Friction of the short model ski at low velocity

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Abstract. Frictional coefficients of a model ski (10 cm length) were measured at low velocity (0.005 ~ 1 m/s) by means of the tribometer method. The coefficient values depend on sliding velocity, snow temperature and snow grain size. No load effect was observed for any temperature. The static frictional coefficient was depended on the logarithm of the contact time. Further, the coefficient increased with the temperature going up for the smaller grain snow. These experimental results show that the origin of the friction force of the model ski at low velocity is the shearing force of the adhesion between snow and polyethylene.

1. Introduction

It is well known that the kinetic frictional coefficient (μ) of ski and ice is exceedingly small in comparison with μ of the usual solid-solid contact. There are two hypotheses why ski slides well. One is the adhesion theory that the shearing strength of ice is small in comparison with Brinell hardness [1, 2]. As an example, the friction on (1-10) plain of ice crystal was about two times greater than on (0001) [3]. Another is the melt-water lubrication theory. The water which works as a lubricant is generated with the frictional heat between the snow and the ski [2, 4-8]. For example, the melt-water has been observed in a laboratory experiment for an interface between the slider sole and the ice where the frictional heat is accumulated [7]. The temperature rises of the sole were observed near the melting point (~10 to 0 °C) by thermocouple when a down-hill ski glided with 2 to 10 m/s. The upper most temperature of the gliding ski base was dependent on the ambient temperature [9]. Recently, the influence of the snow temperature (the lowest of μ appeared at around -3 °C) under racing conditions was emphasized [10]. Additionally, the gliding theory other than the melt-water lubrication was proposed to understand the ski gliding in various conditions. A lot of works related to the snow friction were reviewed and discussed by Colbeck [11].

When the ski starts to glide, the temperature of the snow surface which contacts with the ski is heated with the friction and the heat is accumulated. Viewed from the ski, the heat is accumulated for
the ski sole by friction with the snow surface, but the top part of the sole is always cooling by the coming new snow and air. Then the temperature of ski sole would be dependent on the distance from the ski top. The frictional condition is also different with the sole position. The heat accumulation also depend on the heat conduction of ski materials, the snow condition, ambient temperatures and so on. Only an average \( \mu \) value of a sliding ski could be obtained by experiment. It is impossible to analyze the friction state at an individual sole position by changing the friction parameters on experiment. It is also difficult to estimate the real contact area of the gliding skis. We can observe temperatures of a ski sole but cannot observe temperatures of the surface of snow particles, rubbed by the ski. As the \( \mu \) value of a short slider is equivalent to that of the head part of the actual ski, the mechanism of the friction would be simple and the heat accumulation would not occur especially for the slow velocity.

In this paper, nearly the intrinsic frictional resistance of a short model ski at low velocity was observed by means of the tribometer method with carefully prepared hard packed flat snow in the Cryospheric Environment Simulator of NIED with artificial snow and in the fresh air of the Sugadaira Observatory of the University of Electro-communications (UEC) in Nagano, with a variety of natural snow. The snow temperature, the gliding velocity and the load effects of \( \mu \) were observed and the mechanism of the frictional resistance was discussed. In this paper, the low velocity expresses 0.001 to 1 m/s, the low temperature means -10 to -15 °C, and the high temperature is -5 to 1 °C.

2. Experiments

2.1. The tribometer method
A schematic diagram of the tribometer is presented in Fig. 1. As the diameter of the turn-table is 180 cm, the snow track can be regarded as a pseudo-straight track for the short model ski (length: 10 cm, width: 5.5 cm) at low gliding velocity (the centrifugal force of friction is negligibly small). The slider “S” is strapped to a static frame “L” via a load cell and the large snow-table is rotating under the model ski by an electric motor with a speed controller. Snow surface of the track on the table is prepared by a flattening blade “FB” which is fixed to the static frame “L” as horizontal accurately. The apparent \( \mu \) is easily deduced by measuring the traction force “\( T \)” of the slider, by using the load cell. (\( T = \mu \times mg \)) The actual track rotation angle and the velocity are measured with a rotary encoder “R” located at the center of the table.

2.2. The Model Ski
The model ski was a remake of an actual alpine ski with polyethylene-sole. It was cut for a certain length and the sliding surface made flat by means of the insertion of a duralumin plate (10 mm in thickness) on the sole polyethylene. The length and the width of a model ski are 10 and 5.5cm, respectively. The weight is changeable to be four times. No wax was used.

2.3. The Snow Preparation
Artificial snow which made in the Cryospheric Environment Simulator of NIED and a variety of natural snow at Sugadaira in Nagano were used as sample snow. The grain size of snow was selected by sieves. The prepared snow was placed on the turn table of the tribometer and the snow surface made flat.

Snow hardness is an important factor to discriminate the energy loss of a ski sinking into the snow from the sliding resistance, but it is not easy to control the surface one [12]. On the other hand, snow
density is easy to control and seems an important factor correlating to the effect of ski sinking into the snow. In this paper, the snow densities of the test snow track were prepared to be the same for a series of experiments. The density of the sample snow was fixed to be 360–550 kg/m³. Before the experiment, the snow was sintered for 6 to 16 hours at the observed temperature to harden the surface.

In addition, the surface hardness of the test snow was observed by a homemade penetrating type of hardness meter. Indented depth was about 2 mm (diameter of the pressure head was 1 cm). The pressure was around 2 kg/cm². The pressure of the contact area of the model ski was about 4.8g / cm² (1/2 of the actual ski). It may be given as a conclusion that the surface snow condition was hard enough to compare to the actual ski gliding, which indicates that the pack and plow resistances are negligible.

Figure 1. A schematic diagram of the tribometer (L: Static frame, FB: Flattening blade, S: Slider, R: Rotary encoder, D: Gear box, M: Motor).

Figure 2. The snow grains of packed snow surface after sintering. The arrow corresponds to 1 mm in length for both pictures.
3. Experimental Results and Discussions

3.1. Velocity dependence of the kinetic frictional coefficient ($\mu$)

The kinetic frictional coefficient ($\mu$) vs. the sliding velocity for artificial snow at several temperatures is shown in Fig. 3. It suggests that there are several mechanisms of gliding friction working simultaneously or separately. The $\mu$ value was decreasing with the decreasing snow temperature until -10 °C at low velocity (lower than 3 cm/s). The $\mu$ values were exceptionally smaller than the friction between usual solids. The $\mu$ value at around -10 °C (ca. 0.05) was smallest and it is close with the value of the best condition of the actual alpine ski at -3 to -5 °C [10]. The $\mu$ value of fast slides (higher than 10 cm/s) is decreased with the increase of temperature. Namely, the sliding at low velocity showed the high $\mu$ value but the high velocity sliding showed the low $\mu$ value at only the high temperature. These results clearly show that the temperature dependency of $\mu$ is drastically changed with the sliding velocity at high temperature. As a sliding at higher temperature and the faster, the velocity seems to easily generate the melt-water, and it looks reasonable that the feature of $\mu$ can be explained by means of the “well known” melt-water lubrication hypothesis.

![Figure 3. $\mu$ vs. the sliding velocity for artificial snow at several temperatures. The snow grain size is 0.1mm in Fig. 2 (a).](image)

3.2. Normal force effect of the kinetic frictional coefficient ($\mu$)

According to the melt-water lubrication theory, it is reasonable that $\mu$ is expected to be small when the velocity and/or normal forces are increased. It is frequently quoted in the ski science field that the main mechanism of the friction of ski at higher the velocity than 10 m/s is explained by the lubrication of the melt-water which is generated by the frictional heating [4].

The frictional heat ($Q$) expressed as follows;

$$Q = \mu M v \quad (1)$$

Here, $M$ is the normal force, $v$ is the gliding velocity and $\mu$ is the frictional coefficient. It is clear from (1), when the normal force and/or the velocity are increased, the frictional heating and then the
thickness of water film would be increased and then the friction force would be decreased. In fact, the lowest of $\mu$ appeared at around -3 °C for actual ski gliding at racing condition [10]. Velocity dependences of $\mu$ accompanied with the load change of the model ski at the different temperatures are shown in Fig. 4. The load was altered by adding metal plate attachments.

![Figure 4](image)

**Figure 4.** Velocity dependence of $\mu$ using different load ($\bigcirc$: usual weight, $\times$: twice, $\triangle$: forth) of the ski at several temperatures with natural snow. (The tribometer method in fresh air of the Sugadaira Observatory)

Figure 4 shows that $\mu$ decreased when the gliding velocity was increased, but an obvious normal force effect was not observed even when the normal force became twice or four times any temperature. Further, the $\mu$ at lower velocity was larger at higher temperature as the same with Fig. 3. It is unlikely that the melt-water works as lubricant at around 1 m/s for any temperature.

3.3. The contact time dependence of the static frictional coefficient ($\mu_s$)

In Fig. 5, the static frictional coefficient ($\mu_s$) vs. the contact time of the different snow grain size is shown at several temperatures. First of all, $\mu_s$ depended on the logarithm of the contact time for both snows. The $\mu_s$ value increased with contact time. The reason is that the real contact area increases with going time [13, 14]. The contact time dependence of $\mu_s$ affects the velocity dependence of $\mu$. The real contact area decreases with increasing velocity because the contact time is short at high velocity [15]. The friction mechanism would be explained by the adhesion theory. Second, the real contact area would be larger for smaller grain size, because the number of contact positions seems bigger for smaller grain size. In the figure, the $\mu_s$ values were larger for the small grain. It reveals that the real contact area is larger for the small grain. Further, the contact time dependence of $\mu_s$ in Fig. 5 (a) at the high temperature is larger than the low temperature and $\mu_s$ in Fig. 5 (b). The friction force increased very much at high temperature for many contact points case (grain size 0.1mm), and did not increase so much for smaller contact points (grain size 0.5).

These results suggest that the contact between ski and snow is a dry process. Further, it is clear that
the temperature effect was far larger for the small grain. This is a new finding. For the explanation, we introduce the existence of the liquid-like layer on the surface of snow grain. The surface energy of liquid is larger than that of solids. So the adhesion force is larger for liquid-like layers than for solid ice. As a result, it is reasonable that the adhesion force would be enforced by the liquid-like layer. Also, the thickness of the liquid-like layer of snow crystal increased with increasing temperature at premelting point. Then the adhesion force was increased near the melting temperature of the ice.

![Figure 5](image_url)

**Figure 5.** $\mu_s$ vs. the contact time. Each snow grain sizes are (a) 0.1mm and (b) 0.5mm.

3.4. Snow grain size effect of the kinetic frictional coefficient ($\mu$)

We measured the coefficient of bigger grain size (0.5 mm) in Fig. 6. In consequence of the experiment, the $\mu$ value of the bigger grain is smaller than that of the smaller one (Fig. 3). The interesting velocity dependence of the frictional coefficient for the high temperature in Fig. 3 disappeared. But at premelting point, the $\mu$ value of high velocity showed the same value with the small grain. This is reasonable because the friction of high velocity does not have the effect of adhesion so much because the contact area is small. These results are concerned with the smaller contact points, and then the smaller adhesion force.

3.5. Discussion of the origin of the friction force ($\mu$)

It is known that the frictional resistance between two ices is generated by the adhesion at the contact surfaces when the gliding velocity is slower than 10 cm/s. The friction force is regarded as the plastic shear deformation force of the thin film of ice between the contact surfaces [3, 16, 17]. To connect the frictional resistance of ice, it was reported that the $\mu$ value of a steel ball on a single crystal of ice at very low gliding velocity (which means no melt-water generation) became a very small value (0.005 to 0.2). The $\mu$ value on the prismatic plain was twice as large as that on the basal plane and there was no normal force effect, which is explained by the adhesion theory [3]. According to the well-known melt-water lubrication hypotheses, it is unlikely that the melting points are different with the crystal axis of the same crystal.

In the ski sliding, interaction between polyethylene and snow, it seems that the attractive interaction
Figure 6. $\mu$ vs. the sliding velocity for a snow at several temperatures. The snow grain size is 0.5 mm in Fig. 2 (b).

force would arise from the dipole-induced dipole interaction. The dielectric constant of liquid water is far larger compared to the solid ice, because of the mobility of water molecules is far larger for liquid water. The attractive interaction energy of polyethylene is expected to be larger with liquid-water than with solid-ice.

Also, it is well-known that the thickness of the liquid-like layer of snow crystal increased with the increased temperature close to the melting point [18]. It accounts for the adhesion effect increased at high temperature and $\mu$ in Fig. 5 (a) was more than the low temperature. In this case, the gliding resistance is consistent with the shearing force of the adhesion between the snow and the polyethylene sole and means a plastic deformation of the liquid-like layer at the contact surface.

As our experimental results indicate, $\mu$ showed a very small value at around -10 °C for very slow slides (Fig. 3). In this temperature and sliding velocity range, it is likely that no melt-water is expected. This result would be connected with the very small adhesion force between the polyethylene slider and snow. It is reasonable that as the liquid-like layer becomes thin, then the adhesion force also becomes small.

On the other hand, the $\mu$ value was increased with decreasing the temperature from -10 °C. For this condition, the liquid-like layer practically disappeared [18], and at the same time the hardness of the ice increased drastically around -10 °C. Then the origin of the adhesion force changed from the interaction between the liquid-like layer and polyethylene to the solid ice and polyethylene, and then the attractive interaction force became weak but the destruction force (shear force) of the interface material increased because the ice is harder than liquid-like layer (interfacial matter is changed from liquid-water to solid-ice). These effects seem to associate with increased brake effect at very low temperature.

Decreasing the $\mu$ value of high velocity at high temperature (Fig. 3) was not yet explained, but the strong evidence for the dry process indicated that the trace of sliding was observed on the flattened surface on snow truck (Fig. 7). It is reasonable to assume that the ice became soft near melting point then the shearing force also would be weak.
4. Conclusion

For the elucidation of the mechanism of friction between snow and ski, the kinetic frictional coefficient ($\mu$) of a short slider at low gliding velocity (0.001~1 m/s) were observed near the melting point of snow (-20 ~ -1 °C). As the experimental results, the $\mu$ values were dependent on sliding velocity and snow temperature. The $\mu$ value of fast glides (higher than 0.5 m/s) near the melting point was decreased but an obvious pressure effect was not observed. It is unlikely that the melt-water is generated at around 1 m/s for any temperature for the model ski. The smallest $\mu$ value was observed at around -10 °C and slower than 0.01 m/s. It is interesting that the smallest $\mu$ value without melt-water is similar to the value of the best condition of usual skiing, which explained by the melt-water lubrication hypothesis. It is reasonable that as the liquid-like layer becomes thin accompanied with the decrease of temperature, the adhesion force also becomes small.

On the other hand, the $\mu$ value was increased with decreasing the temperature from -10 °C. This is explained by the shearing force of ice becoming large accompanied by the hardness of the ice increasing drastically around -10 °C.

The static frictional coefficient was dependent on the logarithm of the contact time. The results indicate that the real contact area decreased with increasing velocity. Further, the coefficient increased with increasing temperature for smaller grain snow. So the adhesion did not affect the sliding at high velocity and for the bigger grain size. It means the real contact area changed only slightly.

The sliding resistance of the model ski is consistent with the shearing force of the adhesion between snow and the polyethylene sole.

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