Static and dynamic friction of hierarchical surfaces

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Hierarchical structures are very common in nature, but only recently have they been systematically studied in materials science, in order to understand the specific effects they can have on the mechanical properties of various systems. Structural hierarchy provides a way to tune and optimize macroscopic mechanical properties starting from simple base constituents and new materials are nowadays designed exploiting this possibility. This can be true also in the field of tribology. In this paper we study the effect of hierarchical patterned surfaces on the static and dynamic friction coefficients of an elastic material. Our results are obtained by means of numerical simulations using a one-dimensional spring-block model, which has previously been used to investigate various aspects of friction. Despite the simplicity of the model, we highlight some possible mechanisms that explain how hierarchical structures can significantly modify the friction coefficients of a material, providing a means to achieve tunability.

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I. INTRODUCTION

The constitutive laws of friction are well known in the context of classical mechanics, with the Amontons-Coulomb (AC) law, which states that the static friction force is proportional to the applied normal load and independent of the apparent contact surface and that the dynamic friction is independent of the sliding velocity [1]. This law has proved to be useful in many applications. However, due to advances in technologies, with the possibility to perform high-precision measurements and to design microstructured interfaces, its validity range was tested and some violations were observed in experiments (see, e.g., [2,3]). Indeed, despite the apparent simplicity of the macroscopic laws, it is not easy to identify the origin of friction in terms of elementary forces and to identify which microscopic degrees of freedom are involved.

For these reasons, in recent years many models have been proposed [4], additionally incorporating the concepts of elasticity of materials, in order to explain the macroscopic friction properties observed in experiments and to link them to the forces acting on the elementary components of the system. Although many results have been achieved, it turns out that there is no universal model suitable for all considered different materials and length scales. The reason is that the macroscopic behavior, captured in a first approximation by the AC friction law, is the result of many microscopic interactions acting at different scales.

As pointed out by Nosonovsky and Bhushan [5,6], friction is intrinsically a multiscale problem: The dominating effects change through the different length scales and span from molecular adhesion forces to surface roughness contact forces. Hence, there are many possible theoretical and numerical approaches, depending on the system and the length scales involved (see Ref. [4] for an exhaustive overview).

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The situation is much more complicated if the surfaces are designed with patterned or hierarchical architectures, as occurs in many examples in nature: The hierarchical structure of the gecko paw has attracted much interest [7–13] and research has focused on manufacturing artificial materials reproducing its peculiar properties of adhesion and friction. In general, the purpose of research in bio-inspired materials is to improve the overall properties (e.g., mechanical) by mimicking nature and exploiting mainly structural arrangements rather than specific chemical or physical properties. In this context, nano- and bio-tribology are an active research field in terms of both experiment, theory and simulations [14–21].

Since hierarchical structures in nature present such peculiar properties, it is also interesting to investigate their role in the context of tribology, trying to understand, for example, how structured surfaces influence the friction coefficients. This can be done by means of numerical simulations based on *ad hoc* simplified models, from which useful information can be retrieved in order to understand the general phenomenology. From a theoretical and numerical point of view, much remains to be done. For this reason, we propose a simple model, i.e., the spring-block model in one dimension, in order to explore how macroscopic friction properties depend on a complex surface geometry.

The paper is organized as follows. In Sec. II we present the model in detail and discuss results for nonstructured surfaces, which are useful to understand the basic behavior of the system. In Sec. III we present results for various types of patterned surfaces. In Sec. IV we discuss the results and provide the conclusions and future developments of this work.

II. MODEL

As stated in the Introduction, the purpose of this work is to investigate the variation of friction coefficients in the presence of structured surfaces, also taking into account material elasticity. With this in mind, we start from a

