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ADHESIVE COMPONENT OF THE ROLLING FRICTION FORCE

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<u>Summary</u>   A model is suggested for calculating the adhesive component of the friction force in rolling of a rigid rough cylinder on an elastic half-space. The rolling resistance arises due to the energy dissipation which occurs when an asperity approaches the half-space and then moves away from it. The cases of capillary adhesion of surfaces covered by fluid films and adhesion of dry surfaces are considered.

INTRODUCTION

Adhesive forces arise in the contact of bodies due to their surface energy and surface energy of fluid films covering the contacting surfaces. Contact problems for two elastic bodies taking into account adhesion were solved in [1-3] for various approximate forms of the potential of adhesive interaction. In [4,5], 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. On the basis of this result, a model for calculating the adhesive rolling resistance is suggested.

NATURE OF ADHESIVE COMPONENT OF ROLLING FRICTION FORCE

Consider a simple scheme for a rough cylinder rolling on the boundary of an elastic half-space (Figure). The cylinder rolls with the angular velocity ω 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. The shape of an asperity is described by the function $f(r) = Ar^n$, where n is an integer.

When cylinder rolls, the distance between each asperity and the half-space decreases from d_∞, at which the asperity and the half-space experience no adhesive forces, to the minimum distance d_0 corresponding to the point of maximum contact pressure. Then the asperity moves away from the half-space surface up to the distance d_∞.

It is established [3] that if the value of d_0 does not exceed a critical value d_c then the energy dissipation takes place in an approach-separation cycle. The value of this energy dissipation is denoted by Δw. The energy dissipation per unit length of the cylinder in one revolution of the cylinder can be calculated as

$$\frac{w_0}{L} = 2\pi R N \Delta w \tag{1}$$

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., $w_0 = 2\pi R F_a$, we obtain the following relation for the friction force per unit length:

$$\frac{F_a}{L} = \Delta w N \tag{2}$$

Thus, to calculate the friction force, it is necessary to determine the energy dissipation Δw for one asperity in an approach-separation cycle.

ENERGY DISSIPATION IN AN APPROACH-SEPARATION CYCLE

Capillary adhesion

The interaction between a separate asperity and an elastic half-space is considered [5] taking into account a meniscus of fluid in the gap between the surfaces. A method is suggested to solve this problem both for contact between the surfaces and for the case where the surfaces are separated by the meniscus. As a result, the analytical relations for the contact pressure and shape of the boundary of the elastic half-space are obtained, which make it possible to calculate the dependence of normal force applied to the asperity versus distance between the bodies for various amount of fluid, its surface tension, shape of the asperity, and elastic properties of the bodies. It is shown that this dependence is nonmonotonic and ambiguous.
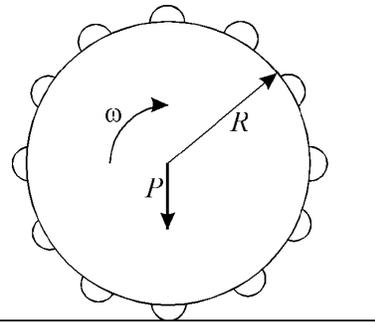
Adhesion of dry surfaces

The method developed for the problem of capillary adhesion is used for solving the problem of adhesion between an asperity and an elastic half-space possessing the surface energy [3]. It is shown that capillary adhesion and adhesion of dry surfaces lead to rather similar effects in contact of elastic bodies, in particular, to nonmonotonic and ambiguous character of the load-distance dependence.

Approach-separation cycle

The cyclic process in which an asperity approaches the elastic half-space and moves away from it is analyzed taking into account the adhesion of different nature [3]. 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. If the asperity tip has a spherical shape of raduis ρ which can be described by a parabolic function $f(r) = r^2/(2\rho)$, then the dimensionless energy dissipation

$$\Delta W = \Delta w \left(\frac{16E^{*2}}{9\pi^5\gamma^5\rho^4} \right)^{1/3} \tag{3}$$

where $E*$ is the reduced elastic modulus and γ is the surface energy (in the case of capillary adhesion, $\gamma = 2\sigma$, where σ is the surface tension of the fluid), can be expressed as a function of the only dimensionless parameter η for the case of capillary adhesion and the parameter λ for the adhesion of dry surfaces. These parameters are given by

$$\eta = \frac{\gamma^{4/3}\rho^{5/3}}{vE^{*4/3}}, \qquad \lambda = p_0 \left(\frac{9\rho}{2\pi\gamma E^{*2}} \right)^{1/3} \tag{4}$$

where v is the volume of fluid, p_0 is the adhesive pressure. 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.

CALCULATION OF THE ROLLING RESISTANCE

Relation (2) and the method developed for the determination of Δw 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 aspeirties. 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).

If asperities have spherical shape of radius ρ, then Eq. (2) can be represented in the form (see Eqs. (3) and (4)):

– for rolling of dry surfaces

$$\frac{F_a}{L} = N \left(\frac{16E^{*2}}{9\pi^5\gamma^5\rho^4} \right)^{-1/3} \Phi_1 \left(p_0 \left(\frac{9\rho}{2\pi\gamma E^{*2}} \right)^{1/3} \right) \tag{5}$$

– for rolling of lubricated surfaces

$$\frac{F_a}{L} = N \left(\frac{16E^{*2}}{9\pi^5\gamma^5\rho^4} \right)^{-1/3} \Phi_2 \left(\frac{(2\sigma)^{4/3}\rho^{5/3}}{vE^{*4/3}} \right) \tag{6}$$

where the functions $\Phi_1(t)$ and $\Phi_2(t)$ are calculated numerically.

Relations (5) and (6) are obtained by using the simplest model of rough body with asperities of the same height and they do not explicitly depend on the load P. The only condition on the value of P is the inequality $d_0 \leq d_c$. Taking into account the height distribution of asperities in modelling roughness leads to substantial dependence of the number of asperities N_1 per unit area for which the energy dissipation takes place on the load P, cylinder radius R, and function $\varphi(h)$ of the height distribution of asperities, i.e., $N_1 = N_1(P, R, \varphi(h))$. In this case, we should set $N = N_1$ in Eq. (2).

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