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Curl Mechanism of a Curling Stone on Ice Pebbles

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Abstract

We present a physical model that accounts for the curl mechanism of a curling stone on ice pebbles. The evaporation-abrasion model is based on the two essential features of curling: pebbles and running band. The ice friction coefficient at the rear half of a running band is larger than that at the front half because of cooling due to evaporation of pebbles. The asymmetry of the friction force is enhanced by mechanical interactions of ice debris produced by the front running band with the rear band, and result in the curl, or lateral deflection of the stone.

The asymmetry is larger, that is the curl distance is larger, at smaller velocity, higher temperature, lower humidity, and larger radius of a running band. However, it is independent of the angular velocity, that is the curl distance does not depend on the total number of rotations.

Key words: curling, pebble, friction coefficient, evaporation, abrasion

1. Introduction

In the game of curling a disk-shaped stone is released on an ice sheet. As the air drag is negligibly small compared with ice friction, its motion can be accurately calculated if the initial sliding and angular velocities and ice friction coefficient are known. This is not correct because it is so hard to determine the friction between the stone and ice. It is a function of velocity, temperature, pressure, and geometry of the sliding surface of the stone, and varies during sliding. We will discuss the following five topics: ice friction coefficient, pebbles, running band, sweeping, and curl, and finally give a new model to explain the mechanism of a stone to curl.

2. Curling and ice friction coefficients

The initial sliding velocity is 1–5 m s^{-1} in the usual curling game. It is well recognized that the physical mechanism of ice friction or sliding in this velocity range is water lubrication due to frictional melting (Petrenko and Whitworth, 1999; Maeno *et al.,* 2003; Maeno, 2004). In Fig. 1 ice friction coefficients measured at −10℃ are plotted against sliding velocity. At velocities above 1 cm s^{-1}, thin ice layer is melted by friction and acts as lubricant so that the friction coefficient is as small as 0.01. As the sliding velocity becomes smaller the ice friction coefficient increases and approaches unity. The sliding mechanism of ice when the stone is to stop is not water lubrication but the adhesion shear deformation of ice (Maeno and Arakawa, 2004), namely the ice adhering with the slowly moving stone is sheared and deformed plastically.

The curling game is unique because the stone experiences the change of the ice friction coefficient by two orders of magnitudes from the start to the stop, and the friction coefficient is intentionally varied by sweeping during the game.

3. Pebbles, running band and sweeping

The surface of an ice sheet is not flat but consists of many small protrusions called as pebbles. Ice pebbles are made by spraying water droplets onto flat ice surface. Average sizes are 1–2 mm in height and 3–10 mm in diameter, and the number density is 2–5 cm^{-2}. The curling stone is a disk-shaped granite rock, about 20 kg in weight. Its bottom is hollowed at the center, and the running band, about 13 cm in diameter and about 5 mm in width, touches with ice. So the average pressure the stone exerts on ice is roughly 0.1–0.16 MPa, but the actual pressure on each pebble is much larger. Calculation using above figures shows that it amounts to 0.4–8.1 MPa.

This fact gives two important aspects. One is that the pressure decreases friction coefficient of ice (Evans *et al.,* 1976; Oksanen and Keinonen, 1982). This is one of the most important reasons why stones can slide so smoothly on the ice sheet. Another as-

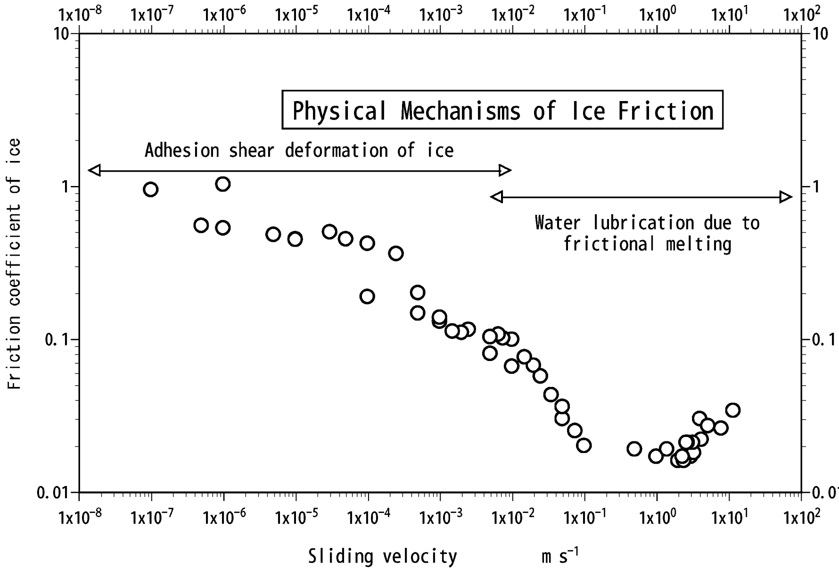

Fig. 1 Friction coefficients of ice at −10℃.
Ice-ice friction coefficients measured by various authors at −10℃ are compiled and plotted in the figure. Data sources are found in Maeno *et al.* (2003), Maeno (2004), and Maeno and Arakawa (2004).

pect is that the physical process of stone sliding is not only smooth friction but also includes mechanical abrasion. Abrasion of ice pebbles takes place because of large pressures as several MPa, or several 10 kilograms of loads acting on square centimeter area. It is often noticed that pebbles are deformed and broken and fine ice fragments and debris are formed on the ice sheet.

The original purpose of sweeping was to clear various dusts and other fragments on the path of a stone, but it should be considered essential because the production of fine ice debris is inevitable at the running band on ice pebbles, and furthermore the friction coefficient of ice can be controlled by changing the pebble temperature.

4. Physical mechanisms of curl

It is known that the initial counter-clockwise rotation causes the stone to deflect left and clockwise rotation to deflect right. Ice friction is the only external force exerting to the stone, and the deflection or curl might be assumed to be caused by the left-right asymmetric friction due to rotation. However, it is not correct as understood in Fig. 2. As the friction forces F_F at a point F (angle ϕ) and F_R at a symmetric point R on the running band are equal in magnitude and make the same angle with y-axis but opposite senses, they combine to give a net force in the negative y-direction and no net force in x-direction. If we take account of the variation of friction coefficient with sliding velocity (Fig. 1), the friction forces at $\phi=0$ and $\phi=\pi$ do not cancel but the net force of their combination is only in y-direction and cannot curl a stone. A simple left-right asymmetry model cannot explain the curl correctly.

Several models have been presented to explain the curl of a stone on an ice sheet. Johnston (1981) proposed that the deflection mechanism of a glass sliding on a table may be applied to the curling stone. If an empty top-down glass is rotated counterclockwise and allowed to slide on a smooth table, it deflects right because it tends to tip forward, resulting in the increase of pressure and friction force at the front. In the case of curling stone, he assumed that the similar increase in pressure at the front decreases the friction force F_F and leads to the deflection opposite to the glass.

However, his pressure-difference model cannot explain the curl of a stone on ice because it has been confirmed experimentally and theoretically that the friction coefficient of ice (μ) decreases with pressure (p) as $\mu \propto p^{-1/3}$ (Evans *et al.*, 1976) or $\mu \propto p^{-1/4}$ (Oksanen and Keinonen, 1982), and therefore the friction force (F) increases as $F \propto \mu p \propto p^{2/3}$ or $F \propto \mu p \propto p^{3/4}$. That is, if the pressure at the front is larger than the back the friction force is also larger, $F_F > F_R$, and the stone will curl in the same direction as a glass. In the case of ice the increase in pressure leads to decrease in friction coefficient but increase in friction force.

Shegelski *et al.* (1996) proposed the water-layer model and wrote 'In the final phase, the rock moves slowly enough to drag some of the liquid film from the back to the front of the rock, with the consequence that the wet friction acts predominantly on the front half of the annulus'. They assumed that water formed by frictional heat is drawn around the outer part of the leading running band, and leads to the friction force relation, $F_F < F_R$, so that a stone curls in the correct direction.

The water they assumed seems to be bulk water, and different from a thin microscopic water film frequently assumed in frictional heating of ice surface. However, the existence of such bulk water has not been confirmed experimentally. The physical mechanism of transport of the water to the leading half has not been understood either and should be studied in more detail.

In the snowplow model Denny (2000) assumed that ice fragments and debris formed by a running band are carried and accumulated at the leading half, *e.g.,* on the left side if the rotation is counter-clockwise, and that the friction coefficient is reduced due to friction of ice-ice rather than ice-granite. However, such reduction in friction coefficients has not been observed in the measurement of the ice-ice friction coefficient (Yasutome *et al.,* 1999; Maeno *et al.,* 2003). Furthermore the accumulation of ice debris at the leading half has not been observed, and the mechanism seems similar to that of the water-layer model and has not been understood.

The left-right asymmetry model proposed by Denny (1998, 1999) claims that the difference in velocity due to rotation produces a net asymmetric friction force at the right and left, leading to curl. However, the net friction force produced by the left-right asymmetry has no components in x-direction to cause curl as explained above. Penner's (2001) suggestion of the net friction force and adhesion at the right and left to cause a pivoting-like action is worth studying if taking account of the increase in adhesion due to ice sintering at low sliding velocities (Maeno and Arakawa 2004).

The above brief introduction of proposed models so far shows that none of them are complete and cannot explain why a stone curls. A correct model must satisfy the following two requirements:

a) The initial counter-clockwise (clockwise) rotation causes a stone to curl left (right).

b) The curl distance is insensitive to the initial angular velocity or total turns.

The requirement (b) is often heard from curlers, and shown clearly in Fig. 3, which gives the measurements by Penner (2001) and Jensen and Shegelski (2004). The curl distance was measured on local curling ice sheets by throwing stones with appropriate initial translational and angular velocities so that they stop around the house. Except two inaccurate data points near 0 rotation, it is clear that measured curl distance is almost constant falling between 0.7 to 1.3 m when the total rotation varied from 0 to 12. All the models proposed so far suggests that the curl distance increases with increasing rotation, and do not satisfy the requirement (b), but the evaporation-abrasion model, to be introduced in the next section, satisfies both the requirements.

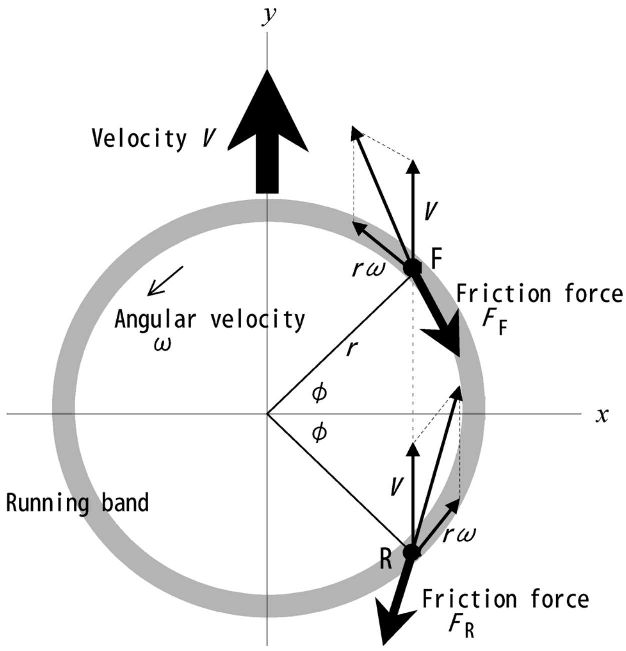

Fig. 2. Schematic diagram of a running band. Translational and angular velocities are shown together with the vector sum. Friction forces at symmetric points F and R angle ϕ are also given.

5. Evaporation-abrasion model

The evaporation-abrasion model was constructed by Maeno (2009) to take into account the two most characteristic properties of curling: pebbles and running band. We report here only briefly the derivation of the model and the details are reported elsewhere. When a stone slides on an ice sheet, a pebble in touch with a running band at F will be in touch with R after time $t = 2r \sin\phi / V$ where V is the translational velocity, r is the radius of a running band and ϕ is the angle (Fig. 3). t is roughly ten to hundred milliseconds. At F, frictional heat melts instantly the surface, but then evaporation begins and the surface temperature is lowered during the time t. We have a result of measurements of ice surface temperature change by evaporation. In the study of surface electric conduction and lattice defects of ice Maeno and Nishimura (1978) set a 0.1 mm thick thermocouples at the surface of ice single crystal and measured the change when the air over the ice surface was suddenly evacuated. Their result showed that the surface temperature dropped over 1℃ within 1 second.

We estimate the temperature lowering ΔT by the following relation:

$$\Delta T = \frac{(Jst)L}{cds\rho} = \frac{JLt}{cd\rho}, \quad (1)$$

where J is the evaporation flux, s is the surface area of a pebble tip, L is the latent heat of evaporation, c is the specific heat of ice, ρ is the density of ice, and d is the depth of ice associated with heat conduction and approximated as $(D_{heat}\, t)^{1/2}$, roughly 0.1–0.5 mm (D_{heat}, heat diffusivity of ice).

In calculating the evaporation flux, J, we adopted two cases of the diffusion-controlled and molecular kinetics, and concluded that in a short time when a pebble is rubbed by a leading band and then in touch with the trailing band, the diffusion rate of water vapor is not a primary factor to determine evaporation. According to the theory of molecular kinetics the number of colliding molecules onto solid surface is $P(2\pi mkT)^{-1/2}$ at equilibrium, where P is the equilibrium vapor pressure, m is the molecular mass, k is Boltzmann constant, T is the absolute temperature. As the number of colliding molecules is equal to that of evaporating molecules at equilibrium, this gives the maximum.

Writing the water vapor pressures on the ice surface and surrounding environment as P_0 and P respectively, the evaporation flux at the ice surface is written as

$$J=\alpha\frac{M}{N}(2\pi mkT)^{-1/2}(P_0-P)=\alpha\left(\frac{M}{2\pi RT}\right)^{1/2}(P_0-P), \tag{2}$$

where N is the Avogadro number, M is the molecular weight of water, and α is the evaporation or condensation coefficient. Then the temperature lowering is

$$\Delta T=\frac{JLt}{cd\rho}=\frac{JL}{c\rho}\left(\frac{t}{D_{hest}}\right)^{1/2}=\frac{\alpha L}{c\rho}\left(\frac{rsin\phi}{D_{hest}V}\right)^{1/2}\left(\frac{\mathrm{M}}{2\pi RT}\right)^{1/2}(P_0-P), \tag{3}$$

and putting numerical values,

$$\Delta T=0.024(P_0-P)\sqrt{\frac{r\sin\phi}{V}}. \tag{4}$$

In Eq. (4) α was put as 5×10^{-4}, which was obtained by analyzing the Maeno and Nishimura's (1978) data though much larger values were reported by Delaney *et al.* (1964) for a polycrystalline ice surface. Then if we put $P_0=610$ Pa (saturation water vapor pressure at 0℃), $P=437$ Pa (that at −4℃), $\phi=\pi/2$, and $r=0.065$ m, we get $\Delta T=0.52$℃ and 1.04℃ at $V=4$ m s^{-1} and 1 m s^{-1} respectively. It is concluded that the surface temperature of a pebble in touch with the leading running band decreases by evaporation about 0.5–1℃ at the sliding velocity 1–4 m s^{-1}.

The friction coefficient of ice is a complex function of pressure (p), temperature (T), and velocity (V), but can be expressed by the following simple equation in a narrow range where curling games are held,

$$\mu=Ap^{\alpha}(T_M-T)^{\beta}V^{\gamma}, \tag{5}$$

where A is a constant and T_M is the melting temperature of ice (273 K). The power indexes are known experimentally and theoretically as $\alpha=-1/3$ or $-1/4$, $\beta=1$ and $\gamma=-1/2$. Then writing the friction coefficients at the points F and R in Fig. 3 as μ_F and μ_R, and assuming $T_R=T_F-\Delta T$, we obtain

$$\mu_R=\mu_F\frac{T_M-T_R}{T_M-T_F}=\mu_F\left(1+\frac{\Delta T}{T_M-T_F}\right). \tag{6}$$

In the calculation we assumed that the temperature, T_F, of a pebble at F at the moment of friction by the leading running band is equal to the average surface temperature of the ice sheet. The heat produced by the brief friction of the leading band, during roughly a few milliseconds, can only melt 160 nm thick ice at most. The thin layer provides a source of water vapor to evaporate but does not seem to vary much the temperature of the bulk ice. Finally by combining with Eq. (4) we get

$$\frac{\mu_R}{\mu_F}=1+0.024\frac{P_0-P}{T_M-T_F}\sqrt{\frac{r\sin\phi}{V}}. \tag{7}$$

Eq. (7) shows that the friction coefficient of ice at the trailing running band is larger than that of the leading, and that the magnitude is dependent on sliding velocity, temperature, and water vapor pressure (or humidity). Numerical values obtained above at $\phi=\pi/2$ give that μ_R is larger than μ_F by 13 and 26% at $V=4$ m s^{-1} and 1 m s^{-1} respectively. It may be more convenient to use the relative humidity (H) instead of P in Eq. (7). In that case P is defined as

$$P=HP_s/100, \tag{8}$$

where P_S is the saturation water vapor pressure at the environment temperature. The value of μ_R/μ_F becomes larger at smaller humidity H.

Fig. 4 shows the distribution of the ratio μ_R/μ_F on a running band. It should be noted that the friction coefficient μ_R is larger than μ_F at every corresponding point. As a result a net lateral friction force is produced from the rear half, and acts on the center of gravity of the stone to curl because it has a component transversal to the sliding direction.

There is one more mechanism to make the ratio μ_R/μ_F larger than unity, which is related to mechanical abrasion of pebbles. As mentioned in 3, pebbles are deformed and broken by the large pressure due to sliding stone, 0.4–8.1 MPa. Ice fragments and debris produced by the leading running band meet with the trailing band, and act as obstacles or drag to the motion. The mechanical interaction is complex and accidental, but it is reasonable to assume that it results in the enhancement of μ_R to result in curl.

Ice debris and other obstacles on an ice sheet can be removed by sweeping, but the trailing running band cannot avoid the debris produced by the leading band. Therefore, it may be stated that the debris is another essential friction force to cause curl.

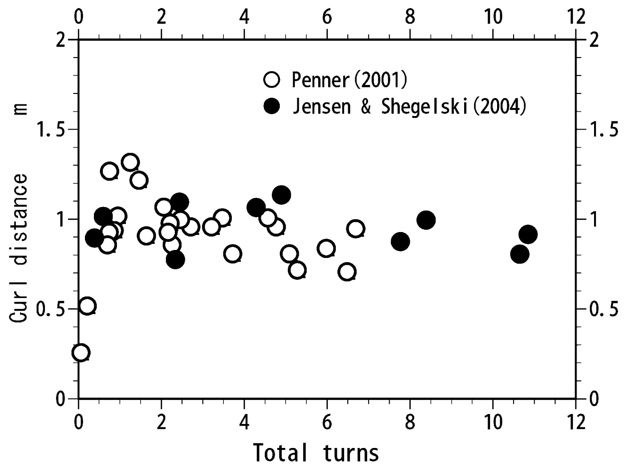

Fig. 3. Measured curl distance versus total turns. Numerical data were obtained by reading figures in the papers by Penner (2001) and Jensen and Shegelski (2004). Their measurements were made at appropriate translational and angular velocities so that a stone stops around the house.

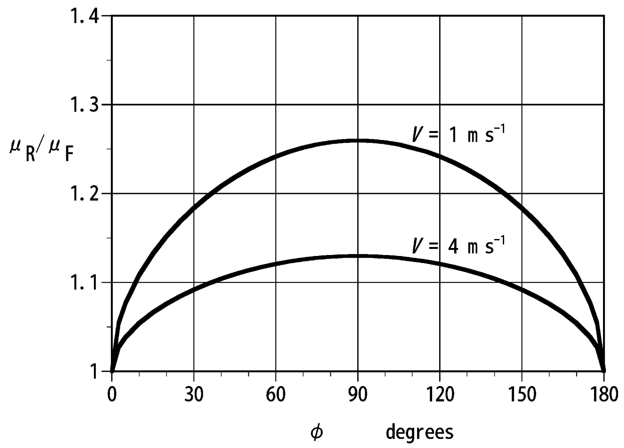

Fig. 4. Ratio of ice friction coefficients at the rear and front of a running band (μ_R/μ_F).
Calculated by Eq. 7 at −4℃, H=100%, r=0.065 m, and V=1 m s^{-1} and 4 m s^{-1}.

6. Conclusions

Pebbles and running band are essential features in curling. They lead to the increase of the force exerting to ice, resulting in the reduction of friction coefficient of ice. Moreover they strengthen the effect of stone rotation and sweeping, and they produce ice debris and give delicate effects to the stone motion.

The pressure-difference model, water-layer model, and snowplow model are not perfect but contain some physically unreasonable defects, and cannot explain the insensibility of the curl distance to angular velocity.

The evaporation-abrasion model is based on the two facts: the friction coefficient of ice at the rear half is larger than the front because of evaporation of pebbles, and ice debris produced by the front running band interacts mechanically with the rear. The model is summarized as follows:

A) μ_R is larger than μ_F due to the process of friction, evaporation, and cooling of pebbles.

B) The ratio μ_R/μ_F is a function of sliding velocity, temperature, humidity, and size of running band, Eq. 7. Its magnitude is larger, that is the curl distance is larger, at smaller velocity, higher temperature, lower humidity, and larger radius of a running band.

C) The ratio μ_R/μ_F is independent of the angular velocity, so the curl distance does not depend on the total number of turns.

D) The asymmetry that μ_R is larger than μ_F, is enhanced by the mechanical interaction of ice debris produced by abrasion, but the interaction is accidental and difficult to estimate.

E) There is a possibility to vary artificially the sliding and curl of a stone by controlling the size and roughness of a running band, and also number density, forms and sizes of pebbles.

Finally some measurements were tried to confirm the variation of the temperature of pebbles due to friction and evaporation. Thermocouples 0.1 mm in diameter were set near the surface of ice and temperature change was measured, but accurate and meaningful results could not be obtained. It was suggested that such direct measurements are not possible because the thickness of ice melted by friction is as thin as 100 nm. More elaborate indirect technique such as using light interference should be made in the future.

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