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Acoustic Emission at the Wheel-Rail Contacts with Micro-Slip and Stick-Slip

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ABSTRACT

The paper aims to analyse the occurrence of acoustic emission at the wheel-rail contact during micro-slip. The experimental model allows the different loads and the low sliding speeds specific to the wheel-rail contact. It is determined experimentally the appearance of the stick-slip phenomenon at the Hertzian contact of cylinder type (fixed-wheel specimen) - plane (mobile with very low speed - rail specimen). The experimental stand simultaneously measures the normal force, the friction force and the acoustic emission at different normal forces, sliding speeds and rigidities of the wheel specimen fixing system. The specimens are made of UIC standard materials used in the driving wheels and rails. The stick-slip phenomenon occurs at low micro-slip speeds and normal bending stiffness. Experimentally, it is found that the jumps specific to the stick-slip phenomenon (friction coefficient-COF) are accompanied by the acoustic emission (AE) at the cylinder-plane interface. The energy emitted by AE (W_{AE}) is correlated with the energy consumed by friction during the stick-slip period (W_{COF}).

1. INTRODUCTION

The stick-slip phenomenon occurs if two types of conditions are met: necessary conditions in which the kinetic coefficient of friction decreases as the sliding speed increases, but reaches a finite limit at high speeds, while the static coefficient of friction is higher than the coefficient of kinetic friction and

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sufficient conditions where there is a quantitative relationship between the sliding velocity in the order of microns/s to mm/s, the moving body mass and the finite stiffness in the sliding direction). [1,2]. The stick-slip phenomenon occurs mainly at low and very low speeds and under certain conditions of system rigidity.

For any mechanical system with finite stiffness, relative sliding motion and conventional dry friction (without special lubricant), a maximum speed can be defined until the stick-slip phenomenon occurs (stick duration is much more extended than slip duration). This speed can be considered the critical speed up to which the stick-slip phenomenon occurs. At a higher speed than the critical one, the frictional auto vibrations appear (stick duration equal to the slip duration periodic sinusoidal motion with a variable amplitude dependent on damping) from a minimum speed. Therefore, in a given system (rigidity, mass, mechanical properties of materials and torque known), a critical speed of the stick-slip phenomenon can be defined depending on the variation of the coefficient of friction with the speed. In the presence of conventionally dry friction, the bending movement, characterised by elongation at relatively low speeds and finite rigidity, takes place in two forms: jerky movement (slip periods much shorter than a stick) and the periodically self-vibrations form maintained by the friction force itself at higher speeds with the specification that the amplitude of the self-vibrations decreases with increasing speed and rigidity. At the wheel-rail contact, for the drive wheels and the braked wheels, the rolling movement is always accompanied by micro-slides, dependent on the rolling speed, the normal load, the wheel-rail material couple, and the contact geometry surface between the wheel and the rail, mainly elliptical. Therefore, the necessary conditions for the stick-slip phenomenon are met [3-5].

When the tangential force exceeds a specific critical value, depending on the static and kinetic friction particular to the material properties and on the normal force, the micro-slip appears). Deformations accompany the dynamic friction process at the level of the entire contact area, the appearance of waves of elastic, plastic and elastoplastic deformations, the formation and development of microcracks, and wear particles [6-9]. A less analysed aspect of the friction process at low and very low speeds is the generation and propagation of high-frequency elastic waves (in the range of kilo and megahertz), a phenomenon called acoustic emission (AE). The stick-slip phenomenon occurs mainly at low and very low speeds and under certain conditions of system rigidity. The propagation of elastic waves and oscillations as well as the appearance of microcracks in solid bodies, are manifested by acoustic emission. One of the effects of the stick-slip phenomenon is the appearance of vibrations and acoustic emission [10-11].

The present paper aims to determine the acoustic emission (AE) for the stick-slip phenomenon at the Hertzian contact for dry friction. It also experimentally highlights the correlation between the stick-slip phenomenon (static and kinetic friction coefficient, sliding speed), motion dynamics and acoustic emission (AE) at the Hertzian linear contact.

2. EXPERIMENTAL MODEL - GEOMETRY AND MATERIAL OF SPECIMENS

The cylindrical and plane specimens could be considered a simplified case of wheel and rail were made of material specific to the driving wheel and rail, with steel type R260 for rail (EN 13674-1:2012) and ER7 for the wheel (EN 13262:2021). Also, the dimensions of the wheel and rail specimens (similar in order of size) are shown in Figure 1. The sample wheel was attached to the tribometer using a drawbar with the following characteristics: diameter, 5 mm, length, 63.1 mm and a rigidity system, 30.427 N/mm. The drawbar (figure1) is embedded in the loading device to the tribometer.

The application of known tangential force on its free end causes a bending of the drawbar that can be measured and thus, obtain the stiffness of the sample (straight slope - 30.427 N/mm).
The wheel specimen moves vertically until it encounters the rail specimen. In this position, it is loaded at the normal force (*F*=20, 40, 60 N) and is kept constant, while the lower rail sample has a linear motion in a horizontal plane with the required speed (v=0.2, 0.1, 0.05 and 0.001 mm/s), achieving the friction force. This relative movement corresponds to the micro sliding of the wheel (driven or braked) on the rail.
The elastic properties of the materials and the sliding speed allow obtaining the specific Hertzian parameters of the real contact between the locomotive driving wheel and rail.

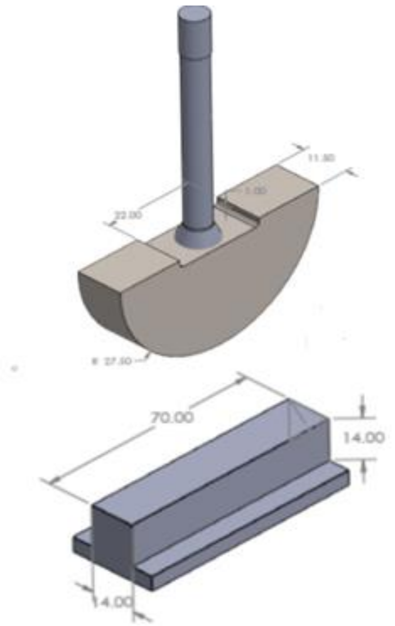
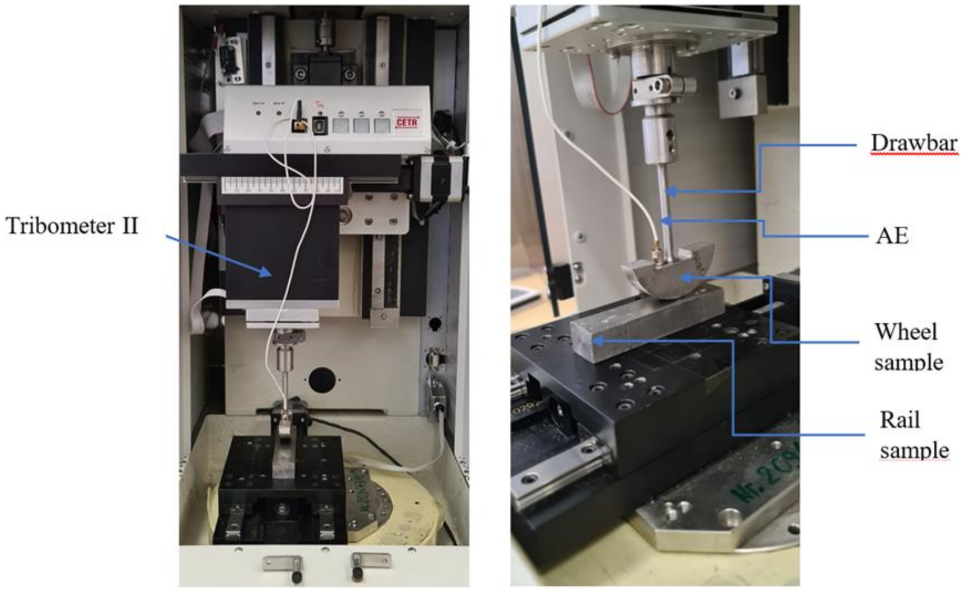


Figure 1: Dimensions for cylindrical and plane type specimens used for tests

3. EXPERIMENTAL TESTS

The experimental configuration presented in this paper is carried out in a UMT-2 tribometer, which can be used to test the stick-slip phenomenon for different kinds of materials. In order to perform these experimental tests, the tribometer was adapted to the specific sliding conditions of the linear Hertzian contact. Figure 2 shows the experimental system with specimens mounted in contact with the tribometer. The force sensor with which the tribometer was equipped, a two-dimensional force sensor used to measure the friction force between the upper and lower test piece and measure and control the normal loading force. The AE sensor integrated with the tribometer measured acoustic emission signals during the friction test. During the tests, its permanent evolution was monitored so that AE was used to indicate the phenomena in stick and slip time. The presented tests had as their primary purpose the determination of the evolution of the coefficients of friction, both static and kinetic, on the stick-slip phenomenon accompanied by the appearance of the acoustic emission at the Hertzian contact. The beginning of friction is a fundamental and essential issue in understanding the principle of tribology. This effect was observed experimentally for different sliding speeds, specifically the micro- slips inherent in the rolling motion that transmits the tangential forces.



a) b)

Figure 2: Tribometer to study the phenomenon of stick-slip
a) general view; b) cylindrical sample and plane sample

4. RESULTS AND DISCUSSION

The main objective of the experiments was to detect the stick-slip phenomenon by the appearance of acoustic emission for radio contact when a micro-slip and stick-slip occur.

For the analysis of the stick-slip phenomenon, 12 tests were performed, three normal forces and four velocities). For example, at an average force of 40 N and speed of 0.01 mm/s, the friction force, normal force and AE are recorded simultaneously for 1000s (friction length 10 mm). The stick and slip zone are analysed, and the (static and kinetic friction coefficients are calculated. The determination of the statistical parameters was done using a constant rigidity of the system bending rigidity of drawbar with wheel sample fixed) and very low sliding speeds.

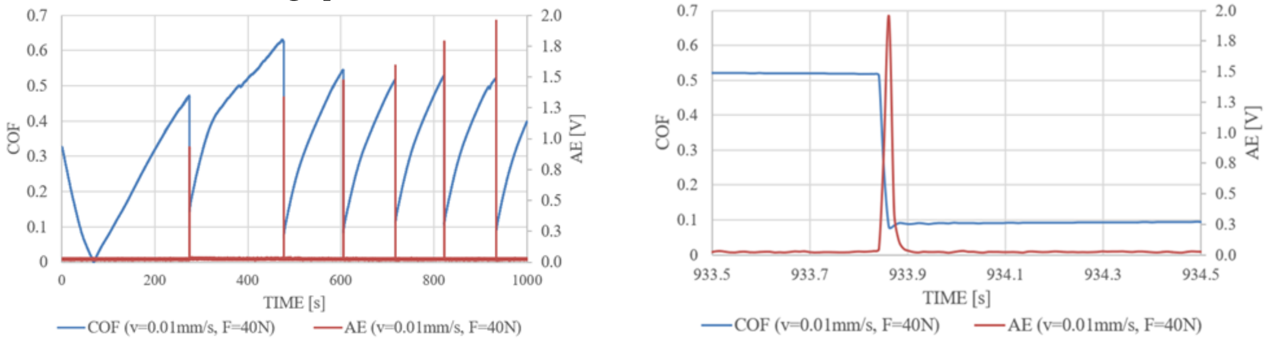
The energy consumed by friction (W_F) during the slip period is the integral (area) defined by the friction force (F_f = Fn COF) and the length of the friction path (L_f= v t). The friction energy (W_{COF}) is defined as the friction energy consumed (W_F) divided by the normal force (Fn) and speed of the drive (v), resulting in this specific energy ($W_{COF} = W_F/(Fn\ v)$= Area of COF in time t). The energy generated by the acoustic emission (W_{AE}) during the stick-slip period is defined as the integral (area) of the voltage (V_{AE}) emitted over time (t).

In the experiments to highlight the phenomenon of AE and COF, all stick-slip periods were taken into account from the stabilised zone.

The onset of friction is a fundamental and essential issue in understanding the principle of tribology. As it is well known, the frictional force in the sliding friction usually depends on both the actual contact area and the shear strength of a micro-contact. The frictional force emits elastic waves that occur during the passing from static to kinetic friction in a stick-slip presence per-formed.

Additionally, it was also observed that the delimitation of the stick and slip phases is signalled by acoustic emission, a specific micro-slip effect inherent in the rolling motion that transmits the tangential forces. Therefore, the stick-slip phenomenon is always accompanied by AE. The acoustic emission was observed experimentally for all four sliding speeds and three normal forces.

The results of the experiments were analysed and presented graphically to highlight by comparison the influence of normal force and sliding speed on the evolution of the coefficient of friction and acoustic emission. Thus, by applying three different forces, an increase was observed following the triggering of the slip event in the continuous activity of the AE. E.g., at a loading force of 20 N, many waves of low-amplitude continuous AE appear and overlap over the stick phase. As the loading force increases to 60 N occurs to only a few high-amplitude, burst-type AE peaks sporadically and coincide with the stick phase. The evolution variations of COF and the AE during the movement were determined for all four sliding speeds.



a) b)

Figure 3: A sequence of stick-slip phenomena: a) Stick-slip and AE phenomenon for 40N force at the speed of 0.01 mm/s with a time duration of 1000s, b) The variation of friction coefficient and acoustic emission (peak extracted).

The results relating to the evolution of the friction coefficient (stick-slip phenomenon) accompanied by acoustic emissions during sliding (rolling with the transmission of tangential forces is always accompanied by micro-slip) are presented as an example for the sliding speed of 0.01 mm/s at the normal load force of 40 N and for the time of 1000 s in figure 3a).

The peak of AE occurrences can be observed when moving from the stick phase to the sliding phase, highlighting the synchronous appearance with a slight delay of stick-slip jumps and AE jumps (figure 3b)). During the tests, it was observed that the acoustic emission increased from one test to another, both in amplitude and frequency, stabilising in value in the last four tests (F = 60N).

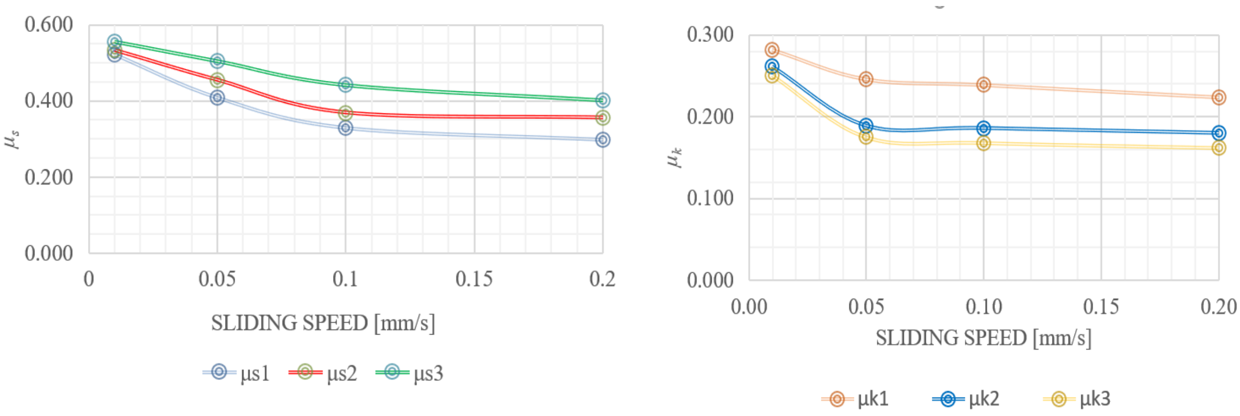
The stick-slip phenomena are analysed by the static friction coefficient μ_s (the peak of the phenomenon) and the kinetic friction coefficient μ_k (the minimum of the phenomenon.

Table 1: Value for the friction coefficients.

Sliding speed [mm/s]	**F=20N**		**F=40N**		**F=60N**	
	μ_{s1}	μ_{k1}	μ_{s2}	μ_{k2}	μ_{s3}	μ_{k3}
0,2	0.304	0.224	0.386	0.18	0.417	0.162
0,1	0.383	0.239	0.418	0.186	0.429	0.168
0,05	0.461	0.246	0.47	0.189	0.485	0.175
0,01	0.525	0.282	0.557	0.262	0.582	0.25

Figure 4 shows the static and kinetic friction coefficient and different sliding speeds. It is observed that the static and kinetic friction coefficient decreases with increasing relative speed. The growth of the static friction coefficient with the stick time is due to the phenomenon of "saturation" of the real contact area. The hypothesis regarding the increase of the static friction coefficient with the stationary time is unanimously accepted.

Also, the actual contact area increases with load and contact "saturation" is faster, so the stick phase duration decreases with time at the same sliding speed. Implicitly, the static friction coefficient decreases with increasing normal force. This dependence is consistent with the molecular-mechanical theory of dry friction (tangential frictional stress decreases hyperbolically with normal force in the area of elastic deformations).



(a) (b)

Figure 4: The influence of the relative slip speed of the frictions coefficient: (a) static friction coefficient, (b) kinetic friction coefficient

The friction coefficient area and the acoustic emission curves as a function of time in all the stick-slip periods in the stabilised zone are obtained. Further, a correlation is proposed between the stick-slip phenomenon and the acoustic emission phenomenon based on these energies.

The energy consumed by friction (W_{COF}) along with the energy generated by the AE (W_{AE}) and the ratio of these energies ($r_{AEF}=W_{AE}/W_{COF}$) were calculated for the three normal forces (20, 40 and 60 N). This energy consumed by friction (W_{COF}), calculated depending on the driving speed, normal force and friction coefficients, could be observed in fig.5a). Similarly, in fig. 5b) and fig. 5c) is presented the energy generated by AE(W_{AE}) and specific ratio (r_{AEF}). Thus, the results below show that during the stick-slip period, when the force increases and in the sliding regime 0.01-0.2 mm/s, it is surprising that the energies decrease with increasing speed, reaching a stabilisation. This decrease in energies with the sliding speed can be explained by reducing the dry friction coefficient with the sliding speed (the necessary condition for the stick-slip phenomenon and self-vibrations). Also, the specific ratio increases with the normal load.

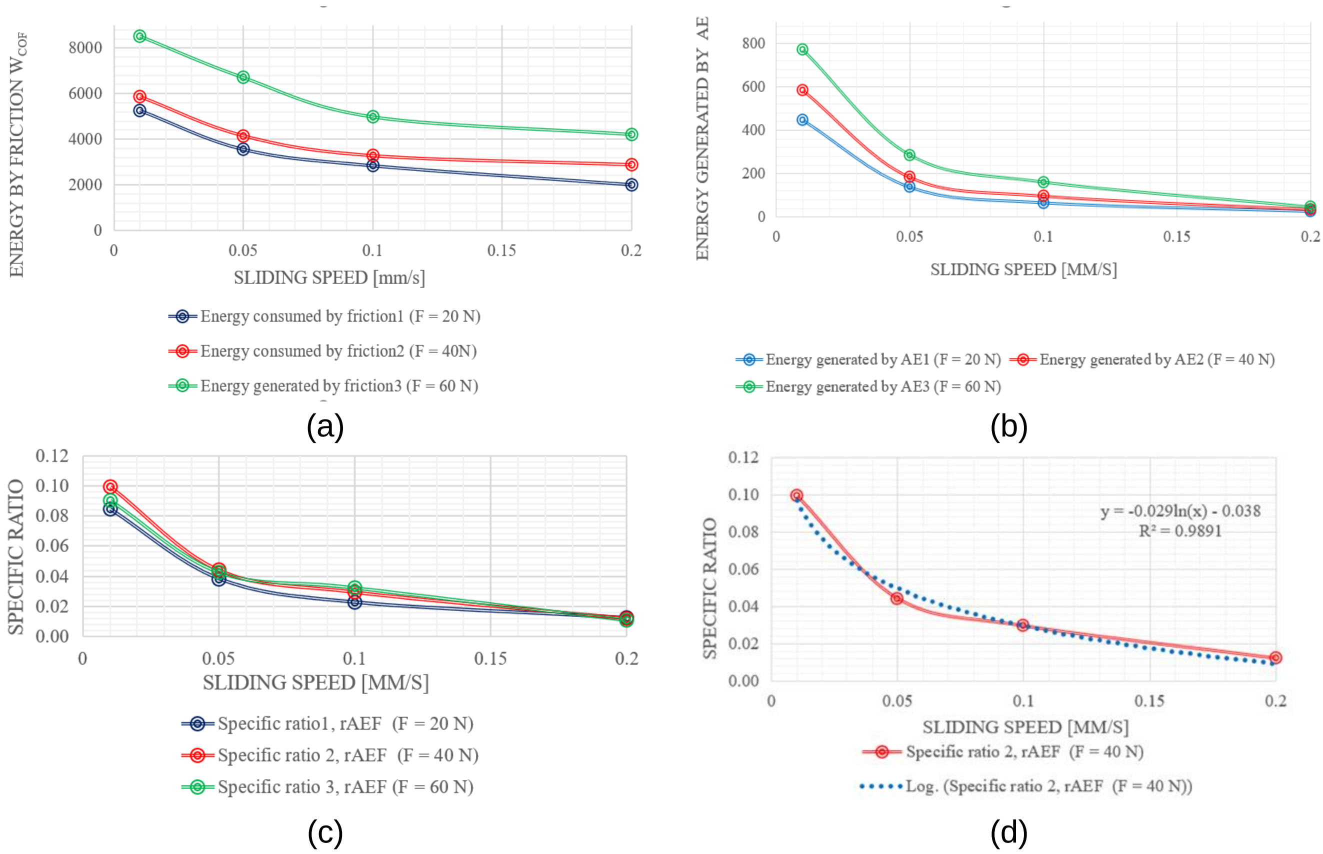


Figure 5: Variation of energies with sliding speed (mm/s): a) Energy consumed by friction, W_{COF} (s), b) Energy generated by AE, W_{AE}(Vs), c) Specific ratio, r_{AEF}(V), d) Analytical interpretation of the logarithmic curve of the specific ratio for the load 60 N.

Figure 5c) obtained from experiments and Fig. 5d) obtained by fitting the experimental results with continuous analytical functions show that between the energy generated by AE (W_{AE}) and the energy consumed by friction (W_{COF}) is a logarithmic dependence with proportionality constant, k, as a function logarithmic speed and load: $W_{AE} = k.W_{COF}$, where k is the constant of proportionality and represents the function y in figure 5d).

5. CONCLUSIONS

The results of the experimental research accompanied by the analytical interpretation revealed that an increase of the normal force with a decrease of the relative speed between the surfaces of the two specimens in contact implies a growing amplitude of the stick-slip phenomenon.
The acoustic emission accompanies the stick-slip movement for all the normal force and the sliding speeds. The jumps from static to kinetic friction (COF) are followed at concise time intervals (milliseconds) by acoustic emission (AE) jumps. The specific energies consumed by friction and those generated by the acoustic emission confirm the direct dependence between the stick-slip and acoustic emission phenomena for the non-lubricated Hertzian contact.

The values of the friction coefficients to the stick-slip phenomenon (μ_s, μ_m and μ_v) decrease with the increase of the relative sliding speed.

The experimental results showed that the acoustic emission accompanies the stick-slip jumps by applying the three normal contact forces at the four very low speeds.

AE is undoubted dependent on the appearance of the stick-slip phenomenon, a phenomenon observed experimentally in the laboratory for a Hertzian contact. Any AE accompanies the jump from static to kinetic friction with a delay of a few milliseconds, and the AE signal's amplitude can be considered an indicator of the amplitude of the stick-slip phenomenon.

The energy generated by AE is proportional to the energy consumed by friction in the stick-slip phenomenon for Hertzian contacts. AE transducers can be placed directly at the wheel interface and detect waves of transient elastic stress resulting from the elastic/plastic deformation that accompanies friction, becoming a non-destructive means of detecting the stick-slip phenomenon.

For event counting rates, it has been found that AE increases with the coefficient of friction and increases with sliding speed. Therefore, the wavelength of AE can be associated with stick-slip events and the normal force applied and also can be used to predict COF.

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