Correlation between Acoustic Emission and Torque in Drilling

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Abstract
This work involves the search of predictive parameters for assessing the condition of cutting tools in metal machining. The indirect method chosen is based on the acoustic emission generated during the cutting process. The aim of this research is to shorten the way for utilization of control systems for possible application in industrial machinery. A large number of hexagonal cylindrical steel samples with good homogeneity were prepared and consecutively drilled at their centers with drill bits having different levels of damage at the edges and at the outer corners. The wear of these tools was obtained artificially by spark erosion, but also mechanically. By scanning electron microscopy the evolution of the damage was monitored. During the machining process, the features of acoustic emission and torque were recorded. For different conditions of the drill bits, the acoustic emission parameters and torque were correlated. The "Mean MARSE Power", defined as MARSE energy divided by duration of the hit, showed a linear correlation with torque.

Keywords: Acoustic Emission (AE), drilling, torque, AE features, wear, Mean MARSE Power

1. Introduction

During cutting in drilling, the drill gives work to the piece, and activates various mechanisms that generate elastic waves, with frequencies in the range of ultrasound [1,2]. The Acoustic Emission (AE) method allows the study of these elastic waves. Along with other indirect methods, the aim of AE is to get information of the cutting process in real time [3,4]. AE signals can be transient (burst) or continuous depending on the type of process in the emitter source. The occurrence of both types of signal is determined by the mechanisms involved in each specific case of cut [5,6]. Chip fracture, breaking of the tool edge, and the chip hitting on workpiece and tool are AE burst sources. Otherwise, plastic deformation of the workpiece, and the chip and friction between tool, workpiece and chip are sources of continuous AE [6]. These signals come from stochastic processes [7] and can be studied from the characteristic parameters or waveforms themselves. It should be noted that the stochastic nature of the cutting process may also be related to material properties such as strength and hardness that can cause random fluctuations in the forces associated with the cut, as also in AE features [8]. In previous works, some authors [9] observed the good qualities of the AE method for detection of chip breakage, compared with the poor results obtained for the signals of cutting forces.
The classical AE parameters for transient signals are: hit time, duration, rise time, ring down counts, MARSE energy, amplitude, root mean square (RMS), average frequency and others [10]. Also the MARSE mean power (MP) and its variance can be defined as signal features [11]. The last four mentioned parameters are not dependent on signal duration and for that reason they can be applied to all types of AE signals.
This work evaluates the effectiveness of different AE parameters to represent the condition of cutting tools and process in metal machining. The aim is to find one that simplifies the subsequent steps to extract the needed information of the signal, trying to avoid sophisticated mathematical algorithms. In that way, the AE features will be related with a mechanical parameter, the torque.
The torque produced by the drill bit on the workpiece during drilling has shown, in the literature, to be a good parameter to obtain information about the dynamics of the process. Differ-
ent models have evolved how the characteristics of the drill bit material and the cutting process can be related with the torque [12-15]. Also the torque together with the feed force has been widely used as a reference parameter to characterize rotating tool wear [2]. Then, the information obtained by the AE produced in drilling for different conditions of the drill bits could be correlated to the torque, to compare both results and give a mechanical frame of reference to the AE parameters of the measured signals. Following previous works of the authors [16,17], the MARSE mean power was evaluated as a good parameter to get information about the tool condition and the cutting process.

2. Experimental Method

The aim of this study was to characterize tool wear and cutting process in a set of tests, in which AE features and torque were measured. For carrying out the tests, the workpiece, the drill bit and the machining parameters were fixed as follows.

2.1. Hardware

2.1.1 Workpiece specimens
Workpiece specimens were produced by cutting 95-mm long pieces from an SAE 1040 steel drawn hexagonal bar 14-mm wide (Figure 1). The material of the workpiece showed homogeneity and low content of inclusions in the zone to be drilled. It was assessed by different studies. Optical metallography showed a 7-8 mean grain size accordingly with ASTM E112 standard (Figure 2). In microstructures, inclusions and precipitates were not observed in quantity and size that could affect the state of the drill bits or the rate of emission of AE signals. Rockwell B average hardness was found to be 98.5 ± 1.5 for ten randomly selected specimens. These features were essential to ensure the repeatability of the tests and results. The chemical composition of the steel given by the manufacturer was: C: 0.40, Mn: 0.72, Si: 0.29, P: 0.011, S: 0.012.

![Figure 1. Hexagonal workpiece with pilot hole](image1)

![Figure 2. Microstructure of steel SAE 1040](image2)

For every specimen, a pilot hole 10-mm depth and 1.5-mm in diameter was drilled on an end face along the longitudinal axis. This pilot hole allows to study two situations during drilling, one avoiding the contribution of the chisel edge to the cutting process while the drill bit works in the pilot hole, and the other when the chisel works in drilling deeper than the pilot hole.

2.1.2 Drill bits
Cutting tools used in the tests for the present experiment were commercial HSS high-speed steel drill bits of 5-mm diameter. Defects were produced in a controlled manner on the cutting
edges and the outer corners of the flute edges to simulate different degrees of wear of the drill bits. The artificial wear was produced by mechanical procedures and by spark-erosion. HSS was the material used in drill bits to avoid large wear time in a future correlation between the action of drills artificially worn and drills with real wear.

Table 1 shows the condition and nomenclature of the eight drill bits used in this work. The condition of the drills were: New with sharp edges, used with sharp edges, new with defective edges, spark erosion dented cutting edges, spark erosion blunted cutting edges, mechanically dented cutting edges and mechanically worn flute edges. The former two drills correspond to no damage state.

<table>
<thead>
<tr>
<th>Drill</th>
<th>Name</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NE1</td>
<td>New, with sharp cutting edges</td>
</tr>
<tr>
<td>2</td>
<td>NE2</td>
<td>Used, with sharp cutting edges</td>
</tr>
<tr>
<td>3</td>
<td>NE3</td>
<td>New, with defective cutting edges</td>
</tr>
<tr>
<td>4</td>
<td>SDE</td>
<td>Spark erosion dents on cutting edges (small craters)</td>
</tr>
<tr>
<td>5</td>
<td>BE1</td>
<td>Spark erosion blunted cutting edges (case 1)</td>
</tr>
<tr>
<td>6</td>
<td>BE2</td>
<td>Spark erosion blunted cutting edges (case 2)</td>
</tr>
<tr>
<td>7</td>
<td>MDE</td>
<td>Mechanically dented cutting edges (big craters)</td>
</tr>
<tr>
<td>8</td>
<td>WF</td>
<td>Mechanically worn flute edges (worn outer corner)</td>
</tr>
</tbody>
</table>

Spark-erosion or EDM is the process of particle removal from a workpiece by an electric arc formed between electrode and workpiece, which are separated by dielectric liquid. The spark-erosion was produced on drill bits by an EDM machine. Different electrodes were used for cases of blunted and dented edges. In the first case a flat shaped electrode was located with different angles to achieve the condition of blunted edges BE1 and BE2. Those conditions were adopted as an intermediate condition between sharp cutting edges and excessive worn edges (as the mechanically dented cutting edges or MDE condition), altering the effective cutting angle and producing a larger contact surface between the tool edge and the workpiece. For the second case, a cylindrical electrode (a wire, 0.3 mm diameter) was used to obtain dents (or craters) of 500-µm diameter on the middle of the cutting edges. About the mechanical wear, the extreme condition MDE of big craters on the edges was obtained by regular drilling in very low-quality steel with hard inclusions. Also in WF condition, the flute edges (outer corners) were mechanically worn with a drill sharpener to simulate other typical kind of tool wear.

![Figure 3. SEM images of damaged drill bits](image)

The evolution of the drill bits condition was assessed by means of scanning electron microscopy (SEM). Figure 3 shows a qualitative example of SEM images of damaged drill bits. The advantage of this method of observation, beyond the possibility of obtaining a higher magni-
fication, is its excellent focal field, very useful for viewing a body of overall size and macroscopic three-dimensional shape such as a drill bit, and in particular its tip which is the object of study.

### 2.1.3 Drilling operation

The drilling operation was performed in a FIRST LC 50RS vertical mill, in continuous drive mode. Each test was performed at the same cutting conditions. The rotational speed was (530 ± 8) RPM and the feed rate was (0.353 ± 0.005) mm/s. The tests were carried out using continuous lubrication with Kansaco machining soluble oil at a dilution of 20 parts of water per lubricant part. The lubricant flow rate was 250 ml/min. The depth of drilled holes was 20 mm, with 10 mm pilot hole.

### 2.1.4 AE and torque measurement

Elastic waves produced by AE sources during metal machining were detected using a PAC WD broadband AE sensor. A broadband CISE preamplifier of 40 dB gain (100 x) conditioned the sensor signal and a PAC PCI-2 AE system with 18-bit amplitude resolution was used to acquire, digitize, parameterize and store the AE measurements. AE sampling rate was 5 Ms/s. The torque was measured using an Instron torsion cell and a CNEA signal conditioner (source and amplifier). This torque signal was measured as an external parameter by the PCI-2 AE system and it was digitized with a resolution of 16 bits in amplitude at a sampling rate of 10 ks/s. The typical AE features and torque were acquired simultaneously and recorded in the same data files. The AE signal acquisition was triggered at a threshold of 27 dB_{AE} in order to minimize the influence of background noise. Figure 4 shows the block diagram of the AE system. Figure 5 shows the drilling machine, the mounting of the workpiece in the torque cell and a sketch of the drilling path. Several thousand hits, and their corresponding parameters (and waveforms), were recorded for each test.

![Figure 4. AE system block diagram in a drilling test](image)

Amplitude, RMS, counts, MARSE energy and duration of the AE signals and torque were recorded for each AE hit. The duration of the AE hits was up to 20 ms (defined by the max. duration time) for the AE signals measured in stationary drilling. MARSE energy and duration were used to calculate the MARSE mean power or MP, defined as MARSE energy divided by duration. Counts and duration were used to calculate the average frequency (AF), defined as counts divided by duration.

Before each test, the correct operation of the sensor and its acoustic coupling to the probe were verified by means of the Hsu-Nielsen method. Also for each session of measurements, the torque cell was calibrated.
2.2 Performing drilling tests

The cutting conditions, defined by parameters such as speed of rotation and feed rate, or additional procedures such as lubrication, were adjusted to replicate a typical situation of drilling. In the literature some studies have chosen typical cut and feed rates close to those used in this work [18-20].

All tests were performed on many sessions, maintaining the same cutting conditions, to enhance the statistical independence of sampling experiments. The meaning in this work of the word “test” will be defined to one drilling operation over one workpiece sample with a drill bit with a particular condition. Then 32 tests were performed in which the tool condition was varied, with 8 cases or states of the edges of the drill bits used. The details of the feed rate and rotation speeds, and lubrication were given in Section 2.1.3.

Drilling procedure

For each of the specimens, a single hole was drilled. Each hole was drilled with a drill representing a specific condition of the edges. At least three trials were performed for each condition of wear to obtain representative results. Each test drilling was divided into stages in agreement to the guidelines detailed in literature [17,22]. The description of each of these stages is described as follows:

- **First stage**: approach of the drill bit to the sample, free rotation.
- **Second stage**: contact between the drill bit and the piece, slip.
- **Third stage**: start of the drill bit cutting, until its tip enters fully into the hole. The chisel of the drill does not enter in contact with the workpiece as it rotates inside the pilot hole.
- **Fourth stage**: the wall of the hole contains the outer corners. The drill goes into a quasi-stationary regime of cut (after the initial transient) in the region with pilot hole.
- **Fifth stage**: the chisel contacts the bottom of the pilot hole.
- **Sixth stage**: the cutting edges restart the action of cut (transitional).
- **Seventh stage**: quasi-stationary regime of drilling deeper than the pilot hole.

At the end of the seventh stage, the drilling ends abruptly with the rapid removal of the drill out of the hole.

2.3 Signal analysis
The aim of the signal analysis was to find a correlation between typical AE parameters, representing stress waves released during drilling, and torque representing a mechanical parameter in that process.

2.3.1 Average of the AE features and torque for quasi-stationary drilling
For each of 30 drilling tests, for eight drill bit conditions, the AE and torque signals were averaged in a time window of approximately 20 seconds, corresponding to all the hits measured in the fourth stage of cutting of quasi-stationary drilling with pilot hole, avoiding the chisel action. After taking each average, the results for tests with the same tool condition was grouped and averaged again, to represent in a graph the studied parameters as a function of each drill bit condition. Then the average of amplitude, RMS, MP and AF of AE were plotted in terms of the drill bit condition. The behavior of each AE feature on the evolution of the degree and the type of wear of the tools was evaluated. Also the torque was computed and plotted with identical methodology.

2.3.2 Linear correlation between AE parameters and torque
After finding a strong correlation between torque and MP the study was continued in that direction. In the literature, torque has shown to be an old and good indicator of the mechanics of the cutting, having been used in many works as predictive parameter of the process status for rotating tools (such as drilling or milling) [2,21,23]. Therefore, the study of the linear correlation between torque and the two main AE features for continuous AE signals as MP and RMS was proposed. Then for the measured signals, each AE feature and torque were correlated in a time window of approximately 60 seconds, corresponding to each whole drilling test for each case performed at similar cutting conditions (velocities, lubricant, drill diameter, etc.). Both the torque and the RMS are lower frequency signals than the MP, then before correlation the rapid variation of the MP was filtered applying a moving average to MP. The moving averaged mean power of AE (MAMP) was calculated with a moving window of 10 neighboring points and acted as low-pass filter.

Then, the correlation between torque and MAMP was calculated and the results were plotted and compared with those for RMS to find the best AE feature to evaluate mechanical characteristics of drilling.

3. Results and discussion

The AE signals and parameters measured in drilling tests with different tool condition were performed at the same cutting conditions. The acquired data was studied in two parts, one in which the average of the torque and the AE features were computed in the stage of quasi-stationary drilling, and the second in which the correlation between the torque and the AE parameters (RMS and MAMP) were evaluated for each complete test.

3.1 Average of AE features vs. drill condition

Figures 6, 7, 8 and 9 show the behavior of the AE features evaluated for the different states of wear of the drill bits. It should be remembered that this part of the study does not take into account the action of the chisel edge of the tip of the drill, as the analyzed signals correspond to the stationary cutting with pilot hole.

In Figure 6, the average of amplitude of the hits of AE for different drill bit conditions is plotted. The graph showed a growth of this parameter as a function of the wear of the cutting edges. The averaged amplitude for the condition of worn outer corners (WF) showed a lower level than in the most worn cutting edges.
In Figure 7 the evolution of the average of the RMS value of the AE plotted as a function of the different tool condition was shown. In this figure, a similarity with the Amplitude in low and high wear was observed.

Figure 6. Averaged Amplitude vs. drill bit condition.

Figure 7. Averaged RMS vs. drill bit condition.

Figure 8. Averaged AF vs. drill bit condition.
The average of the AF plotted in Figure 8 also shows a behavior in which there are three zones, one starting with the new bit, an intermediate with less damaged bits, and a third with the most damaged bits, the last two in the form of two closely spaced plateaus, within which one cannot distinguish the different cases belonging to these. This would indicate that in the test conditions, the AF would not be a good parameter to classify the degree of wear.

In Figure 9, the average of the "MARSE mean power" (MP) showed three different behaviors depending on the progress of the variable "drill bit condition". First, for new drill bits (NE1) the averaged MP showed a very low value. Second, the next three conditions with little damage or wear (NE2, NE3 and MDE) showed a plateau, with no difference in MP between drills with little use, poor completion of manufacture, and edges with indentations by EDM. The third set corresponds to the case of further deterioration (FE1, FE2, MDE and WF), for which a monotonically increasing approximately linear behavior can be observed. This linear behavior could be used to discriminate the degree of damage. In this analysis, the drill bit with worn outer corner (WF) can be separated from the drill bits with damage in cutting edges. For this particular case, the averaged MP showed a larger value than that obtained for the drill condition MDE, with the greatest damage on their cutting edges (highly cratered mechanically). Thus, there is a relationship between the averaged RMS and MP for cases with damage in the edges. For the case of the worn outer corner, mostly the behavior is similar to what happened to the study of the amplitude of AE.

![Figure 9. Averaged MP vs. drill bit condition.](image)

![Figure 10. Averaged Torque vs. drill bit condition](image)
3.2 Average of torque vs. drill condition

Figure 10 shows the mean torque for each drill bit condition with the corresponding standard deviation. Analogous to the behavior of the MP plotted in Figure 9, the torque showed little variation for drilling with low wear drill bits (less than for the three cases of the parameters of the AE) and a marked variation in cases of major damage to the edges and wear on the outer corner. For lower wear, torque occurring in a plateau of indistinguishable values, and for higher wear the mean torque is increased with the degree of damage of the drill bit (in both edges and in the outer corner). For this second case, it would be possible to evaluate the degree of wear of the drill bit analyzing the measured torque during drilling. The values obtained for the torque in this work are in agreement with other studies measured in similar conditions [21].

3.3 Relationship between averaged Torque and AE features

Comparing torque and MP as a function of drill bit conditions in Figures 9 and 10, the same behavior can be adjusted to both parameters, neglecting the first point representing the new bit condition. A linear ratio with torque is obtained applying to the MP a multiplicative constant and a shift with respect to zero. Figure 11 shows the fitting of torque and MP, adjusted from the equation (1).

\[ Torque = MP * 0.188 \times 10^{-3} \frac{kg\cdotcm\cdots}{E_{counts}} + 2.26 \text{kg cm} \]

For the conditions of this study, we can conclude that a proportionality or linear relationship between the results of mean torque and averaged MP has been found. Both parameters were calculated as averages over a large number of AE hits (the torque was sampled simultaneously to each AE hit), which were studied in steady cutting regime, drilling with pilot hole. The linearity observed for the four cases of major wear would allow estimating the torque applied by the drill bit to the workpiece, from the MP of AE.

![Figure 11. Fitting of torque and PM vs. drill bit condition.](image-url)
3.4 Correlation between torque and AE features

Another point of view of the relationship between AE features and torque was obtained by means of the study of the linear correlation between some AE features and torque as time functions. In Figure 12, the correlation coefficients were plotted as a function of the drill bit condition. The plotted conditions were: new (NE1, NE2 and NE3), edges worn by EDM (BE1 and BE2), worn outer corners (WF) and mechanically dented edges (MDE). The selected AE features for this evaluation were MAMP and RMS, based in a previous work [17]. In the graph, the red circles represented the correlation between torque and MAMP and the brown circles the correlation between torque and RMS. This figure shows clearly that MAMP have the best correlation with torque as a function of time. The correlation coefficient for the MAMP is higher than that for the RMS. RMS is the most used parameter in the applications of AE in metal machining and one of the recommended in the literature [24]. Although the mathematical procedure for both parameters is comparable, MAMP analysis showed better results than the RMS.

![Figure 12. Correlation of MAMP (red circles) and RMS (black squares) with torque](image1.png)

![Figure 13. MAMP and torque vs. time, for a test of drilling for BE1 condition](image2.png)

The good correlation between torque and MAMP, specified in Figure 12, is evidenced in Figure 13 in which are shown MAMP and torque versus time for a new drill bit. Both graphs,
torque and MAMP show the different stages of the cutting process, which were previously detailed. For example, watching the MAMP AE signal the drilling machine operator can infer if the tool is entering in the material (second stage), drilling through the pilot hole (fourth stage) or through the region without a pilot hole (sixth stage). Irregularities related to abnormalities of the machining process could be observed in the signals. In earlier works, Carpenter [25] showed the same high correlation behavior between AE RMS and frictional force, and Marinescu and Axinte [26] correlating the MARSE and the cutting force.

The energy of the rotating drill is transmitted to the sample through the friction of the chisel with the end of the hole and the flute with the wall, and in proper cutting of the material (plastic deformation). This is actually measured by the torque. It is outstanding how accurately the AE follows these mechanical changes giving place to an important correlation.

For higher sampling frequencies, the AE MP should show greater sensitivity compared to the dynamic response of torque, due to its higher bandwidth for detection of fast transients, as the elastic waves emission of the chip breaking. Another advantage of the AE in the sensing of the cutting process could be looking at a simpler implementation and lower cost. Regarding the use of the MAMP, it is based on the stochastic nature of AE, which according to the wear of the drill bit varies the dispersion in the MP. Filtering the higher frequency, the dispersion of the remaining variations is coincident with the detected torque [6]. The moving average acts as a low-pass filter to reveal information related to mechanical processes of lower characteristic frequency.

4. Conclusions

For the drilling conditions of this study, a proportionality or linear relationship between the results of the mean torque and the averaged MP has been found. This correspondence could be useful to estimate torque values from the MP of AE signals.

Analogous to the behavior of the averaged MP, the mean torque showed little variation for drilling with low wear drill bits (less than for the three cases of the parameters of the AE) and a marked variation for major wear on the edges and wear on the outer corner. For these four conditions it would be possible to evaluate the degree of wear of the drill bit analyzing the measured torque during drilling.

The analysis of the linear correlation between torque and AE features as function of time showed that the correlation coefficient for the MAMP is higher than that for the RMS. The moving average acts over the MP as a low-pass filter to reveal information related to the mechanical processes of lower characteristic frequency, as that detected by the torque.

Other findings include:

The averaged Amplitude of the AE showed a growth behavior depending on the wear of the cutting edges. This parameter for the condition of worn outer corners (WF) showed a lower level than in the most worn cutting edges.

The evolution of the averaged RMS value of the AE as a function of the tool wear showed a similar behavior to the averaged Amplitude.

The averaged frequency (AF) of the AE showed no qualities to classify the degree of wear of the drill bit.

The averaged MP showed three different behaviors depending on the progress of damage in the cutting edges. For new drills the MP showed a low value. The next three conditions with little wear showed a plateau, with no difference in MP. The third set corresponds to the case of further deterioration on cutting edges, for which the averaged MP manifested a monotonically increasing linear behavior, which could be used to discriminate the degree of damage. The condition WF showed a higher value than that obtained for the condition MDE, with the greatest damage on their cutting edges (highly cratered mechanically).
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References