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Tuning friction with composite hierarchical surfaces

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ABSTRACT

Macroscopic friction coefficients observed in experiments are the result of various types of complex multiscale interactions between sliding surfaces. Therefore, there are several ways to modify them depending on the physical phenomena involved. Recently, it has been demonstrated that surface structure, e.g. artificial patterning, can be used to tune frictional properties. In this paper, we show how the global friction coefficients can also be manipulated using composite surfaces with varying roughness or stiffness values, i.e. by combining geometrical features with the modification of local friction coefficients or stiffnesses. We show that a remarkable reduction of static friction can be achieved by introducing hierarchical arrangements of varying local roughness values, or by introducing controlled material stiffness variations.

1. Introduction

The constitutive laws of friction appear to be very simple at the macroscopic scale, indeed they were already formulated by Leonardo da Vinci, and later introduced in the context of classical mechanics with the so called Amonton's-Coulomb (AC) law: the friction force is proportional to the applied normal load and is independent of the apparent contact surface and of the sliding velocity [1]. The proportionality constants are called friction coefficients, which are different in the static and the dynamic sliding phase. Although some violations have been observed [2], this is a good approximate description of the macroscopic frictional force between two solid sliding surfaces [3].

However, the origin of this behaviour turns out to be much more complicated, since friction coefficients are effective values, enclosing all the interactions occurring from atomic length scales, involving "dry" or chemical adhesion forces, to macroscopic scales, involving forces due to solid deformation and surface roughness. Moreover, friction coefficients are not a specific feature of the specific material, rather they are the result of the complex interplay between the contact surfaces occurring at various length scales in that material and involving different basic physical mechanisms [4,5]. Thus, in order to modify the macroscopic emergent behaviour, one can intervene on the single mechanisms involved. For example, it is possible to modify the interactions at the microscopic level by means of lubrication between surfaces, so that solid-solid molecular forces are switched to liquid-solid interactions and friction is reduced. At the macroscopic level, friction can be reduced by means of smoothing or polishing procedures, in order to remove surface asperities hindering relative motion. Thus, problems related to friction, which is a complex multiscale phenomenon, can be addressed with different methods, from a practical and a theoretical point of view [6].

Another way to modify frictional properties is to manufacture sliding surfaces with artificial patterning, from micrometric to millimetric scales, e.g. grooves and pawls perpendicular to the direction of motion. The effects of these structures have been studied both numerically [7] and experimentally [8,9], and recently their hierarchical arrangement has also been investigated by means of numerical simulations [10]: results show that by changing the architecture of the contact surface only, the global static friction coefficients can be tuned without changing the chemical or physical properties of the material. This is because by exploiting patterning it is possible to modify mesoscopic features, i.e. the effective contact area and the stress concentrations occurring in the static phase, providing a way to modify macroscopic friction coefficients.

In this paper, we show that this approach can be combined with the local variation of friction coefficients, corresponding to a local change of material properties or of local surface roughness, in order to reduce static friction. We consider only roughness modifications occurring at the

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mesoscopic scale, using a statistical description based on a one-dimensional version of the spring-block model [11]. This approach allows to address the problem of friction in composite materials, which are widely used in practical applications [12–16] but whose frictional behaviour is still scarcely studied from a theoretical and numerical point of view. Moreover, we consider local hierarchical arrangements of surface properties on different characteristic length scales. This allows us to highlight the main mechanisms taking place in the presence of different length scales, which could be exploited to design artificial surfaces with specific tribologic properties.

Finally, we also consider a composite material with varying elastic properties, i.e. in which the elastic modulus is characterized by a linear grading. This can be found for example in functionally-graded composite materials, i.e. inhomogeneous materials whose physical properties are designed to vary stepwise or continuously [17,18] to manipulate global properties such as elasticity, thermal conductivity, hardness etc. These types of composite materials are widely adopted in practical applications, so that it is useful to investigate their frictional properties. A linear grading of elastic properties can be also combined with a local change of surface roughness in order to exploit both effects.

2. Spring-block model

In order to study the effect of varying local friction coefficients on a surface, we adopt the one-dimensional spring-block model [19,20], which is schematically represented in Fig. 1: the material is discretized in N blocks of mass m along the direction of motion, connected by means of springs of stiffness K_{int} and rest length l_x. Each block is also attached by means of shear springs of stiffness K_s to a slider which is moving at constant velocity v. A normal pressure P is uniformly applied on the surface, so that the same normal pressure is acting on all blocks. A viscous force with damping coefficient γ in the underdamped regime is also added, in order to eliminate artificial block oscillations. Despite its simplicity, this model has already been used in many studies to investigate the frictional properties of elastic materials [11,21–30].

The blocks, representing a region of characteristic length l_x on the surface of the material, are in contact with an infinitely rigid plane. Friction at the block scale is introduced through the classical AC friction force: each block is characterized by microscopic static and dynamic friction coefficients, respectively μ_{si}, μ_{di}, extracted from a Gaussian statistical distribution. In the following, we will drop the subscripts s or d of the friction coefficients every time the considerations apply to both the coefficients.

This distribution does not necessarily represent the statistics of the contact points due to the surface roughness, rather it is a distribution of force thresholds for an elementary surface unit, used to provide an effective statistical description of the AC friction force at larger length scales than those relative to micro-scale phenomena. Though others can also be appropriate, the Gaussian distribution is a conventional choice that can be used to approximate any peaked distribution with parameters that are easily associated with the mean value and the standard deviation. The probability distribution is $p(\mu_i) = (\sqrt{2\pi}\,\sigma)^{-1}\exp[-(\mu_i - (\mu)_m)^2/(2\sigma^2)]$, where $(\mu)_m$ is the average microscopic coefficient and σ is its standard deviation. This distribution is adopted for both the coefficients but with different parameters.

The global friction coefficients, obtained from the sum of all the friction forces on the blocks, will be denoted with M, i.e. $(\mu)_M$. The global dynamic friction coefficient is calculated from the time average during the dynamic phase. The model does not include any wear phenomena or other long term effects occurring after the onset of macroscopic sliding. Results regarding the dynamic friction are to be intended within the limits of this approximation. The global static friction coefficient is calculated from the maximum of the total friction force during the initial static phase, identified using the absolute maximum of the number of moving blocks, representing a macroscopic sliding event. In most cases, this coincides with the maximum of the total friction force over time.

In summary, the forces acting of each block are: the shear elastic force due to the slider uniform motion, $F_s = K_s\cdot(vt + l_i - x_i)$, where x_i is the position of the block i and l_i is its starting rest position; the internal elastic restoring force between blocks $F_{int} = K_{int}\cdot(x_{i+1} + x_{i-1} - 2x_i)$; the normal force $F_n = P\,l_x l_y$ and the viscous force $F_d = -m\gamma\dot{x}_i$; finally, the AC friction force F_{fr}: if the block i is at rest, the friction force is equal and opposite to the resulting driving force, i.e. $F_{fr} = -(F_s + F_{int})$ up to the threshold $F_{fr} = \mu_{si}F_n$. When this limit is exceeded, a constant dynamic friction force opposes the motion, i.e. $F_{fr} = -\mu_{di}F_n$. Thus, the equation of the motion for the block i along the sliding direction x is obtained from Newton's law: $m\ddot{x}_i = F_{int} + F_s - m\gamma\dot{x}_i + F_{fr}$.

The friction coefficients are fixed at the beginning of the simulation by extracting their values from the chosen distribution with a pseudo-random number generator. We have adopted a generator based on the Mersenne-Twister algorithm [31]. The overall system of ordinary differential equations can be solved numerically with a fourth-order Runge-Kutta algorithm with constant time step integration [32]. Since the friction coefficients of the blocks are assigned after generating them with a pseudo-random number generator from the chosen distribution at each run, the final result of any observable consists on an average of various repetitions of the simulation. Usually, we assume an elementary integration time step $h = 10^{-4}$ ms and we repeat the simulation about twenty times for statistical reliability.

The values of the parameters can be assigned by relating them to the macroscopic properties of the material, such as the Young's modulus E, the shear modulus G, the mass density ρ, the transversal dimensions l_y, l_z and the total length $L_x = Nl_x$. The mass is $m = \rho\,l_x l_y l_z$, the stiffnesses are $K_{int} = E\cdot(N-1)l_y l_z/L_x$ and $K_s = G\cdot l_y l_x/l_z$. The stiffnesses are assumed constant for all the blocks, also in presence of different roughnesses, unless grading is explicitly introduced (see Section 6). This choice is made to reduce the number of free parameters of the model, but other formulations are equally valid (e.g. with constant friction coefficients and a statistical dispersion on the stiffnesses) and would not significantly affect the qualitative behaviour. We choose the global shear modulus as $G = 5$ MPa, the Young's modulus $E = 15$ MPa, the mass density $\rho = 1.2$ g/cm^3, which are typical values for a rubber-like material with Poisson ratio $\nu = 0.5$.

The length l_x is an arbitrary parameter representing the elementary discretization of the material and, consequently, the smallest surface feature that can be described in the model. We have fixed $l_x = 0.05$ mm,

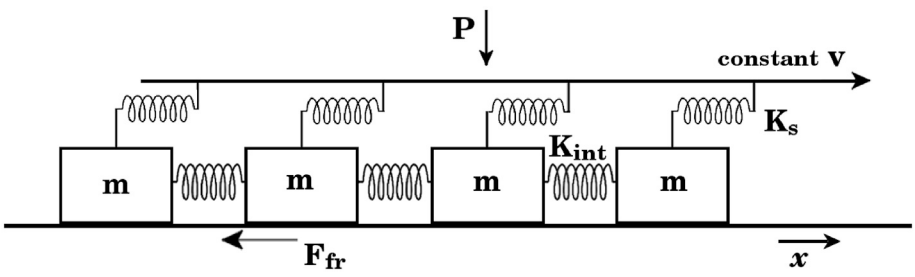

Fig. 1. Schematic of the spring-block model with the notation used in the text.