Acoustic Emission in Friction: influence of driving velocity and normal force.

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The purpose of this work is the study of the acoustic emission occurring when an aluminium block slides at imposed constant velocity over an emery cloth. It is evidenced that amplitude and energy of acoustic emission signals are statistically distributed following a mixed probability law. A criterion to distinguish two types of signals is established. The most abundant type of signals (type 1) follow an exponentially damped power law distribution. And the less abundant signals (type 2) follow a distribution centred at a certain typical value. Type 2 signals occur when the pulling force exhibits local maxima, prior to the sliding events.

I. INTRODUCTION

The etymological definition of tribology is the science of rubbing. The word comes from the Greek words *tribos* and *logos* which mean rubbing and science respectively. It comprehends what in popular English language is known as friction, wear and lubrication. Furthermore it can be defined as *the science of interacting surfaces in relative motion*[1]. Although the name is quite new (first reported in 1966) the interest in its constituent parts is much older. The first scientific approach to friction was done by Leonardo Da Vinci but his work had no influence due to the fact that his notes were not published. In 1699 Guillaume Amontons proposed two laws of friction. They state that friction force is independent of the apparent area of contact and it is proportional to normal force. In 1785 Charles-Augustin Coulomb proposed the third law of friction which postulates that friction force is independent of the sliding velocity.[2]

From a macroscopic point of view there are two types of friction force. One is called static friction and it is defined as the minimum lateral force needed to start the relative motion of the objects. It limits lateral motion in any direction and it is more a threshold than a true force. Since it does not involve displacement work is not done. The other type of force is kinetic friction and it is the force needed to maintain sliding at steady velocity. It is related to dissipation mechanisms. And it is equal to the work done on the system divided by the amount of distance displaced.[3]

From a microscopic point of view the kinetic friction force made to maintain the sliding at steady velocity shows deviation from constant behaviour. The plot of the force with the time presents some sort of sawtooth shape without constant periodicity.

The focus of this work is the study of acoustic emission (AE) which is known to happen in the materials while they slide one from each other. Acoustic emission consists in the emission of elastic waves due to a sudden redistribution of stress in a material. The generated waves travel from its source to the surface where they are measured. Technology enables the detection of surface oscillations of picometer order. AE examination is useful in the study of fractures and has many applications in engineering like weld monitoring, bridges, aerospace structures...[4] Despite the previously cited applications the goal of this work is to analyse the data obtained from AE measurements from an "out-of-equilibrium" statistical mechanics point of view looking for the existence of possible critical behaviour.

Laura Menéndez Vallejo studied the acoustic emission in sliding friction of an aluminium block moving over an emery cloth before this work. She repeated the experiment for emery clothes of different grit (800 and 1000). And found that two types of AE hits with two different duration ranges emerge as grit increases. Moreover the energies and amplitudes of the hits with shorter duration seemed to be distributed as predicted by power law in the range of small values.[5] The focus of this work is the study of AE changing the velocity and changing the normal force. It is also focused on the understanding of the instants of occurrence of the AE signals.

II. EXPERIMENTAL SETUP.

The setup (see fig. 1 (a) and (b)) consists in an aluminium block, which is dragged over an emery cloth by a Z005 Zwick/Roell testing machine that applies the required tension, to keep the block moving at constant velocity, through a fluorocarbon thread, which can be considered inextensible. The thread is knotted to the testing machine and a load cell which is screwed to the block. An AE sensor is placed on the block which records ultrasonic signals with frequencies spanning from 100kHz to 3MHz. A thin layer of vaseline is placed between the sensor and the block in order to improve the acoustic coupling of the transducer. The aluminium block dimensions are $1.3 \times 9.6 \times 5.0$ cm and its mass is 161.54 g. The emery cloth is grit 1000, its dimensions are $22,8 \times 28$ cm and it is made of silicon carbide. The output signal of the transducer is preamplified (by 60dB) and sent to a

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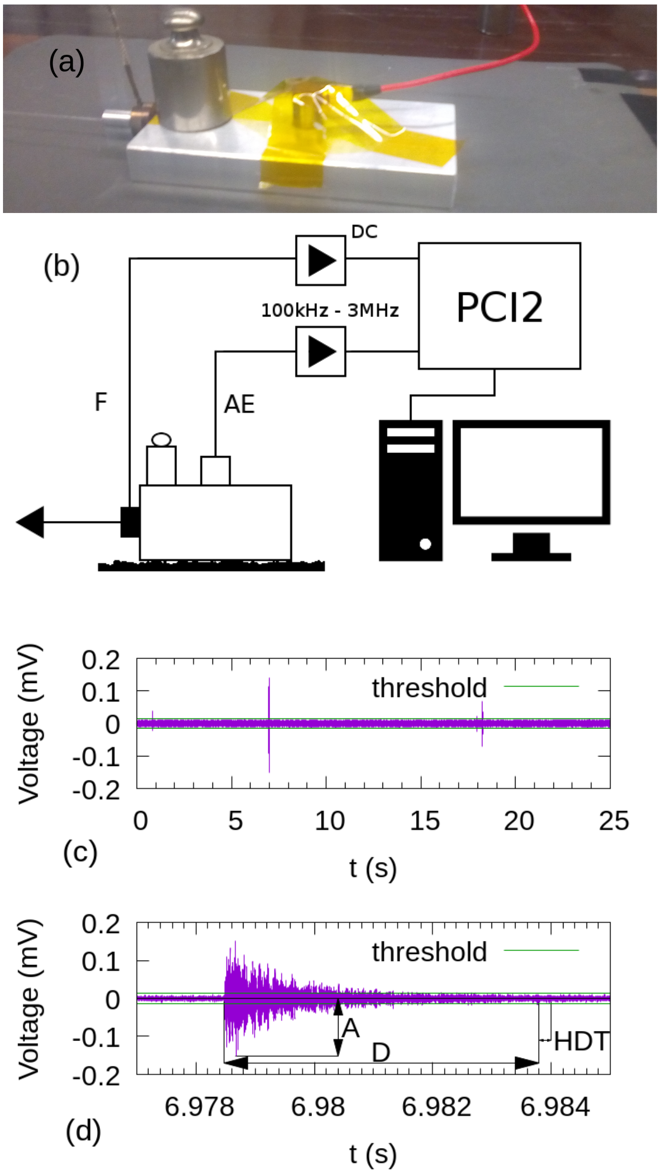

FIG. 1: (a) Image of the experimental setup. (b) Sketch of the experimental setup. (c) Example of voltage signal against time t. (d) Close up of fig 1 (c).

computer which receives the data by means of a PCI-2 acquisition system from Euro Physical Acoustics. The system picks up and processes the voltage of the transducer at 40MHz sampling rate. The system also acquires the signal of the load cell (after amplification) at 100Hz sampling rate.

Fig 1 (c) shows an example of voltage as a function of time. As can be seen the response of the system is a sequence of AE signals (called hits) separated by long periods without AE activity. This suggests avalanche-like response which can be studied by means of an appropriate statistical treatment. In order to mathematically define separated individual hits a threshold and a hit definition time (HDT) are defined. When the voltage of the transducer rises above the threshold a hit starts. The hit ends when the voltage falls and remains below threshold for more than a HDT. All experiments were done with a threshold equal to 23 dB ($14\mu V$) and a HDT of 200 μs. The value of the threshold was chosen looking upon the noise signal in a blank measurement.

The analysed variables come from two measurement sources. On the one hand the pulling force (F) is measured by the load cell. On the other hand the variables which characterize the AE signals (see fig. 1 (d)) of the individual hits are duration (D), amplitude (A) and energy (E). E is obtained using the following expression:

$$E = \frac{1}{R}\int_0^D V^2 dt \quad | \quad R = 10k\Omega \tag{1}$$

Hits with E lower than 5 aJ or D shorter than 1 μs are not taken into account. They are considered noise.

The results of the experiment are affected by a number of external control parameters: a weight settled on the block and the relative location of their centres of mass; the velocity of the block imposed by the pulling machine and the grit of the emery cloth. The first and third parameters modify the normal force and the friction constants respectively. The experiment was repeated for a constant velocity of 0.1mm/min at weights 0, 50 and 200g and for a fixed weight of 50g at velocities 0.1, 0.5 and 2.0 mm/min.

III. RESULTS

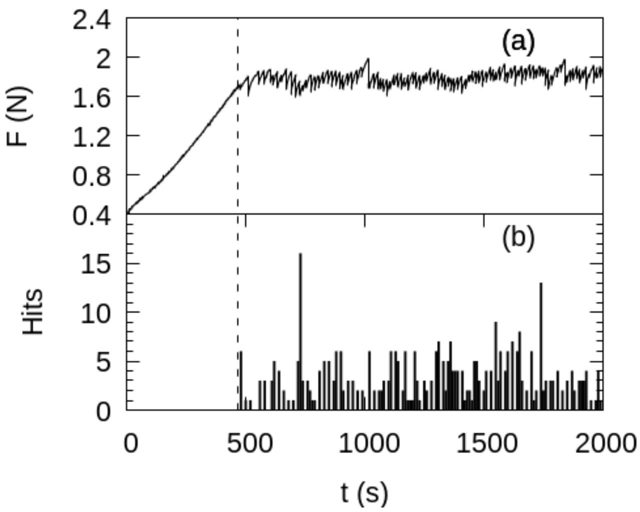

FIG. 2: (a) F against time (t) above. (b) Number of hits is against t. Each bin is 10 second wide. The dashed line separates the static and kinetic regime.

The behaviour of the friction force as a function of the motion of the block partly follows the Amonotons-Coulomb friction laws (see fig. 2). When the block is

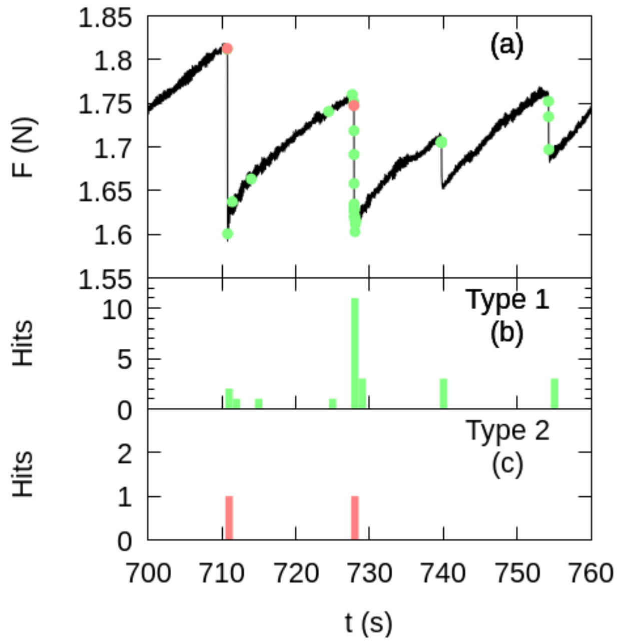

FIG. 3: (a) F against time (t) as a black line, type 1 hits as green circles and type 2 hits as red circles. (b) The number of type 1 hits against t. (c) The number of type 2 hits against t. Each bin is 1 second wide.

not moving the friction force increases matching F until a threshold value is reached and the block begins its motion, as expected. After the object starts its motion at constant velocity Amontons-Coulomb laws predict constant friction force proportional to normal force with a coefficient named kinetic friction coefficient. Nevertheless the plot of F against the time (t) shows some sort of sawtooth shape without constant periodicity (see fig. 2 and 3).

Looking at fig. 3 which is a magnification of fig. 2 it can be seen that most AE hits occur during the sharp drops of F. As a result of a criterion which will be established later, two types of hits will be studied and are shown separately in fig. 3 (b) and 3 (c).

In fig. 4 and 5 the A and E histogram of both hit types are represented as blue line.

Fig. 6 shows the maps of A against $20 \cdot log_{10}(D/1\mu s)$ where the colour stands for the number of hits included in the corresponding two dimensional bin. Each map describe the AE hits detected on the block moving at 0.1 mm/min and supporting different added weights (0g, 50g and 200g). Fig 6 (c) shows the emergence of two types of AE hits when the mass of the weight is increased. Therefore the green line on this map is used as a phenomenological criterion for the the separation of two kinds of signals. On one hand the hits with D lower than $D^*(A)$ will be considered belonging to type 1 group. On the other hand hits with higher D than $D^*(A)$ will form the type 2 group. The separation line depends on:

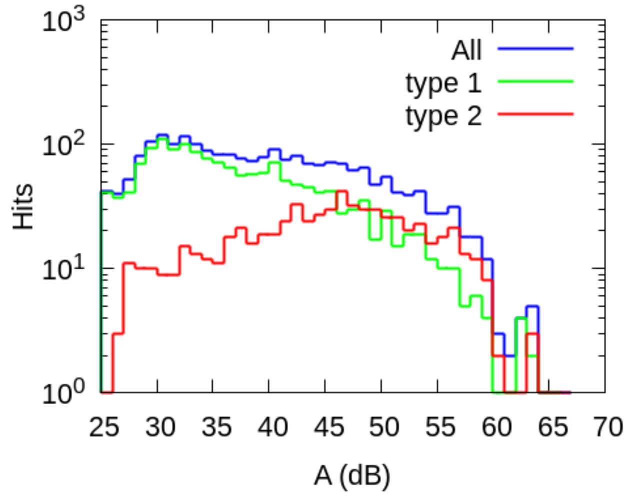

FIG. 4: Histogram of A. The blue line is the A histogram of both hit types. The green line is the A histogram of type 1 hits. And the red line is the A histogram of type 2 hits. Each bin is 1 dB wide.

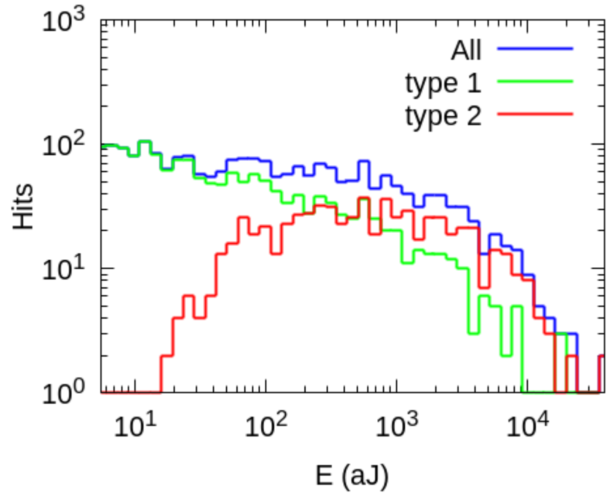

FIG. 5: Histogram of E. The blue line is the E histogram of both hit types. The green line is the E histogram of type 1 hits. And the red line is the E histogram of type 2 hits.

$$20 \cdot log_{10}\left(\frac{D^*(A)}{1\mu s}\right) = \frac{2}{7}A + \frac{461}{7} \qquad (2)$$

Fig. 7 shows a set of maps representing A against $20 \cdot log_{10}(D/1\mu s)$ for different velocities of the block. Clearly the distinction of the two types of signals vanish when the velocity increases.

Considering the criterion established by the eq. (2) and looking at fig. 3 (b) and (c) it is observed that type 2 hits are found on top values of F previous to the force drop and type 1 hits are distributed mainly all the way down during the force drop. This observation can be confirmed

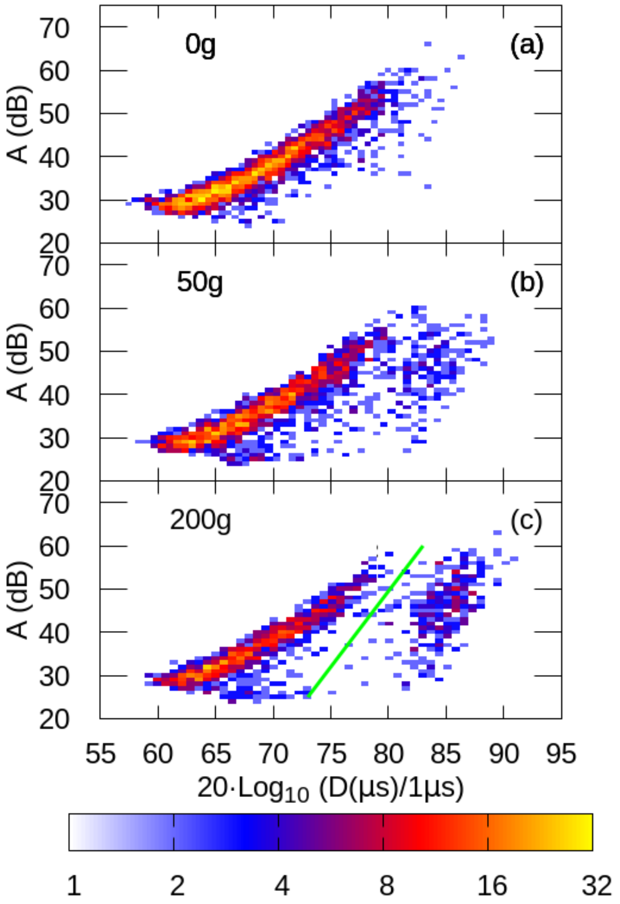

FIG. 6: Map of the A against the $20 \cdot log_{10}(D)$ for different weights added on the block. (a) no weight. (b) 50g. (c) 200g. The colour stands for the number of hits which belong to the corresponding two dimensional bin.

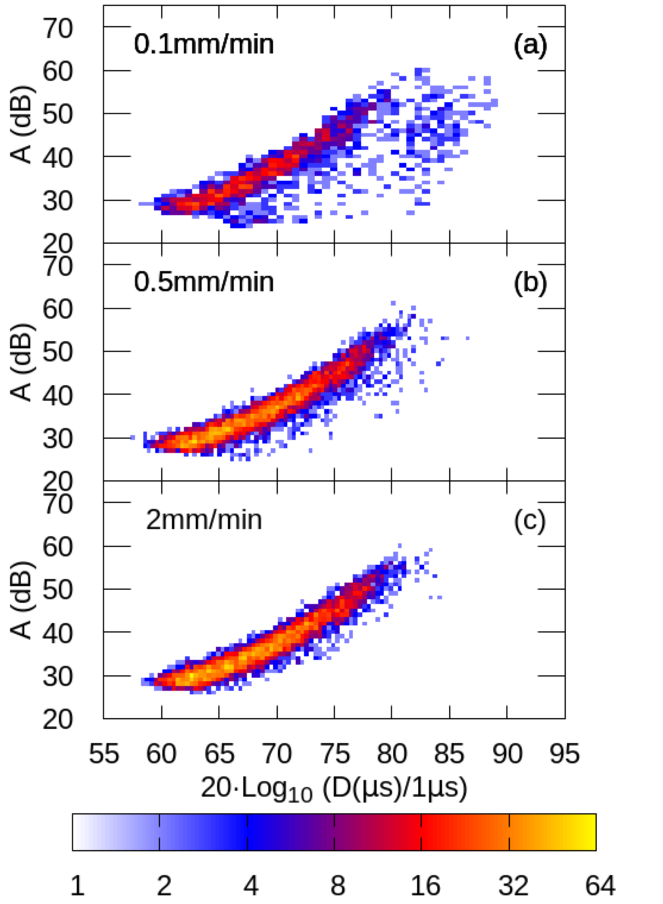

FIG. 7: Map of the A against the $20 \cdot log_{10}(D)$ for different velocities of the block. (a) 0.1mm/min above. (b) 0.5mm/min. (c) 2.0mm/min. The colour stands for the number of hits which belong to the corresponding two dimensional bin.

by studying the figure 8. In fig. 8 (a) the green line histogram represents the number of type 1 hits occurring when the F_k is registered against the force difference $F_k - F_{k-1}$ where F_{k-1} is the F measured when the previous hit was read disregarding its type. In fig. 8 (b) the red line histogram represents the same but the F_k is measured when type 2 hit takes place. Comparing the graphs it is clearly seen that type 2 hits tend to be at the top of the successive local F maxima since their F increments are mostly positive. In both representations there is an occurrence peak at zero F increment due to the fact that hits happen in a brief period of time.

In fig. 4 the A histogram of type 1 hits is sketched as green line and the histogram of type 2 hits amplitudes is drawn as red line.

In fig. 5 the E histogram of type 1 hits is drawn as a green line and the histogram of type 2 hits energies is sketched as red line. At first glance it seems that type 1 hits energy distribution may be described by a power law, also called fat tailed distribution, while the type 2 hits energy distribution is centred at some value. In order

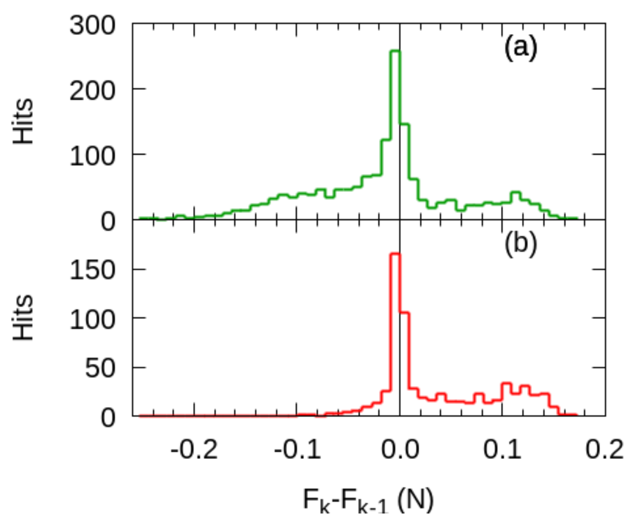

FIG. 8: (a) Histogram of $F_k - F_{k-1}$ for type 1 hits. (b) Histogram of $F_k - F_{k-1}$ for type 2 hits. Each bin is roughly 0.04N wide.

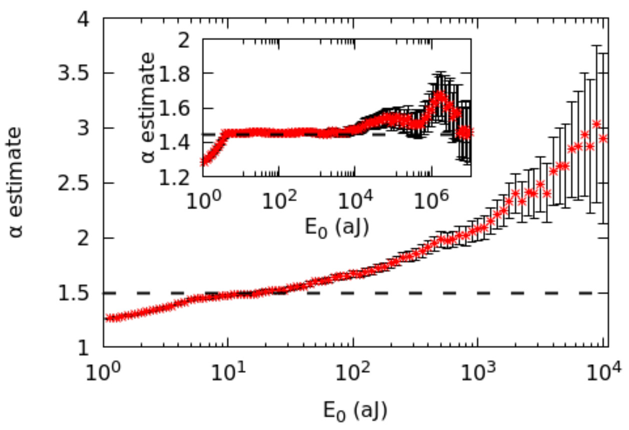

FIG. 9: Power law exponent α computed from the experimental data set got from the block moving with a velocity of 0.1mm/s and an added weight of 200g is plotted against E_0. The dashed line represents de exponent found in ref. [5]. In the inset, the power law exponent α computed form synthetic data generated following pure power law with exponent 1.44 is plotted against E_0.

to find out the kind of distribution of the data set, the method followed in ref. [6] consists in applying the expression (3) to different data subsets of the experimental data set. Each subset includes all values of the studied magnitude above some value E_0. The sum in expression (3) comprehend all values above E_0. By means E_0 variation, from values below the minimum E of the experimental data set to values above it, a collection of α exponent values is obtained. When the data set follows a power law distribution, in the plot of α exponent as a function of E_0 can be distinguished between 3 regions as can be seen in the inset in fig. 9. For values of E_0 below the minimum E of the experimental data set, α increases with E_0 and has low uncertainty. For values of E_0 immediately above the minimum E of the experimental data set, α does not vary with E_0 and its uncertainty is moderate. And finally for values of E_0 far above the minimum E of the experimental data set, α vary with E_0 and its uncertainty is great. Nevertheless in the plot of α against E_0 an increase of the exponent with E_0 is found for values of E_0 immediately above the minimum E of the experimental data set (see fig. 9). This behaviour is also found in the representation of α against E_0 when the exponent is computed from synthetic data generated following an exponentially damped power law.

$$\alpha = 1 + \left(\frac{1}{N} \sum_i ln \left(\frac{E_i}{E_0} \right) \right)^{-1} \tag{3}$$

IV. CONCLUSIONS

Two types of *AE* hits appear as the block velocity is decreased or the normal force is increased.

The suitability of a power law for the description of a magnitude distribution imply its lack of characteristic scale. It is the typical behaviour of some variables when critical phenomena takes place. On one hand, unlike what was expected, type 1 hits present an A and E distributions similar to those obtained from synthetic data generated following a power law with exponential damping at high values. And this kind of distribution do not suggest a lack of characteristic scale. On the other hand type 2 hits present an A and E distributions centred of some typical value so the magnitudes do not lack characteristic scale.

Hits occur during the F drop. This suggests that *AE* hits correspond to the detachment of contact area fractions.

Type 1 hits take place all the way down the F drop while type 2 hits happen on the top F values before the F drop. It can be speculated that type 2 hits correspond to the detachment of the whole area of contact while type 1 hits are due to the detachment of small region of contact area.

Acknowledgments

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