Tribological behaviour of nano-composite UHMWPE on ski surfaces and the role of hydrophobicity

Anders Backéus
Abstract

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Ultra High Molecular Weight Polyethylene (UHMWPE) has been used as a ski sole material for many years due to its good tribological properties, good wear resistance and low friction coefficient. Recent studies have showed improved performance on wear rate and hydrophobicity with nanoparticle reinforced UHMWPE. In this study, different kinds of nano-composite UHMWPE’s were tested on snow to investigate if they are suitable as a ski sole material and to find the type of nano-composite UHMWPE that has the greatest potential. Further, the mechanisms of hydrophobicity and its influence on the friction level were examined. The friction coefficient was measured in a ski test rig and simple demonstrations under a microscope were made to simulate how water is dragged along the ski sole in contact with wet snow. Mechanical properties were measured with a CSM Nanoindentation Instrument and surface topography was examined in a Wyko Optical Profiler.

The cross-linked UHMWPE material showed the lowest friction coefficient on snow. The hydrophobic demonstrations, together with the ski test results, questions the suggestion that high hydrophobicity enhances the ski glide. Nanoindentation was proved to give valuable data for mechanical properties, but it should be questioned whether it is a good technique for comparing different nano-composite UHMWPE materials. The ski tests show the importance of the characteristics of snow.

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ISSN: 1650-8297, UPTEC K 15003
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1. Introduction

Skiing has gone from a way of transportation through snowy landscape to run as fast as possible for 1.5 to 90 km. Even though skiing is still just recreational for a lot of people, more and more people are using a pair of skis for competition, for example in the famous ski race Vasaloppet. The greater interest in performance has increased the demand for expensive equipment, which has led to big price inflation on the ski market. The development has led to a wider discussion about the material; if the skis are light and fast enough, whether waxing can enhance the glide and so on. Waxing has been questioned not only for its doubtful improvements on the ski glide but also for the health and environmental risks from toxic gases that are released during the preparation of the ski. One of the common ski wax polymers, perfluoro-n-alkanes, is suggested to repel water and dirt. However, it is insoluble in polyethylene ski surfaces and only adsorbs physically and will therefore not last for long (Gambaretto, Conte, Fornasieri, et al., 2003). When Kuzmin (Kuzmin, 2010) introduced his Kuzmin-scraper, that is used to scrape off material to keep a smooth surface, he claimed that it could replace ski-wax for better glide. At that point big and interesting discussions were started.

Earlier ski friction experiments, investigating the friction level and different structures on the ski sole, have been made at Uppsala University; first experiments on ice (Sturesson, 2008) and later on different snow types (Forsberg, 2009). There are a lot of parameters to take into account when discussing the ski glide and how to improve it. The material properties of the ski sole (the part of the ski which will be in contact with the snow) are of course the most important part, but the ski glide will also depend on the external circumstances such as snow temperature and crystallinity, dirt in the ski track and how the ski is constructed. Not only a low friction is favourable, but also if the ski sole material is more wear resistant it could have a positive effect that enables the surface structure to last longer, which will reduce the material that has to be scraped of and thereby it will be less time and cost consuming.

Since many years back, Ultra High Molecular Weight Polyethylene (UHMWPE) has been used as a ski sole material, replacing the old wooden ski, due to the enhanced tribological properties of the polymer, e.g. good wear resistance and low friction coefficient (Fischer, Wallner, & Pieber, 2010). When manufacturing the ski surface material, the polyethylene undergoes several steps: formulated polyethylene compounds with fillers (carbon black, silicones, metal salts, etc.) are sintered or extruded before the films are post-treated and glued onto the ski sandwich core (Fischer, Wallner, & Pieber, 2010). Studies at Luleå University of Technology (LTU) has shown that compositions of 0.5 wt% additives, multi-walled carbon nanotubes (MWCNT) or graphene oxide (GO), in the UHMWPE will get an increased hydrophobicity and wear reduction compared to pure UHMWPE (Moreno, 2013). Since a hydrophobic surface is suggested to lower the friction and thereby enhance the ski glide (Hogmark, Sturesson, & Jacobson, 2008; Kuzmin, 2010) this nano-composite UHMWPE could be a promising ski sole material.

The purpose of this master thesis is to investigate the tribological properties of nano-composite UHMWPE as a ski sole material and to examine the mechanisms of hydrophobicity between the ski sole and the snow and its influence on the friction level. Six different types of materials plus one reference material will be studied to find the type of nano-composite UHMWPE that has the greatest potential as a ski sole material. In addition to friction test, the materials mechanical properties will be investigated with dynamic indentation testing.
2. Background & Theory

To get a better understanding of the ski sole materials used today, how they can be improved and the importance of friction and hydrophobicity, this background will give an introduction of the main theories of each part.

2.1 UHMWPE

Polyethylene is a viscoelastic material, with the simplest structure of all polymers, \((\text{C}_2\text{H}_4)_n\), that is known for its low price, good processability and toughness. Ultra high molecular weight polyethylene (UHMWPE) has a molecular weight of \(3 000 000 – 6 000 000 \text{ g/mol}\) and is widely used because of its good tribological properties (Brydson, 1999). Due to its good wear resistance and low friction coefficient, UHMWPE has been used as a bearing material in total joint replacements (TJR) for more than 50 years (Enqvist, 2013). However, a major problem and a controlling factor of durability is the releases of wear particles, which has led to increased research on improved abrasion resistance such as reinforced UHMWPE (Sawae, 2009).

UHMWPE’s can be processed with different kinds of particles and compounds to form composite materials. A lot of research on reinforced UHMWPE has been done and the results indicate a higher wear resistance compared to pure UHMWPE (Galetz, Blass, Ruckdaschel, Sandler, Altstadt, & Glatzel, 2007). UHMWPE with 1 wt% of multi-walled carbon nanotubes (MWCNT) shows a significant increase in tensile strength and modulus (Ruan, Gao, Yang, & Yu, 2003). Studies at Luleå University of Technology (LTU) has shown that compositions of 0.5 wt% additives, MWCNT or graphene oxide (GO), in the UHMWPE nano-composites will get an increased hydrophobicity and wear reduction compared to pure UHMWPE (Moreno, 2013). This is very favourable for a ski sole material.

2.1.1 Carbon Nanotubes (CNT)

Carbon nanotubes are graphene rolled up into single-walled (SWCNT), double-walled (DWCNT) or multi-walled (MWCNT) tubes (Enqvist, 2013). CNTs are reported to be extremely strong (~39 GPa), stiff (~0.64 TPa) and also very flexible (with a fracture strain larger than 5%). MWCNT is more commercially used than SWCNT because of its lower cost (Baughman, Zakhidov, & de Heer, 2002). The MWCNTs in this study had a particle diameter of 5-10 nm and a length of 1-5 \(\mu m\) (Wikner, 2014).

2.1.2 Graphene Oxide (GO)

GO is suggested to be a good nanofiller in UHMWPE composites since it shows a significant increase in wear resistance (Tai, Chen, An, Yan, & Xue, 2012). However, with an increased amount of GO the friction coefficient also increases, which is not favourable in a ski sole material. The starting material in the process is graphite oxide, which can be achieved by using strong oxidisers in the “Staudenmaier oxidation” or the “Hummer process”. Furthermore, graphite oxide can be exfoliated into GO by using sonication (Tjong, 2012). The GO consisted of monolayer sheets with a thickness of 0.7-1.2 nm and a length of 3-5 \(\mu m\) (Wikner, 2014).
2.1.1 Cross-linked UHMWPE

For improved abrasion resistance, UHMWPE materials are sometimes cross-linked, which can be done either chemically, such as peroxide cross-linking or vinyl silane cross-linking, or by ionizing radiation (Brydson, 1999). Cross-linking branches the long chains of UHMWPE together into a network that increases the molecular mass. Even though cross-linking can lead to an increased wear resistance, mechanical properties like toughness, yield strength and crack propagation resistance of the polymer might decrease (Muratoglu, Bragdon, O'Connor, Jasty, & Harris, 2001), especially at high levels of cross-linking (Pruitt, 2005). By using ionizing radiation, electron beam, gamma or x-ray, the amount of cross-linking can be controlled by the amount of irradiation (Parks, 2010).

2.2 Friction mechanisms between snow and ski sole

The friction force created by the ski movement over the snow is dependent on the contact area between the two materials. A rough estimation of the real contact area, \( A_r \), is given by

\[
A_r = \frac{F_N}{H}
\]

(1)

where \( F_N \) is the normal load and \( H \) is the hardness of the softer material (Jacobson & Hogmark, 2011). Friction takes place on a microscopic level on the snow grains and therefore it is the hardness of ice that matters rather than the hardness of the ski track (macroscopic level).

The total nominal area of the glide zones of a pair of cross-country skis can easily be calculated. If a pair of 2 meter long and 4 cm wide skis has a glide zone of approximately 1 m each the nominal area is about \( 2 \times 40 \text{ mm} \times 1000 \text{ mm} = 80000 \text{ mm}^2 \). To understand the friction mechanisms it is useful to consider an example with a person of 80 kg on a pair of skis. Without glide wax, in -12 °C (\( H_{\text{ice}} \approx 30 \text{ MPa} \)), this gives a real contact area of only 30 mm\(^2\). Eq. 1 underestimates the real contact area since the elastic deformation of the ski sole material will contribute to it. However, this is not significantly greater than the calculated value.

The five mechanisms explained below were proposed by Hogmark, Sturesson & Jacobson (2008) to be the main contributions to friction in skiing.

2.2.1 Dry or boundary lubricated friction in load bearing contact spots: shear of snow or ski sole

For low temperatures and rough surfaces there will be no or a too thin lubricating water film so the shearing will follow the classical dry friction theory. The friction force, \( F_T \), will be proportional to the real contact area, \( A_r \), and the shear stress, \( \tau_y \). Shearing will take place in the softer of the two interacting materials.

\[
F_T = A_r \times \tau_y
\]

(2)

2.2.2 Friction due to ploughing of the ski sole

As the temperature drops the snow becomes harder and pointier, which will increase the ploughing of the softer ski sole material. Ploughing also increases if the ski sole has high angle surfaces facing the glide direction or if there is dirt in the track.
2.2.3 Friction due to ploughing of the snow

The ski sole material is softer than ice under most conditions. However, if the ski surface is rough so that the load will be on a macro level instead of a micro level, on single ice grains, ploughing can occur since the snow is much softer on macro level.

2.2.4 Viscous friction in load bearing contact spots: Shear of water film or quasi-liquid ice film

For temperatures above -15 °C there will be a thin quasi-liquid or a liquid water layer between the two surfaces at the contact spots. The size of the contact spots will marginally be affected since the thickness of the film is very thin compared to the dimensions of the contact spots, 20 -100 nm compared to 100 – 300 µm. Hence, the viscous shear will take place in the same contact spot areas as for the dry friction (eq. 2).

\[ F_T = \eta * \nu * A_r / h \]  

(3)

where \( \eta \) is the viscosity of the film, \( \nu \) is the skiing speed and \( h \) the film thickness. The quasi-liquid film has an unknown viscosity (not the same as for water at 0 °C) and the thickness \( h \) is depending on the snow temperature and the generated friction heat. The thickness can also be reduced when the two surfaces, ski and snow, are pressed against each other and the water film will try to escape. This squeeze out effect is very limited due to the short contact time, resulting in a thickness change of 80 – 100 nm according to Bäurle et al. (2006).

According to eq. 3 an increased speed will lead to an increased friction. At the same time a higher speed may generate a thicker film as the ice melts due to frictional heat, which will lead to a lower friction. Thus, the friction \( F_T \) is very difficult to calculate.

2.2.5 Viscous friction outside load bearing contact: Shear of water film

Increasingly amount of water in the track, due to increased temperature or other reasons, will lead to a higher volume of water between the ski sole and the snow, which will extend the water film to shear outside the load bearing contact spots. The film cannot contribute to the load carrying and as a result the friction will increase due to increased shearing.

An important parameter here is the wetting properties of the ski sole material. If the water outside the contact spots can be spread out more easily it will lower the friction. If the ski sole is very hydrophobic the water dragged along will be minimised.

2.3 Hydrophobicity

As described above, in section 2.2.5, it is suggested in earlier studies (Kuzmin, 2010; Hogmark, Sturesson, & Jacobson, 2008) that a highly hydrophobic surface can enhance the ski glide by lowering the friction on snow. It is therefore interesting to investigate the mechanisms of what is happening between a ski sole and snow under wet conditions.

To calculate the hydrophobicity the Young wettability model can be used for smooth flat surfaces, but for rough homogenous surfaces or for rough heterogeneous surfaces Wentzel’s or Cassie-Baxter’s model respectively must be used (Hongyun, Wen, Daoyi, Zhiwei, & Liang, 2012). When looking at the hydrophobicity at the micro and nano scale, special
wetting behaviours, called superhydrophobicity, occur (Li & Amirfazli, 2005). A parameter, which is important for ski gliding over a water film, is the contact angle hysteresis (CAH) (Kuzmin, 2010). CAH is the difference between the advancing (maximum) and the receding (minimum) contact angels and is directly correlated to how a liquid drop moves on a surface (Li & Amirfazli, 2005).

It is shown that the Wentzel model will increase the CAH, which will lead to a higher friction. Therefore, the aim must be to create a surface that follows the Cassie-Baxter model, which means that the cavitations have to substitute water with air as fast as possible. (Kuzmin, 2010).

2.4 Ski test

When the first ski friction tests were performed at Uppsala University a custom made pin-on-disc apparatus, made to measure friction between the ski surface and the snow, were developed (Sturesson, 2008). This ski test rig is the one used in this study, with only a few adjustments when preparing the snow.
3. Experimental

In this study the friction coefficient and mechanical properties for six different materials were investigated. For comparison, two reference materials were tested. Before the friction test could be done the materials were prepared and the test rig was set up with snow and ski track.

3.1 Samples

The following samples were tested
Ref – UHMWPE
UHMWPE C-L – Cross-linked UHMWPE
CNT – UHMWPE with carbon nanotubes
CNT C-L – Cross-linked UHMWPE with carbon nanotubes
GO – UHMWPE with graphene oxide
GO C-L – Cross-linked UHMWPE with graphene oxide

3.2 Reference materials

Two reference materials were used: Pure medical-grade UHMWPE (GUR 1020), prepared according to section 3.3.1, without additional carbon particles and a Fischer RCS Carbonlite Classic Plus ski (manufactured in year 2008). The Fischer ski is a common choice by elite skiers. These two were used to distinguish the nano-composite materials from the pure material and from the ski material that is used today.

3.3 Material preparation

3.3.1 Nano-composite UHMWPE

All samples were made in a laboratory environment at LTU (Wikner, 2014). Compositions of 0.5 wt% MWCNT or GO in the UHMWPE nano-composites have shown an increased hydrophobicity and wear reduction compared to pure UHMWPE. Therefore, this was the combination used in all samples with additives.

The material preparation can be divided into two steps: Powder preparation and Hot-press sintering. The powder was prepared by letting an additive-ethanol mixture lay in an ultrasonic cleaner before it was mixed with UHMWPE powder in a ball-mill. To remove the ethanol the mixture was first dried out in an oil bath and as a last step dried in an oven. The right amount of powder was then poured into a steel frame, containing space for four samples with the right geometries of 4x2 cm², before it was covered with brass foil and a steel plate on top. The sintering process was made in a hot press, set at 190 °C and 105 kN, by letting the samples undergo a melting-pressure sequence for 70 minutes before cooling down to 40 °C. The samples of 4x2 cm² were then cut of from the steel frame using a razor blade. The samples had a smooth enough surface after the preparation so no extra polishing was needed.
3.3.2 Fischer ski

A 4x2 cm² piece (the same size as the other samples) was carved out from the Fischer RCS ski. The ski was fixed in a vice and the ski sole was removed with a small saw and a knife.

3.4 Surface treatments

The sole of the Fischer ski had a structure, stone grinded from manufacturing, which made it unfair to compare it with the much smoother samples from LTU. Therefore, at the third test run a 4000 abrasive paper was used to polish the Fischer ski to equalise the surface roughness with the surface roughness for the other samples.

3.5 Analysing methods

3.5.1 Mechanical properties/Dynamic indentation testing

When investigating the mechanical properties (hardness, storage and loss modulus etc.) of polymers, dynamic indentation testing is very suitable. During an indentation cycle the resulting displacement will be measured while a small oscillating force is applied to the load signal (CSM Instruments, 2003; CSM Instruments, 2006). A typical force sinus-displacement curve is shown in figure 1. Three parameters were specifically investigated when comparing the different samples: Indentation hardness (HIT), indentation modulus (EIT) and indentation creep (CIT). CIT is the relative change of the indentation depth whilst the applied load is kept constant.

Measurements were made with a CSM Instruments nanoindentation tester with a Visual matrix/Sinus mode. A Berkovich diamond tip (20 µm radius) with the amplitude of 50 µN and a frequency of 10 Hz was used. Maximum load was set to 500 µN, loading and unloading rate to 250 µN/min and a pause of 20 s. Four samples (UHMWPE, CNT, GO and Fischer) were analysed with many impressions, hoping to find variations in data when hitting a nanoparticle in the material. The indentation measurements were carried out in room temperature.

![Figure 1](image-url)

Figure 1. A typical nanoindentation a) load-displacement and b) load/displacement-time curve of a UHMWPE sample, using the sinus mode with an amplitude of 50 µN and a frequency of 10 Hz.

The nanoscratcher was used to see if any nanoparticles could be identified in the material and thereby ease the searching for particles in the nanoindentation measurements. Each test was done with a sphere-conical diamond tip (20 µm radius) and had a scratch length of 1 mm with a constant force of 15 mN.
3.5.2 Hydrophobicity

At LTU there has been a parallel study, on the same materials as in this study, where contact angle measurements have been done. Hence, in this study there will be experiments to investigate and try to understand the general mechanisms of hydrophobicity and its role to obtain better ski glide. Investigations of how the wettability of the ski sole, the hydrophobicity, affects the glide friction require a rather complex test arrangement. One needs to simulate the real life skiing movement and be able to distinguish the contact spots and how the water is dragged along the ski sole in contact with wet snow.

To get a first insight of how hydrophobic the different materials are, some simple inspections were made under the microscope. Water droplets were sprayed on the sample and then a polymethyl methacrylate (PMMA) glass was moved on top of it to see how the water was dragged along, figure 2. The wetting behaviour was documented under a DinoXcope USB camera.

![Figure 2. Hydrophobic measurements under microscope.](image)

3.5.3 Ski surface topography

White light interferometry (VSI) images were taken on all samples before and after the ski tests. Average surface deviation ($R_a$) values were examined to confirm the structure and its possible impact on the friction (section 2.2) and to see if the surface structure were changed during testing. Four $R_a$ values per sample were logged; covering 10 % and 50 % of the image, along and cross the sliding direction. Since VSI is based on optical reflection a thin layer of a gold palladium alloy was sputtered onto the surface area on all samples. Since the layer was only a few nm thick it could be removed easily, by rubbing a paper or finger on the surface, and did not affect the friction testing.

3.6 Ski test rig

A custom made pin-on-disc apparatus was used to measure friction between the ski surface and the snow. The test rig, originally designed by (Sturesson, 2008), has dimensions that are adjusted to fit into a chest freezer given by GB Glace AB. The main components of the test rig are listed in figure 3, and some of them are described in detail below.
3.6.1 Motor system

A 1.5 kW 3-phase electric motor is mounted vertically on the frame and runs the rotating disc. The rotating disc is controlled by an Omron frequency controller, which is connected to the motor and placed outside the freezer.

3.6.2 Friction sensor

A strain gauge bridge-sensor, figure 4, is installed on the side of the disc, in level with the profile test arm, as seen in figure 3. When a horizontal force, i.e. friction force, is applied on the sensor a deformation of the vertically strain gauge resistors occurs (figure. b). The deformation of the resistors causes a change in resistance, $R$, due to a shortening/extension of the resistor length and thus an increase/decrease in resistor section area. Four strain gauges are attached on thin bearers are coupled to create a Wheatstone bridge, as seen in figure 5. The voltage, $V$, can be calculated as in Eq. 4.

$$V = \left( \frac{R_1}{(R_1 + R_4)} - \frac{R_3}{(R_2 + R_3)} \right) V_s$$  \hspace{1cm} (4)
3.6.3 Ski holder

The sample material is glued on an aluminium ski holder, which is attached to the profile arm by a ball joint. The ball joint allows the ski to adjust to an uneven surface and is inserted into a rubber hose, to avoid rotation of the sample. The bottom surface of the ski has an area of 8 cm².

3.6.4 Temperature measurements

Two thermocouples, one for the environmental and one for the snow measurements, are placed in the chest freezer. One thermocouple was placed right above the snow, figure 6.a, to monitor the temperature at the track. The other one is placed around 10 cm above the track, figure 6.b, to observe the air temperature.

3.6.5 Control system

By connecting the Omron frequency controller, the strain gauge bridge-sensor and the thermocouples to a National instrument data acquisition (DAQ) module, the system could be controlled and monitored using a LabView program.
3.6.6 Snow gun

A modified airbrush, with an air and a water outlet, was used as a snow gun (figure 7). The air and the water flow could be varied to create the optimal mixture for the desired condition (Forsberg, 2009).

Figure 7. Snow gun.

3.7 Snow preparation

Initially, to get an even surface for the snow to grow on, water was poured on the aluminium disc to create a centimetre thick layer of ice. The snow gun was using tap water and air from Ångströms dry air outlet. The water was filled up in a bucket with adjustable flow, figure 8.a, together with ice (the colder the water, the easier snow can be produced). Both the air and the water hoses were placed inside the freezer in attempt to cool it down further.

During the snow production the disc was rotated, in order to level out the snow layer. This also gave some extra time for the excess water to freeze. The hardest part was to prevent an ice layer to form on top of the snow. To avoid this the temperature had to be low enough and the water flow had to be minimised. The spraying procedure, figure 8.b, could be carried out up to around -8 °C. Above this temperature too much water was accumulated and an ice layer was created instead of a thicker layer of snow. If the spray beam was directed over the disc the foremost part water would hit the wall on the other side of the chest freezer and the colder snow particles would fall on the disc. Under normal weather conditions a snowflake will form and grow on its way through the sky. However, in this experiment the size of the chest freezer limited the snow to form larger snowflakes. Instead the snow particles were growing into larger crystals and sintered together over time, like artificial snow.

To create a snow layer that was thick enough, the spraying had to be done in several steps. First the freezer had to be cooled down over the night, then the spraying procedure had to be repeated for about four to six times before the disc was covered. If the spraying is performed two times a day, one in the morning and one in the afternoon, it will take two to three days creating the snow. Between each test run a new snow layer of around 2 cm was produced on top of the older snow, which was just levelled out after the test. As in real life skiing, this will simulate a track with new snow on top of the older track.
3.8 Creating the ski track

Before the actual track was formed the snow layer had to be levelled out and packed. A ruler, figure 9.a, was used to level out the new snow surface and fill up the crevices that arose after spraying the snow. Then a pre-cooled cylindrical shaped roller, made of stainless steel and connected to a fixed clamp, was rolled on the surface to pack the snow (figure 9.b). The new surface was then left for some time, letting the snow “age” so that the crystals could sinter together again.

The formation of the ski track was done by cylindrical roller, figure 9.c, similar to the packing roller but this one was fixed and only 4.5 cm wide to suit the ski samples. The roller was attached to the side of the test rig and could be positioned on a desired level. While the disc was rotating on a low speed, the track roller was lowered gently. This was a critical moment since the track easily broke if the roller was pressed down too fast or too hard. When the snow was compact enough to carry the normal load of 11 N, i.e. the ski could run without damaging the track, the ski was left to run for about 5 – 10 min.
Figure 9. Creating the ski track by a) levelling out the surface with a ruler, b) packing the snow with a cylindrical roller and c) shaping the track with a fixed cylindrical roller.
3.9 Ski friction test

The friction tests were run at 1 m/s with the load of 11 N. This was far from the around 750 N for a “normal” size skier, but looking at the pressure that is spread out on the ski samples with a nominal area 8 cm², it was quite representative when comparing with a nominal area 80 000 cm². The chosen speed of 1 m/s was far from the 5 to 10 m/s in outdoor skiing, but was restricted to this speed due to the fragile track that had to withstand several runs without cracking. The load and time dependence tests were done to get a better general understanding of the friction mechanisms on snow. Since this study is built on the comparison between the different materials the most important thing is to run the test in each test run under similar conditions with constant parameters.

3.9.1 Load and time dependence test

The load dependence test was run as a pyramid test with a constant velocity of 1 m/s. The loading and unloading were done every 20 s with the following sequence: 6.2 – 7.4 – 8.7 – 9.9 – 11.1 – 12.4 – 11.1 – 9.9 – 8.7 – 7.4 – 6.2 N.

The time dependence test was carried out over 1000 s with a constant load of 11 N and a constant velocity of 1 m/s. This test was done on an old icy ski track with some icy powder snow upon.

3.9.2 Material comparing test

The ski friction tests were carried out under similar conditions with a constant speed of 1 m/s and a constant load of 11 N. The temperature, of both air and snow, were held constant but varied a little bit during each test because cold air was released when opening the freezer to change sample. There were also some small temperature differences between the three test runs (-15 – -18 °C). The snow type, i.e. age and structure, differed some between each test run as well. To take the condition fluctuations between each test into account, the reference sample (pure UHMWPE) was run after each test (according to the test sequence; sample 1 – ref – sample 2 – ref etc.). If the friction coefficient for the reference sample differed in the test run, it was predicted that the snow had changed and as a result also the friction coefficient for the other tests. Furthermore, for each test run the samples were run in different orders, table 1, to give them as equal environmental conditions as possible. There was a failure when running the first Fischer sample, so no data could be collected. Therefore, it is a gap in the first test run. At some stage in each test run the track broke and had to be prepared really quickly (see section 3.8) before the next test could be run. This moment is pointed out in the compilation box diagrams as “(TRACK PREP)”. There were many reasons why the test runs were carried out under such cold conditions. The major reason is because the temperature setting of the freezer was difficult to control and the chosen temperature was the best option to keep it stable. Another reason was that the track became more fragile under warmer conditions, and thereby harder to keep the conditions equal.

To give the tests equal conditions, to avoid snow formation during the test run, each test was run for 2 minutes. Looking at the results from this study (section 4.3.2), one can see that the friction coefficient stabilises after a short break-in period. This confirms that the test could be run for such a short time.

The last layer of snow was produced earlier in the day before the test run, to let the ice crystals sinter together for a couple of hours. The track was then created around one hour
before the test run. For test run number three the track was formed one day before the actual test, so the test conditions were a little bit different from the first two.

Table 1. Ski test sample order.

<table>
<thead>
<tr>
<th>Sample Test run</th>
<th>CNT</th>
<th>CNT C-L</th>
<th>GO</th>
<th>GO C-L</th>
<th>UHMWPE C-L</th>
<th>Fischer</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>#2</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>#3</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>
4. Results & Discussion

4.1 Analysing methods

4.1.1 Mechanical properties

The nanoindentation measurements, table 2 and appendix 2, showed similar values (hardness, elasticity and creep) for all three samples, which was expected since they have the same base material, UHMWPE. However, possibilities to hit a nanoparticles that should record a local increased hardness were desired, since it could give an indication of the influence of the added particles to the material. This was not achieved, probably due to a too big impression from the 20 µm tip radius. Nevertheless, to imitate a real life wear on a pair of skis running in a ski track, the impact on micro scale (or even macro scale) is far more interesting than an impact in nano scale.

In table 2, the results from the indentation tests are listed with mean values for indentation hardness \(H_{IT}[\text{MPa}]\), indentation modulus \(E_{IT}[\text{GPa}]\) and indentation creep \(C_{IT}[/\%]\). The hardness values are a little bit higher for the nano-composite UHMWPE’s than for the pure UHMWPE and the Fischer ski, which is promising, but it might not be a significant difference. Hardness measurements on polymers should be treated with caution since the elastic effect is hard to calculate. Nevertheless, it is interesting to compare the materials with each other. Looking at the hardness and indentation modulus as a function of depth, all tests follow the general hardness-modulus curve for viscoelastic materials (CSM Instruments, 2003).

<table>
<thead>
<tr>
<th>Sample</th>
<th>(H_{IT} [\text{MPa}])</th>
<th>(E_{IT} [\text{GPa}])</th>
<th>(C_{IT} [/%])</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHMWPE</td>
<td>67</td>
<td>1.3</td>
<td>5.0</td>
</tr>
<tr>
<td>CNT</td>
<td>73</td>
<td>1.1</td>
<td>5.2</td>
</tr>
<tr>
<td>GO</td>
<td>82</td>
<td>1.0</td>
<td>5.2</td>
</tr>
<tr>
<td>Fischer</td>
<td>59</td>
<td>0.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

According to CSM Instruments, 2006, both hardness and modulus are influenced by the creep behaviour, i.e. duration of the hold period (pause) and the loading rate. Its effect is reduced with a longer pause. For the hardness the creep effect can be neglected after 100 s of hold and for the modulus after 40 s. The importance of the time of hold was discovered after this experiment and should be taken into account if further measurements are to be done.

The nanoscratching measurements, appendix 2, gave no obvious indication of hitting a nanoparticle. There was no peak in the surface profile, showed in figure 10, which indicated hitting a particle. As for the nanoindentation measurements, the size of the scratch could be too big to discover the small particles. The diamond tip has rolled some polymer material over the big scratch, which can be seen in level with the white line. This could indicate that when scraping a ski sole to smoothen out the surface, one actually fills the crevices in the material. This could be beneficial because it would reduce the number of passages with the scraper to even out the surface, and thereby save material from being scraped off.
Dynamic testing on polymers is a rather new area at Uppsala University. Additional investigations of how to use the nanoindenter and nanoscratcher on polymers and how to measure wear and friction has to be done in order to discuss it further.

Figure 10. Nanoscratching of a GO sample, with the surface profile underneath. The arrow indicates the width of the scratch. Notice that the diamond tip has moved some polymer material over the big scratch (in level with the white line).

4.1.2 Hydrophobicity

Measurements made at LTU showed an increased contact angle according to: Fischer < UHMWPE < CNT < GO (Wikner, 2014). From the microscopic investigation there is hard to distinguish the wettability between PMMA and the nano-composite UHMWPE materials and which of the later materials that has the highest hydrophobicity. In figure 11, a PMMA glass is slid over the fixed UHMWPE sample (pure UHMWPE, CNT, Fischer and GO). The crosses, painted on the PMMA glass and the samples, indicate their positions. One single droplet on each sample is encircled with blue rings, to show how it moves when the PMMA glass is moved. If a really simple calculation is made; measuring how far the PMMA glass was moved versus the water droplet and equalise this with how hydrophobic each material were, the materials has an increased hydrophobicity according to: UHMWPE < CNT < Fischer < GO. This is similar to the contact angle measurements presented by Wikner, 2014, except from the Fischer material. However, in this study the Fischer material was polished differently, which will give a different result on the contact angle measurement. This is mostly a method to demonstrate how the water is dragged along and it is hard to quantify the hydrophobicity with this simple process. The water droplets in this test were acting differently depending on how hard the glass was pressed against the samples and if the samples were slightly bent the droplets lost the contact with the glass and stopped moving.
Figure 11. Sliding a PMMA glass over a) - b) a UHMWPE sample, c) - d) a CNT sample, e) - f) a Fischer (polished with a 1000 paper) sample and g) - h) a GO sample. A cross is painted on the PMMA glass and the UHMWPE samples to indicate its positions. The blue rings encircle one single droplet to see how it moves when the PMMA glass is moved.
4.2 Ski surface topography

Images, with respective surface roughness values ($R_a$), were taken before and after each ski friction test. In appendix 1 the samples from the third ski test are shown. There was not a distinct difference in surface roughness between the samples before the test, table 3, at least nothing that could be said to be a determining factor in how the results were reflected.

Notice the big difference in surface roughness between the stone grinded Fischer ski, figure 12.a, and the UHMWPE sample, figure 12.b. Even after polishing the Fischer ski, figure 12.c, the surface was much rougher. It is hard to compare the Fischer ski as a reference material if the structure differs too much. A positive side of this is that the nano-composite UHMWPE’s clearly showing a nice smooth surface without treatment.

Table 3. $R_a$-values

<table>
<thead>
<tr>
<th></th>
<th>CNT</th>
<th>CNT C-L</th>
<th>GO</th>
<th>GO C-L</th>
<th>UHMWPE</th>
<th>UHMWPE C-L</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{a,\text{along}}$ (before)</td>
<td>0.08</td>
<td>0.08</td>
<td>0.06</td>
<td>0.06</td>
<td>0.08</td>
<td>0.06</td>
</tr>
<tr>
<td>$R_{a,\text{cross}}$ (before)</td>
<td>0.15</td>
<td>0.14</td>
<td>0.12</td>
<td>0.13</td>
<td>0.12</td>
<td>0.13</td>
</tr>
<tr>
<td>$R_{a,\text{along}}$ (after)</td>
<td>0.13</td>
<td>0.15</td>
<td>0.22</td>
<td>0.08</td>
<td>0.26</td>
<td>0.10</td>
</tr>
<tr>
<td>$R_{a,\text{cross}}$ (after)</td>
<td>0.16</td>
<td>0.20</td>
<td>0.23</td>
<td>0.13</td>
<td>0.24</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Figure 12. a) Fischer (before any preparation). $R_a$: 10 % along – 0.6, cross – 2.5. 50 % along – 0.34, cross – 2. b) UHMWPE. $R_a$: 10 % along – 0.13, cross – 0.22. 50 % along – 0.08, cross – 0.12. c) Fischer after preparation with a 4000 abrasive paper. $R_a$: 10 % along – 0.25, cross – 0.30. 50 % along – 0.15, cross – 0.20

An indication of the big difference in surface roughness between the ski material, with the stone grind structure from manufacturing, and the UHMWPE sample. The numbers for the resolution in a) is not right, it should be the same as for the other two (3.5x4.6 mm)
4.3 Friction

4.3.1 Load and time dependence test

The load dependence test, figure 13, showed an increase in friction coefficient, $\mu$, with increased load, stated by the loading and unloading curve. This is consistent with previous experiments on snow (Forsberg, 2009).

![Load dependence curve](image)

Figure 13. Load dependence curve, friction coefficient against normal load (6.2 – 12.4 N) at 1 m/s and -18 °C, shows an increase in friction coefficient with increased load. The load off curve (red) is almost identical and proves that it is reliable.

In the time dependence test, figure 14, the friction coefficient increases at the beginning of the test and stabilises after around 400 s. The big increase in the beginning is probably due to the old track the ski was run in. It was an old icy track with a thin layer of new snow upon. As the snow layer was removed the friction coefficient increased until the old icy track was exposed and the friction coefficient was stabilised. If the track had been constructed on a thicker layer of snow it is possible that the ski would not have run through to the ice sheet and the curve would have been of a different shape.
4.3.2 Ski test

The first ski test was run on newly made snow (made earlier the same day) and with a temperature around -15 – -16 °C. The results from the first friction test are presented in figure 15. This shows how the friction coefficient, $\mu$, varies with the time. A compilation box diagram, figure 16, combines the data from the ski test, showing how the friction coefficient varies between the samples. The boxes, including error bars, median, 1$^{st}$ and 3$^{rd}$ quartile, are placed in the same order as they were run during the test (from right to left).
Figure 15. Friction measurements from ski test 1. The Friction coefficients, $\mu$, were recorded for all test samples against the test time (120 s) at the speed 1 m/s. The legend is showing the test order from the top and down. The reference sample, UHMWPE, which was run between each sample, is not displayed in this diagram.

By looking at the compilation diagram, figure 16, from the first ski test, there are two samples that stand out with lower friction coefficients compared to the others: CNT C-L and UHMWPE C-L. From this diagram one can also see that the values for the reference sample, pure UHMWPE, differs throughout the test but in general has the highest friction coefficients.
Figure 16. Box diagram, showing the error bars, median and 1st and 3rd quartile, from ski test 1. The chart is showing the test order from left to the right, including the stop for track preparation “(TRACK PREP)”. The reference sample, pure UHMWPE, was run between, just after each of the other samples. “REF (all)” contains the combined values from the reference sample from the test.

The second ski test was made under similar conditions as for the first test (-15 – -16 °C and newly made snow). The friction coefficients are in the same range as in the first test (figure 17).
Figure 17. Friction measurements from ski test 2. The Friction coefficients, $\mu$, were recorded for all test samples against the test time (120 s) at the speed 1 m/s. The legend is showing the test order from the top and down. The reference sample, UHMWPE, which was run between each sample, is not displayed in this diagram.

The results from the second test, figure 18, look a bit different compared with the results from the first test. GO is here showing a lower friction coefficient while CNT C-L is higher. The reference sample still tends to have the highest values and UHMWPE C-L the lowest.
Figure 18. Box diagram, showing the error bars, median and 1st and 3rd quartile, from ski test 2. The chart is showing the test order from left to the right, including the stop for track preparation “(TRACK PREP)”. The reference sample, pure UHMWPE, was run between, just after each of the other samples. “REF (all)” contains the combined values from the reference sample from the test.

The third ski test was run under different snow conditions compared to the first two tests. The snow and the ski track was prepared two days before, leading to a more stable track with a 2 – 3 degrees colder snow. This is reflected in the friction coefficient, figure 19, which is much lower than earlier tests due to the icier track. However, the values relative to each other are still the most interesting part.
Figure 19. Friction measurements from ski test 3. The Friction coefficients, $\mu$, were recorded for all test samples against the test time (120 s) at the speed 1 m/s. The legend is showing the test order from the top and down. The reference sample, UHMWPE, which was run between each sample, is not displayed in this diagram.

In the third test the samples were more spread out (figure 20). Furthermore the values for the friction coefficient were much lower than from previous tests. This could be explained by the snow character, which was one day old and more “icy” during this test run. UHMWPE C-L has once again the lowest values but in this test it is GO C-L that has a notable low friction coefficient (compared to earlier test runs), even though the reference sample showing high values before and after the test. Surprisingly, GO is showing much higher friction values than the rest of the field, although the reference run before and after indicates that the snow has not changed.
Figure 20. Box diagram, showing the error bars, median and 1st and 3rd quartile, from ski test 3. The chart is showing the test order from left to the right, including the stop for track preparation “(TRACK PREP)”. The reference sample, pure UHMWPE, was run between, just after each of the other samples. “REF (all)” contains the combined values from the reference sample from the test.

The summarising diagram, figure 21, illustrates the mean values for each material from all three tests. This confirms that the UHMWPE C-L has the lowest friction coefficient on snow. CNT and GO C-L are almost equal, but the later has a more scattered result. UHMWPE, CNT C-L and GO over all tend to have higher friction values. Adding table 4, one can get an even clearer view of the results. In this table the samples are graded from 1 to 10 in each test, with 1 being the best (lowest friction coefficient).

These results differ a lot from other pin-on-disc friction tests, from a parallel study at LTU (Wikner, 2014), where the wear rate and friction force seems to go hand in hand. Since the measurements from this study were made on a steel disc under much harder conditions, the wear rate had a bigger impact. This shows that friction measurements on snow do not have the same mechanisms. However, it is interesting to look at the wear rate when evaluating which material is the most favourable for skiing. A more wear resistant ski sole material could have a positive effect as it could enable the surface structure to last longer, which would reduce the amount material that has to be scraped off and therefore it will be less time and cost consuming. According to (Wikner, 2014), CNT has a much lower wear rate than UHMWPE C-L and could therefore be preferred as a ski material since it also has been showing a low friction coefficient on snow during these tests. According to the surface topography measurements there is no big difference before and after the tests and it is hard to say if one material has a better wear resistance on the low friction level presented on snow.
Figure 21. Compilation bar chart showing friction coefficient mean values for each material over all ski tests.

Table 4. A summary of the ski tests, grading the samples from lowest to highest mean friction coefficients values (1-10).

<table>
<thead>
<tr>
<th>Test</th>
<th>Sample</th>
<th>CNT</th>
<th>CNT C-L</th>
<th>GO</th>
<th>GO C-L</th>
<th>UHMWPE</th>
<th>UHMWPE C-L</th>
<th>Fischer</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td></td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>#2</td>
<td></td>
<td>3</td>
<td>7</td>
<td>2</td>
<td>5</td>
<td>6</td>
<td>1</td>
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<td>#3</td>
<td></td>
<td>3</td>
<td>6</td>
<td>7</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

In Figure 22, one can see how the reference sample differed between each test. As mentioned earlier, the third test was run under faster (lower friction coefficients) conditions.
Figure 22. Box diagram based on the combined values from the reference sample from each test, showing the error bars, median and 1st and 3rd quartile.

4.4 Summarising discussion

The hydrophobic measurements did not match the friction tests as they were expected to do. Together with results from Wikner (2014), this study shows that earlier suggestions that high hydrophobicity goes hand in hand with low friction should be questioned. For example, GO had the highest contact angle and the highest hydrophobicity but also the highest friction coefficient on snow. However, the hydrophobic test in this study should be treated with caution before drawing any bigger conclusions. The reason why the hydrophobicity did not influence the outcome of the results could be that the temperature was too low and the ski tests were performed in the dry friction zone. The mechanisms of hydrophobicity could be studied further by developing a test rig, where the ski sole against snow can be recorded. One idea is to build a thin transparent polymer layer on a glass, run it against a snow surface while pouring water on the snow. This could give a sense of the hydrophobic mechanisms on snow.

The results in this study differ a lot from a parallel pin-on-disc friction study at LTU (Wikner, 2014), where the friction coefficient was increasing with increasing wear rate. Since the measurements from that study were made on a steel disc under much harder conditions, the wear rate had a bigger impact and therefore nano-composite UHMWPE’s had both lower wear rate and friction coefficient than pure UHMWPE (cross-linked and none cross-linked). However, this study showed that pure UHMWPE C-L had lower friction coefficients than nano-composite UHMWPE’s, which proves that friction measurements on snow do not
follow the same mechanisms as on a steel disc. This shows the importance of the snow quality and that the aim should be on making snow similar to real outdoors conditions. A test rig in a larger scale would give a more reality-based environment and could improve ski testing even more.

In those test runs where the Fischer ski were measured the nano-composite materials showed equal or even better results, just looking at the friction coefficient. Since both the geometry and the surface of the Fischer samples differed from the rest it is unfair to compare these fully, but it gives an indication that nano-composite UHMWPE’s are promising as a ski sole material.

Based on the surface topography measurements, no big difference could be seen before and after the tests and it is hard to say if one material has a better wear resistance on this low friction level. The values from the nanoindentation tests show promising results for the nano-composite UHMWPE’s and all tests follow the general hardness-modulus curve for viscoelastic materials. More tests have to be done to see if nano-composite UHMWPE’s have a significantly increased hardness compare to the pure UHMWPE and the Fischer ski. If one actually fills the crevices in the material when scraping the surface for polishing it could be beneficial because it would save material from being scraped off.
5. Conclusions

- The cross-linked ultra high molecular weight polyethylene, UHMWPE C-L, is proven to have the best ski glide (lowest friction) on snow.

- The hydrophobic measurements showed equal results as with earlier studies on the same materials (Wikner, 2014). However, the role of hydrophobicity and how it is suggested to lower the friction should be questioned and further investigated.

- By the results from the variation in friction coefficients in figure 22, it is confirmed that the snow type (age, temperature, etc.) has a bigger impact on the friction ski glide than the ski sole material.

- Friction measurements on snow do not follow the same mechanisms as on a steel disc and therefore it is important to perform ski tests in reality-based environment.

- Nanoindentation is proven to give some interesting and valuable mechanical data for polymers and all tests follow the general hardness-modulus curve for viscoelastic materials. It should be questioned whether it is a good technique for comparing different nano-composite UHMWPE materials since the indentation test was not able to distinguish the nanoparticles in the nano-composite UHMWPE’s.

6. Future work

In order to find the materials best suited for skiing, more research is needed. Based on this study future work should focus on:

- Additional ski tests on nano-composite UHMWPE materials to see how they behave on different snow conditions, at different velocities, different loads and how they change over time. Especially to see how UHMWPE C-L and CNT perform against each other since they showed the best results in this study.

- More testing against the ski material used today, with similar surface roughness and in different conditions.

- Further studies on the mechanisms of hydrophobicity with developing a test rig, where the ski sole against snow can be documented. There are ideas of building a thin transparent polymer layer on a glass and run it on snow while filming.

- Develop the test rig into larger scale testing. A freezer with more space and where the environmental conditions could be controlled more easily would ease the snow production and make it more similar to real life skiing. When producing the snow, the ice crystals would get more time to fall and grow bigger, which would represent real snow. In larger scale, one can test bigger samples with higher speeds and higher loads, which were all limiting factor here.
7. Acknowledgements

This study has been done at the Department of Engineering Science; Applied Material Science at Uppsala University. A big thanks to all my co-workers who helped me with valuable discussions, especially to Harald Nyberg for all the technical help in tribolab, Peter Sturesson for all the discussions and common knowledge about the ski rig and to my supervisor Staffan Jacobson. Thank you GB Glace AB, for sponsoring me with a new chest freezer, and many thanks to my girlfriend Ida Morén who really contributed with good comments and discussions when writing the report.
References


Appendix 1

Surface topography

Before test

Figure 23. Fischer (before any preparation). An indication of the big difference in surface roughness between the samples and the reference ski material with the stone grind structure from manufacturing. $R_a$: 10% along – 0.6, cross – 2.5. 50% along – 0.34, cross – 2.
Figure 24. Fischer scraped. After preparation with a Primateria scraper. $R_a$: 10 \% along – 0.65, cross – 1.0. 50 \% along – 0.50, cross – 0.75

Figure 25. Fischer 4000p. After preparation with a 4000 abrasive paper. $R_a$: 10 \% along – 0.25, cross – 0.30. 50 \% along – 0.15, cross – 0.20
Figure 26. CNT C-L. R₅: 10 % along – 0.15, cross – 0.21. 50 % along – 0.08, cross – 0.14.

Figure 27. CNT. R₅: 10 % along – 0.12, cross – 0.24. 50 % along – 0.08, cross – 0.15.
Figure 28. GO C-L. $R_z$: 10 % along – 0.12, cross – 0.19. 50 % along – 0.06, cross – 0.13.

Figure 29. GO. $R_z$: 10 % along – 0.11, cross – 0.21. 50 % along – 0.06, cross – 0.12.
Figure 30. UHMWPE C-L. R₆: 10 % along – 0.12, cross – 0.22. 50 % along – 0.06, cross – 0.13.

Figure 31. UHMWPE. R₆: 10 % along – 0.13, cross – 0.22. 50 % along – 0.08, cross – 0.12.
After test

Figure 32. CNT C-L. $R_c$: 10 % along – 0.20, cross – 0.28. 50 % along – 0.15, cross – 0.20.

Figure 33. CNT. $R_c$: 10 % along – 0.18, cross – 0.24. 50 % along – 0.13, cross – 0.16.
Figure 34. GO C-L. $R_s$: 10 % along – 0.12, cross – 0.21. 50 % along – 0.08, cross – 0.13.

Figure 35. GO. $R_s$: 10 % along – 0.25, cross – 0.30. 50 % along – 0.22, cross – 0.23.
Figure 36. UHMWPE C-L. $R_a$: 10% along – 0.15, cross – 0.25. 50% along – 0.10, cross – 0.20.

Figure 37. UHMWPE. $R_a$: 10% along – 0.34, cross – 0.30. 50% along – 0.26, cross – 0.24.
Appendix 2

Mechanical properties

Indentation

Table 5. Nanoindentation measurement of a UHMWPE sample.

<table>
<thead>
<tr>
<th>Property</th>
<th>Data : 2</th>
<th>Data : 3</th>
<th>Data : 4</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Min</th>
<th>Max</th>
<th>N</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H_{IT}) [MPa]</td>
<td>68.436</td>
<td>64.996</td>
<td>66.988</td>
<td>66.806</td>
<td>1.727</td>
<td>64.996</td>
<td>68.436</td>
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</tr>
<tr>
<td>(E_{IT}) [GPa]</td>
<td>1.286</td>
<td>1.249</td>
<td>1.262</td>
<td>1.266</td>
<td>0.019</td>
<td>1.249</td>
<td>1.286</td>
<td>1.262</td>
<td></td>
</tr>
<tr>
<td>(C_{IT}) [%]</td>
<td>5.249</td>
<td>4.845</td>
<td>5.034</td>
<td>5.043</td>
<td>0.202</td>
<td>4.845</td>
<td>5.249</td>
<td>5.034</td>
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</tr>
</tbody>
</table>
Figure 38. A load-displacement curve of UHMWPE.

Figure 39. Hardness and indentation modulus as a function of depth for UHMWPE.
Table 6. Nanoindentation measurement of a CNT sample.

<table>
<thead>
<tr>
<th></th>
<th>Data : 1</th>
<th>Data : 2</th>
<th>Data : 3</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Min</th>
<th>Max</th>
<th>N</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{IT}$ [MPa]</td>
<td>69.314</td>
<td>81.817</td>
<td>67.325</td>
<td>72.819</td>
<td>7.856</td>
<td>67.325</td>
<td>81.817</td>
<td>3.000</td>
<td>69.314</td>
</tr>
<tr>
<td>$E_{IT}$ [GPa]</td>
<td>1.063</td>
<td>1.331</td>
<td>1.011</td>
<td>1.135</td>
<td>0.172</td>
<td>1.011</td>
<td>1.331</td>
<td>1.063</td>
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</tr>
<tr>
<td>$C_{IT}$ [%]</td>
<td>5.638</td>
<td>4.419</td>
<td>5.432</td>
<td>5.163</td>
<td>0.652</td>
<td>4.419</td>
<td>5.638</td>
<td>5.432</td>
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</tbody>
</table>
Figure 40. A load-displacement curve of CNT.

Figure 41. Hardness and indentation modulus as a function of depth for CNT.
Table 7. Nanoindentation measurement of a GO sample.

<table>
<thead>
<tr>
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<th>Data : 1</th>
<th>Data : 2</th>
<th>Data : 3</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Min</th>
<th>Max</th>
<th>N</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{IT}$ [MPa]</td>
<td>78.039</td>
<td>97.403</td>
<td>69.887</td>
<td>81.776</td>
<td>14.134</td>
<td>69.887</td>
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<tr>
<td>$E_{IT}$ [GPa]</td>
<td>0.971</td>
<td>1.214</td>
<td>0.856</td>
<td>1.013</td>
<td>0.183</td>
<td>0.856</td>
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<tr>
<td>$C_{IT}$ [%]</td>
<td>5.172</td>
<td>5.797</td>
<td>4.667</td>
<td>5.212</td>
<td>0.566</td>
<td>4.667</td>
<td>5.797</td>
<td>5.172</td>
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</table>
Figure 42. A load-displacement curve of GO.

Figure 43. Hardness and indentation modulus as a function of depth for GO.
Table 8. Nanoindentation measurement of a Fischer sample.

<table>
<thead>
<tr>
<th></th>
<th>H_{IT} [MPa]</th>
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<th>E_{IT} [GPa]</th>
<th></th>
<th>C_{IT} [%]</th>
</tr>
</thead>
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<tr>
<td></td>
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<tr>
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</tr>
<tr>
<td></td>
<td>Mean</td>
<td>38.796</td>
<td>Mean</td>
<td>0.538</td>
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</tr>
<tr>
<td></td>
<td>Std Dev</td>
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<td>Std Dev</td>
<td>0.058</td>
<td>Std Dev</td>
</tr>
<tr>
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<td>0.479</td>
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<td>Max</td>
<td>0.596</td>
<td>Max</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>3.000</td>
<td>Median</td>
<td>0.539</td>
<td>Median</td>
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</tbody>
</table>
Figure 44. A load-displacement curve of Fischer.

Figure 45. Hardness and indentation modulus as a function of depth for Fischer.
**Scratch**

Figure 46. Nanoscratching of a UHMWPE sample, with the surface profile under. The arrow indicates the width of the scratch.

Figure 47. Nanoscratching of a CNT sample, with the surface profile under. The arrow indicates the width of the scratch.
Figure 48. Nanoscratching of a GO sample, with the surface profile under. The arrow indicates the width of the scratch.