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Assessment of cutting tool condition by acoustic emission

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Abstract

Acoustic emission (AE) signals, generated during the machining of steel, were analyzed in order to extract information about the condition of the cutting tool. Drill bits with different cutting edge conditions were used to drill steel specimens while registering the AE generated during cutting. Artificial wear of the drill bits was produced by spark erosion and by mechanical means and was assessed by scanning electron microscopy (SEM). During cutting typical parameters and waveforms of AE and torque were recorded. The relationship between MARSE (Measured Area under the Rectified Signal Envelope) Mean Power (MP) and torque was studied for the different conditions of the drill bits. The evolution of the mobile variance of MP in terms of its moving average was also analyzed with interesting results for determining the condition of the tool. Furthermore, the waveform of AE signals was evaluated through the power spectrum and, from these and from previous results, it was possible to separate the contributions to MP from different AE sources.

Keywords: Acoustic emission, drilling, mean power, torque;

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1. Introduction

One very important point in machining processes, for reasons ranging from economics to function and aesthetics of the manufactured product, is the monitoring of the condition of the cutting tool. The term wear is used to describe the degradation of the edge and of surface quality, the fracture of the tool or the reduction of mechanical properties by temperature, Dornfeld, 1980. Direct and indirect methods have been developed to detect tool wear, the later being the easiest to implement, Teti, 2010. These can include measurement of power, torque and feed force, mechanical vibration and acoustic emission performed during the cutting process. Iturrospe et al., 2005, have shown that AE is the method that has the highest sensitivity for machining processes like turning.

Terminology

AE	Acoustic emission
MARSE	Measured area under rectified signal
MP	Mean (AE MARSE) power
MAMP	Moving average of MP
MVMP	Moving variance of MP
ASP	Averaged spectral power
QSR	Quasi-stationary waveforms rate (emitted by time unit)

The AE method consists of studying the elastic waves (ultrasound), generated as a stochastic process by tool-specimen interaction during cutting, with the aim of predicting undesired effects such as tool wear or damage. The AE equipment detects the elastic waves generated on the surface of the specimen (or tool) and converts them into electrical signals through a piezoelectric sensor. Depending on the type of process in the emitter source, AE signals can be transient (burst) or continuous. Chip fracture, breaking of the tool edge, and the chip hitting on tool and workpiece can be mentioned as AE burst sources. Otherwise, plastic deformation of the workpiece and the chip and friction between tool, workpiece and chip are sources of continuous AE, Li, 2002, Teti et al., 2010. The detected and stored AE signals are then analyzed to relate them to the condition of the tool. Typically, AE signals are studied in two ways; the easiest, the AE signal features, the hardest, the waveforms. For the first case, the AE system is able to extract some useful characteristic parameters from the AE signal. 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, Spanner et al., 1985. Also MARSE mean power (MP) and its variance can be defined as signal features, Gomez et al., 2007. 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. Based on previous works, Gómez et al., 2009, 2010, the MARSE mean power was chosen as the main AE parameter, the tool condition information being obtained by plotting the moving variance of MP as a function of their moving average. Another reference parameter used was torque which together with feed force, have been widely discussed in the literature to characterize rotating tool wear, Jantunen, 2002.

Waveform allows a more profound and informed analysis of, for example, the frequency spectrum. Studies have been made of average spectral power showing an increase in the most energetic EA frequencies for high tool wear conditions, Du et al., 1991, Marinescu and Axinte, 2009, Kunpeng et al. 2009.

Further details of the present work can be found in a PhD Thesis, Gómez, 2011.

2. Experimental method

This section describes briefly the methodology used to perform 30 drilling tests with 8 drill bits with different wear conditions. AE and torque were measured in all the cases. The procedure for AE signal processing is also described. Synchronized video recordings were also made to evaluate the chip formation.

2.1. Specimens

Specimens were produced by cutting 95 mm long pieces from an AISI 1040 steel hexagonal bar 14 mm wide. The homogeneity of the material was assessed by optical metallography; an ASTM 7-8 grain size was measured. Rockwell B average hardness was found to be 98.5 ± 1.5. A pilot hole 1.5 mm in diameter and 10 mm deep was drilled on one of the faces of every specimen along the longitudinal axis. The pilot hole in the workpieces is for avoiding the contribution of the chisel to the cutting process, focusing the study in the action of the cutting edges and the outer corners of the drill bit.

2.2. Drill bits

Defects were produced in a controlled manner on the cutting edges and the flute edges on the tip of 5 mm diameter commercial high speed steel (HSS) drill bits. The artificial wear was produced by mechanical procedures and by spark erosion (Table 1). Fig. 1 shows SEM images of the damaged lips. HSS was the material chosen for the drill bits to decrease the elapsed time in the mechanical wear process.

Table 1. Drill bit condition.

Drill bit	State	Condition	Name
1	No damage	New, with sharp cutting edges	NE1
2	No damage	Used, with sharp cutting edges	NE2
3	No artificial damage	New, with defective cutting edges	NE3
4	Artificial damage	Spark erosion dents on cutting edges	SDE
5	Artificial damage	Spark erosion blunted cutting edges (case 1)	BE1
6	Artificial damage	Spark erosion blunted cutting edges (case 2)	BE2
7	Real damage	Mechanically dented cutting edges	MDE
8	Artificial damage	Mechanically worn flute edges	WF

The condition of the blunted edges (BE1 and BE2) condition is a first approximation for the transition from the sharp cutting edges to a condition of excessive wear, altering the effective cutting angle and producing a bigger contact surface between the tool edge and the workpiece. The spark-erosion dents represented a typical condition of little craters in the cutting edges. Mechanically dented cutting edges (MDE) is an extreme condition and it was obtained drilling a very low-quality steel with hard inclusions. In WF condition, the flute edges were mechanically worn with a drill sharpener to simulate other typical kind of tool wear.

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, following the pilot hole. 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 cm^3/min.

2.3. AE and torque measurements

Fig. 2 (a) shows the AE system block diagram. Elastic waves produced by AE sources were converted to electrical signals of very low amplitude by a PAC WD broadband AE sensor attached on the workpiece (Fig. 2 (b)). A broadband CISE preamp of 40 dB (100 x) gain 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. The characteristic parameters and waveforms were acquired simultaneously and the signal from the torque cell was synchronized with AE and recorded in the same data files as an external parameter. The AE signal acquisition was triggered at a threshold of 27 dB_{EA} in order to minimize the influence of background noise. The sampling frequency was 5 megasamples per second (Ms/s). Several thousand hits, and their corresponding parameters and waveforms were recorded for each test (hole).

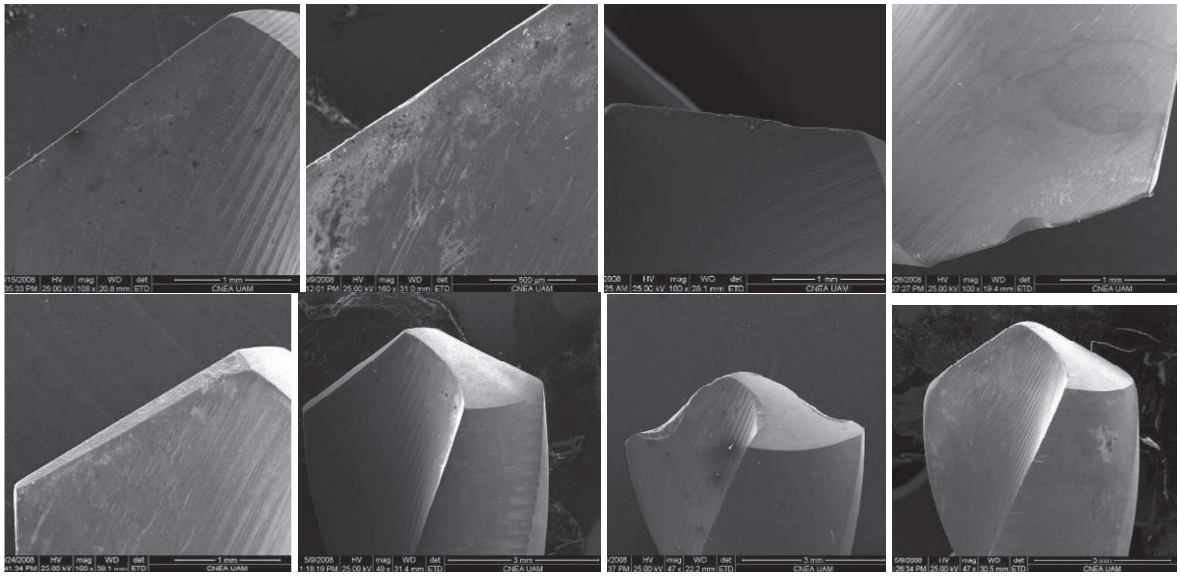


Fig. 1. Modification of cutting edge and flute edge conditions introduced by several means. From left to right and from top to bottom: NE1, NE2, NE3, SDE, BE1, BE2, MDE, WF.

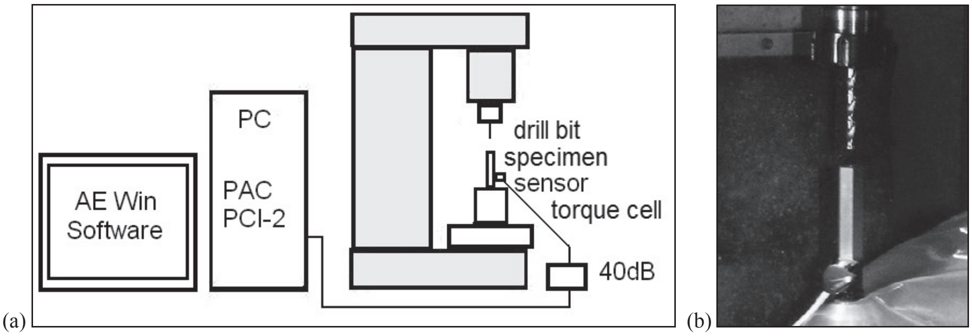
The MARSE energy parameters and the duration of the AE signals, recorded in 20 ms periods, were used to calculate the MP. For the waveforms, 15 kilosamples fractions of the digital signal, equivalent to 3 ms in time, were used. Before each test, the correct operation of the sensor and its acoustic coupling to the workpiece were verified by means of the Hsu-Nielsen method.

The torque was measured using an Instron torsion cell and processed by a CNEA signal conditioner. The acquired signal was digitized with a resolution of 16 bits in amplitude at a sampling rate of 10 ksamples per second. Each specimen was mounted on the torque cell through a mandrel in the manner indicated in Fig. 2(b). Tests for each drill condition were repeated three to four times.

2.4. Signal analysis

The AE data was obtained during the uniform cutting phase along the pilot hole, resulting in approximately a thousand AE hits for each drilling test. AE parameters were analyzed by two different methods. First, the

MP and torque for each condition (3 or 4 tests per case) were plotted and compared. Second, the moving variance (MV) and the moving average (MA) of MP were calculated and plotted as MVMP vs. MAMP graphs. The variations observed in those graphs, with reference to the number of neighboring points (in the moving window), were evaluated.



(a) (b)

Fig. 2. (a) AE system Block Diagram in a drilling test; (b) AE Sensor on hexagonal sample.

Furthermore, non-stationary and quasi-stationary AE waveforms were evaluated and separated by means of an algorithm using statistical moments, where the first set of signals represents emissions containing transient behavior (burst type) and the later those of the continuum type.

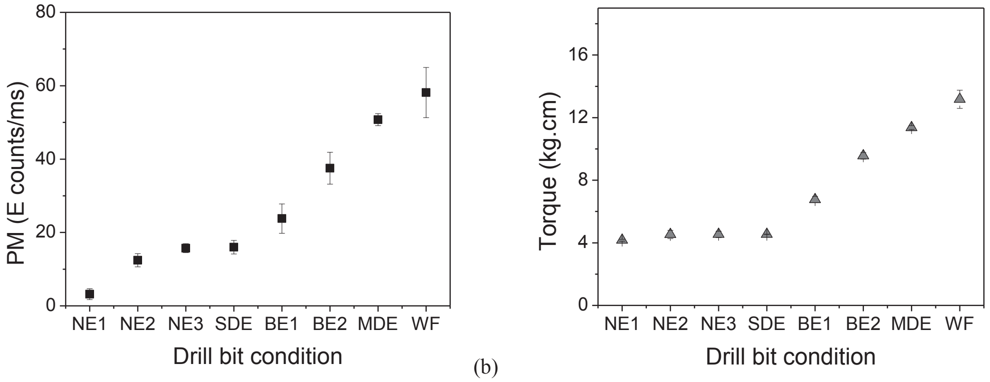
Another representative variable, the number of quasi-stationary waveforms emitted by time unit or quasi-stationary waveforms rate (called QSR), was calculated and plotted. The averaged spectral power (ASP) in three frequency bands (50-150 kHz), (150-250 kHz) and (250-350 kHz) was also calculated and evaluated with reference to the drill bit condition.

Finally, using the results obtained from the ASP, the MP was calculated for the case of the waveforms without chip breaking (no burst type signals) and compared with the MP calculated from the AE parameters containing hits. It was then possible to estimate the MP of each of the two main mechanisms of AE generated during drilling.

3. Results and discussion

Fig. 3 shows the MP and torque measurements for each test trials averaged for each drill bit condition. It is apparent that these two parameters are not sensitive enough to differentiate the drills bits with low wear, except for the case of the AE MP in the new drill bit condition. The ability to differentiate between wear conditions in the four cases of highly damaged cutting edges is much higher. There is also a strong correlation between both parameters.

Fig. 4 shows the evolution of VMPM vs. MAMP of AE signals according to each condition for 5, 20, 100 and 300 nearest neighbors, where the increased number of neighbors means a greater accumulation of temporary data. It also shows how an increase in the number of neighbors for each point, for MA and MV, increases the definition of the zones representing the different wear conditions. At the bottom of Fig. 4 two well-defined behaviors may be observed: one for the AE signals from drill bits with worn cutting edges and another from those with worn flute edges. An exponential function was adjusted for the first case. The AE generated in drilling is a stochastic process and the results for each test are expressed as "clusters" in the two-dimensional graph. The points corresponding to a defined condition of the drill bit are located around the center of mass of each "cluster". When new data values are added to the charts these overlap according to the corresponding condition. Cases with little or no wear overlap in small clusters while larger clusters are observed for high wear conditions.



(a) (b)

Fig. 3. (a). MP (AE) as a function of drill bit condition. (b). Torque as a function of drill bit condition.

The developed method would be useful for application to repetitive processes, i.e. the production of the same type of part, with a given material, at constant conditions of speed, lubrication, diameter of the drill bit, etc.

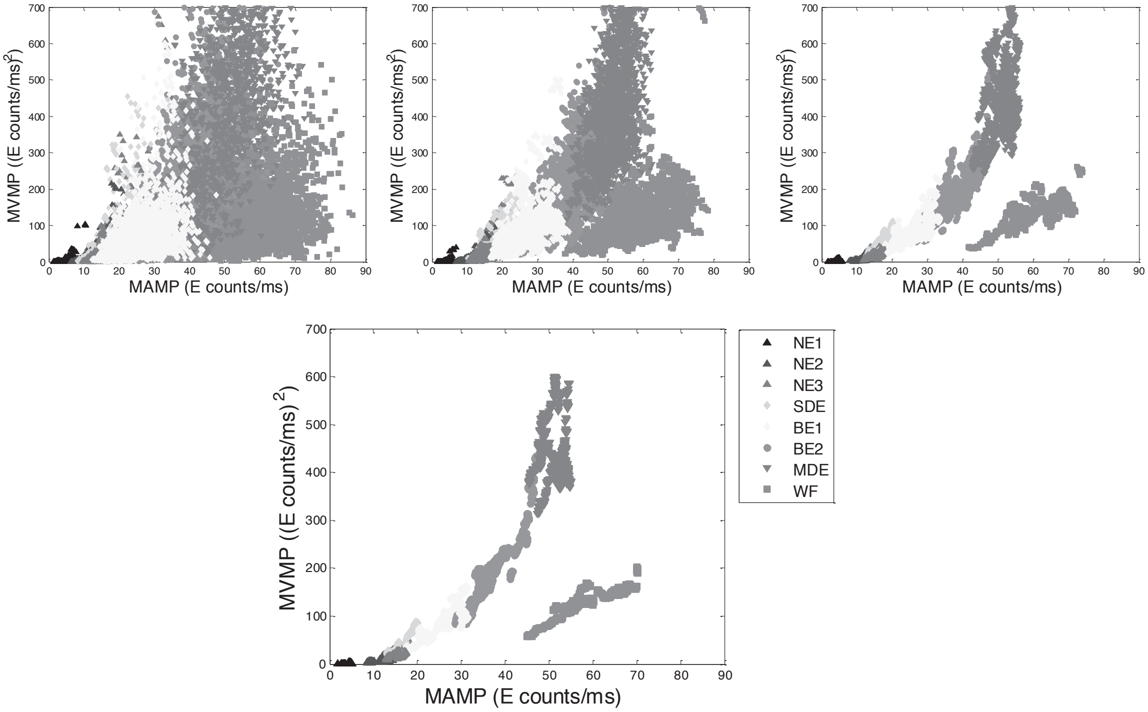
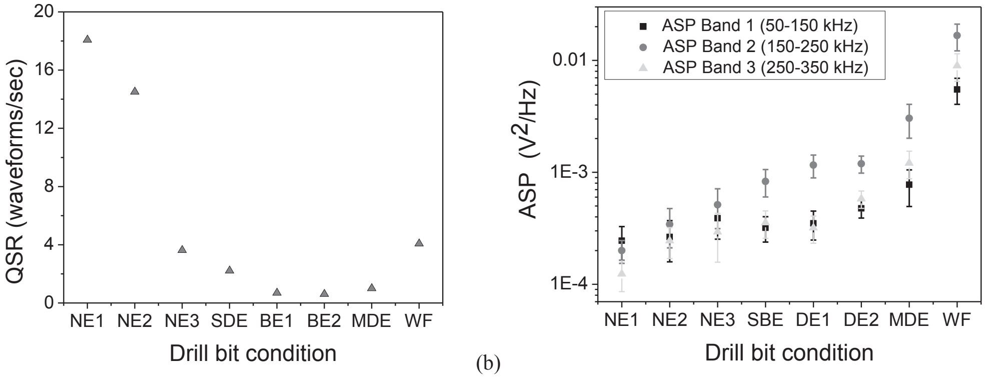


Fig. 4. Evolution of MVMP vs. MAMP of AE signals according to drill bit condition. From left to right and from top to bottom: 5, 20, 100 y 300 first neighbors.

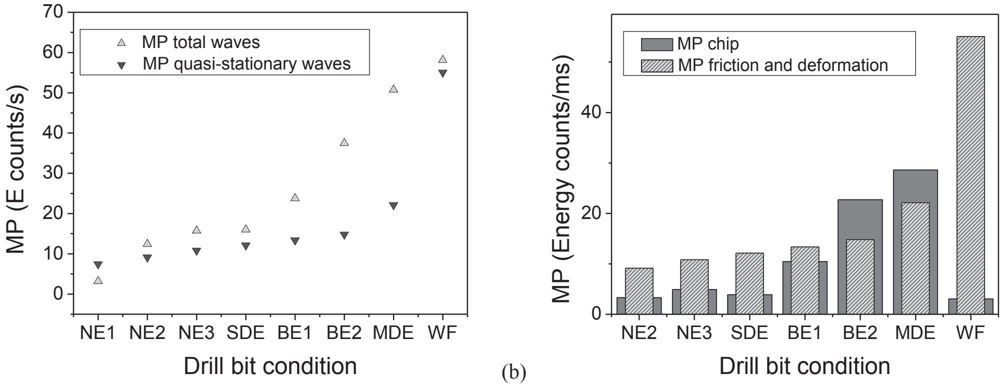
Fig. 5 (a) shows the emission rate of "quasi-stationary" AE waveforms per unit time and Fig. 5 (b) shows the ASP for different frequency bands for each of the waveforms for each condition. The relationship between "burst type" AE emissions with chip breaking was confirmed and qualitatively correlated by synchronized video recordings. Fig. 5 (b) also shows that the highest values for the frequency band are produced by the conditions designed as MDE and WF.



(a) (b)

Fig. 5. (a) QSR (waveforms/sec) vs. drill bit condition. (b) ASP vs. drill bit condition, for each frequency band.

According to the literature, continuous AE may be produced by friction and by plastic deformation, while the burst type signals have, as the primary mechanism, the breakage of the chips. In Fig. 6 (a) the green up triangles represent the mean power obtained from AE parameters extracted from the whole set of AE signals, while the blue down triangles correspond to the mean power calculated from the quasi-stationary AE waveforms. Also, in Fig. 6 (b), an approximation of the MP of the AE corresponding to the burst type signals (red bars) is shown, related to chip breakage. It was estimated by subtracting the MP of the quasi-stationary AE signals from the MP of the whole set of AE signals. Similarly, Fig. 6 (b) shows the MP corresponding to the continuous mechanisms related to friction and plastic deformation, displayed as green bars. This is consistent with experimental observations for conditions BE1, BE2 and MDE, where chip breakage is high, so it is logical that in those three cases, the PM of the non-stationary waveforms shows the highest values. The WF condition also produces continuous chip, in agreement with the increase of quasi-stationary AE in Fig. 5 (a) and the decrease of MP, related to a reduction in chip breakage.



(a) (b)

Fig. 6. (a) Mean power related to condition for all signals and stationary signals. (b) Discrimination of the two main AE source types.

4. Conclusions

AE MP and torque measurements may be correlated to conditions of high damage in drill bits cutting edges, but are not sensitive enough in low damage conditions. A strong correlation between both parameters was observed which may be of value in the application of AE MP as a monitoring parameter.

AE generated during drilling is a stochastic process and graphs of MVMP vs. MAMP show a series of clusters related to each cutting edge condition. Data points for a given condition tend to group together. The size of the cluster is relatively small for low damage conditions and becomes larger when damage of the cutting edges is increased. The shape of the clusters becomes more defined when data is added, increasing the number of neighbors involved in the averaging of results. Different behaviors were observed between damaged cutting edges and blunt flutes. The clusters obtained for drills with damaged edges were aligned as a power function of the drill wear, the clusters for drills with blunted flutes shown a separated location in the MVMP-MAMP plane. The method described might become useful in the monitoring of repetitive processes.

AE signals produced during the drilling process were evaluated and separated into two groups: quasi-stationary and non-stationary. The rate of quasi-stationary AE signals was associated with the chip breaking process. Also, for quasi-stationary AE signals, an increase in tool wear produced a shift to highest frequencies of the AE power distribution.

The MP of the AE produced by chip breakage might be estimated from the values obtained in the calculation of the MP, including all the AE values and the values of ASP derived from "quasi-stationary" condition involving friction and plastic deformation. This was in agreement with experimental observations.

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