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Generalized master curve procedure for elastomer friction taking into account dependencies on velocity, temperature and normal force

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ABSTRACT

The friction between an elastomer and a rigid substrate may depend on a large number of system and loading parameters. Based on a general structure of the law of friction, we propose a generalized master curve procedure for elastomer friction where the significant governing parameter – indentation depth (or normal force) was taken into account. Unlike the generation of the classical master curve by horizontal shifting of dependence "friction - logarithm of velocity" for different temperatures, in the case of various indentation depth the shifting in both horizontal and vertical direction is required. We experimentally investigated coefficient of friction of elastomer on sliding velocity for different indentation depths and temperatures, and generated a 'master curve' according to this hypothesis.

1. Introduction

Friction exists everywhere in both nature and man-made objects. It can be beneficial, such as book flipping or product transportation on conveyor system [1] [2]; sometimes friction is expected to be reduced because it causes the unwanted loss of energy [3–5]. A simple but today still widely used law of friction is Amontons' law which states that friction force is proportional to the normal force, the ratio is known as coefficient of friction [6]. However, since Coulomb it has been already known that coefficient of friction may depend also on material, normal load, system size, time, sliding velocity and so on [7–9]. These factors will have a significant influence on friction of elements in precision instruments. Especially in micro/nano-scale system, due to the high surface area-to-volume ratio and surface interaction, the frictional behavior is more complicated and usually cannot be described by a general law [10–12].

It is well known that for rubber like viscoelastic materials friction in a contact with a hard counter surface is velocity-dependent [13]. A large number of studies have shown that friction between elastomer and rigid surface depends on all loading parameters and material parameters, in particular strongly on sliding velocity, normal load and temperature [14–18]. In 1963 Grosch firstly presented the so-called master curve procedure [19] which since then became a standard procedure in rubber industry. It is based on the shifts of dependencies of the coefficient of friction on logarithm of velocity measured at different temperatures in horizontal direction by the WLF (Williams, Landel, Ferry) factors [20], to a single continuous 'master curve' which describes the frictional behavior of rubber in a large velocity range and at the same time at different temperatures. This method has been widely applied in analysis of elastomer friction [21] [22]. Similar master curve for stress (or shear modules)–frequency dependence investigated by dynamic mechanical analysis and dielectric spectroscopy is also a common method to study and characterize the viscoelastic properties of polymer material, including determination of complex modulus and glass transition temperature [23] [24]. It is noted that the master curves are generated under assumption that all contributions to the friction force have the same temperature dependence. Usually these master curves of friction-velocity and stress-frequency dependences are generated by horizontal shifting because only one further parameter, temperature is considered. However it is found that a vertical shift procedure has to be introduced into the generation of master curve in some cases due to the complex interaction of internal structures [25]. Furthermore, influence of other loading parameters such as normal force, have been rarely taken into account [26], in spite of the obvious practical importance.

Recently it was argued that, although there are a large number of parameters which affect the friction, it occurs to be possible to reduce the number of parameters by choosing corresponding parameter combinations which mostly directly and robustly determine friction. It was

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argued that the contact configuration in a broad sense (all parameters including the shape of the contact, contacts area, contacts gradients, contacts stiffness and so on) is the most immediate function of the indentation depth. The coefficient of friction will be then the function of the indentation depth independently of what detailed rheology or local friction law [27]. A simple example of this robustness is well known: the relation between contact radius and indentation depth in a non-moving sphere contact, $a = \sqrt{Rd}$, is determined solely by the indentation depth (for a given shape) independently of the elastic properties of the medium. In addition, for frictional contact it is already theoretically and experimentally shown that the maximum pre-sliding displacement is function of only coefficient of friction and indentation depth, $u_{x,\max} = 1.5\mu d$ [28] [29]. Based on discussion of these robust governing parameters in papers [26–27], we suggest a generalized master curve procedure of elastomer friction taking into account sliding velocity, temperature and now also the normal force. These loading parameters can be easily experimentally realized and controlled. For verification we carried out corresponding experiments using a tribometer with controlled indentation depth. In this paper, we restrict ourselves to the case of constant temperature, which means that the local temperature changes in contacts are neglected. Some ideas for a further generalization of the master curve procedure with a consideration of local temperature changes can be found in Ref. [30].

2. Theoretical analysis

Just for illustrating the main idea of the new suggested method let us consider several simple examples of friction of a rigid indenter against an elastomer. As examples, we consider two contacts of conical indenters with viscoelastic media having different rheology and one example of a parabolic indenter in contact with a Kelvin body. For the sake of a simple illustration we consider one-dimensional contacts with elastic foundations. However, the results have been confirmed through complete three-dimensional boundary element simulations [31] (see also results below in this paper). The rigid indenter is pressed against a viscoelastic foundation with indentation depth d and then slides tangentially with a constant velocity v. If the indenter has a conical profile $z = g(x) = c|x|$ with $c = \tan\theta$ (θ is the cone angle with respect to x-axis), and viscoelastic material is modelled as a combination of series of Kelvin-element, as shown in Fig. 1a, the coefficient of friction between these the contacting bodies is given by the equation [32].

$$\mu = \nabla z \frac{\left[2\left(\frac{\nabla z\cdot v\tau}{d}\right) - \frac{1}{2}\left(\frac{\nabla z\cdot v\tau}{d}\right)^2\right]}{\left[1 + \frac{1}{2}\left(\frac{\nabla z\cdot v\tau}{d}\right)^2\right]}, \tag{1}$$

where ∇z is surface gradient and equal to profile coefficient $\nabla z = c$, τ is relaxation time of the elastomer. If Kelvin-elements are replaced by Maxwell-elements (Fig. 1b), then the result, as found in Ref. [32], reads:

$$\mu = \nabla z \cdot \frac{\frac{d}{\nabla z\cdot v\tau} - 2\left(1 - e^{-\frac{d}{\nabla z\cdot v\tau}}\right) + \ln\left(2 - e^{-\frac{d}{\nabla z\cdot v\tau}}\right)}{\frac{d}{\nabla z\cdot v\tau} - \ln\left(2 - e^{-\frac{d}{\nabla z\cdot v\tau}}\right)}. \tag{2}$$

For sliding contact of spherical indenter (radius R_1) whose profile is described as $g(x) = x^2/R_1$ with a Kelvin-element foundation (Fig. 1c), the coefficient of friction was found in Ref. [32] to be

$$\mu = \nabla z \frac{\xi\left[2 - 3\xi - 2\xi^3 + 2\left(1+\xi^2\right)^{3/2}\right]}{\left[1 - \xi^3 + \left(1+\xi^2\right)^{3/2}\right]^{4/3}}, \tag{3}$$

where $\xi = \frac{v\tau}{(2R_1 d)^{1/2}} \approx \frac{v\tau}{a}$ and a is contact radius.

The results presented above have been confirmed through complete three-dimensional simulations, where tangential contact problem between a rigid indenter and a viscoelastic half space was solved based on the boundary element method [31]. In the paper [31], the viscoelastic half-space was modelled as “standard body” (see Fig. 2), and the indenter had a conical or parabolic shape. A part of simulation results are shown in Fig. 3, where the line marked with red circles for $\overline{G} = G_\infty/G = 0$ corresponds to the case of contact between a cone and a Maxwell-foundation (its one-dimensional model is Fig. 1b, and solution in equation (2)). In Fig. 3 the symbol c_{3d} is the constant and equal to $c_{3d} = c = \nabla z$ for cone-shape indenter, and δ is indentation depth. It is seen that the y-axis of Fig. 3 is actually the logarithm of $\mu/\nabla z$ which is the left-hand side of equation (2) divided by ∇z, and the x-axis is the logarithm of $d/(\nabla z\cdot v\tau)$ which is the combination of four parameters in equation (2). From this curve for $\overline{G} = 0$, we can find that the simulation results with different sets of parameters including sliding velocity, relaxation time, normal force and indentation depth finally merged into one master curve, which not only validates the general structure of solution (2), but also proves the general conclusion that the coefficient of friction depends solely on the combination $d/(\nabla z\cdot v\tau)$.

Thus, in all considered cases – independently on the dimensionality - the dependence of the coefficient of friction on parameters has the same structure:

$$\mu = \nabla z\cdot\Psi\left(\frac{v\tau}{a}\right). \tag{4}$$

Similar results have been obtained also for rough fractal contacts [27]. This simple equation is of course just a representation of the old and well-known results that the rheological contribution to elastomer friction is a product of the rms slope of the surface roughness and the rheological factor depending on the product of the characteristic frequency v/a and the relaxation time of the elastomer [16]. The geometrical parameters of the contact configuration, ∇z, and the characteristic size of the “asperities”, a, can of course depend on the indentation depth. But according to the Archard's idea, the geometrical parameters of contact asperities are only weakly dependent of loading conditions. As no loading parameter is involved in (4), this equation will also be valid for multi-contact configuration.

In equation (4), the parameters surface gradient ∇z and size of local contact a depend not only on the indentation depth but also on the surface roughness. It is practically impossible to measure these properties. But for our purpose this is not needed, as only the general structure given by equation (4) is important. It is sufficiently to know that these

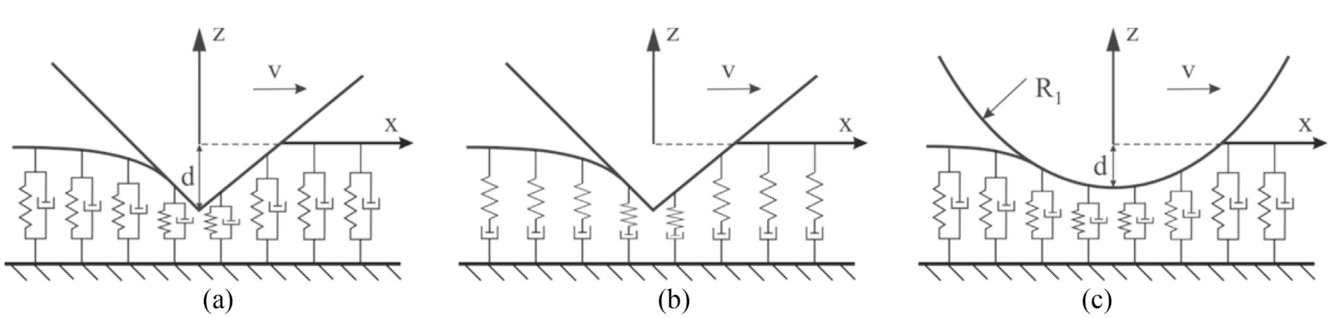

Fig. 1. Contacts between rigid indenters and viscoelastic foundations.