Simulation of the influence of ultrasonic in-plane oscillations on dry friction accounting for stick and creep

J. Starcevic* and A.E. Filippov[1]

Berlin University of Technology, Berlin, 10623, Germany

[1] Donetsk Institute for Physics and Engineering NASU, Donetsk, 83114, Ukraine

We consider a pair of bodies contacting on an elastic substrate; the distance between the bodies oscillates harmonically at a high frequency. If a horizontal force is applied to the bodies, macroscopic movement starts only after achieving some critical value, which we identify with the static friction force of the oscillating system. The dependence of the static friction force on the oscillation amplitude is simulated numerically using the method of reduction of dimensionality. Results of simulation are compared with experimental data.

Keywords: method of reduction of dimensionality, contact stiffness, ultrasonic oscillations, tangential dynamic contact

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1. Introduction

The influence of oscillation on friction is a topic of great interest for many applications [1]. It was studied in connection with wire drawing [2], press forming [3], travelling wave ultrasonic motors [4, 5] and many other applications. In the past, it was studied both theoretically [6] and experimentally [7–9]. However, the detailed contact configuration and the microslip in the contact area were not taken into account in the previous works. This is, however, of essential importance for tangential contacts. In a real experiment, the contact area of the bodies is normally curved. It is well known that in such contacts — when tangential force is applied — a microslip occurs at the boundary of the contact area, which influences the dependence of the tangential force and tangential displacement until complete sliding begins [1]. Similar effects should occur in dynamically loaded contacts. In the present paper, we simulated the dynamically loaded tangential contact in the presence of a constant tangential force and studied the dependence of the critical force for the start of macroscopic sliding on the oscillation amplitude. These results are used for the interpretation of experimental results.

* *Corresponding author*

Dr. Jasminka Starcevic, e-mail: j.starcevic@tu-berlin.de

2. Model, numerical simulation and comparison with experiment

The model used is schematically represented in Fig. 1. Two bodies with the total mass m are coupled with an oscillating bond, the length of which is changed according to the harmonic law

$$l(t) = l_0 + \Delta l \cos(\omega t). \tag{1}$$

The bodies are pressed onto the underlying substrate with the normal force F_n. At the same time, a constant tangential force F is applied to the pair. It is assumed that there is a frictional force between the bodies and the underlying substrate with a constant coefficient of friction μ_0. The radius of curvature of the bodies in the contact points is denoted as R_3D.

For the simulation of the dynamic tangential contact, we use the method of reduction of dimensionality, first proposed in [10]. According to this method, a three-dimensional contact of a body of revolution with an elastic half-space can be reproduced exactly if the radius of curvature in the equivalent one-dimensional system is taken to be $R_\text{1D} = R_\text{3D}/2$ and the stiffness of the elastic foundation is chosen according to the following rules [11, 12]:

$$\begin{aligned} &\Delta k_z = E^* \Delta x \ \text{ for normal stiffness,} \\ &\Delta k_x = G^* \Delta x \ \text{ for tangential stiffness,} \end{aligned} \tag{2}$$

where E^* and G^* are effective elastic moduli

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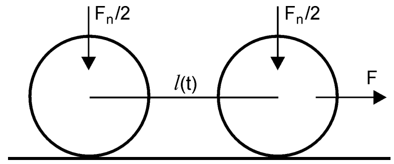

Fig. 1. Schematic presentation of the model: two elastic bodies with curved surfaces are connected with an oscillating bond and are in contact with a plane foundation. The system is being acted upon by a constant external tangential force F

$$\frac{1}{E^*}=\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2},$$
$$\frac{1}{G^*}=\frac{2-\nu_1}{4G_1}+\frac{2-\nu_2}{4G_2}, \quad (3)$$

E_1 and E_2 are the Young's moduli of the contacting bodies, G_1 and G_2 are the shear moduli and ν_1 and ν_2, their Poisson ratios.

We assumed that the oscillation frequency is so high that the oscillation movement and the translational movement of the couple as a whole can be considered as being completely decoupled. This means that the kinematics of both bodies was given, and only the instant and the average forces over one period of oscillations were calculated.

The simulation consisted of two parts. First, an increasing tangential displacement was applied and the two characteristic quantities identified: (i) the maximum force, which is achieved after the start of macroscopic (continuous) sliding (in our case it is simply $\mu_0 F_n$ and (ii) the maximum tangential displacement $u_{x,\max}$ which is achieved without macroscopic sliding. In the second step, the system was moved tangentially with a very small tangential velocity. At the same time increasing oscillation amplitude was applied. In this way, the stationary force at very slow sliding was determined. This force was identified with the static force of friction. As we did not consider inertial properties, the problem was quasistatic and the results did not depend on the oscillation frequency, which only had to be sufficiently high. It is sensible to introduce dimensionless variables by normalizing the force to its maximum value $\mu_0 F_n$ and the oscillation amplitude to the characteristic displacement $u_{x,\max}$. In this case, the dependence of the static frictional force on the oscillation amplitude has a universal form, which does not depend on any geometrical or loading parameters. This universal non-dimensional dependency of the normalized macroscopic coefficient of friction on the normalized oscillation amplitude is shown in Fig. 2. In the same figure experimental data are shown for a number of tribological couples. The experimental data were normalized in the same way as the theoretical curve: The coefficient of friction was divided by its maximum value without oscillations and the oscillation amplitude was normalized by the value $u_{x,\max}$, which was found by best fitting to the theoretical curve for small oscillation amplitudes. The resulting characteristic amplitudes are summarized in the Table 1.

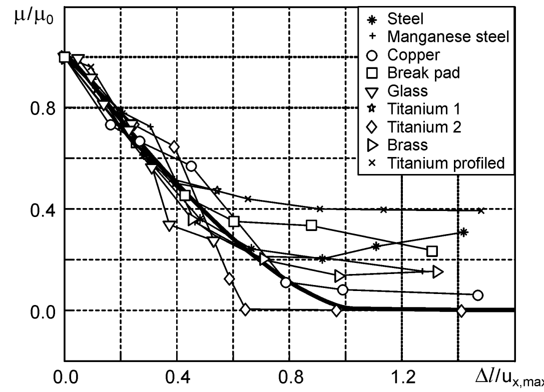

Fig. 2. Dependencies of the normalized static coefficient of friction on the normalized oscillation amplitude for pairings of different materials and steel C45. Thick line represents the results of the numerical simulation

Note that the theoretical prediction for $u_{x,\max}$ [12] is

$$u_{x,\max}=\mu\frac{E^*}{G^*}d, \quad (4)$$

where d is the indentation depth of the bodies into the elastic half-space. Thus, the critical displacement is typically on the order of magnitude of the indentation depth multiplied with the coefficient of friction: $u_{x,\max}\approx \mu d$.

3. Discussion

In the paper [8] we showed that the friction systems are characterized by some characteristic length. We interpreted this length from the viewpoint of stochastic Prandtl–Tomlinson models [13]. At the same time, we stressed that the properties of a tribological system connected with this characteristic length can be phenomenologically described just by introducing a contact stiffness. This phenomenological approach provides practically the same macroscopic behavior as the microscopically motivated one. In the present paper we considered this alternative interpretation in more detail and have shown that the initial part of the dependencies of the static force of friction on the oscillation ampli-

Table 1

Characteristic critical tangential displacement for different tribological couples

Material of the substrate	Steel	Manganese steel	Copper	Brake pad	Glass	Titanium 1	Titanium 2	Brass	Titanium profiled
Displacement $u_{x,\max}$, μm	0.2492	0.1277	0.1088	0.1193	0.5508	0.2024	0.1111	0.0871	0.3177

tude can be described well with a simple model of a tangential dynamic contact. Thus, the simplest model of tangential contact is sufficiently well in the region of the amplitudes which is most important for practical applications. However, the behavior at large oscillation amplitudes is not described accurately. This means that the simple model for Coulomb's law of friction with a constant coefficient of friction cannot be applied for the analysis of friction at larger oscillation amplitudes. The discrepancy at large oscillation amplitudes can be due to the fact that we considered the supporting plate as being ideally flat. Final static friction force at large amplitudes can be due to the roughness of both contacting surfaces. Further investigations are needed to understand this behavior in detail.

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