THE FRICTION OF SNOW SKIS

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ABSTRACT

Snow friction results from a mixture of processes. Usually the snow and ski surfaces are partially separated by melt water but, when too much water is present, the contact area and friction increase. Ski thermal conductivity and color are very important. Heat is generated by friction and solar radiation absorption and is conducted away by both ski and ice particles. The remaining heat generates melt water, which acts as a lubricant. The important processes operate, not at the air temperature, but at the ski base temperature, which is highly dependent on such things as snow-surface temperature, load, and speed.

INTRODUCTION

Skis have been developed to a very high level without a good physical understanding of the frictional processes, although much work has been done on snow friction. The outstanding questions require increased knowledge of the contact area between snow and skis, the role of melt-water lubrication including thickness of the water films, occurrence of electrical charges, and capillary bonds, action of dirt at the interface, and dry frictional processes. Knowledge of the effects of load, speed, temperature, snow type, and ski properties on all of these processes and parameters is critical to understanding the behavior of skis.

The snow temperature, density, strength, liquid-water content, and crystal types are of particular interest, but these parameters are difficult to measure on the surface and may assume different values there. Furthermore, the passage of a ski affects some of these parameters, especially temperature, density, liquid-water content, and crystal shape. Skiers have learned that cold, fresh snow and manmade snow are "aggressive" and require harder waxes, but the lack of information about the compactive strength, porosity, and angularity of different types of snow surfaces limits the application of knowledge about snow to general statements about the prevailing conditions.

Figure 1. An ice particle that was polished by repeated passes of Nordic skis.

Snow grains polished by ski passes (Fig. 1) show melt-water caps formed on the snow surface. Highly polished surfaces have lower coefficients of friction (μ) than unpolished surfaces, possibly because of the dynamics of larger contacts (Colbeck, 1988) or the lack of angular ice grains. Evidence of surface conditions during sliding is difficult to gather, and the actual contact area is especially difficult to estimate during sliding.

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SLIDING MECHANISMS

Various mechanisms contribute to sliding resistance. They do not operate independently, but different mechanisms dominate under different conditions. The boundaries between these regimes are indistinct when melt films only partially separate the two solids. Plowing, dirt, and capillary forces increase drag. Snow compaction causes compression bulbs below a ski. This process depends greatly on the density of the snow and the pressure exerted, while temperature and speed are also important. It seems likely that factors such as density, speed, and weight interact with the temperature and snow type to determine sinkage depth, and therefore the frontal resistance.

When melt-water lubrication is insufficient, sliding must proceed totally or in part by elastic or plastic deformation and/or fracture of asperities on the surfaces. Barnes et al. (1971) suggested that no melt water was generated at –12°C and low speeds, but it is clear that melt water is generated in all but the coldest cases of skis traveling at normal speeds on snow. Ice is more plastic at higher temperatures, especially above about –8°C. Bowden and Tabor (1964) believed that asperities on softer surfaces always yield plastically and stated that snow must behave in this way. Then movement is thought to be due to the deformation of ice grains and not to the deformation of the ski or its coatings. Thus it is generally thought that the ski base should be harder than ice at the ambient temperature. However, the bottom of the ski will be heated along its length so that deformation on the surface of the snow grains will actually take place at a temperature greater than the ambient temperature, especially over the parts of the ski that carry most of the load. In spite of the softer material being more easily deformed, the front of aluminum aircraft skis are degraded by dry friction (Klein, 1947). According to Barnes et al. (1971), the effect of plowing of the softer material can be reduced if the ski is harder than the ice and the ski is smooth. The hardness of ice increases rapidly as temperature decreases, whereas the hardness of waxes and plastics increases much more slowly over the same temperature range (Fig. 2). For the materials tested, Bowden and Tabor (1964) showed that only PTFE is harder than ice and only at temperatures above about –15°C.

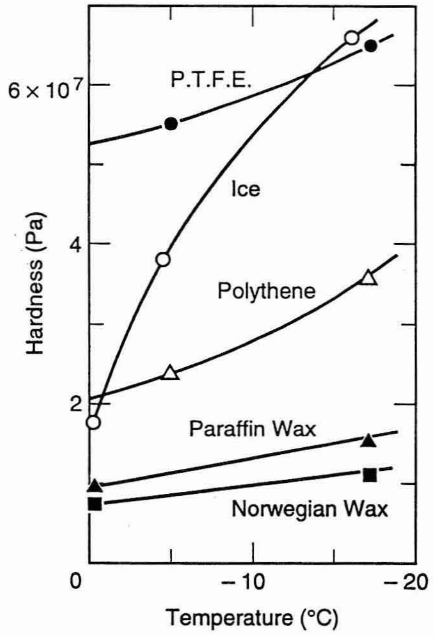

Figure 2. Hardness versus temperature, from Bowden and Tabor (1964).

The rate of heat generation by a ski is μ times the speed times the normal force on the snow. Although the fractional contact area has not been measured for dry sliding over snow, solid-to-solid contact areas are generally thought to be of the order of magnitude of 10^{-3} (Bowden and Hughes, 1939) or smaller, so the stress concentration is large and the heat is dissipated through a small area. This at least softens the ice even if it does not reach its melting temperature and produce melt water. In addition, μ is larger for dry friction than for lubricated friction so that the heat generation is correspondingly greater. If it is assumed that the ski is perfectly smooth and that all of the asperities are ice particles in the snow, the ice particles are in contact along the entire length of the ski while any point on the ski is in contact intermittently with the ice particles. When contact is made, the temperature of an object rises above its initial value as $\sqrt{t}$. Accordingly, an ice grain traveling along the length of a ski would reach a higher temperature than any point on the ski because the ice grain would be in continuous contact whereas a point on the ski would not. Once motion stops, the temperature decays slowly back toward the ambient value. An example of the $\sqrt{t}$ temperature rise and the slow decay measured at the base of a ski subjected to three cycles of stop-and-go motion is shown in Figure 3.

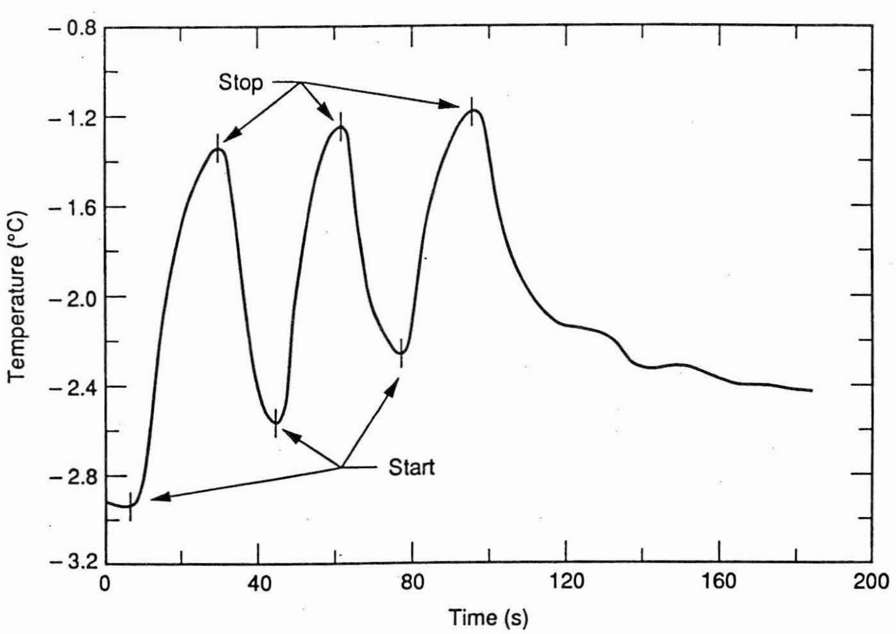

Figure 3. Temperature measured at the base of a ski during three cycles of start and stop (from Colbeck and Warren, 1991).

As shown by Colbeck and Warren (1991), given enough time any point on a ski is heated until a plateau is reached. However, the temperature of the ice particle would rise steadily until it began melting. The maximum possible temperature rise of an ice particle increases with the length of the ski. This suggests a greater possibility of reaching the melting temperature and experiencing melt-water lubrication in longer skis. In addition, μ decreases as speed increases above the very low speeds where no melt water is thought to exist and where dry rubbing occurs. For typical values for dry friction and downhill skis, it is easy to show that the ice grains would begin melting close to the front of the ski and that most of the ski is lubricated by melt water. The fraction of the length of the ski that is dry affects the total friction. Moreover, the dry portion of a ski should be made from harder polymers and should be waxed for both lower temperatures and harder ice. Application of Colbeck's (1988) equation suggests that the results of many laboratory experiments cannot be applied to snow skis because the skis used in the laboratory were too short and the speeds too low, thus giving very different proportions of dry to lubricated sliding between laboratory models and skis.

Contacts may not be completely separated by the melt-water film, but solid-to-solid interaction may occur in contacts that are partly lubricated by melt-water films. The Plasticity Index (Fein, 1984) suggests that plastic yield is more likely than elastic deformation at a ski/snow interface when the asperities are as peaked as they would be for fresh snow. However, once the sharper asperities are removed and the ice contacts are flattened by rubbing (Fig. 1), the geometry of the asperities suggests that the ice and/or the ski should respond elastically. Thus, fresh snow should yield plastically (or fracture), whereas polished ice grains should respond elastically because of their flat surfaces.

At low temperatures where melt-water lubrication disappears, μ for snow is similar to that of sand (Bowden, 1953). The idea of melt-water lubrication by frictional heating has been supported by much of the past research. Melt water and its ejecta have been seen when objects slide on ice. Probably because of melt-water lubrication, the addition of heat has been shown to be beneficial at low temperatures. Assuming that no solid-to-solid contact occurs and ignoring the energy conducted away from the interface, we can calculate an upper limit for the thickness of the melt-water film by assuming that the power required to propel an object equals the power consumed by phase change. If the water were removed from the contacts by squeeze only, the thickness of the film would be in balance when the film thickness would be 1.5 μm. This value is less than the values deduced by Ambach and Mayr (1981) from dielectric measurements, but it is greater than that calculated by Colbeck (1988). It suggests a μ of 0.036, which is about correct. A much smaller value for the film thickness is calculated using the shear removal mechanism whereby the thickness for a speed of 10 m/s is then less than 0.43 μm and μ is 0.13. Accordingly, the calculated value for film thickness is probably too small to separate the solids under most conditions of interest, even when only squeeze occurs, and suggests that there is solid-to-solid interaction as well as melt-water lubrication. Even if only squeeze removal occurred and no heat were conducted away from the interface, the melt-water film would be only 0.17 μm thick, probably not enough to separate the solids. Thus it is likely that both melt-water lubrication and solid-to-solid interaction take place in most cases of skis on snow unless melt water and/or heat are available from other sources.

The theory of melt-water lubrication for snow includes slippage of the water films along the ski. If the ski base is smooth and hydrophobic, melt films can be observed to slide along the base of the ski. At low temperatures where melt-water lubrication is marginal, a smooth gliding surface would be desirable to allow water slippage, whereas at high temperatures, where water attachments increase drag, a rough ski surface would be useful to disrupt the water attachments. Since water slides more readily along hydrophobic surfaces, a hydrophobic surface would appear to be advantageous at all temperatures.

From the Plasticity Index, an ice/polyethylene interface should respond elastically when asperities interact as long as their surface slopes are less than about 1%. Asperities with steeper slopes would be subject to plastic deformation and, if ice, removal by melting as well. Thus, to minimize μ the sliding surface should be hard but elastic with very gently sloping surface relief. Skis structured by indentation may have the additional advantage of providing a smooth running surface while the indentations allow increased flexure of the polyethylene. With increased flexibility, the polyethylene base could act like a series of shock absorbers that flex individually as the ice passes. This scenario suggests that the ice grains are smoothed by melting to accommodate the scale of roughness on the ski, and thus the roughness of the ski would determine the roughness of the ice grains after the ski had passed a short distance. The thickness of the water films away from the high points of the asperities could be considerably greater than those portions of the films trapped between the solids, which may account for the difference between the thick films reported by Ambach and Mayr (1981) and the thin films calculated above.

Patir and Cheng (1978) have shown that the thickness of a water film can change with the orientation of the roughness elements. When the elements are oriented longitudinally with the ski, the melt-water films tend to be thinner. Thus if longitudinal gouging occurs because the films are thin, the water film thickness would be reduced even more. When the elements are oriented transversely across the ski, the water film thickness increases as fluid pressure increases on the upstream sides of the asperities. Thus, when the water film is too thin or too thick, its thickness and the entire dynamics of the interaction of the asperities can be modified to a substantial degree by changing the orientation of the surface structure of the ski. The orientation is especially important when the surface roughness elements on the ski are not as thick as the water film would be if the surface were smooth. This is the case for most situations with skis on snow, and thus a transverse structure should be beneficial at low temperatures while a longitudinal structure should be better at high temperatures. As a rule of thumb, lubrication works well when the lubricant separates the solids by a distance of at least two to four times the rms value of the surface roughness. Since this quantity of lubricant is not usually available for skis moving over snow at subfreezing temperatures, it is clear that some consideration has to be given to ways of making the sliding process as efficient as possible.

Bowden and Tabor (1964) reported contact angles for various substances of interest; for some of these surfaces, the angle decreases with time as the molecules in the substance reorient. This shows the disadvantage of the old ski lacquers and the great advantage of PTFE. It also points out one of the great differences in polymers. Some, such as nylon, will allow water to penetrate, which reduces strength, increases real contact area, and thus increases μ.

The heat available for melting at the interface is the heat generated by μ and radiation absorption minus the energy lost to conduction. Colbeck (1992) evaluated these terms individually and constructed an empirical model to describe the contributions of the basic processes. Overall μ is a balance among its different components with the result that it reaches a minimum at intermediate values of film thickness.

MEASUREMENTS ON SNOW

Much of the problem with understanding ski glide is the lack of measurements under the conditions of primary interest: long skis moving at high speeds under a variety of natural snow conditions. The available experimental results are useful for investigating the important processes but do not provide information about μ under most conditions of interest. The existing experimental evidence does give us information about how μ varies with parameters such as speed, load, and temperature under laboratory and some field conditions.

Bowden and Tabor (1964) found that μ dropped greatly when the speed was increased to 5 m/s, presumably because of greater heat and melt-water production at these speeds. Shimbo (1961) observed similar behavior for PTFE with μ dropping very rapidly as motion first started (Fig. 4). For snow it is usually found that μ increases at speeds above 5 to 10 m/s. It is not likely that the trend seen in the data can continue since aircraft landings on snow and ski racing would be impossible. However, it does appear to be correct that μ increases at higher speeds, possibly because of both the dynamics of the water film (Colbeck, 1988) and because the average heat flow into the ice grains increases with speed as would the convective heat losses from the ski.

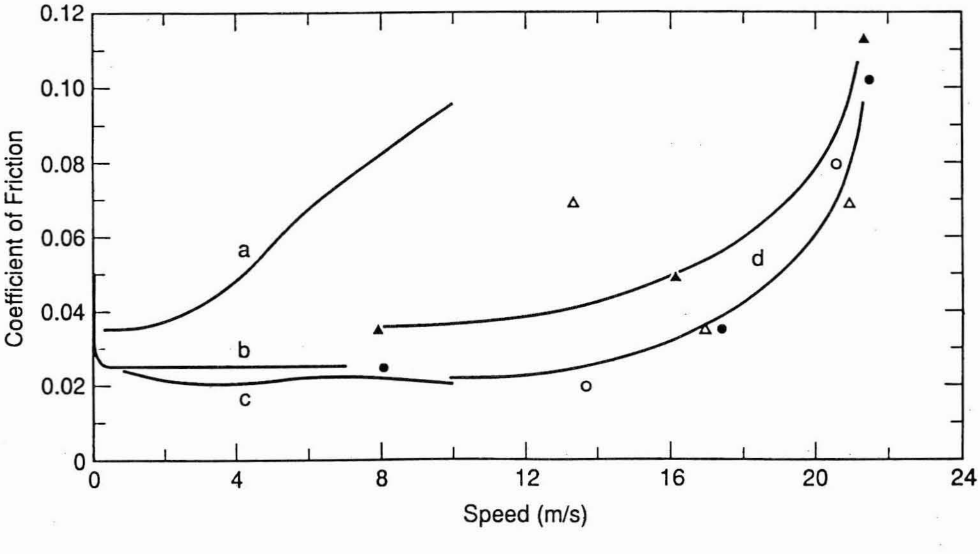

Figure 4. Measured values of coefficient of friction versus speed:

a. From Spring (1988) for dense, wet snow.
b. From Shimbo (1961) for PTFE on wet snow.
c. From Spring (1988) for dense, dry snow at –7.5°C.
d. From Kuroiwa (1977) for waxed (circles) and unwaxed (triangles) polyethylene on dry (solid) snow at –2.5 to –1.6°C and on wet snow (open).

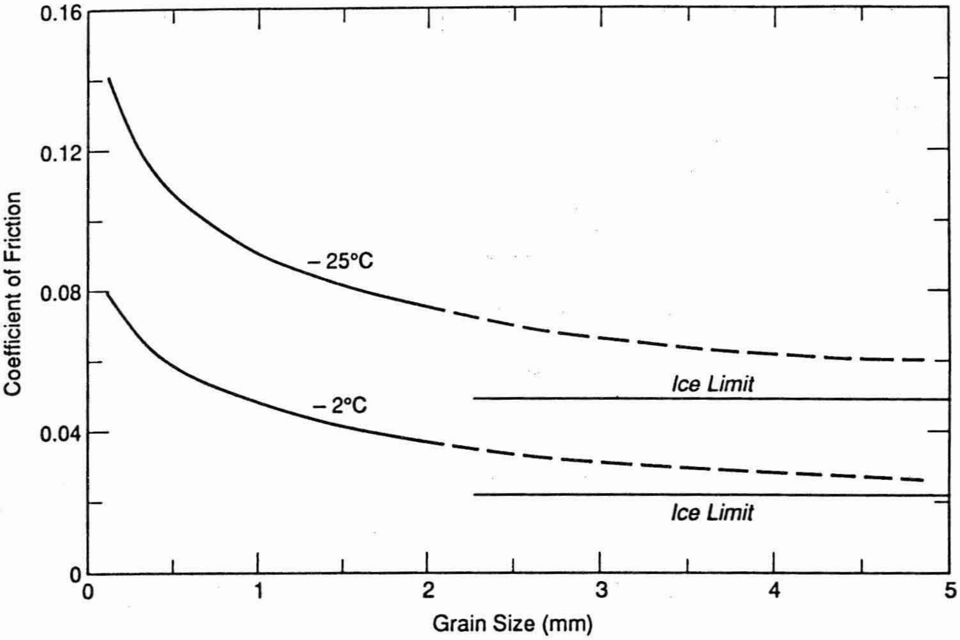

Figure 5. Coefficient of friction versus snow grain size (after Ericksson, 1955).

Kuroda (1942) found that static friction remained constant with increasing pressure for a variety of snow conditions and materials. Bowden (1953) found a similar result and showed that μ depended on the surface material, being lowest for PTFE. Bowden and Hughes (1939) found that, at a speed of 0.1 m/s, μ of a ski on snow decreased when the load exceeded about 50 kg, and Ericksson (1955) found that it decreased for increased loads at 2.5 m/s. With these speeds and ranges of loads, the controlling processes would have changed from dry to lubricated processes as the load increased.

Bowden and Hughes (1939) and Klein (1947) measured increased μ with decreased ambient temperature, and Colbeck and Warren (1991) found that ski bases were colder at lower ambient temperatures. Ericksson (1955) observed a more rapid rate of increase in μ for steel runners than for wooden runners at a speed of 2.5 m/s as the temperature dropped, presumably because of the greater heat loss through the metal. However, Ericksson found that μ of wood runners increased above about −1°C, not above 0°C as Bowden had observed. The minimum μ may occur at different subfreezing temperatures for different ski surfaces.

It is generally agreed that fresh, cold, and manmade snow are aggressive because they erode the base of a ski and increase μ. Conversely, old, warm, and dense snows exhibit lower μ partly due to the decrease in μ with increasing grain size (Fig. 5) and the greater elastic response when the grains are bigger or smoother. Klein (1947) stated further that the resistance to sliding was high with fresh snow until it lost its dendritic structure, and he also suggested that finer snow structures had higher sliding resistances.

The reduction of μ with increasing length observed by Ericksson (1955) can be at least partly explained by the thickening of the water film along the length of the ski. The effect of the thermal conductivity of a ski was observed by Bowden and Hughes (1939) who first suggested use of low conductivity metals for ski edges. Colbeck and Warren (1991) suggested that highly conductive materials such as aluminum should be avoided, especially close to the base of the ski. Shimbo (1961) showed the effect of hardness and roughness of a ski surface on kinetic friction. At an ambient temperature of 3°C, the kinetic friction is less for rougher surfaces (Fig. 6), whereas at −2°C, the kinetic friction increases slightly with roughness. Figure 7 shows that the effect of hardness is especially pronounced at lower temperatures where μ decreases rapidly as wax hardness

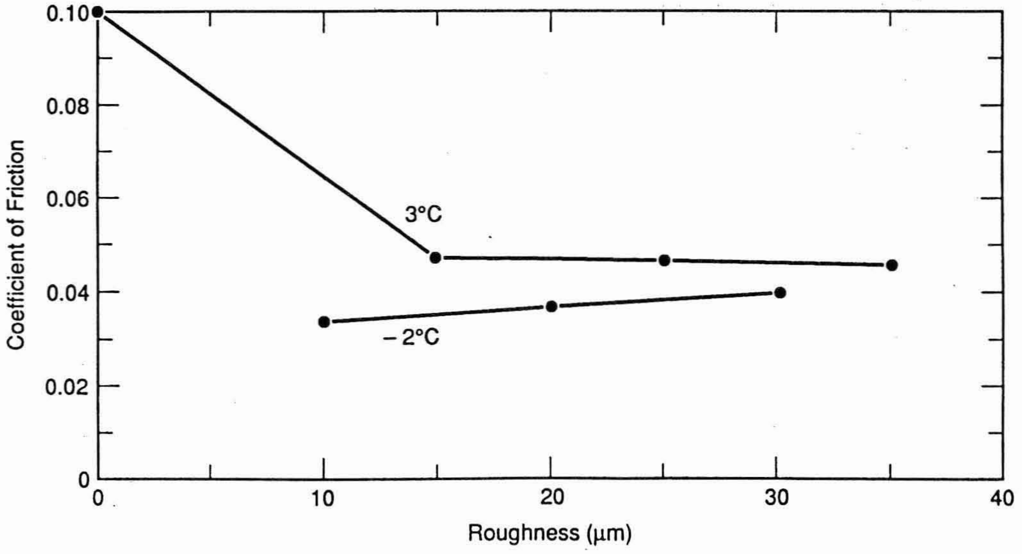

Figure 6. Coefficient of friction versus roughness (after Shimbo, 1971).

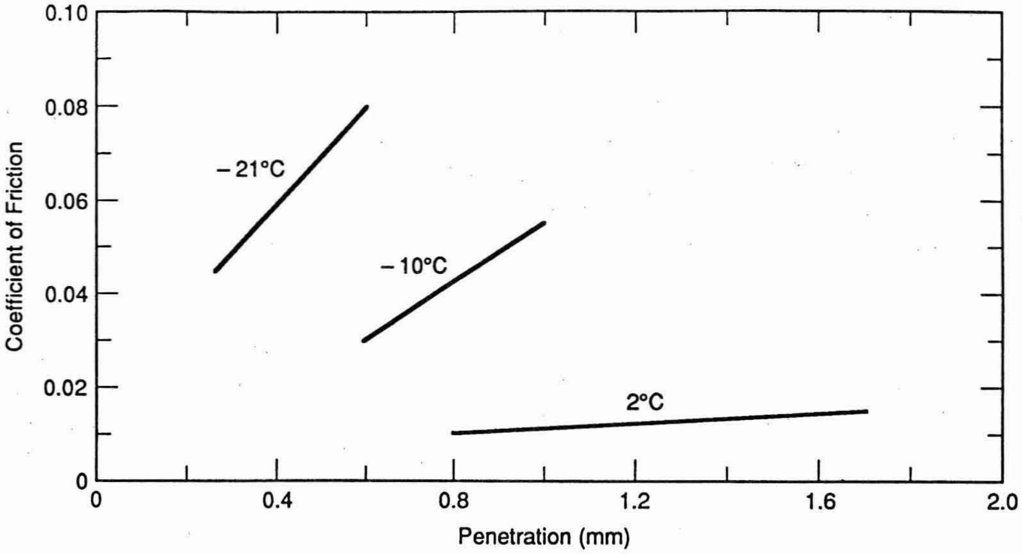

Figure 7. Coefficient of friction versus penetration (after Shimbo, 1971).

increases, possibly because the harder ice surfaces are capable of penetrating the polymer bases of skis at these temperatures (Fig. 2). Since ice is capable of eroding ski bases at lower temperatures, it is very important to protect them from roughening at lower temperatures since μ increases with roughness at subfreezing temperatures.

Ambach and Mayr (1981) showed that the water film thickness decreased with both snow and air temperatures and varied with the wax but not roughness. Their observations suggest that the water film was about 1.5 μm thicker for a TOKO green than a TOKO yellow wax at a snow temperature of −11°C. Colbeck (1992) showed that the yellow wax in this case would increase μ by 30% over the better lubricated green wax, a difference that is great enough to be observed by skiers and explains why wax technology has evolved to a high level without detailed measurements of the dominant processes.

Measurements at the bases of skis show a sudden increase in temperature at the onset of motion and a temperature plateau if given sufficient time (Colbeck and Warren, 1991). At subfreezing temperatures, the plateau is always below the melting temperature because a point on the ski is only in intermittent contact with the melt-water films. The temperatures in a transverse profile across the base of the ski respond quickly to pressure changes while turning, and temperatures are a good measure of the weight distribution both across and along a ski. Colbeck and Warren (1991) also showed that the temperature rise at the base of a ski decreases with increasing ambient temperature but increases with increasing load and speed. The heat flow patterns can be derived from the temperature response at different levels in a ski. In a model Colbeck and Warren (1991) found that, with a large aluminum plate running across the base of a ski with steel edges, the heat available for melting at the base in the center section of the ski is reduced by about 50%.

FRICTION ADJUSTMENTS

Waxes work at the sliding interface, where the temperature can be considerably greater than the air temperature, so knowledge of that temperature is needed to choose the proper wax and/or surface structure for the prevailing conditions. The total energy balance (Colbeck, 1992) shows that friction can produce 120 W of heat at 10 m/s. Thus, as a rule of thumb, a downhill racer typically generates 200 or 300 W of heat under each ski. In addition, more than 100 W may be added to a black base by solar heating.

"Binders" are commonly used to coat surfaces subjected to frictional wear. Oleamide and stearamide are known to lubricate polyethylene and can be incorporated in the bulk of the polymer where they diffuse to the surface to provide an effective lubricating layer. Waxes are applied to skis for several reasons (e.g., to control hydrophobicity and hardness, increase electrical discharge, and prevent oxidation and wear), and different waxes have different effects on snow friction. To be most effective, the wax must not interfere with the desired surface roughness of the ski, which suggests that wax applications should be very thin.

A surface layer of polyethylene has several distinct advantages over most other materials. All plastics have low thermal conductivity but, unfortunately, their electrical conductivity is also rather low. Most plastics have the important advantage of absorbing vibrations well because of their high elasticity, and some have high impact resistance too. High molecular weight polyethylene has outstanding abrasional resistance and favorable elastic properties. In general, higher molecular weight polyethylenes are used at lower temperatures where higher impact resistance and better wear characteristics are important.

SUMMARY

Snow surface roughness measurements would help understand the scales at which the prevailing processes occur and how the basic processes differ with the type of surface. The drag on a ski consists of a mixture of components that arise from different mechanisms operating simultaneously. When melt water is generated by phase change at the interface, combined solid-to-solid interaction and melt-water lubrication occur since there does not appear to be enough melt to completely separate the surfaces. When greater quantities of melt water are present, complete separation of the asperities is possible but the surface area for drag increases considerably. Melt-water production is probably the most important single consideration, and its generation is controlled by heat production at the interface and heat loss into both the ski and the ice grains.

μ is high with either too much water or too little; it is lowest at or just below 0°C. Some roughness is desirable when too much water is present, probably because it helps break up the water films, and longitudinal patterns should help to remove water. μ decreases as speed first increases because of the onset of lubricated melting but then increases at higher speeds. Under most conditions μ is reasonably independent of load because the contact area increases proportionately. μ decreases as ski length increases because a greater proportion of its length is lubricated by melt water, and μ decreases as grain size increases because of the dynamics of the water films.

Ambach and Mayr (1981) found film thicknesses of 5 to 10 μm; the films were thicker at higher temperatures and when the proper ski wax was used. However, films of these thicknesses cannot be explained by the energy available to create melt water, even when fairly extreme assumptions are made about the processes. It is very important to resolve this issue because the energy balance method suggests that the films are too thin to completely separate the surfaces, although the capacitance results suggest otherwise.

If contact area were determined by the hardness of ice, it should be less than 10^{-4}, but it appears to exceed 10^{-2} most of the time. Ski temperatures can be easily measured and provide indirect evidence about the frictional processes. Furthermore, since wax applications work at the interface, their selection should be guided by knowledge of the temperature at the ski interface, not by air temperature. Interface temperatures increase rapidly following the onset of motion unless the ski has been preheated by direct solar radiation absorption. The effectiveness of waxing can be seen by the different temperatures at which waxed and unwaxed interfaces run, and the heat conduction through the ski can be observed. The heat flow through skis of complex structure has been computed with a numerical model and the results show that the use of highly conductive materials at the base of a ski can cause a significant reduction in the heat available for melting.

Polyethylene surfaces are known to have low μ and are better than most other polymers. Polyethylene works well because it is hydrophobic (and remains so under humid conditions), hard, highly elastic, can be smoothed and imprinted with different patterns, can be made porous, can be easily coated with waxes, does not readily adhere to ice, and has a μ that is not greatly affected by surface contamination.

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