Why is ice and snow slippery?
The Tribo-physics of skiing

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In memory of Martin Matsbo (1911-2002)

Abstract

The low friction on snow and ice under normal winter temperatures is due to the special material properties of snow and ice, low shear strength, relative high values of hardness close to its melting point and the presence of a pre-melted layer well below the melting point. In this paper we present the factors contributing to the total friction between a slider and snow and ice. The relative importance of the factors contributing to the total friction change under different meteorological and snow conditions, in addition the pressure exerted by the slider and its velocity is also important factors for the friction. One reason for the wide temperature range under which snow and ice is slippery is the existing non nucleation barrier during melting.

<div align="right">Oslo, 30. September, 2005</div>

1. Introduction

The classic laws of friction inspired by Leonardo da Vinci and developed by Amontons and Coulomb state that

    i.   The friction force is proportional to load and is acting in opposite direction to the relative velocity of the surfaces in contact.

    ii.   The coefficient of friction is independent of apparent contact area.

    iii.   Static friction coefficient is greater than the kinetic coefficient.

   iv.   Coefficient of friction is independent of sliding speed.

> **The empirical law of friction, first enunciated by Leonardo da Vinci:**
>
> *The magnitude of the force of friction between unlubricated, dry surfaces sliding one over the other is proportional to the normal force pressing the surfaces together and is independent of the (macroscopic) area of contact and relative speed.*
>
> This observation holds because what determines the amount of adhesion is not the macroscopic contact area, but the microscopic area of contact.

These rules, known as the "Amonton-Coulomb laws" of dry sliding have been used throughout the years although recent research has shown that the laws have their shortcomings (Moore, 1975; Czichos, 1978). The first law, $F = mW$, where F is the friction, m is the coefficient of friction and W is the normal force, is correct except at high pressure when actual area of contact approaches apparent contact area. The second law is not valid for elastic and visco-elastic materials, but holds for metals with a definite yield point. The third law does not hold for visco-elastic materials. And the fourth law does not hold for any material. A fifth law, or experimental observation, states that m is dependent of material.

In the dry friction regime the load is carried by asperities on the surfaces, and the friction is determined by physio-chemical interactions at the interface. By introducing a fluid film between two moving surfaces the friction between them can be substantially reduced. Under such circumstances the frictional resistance is due to internal friction (viscosity) of the lubricating fluid. The regime between these two extremes is called mixed lubrication and is, as the name implies, a mixture of both dry and hydrodynamic lubrication. The three regimes discussed can be summarised by the "Stribeck"-curve (Fig. 1).
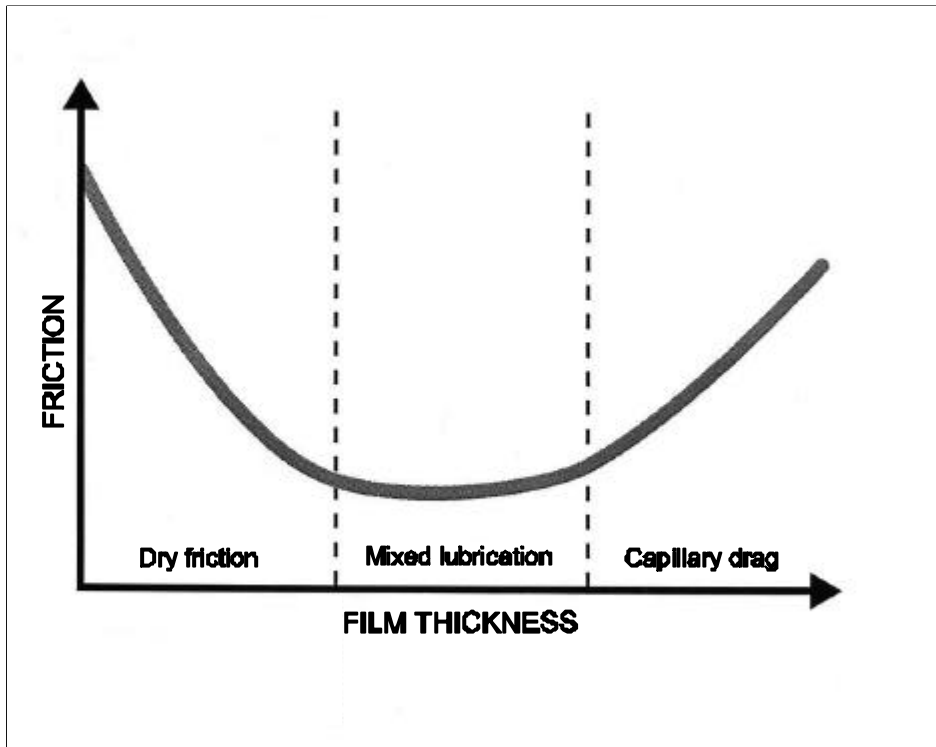
Figure 1. A schematic view of lubricating regimes also called the "Stribeck" curve after the work done by Stribeck in the early 20th century.

1.1. Friction on snow and ice

The total friction between snow and a slider is determined by the snow/ice conditions, slider surface and material, atmospheric conditions, and the interactions at the snow slider interface. The processes making up the total friction is plowing (*µplow*), solid deformation (*µdry*), water lubrication (*µwet*), capillary attraction (*µcap*) and surface contamination (*µdirt*) (Colbeck, 1992).

$$m = m_{plow} + m_{dry} + m_{wet} + m_{cap} + m_{dirt} \qquad (1)$$

The processes do not act independently which makes the friction mechanisms of snow and ice more complicated. When two or more processes act in parallel the total friction can be expressed as

$$\frac{1}{m} = \frac{1}{m_{dry}} + \frac{1}{m_{wet}} + \frac{1}{m_{cap}} \; . \qquad (2)$$

The different friction mechanisms dominate under different meteorological and snow conditions. In his review (Slotfeldt-Ellingsen, 1979) also included air drag as part of the total friction. However, not exactly a part of the friction mechanisms involved at the slider-snow interface, the air drag is a very important term at higher sliding speeds (Fig. 2).
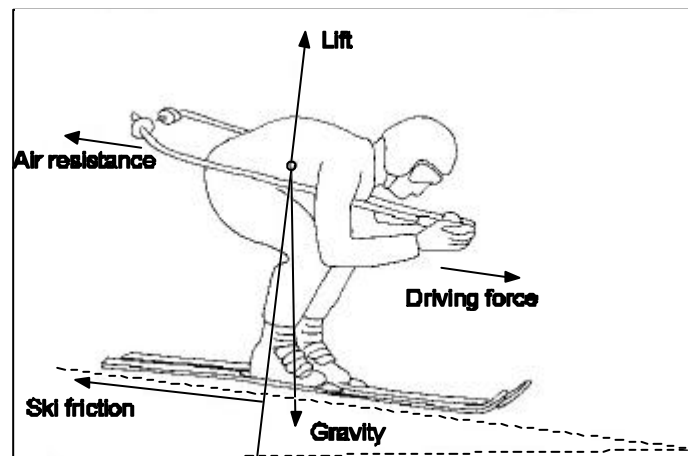
Figure 2. Schematic overview of the forces acting on a downhill skier during descent, the force vectors are not drawn to scale.

(Glenne, 1987) summarised the main variables affecting sliding snow resistance as:

- Snow compressive strength
- Snow moisture and meltwater
- Snow density and compaction
- Snow crystal hardness (temperature)
- Snow crystal size and angularity (metamorphism)
- Bearing load on snow (local contact pressure)
- Slider area, shape, and elasticity
- Base material (hydrophobicity)
- Material texture
- Sliding velocity

The stage of metamorphism of snow is determining much of the compressive strength of the snow. Bearing load and compressive strength determines the actual sliding contact area between slider and snow. This area is difficult to define (Kuroiwa, 1977). The resistance to sliding is sensitive to a runners surface and texture (Glenne, 1987). At lower snow temperatures the hardness and smoothness of the surface and its heat conductivity are the important properties. Whereas during warmer snow conditions hydrophobic material, wax impregnation and surface texture matters more (Slotfeldt-Ellingsen, 1979; Oksanen and Keinonen, 1982; Spring and others, 1985; Lehtovaara, 1985).

Definition of technical nomenclature used in the text:

- **Adhesion:** Adhesion is the molecular attraction exerted between bodies in contact. A union of two surfaces that are normally separate. The attraction of water molecules to other materials as a result of hydrogen bonding.

- **Cohesion:** The force that holds molecules of the same substance together - tendency of a single substance to adhere to itself. Also, the force holding a single substance together. The attraction of water molecules to each other because of hydrogen bonding. Also known as *surface tension*.

- **Contact angel:** An angle formed between two substances, as determined by their surface tensions, when in contact.

- **Hydrophilic:** Water-receptive, attracting moisture.

- **Hydrophobic:** A qualitative term referring to the water-avoiding nature of a species (compounds that repel water). Water repelling; having a low degree of moisture absorption or attraction. A functional group of a molecule that is not very water-soluble is referred to as a hydrophobe.

- **Surface energy:** Technical measure of the tendency of a surface to repel molecules of another substance. Low surface energy refers to a repelling action. The measure of surface tension is in dynes. The lower the surface energy of a substrate, the more difficult it becomes for an adhesive or coating to wet out that surface. Also a measure of the surface area to volume ratio.

- **Surface tension:** The cohesive force exerted at the surface of a liquid that makes it tend to assume a spherical shape. Surface tension is related to the interactive forces between molecules of a liquid, and is caused by the fact that molecules at the surface are not surrounded by molecules on all sides and consequently they interact more strongly with those directly adjacent to them on the surface. Surface tension causes water to form spherical drops, and to reduce penetration into fabrics. Soaps, detergents and wetting agents reduce surface tension and increase penetration by water.

The research on the topic of snow and ice friction has a fairly long tradition with high activity in the twentieth century. In addition to skiing, much of the research has been promoted by air operations (*e.g.* McConica, 1951; McConica, 1952), forest industri (*e.g.* Ericksson, 1949) (Korunov, 1947) and car tire industry (*e.g.* Holmer and Antvik, 1961; Lindqvist, 1979), and pure scientific curiosity.

The low friction of ice has traditionally been explained by a thin film of melt-water between the ice and slider. The melt-water film has been proposed to originate from pressure melting (Reynolds, 1899) or induced by frictional heating generated at the ice slider contact (Bowden and Hughes, 1939). The idea of pressure melting has been modified and rejected (Bowden and Hughes, 1939) because of the high pressure needed to lower the melting point sufficiently. The pressure melting theory is only applicable at temperatures close to 0°C. The heat generated due to friction is sufficient to melt ice and create a liquid layer that can lubricate the ice-slider contact. However, at higher temperatures friction may increase due to viscous resistance (Huzioka, 1963). Tusima (1977) argued that the low friction of snow and ice cannot be explained by the friction melting theory, but rather understood by adhesion theory (dry lubrication). However, Colbeck (1992) ignore the adhesion theory in his review of processes that control snow friction because snow grains usually slide on dissimilar materials

such as polyethylene, ski-wax or a mixture thereof. Normally, adhesion is an important part of friction when the sliding materials are similar in their molecular structure, are macroscopically smooth, and have time to bond (Rabinowicz, 1984). Earlier studies (Evans and others, 1976) (Barnes and others, 1971) suggest however, a type of boundary lubrication or mixed lubrication. That is, water is created at the area of contact and supports the load of the slider causing wet lubrication. At some high points the surfaces do come in contact and here dry friction is more important. These areas of dry friction contribute most to the friction (Evans and others, 1976). The friction mechanism explained above can be divided into three regimes with regard to the sliding speed. At low sliding speeds re-crystallization is produced at the interface, with the basal plane being oriented in the direction of sliding. At higher speed, where the process of re-crystallization is too slow to be able to release stress in the snow and ice, shear failure and brittle fracture occur. At even higher speed, frictional heating at the slider snow interface is sufficient to produce water melt and the coefficient of friction falls to 0.05 or less, due to wet lubrication (Barnes and others, 1971).

Other reports argue that low friction of snow and ice derives not only from a film of melt-water, but also from the unique characteristics of the ice surface (McConica, 1950; Jordan, 1955; Niven, 1959). They viewed ice as a solid lubricant where crystallographic planes might slide past each other by dislocations. The idea of a unique characteristic of the ice surface was first proposed already by (Faraday, 1860). A theoretical description of the liquid like layer was first proposed by Fletcher (Fletcher, 1962; Fletcher, 1968; Fletcher, 1968; Fletcher, 1970). It is during the last part of the 20th century that a more clear understanding of this "unique characteristic" has emerged. The theories of surface melting and the fact there is no nucleation barrier for melting as it is for freezing (Oxtoby, 1999), can explain the characteristics. The reason for a non-melting nucleation barrier is due to a high temperature spinodal, a point at which the crystal becomes mechanically unstable to small temperature fluctuations.

The modern description of surface melting is that "the surface of a solid, at uniform temperature, develops a thin layer of its melt at temperature below the bulk transition temperature" (Wettlaufer, 1999b) (Fig. 3). The layer is a precursor of the complete melting of the solid and influences adhesion, crystal growth and other behaviour of the material (Wettlaufer, 1999a). Molecular solids, like ice as well as other materials, undergo the process of surface melting. It begins well below the melting point of the material and gradually thickens with rising temperature. At start, the layer is a few molecules thick and at the melting point the layer diverges. As outlined by Wettlaufer (1999a), surface melting is a special case of wetting, where the intra fluid forces (cohesive forces) are weaker than the adhesive forces of the substrate (the solid). This pre-melted layer probably is an important factor, reducing friction at lower temperatures. Because of the non-nucleation barrier during melting, this effect is valid over a wide temperature range, whereas if it would have been a nucleation barrier, the temperature range for the influence would have been much narrower.
The phenomenon of surface melting on a microscopic scale has impact on several macroscopic processes such as slipperiness of ice, facilitates sintering of snow, thundercloud electrification and frost heave (Dash and others, 1995; Wettlaufer and Dash, 2000). The thickness of the liquid like layer is between ~50 monomolecular layers close to 0°C and reduces to ~3 monolayers (the thickness of a H_2O molecule) around -10°C. Other important material properties for the slipperiness of ice is the low shear strength and the relative high values of hardness, even close to its melting point.

Air

Liquid film
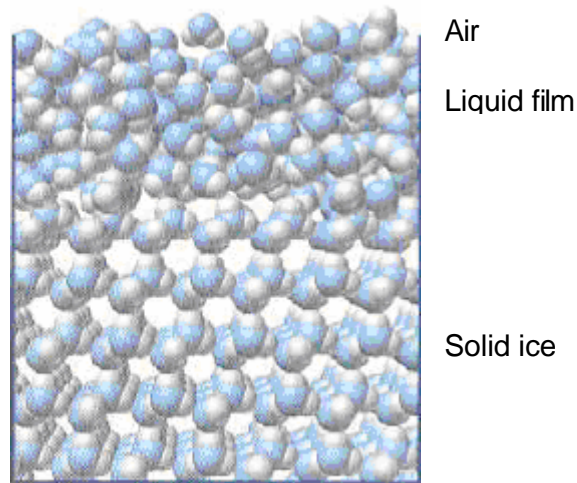
Solid ice

Figure 3. The surface structure of solid ice. The liquid like disordered structure appears at the surface of the solid even at temperatures below the bulk melting temperature (Wettlaufer and Dash, 2000).

In summary, the research on friction of snow and ice has followed several paths: i. Pressure melting. ii. Friction melting. iii. Surface melting. iv. Free water. In addition to these four processes several works by Petrenko and co-workers suggested that electric phenomena may alter the friction between snow/ice and a slider (Petrenko, 1994; Petrenko and Colbeck, 1995; Petrenko, 1996).

A possible conclusion about friction on snow and ice is that all mentioned mechanisms do contribute in reducing the friction, but the relative importance of the processes is varying with the characteristics of the elements involved in the system. One important reason for this is the fact that most sliding on snow occurs at the triple point, the point where H_2O coexist in all three phases (Fig. 4).
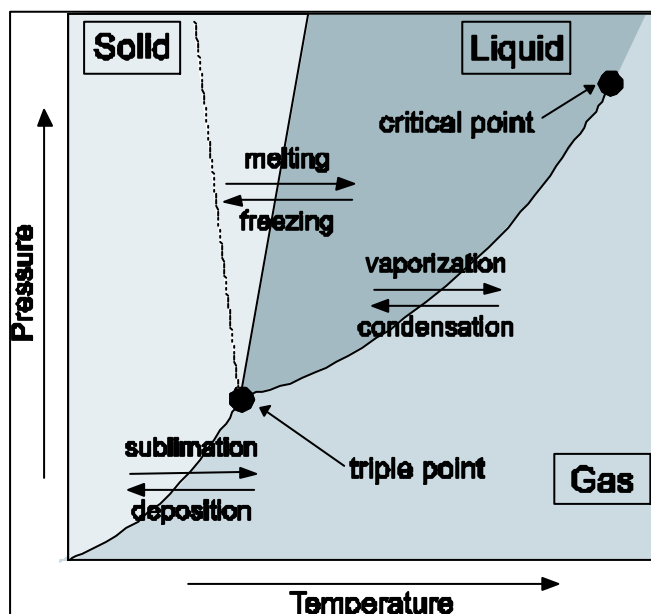

Figure 4. Phase diagram depicting the boundaries (solid) between solid, liquid and gas phases as a function of temperature and pressure. For water the boundary between solid and liquid (dashed) has a negative slope. This means that the melting point is decreased with increased pressure. Most materials prefer solid phase at higher pressure (the molecules are packed closer together), since ice has a lower density than water (water molecules are closer packed as a liquid the consequence is that the melting point is decreased at higher pressure. Most of the sliding on snow and ice occurs at the triple point. The point at which solid, liquid and gas coexists.

Tribology can be used to deduce and examine the relative importance of the including processes. Tribology, after the Greek word "tribos" eq. rubbing, is the science and practice of friction, lubrication and wear applied to engineering surfaces in relative motion (Moore, 1975). The most important aspects of tribology, related to skiing, are the influence of the frictional mechanisms, either to improve gliding by reducing the kinematic friction or, in the case of cross country classic skiing, to optimise grip by increasing the static friction. In skiing, the tribo-system is made up of four tribo-elements with the following characteristics (Fig. 5).

1. The properties of the material of the moving element such as structure, hardness and hydrophobity.
2. The stage of the metamorphism of the snow, the quasi-stationary element.
3. The interface, the area of interactions between elements 1, 2 and 4.
4. The atmosphere being the supplier of external energy and exchange of energy.

A full understanding of the importance of the including elements is of utter importance when solving the problems of slider base treatments for optimum friction properties. The above mentioned points will be discussed further below in order to understand the factors influencing the major interest of a skier: How to explain movement in snowy environment over longer distances with highest possible speed using least amount of power?
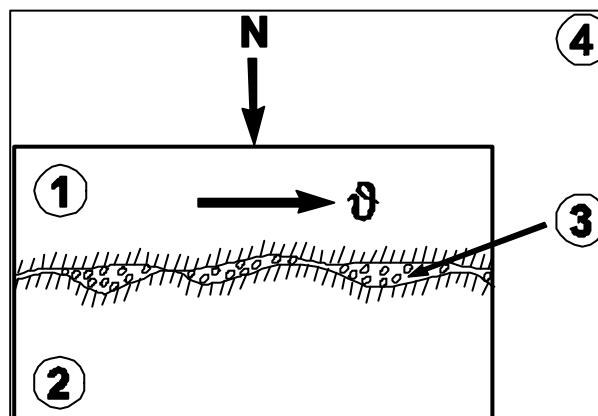
Figure 5. Schematic description of a tribological system and its constituting elements: 1. The element in motion, 2. The stationary element in this case the snow surface, 3. the interface and 4. The surrounding atmosphere, influencing the three other elements.

2. Triboelement 1 (moving)

2.1. Slider base material
The slider base that is in contact with the quasi-stationary element (the snow surface) should show the following characteristics:

  i.   Low friction coefficient against snow
  ii. Resistance to wear
  iii. Good adhesion to ski waxes and possibility to absorb the wax
  iv. Heat stability

A material that has proven to fulfil these requirements is Ultra High Molecular Weight Polyethylene (UHMW-PE). The molecular weight is a decisive factor for material properties. Polyethylene with molecular weight over 5x105 to 8x106 is used for ski and snowboard bases. PE with such high molecular weight is very viscous when melted. This means that it cannot be extruded (a common production process for PE) but has to be sintered. The sintering process is a more complicated and expensive process than extrusion. The sintering is performed by filling a sintering form with PE-powder and then exerting pressure on the material for some time. The sintering cycles consist first of a period with increased pressure with no extra heat added. The next step is the addition of external heat and a slight reduction in pressure. During the cooling period the pressure is increased again. The full cycle takes several hours (Slotfeldt-Ellingsen and Torgersen, 1982). The completion of the sintering results in a polyethylene cylindrical block, which can only be processed by slicing. The block is peeled externally by veneer slicing (Fig. 6). The obtained strip is then flame treated on one side in order to make it suitable for adhering to the base of the ski or snowboard.

The low friction coefficient of PE to snow has been proposed to be due to the polarity of the H_2O molecule. In general the PE is non polar, except at the ends of the molecule chain. By creating longer chains (higher molecular weights) the number of ends decrease per unit contact area, thus making the base of the slider more hydrophobic. In fact, PE is one of the polymeric materials having the lowest surface energy (more hydrophobic). Only fluor-polymers have lower surface energy. This indeed would suggest that fluor-polymers are the better slider material. However, when considering the mechanical characteristics and ability to absorb wax, it becomes evident that pure fluor-polymers are not suitable compared to PE.
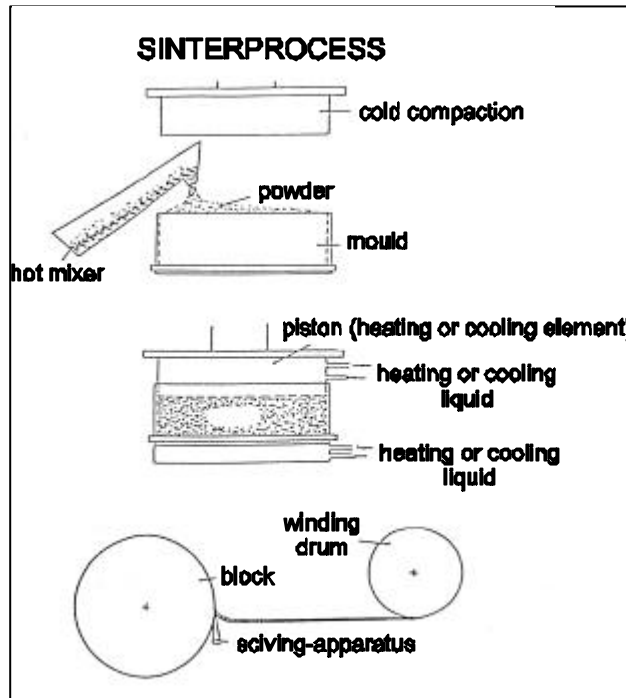
Figure 6. Simplified overview of the process of UHMW-PE- sintering, from R. Schamesberger (personal communication, 1988).

The PE has both a crystalline and an amorphous part (Fig. 7). Because of the extremely long molecular chains in UHMW-PE, only small crystalline regions build, which lead to a reduction in density. With larger amorphous part the possibility for the PE to absorb wax is increased. In general, the UHMW-PE has a larger ratio of amorphous parts.

Due to the open structure of the amorphous parts, molten ski wax is allowed to penetrate the surface and mix in the amorphous regions but not in the crystalline ones (Fig. 8).
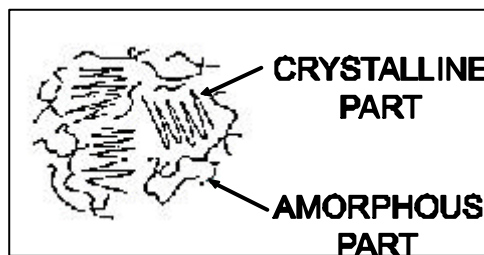
Figure 7. The UHMWE-PE- structure. The PE is made up of both crystalline and amorphous parts.
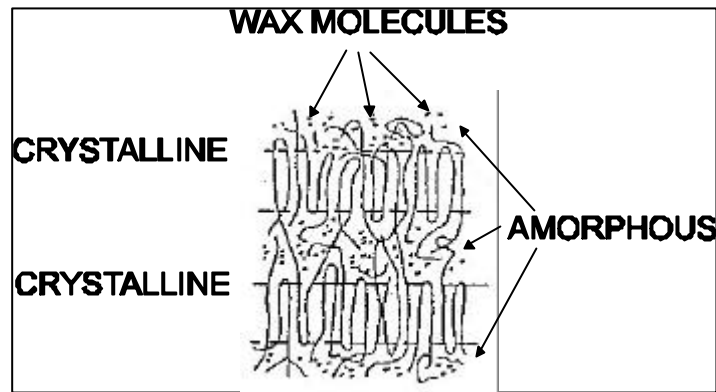
Figure 8. The wax particles penetrate and fill up the open structure of the amorphous parts of the PE. No wax particles may enter the crystalline parts. The density is a good measure of the ratio of crystalline and amorphous parts. UHMW-PE with lower density has a larger ratio of amorphous material and thus absorbs more wax.

The wax normally is warmed in to the base with an iron or cork. The driving force is diffusion of wax particles into the base structure, both due to the temperature and concentration difference.

This diffusion process can be described in the following way. The wax concentration c at distance x from the surface after t time of exposure to the surface, at temperature T is,

$$c(x,t,T) = \frac{c_0(T)}{\sqrt{p \cdot D(T) \cdot t}} \int \exp\left[-\frac{(x-x^1)^2}{4 \cdot D(T) \cdot t}\right] dx$$

(3)

$$= \frac{1}{2} c_0(T) \cdot \left[1 - erf\left(\frac{x}{4 \cdot D(T) \cdot t}\right)\right].$$

Where $D(T)$ is the constant of diffusion at temperature T, $C_0(T)$ is the wax concentration just below the base surface i.e. the maximum wax concentration the PE base can attain at the current temperature and erf is the error function.

It has been shown by (Slotfeldt-Ellingsen and Torgersen, 1982)), that during waxing a small increase in temperature leads to marked increase in wax absorption. The result of changing the temperature is that the position of wax equilibrium in the base is changed. In the same study it was also shown that waxes with lower molecular lengths do penetrate further into the PE than the longer ones. The time for which wax is exposed to the surface also is important for the wax penetration into the base, however the temperature is most important (Fig. 9).
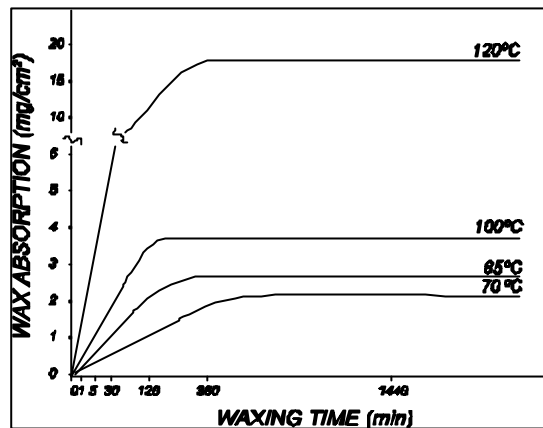
Figure 9. The correlation between wax absorption, wax temperature and time of exposure. It is evident that temperature is the most decisive factor. That is, waxing should be performed at as high temperature as possible without causing evaporation of the wax or melting of the PE.

During sliding, first the thin wax layer at the surface wears off, then the "stored" wax in the base is "sweating" due to a reversed diffusion process and supplies the gliding interface with lubricating material (Fig. 10). Further sliding after all lubricating material is consumed leads to sliding on the wear resistant PE.
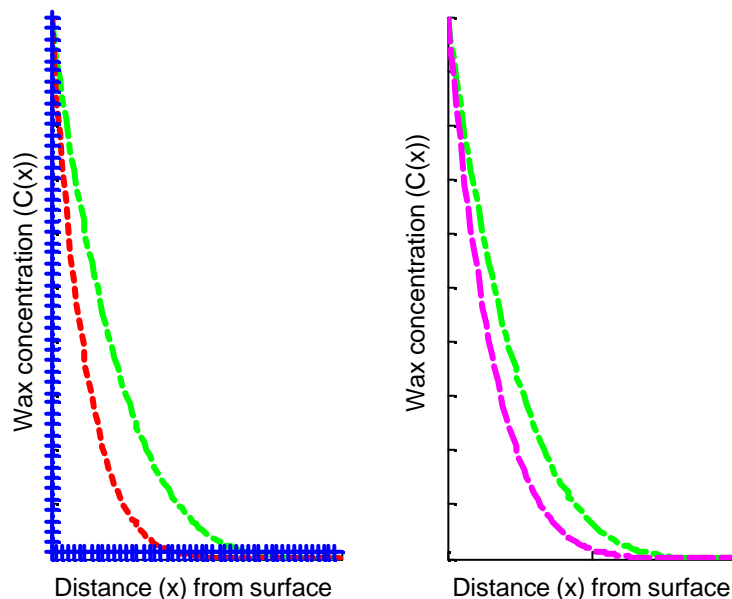
Figure 10. Schematic change in wax concentration during waxing (left panel) and during skiing (right panel). In the left panel, + indicate wax concentration at start of waxing, - indicate wax concentration during waxing and - - indicate the state of wax concentration at end of waxing. The point where the three curves intersect at the y-axis indicate the equilibrium concentration at a given temperature. The right panel shows the "sweating" of wax during skiing. First the thin layer of wax is worn off, and then the absorbed wax is diffused back to the surface.

As discussed below, the hardness of materials in contact and the reduction in chemical reaction (adhesion) are important factors for the reduction of dry friction. UHMW-PE is a remarkable material. However, it still needs to be adjusted to match the changing conditions of the snow surface. By applying wax and other additives to the slider base, the physical properties of the slider are altered. The purpose of ski wax is to reduce adhesion forces, to reduce surface tension, and to prevent ploughing by adjusting the slider base hardness to

the hardness of the snow. For example, by applying harder waxes the slider surface hardness is increased, or by applying soft kick-waxes the contacting surface is made so soft that it allows for snow particles to penetrate the wax and give very high static friction. Further, by making the surface more hydrophobic, adhesion is reduced at the contact points.

2.2. Wax components

Wax is a generic term for a group of natural and synthetic substances having the following physical characteristics in common.

- Solid at normal (room) temperatures.
- Of appearance and feel analogous to beeswax
- Having a relative low melting point.
- Melted wax has a low viscosity at temperatures just above its melting point.
- Able to re-solidify unchanged after melting and cooling
- Insoluble in water
- Combustible
- Capable of making glossy surface to which it is applied by rubbing lightly.

In connection to this, Deutsche Gesellschaft für Fettwissenschaft in 1954 made the following definition of wax:

- Solid at 20 deg C, and at that temperature has a consistency which may vary from soft and plastic to hard and brittle.
- In solid state, coarse to fine crystallization, transparent to opaque, but not glass-like.
- Melt without decomposition above 40 deg C.
- Have a relatively low viscosity at temperatures slightly above the melting points.
- Varies greatly in consistency and solubility with changing temperatures.
- May be polished by rubbing using light pressure.

A large number of chemical compositions have been commercially available under the name "wax". They may have plant, insect or animal origin, as well as all those derived from mineral origin, including raw oil (petroleum waxes) and from chemical synthesis (synthetic waxes).

In general, waxes can be classified after origin:
- Animal waxes
- Insect waxes
- Vegetable waxes
- Mineral waxes
- Synthetic waxes

In the early days of ski-wax production, from 1900 to1940, beeswax was the most commonly used wax type. In addition other animal and vegetable waxes where also used. Today, in ski-wax production, only mineral and synthetic waxes are of any interest. Mineral waxes are saturated hydrocarbons and have melting points from 40° to ~100°C. Of the mineral waxes, petroleum waxes are now the major raw material used in ski waxes. Mineral waxes are obtained from the refining of crude oil.

There are three main types of petroleum waxes: paraffin, intermediate, and microcrystalline. Petroleum waxes are composed of straight-chain saturated hydrocarbons (n-alcanes) whose constituent molecules have about 18 to 70 carbon atoms and twice as many hydrogen atoms (Fig. 11a). The intermediate waxes are a mixture of straight-chain, branched chain and cyclo-paraffinic hydrocarbons (intermediate in character between paraffine and microcrystalline waxes) (Fig. 11b-c). As the name indicates, microcrystalline waxes are composed of minute crystals, far smaller than those of paraffin waxes. Microcrystalline waxes have a higher molecule weight than the paraffine waxes and they contain a large part of branched chain and cyclo-paraffinic hydrocarbons (Fig 11b-c). In addition to these are the synthetic waxes that are made of long straight chain saturated hydrocarbons. They are hard and brittle due to their higher molecular weight and higher melting point compared to the paraffines.
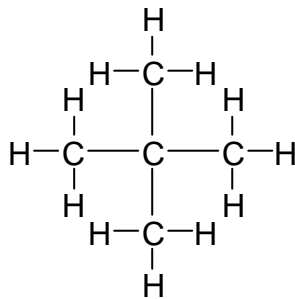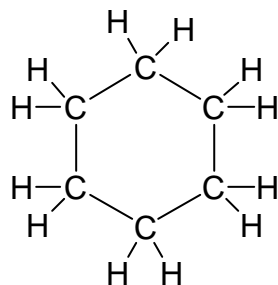
Hydrocarbons   Alcanes

C_nH_{2n+2}
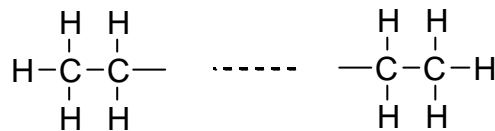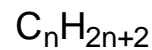
a.

b.

c.

Figure 11. The chemical structure of the hydrocarbon molecule. **a.** Straight chain, **b.** Branched chain and **c.** cycloparaffinic.

As mentioned in the previous section one of the purposes of ski waxing is to decrease the friction. Both m_k and m_s is strongly dependant on the adhesion between slider and snow. Ski bases and waxes should have low adhesion to snow. One convenient measure of the adhesion is the contact angle formed by a droplet of water resting on a flat surface of the material (Jellinek, 1957) (Fig. 12). In general, the higher the contact angle the less the coefficient of friction. Thus, materials with high contact angel (*i.e.* low surface tension compared to water) are preferred. Fluorocarbons (perfluoroalkanes) have shown to fulfil these requirements (Traverso, 1986). Skis prepared with fluorocarbon additives can reduce its friction on snow to a large degree. The molecular structures of fluorocarbons are similar to hydrocarbons although each hydrogen atom is replaced by a fluorine atom (Fig. 13).
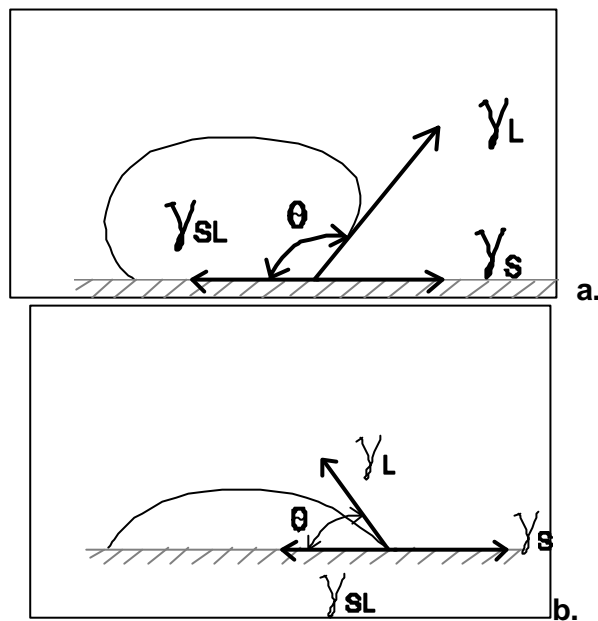
Figure 12. a. Water droplet on a hydrophobic surface and **b.** Water droplet on a hydrophilic surface. The contact angel θ is determined by the surface tensions for the liquid (γ_L), solid liquid (γ_{SL}) and the solid (γ_S) and can be described by Young-Dupré equation, $g_S = g_{SL} + g_L \cos q$.

Fluorocarbons   **Alcanes**

C_nF_{2n+2}
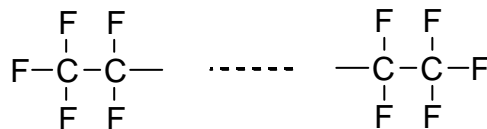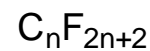
Figure 13. The chemical structure of the fluorocarbon molecule.

The hydrophobicity of the surface helps to reduce the wetted surface of the slider, which is of great importance when the slider is moving over a wet surface. By reducing the wetted surface, the amount of adhesion contact points is reduced and the "suction/drag" of the slider onto the surface is reduced. A further reduction is achieved by structuring the base of the slider in order to shorten the length for which water droplets can be stretched but also increase the hydrophobicity and thus reduce the drag. Base structure is a term used to describe patterns cut into the slider base. These patterns are produced by machine grinding or by hand tools. In general, the ski base structure should increase with the water film thickness. Further, coarser structures have also performed better at higher speeds (Moldestad, 1999) which is an indication of the increased thickness of the water film at higher speeds where more frictional heat is generated. The influence of structuring on the friction properties so far has not been conducted in such detail that one can say that a structure increasing in coarseness along the ski base has an advantage over constant but "correct" structure along the whole ski. The general consensus to date states that finer structure, <0.5mm, is used under cold conditions, a medium structure, 0.5-1 mm, is used around the melting point and coarse structure, 1-3mm, during wet conditions with air temperatures above 0 degrees C. The aim is to achieve a base structure coarse enough to avoid total wetting by water. However, a too coarse structure on dry conditions (less lubricating water) increases friction. A possible explanation for this might be that small snow grains fill up the structure grooves resulting in areas in the slider snow interface with snow-snow friction instead of skibase-snow friction, the former having a higher friction coefficient.

3. Triboelement 2 (stationary)

The snow surface on which gliding occurs can be regarded as stationary in a relative sense with respect to the first element, the ski base. However, parts of the snow surface are moving during sliding both due to compaction, turbulent lifting and rolling of the snow grains.

### 3.1 Snow formation in cloud and deposition

Water droplets make up atmospheric clouds. The droplets form by condensation of water vapour on condensation nuclei (dust and salt particles). When the air temperature in the cloud drops below 0°C it is possible to form snow. To form the small ice crystals that make up snow, freezing nuclei are needed. The amount of suitable freezing nuclei varies with temperature and becomes more abundant as the temperature decreases. At -40°C water droplets will freeze without the aid of freezing nuclei (spontaneous nucleation). Further growth of ice crystals are determined by two processes. One is the growth due to the diffusion of water droplets toward the ice crystals. This diffusion is driven by the pressure difference between the water droplet and the ice crystal. The second mechanism is due to the movement of ice crystals within the cloud and subsequent collision and mass gain due to riming. When the snow or ice crystals have grown large enough, they fall out of the cloud. The forms ice crystals attain during the descent in the atmosphere has a bearing on at what stage the metamorphism starts, once the ice crystal is deposited. Snow crystal shape at the ground is dependant on the temperature and the humidity of the air layers it has been descending through. More dentritic forms need a longer time to attain low surface energy. After deposition snow can be further redistributed by wind. The effect of wind blown distribution is related to the wind speed (amount of snow that can be transported) and the topography (determining the near-surface wind pattern) (Abele and Gow, 1975; Nemoto and Nishimura, 2001). During wind transportation the snowflakes may be altered due to fracturing because of collisions with other flakes and the ground. Sublimation is also an effective process as the wind maintains the humidity gradient that partly drives the sublimation process. Sublimation leads to loss of mass from the snow to the atmosphere.

3.2. Snow metamorphism

After the snow is deposited, the structure of the crystals and grains are under a constant change due to the effects of temperature and pressure. The process is called metamorphism, and the term is borrowed from geology and has the same meaning. The metamorphism changes the snow properties. Sintering of the snow leads to higher density and structural strength of the snow pack. As the bonding of the snow grains progress, the permeability, thermal conductivity and electrical properties also change. One very important result of the metamorphism is the change in albedo of the snow surface. With changing reflectivity, more energy may enter into the snow pack that further influences the metamorphic process. This external energy interaction is further discussed under the fourth tribo element, the atmosphere.
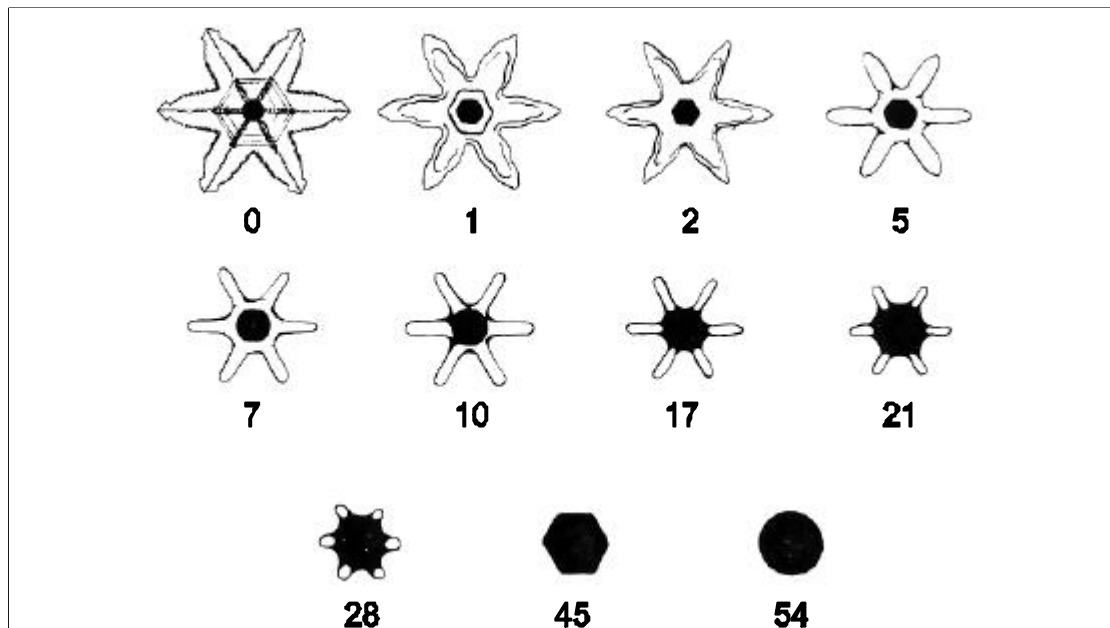
3.2.1. Equi-temperature metamorphism

The equi-temperature metamorphism (ET) occurs due to the thermo-dynamical instability of well faceted snow crystals, *i.e.* large surface to volume ratio, which gives large surface energy. Thermodynamic equilibrium occurs when the ratio surface to volume reach a minimum, and this condition is met when the shape is a sphere. The driving force in ET-metamorphism is the vapour pressure differences between the points and crests of the flake. The pressure gradient moves the water molecules from the points towards the crests thereby rounding off the particle and lowering the surface energy (Fig. 14).
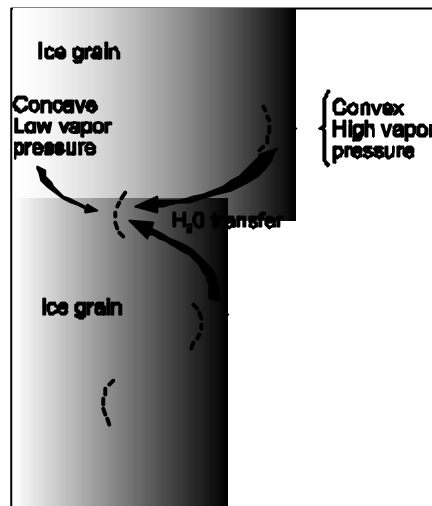
Figure 14. A schematic description of the mass movement along the vapour pressure gradient on snow particles, the transfer is from convex areas of high vapour pressure towards concave areas with lower vapour pressure.

Snow crystals with the highest surface to volume ratios, like dendrites, are the most unstable and thus change their form most quickly. When the branches of the dendrites disappear, there is a general decrease in particle size in the snow pack. After the branches have disappeared, the general size starts to increase. The reason for this is that larger particles grow at the expense of smaller due to more efficient condensation over larger particles. The higher radius of curvature for smaller particles, and therefore higher vapour pressure compared to larger surfaces with lower vapour pressure, drives the process. Or in other words, sublimation is more efficient from small particles. This type of metamorphism is called equi-temperature metamorphism or destructive metamorphism, the original forms are destroyed and the density is increased (*e.g.* Colbeck, 1982) and references therein (Fig. 15). The break down of dendrites initially leads to rounder grains and eventually less stable snow pack. However, during the rounding of the snow grains, the contact points between grains also form and grow stronger. Bonding of snow grains occurs by the process of redistribution of water molecules from points towards hollows. The redistribution is driven by the same diffusion process as mentioned above, and the rate is determined by the amount of energy available (heat). Thus, the rate of metamorphism increases with higher temperature.

Compaction of the snow pack by overburden pressure increases the metamorphose rate. The later is especially important for artificially groomed trails, where the packing of the snow by tracked vehicles increase the sintering rate. ET metamorphism leads to *rounding of grains*, increase in *particle size*, and an increase in *density* and *structural change* due to sintering. Important parameters for ET metamorphism are low temperature gradient in the snow pack and the radius of curvature of snow grains for vapour diffusion.

Figure 15. The evolution of a snow crystal during equi-temperature metamorphism. The numbers refer to days. After (Bader and others, 1939).

3.2.2. Temperature gradient metamorphism

When a strong temperature gradient (>10°C m^{-1}) is present in the snow pack, a type of constructive or temperature gradient (TG) metamorphism occurs. This kind of process leads to hoar formation that increases the size of snow particles, leads to angular grains with poor sintering and thus reduces the density and structural strength of the snow. The driving force is the temperature gradient and the accompanying mass transfer of water vapour along the temperature gradient from the warmer areas towards the colder. Hoar formation occurs mostly on top of layers with higher density and the reason for this is the higher thermal conductivity of the high density layer.

The hardness of the snow surface is important for the total friction of the slider. However it is important to distinguish between hardness at micro scale (~1mm), individual grains and crystals and macro scale (~10 mm) (larger snow samples). For waxing and friction the small scale hardness is of importance and for the shear and loading strengths (amount of plowing of the slider) the larger scale hardness is of importance.

3.3 Dielectric properties of snow and the water content determination

The dieclectric constant, or relative permittivity (e,) is the ratio of the electric flux density <u>D</u> to the field strength <u>E</u>. For direct current, the dielectric constant is directly determined by the ratio of capacitance of a snow slab (C_n) to the capacity of the same volume of free space (C_a),

$$ e = \frac{D}{E} = \frac{C_n}{C_a} \qquad (4) $$

For an alternating current environment the <u>D</u> and <u>E</u> vectors are not in phase. In this case the dielectric behaviour is described by the complex dielectric constant (e*)

$$ e^* = e^{'} + i e^{''} , \qquad (5) $$

where e'is the real part, e" is the imaginary part or the loss factor and $i = \sqrt{-1}$. Snow imposed to an electrical field can be regarded as a capacitor and can be described in terms of capacitance and resistance. In a time varying field with an angular frequency the capacitance C_w and resistance R_w are

$$e^{'} = \frac{C_w}{C_a} \qquad (6)$$

$$e^{''} = \frac{1}{w R_w C_a} . \qquad (7)$$

The angle(d) between the total current vector and the charging current vector is given by

$$\tan d = \frac{e^{''}}{e^{'}} . \qquad (8)$$

Here the e" is the loss factor, or in other terms, the conductivity of the material.

When an externally imposed electrical field is applied, the response of the molecules will be of two types, polarization and conduction. The dielectrical constant of the material characterises this response. In the case of water and ice having molecules with a dipole moment, there will be an orientational polarisation. For non-polar materials there is a shift in the position of the electron cloud. In ice, the orientation takes place through proton jumps associated with orientational defects in the ice crystals. The dipoles orient parallel and opposite to the direction of the electrical field. There is a delay in this polarisation, and the time lag is dependent on temperature. This delay is the cause for the phase shift in alternating fields. It is further important in such fields, as it makes the dielectric constant frequency dependent.

The dielectric constant describes the reduction in strength of the original field. The dielectric constant of pure ice is 3.18 whereas for water it is 80. Dry snow has a lower value than ice, but is very dependant on density. The dielectrical contrast between ice/snow and water can be utilized when trying to determine the free water content in snow. For any given density, the dielectric constant increases as the free water content increases. It has been shown that there is a linear relationship between free water content and the increase in dielectrical constant, both at low and high frequency (Kuroiwa, 1954; Ambach, 1958). Several different instruments have been developed. One commercial instrument to determine water content in snow measures the capacitance of the snow relative to a calibrated standard and from there calculates a % -value. The value has nothing to do with real % water content in the snow, but is linked to a relative scale to describe the snow humidity. The measuring device is an open capacitor with bend electrodes. A measurement is performed by placing the electrodes on the snow surface. The values obtained are dependant on pressure by which the electrodes touch the snow and the electrode area. The results have a rather large variation due to measurement uncertainties and natural variations in water content in the snow. Reliable snow humidity readings must be based on several measurements along the track.

Other methods of determining the free water content in snow is based on measuring the volume difference of water in solid and liquid phase (Leino and others, 1982). The theory can be described as follows. Consider melting 1 gram of ice or dry snow then its volume decreases by 0.0905 cm^3 The change in volume (V) at temperature of 0 °C is thus,

$$V = 0.0905(M - m)^3 \ \text{cm}^3, \qquad\qquad (9)$$

Where M is the total mass of the wet snow and m is the mass of free water in the snow. The free water mass obtained from equation 9. is

$$m = M - 11.05V . \qquad\qquad (10)$$

The relative humidity W is given by

$$W = \frac{m}{M} \times 100\% \qquad\qquad (11)$$

By substituting equation (10) into equation (11) the relative humidity of the snow can be expressed by,

$$W = \left(1 - 11.05\frac{V}{M}\right) \times 100\% . \qquad\qquad (12)$$

4. Triboelement 3 (The interface)

The friction coefficient is determined at the interface and it is here the other tribo-elements interact. The interface is constituted of snow/ice particles (water in all three phases may exist), lubricating material, like ski wax etc., and maybe dirt. Its properties under the slider are determined by the state of the ski/snow boundary layer ahead of skier, the pressure exerted by the skier and the velocity of the skier.

Thus several points need to be considered when discussing this element, also how they interact simultaneously in a matrix. We will now discuss the contribution of the friction terms mentioned in (1).

4.1. Compaction- plowing

The plowing of snow (m_{plow}) is an important term when travelling over a non groomed area. The energy (E) needed to promote sliding must exceed the energy lost due to compaction and displacement of snow as well as turbulent lifting of snow particles. The compaction (E_{comp}) occurs as the tip of the ski is cutting through the snow surface, the pushing in the direction of travel causes the displacement (E_{disp}) as well as the lifting (E_{lift}) of snow particles. The energy dissipated given rise to the friction can be written,

$$E_{plow} = E_{comp} + E_{disp} + E_{lift} \qquad (13)$$

the first two terms are the more important. When the snow is deep the m_{plow} in eq. 1 becomes the most important term. However, also in groomed trails that have been under wear of several skiers this factor can be dominant. The stage of metamorphism of snow is also an important factor as the shear strength of the snow surface is related to the density (Abele and Gow, 1975; Colbeck, 1992). The quasi plastic compaction that occurs during track setting with a ski can be written as

$$\boldsymbol{m}_{comp} = \left(\frac{\Delta y}{L} \right) P \qquad (14)$$

Where Δy is the vertical snow compaction distance, L is the length of the ski and P is the normal load. Assuming a a compaction of 0.15 m and a ski length of 2 m would give a friction factor due to compaction of 0.1. The displacement or frontal impact resistance which E_{disp} must overcome may be approximated via momentum considerations,

$$\boldsymbol{m}_i = \boldsymbol{r}_s B(\Delta y) V^2 \qquad (15)$$

Where B is the total runner width, $\boldsymbol{r}_s$ is the snow density and V is the skiing velocity (Glenne, 1987). Currently there is no mathematical formulation for E_{lift}, however the lift term can probably be neglected when skiing in deep snow.

4.2. Dry friction

Dry friction (m_{dry}) occurs when no lubricating layer is present in the form of water. The lubricating layer is only a few monolayer thick and there is a direct contact of asperities of the two sliding surfaces. The sliding must then proceed by elastic or plastic deformation and fracture of asperities on the surface (Kuroiwa, 1977). Dry friction may occur at either very low temperatures (temperatures so low that the frictional heat may not produce a liquid layer) or at low sliding velocities.

Ice is stronger for faster rates of loading (Bowden and Tabor, 1964). However, in the case of skiing the loading rates are well above where this might have an effect. The ice hardness decreases with temperature and changes rapidly over the temperature interval of 0- -20°C. The contact points between snow and slider deform either plastic or elastic. The sharper asperities, of new snow, yield plastically or fracturally whereas more polished asperities respond elastically (Colbeck, 1996). The change in ice hardness further enhances this process as point contacts that are flash heated during sliding will yield as the snow is heated and eventually will start to melt and create a liquid film. From dry friction theory (*e.g.* Bowden and Tabor, 1964) it is known that in the case of two surfaces in contact with different hardness, asperities at the harder surface will plow into the softer surface and increase friction. The two materials optimally should be of similar hardness to prevent the increase in friction. Since ice is harder than PE in most temperatures and has a larger change in hardness as well one of the purposes of wax is to adjust the hardness of the sliding surface to match the hardness of the snow. In a situation where ploughing forces may be neglected, the total dry friction force may be written as

$$m_{dry} = A_c t = \frac{P}{s} t = f_d P \qquad (16)$$

Where A_c is the actual dry contact area (5-15% of apparent ski area (Pihkala and Spring, 1986)), t is the shear strength of the softer material at the junction, s is the unconfined compressive strength and f_d is the dry friction coefficient, which is about 0.06 for ice (Slotfeldt-Ellingsen, 1979). Equation 16. describes a Coulomb-type friction. As discussed in the introduction this type of friction is rarely the case during skiing. For equation 16 to describe low temperature conditions, the friction coefficient must increase with crystal hardness (higher shear and compressive strength) and decrease with velocity and snow moisture (Glenne, 1987).

4.3. Wet friction

Wet friction, when an excess of lubricating material is present so that the sliding surfaces are separated, the friction is due to the viscosity of the lubricating material. The resistance from the lubricating layer may be written as

$$m_{wet} = (v h r_w a A_{cw} V)^{\frac{1}{2}} \qquad . \qquad (17)$$

Where v is the viscosity of the lubricating material, *i.e.* water, h is latent heat of melting, $?_w$ is the density of water, a is the size of typical contact area and V is the velocity of the slider (Glenne, 1987).

The thickness of the lubricating layer has to be larger than the surface roughness of the sliding partners for wet friction to occur. There are several ways excess of water may originate (Slotfeldt-Ellingsen and Torgersen, 1983):

- Water due to meteorological/thermo dynamical reasons such as melt water, rain or condensation of water vapour.
- As the liquid phase that coexists with ice during a normal melt freezing process.
- A thin film (Å) due to the molecular structure of the ice (surface melting)
- As water with lowered freezing point due to dissolved impurities, capillary or surface effects.
- Water caused by frictional heat.
- Water induced by pressure melting, by practical means it can only be present at temperatures between 0 and -2 degrees C (Reynolds, 1899; Barnes and others, 1971).

The thickness of the water film has been measured by a dielectric probe mounted on a slider (Ambach and Mayr, 1981) they found the thickness to vary from 13- 5 μm in the snow temperature range 0- -4°C. They also showed that the type of wax applied on the slider had great impact on the optimum water film thickness. The optimum film thickness was achieved with the wax that was recommended by the manufacturer for the given temperature range.

4.4. Mixed lubrication

During mixed lubrication the contact between the sliding materials is both due to a lubricating layer and through direct contact of asperities. This type of lubrication is probably the most usual type during sliding on snow. The load of a skier is supported both by direct snow-ski contact and a liquid film (Fig. 16). This means that friction during mixed lubrication can be described by the theories of dry and wet lubrication in combination. Slotfeldt-Ellingsen (1979) show that the friction coefficient decreases proportional to the fractional reduction in dry contact, this is in accordance with predicted changes when a film of friction-melted water is established. So in summary in groomed trails the resistance due to dry and wet friction can be written,

$$\boldsymbol{m}_{dry-wet} = f_d P + \left(v h \boldsymbol{r}_w a A_{cw} V \right)^{\frac{1}{2}}. \qquad (18)$$
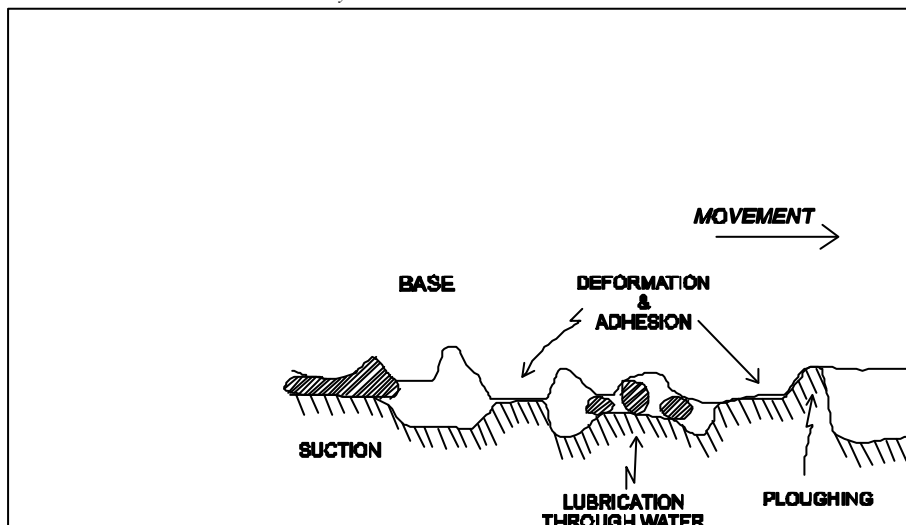
Figure 16. The concepts of mixed lubrication, areas of both dry friction and ploughing and water lubrication as well as capillary drag "suction" co-exists in the slider-snow interface.

4.5. Electrical fields generated by ice and snow friction

Electrical fields are generated during sliding on snow (Petrenko and Colbeck, 1995). The build up of electrical charges are of interest for skiing as the ski may accumulate fine particles of dirt that can interfere with the thin melt water friction at the interface, which indirect will increase the friction force (Colbeck, 1995).

Direct effects of the generated electrical field on the friction is:
1. Electrostatic pressure.
2. Effect on the plastic deformation of ice.
3. Expansion of the contact area.

Electric fields are able to significantly alter the normal pressure (Petrenko, 1994). Petrenko shows that a very strong attraction occur between a slider (dielectric surface) and snow which may alter the normal force by a factor of four (Petrenko, 1996).

As mentioned earlier, part of the friction mechanism on snow is determined by plastic deformation of ice. A reduction in the plasticity of ice in an electric field may result in an increase of resistance to shear stress and consequently results in an increase of frictional force.

The third effect mostly has influence on the static friction. Voids in the contact between ice and slider reduce the real contact area compared to apparent contact area. When a strong electric field is present in the void, ice is attracted to these regions by the electrostatic pressure. The filling of voids due to this effect increases the ice adhesion and thus friction.

- Measured voltages charged during sliding show the following characteristics. Resting on snow or suspended in air resulted in a slow voltage decay, on wet snow the decay was faster probably due to better contact between ski and snow as well as impurities (ionic) in the snow.
- When gliding in soft snow a small positive peak is developed, rapidly dropping to negative voltages. Continued gliding led to a climb towards positive voltages. Probably is the increase in voltage continued until the breakdown voltage is applied.
- Harder and bumpier gliding surfaces shows the same pattern, however with much more noise present also some discharge do occur under these circumstances.

Because of this, high levels of charge are only reached in deep powder snow (Colbeck, 1995). This means that the effect of electrical charging should be greatest under such circumstances. However, during gliding in deep powder snow, the plow term in Equation (1) should dominate the contribution to the total friction.

5. Triboelement 4 (The atmosphere)

The atmosphere surrounding the other three elements does have an influence on some of the characteristics of them, mostly in the form of regulating the amount of energy available for heat increase or decrease and the subsequent exchange of energy between the elements. For example the moving element, *i.e.* the ski base, may be heated by radiation, the metamorphose of snow is increased at higher temperatures as well as fluctuations around zero degrees. The interface is altered due to the change of friction characteristics of the two former elements.

5.1. The energy balance

In the atmosphere there is a mix of solar and terrestrial radiation. These radiation types are well separated in the wavelength domain (5 µm). The solar radiation is often called shortwave radiation (*Shw*) and the terrestrial is called longwave (*Lw*) or infrared. The energy (*E*) is able to warm the snow surface, or when it is at the melting point, to melt snow or ice is given by the surface energy balance.

$$E = \left[R_{net} + SHF + LHF + G \right] \qquad (19)$$

Where R_{net} is the net radiation, which is the sum of incoming and emitted/reflected short wave and longwave radiation fluxes. *SHF* and *LHF* are the turbulent fluxes of sensible and latent heat. Finally *G* is the subsurface heat flux.

$$R_{net} = \left[-Lw\uparrow + Lw\downarrow - Shw\uparrow + Shw\downarrow \right] \qquad (20)$$

The incident solar radiation is absorbed by the surface and by clouds and aerosols in the atmosphere. However some parts are reflected back by clouds or scattered by the air.

The important term albedo (α) is defined as the shortwave reflectivity $a = \dfrac{Shw\uparrow}{Shw\downarrow}$.

The upward long wave radiative flux results from long wave emission from the surface to the atmosphere and the downward flux comes from emission of infrared radiation from the whole atmosphere and clouds. Clouds limit the dependency of net surface long wave radiation on atmosphere temperature. Because when clouds are present, especially low clouds, it is the cloud base temperature that defines the balance *e.g.*(Broeke, 2000).

The turbulent fluxes of heat consist of sensible and latent heat. The sensible heat flux is simply the temperature gradient between the surface and the surrounding atmosphere, with the heat flowing in the direction of the gradient. The latent heat fluxes are dependent on the humidity and its ability to condensate (heating) and evaporate (cooling) on a surface.

The last term, the heat flux through the snow, adds or takes energy from the system by thermal conduction in the snow. For a solid, Fourier's law of molecular heat conduction for solids, states that the heat flux at a point in a medium is proportional to the temperature gradient.

> **Equation of heat conduction:**
>
> $$\frac{\Delta Q}{\Delta t} = -kA\frac{dT}{dx},$$
>
> Where $\frac{\Delta Q}{\Delta t}$ is the heat flow, k is the thermal conductivity, A is the cross sectional area and $\frac{dT}{dx}$ the temperature gradient. Besides conduction, there are two other mechanisms of heat transport: convection (heat stored in a fluid and is carried from one place to another by the motion of the fluid) and radiation (the heat is carried from one place to another by electromagnetic waves).

Dry snow is a mixture of three phases, air, ice and water vapour. The mixture of these three phases makes the heat transport a bit more complicated in snow than for a solid. There are several processes that transport heat in the ice-air-vapour matrix:

- A. Conduction through the ice lattice. This conduction has a strong dependence of snow density.
- B. Latent heat transport across pore spaces due to vapour sublimation and condensation with a strong dependence of temperature.
- C. Sensible heat transport
- D. Convection or wind pumping, differences in air pressure across the mass of snow, leads to forced convection with consequent intensification of heat and vapour transport.
- E. Radiation penetration, more important in ice where the matrix is not ventilated through the pores by the process described in D.

Estimates show that A and B are the more important processes, and that B carries 10-40% of the heat, depending on snow type, density and temperature (Mellor, 1977; Broeke, 2000).

The temperature in the snow varies with the same frequency as the surface temperature. The amplitude of variation is greatest at the surface and decrease exponentially with depth. This leads to a lag of the temperature-wave at depth. These facts have great importance for the rate of snow metamorphism and thus the coefficient of friction of the snow surface. The snow metamorphism increases with higher temperature and with fluctuations around 0°C, melt-freeze cycles increase the density of the snow surface. This leads to denser snow at the surface that in turn reduces friction due to minimizing the factor m_{blow} in Equation. 1. Higher temperatures also facilitate the evolution of a liquid layer during sliding. However, an excess of heat might lead to capillary drag which again increases the total friction. Since the temperature amplitude is greatest at the surface, most of variations in tribo-element 2 occur at the surface, leading to rapidly or constantly changing conditions. This adds to the difficulties faced when performing friction tests in the field.

The temperature lag and direction of temperature gradient in the snow pack may provide the surface with heat that radiation measurements do not register. Therefore snow temperature

measurements should be performed at least at two depths in order to be able to deduce the direction of the snow pack temperature gradient.

Another way of changing the energy balance, not only at the surface but also at depth, is "wind pumping" through the snow matrix (Waddington and others, 1996). The air flow within the permeable snow is driven by internal convection or forced convection. Internal or natural convection is caused by buoyancy forces whereas the forced convection is caused by externally imposed pressure fields. The natural convection requires large temperature gradients and very permeable snow (Sturm and Johnson, 1991). To describe the forced convection, consider a steady air flow over a bump. Then, high pressure zones will occur in troughs and on upwind slopes and low pressure zones develop on crests and leeward slopes. Within the snow the air will flow from high to low pressure. The flow of air may change temperature, humidity and chemical composition in the snow pack. In terms of irreversible trapped species, the process leads to increase in concentration of the specie, whereas for reversible trapped species it also may lead to decrease in concentration.

Solid precipitation in the form of snow changes the conditions of the surface and thereby the factors important for friction, both in terms of increasing the plow term m_{plow} and that the contact surface is less metamorphosed.

6. Discussion

A skier on snow slides on snow crystals and an interface more or less soft, more or less wet and more or less present. The ambient conditions determines in which state (Glenne, 1987). Snow is a material under constant change; although we may alter its properties by grooming or adding chemicals, we can never fix the conditions of snow. The condition of the snow is predetermined by the influence of the atmosphere prior the ski hitting the particular snow. Since we never can fix the conditions of the snow surface it means that our only possibility is to adjust the slider surface so that it glides with least friction against a wide variety of snow conditions. To meet these challenges we adjust the slider surface by waxing and structuring the slider base. At low snow temperatures with low air humidity the hardness of the wax may be the decisive factor for friction reduction, whereas when the humidity increases the hydrophobic properties of the wax becomes important. It is under such circumstances that fluorocarbons with their exceptional low surface tension are preferred. At even more humid conditions the importance of correct structure increase as the structuring help to reduce adhesion between the base and water/snow. The relative importance of hardness, hydrophobity and ski base structure, change under different meteorological and snow conditions, and the interactions of these parameters are important for the experience of optimum glide.

The friction mechanism between snow and ice and a ski slider cannot be described with one single friction mechanism, but with several mechanisms acting together. The velocity of the slider and meteorological and snow conditions determine the relative importance of the mechanisms. It seems like that dry friction is the premier mechanism in terms of that a large part of the load from the ski resting on the snow surface by direct contact of ice/snow crystals and ski, and that the motion of the ski results in shear deformation and yielding of the ice crystals.

The surface properties of ice, described by the theories of surface melting, results in "softening" of the contacting points, which facilitates reorientation of molecules in the direction of sliding and to follow the microscopic structure of the slider. However, the

thickness of this area is too thin to allow for shearing within this liquid-like layer. But the fact that the layer is "soft" should facilitate the macroscopic shearing of the crystal. At temperatures closer to the melting point or at more humid meteorological conditions the liquid layer thickness is increased which induces water lubrication as the friction reducer.

The reason why ice and snow is slippery over a wide temperature range, lies in the fact that there is no nucleation barrier for melting. A layer of surface melting may be present at temperatures well below the temperature of solidification and all the way up to the melting point. Another contributing factor is that the hardness of ice does not change much close to the melting point. As noted above the velocity and snow conditions are important factors for which friction mechanisms that are dominant. This means that the relative importance of the friction mechanisms to the total friction differ between the ski disciplines alpine, cross-country (classic and skating technique) and snow board. For example in the disciplines where the velocity is very high one might anticipate mixed to wet lubrication to dominate. For cross-country skating, the plowing term is more important compared to the classic technique where the ski is gliding in pre made tracks.

7. Conclusion

The science of gliding properties on snow and ice is "*Science Friction*". In the previous sections we have discussed the factors contributing to the friction between a slider and snow in relative motion.

At lower snow temperatures the hardness and smoothness of the surface and its heat conductivity are the important properties. During warmer snow conditions material hydrophobicity and surface texture matters more.

The load and sliding speed determine if the friction mechanism is determined by re-crystallisation, shear failure and brittle fracture, or that the frictional heating at the slider snow interface is sufficient to produce water melt. The low shear strength and the relative high values of hardness even close to its melting point are important material properties causing the low friction between a slider and snow and ice. The existence of a pre–melted layer, the precursor to water melt, is facilitated by the non-existing nucleation barrier during melting. This effect influences the slipperiness of snow and ice over a fairly wide temperature range. For skiers and others who wish to explore the fun and beauty of snow activity, does this temperature range fortunately does coincide with our normal winter temperatures.

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