5 FC8L is the highest of all the samples, therefore this might be one reason for the better performance. For this wax, the field and lab tests were very comparable.

FCG

The contact angle for IS-5 FCG is without doubt the highest of all the contact angles, with an angle of 121,3 ° followed by IS-4 FCG with 106,8 °. For the COF measured with the TE 88 IS-4 have the second lowest COF, while IS-5 have the third lowest COF. There has not been performed any gliding field test on the material with only FCG wax, which could be interesting considered the large contact angle for the IS-5 material. In the lab tests there are many variables to consider, so it is not possible to draw any conclusion at the moment only based on the COF measured without any field reference. The contact angle for both materials, especially IS-5, is very high, the Fluor content is lower than for LF8L, but there is small amount of Gallium (17.6 ppm) which could be contributing to the large contact angle.

AFTER SKI

In the gliding field tests two bases applied CH10 with a layer of FC8L on the top were tested. The two materials glided very equally in the last field test in Holmenkollen, after two 8 km rounds. At this time there was a bit of ice in the track and all the tests were faster than the previous. IS-4 and IS-5 ski pairs had very similar times, the reference ski were slightly faster. However, moving the field test ski track to Granåsen, with no additional skiing, the IS-5 shows much better times than the IS-4 pair. After the skis had skied on for additional 10,6 km, the last field test shows that the IS-5 goes faster than both IS-4 and the reference ski. All these tests have been performed at a temperature around 0 °C, which is very critical temperature considering it is a transition temperature for the snow. The field test shows very different results for IS-5 FC8L 42,3 km than the all the tests done in the lab.

Evaluating the contact angle and the COF obtained in the lab, IS-5 FC8L 42,3 km got the poorest results of all the materials tested. IS-4 FC8L 42,3 km shows a high COF, but the contact angle is higher than for the rest of the worn materials. The contact angle for IS-4 FC8L 42,3 km is only 1,6 ° lower than for IS-4 with no wax. In comparison, IS-5 FC8L 42,3 km shows 16,3° lower than IS-5 with no wax. IS-4 follows the trend for the COF and contact angle and to some degree the field test. While IS-5 FC8L 42,3 km makes an exception in being the very best compared to the reference ski in the gliding field test, but getting the lowest results on both contact angle and COF. The parts where it was FCG wax on the ski, the results are better for IS-5 and poorer for IS-4. This includes the contact angle, the COF and also the amount of Fluor in the base. IS-4 FC8L 42,3 km has a higher content of Oxygen, Sodium and Sulphur than IS-4 FCG, in the IS-5 material this is opposite. It seems like the two ski base material responds differently to the two liquid waxes, however no conclusions can be drawn at the moment since there is a lack of field and lab results for comparison.

6.2 COMPARISONS TO PREVIOUS WORK

There are very little described research in the literature about ski waxes. Sugimura et al. has made a patent for ski waxes contain Gallium. The amount in their papers [25, 48] indicates a very vague amount of Gallium or Gallium alloys. They claim the synthetic resins should contain 0,01 to 10 wt% of Gallium, there are in this project managed to find 17,6 ppm of Gallium in the Gallium wax FCG. This is an extremely small amount, and not comparable with the concentration recommended in [25]. However, the FCG wax makes outstanding results considering the contact angle and there are also found amount of Zinc, which may have contributed to the good results.

In Stamboulides et al. [38, 49] the objectives was to identify ways to increase the hydrophobicity of the ski base material of UHMWPE, aiming at decreasing COF with ice. The fluorine composition on the surface material was measured by using XPS. Contact angle testing was also performed by sessile drop technique to detect the hydrophobicity. To increase the hydrophobicity of the ski base material it was added liquid fluorinated additives by plasma-enhanced chemical vapour deposition (PECVD). The results were an increase of contact angle in the water droplets from 85 ° to 138 °. A decrease in COF of 25 % at the highest rotating velocity were also found [38]. A rotational tribometer was used to measure the friction [49]. Figure 56 shows their results when testing three different materials with different hydrophobicity. Water film made from frictional heating is better exploited by hydrophobic surfaces (in this case PTFE), which is the reason why PTFE has the steepest graph. This experiment was performed on ice, not snow, and the temperature is used as a variable. From -10 °C and warmer these results should be comparable with this project experiments, the COF's are in the same region. The Fluor content and the static contact angle of the material tested are close to the results found in this project using XPS and sessile drop technique.

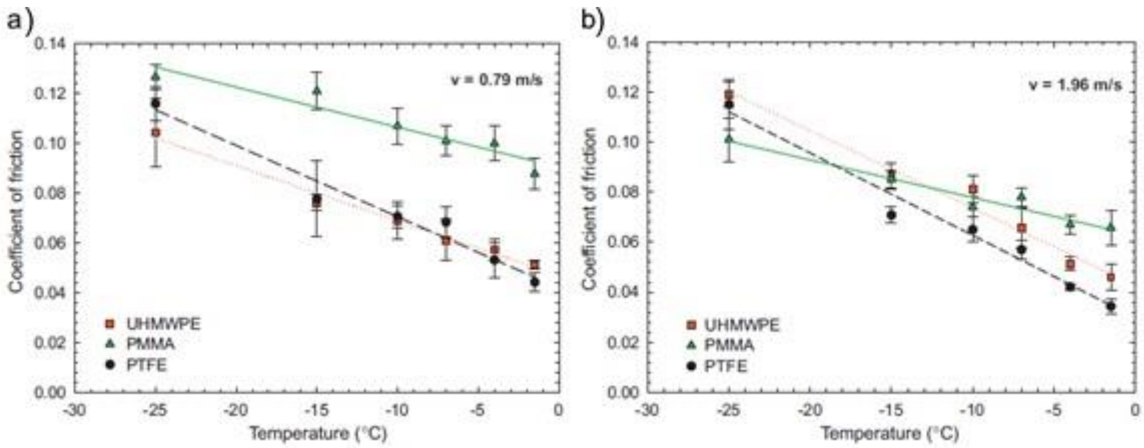


Figure 56 Temperature effect of COF for ice on polymer **a)** 0,79 m/s **b)**1,96 m/s [49]

In another project also performed by Olympiatoppen [50], gliding field tests similar to the ones in this project has been conducted, only in a wind tunnel. This way the weather and snow temperatures are very stable, there is neither wind nor sun, perfect conditions for testing. The results in Figure 57 show significantly lower times for the gliding test for the skis that are waxed. After 10 km, in Figure 58, the difference is lower, there has been a 4,2% increase in time for the waxed skis, and almost no increase for the not waxed skis. The waxed skis was still faster after 10 km. The skis tested are of the same model with the same grinding. The skis tested was prepared as B1 (no wax), B2 (CH-wax), B3 (LF-wax), B4 (HF-wax) wax and B5 (Fluor powder). All the waxes are waxes from Swix.

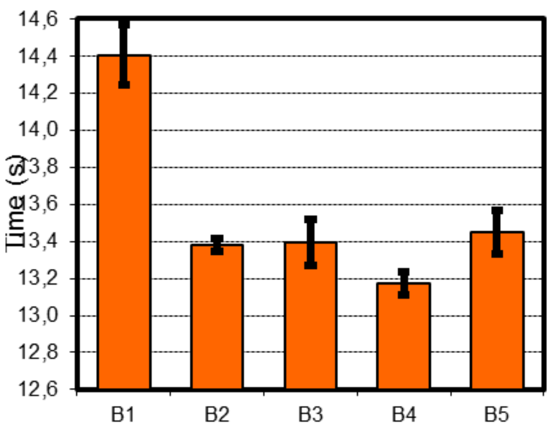


Figure 57 The average time for B1, B2, B3, B3 and B5 before skiing

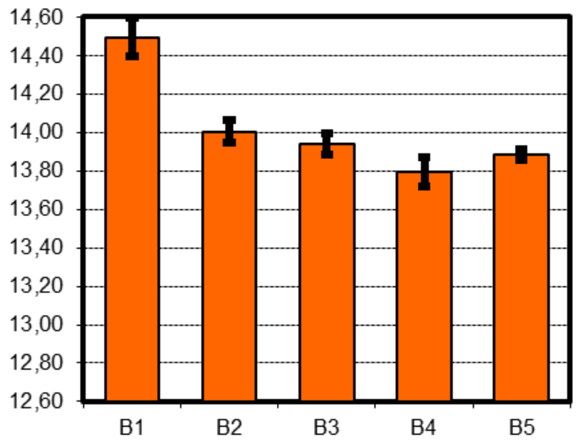


Figure 58 The average time for B1, B2, B3, B3 and B5 after skiing

The results in this project should be comparable to the results from [50] .The results from this project field test show the same expected trend on the three first rounds and are comparable. On the three final rounds however, the IS-5 and IS-4 skis shows improved results compared to the reference ski, which is an unexpected outcome.

6.3 RECOMMODATION FOR FURTHER WORK

There are some unclear results from the XPS considering the amount of Fluor in the ski base IS-4 with no wax added. This sample shows a higher atomic percentage of Fluor in the element composition than the IS-5 material with no wax, but a lower intensity when the graphs are compared with each other. The IS-5 materials have a much higher intensity than the IS-4 materials considering the Fluor content after the materials have been worn. The worn IS-5 materials have approximately the same amount of Fluor as IS-5 without wax, but for the IS-4, the content of Fluor is much lower. One theory is that the IS-4 material has a thin layer of Fluor on the top before the material is skied on and that this layer is later worn away. Another option is that the IS-4 material absorbs contaminations more easily. For further investigations it is recommended to look further into the material composition of the IS-4 material without wax.

The results from the gliding field tests showed that both the test materials got better gliding properties after a long time skiing. Considering the literature and the results obtained in the lab for COF and contact angle for water droplet, this is most likely only a happy coincidence. Further gliding field test to prove this should be performed.

Further tests of the Gallium wax, the FCG, are recommended. The implications Gallium might have for the field tests should be studied in the future and compared to the lab tests. Also further examination of which materials that constitutes to the high contact angle is relevant to investigate. Further material analysis should be carried out. Is the very small amount of Gallium enough to make wonders or is it the Zinc or other elements that are affecting the contact angle? The FCG wax contains less Fluor than FC8L, so not only Fluor is essential considering contact angle.

7 CONCLUSIONS

- The friction properties of a ski are very dependent on the type of snow and the weather conditions. There are many uncertainties when doing scientific research on snow, ice is a more reliable medium. When doing friction tests in lab, there are fewer variables than for outdoor field tests. In a lab test only a small part of the ski is used and the weather conditions are stable and controllable.
- It is difficult to do any direct comparisons between the outdoor field tests and the lab tests in this project. The test material IS-5 FC8L 42,3 km makes a large exception being the best in the track and the worst in the lab. Other than that result there are many similarities between lab and field test.
- The Carbon content of the two ski base materials tested are similar.
- Both the ski base materials tested contains Fluor.
- The white particles in the IS-5 ski base do most likely contain a high amount of fluorine.
- Fluor contributes to a lower surface energy which makes the material water repellent, that results in a higher contact angle. However the Fluor content is not proportional with the contact angle of the material tested. FC8L wax, for both materials, contained the highest amount of Fluor, but had lower contact angle than CH10 waxes, which had the lowest amount of Fluor for both materials.
- The contact angle gets lower after the ski is used. The IS-4 material lowers the contact angle less than IS-5 material after being skied on.
- The IS-5 ski base material makes the largest contact angle of all the materials in combination with FCG wax and has a higher contact angle than IS-4 when no wax is added.
- The Fluor loss is lower for IS-5 than IS-4 after 42,3 km of skiing.
- The surface topography gives no remarkable changes after two runs with the setup as in this project for TE 88. This corresponds to about 500 metres of skiing. There were neither a notable difference in the topography of the ski bases that had skied for 42,3 km and the newly grinded skis with the same roughness.
- There is a common understanding that Gallium wax is good and long lasting and the contact angle for the FCG wax were remarkably higher than for the FC8L. However the Gallium wax tested in this project only contained 17,6 ppm Gallium, which is a very small amount. This is probably not the single reason to make such a large difference in the contact angle. There are probably other elements in combination that contributes to the high contact angle.

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APPENDIX A - DMTA

Dynamical Mechanical Thermal Analysis (DMTA) can measure different properties of a polymer material by applying an oscillating force at various frequencies over a temperature range on a specimen. DMTA are suited for viscoelastic materials, materials that show both elastic and viscous response to deformation. Elasticity is the materials capacity to regain to the original shape after deformation, while viscosity is the materials resistance to flow. Polymers are viscoelastic materials. The DMTA measures the storage modulus (E') and the loss modulus (E''). The modulus is the ratio of stress to strain, it can be viscous or elastic. E' measures the elastic response to deformation and is at low strain rates and room temperature approximately equal to the Young's modulus of the material.

The storage and loss modulus are used to determine the glass transition temperature (T_g) and the crystalline melting temperature (T_m). Tan δ, Equation (A-1), describes how well a material absorbs energy under cyclic load in DMTA. Tan δ-graph indicates T_g when the graph shows a maximum and T_m is indicated when Tan δ shows a minimum. The graphs can plot the modulus and Tan δ as a function of temperature, as shown in Figure A-1.

Damping $\quad\quad$ $\tan \delta = E''/E'$ $\quad\quad$ (A-1)

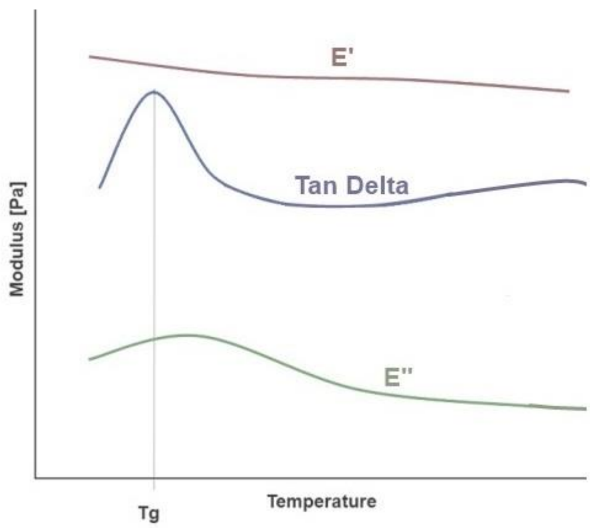


Figure A-1 Illustration of a DMTA graph, where the peak at Tan Delta indicates Tg and

THE DMTA EXPERIMENT

IS-4 and IS-5 without any wax were tested from +30 °C to +150 °C, two series with each material, with the aim to find a crystalline melting temperature for the two materials. It was supposed to do all the tests on minus degrees as well to detect any transition temperatures. Due to technical problems this was only performed one time with the IS-5 material.

The tests were carried out using a dual cantilever bending jig and a set up with temperature as variable. Test specimens were approximately 50 mm x 1,2 mm x 6 mm. The frequency used was at 0,5 Hz and a strain of maximum 0,25% was applied. Thermal equilibrium had to be reached before the measurements of the ski base specimen could start. The tests were performed with two temperature levels. The first level was from 30 °C to 115 °C with a temperature interval of 5 degrees. The second level was from 115 °C to 150 °C with a more accurate temperature interval of 3 degrees. The material were expected to have a crystalline melting temperature between 115 °C and 150 °C, this way the measurement of T_m would be more accurate. The dynamical behaviour over a temperature range was measured and it should be possible to detect any transition points. Figure XX shows parts of the DMTA machine, the test-specimen is fasten to the dual cantilever bending jig in Figure A-2 c) that are locked inside a heat-chamber, Figure A-2 b), and the information is given on the computer, Figure A-2 a). In addition there is air-supply into the chamber, a heater and in the case of cooling, liquid Nitrogen is used.

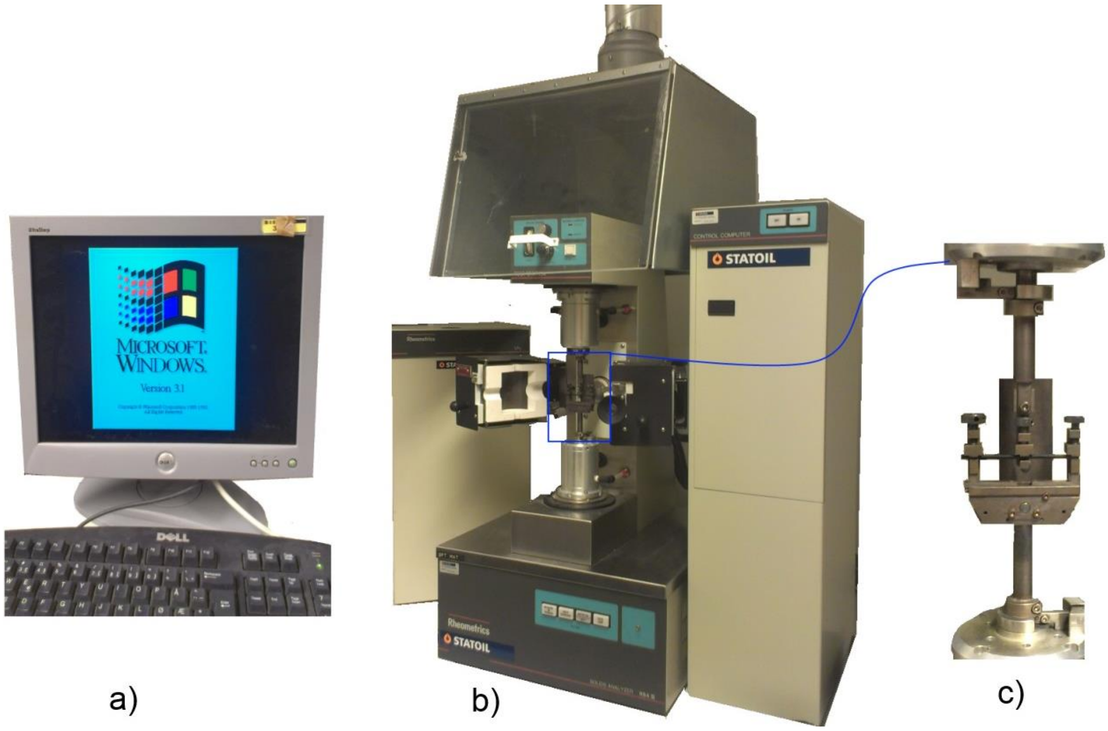


Figure A-2 The DMTA at NTNU, **a)** shows the software used (Windows DOS 3.1 (1992)), **b)** the main part with the sample holder and the motor to the right and **c)** shows the dual cantilever bending jig with a test specimen inside

RESULTS

With the accuracy of the DMTA machine used, it is not possible to differentiate the different type of ski bases. IS-4 and IS-5 was tested from room temperature and supposedly up to its crystalline melting temperature, T_m. Both bases showed a T_m

between 126 °C to 132 °C or the machine stops measuring at this points. There are too small differences to conclude a difference in the mechanical behaviour of the two ski bases, but it if the melting temperatures are around 130 °C it is important to be observant on this when applying wax. The results in Figure A-3 shows the results when IS-5 was tested between -150 °C and +150 °C degrees. There is a glass transition point around -130 °C and the melting temperature is likely around +130 °C. In a competition-like temperature (-20 °C to +10 °C) there are stable mechanical behaviour of the ski base. Figure A-2 and A-3 shows the results for IS-4 and IS-5 tested in a temperature range from room temperature to +150 °C. The Modulus's E' and E'' stops around 130 °C, if this is due to a transition point or if the machine is broken is still unknown.

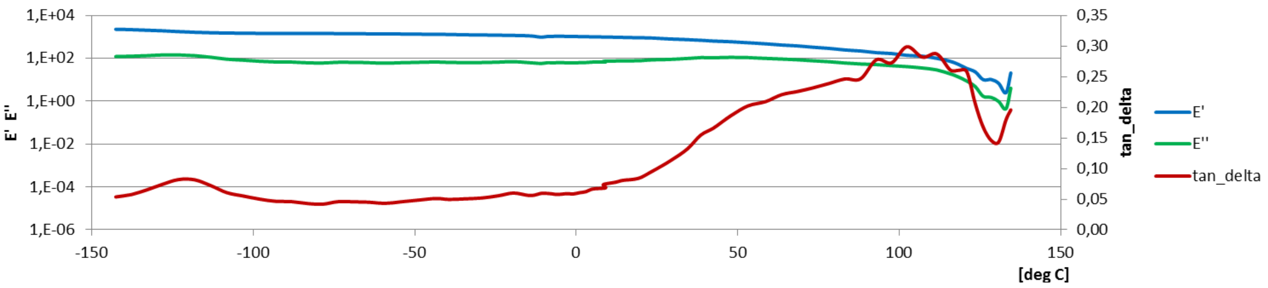


Figure A-3 The IS-5 material tested from -150 °C to +150 °C.

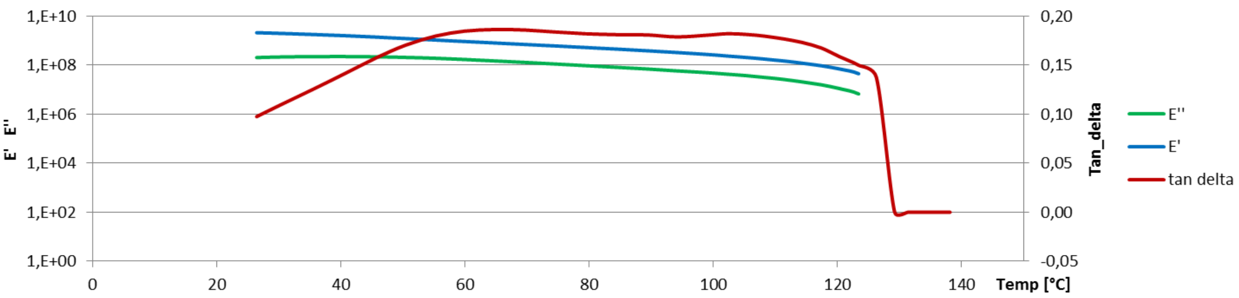


Figure A-4 IS-4 tested with DMTA from room temperature to 150 °C

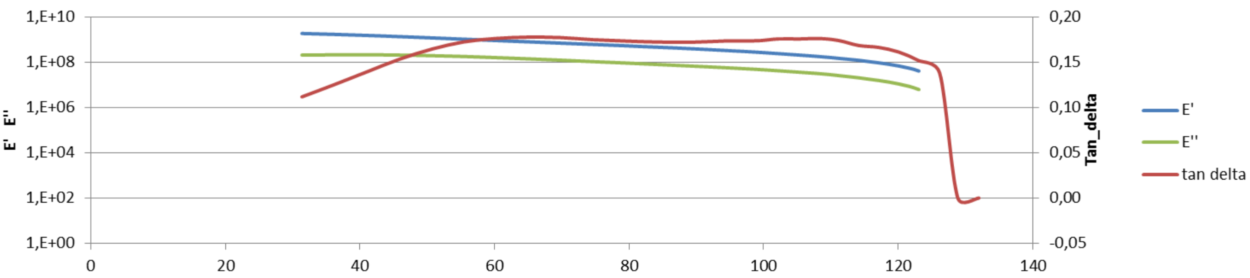


Figure A-5 The IS-5 ski base tested from room temperature to 150 °C

APPENDIX B - XPS

The carbon content for the IS-4 and IS- 5 materials are shown in Figure B-1 and Figure B-2. There are small differences in the amounts within the different materials, this can be caused by the different waxes or by contaminations.

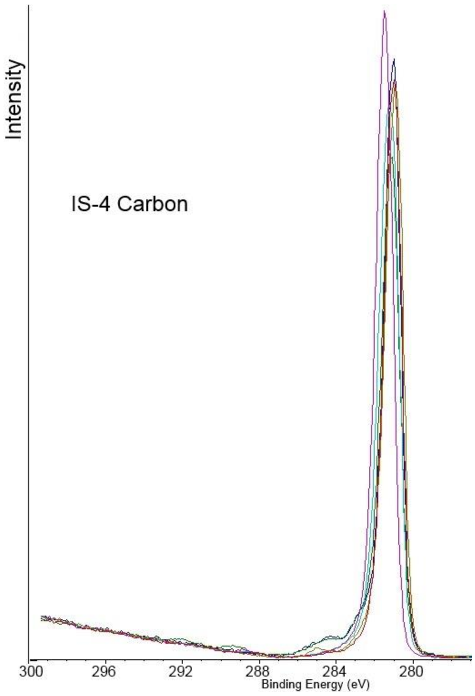


Figure B-1 Carbon intensity for the IS-4 materials in the spectra C 1s

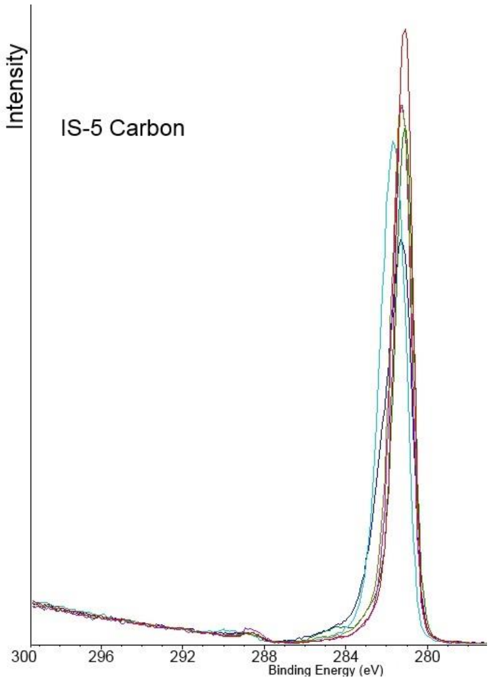
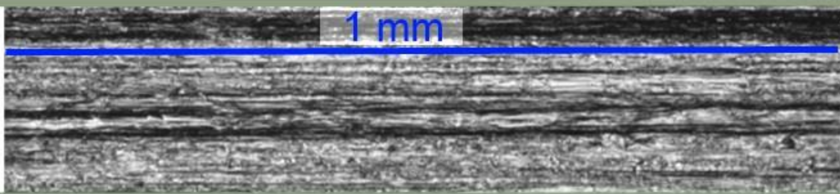
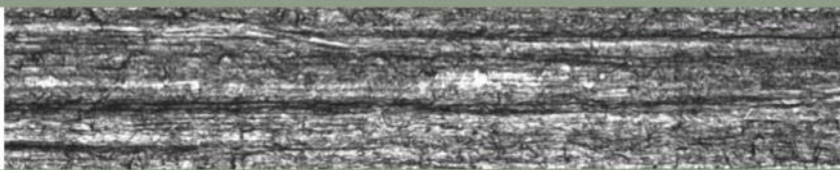
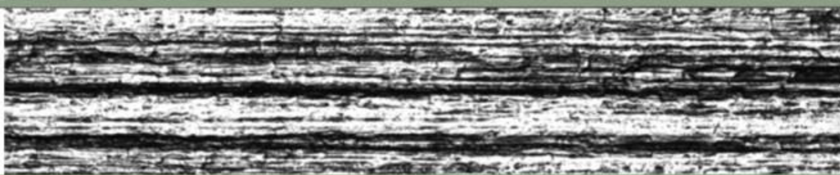
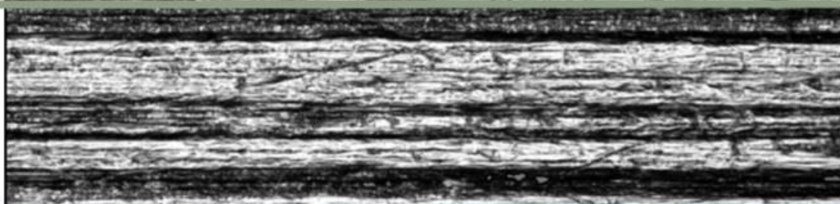
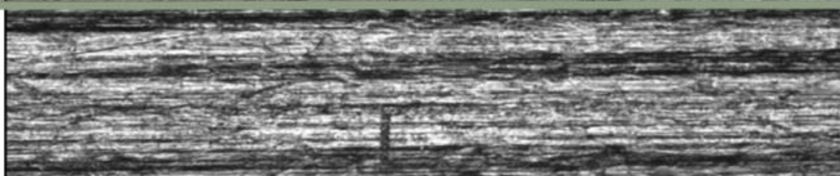
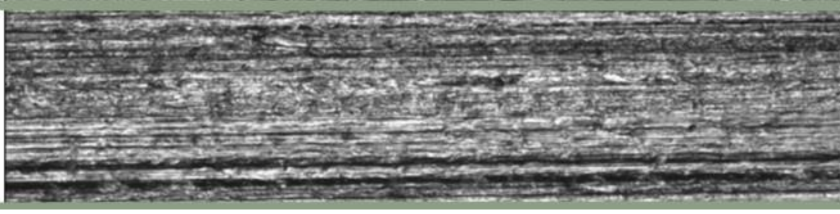


Figure B-2 Carbon intensity for the IS-5 materials in the spectra C 1s

APPENDIX C - CONTACT ANGLE

Roughness and microscopic picture of the material tested with contact angle are shown in Table C-1.

Table C-1 The microscopic pictures conducted while measuring the roughness prior the contact angle tests.

		Contact Angle samples in microscope	Roughness
1	IS-4 u/wax		Ra:2,26 Rq:4,85 RSm:237,27
2	IS-4 m/CH10		Ra:2,23 Rq:2,77 RSm:214,00
3	IS-4 m/CH10 + FC8L		Ra:1,89 Rq:2,45 RSm:188,33
4	IS-4 m/CH10 +FCG		Ra:2,14 Rq:2,83 RSm:263,00
5	IS-4 m/CH10 + FC8L 42,3km		Ra:2,21 Rq:2,65 RSm:332,00
6	IS-4 m/CH10 + FCG 42,3km		Ra:1,87 Rq:2,43 RSm:236,67

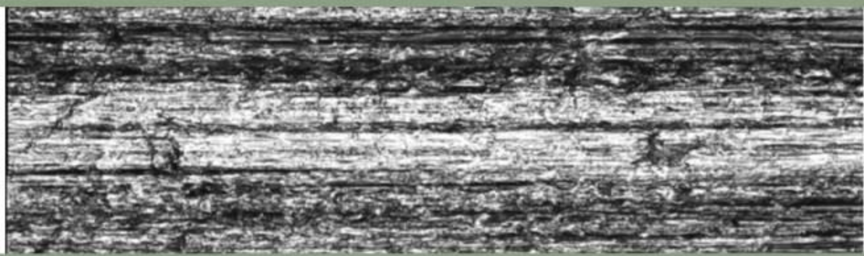
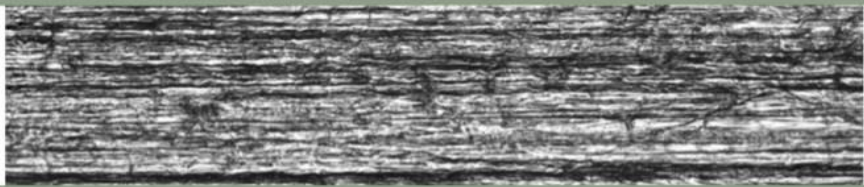
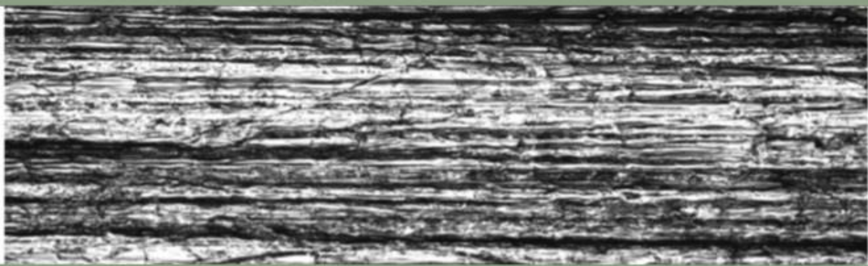
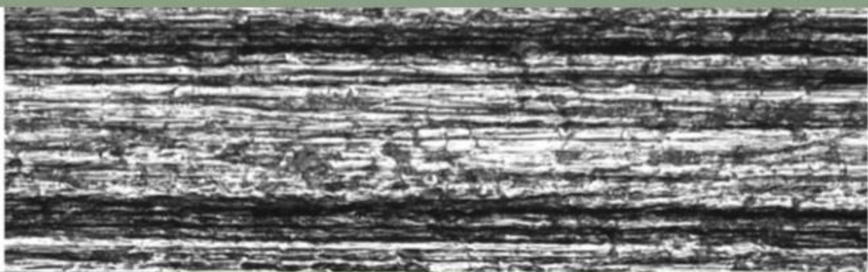
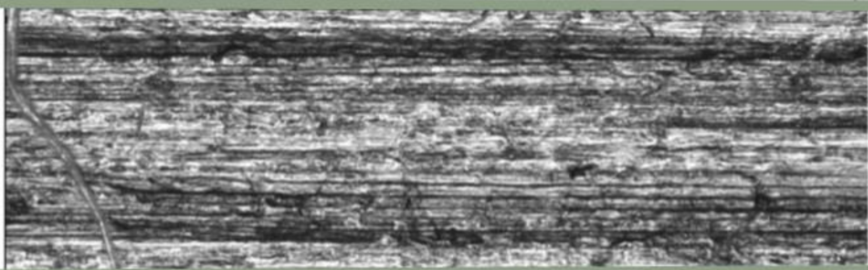
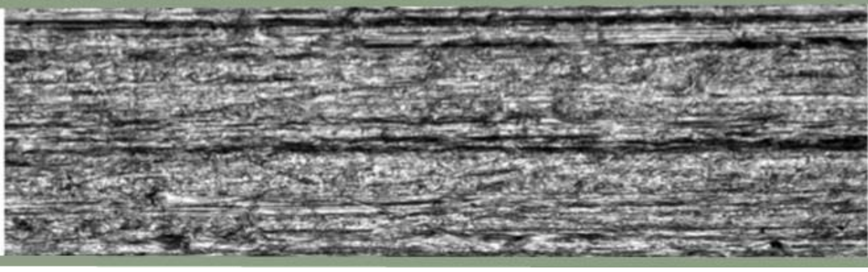
		Contact Angle samples in microscope	Roughness
7	IS-5 u/wax		Ra:2,61 Rq:3,34 RSm:230,67
8	IS-5 m/CH10		Ra:2,22 Rq:2,75 RSm:213,67
9	IS-5 m/CH10 + FC8L		Ra:2,40 Rq:3,10 RSm:200,33
10	IS-5 m/CH10 +FCG		Ra:2,20 Rq:2,71 RSm:206,00
11	IS-5 m/CH10 + FC8L 42,3km		Ra:2,56 Rq:3,21 RSm:287,33
12	IS-5 m/CH10 + FCG 42,3km		Ra:2,58 Rq:3,20 RSm:291,00

Table C-2 The results of all the droplest in the contact angle test

Contact Angle test

02.05.2013 Huiting

Sample name	IS-4 no wax (1)	IS-4 CH10 (2)	IS-4 FC8L (3)	IS-4 FCG (4)	IS-4 FC8L 42k (5)	IS-4 FCG 42K (6)	IS-5 no wax (7)	IS-5 CHIO (8)	IS-5 FC8L (9)	IS-5 FCG (10)	IS-5 FC8L42K (11)	IS-5 FCG 42K (12)
Replicate 1	86,0	100,0	96,0	101,0	88.5	82,0	94,5	98,5	96,0	122,0	79,0	82,0
Replicate 2	88,0	100,0	92,0	104,0	89,0	80,5	94,0	101,0	98,5	121,5	80,0	81,5
Replicate 3	88,0	99,0	92.5	106,0	83,0	80,0	93,5	99,0	98,0	122,5	77,5	82,5
Replicate 4	87,5	98.5	93,0	105.5	87.5	80,5	94,5	99,5	96,0	121,0	77,0	82,0
Replicate 5	87,0	100.5	93,0	110,0	86,0	83,0	94,5	101,5	96,5	122,5	76,0	81,5
Replicate 6	89,0	98,0	92,0	112,0	87,0	82,0	92,5	101,0	97,5	121,5	76,5	80,5
Replicate 7	86,5	99,0	93.5	109.5	83,0	81,0	92,5	101,5	98,5	121,0	77,5	82,0
Replicate 8	88,0	99.5	95,0	108,0	85,0	83,5	94,5	100,5	97,0	122,5	76,0	81,0
Replicate 9	86,0	99.5	94.5	108.5	84,0	81,0	95,0	99,5	98,0	121,5	78,0	80,5
Replicate 10	86,5	97,0	91.5	109,0	85,0	80,0	93,0	98,0	97,5	119,0	77,0	81,0
Replicate 11	85,0	97,0	93.5	104,0	85.5	81,5	93,0	98,5	98,5	120,5	79,0	79,5
Replicate 12	85,5	98,0	94,0	103.5	86,0	82,0	94,0	97,0	96,5	120,0	76,0	78,5
Average	**86,9**	**98,5**	**93,6**	**106,8**	**85,3**	**81,4**	**93,8**	**99,6**	**97,4**	**121,3**	**77,5**	**81,0**
STDEV	**1,2**	**1,2**	**1,5**	**3,7**	**1,9**	**1,1**	**0,9**	**1,5**	**1,0**	**1,1**	**1,3**	**1,2**
Note	wetting			big area variation Sample not homoge neous	wetting	wetting. Air dry before pack					wetting. Air dry before pack	wetting. Air dry before pack

APPENDIX D - FIELD TEST

The gliding field tests were conducted during two days. The first day were in Holmenkollen, Oslo, the other were in Granåsen, Trondheim. The first day in Holmenkollen there were to ski testers, Felix Breitschädel and Håvard Skorstad. They performed four test rounds each, so in total eight tests round. The second test day in Granåsen there were only one ski tester, Breitschädel, two tests were carried out. So in total there were ten tests which all had an excel file similar to the following tables and figures; Table D1-D4 and Figure D1 and D-2 . Each test was including six rounds with all three skis. Time were measured, average times, standard deviation, maximum, minimum were then calculated. If there were too lager differences in time in a round the whole round is not valid. The weather information which includes air temperature, air humidity, snow temperature, snow humidity, snow type, snow track standard, wind, snow crystals and amount of clouds/sun were noted.

Table D-1 Drag number, time and pair number

Drag	Time	Par Nr.
1	13,237	1
2	13,448	2
3	13,135	3
4	13,185	3
5	13,349	2
6	13,183	1
7	13,189	1
8	13,634	2
9	13,451	3
10	13,62	3
11	13,229	2
12	13,069	1
13	12,896	1
14	13,31	2
15	12,951	3
16	13,211	3
17	13,395	2
18	13,155	1
19		
20		

Table D-2 number of pairs, number of rounds and number of valid rounds, the time for each pair and the summary for each round. The line in the bottom ranks the fastest rounds.

Antall par	3									
Antall runder:	6									
Gyldige runder	6									
	Ski Nr.	Hva?	Tid 1	Tid 2	Tid 3	Tid 4	Tid 5	Tid 6	Tid 7	Tid 8
Par 1	RC5		13,237	13,183	13,189	13,069	12,896	13,155		
Par 2	3		13,448	13,349	13,634	13,229	13,310	13,395		
Par 3	10		13,135	13,185	13,451	13,620	12,951	13,211		
Par 4										
Par 5										
Par 6										
Par 7										
Gyldig markere med "x"			x	x	x	x	x	x		

Sammendrag for hver runde

Gjennomsnitt	13,273	13,239	13,425	13,306	13,052	13,254		
Standardavvik (SD)	0,160	0,095	0,224	0,283	0,225	0,126		
Standardfeil (=SD/sqrt(par))	0,092	0,055	0,129	0,164	0,130	0,072		
Rank av raskeste omgang	**4**	**2**	**6**	**5**	**1**	**3**		

Table D-3 summary of each ski in the tests, below is the weather information

Sammendrag for hver ski

Resultat	Average	Back "	Back	Min	Max	SD	SR
1	13,122	0,000	**0,0%**	12,896	13,237	0,124	0,050
3	13,394	0,273	**2,1%**	13,229	13,634	0,139	0,057
2	13,259	0,137	**1,0%**	12,951	13,620	0,239	0,098
	13,122			12,896	13,237	0,124	0,050

Dato:	2.4.2013	Luft:	-1	Snøtyp	Ny	Snøkorn	0.2-0.5
Sted:	Holmenkollen	rH %	99	Spor	poler	Sky	8/8
Ansvarlig:	Felix	Snø:	-1	Wind:	0		1000
		Doser	20	Sol.rad:			
	12:30	Denoth	105/123/296	polert spor			

Table D-4 Another way to evaluate the time and the skis.

Tid 1	Tid 2	Tid 3	Tid 4	Tid 5	Tid 6	Tid 7	Tid 8
13,237	13,183	13,189	13,069	12,896	13,155		
13,448	13,349	13,634	13,229	13,310	13,395		
13,135	13,185	13,451	13,620	12,951	13,211		
x	x	x	x	x	x		

par 1	RC5	par 2	3	par 3	10	par 4	0
1	13,237	2	13,448	3	13,135		
6	13,183	5	13,349	4	13,185		
7	13,189	8	13,634	9	13,451		
12	13,069	11	13,229	10	13,62		
13	12,896	14	13,31	15	12,951		
18	13,155	17	13,395	16	13,211		

The test sequence is pair 1-pair 2- pair 3-pair 3- pair 2- pair 3 –etc-etc

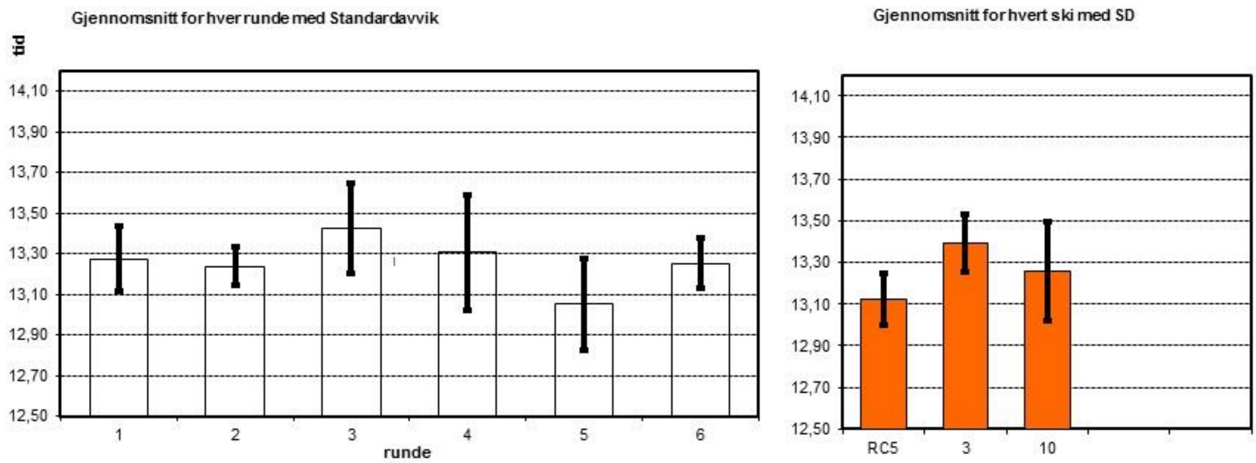


Figure D-1 The graph to the left shows the average time with standard deviation for each round in the run, while the graph to the right shows the average time for each pair of skis with standard deviation.

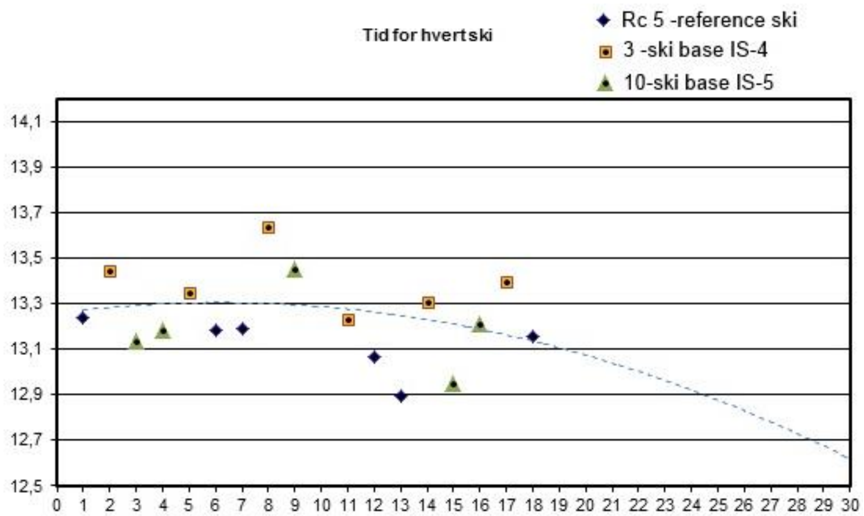


Figure D-2 The graph show the time of the runs as a function of time, this way it is possible to see if there are big differences in the same run, due to weather changers etc.

Table D-5 describes on which distances the 42,3 km were skied on and how far the three pair of skis skied during the field test.

Table D-5 The distance skied by the three skis in total

Distance			**Ref. ski**	**IS-4**	**IS-5**
in Holmenkollen, Oslo			**RC5**	**ski 3**	**ski 10**
1	Gliding test*		3250m	3250m	3250m
2	Gliding test*		3250m	3250m	3250m
3	Long distance			8100m	8100m
4	Gliding test*		3250m	3250m	3250m
5	Long distance			7800m	7800m
6	Gliding test*		3250m	3250m	3250m
in Granåsen, Trondheim					
7	Gliding test		1400m	1400m	1400m
8	Long distance			10640m	10640m
9	Gliding test		1400m	1400m	1400m
	sum		15800m	42340m	42340m

*) test was skied by both Felix Breichädel and Håvad Skorstad

The reference ski was skied quite a lot (15,8 km) during the testing. The two other skis were skied for 42,3 km.

Weather and snow conditions in Holmenkollen 02.04.2013

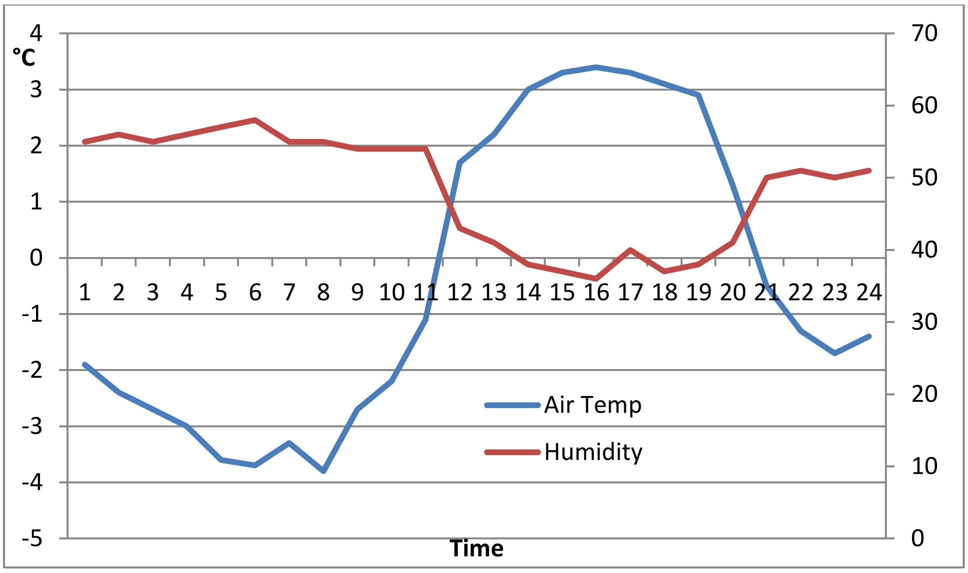


Figure D-3 The air temperature and the relative humidity in Holmenkollen during the field test The wind conditions were even during the whole day, but there was wind

Weather and snow conditions in Granåsen 04.04.2013

Test 1

Humidity:	Temperature:	Snow density :
108 air	+1,4 °C air	
123 snow	-0,1 °C snow	275,9 g snow

Test 2

Humidity:	Temperature:	Snow density :
106 air	+0,5 °C air	
118 snow	-0,1 °C snow	275,9 g snow

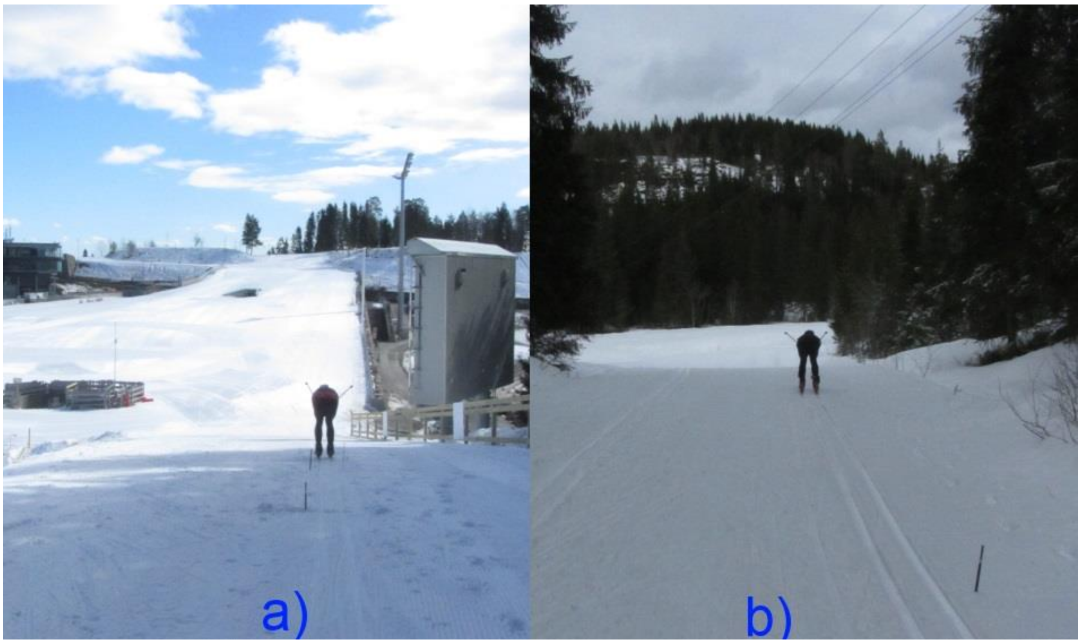


Figure D-4 The weather and ski tracks in **a)** Holmenkollen, **b)** Granåsen

Figure D-5 a) The snow from Holmenkollen 02.04**, b)** The snow from Granåsen 04.04

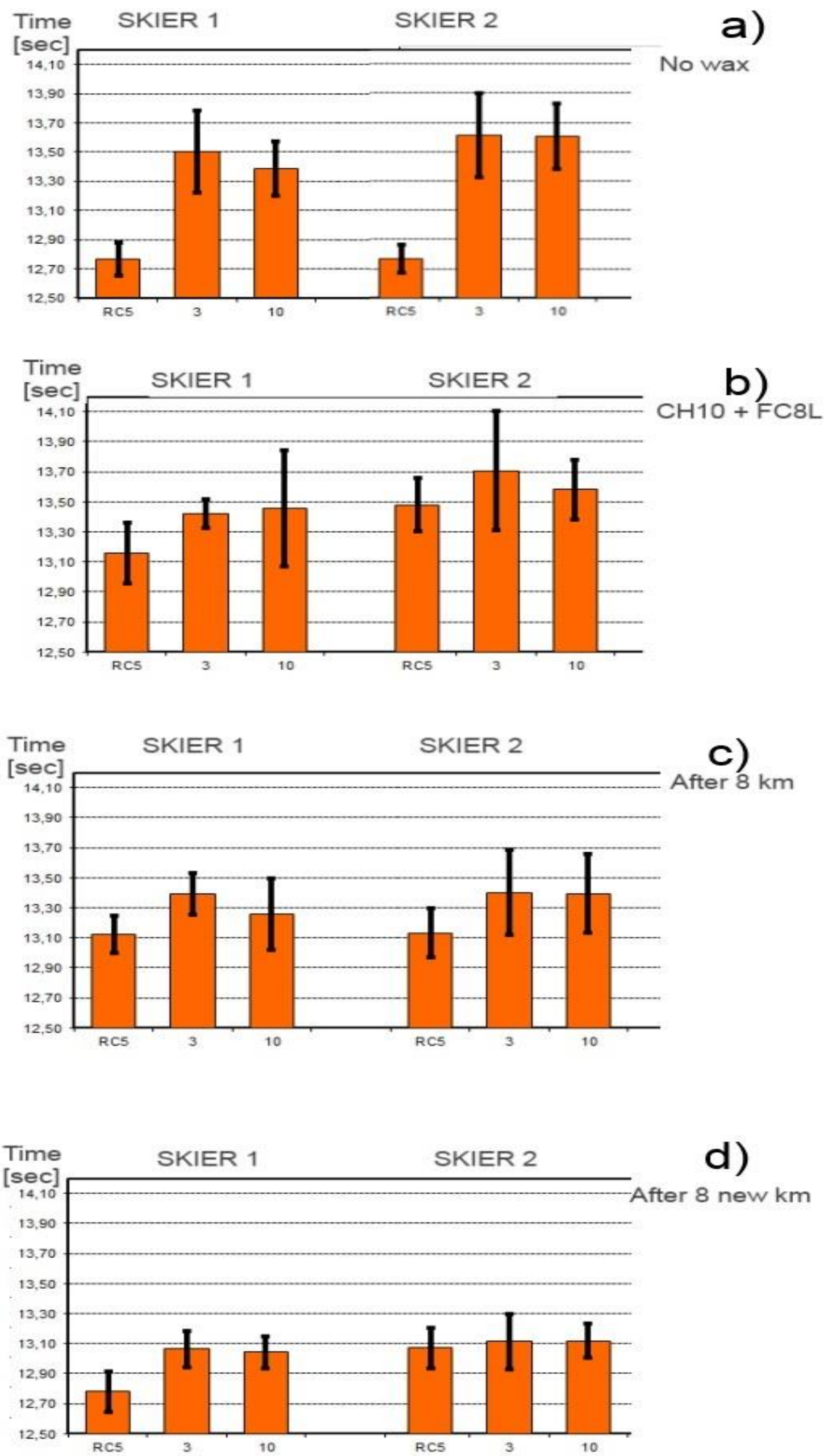
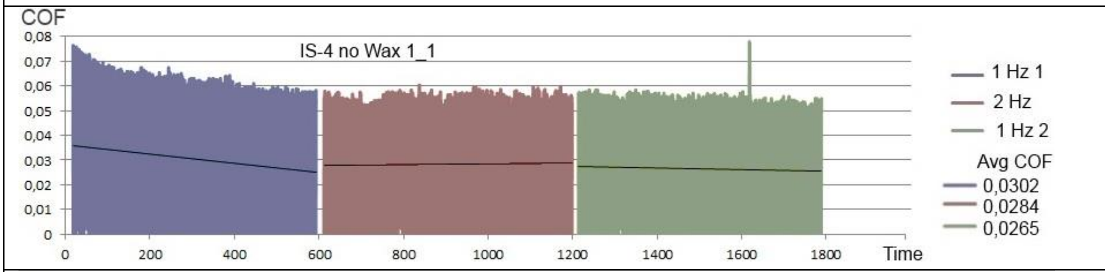
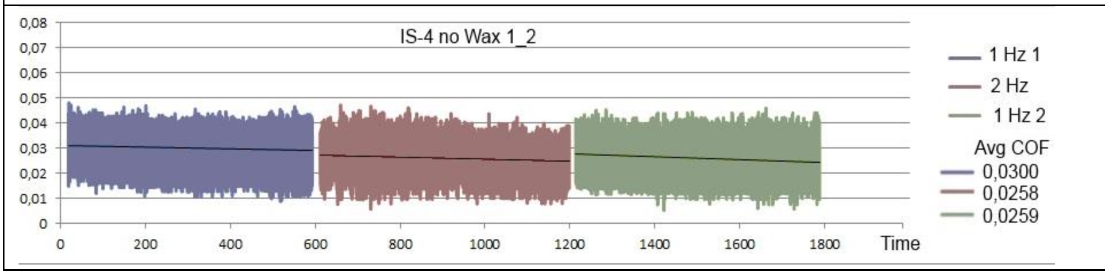
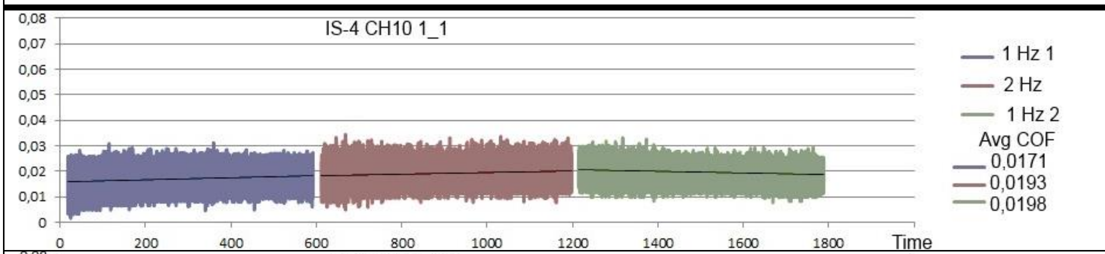
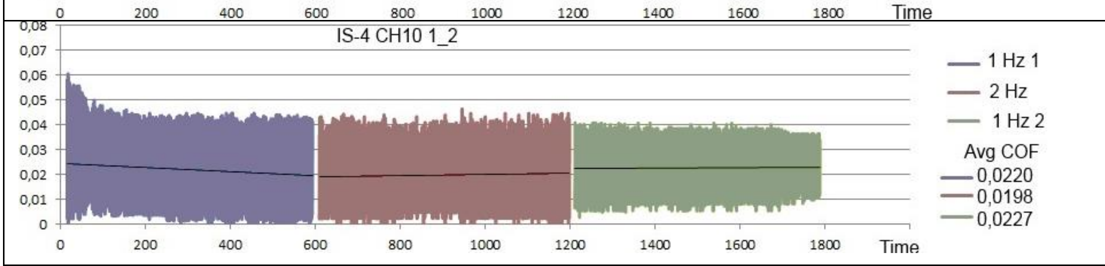
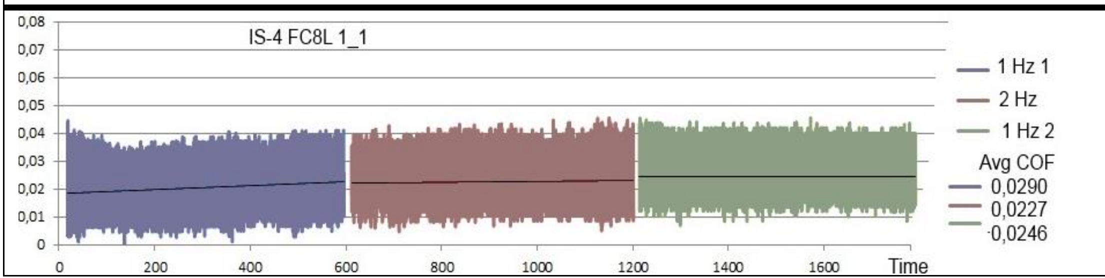


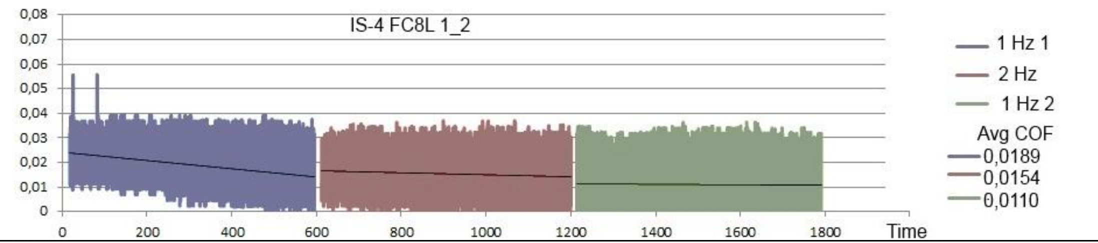
Figure D-6 Comparison of the two test-skiers in Holmenkollen, **a)** with no wax, **b)** new glided woth CH 10 and FC8L, **c**) anfer 8 km skiing and **d**) after additional 8 km of skiing

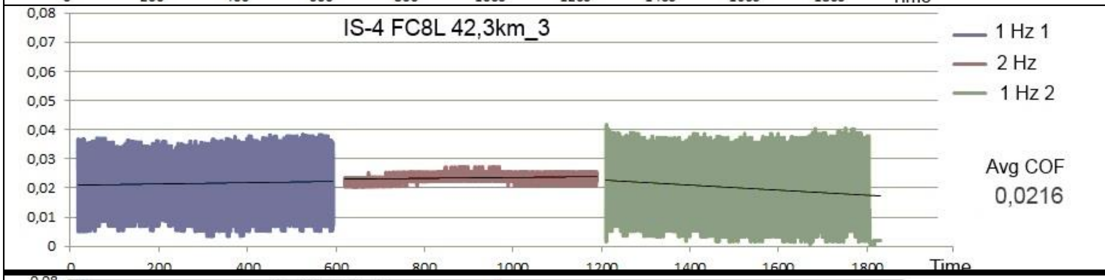
APPENDIX E - TE 88 AND CONFOCAL MICROSCOPE

Table E-1 shows the graphs the COF is calculated from The TE 88 tested friction on a 50 mm area, these graphs are taken between 10mm to 40 mm, so the stops in the end will not affect the coefficient of friction. In the graphs there are also different average COF of the different speed during one test.

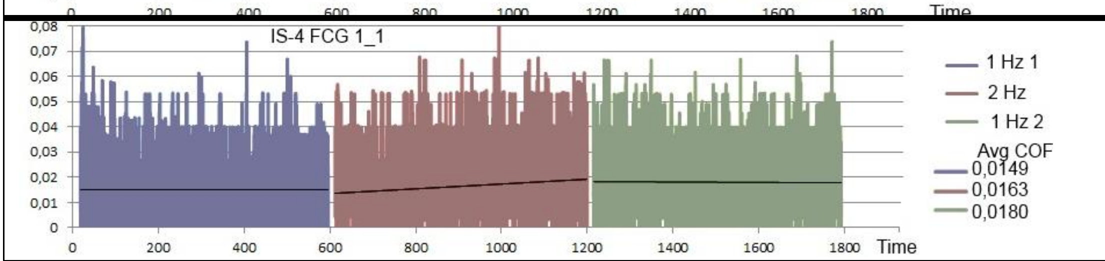
Table E-1 The graphs and average COF produced with the TE 88

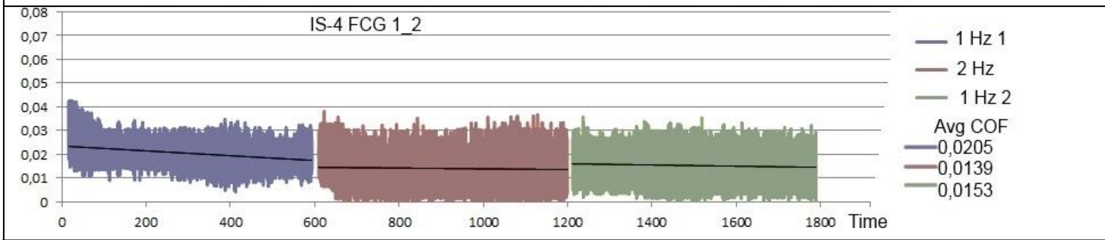
TE88 Results	
	
	
	
	
	

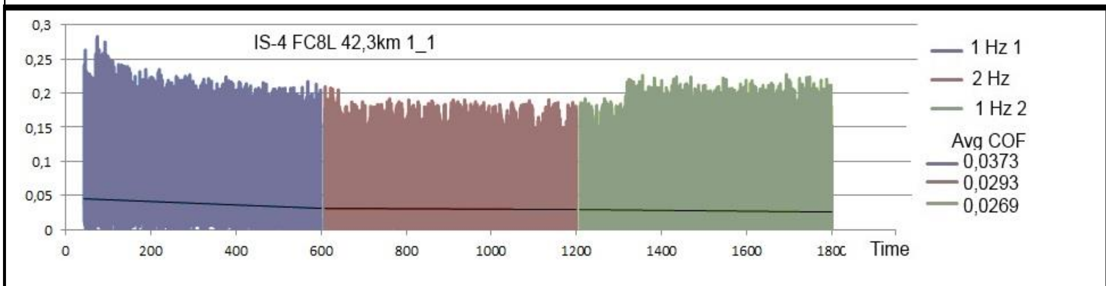




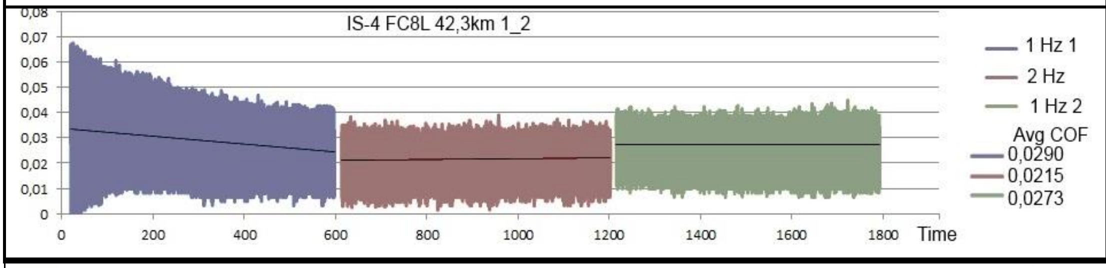
Test done with the last test-setup. (see *)

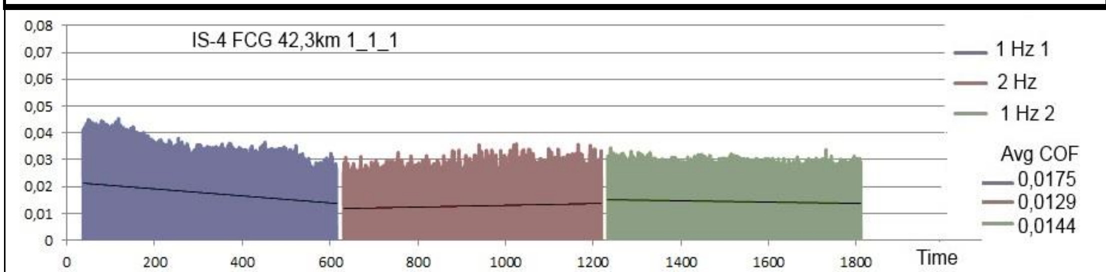




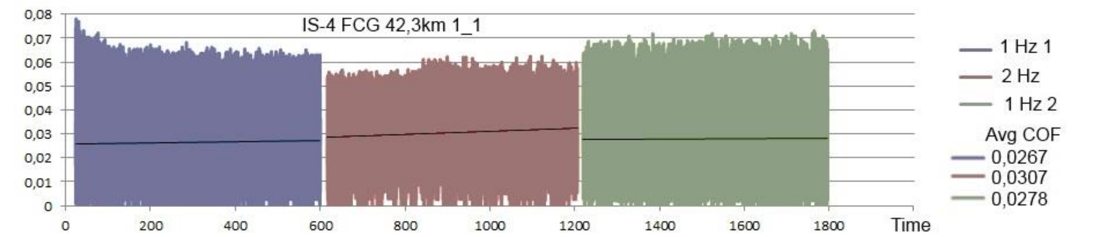


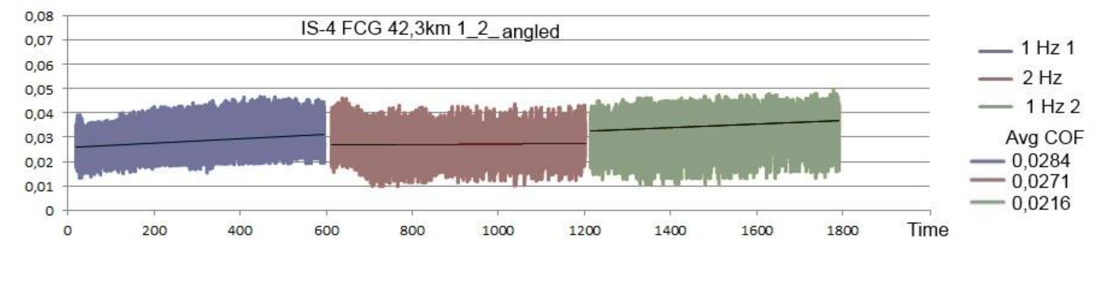
NB!! Another scale. Results similar to next test, so OK!



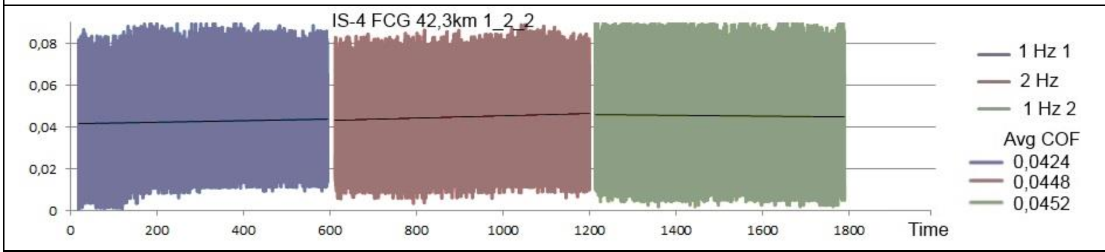


Machine turned off, but file were found …

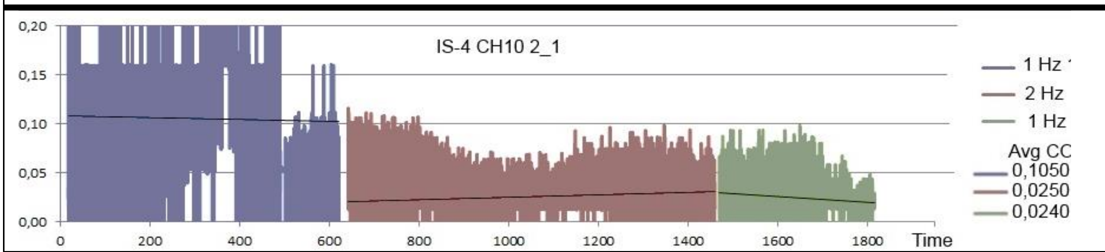




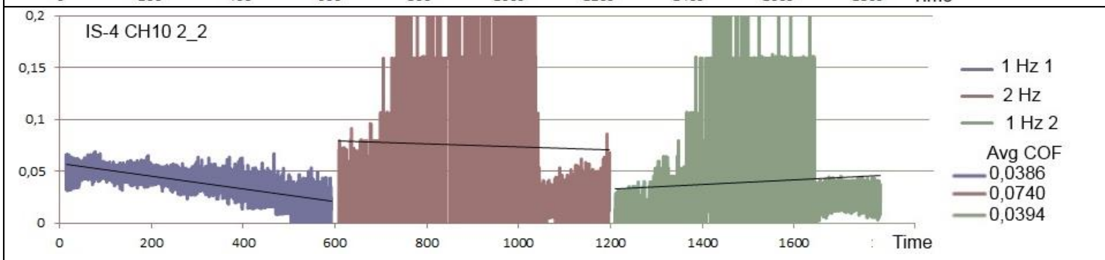
After test stopped, sample had twisted. Result looks OK!



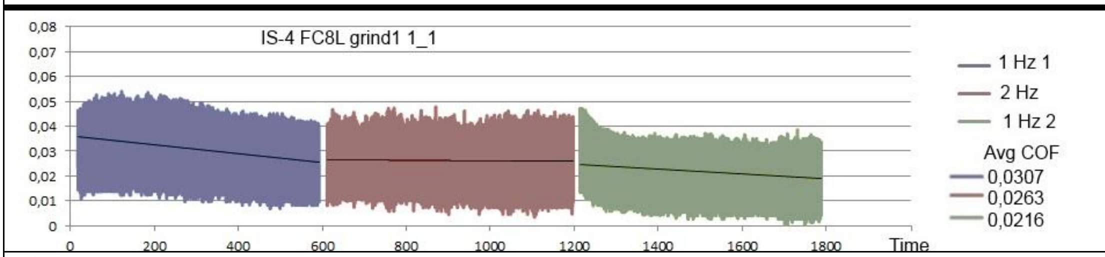
Too high friction- not valid.

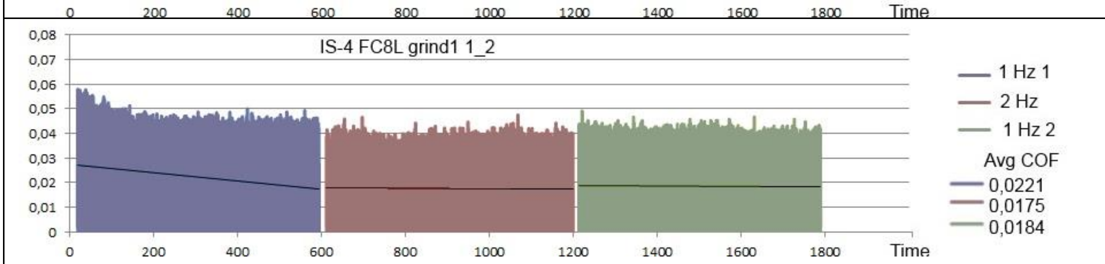


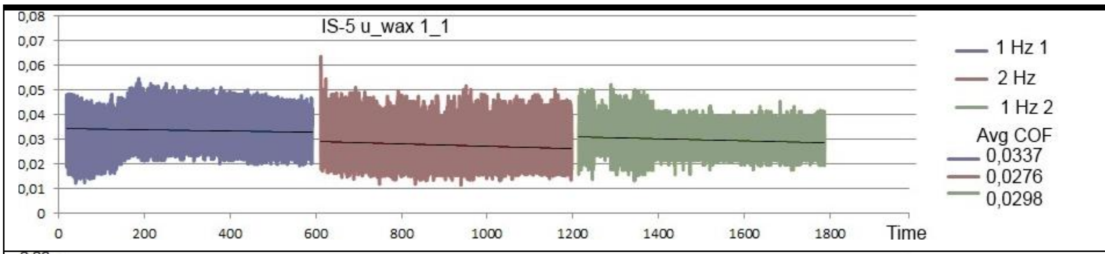
-2 degrees. NB!! Another scale.

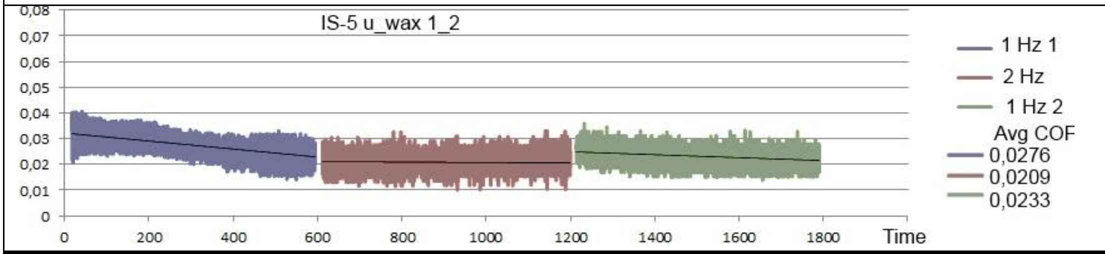


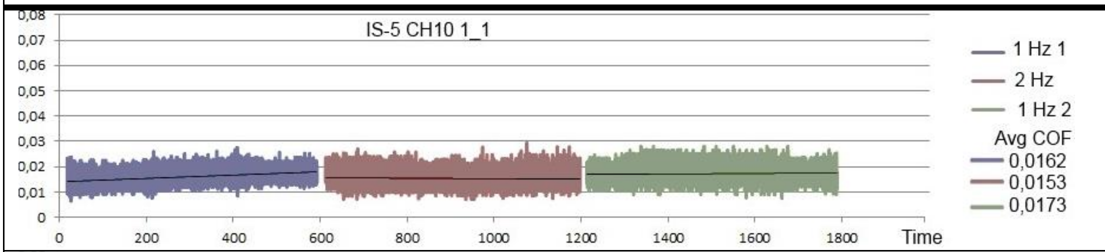
-2 degrees. NB!! Another scale.

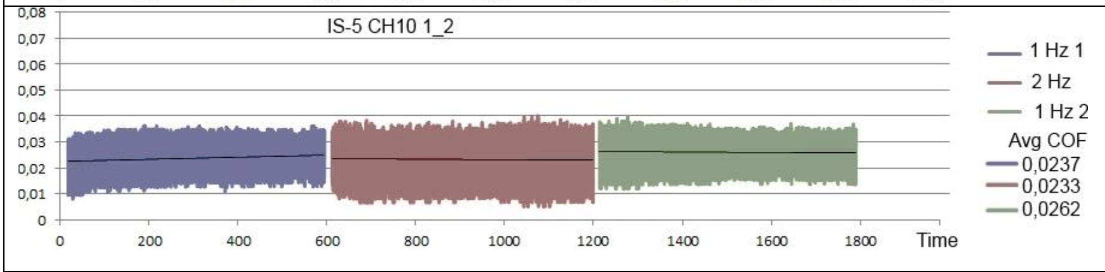


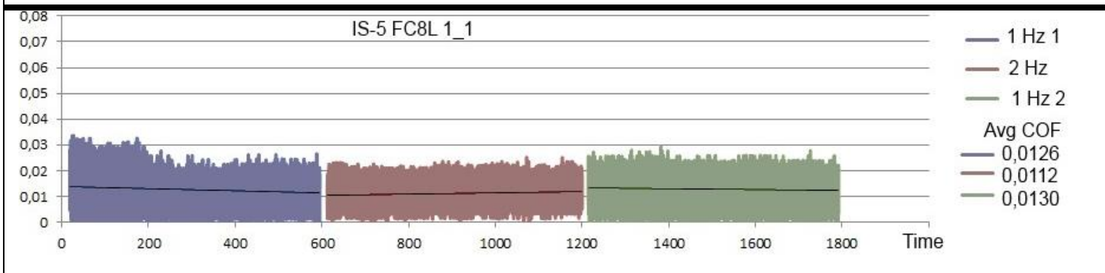


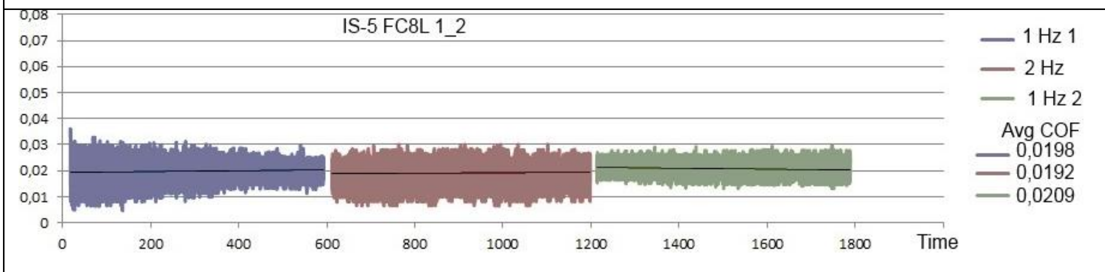

IS-5 u_wax 1_1
1 Hz 1
2 Hz
1 Hz 2
Avg COF
0,0337
0,0276
0,0298
Time

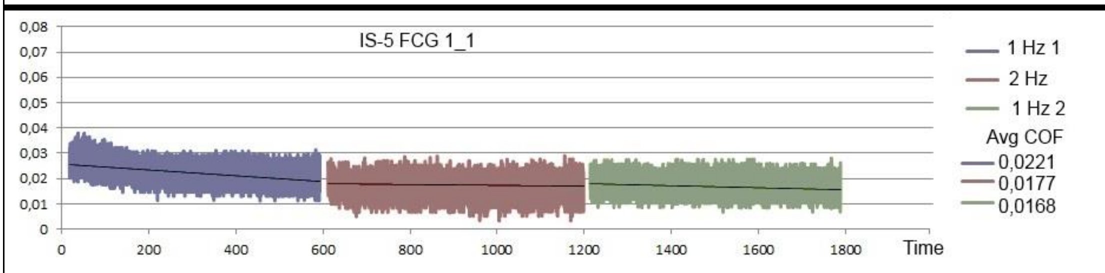

IS-5 u_wax 1_2
1 Hz 1
2 Hz
1 Hz 2
Avg COF
0,0276
0,0209
0,0233
Time

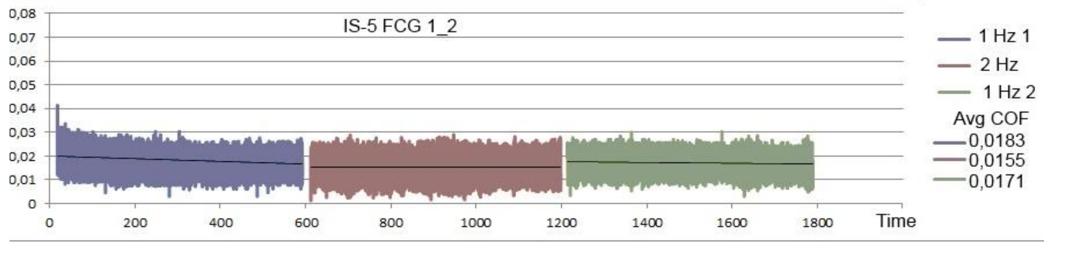
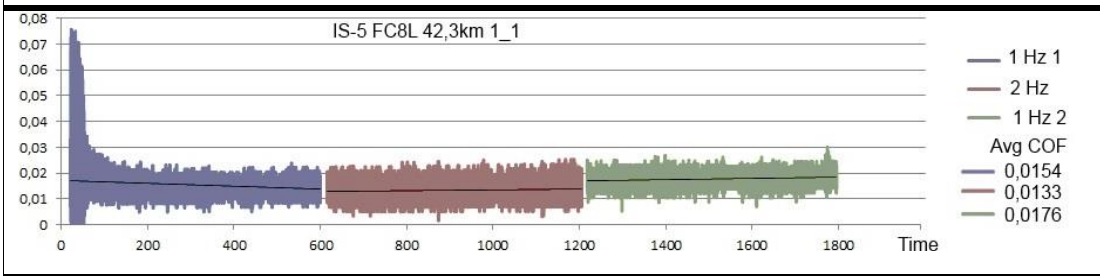
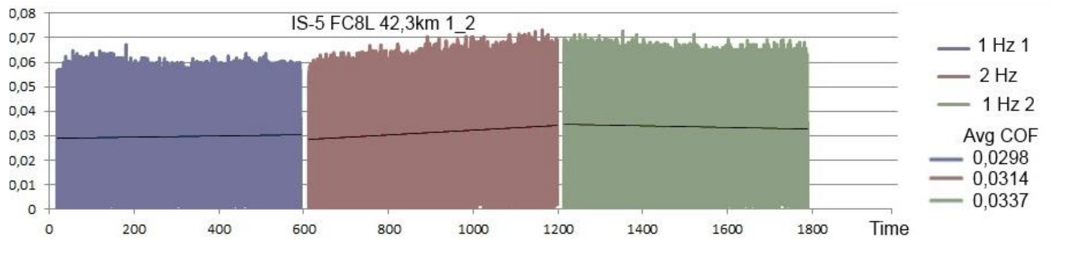
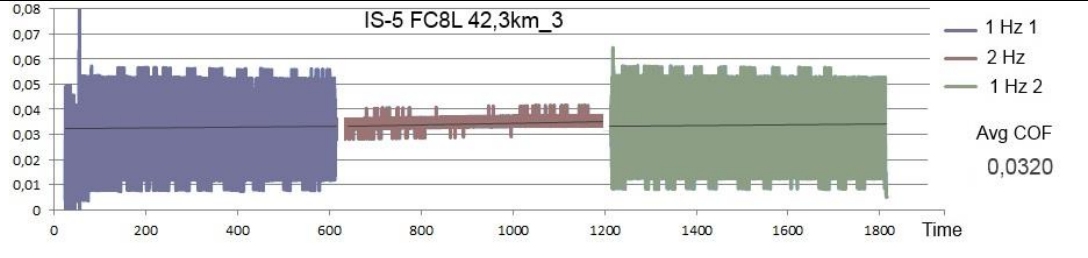
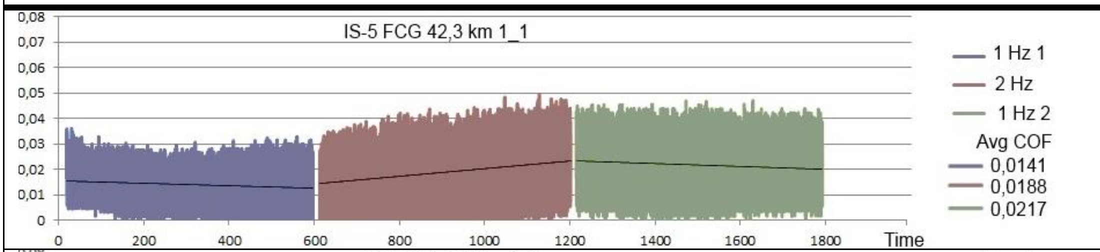
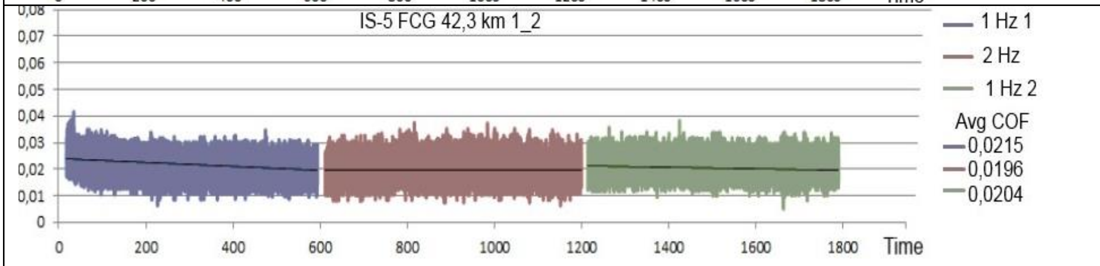
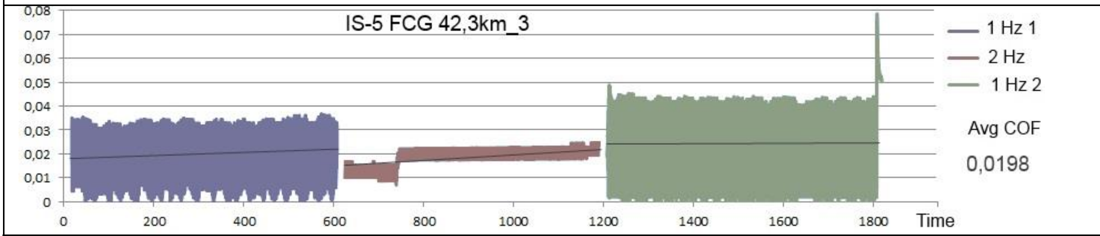

IS-5 CH10 1_1
1 Hz 1
2 Hz
1 Hz 2
Avg COF
0,0162
0,0153
0,0173
Time

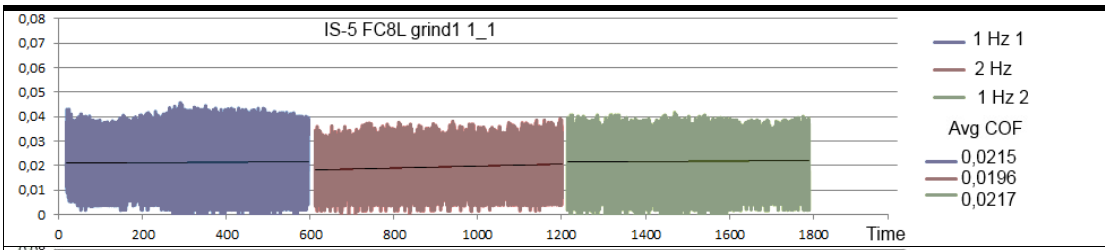

IS-5 CH10 1_2
1 Hz 1
2 Hz
1 Hz 2
Avg COF
0,0237
0,0233
0,0262
Time

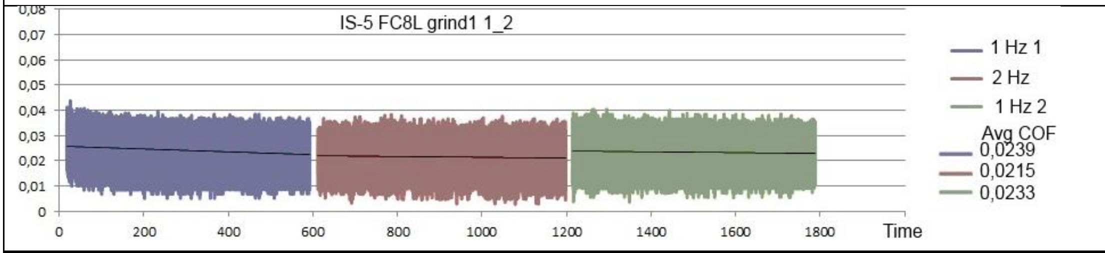

IS-5 FC8L 1_1
1 Hz 1
2 Hz
1 Hz 2
Avg COF
0,0126
0,0112
0,0130
Time

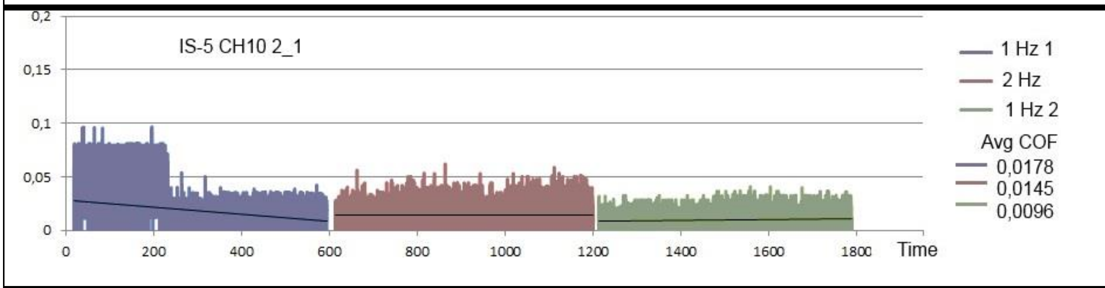

IS-5 FC8L 1_2
1 Hz 1
2 Hz
1 Hz 2
Avg COF
0,0198
0,0192
0,0209
Time


IS-5 FCG 1_1
1 Hz 1
2 Hz
1 Hz 2
Avg COF
0,0221
0,0177
0,0168
Time

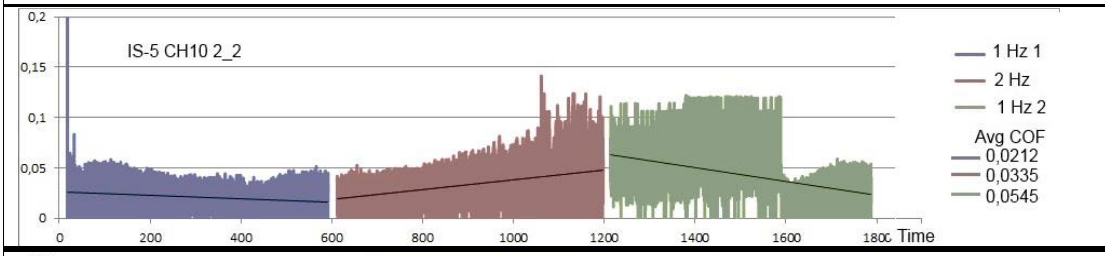
	
	Very low COF compared to next two tests.
	
	The latest setup, see *
	
	
	The latest setup, see *



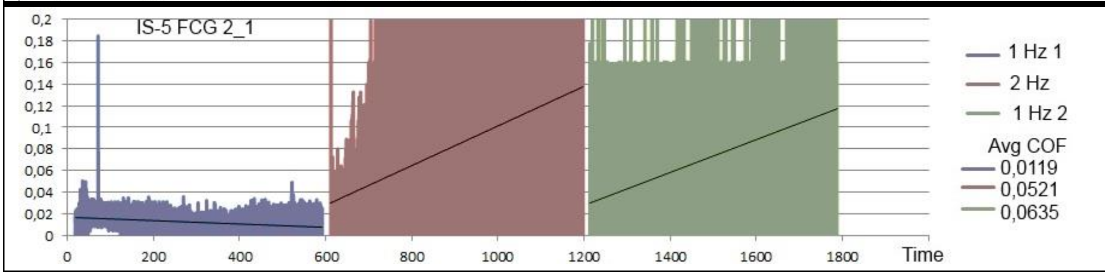




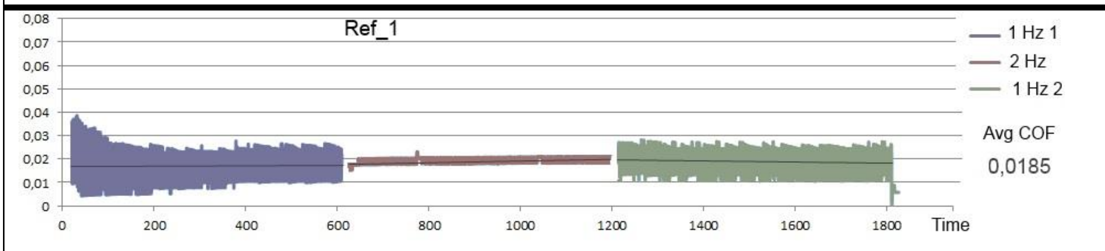
-2 degrees.
..
NB!! Another scale.
-

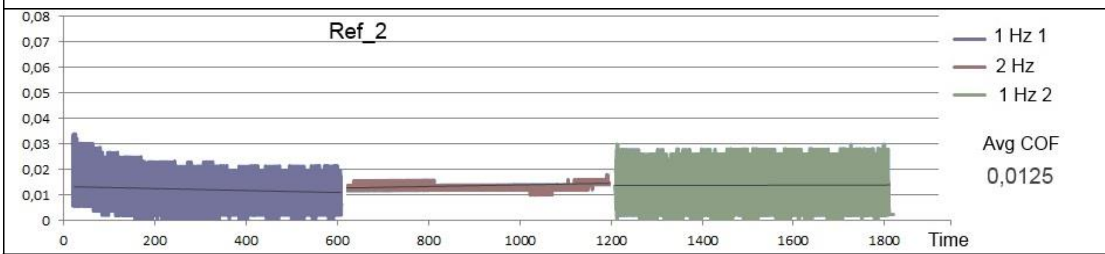


NB!! Another scale.
-2 degrees



NB!! Another scale.
-2 degrees





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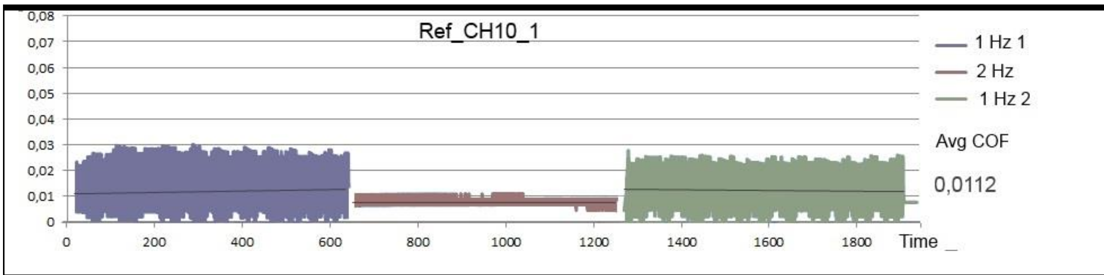
<tr><td>
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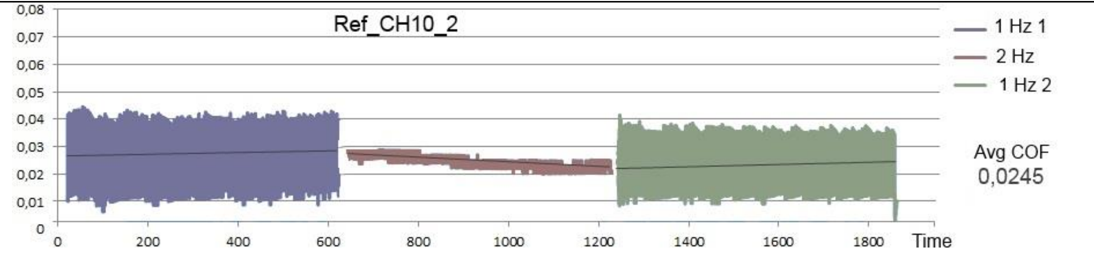
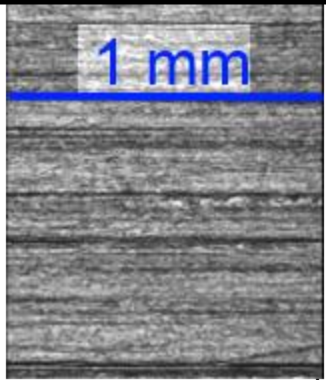
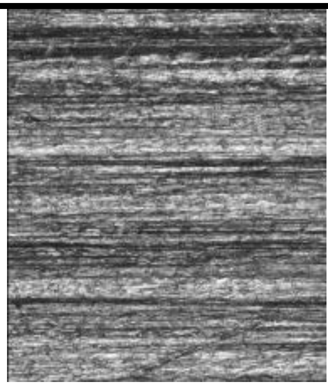
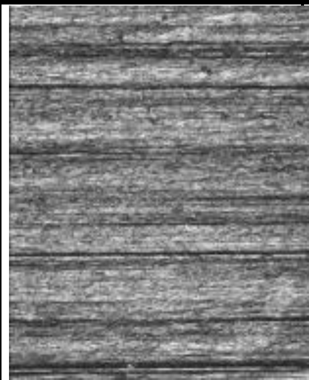
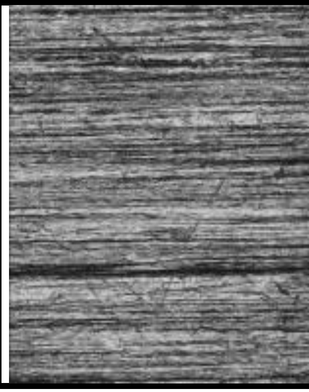
<tr><td>
</td><td>COF too high, twice as high as without wax.</td></tr>
</table>

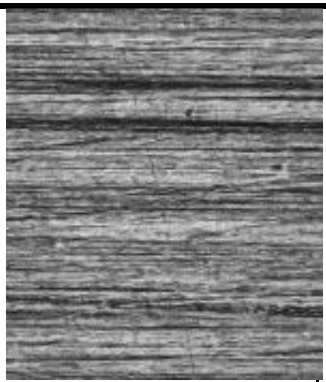
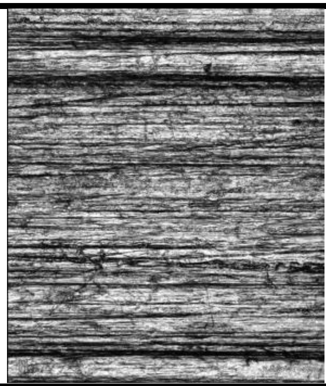
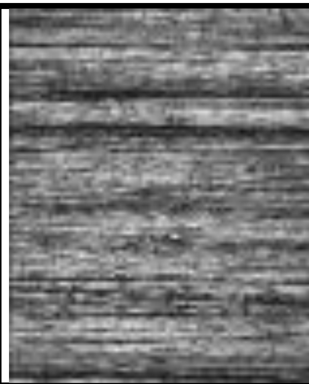
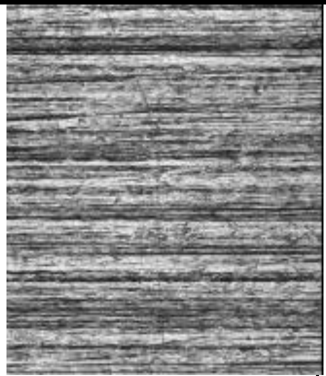
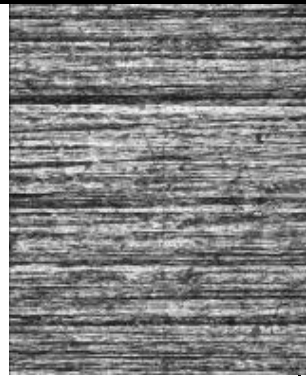
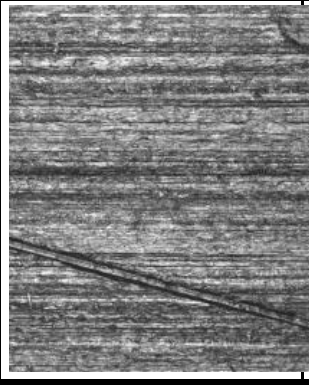
*The tests that are tested a third time and the reference tests are tested with a slightly different setup, there are not as many measurement points, that is why the 2 Hz-part of the graph have a more intense COF. The tests were done after evaluating the results of the other tests, since the COF used is only an average COF there is only found an average COF for the tests in the last test-round.

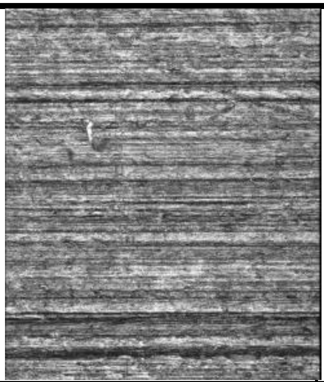
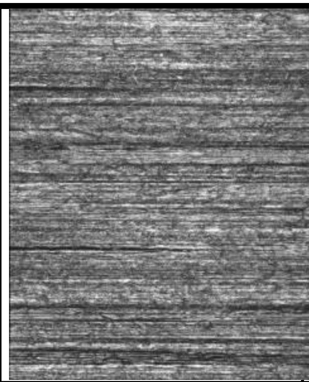
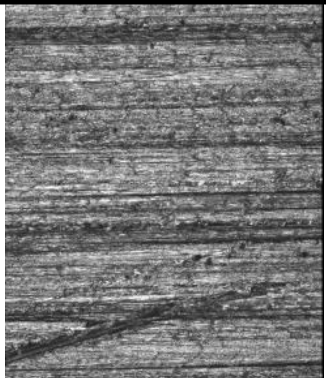
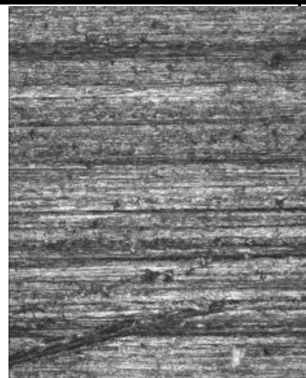
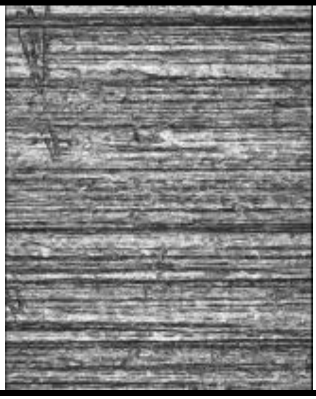
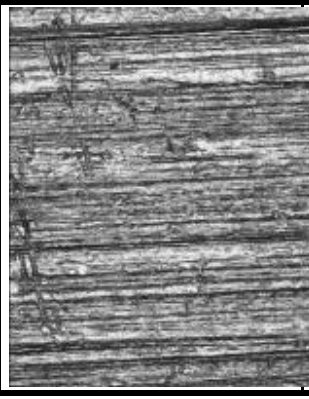
The tests performed at -2 is no valid, as the graphs shows, they are not very reliable.

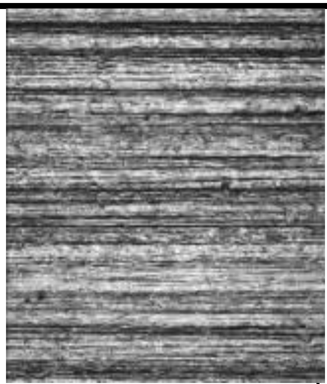
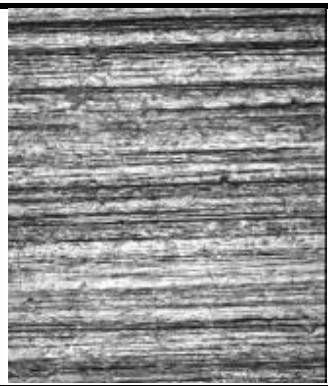
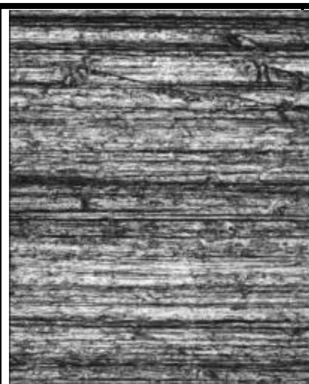
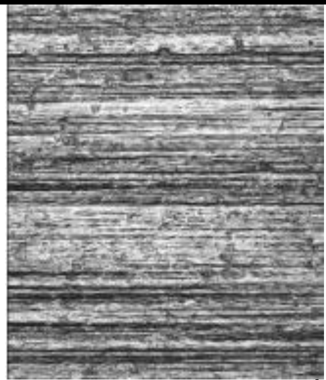
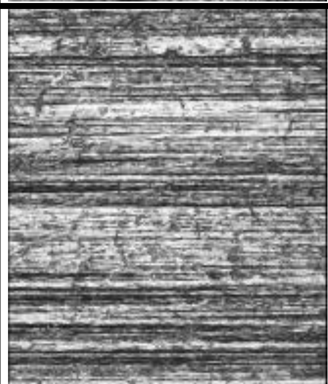
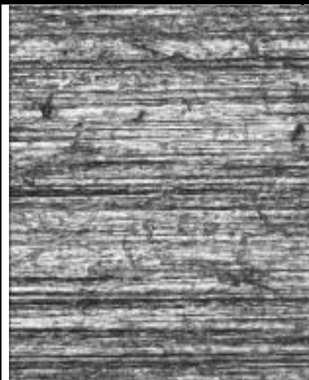
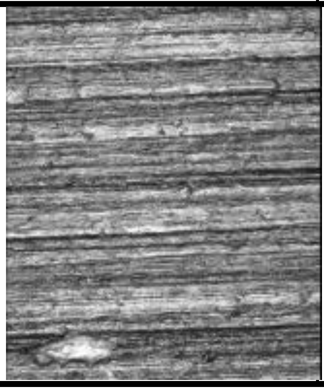
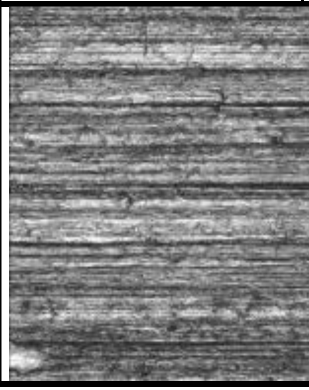
Table E-2 shows the microscope picture before and after testing with the TE 88. There are not much differences, but on some of the materials there are possible to see that the samples gets more scratches after a run or two in the TE 88 due to the way it is applied to the sample holder.

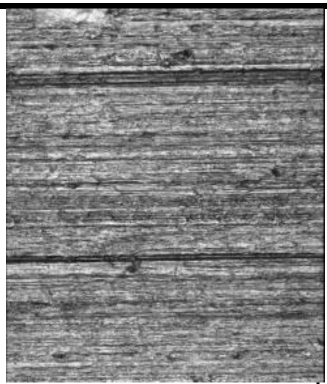
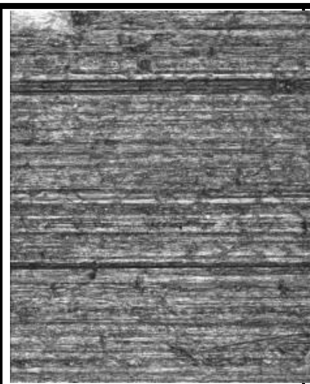
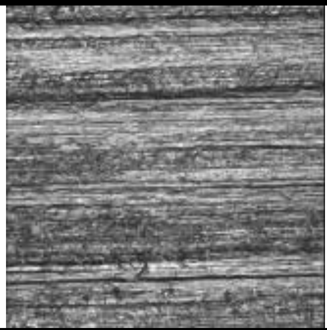
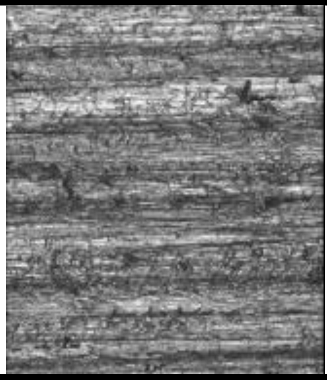
Table E-2 Microscopic picture, roughness and COF measured with the confocal microscope and the TE 88

		Microscope picture	Roughness [μm]	Avg COF TE 88	Microscope picture	Roughness	Avg COF TE 88	Microscope picture	Roughness
1	IS-4 no wax		Ra:2,73 Rq:3,55 RSm:256,9	0,0284		Ra:2,61 Rq:2,47 RSm:295	0,0272		Ra:2,48 Rq:3,25 RSm:259,67
2	IS-4 with CH10		Ra:2,24 Rq:2,80 RSm:210,99	0,0187		Ra:2,23 Rq:2,77 RSm:196,78	0,0215		Ra:2,32 Rq:2,90 RSm:187,17

3	IS-4 with CH10 + FC8L		Ra:2,34 Rq:2,93 RSm:203,93	0,0216		Ra:2,36 Rq:2,98 RSm:210,33	0,0151		Ra:2,42 Rq:3,08 RSm:202,67
4	IS-4 with CH10 +FCG		Ra:1,92 Rq:2,42 RSm:179,4	0,0164		Ra:1,97 Rq:2,47 RSm:174,37	0,0166		Ra:2,14 Rq:2,52 RSm:202,33
5	IS-4 with CH10 + FC8L 42,3km		Ra:1,82 Rq:2,53 RSm:286,11	0,0312		Ra:1,97 Rq:2,58 RSm:344,01	0,0259		Ra:1,70 Rq:2,21 RSm:2,68

6	IS-4 with CH10 + FCG 42,3km		Ra:1,95 Rq:2,61 RSm:285,71	0,0284		Ra:1,97 Rq:2,58 RSm:344,03	0,0257	 Ra:1,89 Rq:2,42 RSm:317,67
7	IS-5 no wax		Ra:2,71 Rq:3,43 RSm:213	0,0304		Ra:2,62 Rq:2,98 RSm:205,2	0,0239	 Ra:2,60 Rq:3,31 RSm:210,67
8	IS-5 with CH10		Ra:2,79 Rq:3,44 RSm:251,18	0,0163		Ra:2,70 Rq:3,37 RSm:248,77	0,0244	 Ra:2,55 Rq:3,19 RSm:225

9	IS-5 with CH10 + FC8L	 Ra:1,99 Rq:2,49 RSm:168,97	0,0123		Ra:1,98 Rq:2,48 RSm:180,68	0,0200	 Ra:2,08 Rq:2,62 RSm:147,33
10	IS-5 with CH10 +FCG	 Ra:2,38 Rq:3,06 RSm:200,33	0,0189		Ra:2,34 Rq:3,03 RSm:252,33	0,0170	 Ra:2,38 Rq:3,06 RSm:261,67
11	IS-5 with CH10 + FC8L 42,3km	 Ra:3,05 Rq:3,77 RSm:336,31	0,0320		Ra:2,76 Rq:3,35 RSm:287,90	0,0316	 Ra:2,91 Rq:3,57 RSm:302,67

12	IS-5 with CH10 + FCG 42,3km		Ra:2,24 Rq:2,82 RSm:269,17	0,0182		Ra:2,42 Rq:3,03 RSm:154,00	0,0205		Ra:2,13 Rq:2,68 RSm:227,67
13	IS-4 FC8L Grinded		Ra:3,73 Rq:4 RSm:294,33	Average COF 0,02275					
14	IS-5 FC8L Grinded		Ra:4,61 Rq:5,32 RSm:346,7	Average COF 0,0219	Average COF is the average coefficient of friction measured by TE 88, the average of the three averages for the speed intervals. The roughness's is the average for three measurements per test, the microscopic pictures shown is only a part of the measured area.				