ROLLING FRICTION AND ADHESION BETWEEN SMOOTH SOLIDS

K. KENDALL

I.C.I. Corporate Laboratory, P.O. Box 11, Runcorn, Cheshire (Gt. Britain)

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Summary

Rolling friction has been explained in terms of crack propagation through an adhesive joint. The contact between a smooth cylinder and flat has been regarded as an adhesive junction bounded by two cracks moving in the same direction at the same speed, one crack continually opening and one closing. Propagation of these cracks requires a force which is calculated from crack theory and shown to be equal to the friction.

The theory has been verified experimentally using glass cylinders rolling on smooth rubber. Results show that rolling friction is closely connected with peel adhesion. Moreover, this adhesion interpretation of rolling friction between smooth surfaces explains several observations:

(a) the existence of a static rolling friction,
(b) the unusually high value of friction and its independence from load and roller radius,
(c) the marked effect of lubricant or dust.

1. Introduction

It is widely accepted that friction, both rolling and sliding, is the sum of two components — an adhesion term and a deformation term [1, 2]. In dry sliding the adhesion term is thought to be dominant [1]. By contrast, rolling friction can often be explained by the deformation component alone [3, 4]. This hysteresis term, due to the energy lost in stressing material under high contact pressure, accounts for the normally low coefficient of rolling friction and also satisfactorily explains the common observation that rolling resistance is not very sensitive to surface contamination by lubricants [3].

However, there is a severe problem in describing certain rolling friction results on this deformation hysteresis hypothesis. If a smooth glass cylinder is rolled on smooth rubber, in a rolling tack tester for example [5], the coefficient of rolling friction may be very high, sometimes greater than one. This is much too large to be accounted for by deformation hysteresis. Moreover, a small amount of water or dust on the surfaces reduces the friction enormously. Since it seems unlikely that deformation hysteresis would be
much affected by such surface contamination, it appears sensible to invoke adhesion as the major cause of rolling friction in this instance.

Here, in an attempt to interpret these observations on an adhesion model, the contact between a smooth rigid cylinder and a smooth elastic flat is treated as an adhesive joint through which cracks may propagate (Fig. 1). Three types of cracking might be envisaged (Fig. 2). When a cylinder is pushed into a flat, the two cracks at the edges of the contact region close and the contact increases in size, Fig. 2(a). Similarly, on pulling the cylinder from the flat, both cracks open to reduce the contact size, Fig. 2(b). These two cases have been considered previously for spheres [6]. In the third case, that of rolling, the crack at the leading edge of the contact is continually closing whereas that at the trailing edge is always opening, Fig. 2(c). The force required to propagate these cracks should give the rolling friction and may now be calculated from established crack theory.

2. Theory

Consider a rigid cylinder of length \( w \) rolling at steady speed along an elastic flat. The force \( F \) required to maintain this motion may be calculated using an energy approach similar to that employed by Griffith [7] in his theory of cracking.

Imagine that the cylinder rolls a distance \( x \). Then the work done by the applied force is \( Fx \). This work is absorbed in two surface terms, one at the trailing edge of the contact where the surfaces are torn apart, and one at the leading edge where the surfaces are drawn together. It is assumed that deformation losses are minor in this case.
The break surface energy $R_b$ is defined as the energy required to separate unit area of contact so that the energy needed over a distance $x$ is $xwR_b$. Similarly the make surface energy $R_m$ is the energy produced by the surface forces in making unit area of interface from two free surfaces so that the energy required for this is $-xwR_m$. Therefore, by the principle of conservation of energy

$$F = w (R_b - R_m) \quad (1)$$

This equation, giving the frictional force, demonstrates clearly that there is no friction unless more energy is expended on breaking the contact than is released on reforming it. Essentially on this model, rolling friction is a result of adhesive hysteresis; the loss of energy owing to irreversible processes when a contact is made and then broken.

Equation (1) certainly differs considerably from some other equations which have been proposed to account for rolling friction [2, 3]. There is, for example, no dependence on normal load or roller diameter. Also, lubricant will affect rolling friction through its direct influence on surface energy [8].

However, the simplicity of the theory is deceptive for a number of reasons. First of all, the definition and measurement of surface energy for solid bodies is difficult. Secondly, previous studies of the fracture of adhesive joints have shown that both crack speed and the contact duration (dwell-time) have an important influence on the breaking force [6]. These problems are best considered experimentally.

3. Experimental

The experimental objective was to verify eqn. (1) by measuring the rolling friction force $F$ under a variety of conditions. This friction could then be correlated with values of the surface energies $R_b$ and $R_m$ measured in separate adhesion tests.

Rolling friction was determined using the apparatus shown in Fig. 3(a), where a glass roller was allowed to move under gravity along an inclined rubber surface. The rubber was ethylene propylene (Enjay 404) made by crosslinking a mixture of the polymer, 0.32% sulfur and 2.7% dicumyl peroxide against a glass plate at 160 °C for one hour. After cooling, the rubber (about 2 mm thick) was peeled from the glass to reveal a very smooth surface. Strips of this material were cut, 10 mm wide, and cemented smooth face up onto a rigid backing plate. A glass cylinder was then lowered onto the smooth rubber and the plate was inclined to allow rolling, the speed being measured meanwhile with a microscope, and the friction force calculated from the inclination $\Phi$ of the plate and the weight $W_c$ of the cylinder by the following equation

$$F = W_c \sin \Phi \quad (2)$$

The adhesive surface energies $R_b$ and $R_m$ were defined experimentally using the peeling geometries shown respectively in Figs. 3(b) and 3(c).
In the \( \pi/2 \) peel test a weight \( W_b \) was suspended from the partly peeled rubber film which then peeled at a constant speed from the glass plate. The speed of peeling was measured and plotted against break surface energy \( R_b \) calculated from the equation

\[
R_b = \frac{W_b}{w}
\]  

The make surface energy \( R_m \) was measured using the apparatus of Fig. 3(c). In this experiment the peeling was reversed by gradually diminishing the peel angle \( \theta \) until the rubber spontaneously pulled itself onto the glass under the influence of the surface attractions. The surface energy was then

\[
R_m = \frac{W_m}{w} (1 - \cos \theta)
\]

In these equations, \( w \) was the width of the rubber strip.

4. Adhesion results

The adhesion results obtained in these tests were conveniently displayed by plotting the surface energies against the crack speed, both on logarithmic scales as in Fig. 4. This graph is most interesting because it illustrates a number of features of solid-solid adhesion which are rather puzzling.

First it is apparent that the energy recovered on reforming the joint is always very much less than that expended in breaking it. On reducing the crack speed sufficiently it would be expected that equilibrium should be achieved and that \( R_m \) should equal \( R_b \). Figure 4 shows that this did not happen even at extremely slow speeds; there existed a definite adhesive hysteresis [6]. This adhesive hysteresis is most important because, according to the suggested theory, rolling friction depends directly on the difference between the make and break surface energies.
Fig. 4. Glass-rubber surface energy results at make $R_m$ and break $R_b$ as a function of crack speed. Crack speed was always considered to be positive.

The speed dependence of the surface energies is another point worthy of note. Not only is more energy required to break a contact at higher speed; less energy is recovered when the joint is reformed at such speeds. The reason for this speed dependence is still a subject for debate [6].

A final point concerns the influence of contact duration or dwell-time on the break surface energy. The results of Fig. 4 correspond to a 300 s dwell-time before peeling. If a shorter dwell-time was allowed, the break energy was reduced whereas longer contact duration increased the surface energy. Results showing this are given in Fig. 5 for a variety of dwell-times. This effect proved to exert a strong influence on rolling friction because, at different rolling speeds, the roller was in contact with the rubber for widely different times.

5. Incorporation of adhesion results into theory

The results of the adhesion experiments showed that the surface energies required to make or break the contact between roller and flat were not constant but varied with crack speed $V$. The break energy also depended on the dwell-time $t$. These observations were incorporated into eqn. (1) by writing

$$F = w[R_b(V,t) - R_m(V)]$$

where the functions $R_b(V,t)$ and $R_m(V)$ were derived from Figs. 4 and 5.

This proved to be fairly simple because the make surface energy turned out to be relatively small and was neglected. The friction force per unit width $F/w$ was therefore given by the break surface energy $R_b$ modified by the dwell-time effect. This dwell-time effect was readily incorporated by realising that, since the contact size was 3 mm, at a speed of 10 $\mu$m s$^{-1}$ the duration of contact between roller and flat was 300 s. This corresponded to
Fig. 5. Results showing the increase in break surface energy $R_b$ with time of contact or dwell-time of rubber on the glass. The crack speed was $1670 \mu m s^{-1}$.

The dwell-time in the adhesion results of Fig. 4. Therefore, at a speed of rolling of $10 \mu m s^{-1}$ the rolling friction should be equal to the $\pi/2$ peel adhesion given in Fig. 4. At lower rolling speeds the friction should be larger than the peel adhesion as a result of a longer dwell-time, whilst at higher speeds the rolling resistance should be relatively smaller because the dwell-time is reduced. An extrapolation of Fig. 5 to shorter times was needed to produce the high speed part of this theory.

6. Rolling friction results

The theory of eqn. (5) is plotted in Fig. 6 to compare with experimental results for a number of different roller weights and radii. It is interesting to note that some of the points on this graph correspond to negative normal loads where the roller was adhering to the underside of an inclined rubber plane. The normal load was varied from $-0.04$ N to 0.2 N yet the friction
points all came near the theoretical line. These results provide convincing evidence that rolling friction between smooth rubber and glass can be explained purely by adhesion between the surfaces. Neither load nor roller radius influenced the friction force. Further corroboration of this idea was obtained by placing a drop of water near the contact between roller and rubber. The rolling friction was instantly reduced by a factor of nearly one hundred.

Two additional observations may be noted here. The first concerns high speed rolling. It was apparent from the adhesion measurements that, at higher speeds than $10^5 \mu m s^{-1}$, the contact between roller and rubber was becoming reluctant to form. In addition, the dwell-time at such speeds was so low that the adhesive energy developed between the surfaces approached zero. As a consequence of these effects it seems possible that the adhesive friction will eventually drop off at high rolling speeds. If this fall off in rolling friction does indeed exist, then it raises the possibility of stick-slip rolling. Stick-slip rolling could provide a partial explanation of the noise emitted by rolling tyres.

The second point concerns low speed rolling. The theoretical line in Fig. 6 predicts that, at low rolling speeds, the rolling friction should increase with decreasing speed owing to the dwell-time effect. This means that steady rolling under a constant force would become impossible at speeds under $10 \mu m s^{-1}$. A slight drop in speed under these conditions would lead to increased friction which would cause a further drop in speed and so on. Measurement showed that this was indeed the case. Steady rolling was easy to achieve above about $10^2 \mu m s^{-1}$. Below this, great changes in rolling speed were prone to occur. In one such case (Fig. 7) a steady decrease of speed was seen as time progressed after making the contact between roller and rubber. In addition, rolling clearly exhibits a definite static friction depending on the contact duration before rolling commences.

7. Conclusions

The rolling contact between a glass cylinder and a smooth rubber flat has been successfully treated as an adhesive joint through which two cracks
propagate at the same speed, one crack continually opening to break the joint, and the other closing to reform it.

Rolling friction on this basis is the consequence of adhesive hysteresis — the energy loss associated with forming and breaking an adhesive bond.

The theory explains a number of experimental observations;
that rolling friction is closely related to peel adhesion;
that a static rolling friction exists;
that friction is independent of normal load and actually arises at negative loads;
that lubricants have a marked effect on rolling friction;
that rolling sometimes slows down at constant force.

In addition it is predicted that pure rolling at high speeds might exhibit stick–slip with attendant vibration and noise.

References