Dry friction: influence of the position of the center of mass on the static friction coefficient and the acoustic emission energy distribution

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Abstract: An experimental study of the dry friction of an aluminum block driven at constant velocity on sandpaper is presented. We have measured the behavior of the pulling force and the generated acoustic emission signals. The goal is to investigate what is the influence of the variation of the position of the center of mass of the block. The results reveal that friction is bigger when the center of mass of the block is closer to the pulling point, although no significant changes have been found on the properties of the acoustic emission. A possible theoretical model for the understanding of the observed dependence of friction with the position of the center of mass is discussed.

I. INTRODUCTION

Tribology is *the science and technology of interacting surfaces in relative motion* [1], equivalently the study of friction between two solid surfaces in contact.

Friction is a macroscopic force, which appears when a body is in contact with a solid surface, that opposes to the relative movement. Friction is a complex phenomenon and it is due to electromagnetic attractive forces which generate chemical bonds between the surface molecules of the two bodies in contact. At atomic scales, friction depends on the number of chemical bonds which depends on the microscopic contact area between the two bodies. This area is a very small fraction of the macroscopic contact area because the surfaces always have roughness at atomic scales [2].

At macroscopic scales, there are three basic laws of the solid friction: 1) friction between two bodies is proportional to the normal force, 2) it is independent of the dimensions of the bodies in contact and 3) it is independent of the sliding velocity. The laws 1) and 2) were proposed by Leonardo da Vinci and later by Amontons, while law 3) was proposed by Coulomb. These laws are the result of empirical observations and it is easy to find exceptions as we will see in this work [3]. We can measure two types of friction forces: the static friction F_{fs} and the kinetic friction F_{fk}. The static friction is the force which opposes the applied force to a body in contact with a solid surface and that it keeps the body static. It has the same module as the applied force until a certain maximum value which corresponds to the minimum applied force to slide the block over the surface. This maximum value is proportional to the normal force N between the body and the surface and the proportionality constant (static friction coefficient μ_s) depends on the temperature and the type of materials [2].

$$F_{fs} \leq \mu_s N \tag{1}$$

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The kinetic friction is the force that appears when the applied force to the body is higher than the static friction and the body slides over the surface. It opposes to the movement and it is supposed to be constant and independent of the applied force. It is proportional to the normal force with a proportional constant called kinetic friction coefficient μ_k which is smaller than μ_s [2], [4].

$$F_{fk} = \mu_k N \tag{2}$$

The above descriptions of these two friction forces are empirical approaches and reality is more complex. The main goal of this work is to investigate if friction also depends on the position of the center of mass of the body on which it acts. To do this, we will slide, pulling with a string, a block over a rough surface at constant speed and we will add weights of different mass at different positions over the block. We will measure the friction as a function of the distance of the extra weights to the pulling point. Simultaneously, we will measure the generated acoustic emission signals during the sliding process in order to investigate possible microscopic differences.

The acoustic emission (AE) signals are high frequency elastic waves which propagate from the contact area producing small displacements at the surface of the block that sensors can detect. These waves are generated by the elastic or plastic deformation of asperities (microscopic contact areas), fractures of asperities or the adhesion between asperities while the block slides over a rough surface. The energy and the number of AE signals can depend on the surface topographic characteristics, the sliding speed, the number of microscopic contact areas which depends on the normal force between the surfaces, the types of materials and the frictions coefficients [5].

In this work, we will perform similar experiment to do of other students in previous years but we will focus on the influence of the variation of the position of the center of mass of the block in the AE energy distribution and friction [6], [7].

II. EXPERIMENTAL SETUP

The experimental setup consists in an aluminum parallelepipedic block which slides over a silicon carbide paper of 1000 grit. The mass of the block is 168 g and its dimensions are 50 x 100 x 12 mm. The block is connected to a Z005 Zwick/Roell testing machine through an inextensible fluorocarbon thread. This testing machine is able to pull the block at a constant and slow velocity and simultaneously can measure by a load cell the applied force to the block which coincides with friction. All the experiments were made with a constant velocity of 5 mm/min. Moreover, we place cylindrical weights of 20 mm diameter above the block at different positions d (Fig.(2)) in order to change the position of the center of mass. The experimental setup is shown in Fig.(1).

FIG. 1: Image of the experimental setup.

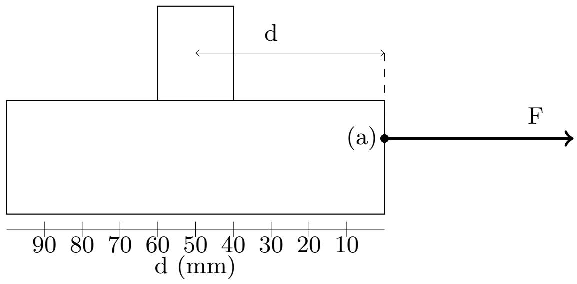

FIG. 2: Figure that shows the different positions d of the weight above the block in relation to the pulling point (a) where F is the pulling force.

In order to record the AE signals the AE sensor is placed on the middle of the block with a thin layer of vaseline between the sensor and the surface of the block to improve the detection of the signals. This sensor converts the mechanical energy of the elastic waves into an electrical signal which is pre-amplified (60 dB) and sent to a computer where the data is analysed with a PCI-2 acquisition system from Physical Acoustics Corporation.

The software AEWIN allows data processing and the configuration of the parameters to perform the measurements. The most important parameters that must be configured are the HDT (Hit Definition Time) and the Threshold. The Threshold is the value above which the setup starts to record the AE signals (hit) and it is important to avoid external noise. The HDT is used to separate two different hits, it is the time that a hit lasts when the signal falls below the Threshold. All the experiments were done with 23 dB of Threshold and 200 μs of HDT. The software converts the electrical signal V of the hits in energy with the equation:

$$E = \frac{1}{R}\int_{t_o}^{t_f} V(t)^2\, dt \qquad (3)$$

where R = 10 $k\Omega$ is a reference resistance, t_o is the time when the hit starts and t_f is the time when it finishes [8]. Two weights of 300 g and 800 g were used in the experiments which were performed under the same conditions and parameters. Firstly, the experiment was repeated (without recording the AE signals) putting the weights in different distances of the pulling point of the block: for the weight of 300 g at distances of 10, 20, 30, 40, 50, 60, 70, 80 and 90 mm and for the weight of 800 g at distances of 10, 20, 50, 80 and 90 mm. Also, the experiment was repeated at distances of 10, 20, 80 and 90 mm with the AE sensor recording the AE signals for every weight.

III. RESULTS

A. Friction measurements

Fig.(3) and Fig.(4) show the evolution of friction during the pulling of the block for the weight of 300 g (Fig.(3)) and the weight of 800 g (Fig.(4)) at different distances of the pulling point of the block. In both graphs we see two different behaviours. At first, when the applied force is not enough to move the block, the graphs show that friction increases linearly (static friction regime) until the maximum of the static friction F_{fs} (Eq. (1)).

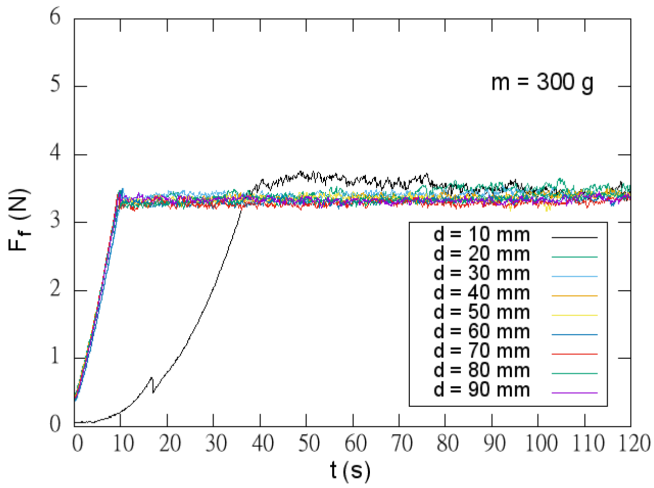

FIG. 3: Friction F_f against time t for the weight of 300 g at different distances of the pulling point d.

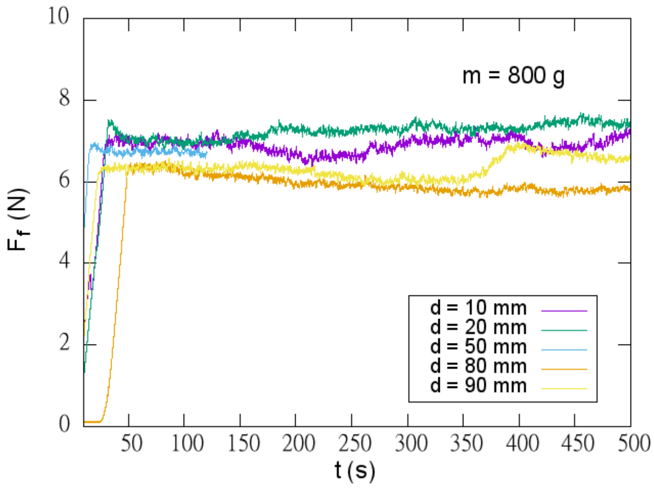

FIG. 4: Friction F_f against time t for the weight of 800 g at different distances of the pulling point d.

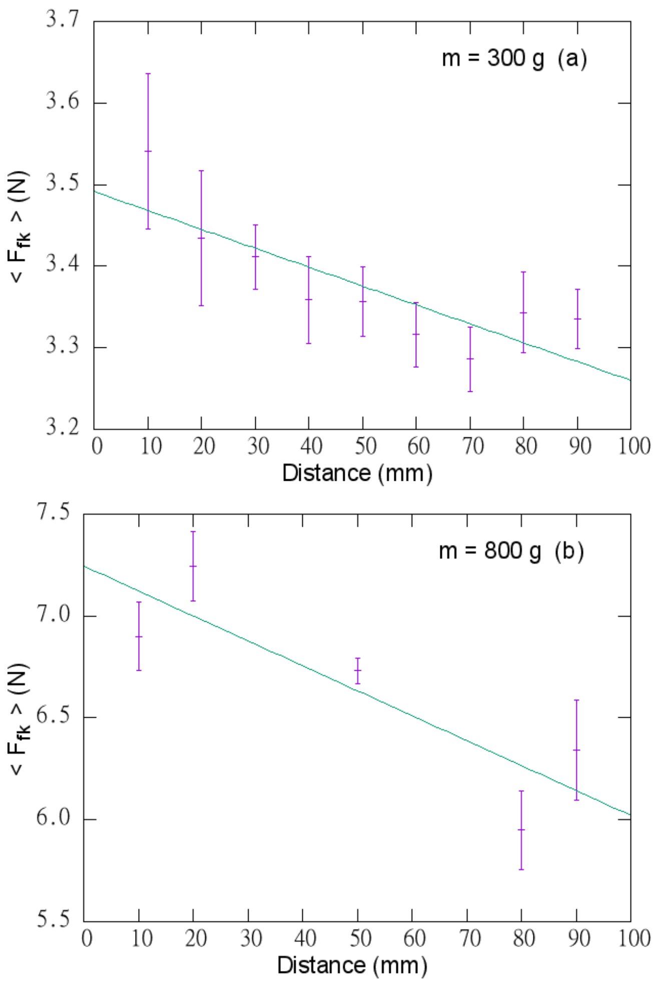

FIG. 5: Average of the kinetic friction $< F_{fk} >$ against the distance of the pulling point for the weight of 300 g (a) and the weight of 800 g (b).

Then the block starts to move and friction falls until a constant value F_{fk} (Eq. (2)) (kinetic friction regime) but with periodic fluctuations which are not described by the three laws of friction. Making the average of all these fluctuations (Fig.(5)) we see that the kinetic friction F_{fk} increases as the weight is closer to the pulling point which indicates that F_{fk} depends on the position of the center of mass of the block.

B. Acoustic emission measurements

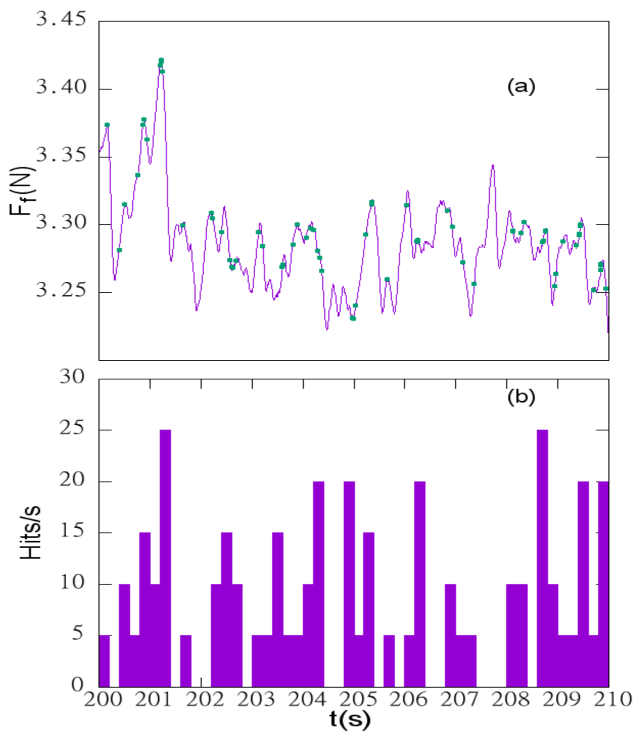

FIG. 6: Friction F_f against time t for the weight of 300 g at 10 mm of distance of the pulling point (a). Histogram of the number of hits (AE signals) against the time t at 10 mm of distance for the weight of 300 g (b). Each bin is 0.2 second wide.

In Fig.(6), the results corresponding to the weight of 300 g at 10 mm of distance of the pulling point of the block are presented. We can see in Fig.(6) (a) the behaviour of the kinetic friction during a interval of 10 seconds where the green points correspon to the hits (AE signals). In Fig.(6) (b), a histogram of the hits activity during the same interval of time is represented. Comparing (a) and (b), we can see that the hits appear statistically during the decreases of the force. In Fig.(7), a histogram of the energy of the hits is represented in log scale for the weight of 300 g (Fig.(7) (a)) and for the weight of 800 g (Fig.(7) (b)) at different distances of the pulling point of the block (10, 20, 80 and 90 mm). In both graphs, we cannot observe any differences between the different positions of the center of mass of the block.

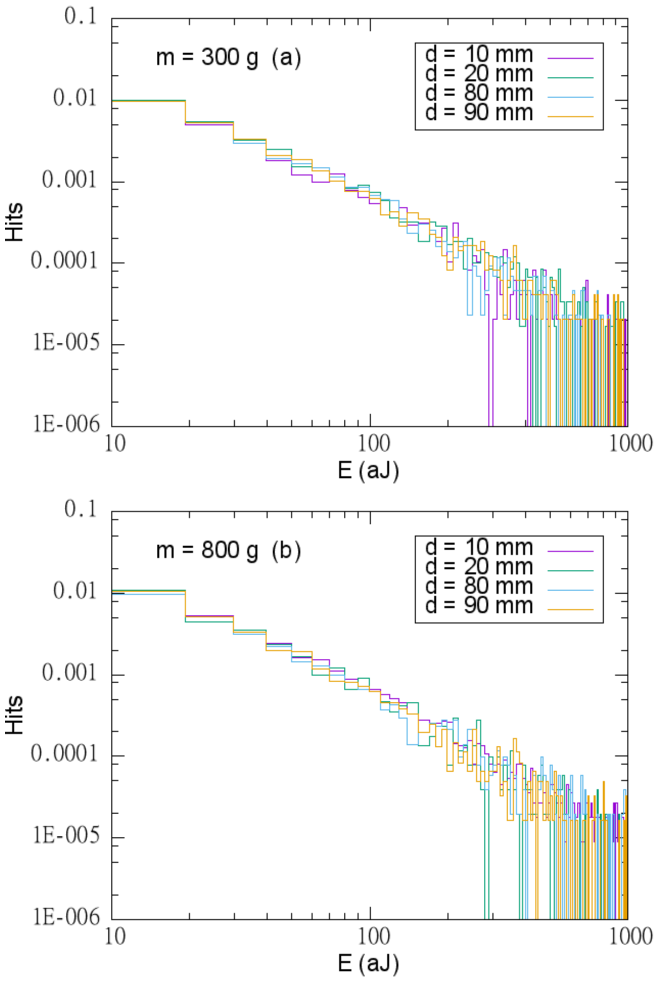

FIG. 7: Histogram in log scale of the energy E of the hits (AE signals) at different distances of the pulling point d for the weight of 300 g (a) and the weight of 800 g (b).

IV. THEORETICAL MODEL

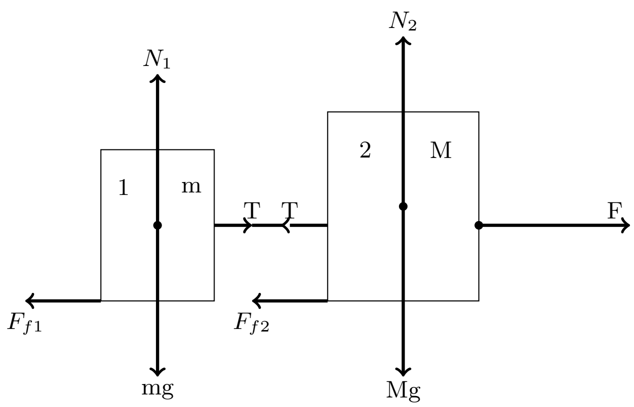

FIG. 8: Figure that shows the forces which act on two bodies of different masses (M, m) connected by a inextensible thread when a force F pulls one of the bodies.

In this section, a possible theoretical model to understand the dependence of friction with the position of the center of mass is discussed.

We will consider the following situation (Fig.(8)) that is a simplified model for a solid with a certain mass distribution:

Two bodies (1, 2) with different masses (M > m) are connected by a inextensible thread over a horizontal surface. Then, we apply a horizontal force F to the body 2 to move the two bodies. Friction forces F_{f1} and F_{f2} act on the bodies 1 and 2. The tension of the thread T mimics a internal force between the two parts of the global system (1, 2). Moreover, we have the normal and gravity forces (Fig.(8)).

Applying the Newton's laws [2] for the two bodies before they move, we obtain the following equations for the horizontal components:

$$F - T - F_{f2} = 0 \tag{4}$$

$$T - F_{f1} = 0 \tag{5}$$

Note that if we add the Eq. (4) and the Eq. (5) we obtain:

$$F = F_{f1} + F_{f2} \tag{6}$$

We have a problem of two equations (Eq. (4), (5)) with three unknowns (T, F_{f1}, F_{f2}) so we can only determinate the sum of the two friction (Eq. (6)) but not it them individually. To proceed, this theoretical model supposes that F_{f1} and F_{f2} are while possible proportional with a unknown coefficient α which might depend on the position of the center of mass:

$$F_{f1} = \alpha F_{f2} \tag{7}$$

Fig.(9) describes the friction behavior during the pulling process of the bodies according to this model where F_{f1} corresponds to the body of mass m and F_{f2} to the body of mass M (independently of the positon of the bodies):

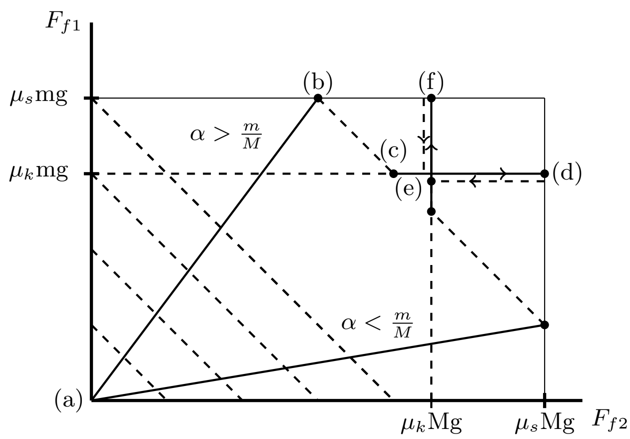

FIG. 9: Graph which shows the friction behavior of the two bodies (F_{f1}, F_{f2}) according to this theoretical model.

The big rectangular area corresponds to the region with the allowed values of F_{f1} and F_{f2} taking into account that they cannot be bigger than the maximum value of the static friction.

We will focus on the case of $\alpha > \frac{m}{M}$. At the beginning, F_{f1} and F_{f2} are static friction and they increase proportionally with the applied force F from the point (a) to the point (b) keeping the ratio α. When F_{f1} reaches its maximum value ($\mu_s$mg) (point (b)) it falls to a constant value ($\mu_k$mg) (point (c)) keeping constant the value of F (Eq. (6)) and it becomes to a kinetic friction before F_{f2}. In this moment, given that F_{f2} is still a static friction, the bodies remain stopped. After that, F_{f2} continues to increase (segment (c)-(d)) until it reaches its maximum value (μ_sMg) (point (d)) while F_{f1} keeps the same value. Finally, F_{f2} decreases to its constant value of the kinetic friction (μ_kMg) (point (e)) and the bodies start to move because both friction forces (F_{f1}, F_{f2}) have already reached the value of the kinetic friction.

When F_{f2} reaches its maximum value (point (d)), according to the Eq. (6) we have that:

$$F = \mu_k mg + \mu_s Mg \tag{8}$$

However, in the case of $\alpha < \frac{m}{M}$ we obtain in the point (f) that:

$$F = \mu_s mg + \mu_k Mg \tag{9}$$

If we consider that μ_k and μ_s are constants coefficients and they do not depend on the mass of the bodies and taking into account that M > m and $\mu_s > \mu_k$, we obtain that the applied force to the bodies F (Fig.(8)) which coincides with the total friction is bigger in the case of $\alpha > \frac{m}{M}$ (Eq. (8)) than in the case of $\alpha < \frac{m}{M}$ (Eq. (9)). Finally, if we suppose that friction of the furthest body to the pulling point always becomes in a kinetic friction before the other, we obtain that the case of $\alpha > \frac{m}{M}$ (Eq. (8)) corresponds to the mass M closer to the pulling point (Fig.(8)) and the case of $\alpha < \frac{m}{M}$ (Eq. (9)) to the opposing situation so friction is bigger when the biggest mass is closer to the pulling point.

V. CONCLUSIONS

In this work, we have experimentally studied the problem of the dry friction between an aluminum block, moving at constant velocity, and a rough surface. We have focused on the influence of the position of the center of mass on different properties: first on the value of friction opposing to the pulling force and second on the microscopic acoustic emission signals generated during the sliding process.

The results have revealed that (i) both the static friction coefficient and the average kinetic friction coefficient depend on the distance of the center of mass to the pulling point (both are bigger when that distance is smaller), and (ii) no significant changes occur in the energy distribution of the AE signals.

We cannot provide a full explanation for these experimental observations but we have proposed a very simplified model that could explain the dependence of the static friction coefficient with the position of the center of mass. The model considers a block divided into two subblocks and extends the standard hypothesis for the static and the kinetic friction coefficients to the friction forces on each subblock. To solve the model we make two extra assumptions: these two friction forces on each subblock are proportional, and friction of the furthest subblock to the pulling point overcomes the static friction limit before the other, decreasing to the kinetic friction even if the block is not moving.

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