ADHESIVE COMPONENT OF FRICTION BETWEEN ROUGH SURFACES


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INTRODUCTION

Adhesion forces associated with molecular attraction have substantial influence on the characteristics of contact and the friction force between highly smooth and chemically pure surfaces. Bodies coated by surface liquid films can also experience significant adhesive attraction due to capillary pressure in liquid menisci formed in the gap between such surfaces.

Contact problems for two elastic bodies taking into account adhesion were solved in [1,2] for various approximate forms of the potential of adhesive interaction. In [3], the interaction of two elastic bodies covered by films of fluid forming a meniscus in the gap between the bodies was investigated. The results show that when two elastic bodies possessing the surface energy cyclically approach each other and move away, the energy dissipation occurs.

In the present study, contact problems for two elastic asperities taking into account adhesion of different nature are considered by using a unified approach. The energy dissipation in an approach-separation cycle is calculated. It is assumed that this energy is dissipated in each elementary approach-separation cycle for two asperities when rough surfaces move with respect to each other. This makes it possible to calculate the adhesive component of the friction force in sliding and rolling contacts of rough bodies.

INTERACTION BETWEEN TWO ASPERITIES

Consider the interaction between two axisymmetric elastic asperities (dashed-line circle domain in Fig. 1). The shape of their surfaces is described by a power function

\[ f(r) = f_1(r) + f_2(r) = Ar^{2n}, \]

where \( n \) is an integer. The boundary conditions at \( z = 0 \) have the form

\[ u(r) = -f(r) - d, \quad 0 < r < a \quad (1) \]

\[ p(r) = -p_0, \quad a \leq r \leq b \quad (2) \]

where \( u(r) = u_1(r) + u_2(r) \) is the total normal displacement of the surfaces of the interacting bodies due to their deformation, \( p(r) \) is the pressure on the body surfaces, and \( d \) is the variable distance between two fixed points of the interacting bodies.

Fig. 1. Adhesive contact of rough elastic bodies.

From condition (1), it follows that the bodies are in contact over the circular domain \( 0 < r < a \). If the contact is absent \( (a = 0) \), this condition is ignored. Condition (2) implies that the surfaces are loaded by an additional pressure \( -p_0 \) outside the contact area, which represents the adhesive pressure. The total normal displacement \( u(r) \) of the surfaces caused by the normal pressure \( p(r) \) is defined by the expression:

\[
u(r) = \frac{4}{\pi E^*} \int_0^b p(r') \left( \frac{2\sqrt{rr'}}{r + r'} \right) r' dr' \quad (3)\]

with \( (E^*)^{-1} = (1 - \nu_i^2)E_i^{-1} + (1 - \nu_i^2)E_2^{-1} \), where \( E_i \) and \( \nu_i \) \( (i = 1, 2) \) are the Young modulus and Poisson ratio of the interacting bodies, respectively, \( K(x) \) is the complete elliptic integral of the first kind.

The equilibrium condition has the form

\[ q = 2\pi \int_0^b rp(r) dr \quad (4) \]

We consider two types of the adhesive interaction between the bodies.

Adhesion of dry surfaces. The dependence of the adhesive pressure on the distance between the bodies is approximated by a step function. The height
of the step is a prescribed value \( p_0 \). The surface energy is defined by the relation
\[
\gamma = \int_0^\infty P(z)dz = p_0 \left[ f(b) + u(b) + d \right] \quad (5)
\]
which gives the condition for the determination of \( b \).

**Capillary adhesion.** Let there be a fluid meniscus in the area \( a \leq r \leq b \). Then the uniform pressure \(-p_0\) applied to the surfaces in this area is the capillary pressure under the curved surface of the fluid, which is defined by the Laplace formula as
\[
p_0 = 2\sigma \left[ f(b) + u(b) + d \right] \quad (6)
\]
where \( \sigma \) is the surface tension of the fluid. In this case, the value \( p_0 \) is unknown. To determine this value, we prescribe the volume of the fluid \( v \) in the meniscus
\[
v = 2\pi \int_0^{\infty} r \left[ f(r) + u(r) + d \right] dr \quad (7)
\]

**ENERGY DISSIPATION IN AN APPROACH-SEPARATION CYCLE**

The cyclic process in which two asperities come together and move away from each other is analyzed taking into account adhesion of different nature. The ambiguity of the load-distance dependence leads to an energy dissipation in this process. A method is developed for calculating the value of this energy dissipation \( \Delta w \). If the shape of asperities can be approximated by a parabolic function \( f(r) = r^2/(2\rho) \), then the dimensionless energy dissipation
\[
\Delta W = \Delta w \left( \frac{16E^*2}{9n^5\gamma^5\rho^4} \right)^{1/3}
\]
can be expressed as a function of the only dimensionless parameter \( \eta \) for the case of capillary adhesion and the parameter \( \lambda \) for the adhesion of dry surfaces:
\[
\eta = \frac{\gamma^{4/3} \rho^{5/3}}{v E^{*4/3}} \quad , \quad \lambda = p_0 \left( \frac{\gamma \rho}{2\pi \gamma E^{*2}} \right)^{1/3}
\]
The functions \( \Delta W(\eta) \) and \( \Delta W(\lambda) \) are determined numerically. For some particular cases, the function \( \Delta W(\lambda) \) which describes the adhesion of dry surfaces is obtained in the closed form.

**ADHESIVE COMPONENT OF THE ROLLING FRICTION FORCE**

Consider a simple example for a rough cylinder rolling on the boundary of an elastic half-space (Fig. 2). The cylinder rolls with the angular velocity \( \omega \) and it is acted on by the normal force \( P \). There are \( N \) asperities of the same height \( h \) per unit area of the cylinder surface. When cylinder rolls, each asperity approaches the half-space and then moves away, the energy \( \Delta w \) being dissipated. The energy dissipation per unit length of the cylinder in one revolution of the cylinder can be calculated as
\[
w_0/L = 2\pi RN \Delta w
\]
where \( L \) is the length of the cylinder. Assuming that the energy dissipation is equal to the work of adhesive friction force \( F_a \) done in a revolution of the cylinder, i.e., \( w_0 = 2\pi RF_a \), we obtain the following relation for the friction force per unit length:
\[
F_a/L = \Delta wN
\]
This relation and the method developed for the determination of \( \Delta w \) are used to calculate the adhesive component \( F_a \) of the rolling resistance. The value of this force is analyzed depending on the surface energy of the bodies, surface tension and volume of fluid, mechanical properties of the half-space, normal load applied to the cylinder, and shape of asperities. The results indicate that \( F_a \) increases as the surface energy increases and the volume of fluid in each meniscus decreases. This force is larger for softer materials (with smaller elastic modulus).

**REFERENCES**