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Model of friction to take into account the sliding distance dependence and its memory effect

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ABSTRACT

Materials sliding on a larger substrate age faster than the substrate itself, but no available model of friction takes into account this aspect. We developed a model based on the memory effect of both the mobile and the plane samples, separately, and characterized by macroscopic geometric measurements (e.g., sliding distances and samples sizes). We studied the contact between fresh paper samples and samples that have already underwent several slidings. Experimental and theoretical results are in good agreement. Finally, we used our model to demonstrate how the existing test methods can lead to differences in the measured forces of friction. The results allow both a better understanding and quantitative characterization of the dependence of friction with the history of the contact.

1. Introduction

The force of friction between two surfaces may depend on the distance of relative sliding. This dependence was intensively studied for sliding distances at a microscale (e.g., static-to-kinetic transition [1]) or for long runs (e.g., wear). However, the dependence of the friction force to sliding distances of the scale of the samples (e.g., few centimeters) remains poorly characterized. Yet this dependence influences the stability of stacks [2] or the touch-feel of tissues [3], for example.

To study this influence of the sliding distance on the friction force, we consider the force of kinetic friction induced by a paper-on-paper contact [4]. Indeed, macroscopic sliding distances between papers induce drops in friction force: a logarithmic-shape decrease up to −50% in 30 cm is typically observed [5–8]. Moreover, this decrease has a persistent memory effect [6]: if the experience is interrupted, the next value of friction is equal to the one prior to the stop, even for hours. Finally, the decrease in friction force with the sliding distance is identical considering (i) one direction, (ii) the opposite direction, and (iii) when switching from one direction to the opposite direction [6–8]. A reorientation of surface structures (e.g., cellulosic fibers) in the direction of the sliding may explain these phenomena [7,8].

A model of the friction force evolution is needed to engineer mechanisms involving friction. Such a model is however still missing for sliding distances of the scale of the samples length. Moreover, the friction force is considered in standards (i) during the first and third repeated slidings, (ii) on a distance of 10 cm, (iii) in the same sliding direction, and (iv) from the same starting point, as the solid is repositioned to its original place after each sliding [9–11]. Two measurements are however not sufficient to properly describe the whole decrease, in particular during the first sliding. In addition, the measurements are time consuming, as numerous repeated slidings are required. The decrease in friction force with the sliding distance may be also wrongly assimilated to the transition from the break-away force to the force of kinetic friction: both decreases have the same shape, but (i) take place on different scales, (ii) are due to different mechanisms, and (iii) have different memory effects. Finally, the force of friction measured on a given sliding distance cannot be considered equal to the one obtained for another sliding distance. Thus, comparing the results obtained with two standards using different sliding distances [7] becomes unfounded. Similarly, the force of friction measured after a 10 cm slide cannot be compared to the friction measured in industrial processes, where the typical characteristic length is of few meters.

Characterizing the decrease in friction force with the sliding distance while minimizing the number of experiments is a challenge we propose to face. We will first propose a theoretical model of the decreasing friction force. Then, we will present the materials and method used for both identification and validation of the proposed model. Finally, the

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results of the experiments will be presented, and both the proposed model and the experimental method will be discussed.

2. Proposed friction model

We develop a model that links the force of friction to dimensional parameters – in particular the sliding distance and the sizes of the samples. We consider a *mobile* sample sliding on a *plane* sample. The surface of both samples has surface structures, reoriented in the direction of the sliding. The size of these structures is infinitesimal compared to the size of the samples.

We call $f_{f,0}$ the contribution to the force of friction, per unit apparent contact area, for surface structures that are fully reoriented in the direction of the sliding (expressed in N m^{-2}). When the surface structures are not fully reoriented in the direction of the sliding, the force of friction increases. The contributions of mobile and plane surface structures to this increase, per unit apparent contact area, are noted $f_{f,mobile}$ and $f_{f,plane}$, respectively (expressed in N m^{-2}). Thus, the force of friction, F_f, is calculated as the sum of those different contributions on the whole apparent contact surface, S:

$$F_f = \int_S \left(f_{f,0} + f_{f,mobile} + f_{f,plane} \right) \, \mathrm{d}S \tag{1}$$

We consider that the mobile and plane surfaces are made from the same material. Their surface structures are therefore of the same nature. Thus, the contribution of these structures to the friction force ($f_{f,mobile}$ and $f_{f,plane}$) can be described by the same function f_f. Literature suggests that the sliding modifies the force of friction. Therefore, we propose that the f_f function depends on the total sliding distances underwent by the surface structures, called *local sliding distances*:

$$\begin{cases} f_{f,mobile} = f_f(d_{mobile}) \\ f_{f,plane} = f_f(d_{plane}) \end{cases} \tag{2}$$

where d_{mobile} and d_{plane} represent the local sliding distances of the mobile and plane surface structures, respectively.

We consider a mobile of length L moving on a plane. At a time t of the sliding number N, the mobile moved from a distance $d(t)$, as represented in Fig. 1.

At a position x of the contact, the local sliding distances are given by

$$d_{mobile}(x,t) = d(t) + D \cdot (N-1) \tag{3}$$

$$d_{plane}(x,t) = \begin{cases} (N-1) \cdot x + N \cdot d(t) & \text{if } x + d(t) < L \\ N \cdot L - x & \text{if } L < x + d(t) < D \\ N \cdot (L-x) + (N-1)(D-d) & \text{if } D < x + d(t) \end{cases} \tag{4}$$

We exemplified these evolutions in Fig. 2.

In particular, the local sliding distances are constant along the samples width, W. Thus, Eq. (1) becomes

$$F_f = W \int_0^L \left(f_{f,0}(x) + f_f(d_{mobile}(x)) + f_f(d_{plane}(x)) \right) \, \mathrm{d}x \tag{5}$$

The functions $f_{f,0}$ and f_f have to be identified to determine F_f. To identify the f_f function, the local sliding distances of both the mobile (d_{mobile}) and the plane (d_{plane}) have to vary separately. In the next section, we will therefore propose a method to achieve this identification. Then we will validate experimentally the model.

3. Materials and method

3.1. Methods

We call hereafter *fresh* and *old* materials that underwent no sliding and 10 repeated slidings, respectively. We carried out three different experiments involving 10 repeated slidings (from $N=1$ to 10):

(i) *PlaneChange* (PC$_N$) – After each repeated sliding, (i) the plane sample is replaced by a fresh one, and (ii) the mobile is lifted and placed at its initial position.

(ii) *MobileChange* (MC$_N$) – After each repeated sliding, the mobile sample is replaced by a fresh one, and placed at its initial position.

(iii) *NoChange* (NC$_N$) – After each sliding, the mobile is lifted and placed at its initial position without replacing any sample. The experiment corresponds to the standard conditions.

Each experiment is carried on 10 different pairs of samples, and the results are averaged. The local sliding distances of the materials at the beginning of the second repeated sliding of each experiment are represented in Fig. 3.

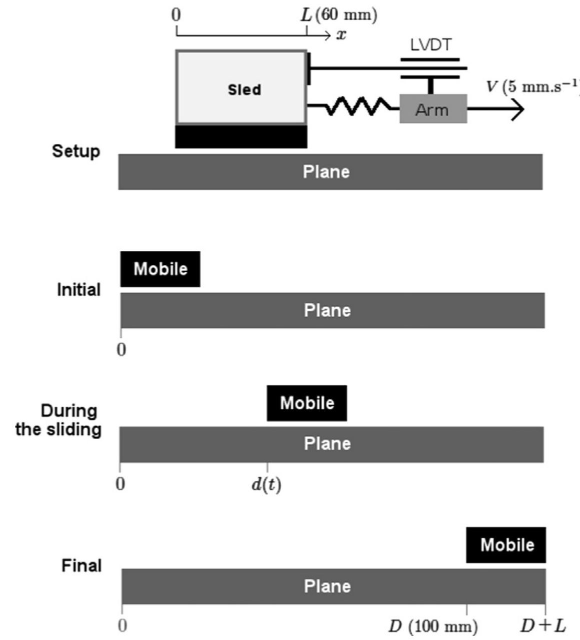

Fig. 1. Schematic view of the experimental setup. An arm moves at constant speed V. A spring and a linear variable differential transformer (LVDT) position sensor are placed between a weighted sled and the arm. The sled has a length L and slides on a plane. The rear of the mobile slides from 0 to D. At a time t during the sliding, the position of the mobile rear is $d(t)$. The position on the contact is called x.

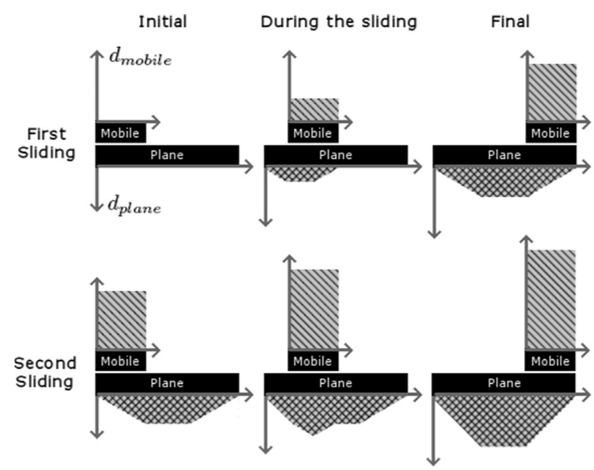

Fig. 2. Evolution of the local sliding distances of a plane (d_{plane}, double-hashed areas) and a mobile (d_{mobile}, simple hashed areas) during two repeated slidings.