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APLICATION OF ACOUSTIC EMISSION FOR MONITORING EROSIVE WEAR TESTS OF LOW CARBON STEEL BY SOLID PARTICLES*

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Abstract

The erosive wear caused by the impact of solid particles against a surface is a tribological phenomenon present in many segments of the industry, such as transportation, aerospace, mining, power generation, among others. The most usual method to set the wear rate is by measuring the mass loss of the material. In order to apply one technique with potential to determine the rate of erosion wear, this study developed a dedicated equipment and conducted preliminary erosion tests monitored by non-destructive testing known as acoustic emission technique (AE). This can be defined as a technique able to detect mechanical waves generated by the release of elastic energy accumulated in the material. Erosion tests were performed in order to evaluate the ability of equipment to collect data from AE and to correlate these data with the wear of the samples. Samples of low carbon steel eroded by the impact of angular aluminum oxide particles suspended in air at three different velocities: 45, 57 and 67 m/s. The impact angle between the particles and the sample was set at 30 degrees and the test temperature at approximately 20°C. The wear rate has changed with the velocity in accordance with the kinetic energy of the particles and the AE parameter RMS showed sensitivity to the variation of particle impact velocity and to the wear of the sample eroded. The rate of AE signals collected over time correlated with the flow of particles striking the sample, and with the parameters of energy, rise time and duration of the signal.

Keywords: Acoustic emission; Erosion; Wear rate; Wear mechanisms; RMS.

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1 INTRODUCTION

Tribology can be defined as the science of friction, lubrication and wear of engineering surfaces, with the aim of understanding the interactions between the materials in contact and maximize its application [1]. Among the main wear mechanisms is erosive wear, caused mainly by impacts of small solid particles suspended in a fluid moving against a surface, causing the removal of material [2]. This wear mechanism occurs in many industries, such as transportation, aviation, mining, power generation [3], and oil and gas [4].
The impact velocity of the particles on the eroded surface exerts a high influence on the rate of wear, since the energy available for the removal of material comes mainly from the kinetic energy of the erodent particles [4]. The larger and faster the particles are, the deeper and wider indentations will be the result on the eroded surface [5].
Erosion parameters such as impact angle and shape of the particles also affect the wear rate. Angular particles colliding against the surface at low impact angles cause wear by cutting and may vary according to the orientation and direction of rotation of the particle [2].
The non destructive technique known as Acoustic Emission (AE) has great potential for detecting and monitoring the development of erosive wear [6]. It also has great potential to determinate the precise location of the acoustic source [7,8]. Hase *et al.* [9] correlated the cutting micromechanism (abrasive wear) with AE signals with low frequency. The phenomenon of acoustic emission can basically be described as a transformation of energy, which can be chemical, mechanical, or electrical into mechanical waves (sound energy) [10]. The AE signal can be characterized as a mechanical wave of spherical shape and an analogy with the propagation of ultrasonic waves can be done [11].
In order to develop the application of AE technique for the detection and monitoring of wear it is necessary to perform experimental procedures, such as laboratory tests. These tests provide control over the variables involved in the process and are very important because they establish correlations between the variables involved in the wear process with the parameters of the AE technique. This paper presents the results of erosive wear tests performed on a dedicated equipment developed with the aim of collecting acoustic emission signals from the erosion of the samples and thus correlate the wear rate with parameters of AE signals collected, such as intensity and RMS.

2 MATERIAL AND METHODS

The elements involved in the tribological system of the tests performed are shown in Figure 1.

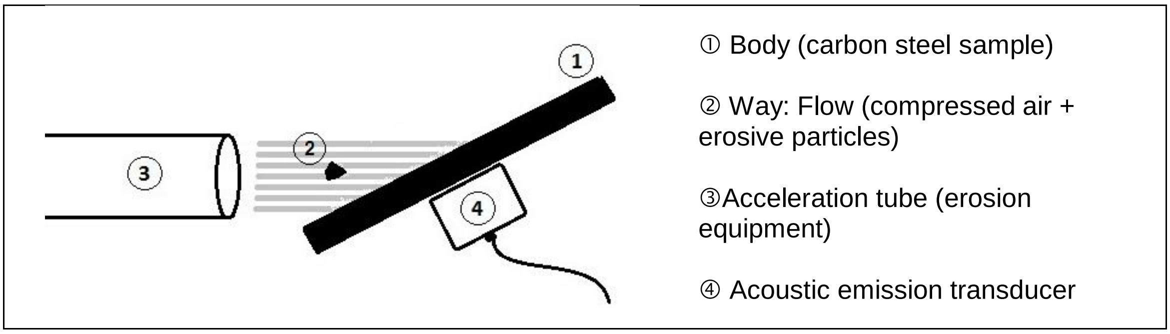

Figure 1. Definition of the tribological system used in the erosion wear tests.

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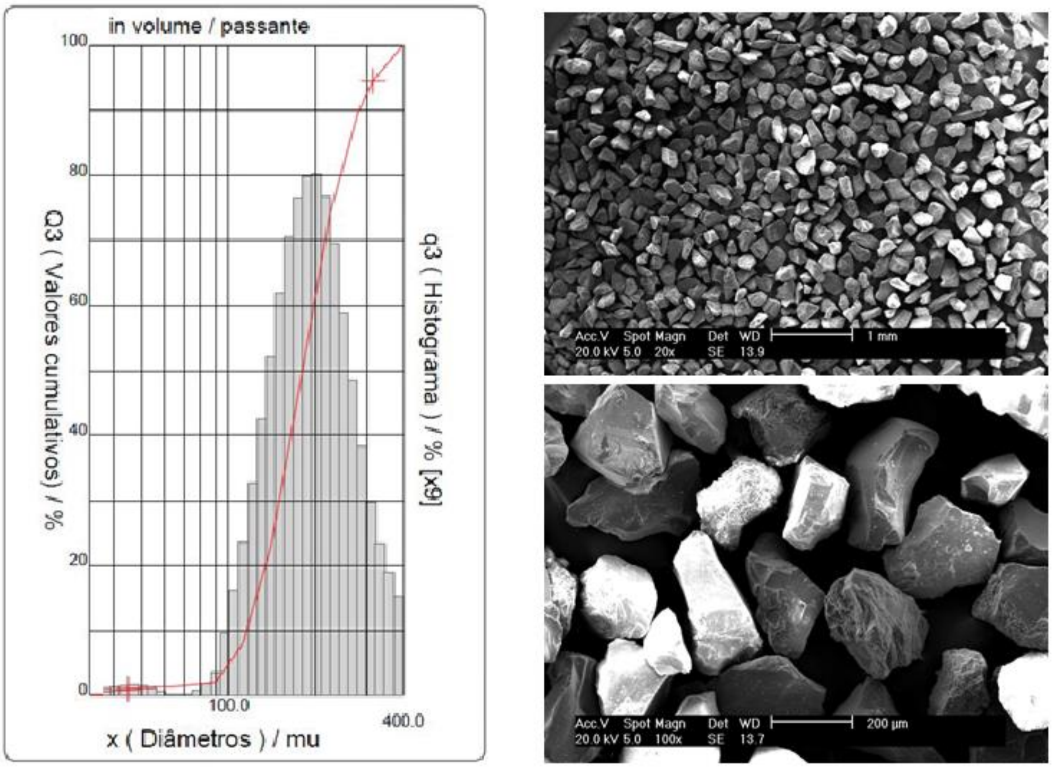
2.1 Experimental Materials

Samples with dimensions of 140 mm x 100 mm x 6 mm, were made from commercial hot rolled low carbon steel plate with hardness of 81 ± 2 HV.
The erodent material is made of aluminum oxide ($Al2O3$) in the form of angular particles with an average diameter of 190 µm and microhardness from 1900 ± 200 HV. The size and shape distribution of the angular particles are shown in Figure 2



(a) (b)

Figure 2. (a) Alumina particles' size distribution, (b) Particles' shape and sizes from scanning electron microscopy (SEM).

2.2 Erosimeter

Figure 3 shows a schematic drawing of the erosimeter (equipment developed for erosion tests) with its main components.

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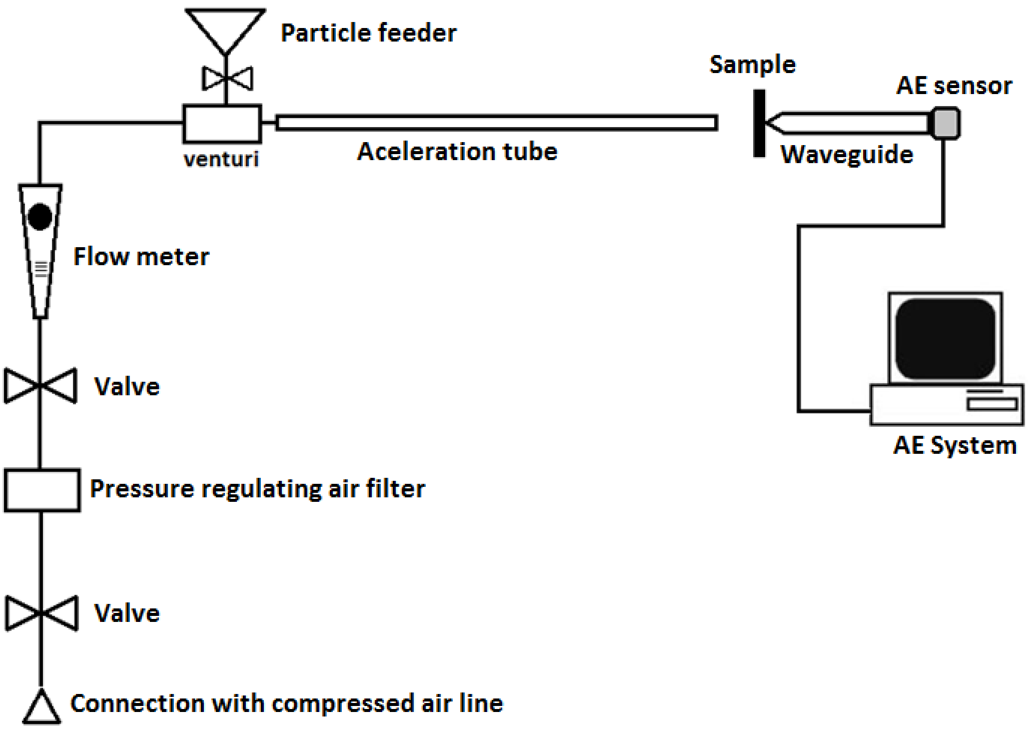

Figure 3. Schematic drawing of the erosimeter.

The sample holder is the core part of the erosimeter and has the ability to position the sample by varying the angle related to the flow direction (compressed air + particles) and collect AE data during the erosive wear testing. The mechanical waves which arise from the impact of the particles in the sample propagate through the waveguide and are captured by the AE sensor which is coupled at the opposite end of the guide. The waveguide causes attenuation on the AE signal. Such attenuation was determined by the use of a standard technique (ASTM E 2075) [12], where graphite mines are broken on regions of interest, and the attenuation was determined from the signals collected. The AE signal generated from the graphite mines are used as a standard signal. In this waveguide the acoustic signal attenuates in about 25.2% in amplitude. Figure 4 shows a schematic drawing of the sample holder with the major components identified.

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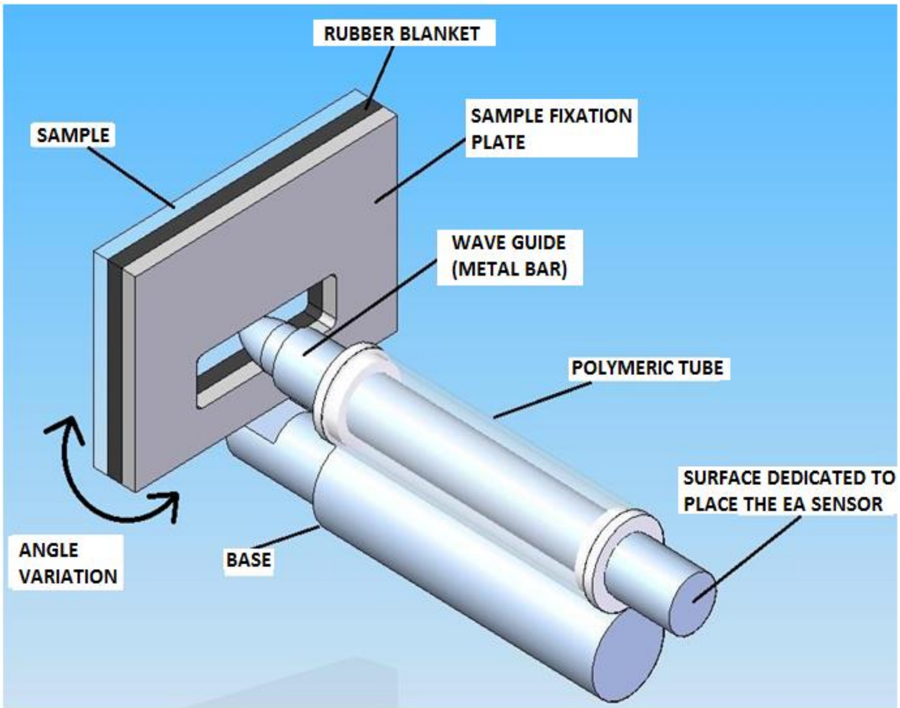

Figure 4 - Sample holder and acoustic emission wave guide.

2.3 Acoustic Emission

The AE acquisition system and signal processing consists of a board model DISP, manufactured by Physical Acoustics Corporation (PAC). The AE sensor model is PAC WDI, with integrated preamplifier of 40 dB and resonant frequency in the range of 90-900 kHz, connected to the board via BNC connectors and coaxial cable (50 ohms).
Figure 5 shows a typical AE transient signal indicating the main parameters of the wave. It can be noticed that all parameters are referenced in the threshold, which basically works as a high-pass band filter (tension - volts).

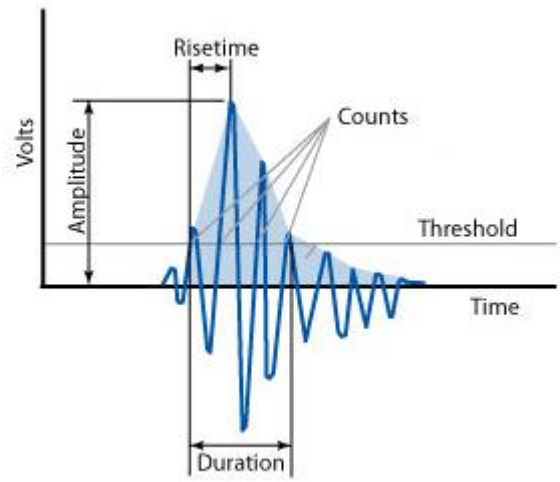

Figure 5 - Parameters of the acoustic emission signal.

The magnitude of the threshold was empirically defined (in decibels [dB]) based on the fact that saturation may occur in the AE system when relatively low values are used for the threshold - the system is not able to process all the signals collected by

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the sensor. Therefore, the values established for each test condition were slightly higher than the saturation limit.

2.4 Erosion Wear Tests

The parameters used for erosive wear tests performed in this study are listed in Table 1.

Table 1- Parameters of the erosion wear tests and of the acoustic emission system used in this work

Erosive wear parameter	Values used in the tests
Particle velocity	45, 57 and 67 m/s
Air flow	16,5; 24,7 and 32,9 m^3/h
Air pressure	4,5 bar
Impact angle	30 degrees
Sample	Low carbon steel plate
Erosive particle	Aluminum oxide (average size 190 µm)
AE parameters	**Value used in the tests**
AE Sensor (transducer)	WDI (wide band - 90 to 900 kHz)
Threshold	61, 65 and 67 dB
Peak definition time - PDT	400 µs
Hit definition time - HDT	800 µs
Hit length time - HLT	1000 µs

2.5 Wear Rate

In order to determine the wear rate of the samples a digital balance (accuracy to 0.001g) was used for measuring the mass of samples both before and after each test and also the mass of the particles used in each erosion test. The wear rate was determined by the ratio between the weight loss of the sample by the total time of exposure to wear, as shown in Equation 1:

$$Q = (m_i - m_f)/t \qquad \text{(Equation 1)}$$

where:

- Q = wear rate [mg/min];
- t = time of wear test [min];
- m_i = initial mass of the sample [mg];
- m_f= final mass of the sample [mg].

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3 RESULTS AND DISCUSSION

3.1 Erosion wear

The results of weight loss as a function of test time (Figure 6) showed a linear increasing trend, indicating that the wear is occurring at a constant velocity for the periods of time used. This trend indicates that the steady state was reached in the beginning of the tests and was observed for all velocities measured. It was not possible to identify an incubation period of wear (running in period).

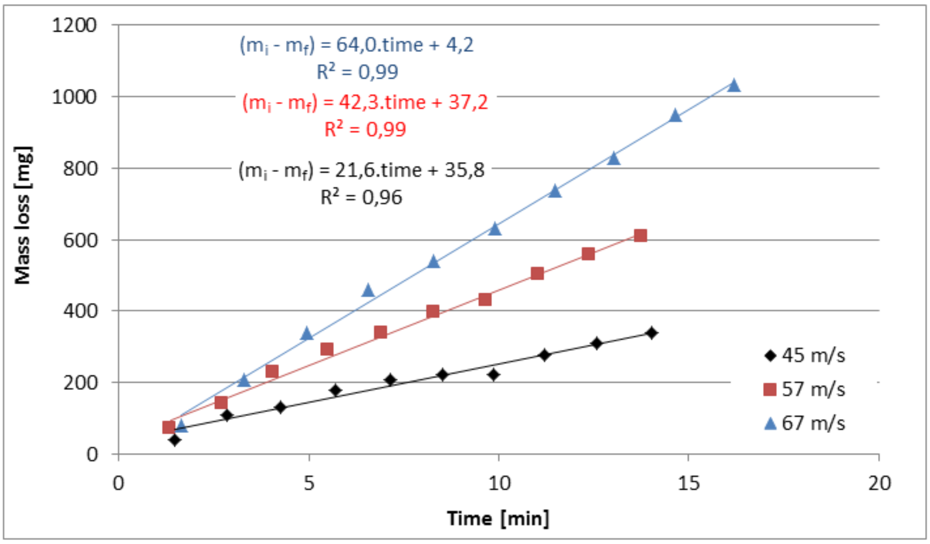

Figure 6 - Mass loss as a function of test time for three impact velocities (300 g of particles in each step of the test).

The wear rate increased with the impact velocity, agreeing with Lindsley *et al.* [13] and Hutchings [2]. The main force involved in the erosive wear process comes from the kinetic energy of the particles, strongly influenced by the impact velocity. Figure 7 shows the graphic used to determine the correlation between the wear rate and impact velocity. The coefficient ***n*** is represented by the exponent of the curve equation (Figure 7). For erosive conditions adopted in the tests of this study, the value of ***n*** = 1.92 is found.

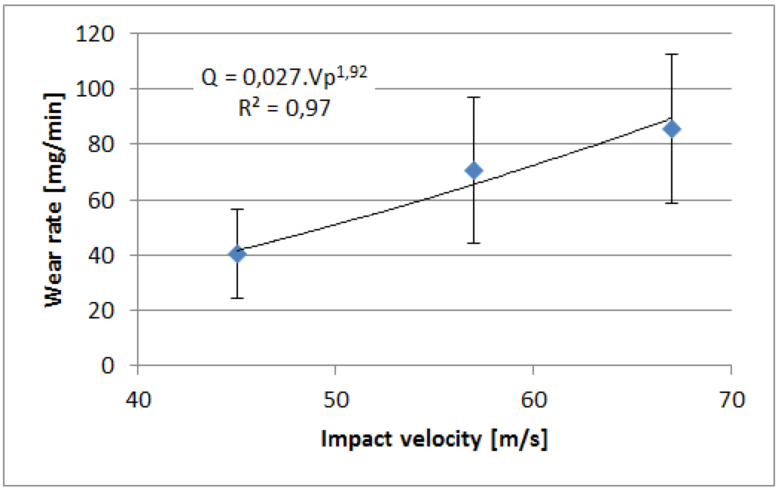

Figure 7. Wear rate versus impact velocity of the particles. Mean values obtained from six trials for each impact velocity.

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The value obtained for the coefficient ***n*** of almost two (2), agrees with the intensity of the kinetic energy of the particles that varies with the square of the particle velocity and confirms the kinetic energy as the primary source of energy involved in the process of material removal of the steel sample.
According to Hutchings [2], angular particles with high hardness (the ratio of abrasive hardness (***Ha***) and sample bulk hardness (***Hs***) - ***Ha/Hs = 29.8***), colliding at low impact angles cause wear by the action of cutting mechanism. Figure 8 shows the eroded image of a sample where the cutting wear mechanisms were observed. Clearly other damage mechanisms in addition to the cutting also occur in the samples. In the worn surfaces analyzed, no evidence of fouling particles was observed.

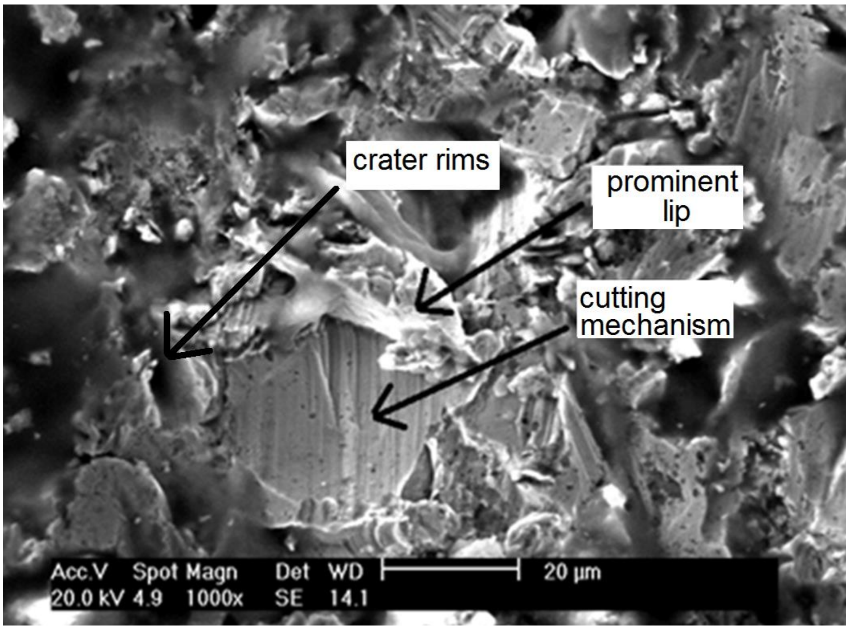

Figure 8. Photograph obtained by SEM of the sample eroded by particles (α = 30º, V = 67 m/s, time = 8 min).

Figure 8 shows a region of the sample worn by the cutting mechanism made by the increased normal component of the impact force (kinetic energy).
In erosive wear caused by cutting, chips of material removed by the erosive particles may be plucked in the first impact or form crater rims and lips, which are removed by subsequent particle impacts. Hase *et al.* [9] proved that cutting generates AE signals with low frequency and high amplitude, and that signals from ploughing (plastic deformation) generate low signal intensity (amplitude). The micromechanisms cutting is ruling the erosive wear process in the conditions adopted in the experiments to this work, which validates the use of the acoustic amplitude parameter to measure the wear rate.

3.2 Acoustic Emission Parameters

The main sources of AE signals present on the erosive wear process can be divided into two groups: from the air flow and from the erodent particles. Tiboni *et al.* [14] evaluated the AE signals from the flow conditions similar to those used in this work. The average values of AE parameters obtained in the tests with and without erodent particles are shown in Table 2.

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Table 2. AE parameters obtained for tests performed with and without erosive particles

	Air velocity [m/s]	Amplitude [dB]	RMS [V]	Threshold [dB]
Without wear particles TIBONI *et al.* [14]	58,2	52	0,019	51
	116,4	59	0,009	56
With wear particles †	58,2	61	0,024	59
	116,4	68	0,059	65

† Mean values obtained from tests carried out in this work

The results in Table 2 indicate that AE signals from the airflow are not being collected in the tests with particles, because the threshold selected is above the average amplitude value of the air flow for tests without particles. It is noteworthy that the RMS parameter is independent of the threshold and therefore is sensitive to sources of signals from the air flow and the erodent particles.
The rate of the signal acquisition (hits / sec) showed a satisfactory correlation with the amount of particles that collide in the sample, as can be seen in the graphic of Figure 9.

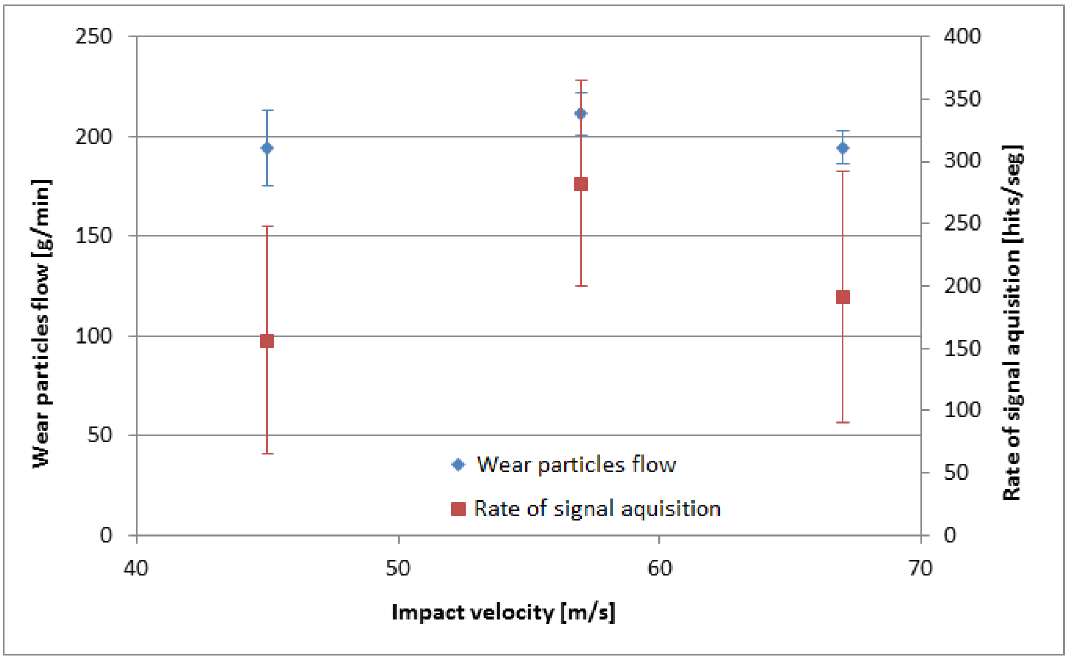

Figure 9. Wear particle flow and rate of AE acquisition signal as a function of impact velocity for 45, 57 and 67 m/s.

This proportionality was observed, suggesting that the sources of acoustic emission signals more sensitive to the data acquisition system are correlated to the phenomena of wear, such as the impact, cutting, plastic deformation, and tearing of material. The change in kinetic energy of the particles, which causes an increase in wear rate, does not vary the amount of AE signals recorded by the system. The dispersion in the rate of AE signals is associated with variation in the flow of erodent particles, the main signal source for this system.
The RMS parameter and the wear rate showed a similar tendency to the impact velocity of the particles, as shown in Figure 10.

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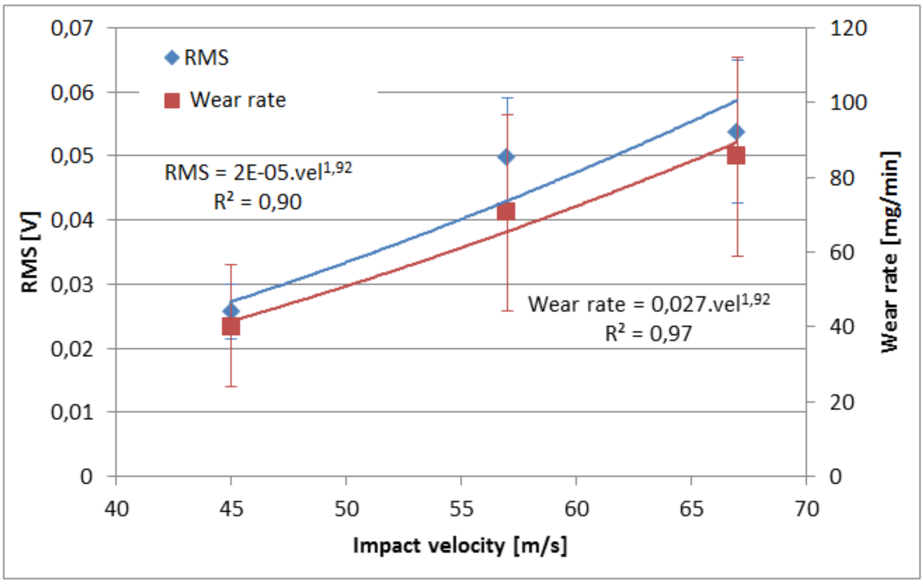

Figure 10. Variation of RMS and wear rate with the impact velocity. Average values of six trials for each velocity: 45, 57 and 67 m/s.

This behavior of RMS regarding the impact velocity suggests that this parameter is sensitive to the variation of energy involved in the erosion process, and therefore to the kinetic energy of the particle, more expressive energy involved in this tribological system. The RMS parameter also varies exponentially with the flow rate of compressed air without the presence of erosive particles, as shown by Tiboni *et al.* [14].

It can be concluded that the RMS parameter is sensitive to variables related to the variation of kinetic energy involved in erosive wear, with an appropriate benchmark to evaluate the wear process by AE technique.

The amplitude parameter of the AE signals also showed sensitivity to the variation of the impact velocity of the particles, with a tendency to increase with velocity. The amplitude is a measure of the signal magnitude which describes the highest voltage value (peak) of the signal. Figure 11 shows the graph of amplitude variation with velocity of the particles. It can be conclude that the RMS parameter is sensitive to variables related to the variation of kinetic energy involved in erosive wear, with an appropriate benchmark to evaluate the wear process by using the AE technique.

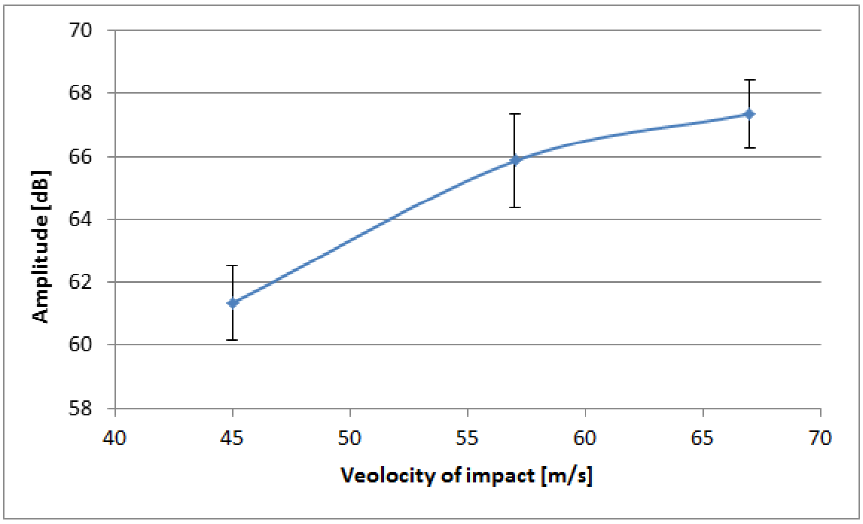

Figure 11. Variation of amplitude [dB] for impact velocity [m/s]. Mean values for six trials at each velocity.

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The trend of increased signal intensity with impact velocity can also be noticed by the waveform signal as can be seen in the graphics of the Figure 12.
As the cutting is considered the most relevant mechanism in the tests performed, it was expected that the EA signal presented high amplitude and low frequencies, thus agreeing with the results obtained by Hase *et al.* [9].

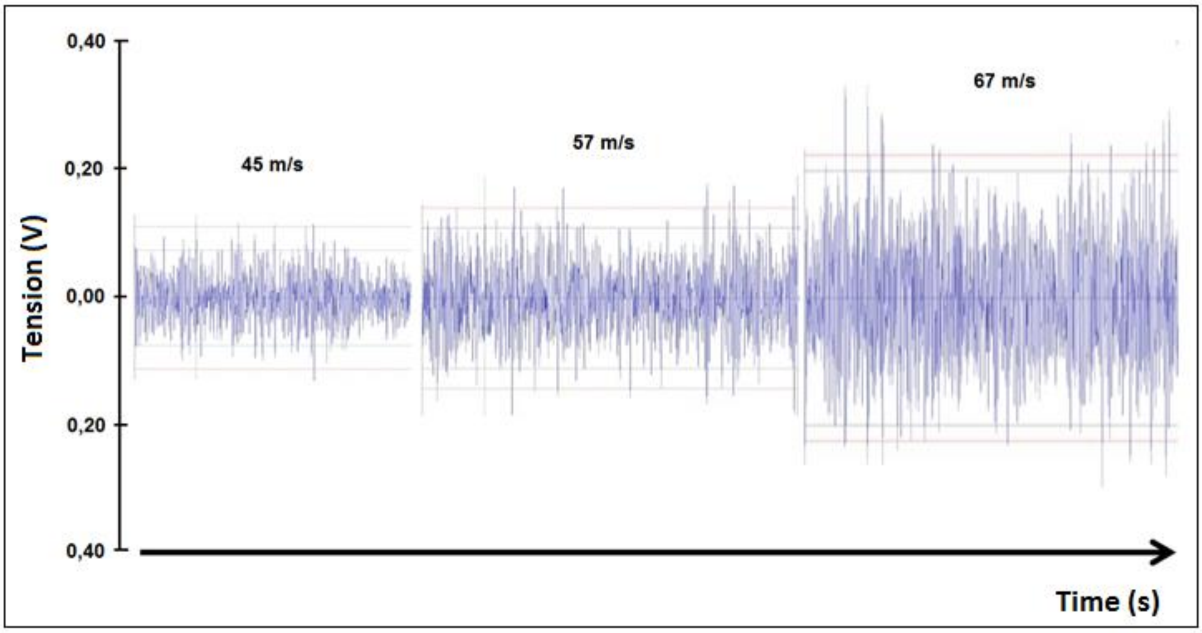

Figure 12. Examples of acoustic emission waves collected during erosive wear tests with impact velocity of 45, 57 and 67 m/s, showing the signal strength during each test.

3.3 Relation between acoustic emission and wear rate

Among the several AE parameters that were recorded in the tests, it was found that for the erosive wear in a gaseous environment with angular particles and under low angles of incidence, both the RMS and the amplitude are the parameters that have a satisfactory correlation with the rate of erosive wear.
The parameter RMS showed a linear trend with the wear rate, as shown in the graphic of Figure 13 The parameter RMS indicates the mean peak voltage of the signal in time, regardless of the formation of AE hit. The increased wear rate in these tests is not correlated with the increase in the number of erodent particles impacting the surface, but it can be correlated with the increase in the kinetic energy of the particles. Such increased power will cause the particles to penetrate deeper into the sample, causing a higher plastically deformed region and deeper cuts, which will be reflected in the intensity of the mechanical waves generated, responsive to the parameters relating to the AE signal strength such as RMS and amplitude.

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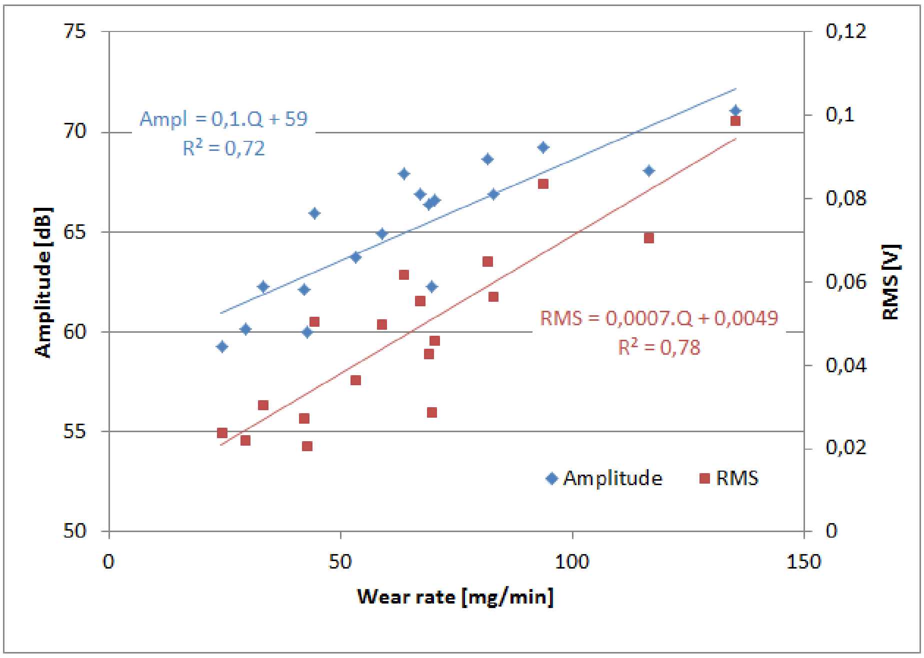

Figure 13. Comparison between the variation of the amplitude and RMS as a function of wear rate for all tests. Printed values are the average values obtained in each test.

The parameter amplitude (Figure 3.8) also shows a satisfactory correlation to the wear rate, but care must be taken in establishing a quantitative analysis, since this parameter is very sensitive to the threshold, which may vary for erosive wear tests repeated even with the same parameters.

4 CONCLUSION

From the above study on the correlation between acoustic emission signals and wear rate, the conclusions are:

- Agreeing with the literature, the trend of wear rate variation with the impact velocity of the particles, varies exponentially with an exponent index near two (2), thus confirming that the intensity of the kinetic energy is the main source of energy involved in the wear mechanism and in the formation of high intensity AE signal.
- The main wear mechanism present in the tests is cutting, with no incubation period and/or encrustation of particles.
- The dispersion obtained for the wear rate was considered low, qualifying the erosion equipment to perform repeated tests with the goal of developing the application of AE technique for monitoring the wear tests.
- The technique of non-destructive testing of acoustic emission proved to be very promising to detect and quantify the erosive wear. The parameters of AE showed efficiency to quantify and assess the extent to which the wear is occurring in the material.
- The AE parameter RMS varies exponentially with the impact velocity of the particles, similar to the behavior of the wear rate. RMS showed to be sensitive to variables related to the variation of kinetic energy involved in erosive wear, with an appropriate benchmark to evaluate the wear process by AE technique.
- RMS parameter proved to be the most suitable one to correlate with the wear process.

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