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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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