Applied Surface Science 394 (2017) 528–533

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

The hysteretic contribution of friction for the polished rubber on the concrete surface

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ARTICLE INFO

Article history:
Received 7 June 2016
Received in revised form 5 October 2016
Accepted 9 October 2016
Available online 18 October 2016

Keywords:
Self-affine fractal
Cross correlation
Friction

ABSTRACT

The rubber friction coefficient, and the contact area during stationary sliding is calculated, for the contact of a polished rubber block and a concrete surface, when both surfaces are rough. The calculation is based on an extended version of Persson's contact mechanics theory. Compared to only the substrate being rough, when both of the surfaces are rough but their cross correlation is zero, the friction coefficient is larger. Introducing a positive correlation decreases the friction coefficient, while introducing a negative correlation increases the friction coefficient.

To support these theoretical arguments, some experiments have been performed. We have produced roughness on the rubber surface, using abrasive paper, and measured the surface topographies for the concrete and the polished rubber surfaces. The auto spectral density functions for the both surfaces have been calculated, and the rubber viscoelastic modulus mastercurve has been obtained. We have measured the rubber friction at different sliding velocities, when the rubber surfaces are rough and smooth, and compared it to the theoretical results. It is seen that when the rubber surface is rough, the rubber friction coefficient is larger compared to the case the rubber surface is smooth. The theoretical results are in good agreement with experimental observation.

1. Introduction

The sliding friction between an elastic block and a hard solid substrate is important in many practical situations [1–12]. Among them are the friction between a rubber tire and the road, and the friction between the rubber blades of wipers and the wind screen. It is also important in cosmetic industry.

The rubber friction has several different contributions described as the hysteretic, adhesion, and wear components [3,4,6]. The hysteretic component originates from the damping of the oscillating forces experienced by the rubber. The adhesion shows itself when the surfaces are very clean and the speeds are small, less than 10^{-8} (m/s) [7]. So in almost all practical cases the internal (hysteretic) friction is the dominant component. For this reason the adhesion component is not included in the model which will be presented here. When the rubber surface moves on the substrate, small rubber particles are removed from the rubber surface, and the energy corresponding to the propagation of cracks in the rubber surface has a contribution to friction. This is called the wear process.

The hysteretic contribution to the rubber friction is calculated by Persson's theory [8–11]. In many studies, the elastic body is assumed to be smooth. However, surfaces are in general not smooth. Here the hysteretic component of the friction between two surfaces is studied, one of which is a rubber block and the other a hard substrate, when both surfaces are rough and self affine. This is done using an extension of Persson's model [13].

The paper's scheme is the following. Section 2 is a review of Person's model of the hysteretic friction. In Section 3, an extended version this model is used to calculate the hysteretic friction, when both contacting surfaces are randomly rough. In Section 4, the characteristics of the rubber and concrete surfaces are presented, which are obtained from the measurements. Section 5 presents the numerical results for a polished rubber block and concrete surface. Section 6 describes the tribometer machine which has been used to measure the rubber friction as a function of the sliding speed and the temperature, and presents the experimental results and a comparison with the numerical obtained from theoretical considerations. Section 7 is devoted to the concluding remarks.

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http://dx.doi.org/10.1016/j.apsusc.2016.10.054
0169-4332/

2. Persson contact theory on rubber friction

The hysteretic friction model developed by Persson [8] is based on the energy dissipation ΔE. As the rubber slides on a hard rough surface, oscillatory forced are experienced by it, which cause energy being dissipated in rubber. This corresponds to the nominal frictional stress σ_f experienced by rubber. The calculation is based on an integral of contributions due to different wavelengths (wave numbers). In [8], equations have been derived which describe the friction on a rubber block which is pressed on a rough surfaces. The frictional stress σ_f is equal to $\mu\,\sigma_0$, where σ_0 is the normal stress. One has

$$\mu \approx \frac{1}{2}\int_{q_0}^{q_1} \mathrm{d}q\, q^3\, C(q)\, P(q) \int_0^{2\pi} \mathrm{d}\phi\, \cos\phi\, \mathrm{Im}\left[\frac{E(-q\,u\,\cos\phi)}{\sigma_0\,(1-\upsilon^2)}\right]. \quad (1)$$

where E is the complex viscoelastic modulus of the rubber block that we have studied it in Section 5 and $C(q)$ is the auto-spectral density function of the hard randomly rough surface. Experiments have shown that a typical road surface [14] and a polished surface by an abrasive paper (polished styrene butadiene rubber (SB)) [15] can be approximated by self-affine fractals. The frequency is written in terms of the slip velocity

$$\frac{u}{\lambda} = u\,q\,\cos\phi, \quad (2)$$

where ϕ is the angle between the sliding direction and the wave vector $\boldsymbol{q}$. υ, the Poisson's ratio of the rubber block, is assumed to be independent of frequency and equal to 0.5. The integration in (1) is performed over the wave vectors. Under the nominal stress σ_0, the surface asperities do not, in general, fully penetrate inside the rubber block and the contact between the substrate and the rubber block is not full. Hence the auto-spectral density function does not contribute in full to the hysteresis friction. This aspect is taken into account in (1) through the factor $P(q)$, which is the normalized contact area:

$$P(q) = \frac{A}{A_0} = \frac{2}{\pi}\int_0^{\infty} \mathrm{d}x\, \frac{\sin x}{x}\, \exp[-x^2\, G(q)] = \mathrm{erf}\left[\frac{1}{2\sqrt{G(q)}}\right]. \quad (3)$$

$$G(q) = \frac{1}{8}\int_{q_0}^{q} \mathrm{d}q'\, q'^3\, C(q') \int_0^{2\pi} \mathrm{d}\phi \left|\frac{E(-q'\,u\,\cos\phi)}{\sigma_0\,(1-\upsilon^2)}\right|^2. \quad (4)$$

The auto-spectral density function for self-affine fractals can then be described by:

$$C(q) \approx \frac{H}{2\pi}\left(\frac{h_0}{q_0}\right)^2 \left(\frac{q}{q_0}\right)^{-2(H+1)}. \quad (5)$$

$$\langle h^2\rangle = \frac{(h_0)^2}{2}. \quad (6)$$

H and $\langle h^2\rangle$ are the Hurst exponent and the root-mean-square roughness of the substrate, respectively.

3. Theory for hysteretic contribution of friction when both surfaces are rough

The frictional shear stress for rubber sliding on a hard substrate is [8]

$$\sigma_f = \mathrm{Re}\left\{\frac{2\pi^2}{A_0\,u}\int_{q_0}^{q_1} \mathrm{d}^2q\,(-\mathrm{i}\,\boldsymbol{q}\cdot\boldsymbol{u})\,[M_{zz}(-\boldsymbol{q}, -\boldsymbol{q}\cdot\boldsymbol{u})]^{-1}\,\langle h_z(\boldsymbol{q})\,h_z(-\boldsymbol{q})\rangle\right\}, \quad (7)$$

$$[M_{zz}(\boldsymbol{q}, w)]^{-1} = \frac{-q\,E(w)}{2\,(1-\upsilon^2)}, \quad (8)$$

where $\boldsymbol{u}$ is the surface velocity (relative to the substrate), and $h_z(\boldsymbol{q})$ is the Fourier transform of the normal displacement of the rubber surface. Now consider that a randomly rough viscoelastic solid slide on a randomly rough hard substrate. Eq. (7) holds, but here for full contact the displacement of rubber is the difference of the fluctuations of the rubber and the substrate:

$$h_z(\boldsymbol{q}) = h_2(\boldsymbol{q}) - h_1(\boldsymbol{q}). \quad (9)$$

An explanation is in order here. It is assumed that parts of the rubber and the substrate which are in contact, both change with time. That's the case when a rubber wheel is rolling on the substrate, or when a rubber piece is rotating on a substrate around a rotation axis normal to the substrate. In such cases, the rubber and the substrate behave symmetrical. Otherwise, if a finite block of rubber is sliding on a larger substrate, with the contact part of the rubber being constant, the contact part of the substrate changes and that of the rubber does not change. This is not the case studied here.

Substituting (8) and (9) in (7),

$$\sigma_f = \frac{2\pi^2}{A_0}\int_{q_0}^{q_1} \mathrm{d}^2q\, q^2\, \cos\phi\, \langle (h_2(\boldsymbol{q}) - h_1(\boldsymbol{q}))(h_2(-\boldsymbol{q}) - h_1(-\boldsymbol{q}))\rangle$$
$$\times\, \mathrm{Im}\left[\frac{E(-q\,u\,\cos\phi)}{(1-\upsilon^2)}\right]. \quad (10)$$

The spectral density function is [13]

$$C_{ij}(\boldsymbol{q}) = \frac{(2\pi)^2}{A_0}\,\langle h_i(\boldsymbol{q})\,h_j(-\boldsymbol{q})\rangle, \quad (11)$$

where A_0 is the surface area and $i = 1, 2$ [16,17]. It is assumed that the joint distribution function of the heights is Gaussian, and the surfaces are homogeneous and isotropic. So,

$$\langle h_i(\boldsymbol{q})\,h_i(-\boldsymbol{q})\rangle = \langle |h_i(\boldsymbol{q})|^2\rangle = \frac{A_0\,C_i(q)}{(2\pi)^2}, \quad (12)$$

where C_i is real function and depends on only $q = |\boldsymbol{q}|$. The coherence function η_{12} is defined through

$$\langle h_1(\boldsymbol{q})\,h_2(-\boldsymbol{q})\rangle = \eta_{12}(\boldsymbol{q})\,\sqrt{\langle |h_1(\boldsymbol{q})|^2\rangle\,\langle |h_2(\boldsymbol{q})|^2\rangle}, \quad (13)$$

η_{12} is in general complex, with modulus not exceeding one [18,19]. For homogeneous and isotropic surfaces, η_{12} is real, depends on only q, and is equal to η_{21}. So the subscripts are dropped. $\eta = 0$, $\eta = 1$, and $\eta = -1$ are special cases, corresponding to uncorrelated surfaces, completely positive correlated surfaces, and completely negative correlated surfaces. Fig. 1 shows examples of completely correlated surfaces.

Substituting (11) and (12) in (10), results in

$$\sigma_f = \frac{1}{2}\int_{q_0}^{q_1} \mathrm{d}q\, q^3\, [C_1(q) + C_2(q) - 2\,\eta\,\sqrt{C_1(q)\,C_2(q)}]\,P(q)$$
$$\times \int_0^{2\pi} \mathrm{d}\phi\, \cos\phi\, \mathrm{Im}\left[\frac{E(-q\,u\,\cos\phi)}{(1-\upsilon^2)}\right]. \quad (14)$$

So the friction coefficient μ would be,

$$\mu = \frac{1}{2}\int_{q_0}^{q_1} \mathrm{d}q\, q^3\, [C_1(q) + C_2(q) - 2\,\eta\,\sqrt{C_1(q)\,C_2(q)}]\,P(q)$$
$$\times \int_0^{2\pi} \mathrm{d}\phi\, \cos\phi\, \mathrm{Im}\left[\frac{E(-q\,u\,\cos\phi)}{\sigma_0\,(1-\upsilon^2)}\right]. \quad (15)$$

As stated earlier, under the nominal stress σ_0, the surface asperities do not fully penetrate inside the rubber block and only a partial contact between the hard surface and the rubber block can be achieved. The introduction of the normalized contact area $P(q)$ in (14) and (15) takes this into account. Roughening the surface of the viscoelastic