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TCM system in contour milling of very thick-very large steel plates based on vibration and AE signals

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ABSTRACT

This paper describes the design and test of a tool condition monitoring (TCM) system during a milling process with an especial king-size multiple insert tool for machining very high thickness and length steel plates. The system focuses on the study of acoustic emission and vibration signals in order to correlate both physical phenomena with tool wear condition. By combining acoustic emission signals and vibration signals, it is possible to identify the tool condition with more reliability. Each of these signals provides complementary results, in different spectral bands. The use of different statistical measurements (RMS, kurtosis and skewness) together with the analysis by frequency bands allows identifying the tool condition and the transition between wear conditions (progressive, intermediate and advanced). The design of the TCM system for signals acquisition and processing is described (instruments and strategies). This work is innovative since there is no prior information about TCM systems applied to machining processes in such severe conditions. This type of control is essential in operations where very high value parts and tools are involved, such as milling of very thick-very large steel sheets.

1. Introduction

Due to its relevance in the industrial field, tool wear condition monitoring has been object of study for several authors in the past decades. Wear monitoring strategies using analysis of vibration signal have been widely used both in turning and milling processes. Lauro et al. (2014) recently wrote a paper with the purpose to understand the procedures for monitoring machining processes based on defined methods, parameters, targets and other factors involved in it. As Lauro et al. stated, an easy way to identify these phenomena is by monitoring machining processes using signals. Vibration signal is highlighted as one of the most useful signals for monitoring the machining operation. Also, Rehorn et al. (2005) presented a very complete review of the state-of-the-art in sensors and signal processing methodologies used for tool condition monitoring (TCM) systems in industrial machining applications. Their review focused on technologies used in conventional cutting operations monitoring, including drilling, turning, end milling and face milling. They indicated that an accurate and reliable TCM system could result in a reduction in downtime by allowing it to be scheduled in advance and an overall increase in savings of between 10% and 40%. In their research, these authors concluded that the use of AE and vibration signals offer a good dynamic threshold and can quickly detect tool breakage; the frequency content of the signal increases as wear and breakage occur.

The most popular procedures for signal processing and analysis are those which are carried out in the domains of time and frequency. Time domain analysis is performed by means of time dependent mathematical functions. Root Mean Square (RMS) signal value and signal correlation are common techniques in the time domain analysis. Acquisition of raw signals and application of transform functions such as Fast Fourier Transform (FFT), makes it possible the treatment and analysis of signals in the frequency domain. Frequency domain analysis allows to identify the frequency components in a signal, as well as its amplitude and phase through spectrum plots. The most important guides related to fundamentals of signal analysis reveal that the success of the monitoring process is leaded by the disposition of adequate vibration and acoustic sensors. Adequate constructive features, sensitivity, dynamic and frequency range assure a precise signal acquisition and measurement.

On the other hand, characteristics and magnitude of vibration phenomena are strongly dependent on the machining process conditions, such as cutting parameters, workpiece composition, use

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of lubricants, fixtures and jigs condition, etc. For example, Zhong et al. (2010) found that vibration in peripheral milling process is significantly affected by cutting fluid. Cutting vibration in peripheral milling is mainly generated by intermittent cutting force, which is inherent to milling operations. Higher cutting speeds, feeds per tooth, radial depths of cut or cutting-fluid flows tend to cause higher RMS values. Moreover, there are another events that can affect and make difficult the tool wear monitoring process, since vibration signals are the result of the contribution of many machinery parts and components. In the research of Zeng et al. (2012) the authors indicate that fixture layout is apt to generate machining vibration, which will seriously affect the machining quality of the surface. They built a dynamic model on the workpiece fixture cutter system. On the basis of this model, an approach to fixture design is proposed and introduced to suppress the machining vibration. It is worth noting that the location, the applied forces and the number of fixture elements can be simultaneously optimized. This means that location of vibration and AE sensors are critical for a reliable tool monitoring system. Bisu et al. (2011) stated that the interest is to separate the contribution of different vibration sources related to failure. The separation will not only locate defaults on the components but also follow the evolution of damage. In their research, the vibration Synchronous Envelope Analysis (SEA) method is proposed to detect the cutting capacity of a tool, necessary for performing a on-line quality monitoring. This method represents a basis for cutting parameter optimization. Authors indicate that it is useful for both dynamic tool characterization and also for monitoring and maintenance purposes.

As an example of previous works on vibration phenomena by means of accelerometers, Zhong's paper can be cited (Zhong et al., 2010), in which a study about cutting tool life in milling processes is presented. The study was carried out under different machining tool conditions with 2 MHz sample rate, in a frequency range between 0 and 80 kHz, in order to show the influence of cutting conditions in tool life by means of vibration signal analysis. Zhong performed both time and frequency analysis, drawn the main conclusions through RMS and FFT signal analysis. Bisu's contribution (Bisu et al., 2011) can also be highlighted, which presents a real time monitoring system for milling processes based on vibration signals, using lower sampling rates (50 kHz). This author used Synchronous Envelope Analysis (SEA) based on Hilbert Transform. Orhan et al. (2007) performed FFT spectral signal analysis focused in the relationship between vibration phenomena and tool wear, highlighting the important information gathered in the range 400–800 kHz. However, there are many other analysis techniques, i.e. the stationary cycle method by mean of the angular domain performed by Lamroui et al. (2014), applied to high speed milling procedures.

Use of AE physical phenomena was initially applied to knowing material structural changes, featured by the transmission of elastic waves within the material as a result of a quick release of energy. Elastic waves may be due to displacement movements, phase transformation, mechanisms of friction, formation of cracks, etc. There are two basic modes of acoustic emission: continuous emission and burst emission (type explosion or blast), the latter being of a transitory nature (Mix, 2005). In a machining operation, these waves are generated in three different areas during the cutting process. As Lu (Lu, 1992) stated years ago, these areas are the primary zone due to chip formation, the secondary zone due to friction between tool and chip and the tertiary zone due to friction between the tool flank and the workpiece.

Numerous authors underline the potential of AE analysis to be incorporated in evaluation of tool wear condition in cutting processes, since information can be useful for monitoring purposes. AE signals are easily distinguishable from other signals of different nature (environmental noise, vibrations, etc.) due to the high frequency of emission (Lu and Chou, 2013). The most common techniques for AE signal processing are the study of the raw signal (AE-RAW) in the time domain, the study of the quadratic mean of the AE-RMS signal and the analysis in the frequency domain by means of AE-FFT and AE-STFT. Also noteworthy is the use of Power Spectral Density (PSD) techniques in the research of Andrade et al. (2015) for the analysis of the spectrum of the acoustic emission signal. The AE signal spectrum is correlated with different tool wear mechanisms and compared to the excitation frequency values associated to these mechanisms. Evolution of the maximum value of flank wear is related to an increase of the amplitude in Power Spectral Density average at the end of tool life.

Useful frequencies as well as sampling rates required for the study can vary greatly depending on the process of machining (milling, turning, drilling). For this reason, in our research we have selected the sensors and parameters of acquisition taking into consideration decisions made previously by different authors. Childs et al. (2000) indicates that the noise emission is due to the deformation of materials with elastic stress waves that occur at a frequency bandwidth typically between 100 kHz and 1 MHz. The work of Marinescu and Axinte (2015) proposed the monitoring of AE phenomena in milling for correlating tool wear and surface quality by studying a range of frequencies between 50 and 400 kHz, with a 800 kHz sampling rate. On the other hand, the appropriate sampling rate for the study of the frequencies of interest in machining processes is established at 1 MHz by Diniz et al. (1992). Lu and Chou (2013) used a sampling frequency of 500 kHz for monitoring machining processes.

The use of monitoring systems based on sensors of different nature provides complementary information which helps to determine more accurately the phenomena associated with the process of cutting. Bhuiyan et al. (2014), for example, concludes in his research that the AE and vibration signature performs exceptionally well to investigate the tool state as well as the different occurrences in machining. The combined application of AE and vibration sensors described the tool wear, tool breakage, chip formation, chip breakage, machine tool vibration, machine vibration, workpiece surface roughness and so on. The raw AE and vibration signals and their frequency analysis are capable of attributing a particular incidence in turning without any ambiguity. However, this research is focused only in turning. Once the monitoring parameters suitable for the process under study have been selected, a relationship can be established between cutting tool wear and different parameters extracted from the acoustic and vibratory signals. Orhan et al. (2007) concludes that a considerable increase in the amplitude of vibration can be observed beyond a particular flank wear considered as critical. On the other hand, some interesting conclusions can be drawn from previous works. For example, Lu and Chou (2013) indicates that the amplitude of frequencies of the AE-FFT spectrum varies depending on the tool condition. In addition, AE-RMS values decrease when the tool has a higher wear. In continuous machining processes, as in metal turning, appreciable increases in AE-RAW value are obtained when the cutting tool wear is high. Andrade et al. (2015) indicates that tool wear can be detected also through amplitude variations in the frequency analysis.

Tool status control is an important task in industry for optimizing roughing and finishing operations. Knowledge of tool wear condition ensures to achieve planned surface finish and tolerances, obtaining also a reduction in unproductive time due to cutting inserts replacement. This paper presents the development of a TCM system through different methodologies of acoustic and vibration signals processing, aimed at the detection of critical conditions of tool wear in edge milling processes of very thick steel sheets, exceeding 40 mm thickness. In this particular context, the very high cost of both product and tool-holder makes the control of the cutting operation a critical aspect. In this task of control, monitoring of tool wear condition is of great importance.

Fig. 1. TECOI TRF milling machine (left) and tool used in the tests (right).

Research in this paper is thought for an industrial implementation. The main objective is to achieve the automation of the milling operation supervision by estimating cutting tool wear through the acquisition and processing of signals. In edge milling operations of very thick plates, as the ones considered in this paper, machining lengths are several meters in each pass. The main drawback in this case is that it is not possible to hold up the operation for tool control in the middle of a several meters pass. Therefore, to ensure that tool wear condition will allow to run a complete pass without damage to the workpiece or the tool-holder is essential. We have used advanced sensors and software to obtain statistical parameters comparable among different conditions of tool. Testing procedures include registration of the RMS signal level, generation of spectra through Fast Fourier Transform (FFT) and the statistical analysis of spectrum bands (values of kurtosis and skewness).

The study has been carried out on a TECOI TRF milling machine with an especial king-size multiple inserts tool for machining high thickness and length steel plates. The innovation is clear since there are not studies in the state of the art which analyse TCM systems applied to such severe conditions with a multi-insert tool.

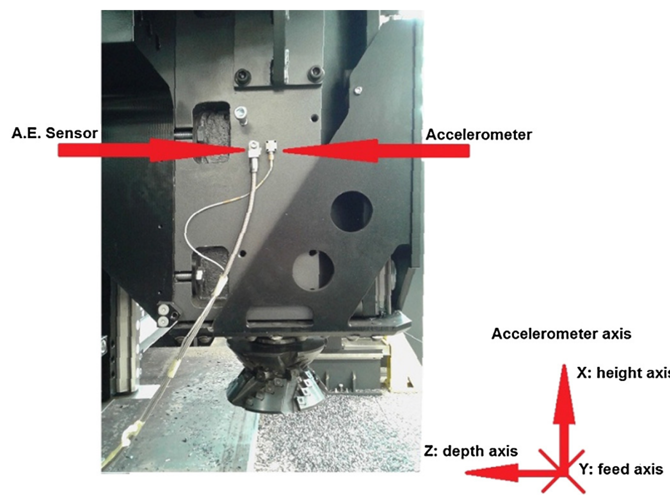

Fig. 2. Location of sensors and axes of the accelerometer.

2. Instrumentation and equipment

2.1. Materials and setup of the monitoring system

Experiments have been carried out in a TECOI TRF milling machine, using a beveling tool MFB5179173/XKEN2966995 (Fig. 1). This tool is composed by six cutting edges, consisting each of them in eight cutting inserts plus a central one. The diameter of the tool is 140 mm measured in the tip of the outer insert and 110 mm in the tip of the inner insert. The used inserts were of Kennametal, uncoated tungsten carbide, rhomboid type fastened by screws, rake angle of 0 without chip breaking. The work material was structural carbon steel S275JR with 45 mm thickness. The sensors used in the tests were located on the envelope surface of the ram, at fixed positions to ensure repeatability of measurements, as shown in Fig. 2. This setup allows to be enough closed to the tool during the cutting process without compromising the integrity of the sensors or their wiring. The AE sensor was screwed into the ram using the torque recommended by the manufacturer. A grease film was applied to improve the transmission of sound waves to the transducer (Diniz et al., 1992). The accelerometer was attached to the head by means of cyanoacrylate adhesive, which reduces the resonant frequency and thus the usable frequency range of the sensor. The X,Y,Z axes of the accelerometer correspond to vertical, depth and feed axis of the tool head (Fig. 2), respectively.

2.2. System of acquisition and processing of vibration signals

Fig. 3 shows the scheme of the acquisition system. The sensor used was a piezoelectric accelerometer Kistler K-Shear 8739A which measures vibrations on three orthogonal axes. Its sensitivity is 10 mV/g and its resonance frequency is higher than 80 kHz. The sensor requires the use of three low impedance couplers (one per channel) Kistler Piezotron 5108A, which supply voltage to the accelerometer and carry the acquired signals. For digitizing the acquired signals a BNC IOTech DBK40 interface was used; an acquisition IOTech Daq2000 (PCI) card is connected to it through a DB37-P1 plug. This card has a resolution of 16 bits, allowing a 200 kHz sampling rate.

Based on previous experience in the machining of similar steels performed by González-Laguna et al. (2015), the frequency range was established in 0–15 kHz, which defines a wide-enough spectrum to record all the frequency components of interest in the machining. The acquisition card was configured so that the three channels had a voltage range of ±10 V, suitable to the voltage output provided by each coupler. With regard to the experimental setup, sampling frequency was established at 303,030 kHz to avoid the phenomenon of aliasing. The acquired raw signals were stored in

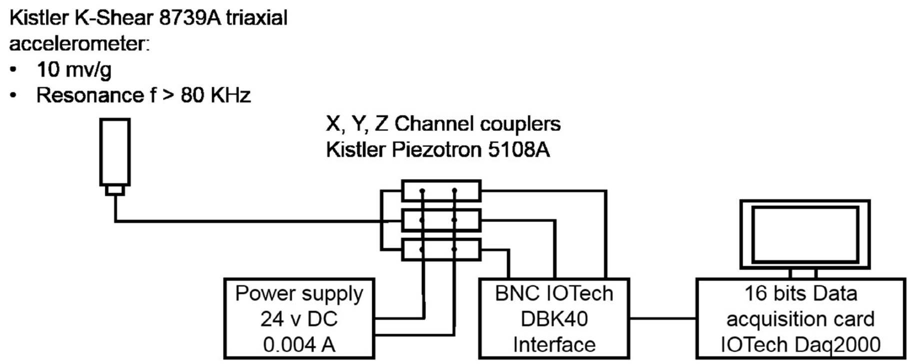

Fig. 3. Acquisition system for vibration signals.

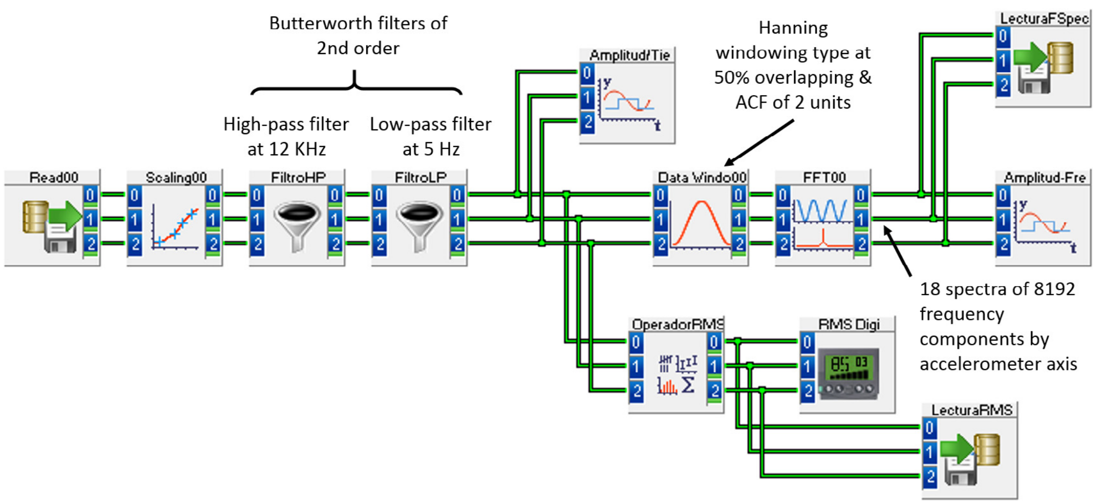

Fig. 4. Processing circuit for vibration signals.

vectors of 214 items, establishing a buffer size of 16384 kBytes. The sampling time was 10 seconds for each reading. Vibration signals processing tasks were conducted by means of DASYLab software. A processing signal circuit was designed using the modules as shown in Fig. 4. Input files to this circuit are those previously recorded with the acquisition circuit.

In this circuit, firstly a scaling is performed to obtain the values of acceleration in m/s^2 with a scale factor given by the sensitivity of the accelerometer. Then, a band-pass filtering of the signal is done, setting cut-off frequencies of 5 Hz and 12 kHz for each channel. Used filters are Butterworth type of second order. For each channel the RMS value of the input signal is calculated for every acquired block, storing the calculated elements in an output file. 18 RMS values were obtained by each reading or record (per channel or accelerometer axis), helping to determine the existence of possible level variations all over the acquisition. The next module in the circuit is responsible for the functions of windowing for minimizing the phenomenon of leakage, allowing a correct representation of the frequency spectrum.

The windowing function is of type Hanning and it provides output vectors composed of 16384 elements. Overlapping is 50% to reduce the loss of information, as well as an ACF (Amplitude Correction Factor) of two units, since the frequency spectrum to be obtained is in amplitude. After the data windowing, the frequency spectra in amplitude are carried out through the application of the Fast Fourier Transform (FFT). The FFT algorithm (Eq. (1)) takes into account the input sequence x and the number of elements in the vector N to get the sequence or resulting spectral vector y_k. The spectra are stored in an output file. These files contain 18 spectra of 8192 frequency components by channel or accelerometer axis, obtained throughout each processed reading (test).

$$y_k = \sum_{n=0}^{N-1} x^{\left(\frac{-j2\pi kn}{N}\right)} \tag{1}$$

2.3. System of acquisition and processing of AE signals

The system scheme for acquiring AE signals is shown in Fig. 5. The used sensor was a piezo-ceramic Kistler Piezotron 8152C1 whose frequency range and sensitivity is 100–900 kHz and 48 dBRef 1 V/(m/s), respectively. The acoustic sensor is connected to a Kistler

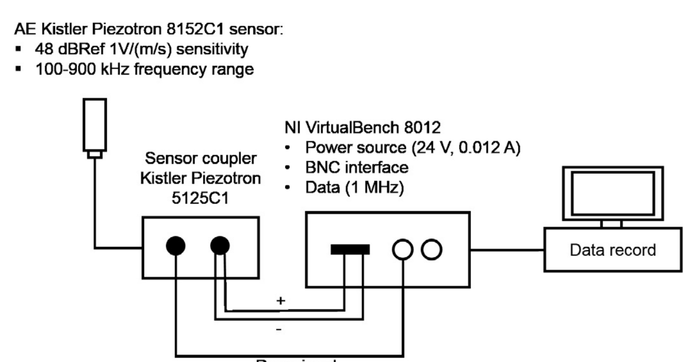

Fig. 5. Acquisition system for acoustic emission signals.

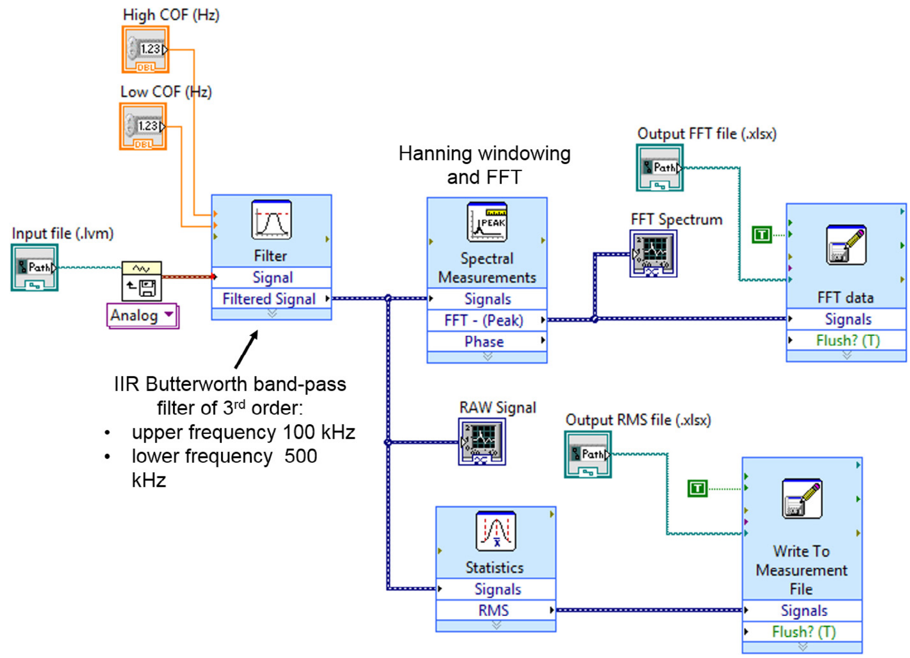

Fig. 6. Processing circuit for acoustic emission signals.

Piezotron 5125C1 coupler, which processes the signals from the sensor, incorporates a band-pass filter appropriate to its characteristics and supplies the required voltage. The system incorporates a device multifunction NI VirtualBench 8012 that meets two basic functions. On one side, it is used as the coupler voltage supply (24 V, 0.012 A) and, on the other hand, it is used as signal acquisition and digitization device through the BNC analog channels that it incorporates. VirtualBench is connected via USB to a personal computer for storing the acquired data. LabVIEW software was used for acquiring AE signals, which provides a graphical programming interface for designing the circuit. The circuit is used to configure the parameters of acquisition, the raw input analog channel and the device power supply for VirtualBench.

The channel resolution in voltage was 10 V. The selected sampling rate was 1 MHz for a time of acquisition of 1 s. The pre-trigger time was set to 0.01 s. Power source is configured to provide a voltage of 24 VDC to a maximum current of 0.5 A.

The signal processing circuit was also designed in LabVIEW (Fig. 6). The previously recorded raw signals were filtered by a IIR Butterworth band-pass filter of third order, with upper and lower frequencies of 100 kHz and 500 kHz, respectively. The cut-off frequencies were chosen according to: the sensitivity of the instrument, the results obtained in the setup tests (carried out at higher sampling rates), the chosen sampling frequency, the criterion of Nyquist, etc. This circuit is also responsible for calculating and storing the RMS value of the input reading. A Hanning windowing of the signal was performed and then the FFT amplitude spectrum of the signal (Eq. (1)) was obtained, which is recorded in a file. This file stores a spectrum which contains 5×10^5 frequency components with 2 Hz frequency resolution.

3. Experimental methodology

The used machining conditions correspond with those of the actual industrial process. In the industrial process, these conditions remain constant for every machining pass and manufacturer only varies the tool head rotation (cutting speed). It is due to the special type of operation and material. In our case, cutting speed was varied to 400, 500 and 600 rpm. This is a special operation where there is not a constant cutting speed due to the high number of inserts involved in the tool. Not all the inserts are at the same diameter in the tool and, therefore, not all of them have the same cutting speed. The only constant parameter is the spindle speed. Speeds of rotation in this range are typical for the real operation. The value of tool feed was f = 900 mm/min and the radial cutting depth a_p = 5 mm. Table 1 shows the relationship between the tests and the speed of rotation of the tool head.

We proceeded to study the AE and vibration phenomena for different conditions of tool wear and using the three selected speeds of tool-holder rotation. Classification of tests were carried out according to five tool conditions:

1. New tool (N): all the inserts are new and have no wear.
2. Progression of wear (NP): operation using the cutting edges used in the former.
3. Intermediate wear (DI): cutting edges are featured by an advanced condition of wear after several machining operations. Wear condition was identified following the advice of the manufacturer.
4. Advanced wear and breakage (DR 15%, DR30%): machining with broken inserts in different proportion (15% and 30%, with regard to the total number of inserts in the tool) combined with inserts featured by a very advanced wear (higher than DI condition).

Classification in one of these classes was done by analyzing the wear of the inserts assembled in the tool. The condition of each insert was decided with the help of industrial experts in this very specific type of machining. It was not necessary to measure the width of wear in the inserts, since it is not intended to give a quantitative and precise measurement of wear but to give a qualitative indication

Table 1
List of readings (tests) and speeds of rotation of the tool head.

Test number	rpm
01–07	400
08–14	500
15–21	600

Tool edges view	Tool edge code n=[1, 6]
	x (n.1) x (n.2) x (n.3) x (n.4) x (A-F) x (n.5) x (n.6) x (n.7) x (n.8)

Tool edge	DR15%	DR30%
n	Replaced inserts	Replaced inserts
1	1.5	1.5, 1.7
2	2.6	2.6, 2.7
3	C	3.5, 3.6, C
4	4.4, 4.5	4.4, 4.5
5	5.3	5.3, 5.4
6	-	-

Fig. 7. Pattern of replacement of inserts in the six cutting tool edges for DRn% tests.

about when it is necessary to change the tool. In this sense, it is not necessary to measure the wear and it is enough with the visual indication of experts in the operation.

The inserts with broken edges were located according to a different substitution pattern on each tool edge (Fig. 7). For replacing them it was taken into account that the beveling operation of the steel plate is asymmetrical and not all the inserts are involved in the machining process. The down side of the bevel is higher than the up side, so that the inserts n.1, n.2 and n.8 of the tool edge were not involved in the cutting.

Images used for measuring the inserts wear were acquired using a Leica microscope. Flank wear measurements were carried out after NP and DI tests to verify that evolution of wear between tests was significant (Fig. 8), so that it is possible to establish different tool condition classes.

Preliminary tests were developed in order to assure a stable operation at different industrial conditions. Once the operation was adjusted and tested for each cutting speed, the final machining tests were carried out. During each of the machining passes (steel plate length of 1200 mm), seven AE and vibration simultaneous signals were recorded for each tool condition and rotation speed. This number of readings was for characterizing the operation during all the machining length. Each of these readings is called Test. Therefore, 7 different readings were acquired for each sensor using the same cutting conditions in order to avoid wrong values. Moreover, several values were obtained by each reading, helping to determine the existence of possible level variations all over the acquisition. Each of the readings corresponds to ten seconds of machining in the case of vibration signal and one second in the case of AE signals. This means that several records of the signals were acquired in order to detect wrong values once preliminary tests were developed to assure the right operation.

4. Analysis and results of vibration signals

Different strategies of analysis were considered for managing the great amount of information generated for each test and each channel of the vibration signal: spectral comparison, analysis of statistical values by bands and comparison of RMS values.

4.1. Spectral comparison

The first step to study the vibration signals consisted in performing a spectral comparison among tests (different conditions of wear for each tool-head revolution and each axis of the accelerometer) to check if there are significant differences among frequency spectra. Each vibration signal reading (ten seconds of machining) gave rise to 18 frequency spectra. After checking that amplitude values

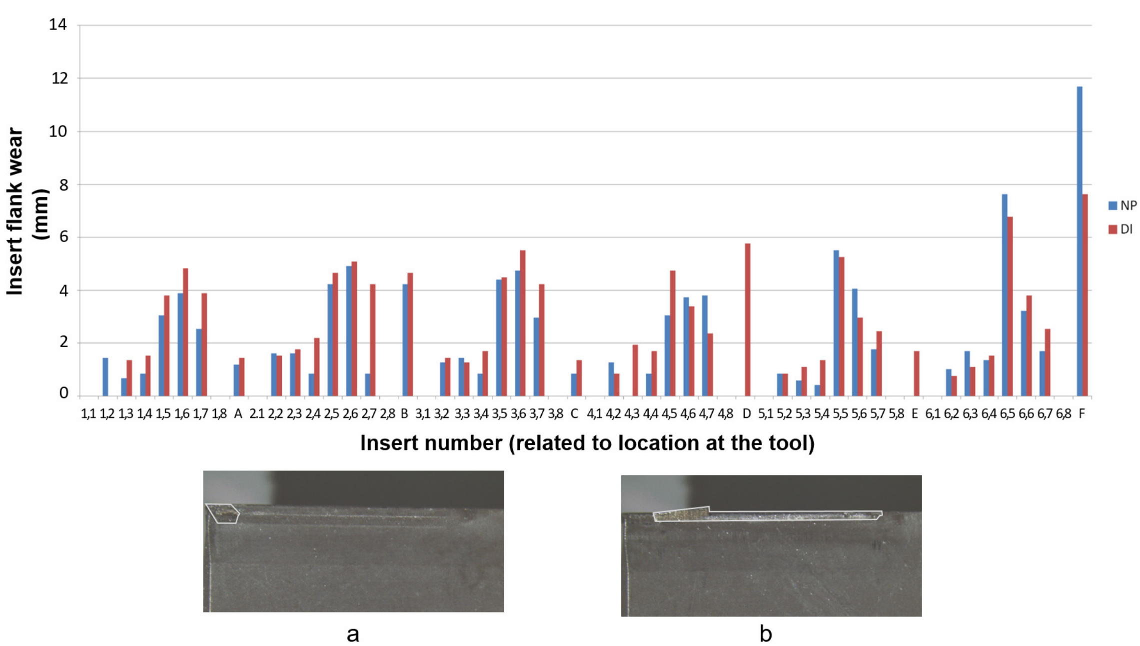

Fig. 8. Measurements of insert flank wear width and examples of images of two inserts located in 2.7 with wear (a) NP = 0.85 mm and (b) DI = 4.23 mm.

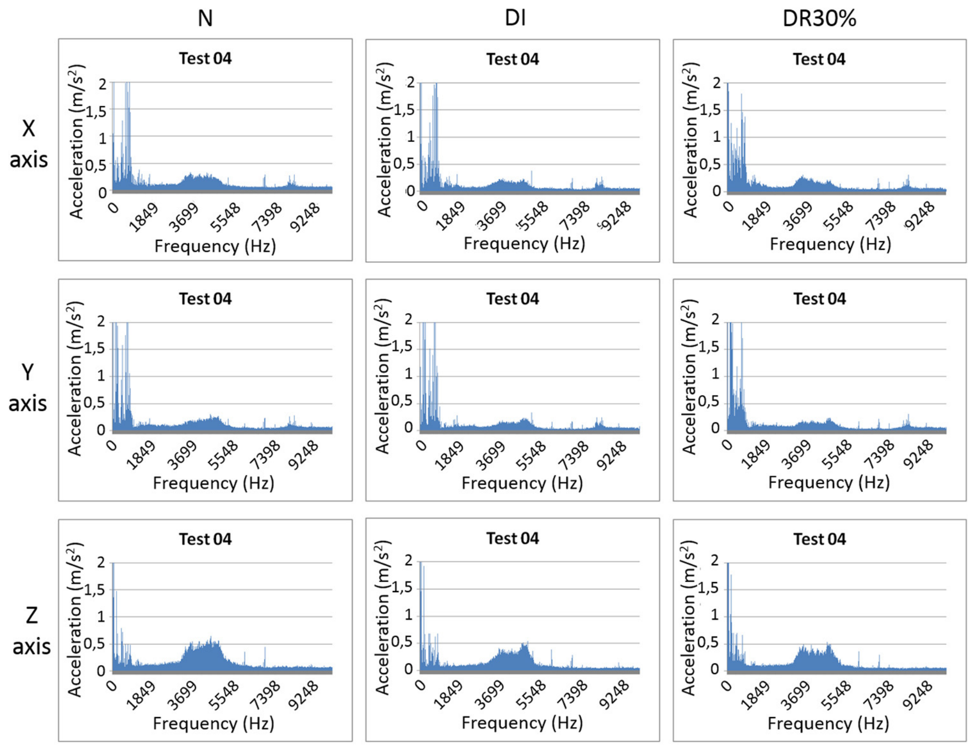

Fig. 9. Characteristic spectra for the different tests carried out at 400 rpm (different conditions of wear).

for each frequency did not suffer significant variations, the median value was calculated for the set of amplitudes related to the same frequency. In this way, a single spectrum by reading is obtained, composed by the median at each frequency in the X, Y, Z axes.

After obtaining these spectra for each test, it was evident that there was not almost variations is amplitude at the corresponding frequencies along the machining time. Therefore, the obtained spectra can be considered characteristic of each wear condition, axis accelerometer and speed of rotation. Fig. 9 shows typical spectra obtained for the X, Y, Z axes at 400 rpm in some of the tests. For all of the tested cases, the highest levels of acceleration are given at low frequencies. There are significant level variations for the bands of interest with the wear condition. It was noted that as higher the tool-head rotation, as higher values of acceleration. When the tool presents a higher wear, the values of amplitude at low frequencies increase significantly, reaching values around 25 m/s^2. However, for severe tool wear the levels of some bands of frequency (between 3000 and 6000 Hz) are lower. In view of the obtained spectra, it was determined that the best way of proceeding was to use spectral analysis using statistical calculation by spectrum bands.

4.2. Analysis of statistical by bands

Once a comparison of frequency spectra for different conditions of wear and tool-head rotation was done, a methodology based on a detailed analysis by spectrum bands was developed in Matlab. In this way, differences were identified in the distribution of frequency amplitudes through the calculation of kurtosis (Fisher's coefficient of tailing) (Eq. (2)) and skewness (Fisher's coefficient of asymmetry) (Eq. (3)) statistical values. These coefficients are calculated by the ratio between the centering moment (third and fourth order, respectively) of a number of elements n in the vector and the standard deviation σ. Therefore, a partition of the FFT spectrum was done in four bands of similar width, as shown in Table 2.

Values of skewness and kurtosis in each of the four bands were calculated for each median spectrum obtained in the frequency set. Since each test consisted of 7 individual records, the median of the statistical values was calculated for the corresponding bands of the different records. The obtained values are characteristic of each wear condition, tool-head rotation and accelerometer axis. It was checked that there were not significant differences in the statistical values for the individual readings in the same test. Figs. 10–12 collect the statistical values of each frequency band. It is clear that skewness and kurtosis coefficients increase as tool wear does.

$$\beta_2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^4}{n\sigma^4} \tag{2}$$

$$\gamma_1 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^3}{n\sigma^3} \tag{3}$$

Based on the obtained results, it is observed that the first and the third frequency band are sensitive to the progressive tool wear. In almost all the cases, it is clear that when the tool has an advanced level of wear, the value of skewness and kurtosis are also higher. Thus, it is possible to fix a variation rate with respect to the values obtained using a good-condition tool, so that it can serve as a wear level indicator. The first frequency band is featured by higher values of the statistical coefficients when the tool has an advanced wear. Fig. 13 shows this fact. In this figure, NP and DI tool conditions have been omitted to highlight mainly the difference among new tool condition (NP) and defective tool conditions (DR15% and

Table 2
Division of the spectrum according to the rows of the input vector and the corresponding frequencies.

	Band 1	Band 2	Band 3	Band 4
Vector rows	1-2047	2048-4095	4096-6143	6144-8192
Frequencies [Hz]	0-3784	3768-7572	7574-11360	11362-15150

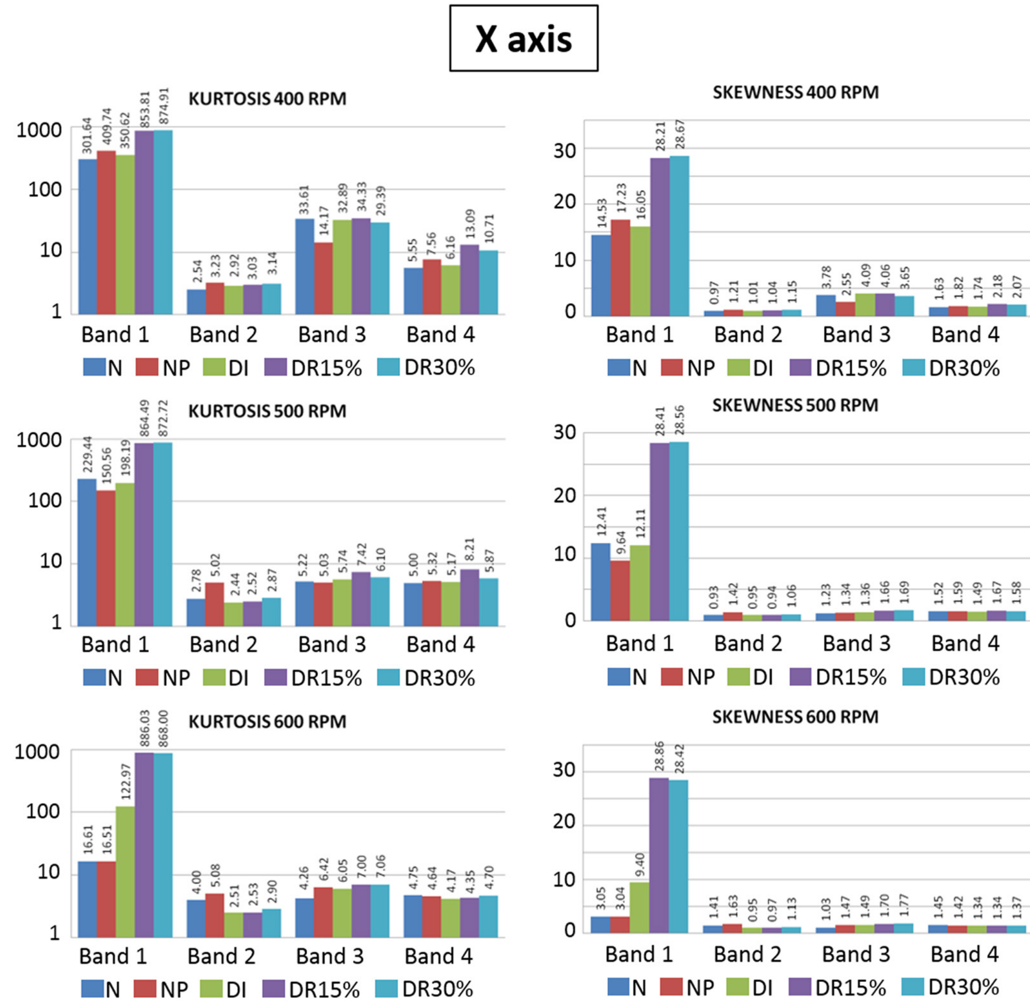

Fig. 10. Statistical analysis by bands for the accelerometer X axis, for different conditions of wear and tool head rotation.

DR30%), which is the mainly objective of this research. Therefore, it can be assured that analysis of skewness and kurtosis coefficients by frequency band spectrum is suitable for monitoring tool wear condition.

4.3. Analysis of RMS values

For each test, a file was recorded containing RMS values (Eq. (4)) calculated along all the recording time, resulting in a discrete value for each acquired block during the test. The graphic representation of these vectors is useful for obtaining information about the stability of the cutting process, as well as to determine if there are noticeable transient phenomena. Fig. 14 shows that RMS values remain practically constant during each machining operation, as an example of the acquired readings for different tool wear conditions at 400 rpm.

$$x_{RMS} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots x_n^2\right)} \qquad (4)$$

As observed, the RMS value increases significantly in the X and Z axes of the accelerometer (vertical and feed axis). Especially significant is the increasing experienced in the X axis. The calculus of the RMS median value of the individual readings provides a unique RMS value that characterizes each test. This way, the evolution of RMS values for different values of tool wear and tool-head revolution can be shown in a simple way. Therefore, special attention is paid to the axis in which greater changes are manifested with the tool wear evolution (X and Z). For tests N and NP similar RMS values are obtained for all spindle speeds. A greater instability of the RMS level is observed when the operation takes place at high speed of rotation. For the wear condition DI, the RMS value remains almost constant, being slightly lower than the initial value. For the wear conditions DR15% and DR30%, the values are similar and clearly higher at the spindle speed recommended by the manufacturer. The spindle speed recommended by the manufacturer is 400 rpm, which offers greater stability for this special type of operations in this type of machine. Fig. 15 shows the RMS values obtained for each reading.

5. Analysis and results of acoustic emission signals

Processing of AE signals was carried out using different functions developed in Matlab. For the study of these signals, spectral analysis using statistical values by frequency bands and RMS values obtained from the raw signal were used.

5.1. Spectral comparison

Processing using the circuit developed in LABView was carried out for the different signals recorded during the tests. An output vector is obtained after applying a FFT processing to the input signal, which contains a single frequency spectrum. When making a comparison among the obtained spectra for the different

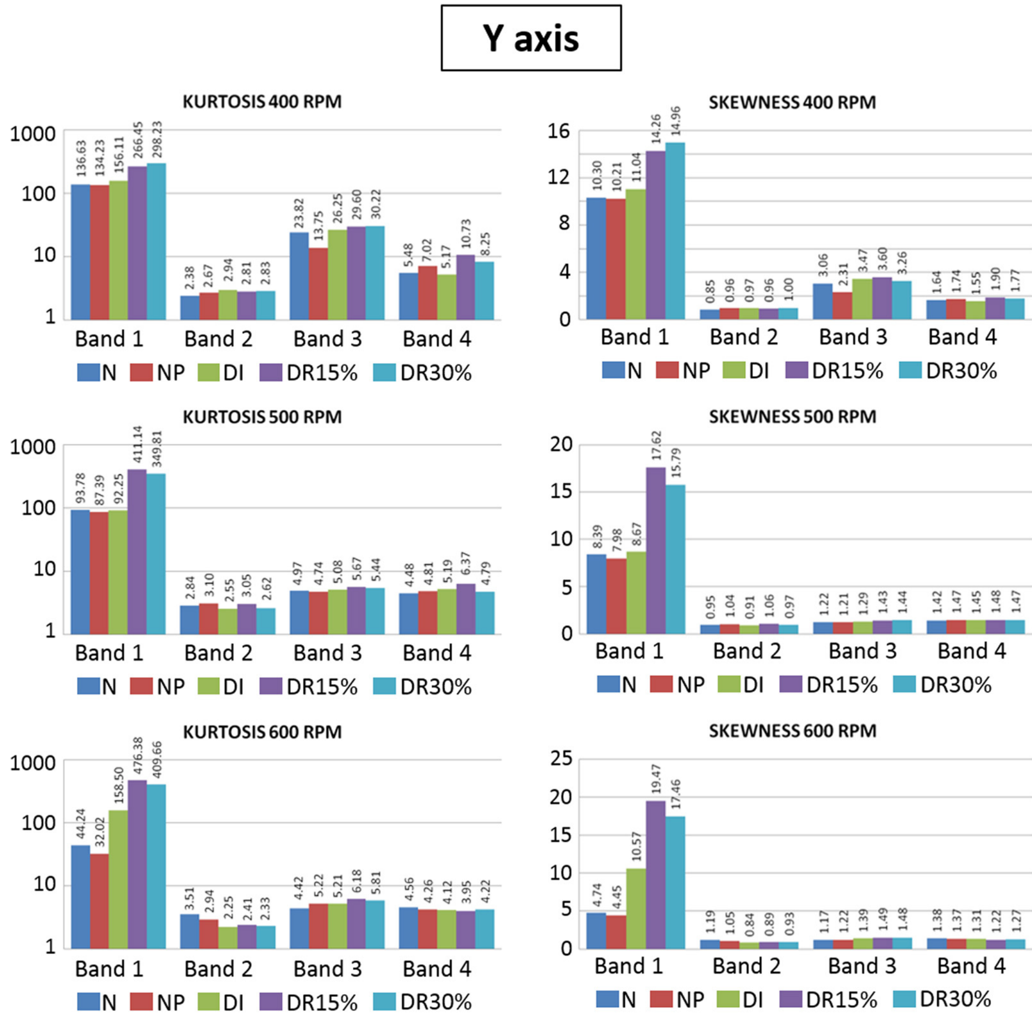

Fig. 11. Statistical analysis by bands for the accelerometer Y axis, for different conditions of wear and tool head rotation.

tests, for each tool condition wear and each spindle speed, certain similarities in the frequency distribution were observed, with the exception of tests done with a new tool (N). The frequencies of interest within each band suffer variations at different wear conditions. As an example, Fig. 16 shows the spectra associated to different tool wears. After evaluating the spectra, we proceed to perform a statistical analysis by bands of the spectrum.

5.2. Analysis of statistical values by bands

The studied spectrum includes frequencies between 100 and 500 kHz, in such a way that it is suitable to perform a division into five bands of 100 kHz frequency bandwidth (Table 3). This division fits well to the characteristic form of the obtained FFT spectra. The statistic values of skewness (Eq. (2)) and kurtosis (Eq. (3)) were calculated for the five bands.

The procedure is similar to the aforementioned for the analysis of vibration signals. Firstly, coefficients of skewness and kurtosis for the five spectrum bands are obtained for each specific reading.

Table 3
Division in spectrum bands for the statistical analysis of AE signals.

	Band 1	Band 2	Band 3	Band 4	Band 5
Frequencies [kHz]	[0–100)	[100–200)	[200–300)	[300–400)	[400–500]

Then, for all the tests corresponding to a specific combination of tool wear condition and spindle speed, a table is elaborated with values of the coefficients for each band. Finally, the median of the coefficients is calculated in each band, which serves as basis for comparing different tool wear conditions.

The results obtained after executing the functions developed are shown in Fig. 17. It can be seen that the first band provides higher values for the skewness and kurtosis coefficients. The value obtained with a new tool is high and it decreases with the progressive wear of cutting edges. Then, it increases again gradually and reaches levels similar to those obtained in the first phase of the machining. The NP wear condition and the transition to high wear condition is easily identifiable through the analysis of this band. The second band offers values for each test that remain within a narrow range for each spindle speed. The value is high with the new tool and it decreases progressively with tool wear. This value is stable and slightly increases at high wear conditions. This band can be used as a threshold for detecting that DI condition has been exceeded. In the third band the value of the coefficients for the initial phases is high and it decreases with progressive wear. Once DI intermediate wear condition is reached, the value of the coefficients is significantly smaller. Thus, the third band provides useful information about the progressive wear of the tool. In almost all the tests the coefficients decrease slightly when increasing the spindle speed. In the fourth band the

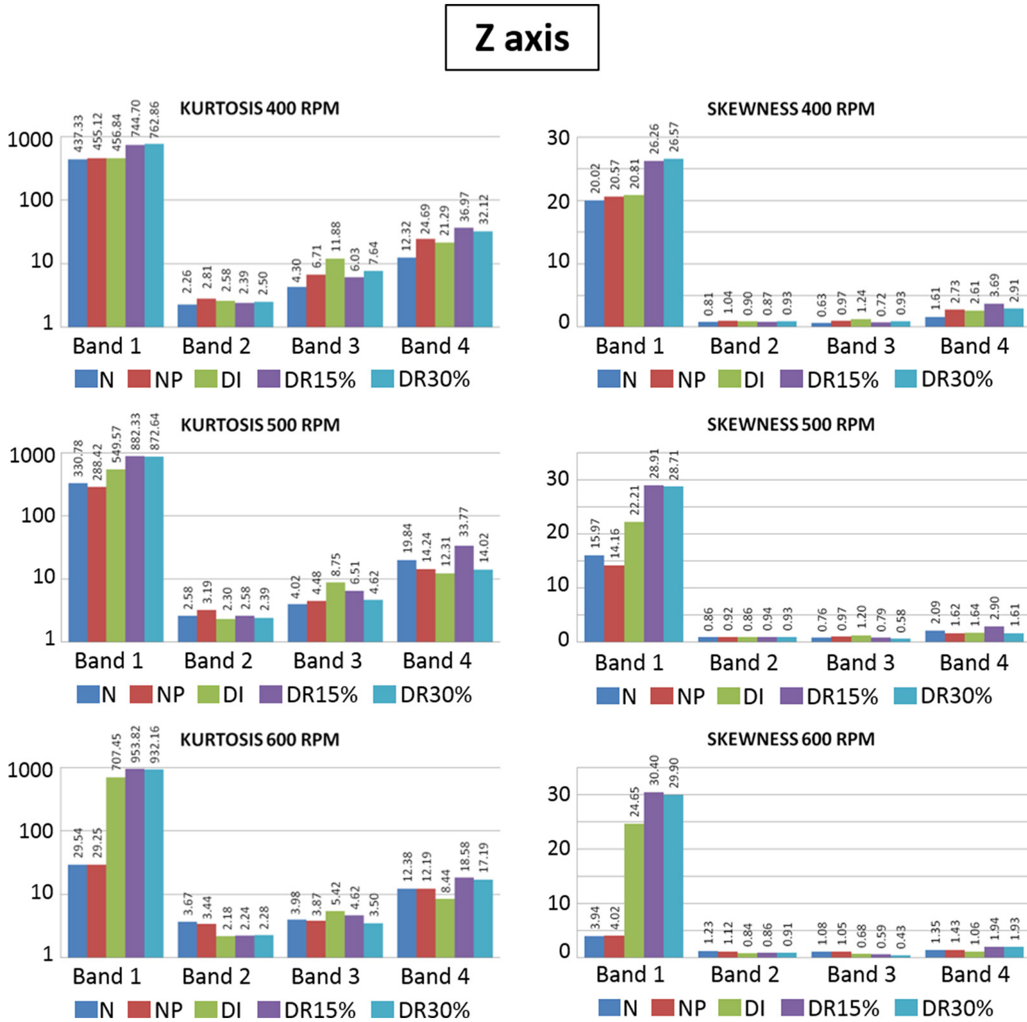

Fig. 12. Statistical analysis by bands for the accelerometer Z axis, for different conditions of wear and tool head rotation.

values obtained for NP wear condition are noticeable. The fifth band evidences a distribution of values, with some significance to DI wear condition. Therefore, it is easy to identify the wear condition prior to edge breaking.

5.3. Analysis of RMS values

A single RMS value is obtained and recorded for each acquired signal corresponding to 1 second of acquisition time. We checked if there were significant variations in RMS values when varying the tool wear conditions and spindle speed. Fig. 18 shows the individual RMS values obtained for the N, DI and DR30% tests. The correspondence between the tests and spindle speed is presented in Table 1.

The analysis of RMS values for the raw AE signals does not provide a priori useful information for monitoring the cutting tool condition. The obtained levels are similar for all the tests for different tool wear conditions and spindle speed. Therefore, it cannot be assured that there is a reliable matching between the tool wear and the RMS values obtained.

6. Conclusions

The following conclusions can be drawn from the study which underline the great utility of analyzing certain parameters and features extracted from acoustic emission and vibration signals for tool wear condition monitoring in very thick edge milling operations.

With regard to the analysis of vibration signals, the frequency spectra show important differences in their distribution and amplitude for different tool wear conditions and spindle speeds. A statistical analysis of the spectrum was carried out by dividing it in four equal bands, obtaining the kurtosis and skewness at different wear conditions and spindle speeds. It is concluded that the study of the first frequency band is especially useful for tool condition monitoring. The main reason is that the analyzed coefficients greatly increase with tool wear for all axes of the accelerometer. The followed strategy of spectral analysis is suitable for tool wear condition monitoring. On the other hand, analysis of RMS information let conclude that this parameter increases clearly in the X-axis of the accelerometer (spindle axis) in the tests carried out with worn and broken tool. Therefore, evaluation of RMS variation in this axis is suitable for monitoring tasks in order to determine a change in tool wear condition.

With regard to the analysis of AE signals, there are also important differences in the frequency distribution among the signal spectra for different tool wear conditions. From the results of the statistical analysis by spectrum bands and the values of kurtosis and skewness, calculated at different wear conditions and spindle speeds, it can be concluded that the analysis of the first band determines the transition between different tool wear conditions. The analysis of the second band indicates that it is possible to

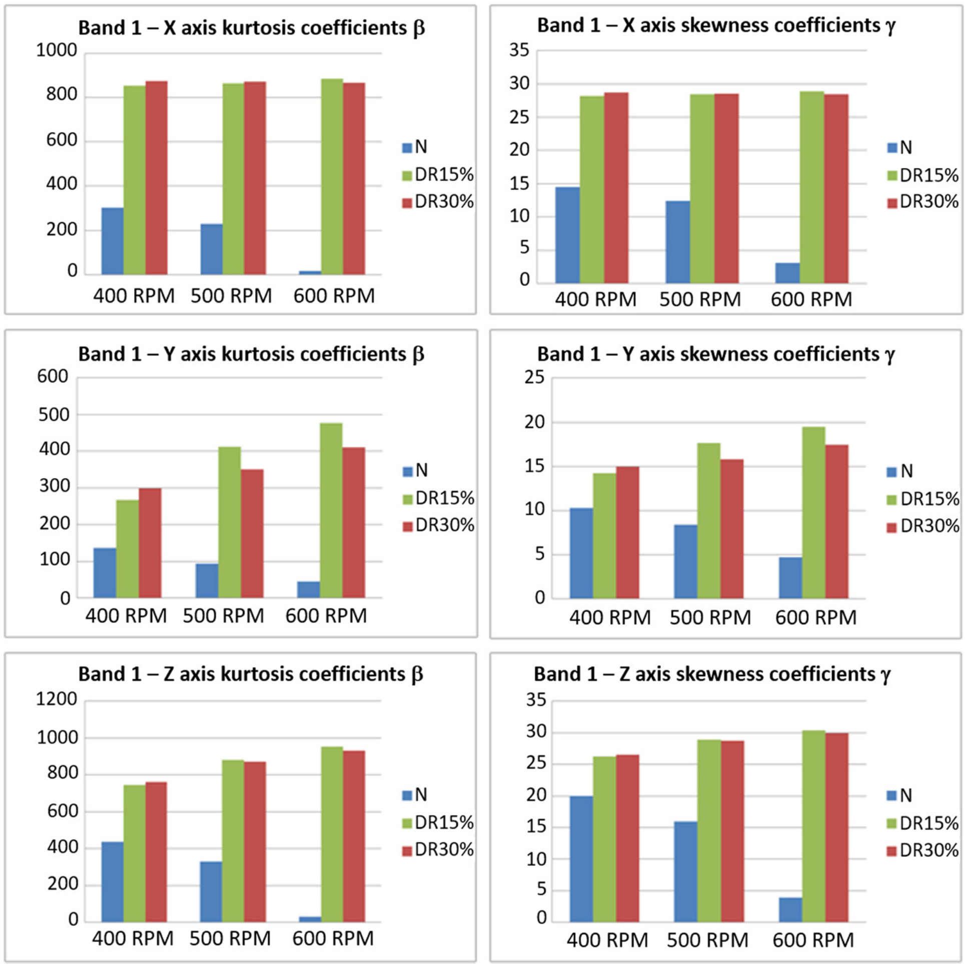

Fig. 13. Skewness and kurtosis for the first band of the spectrum. Tests N, DR15%, DR30%.

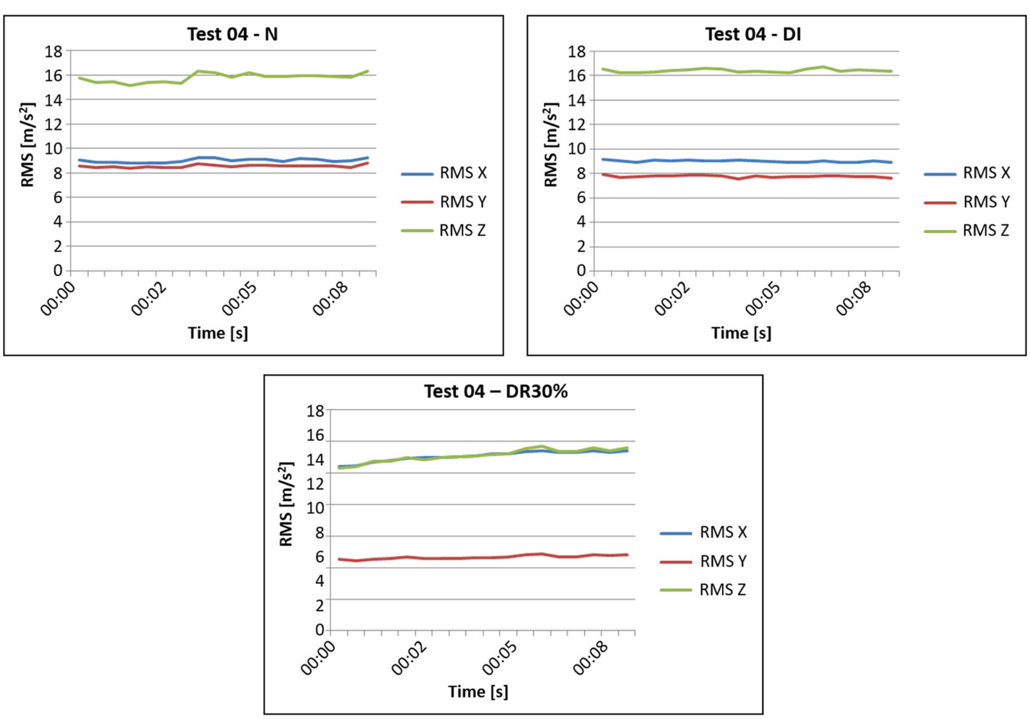

Fig. 14. Instantaneous RMS values for readings acquired at 400 rpm with different tool wear conditions.

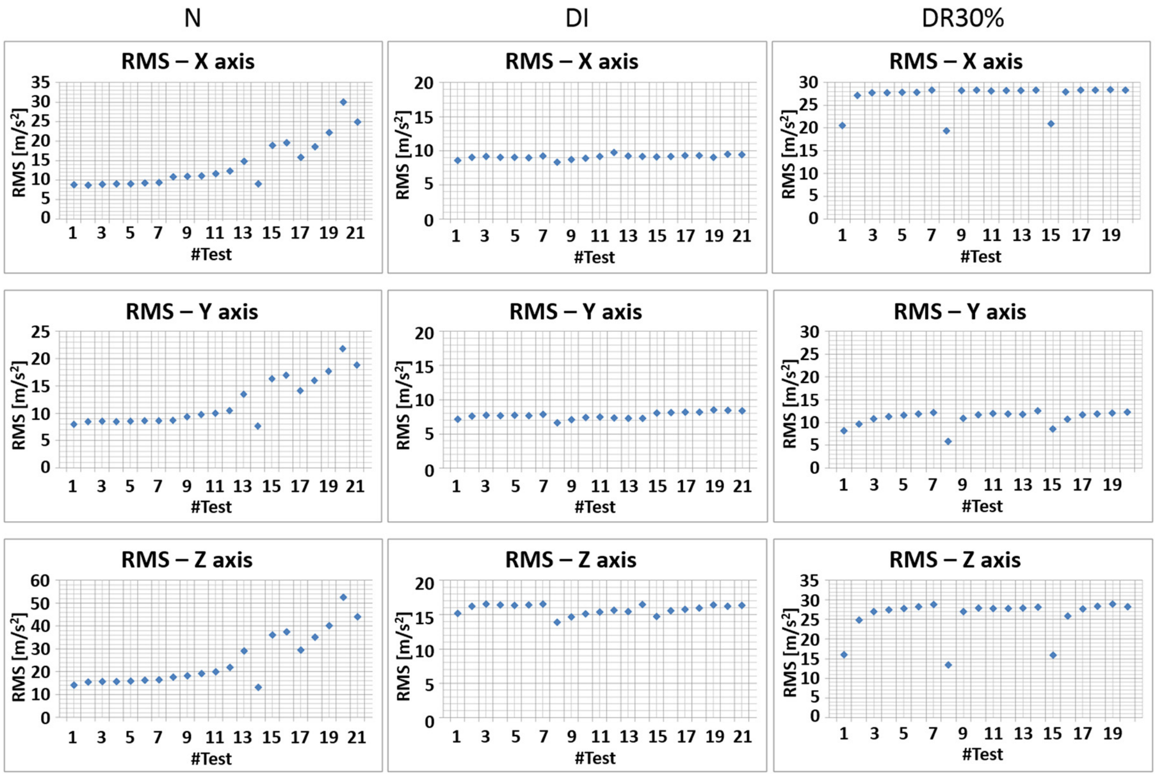

Fig. 15. RMS median values of vibration for different tool wear condition and spindle speed.

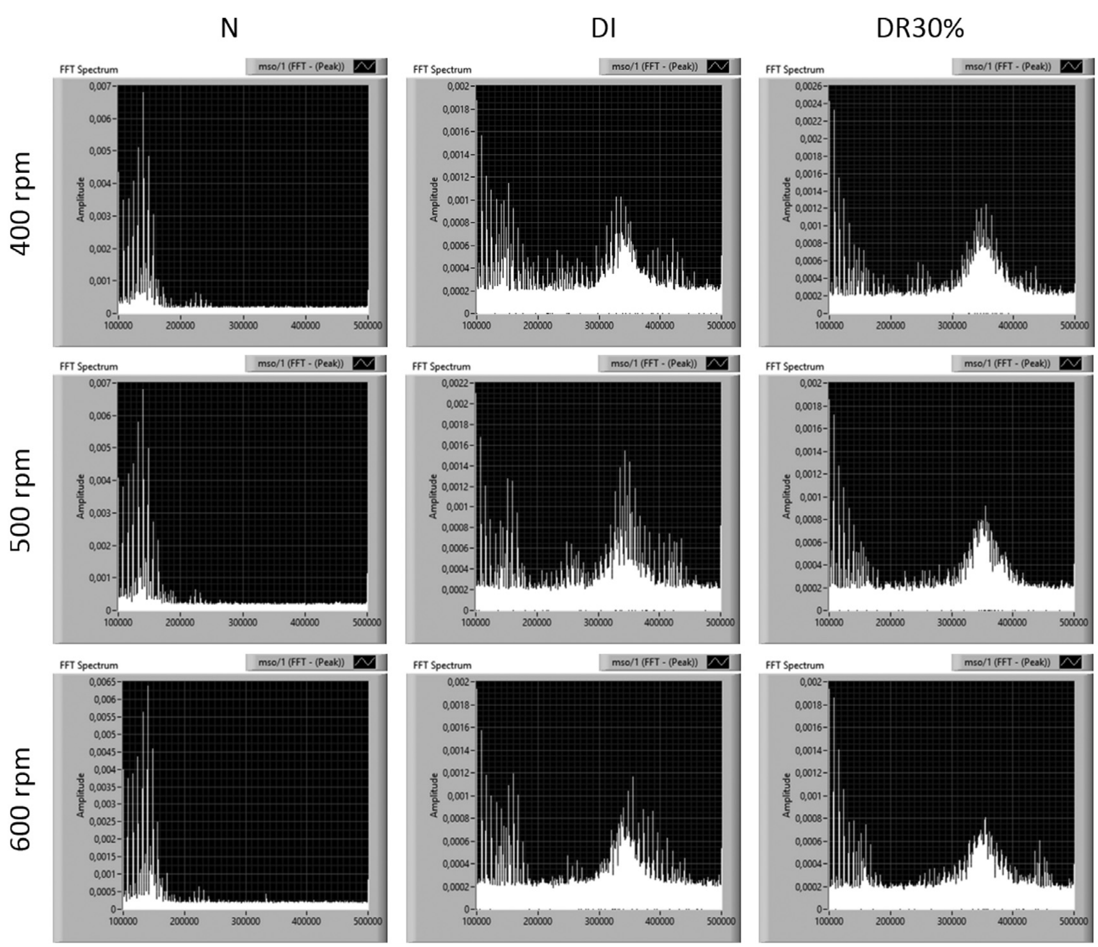

Fig. 16. FFT spectra of AE signals for each tool wear condition and spindle speed. Abscissas is frequency (Hz) and ordinates is amplitude of voltage (V) provided for the AE sensor.

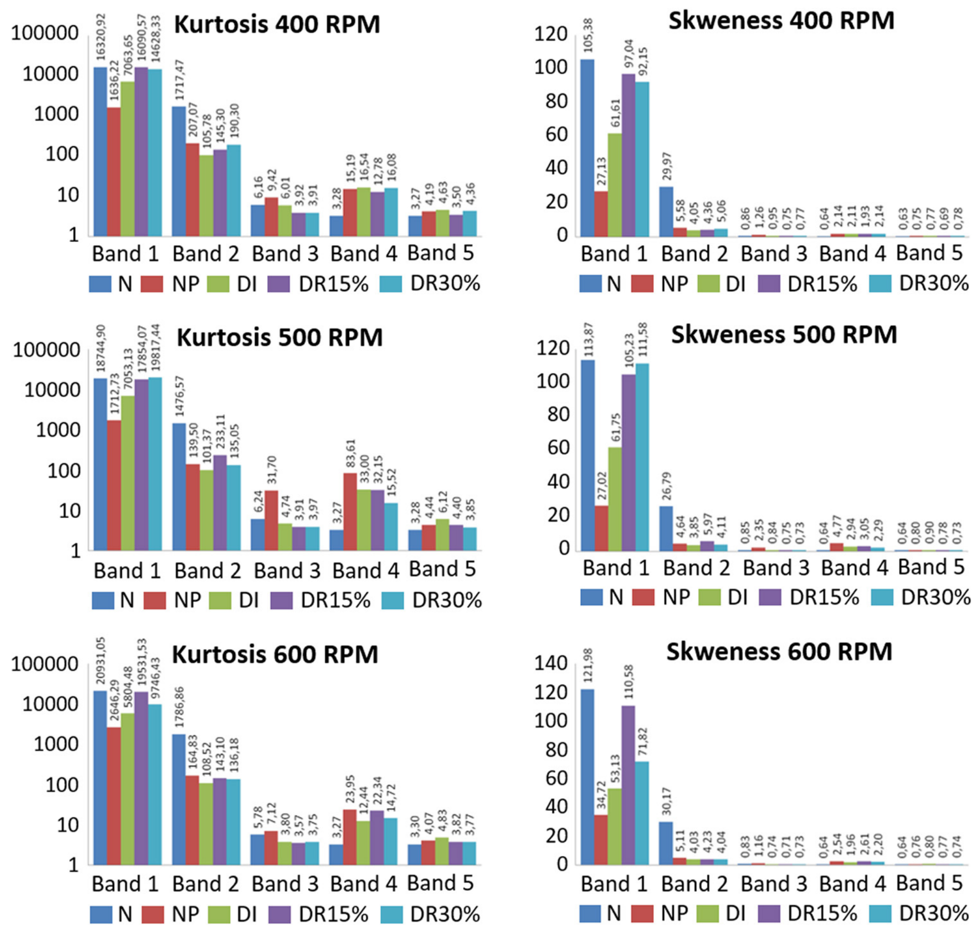

Fig. 17. Statistical analysis by bands of the AE signals spectrum for different wear conditions and spindle speeds.

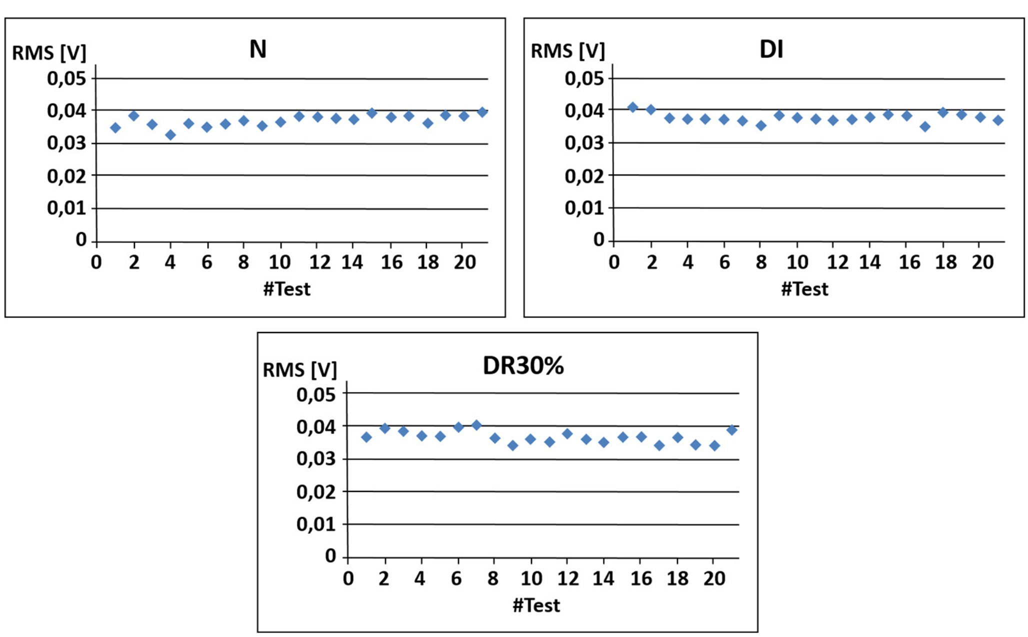

Fig. 18. Values of AE-RMS of each reading for different wear conditions and spindle speed.

detect the intermediate wear condition in all cases (for all spindle speeds). The analysis of the third band allows identifying the NP wear condition (new tool progression). The values of kurtosis diminish for the advanced wear condition, with regard to those obtained initially. The fifth band allows to identify the intermediate wear condition clearly. Identification of transition to advance wear is possible through the analysis of statistical values.

With regard to the obtained RMS values, they are similar for all the tests. Therefore, it is not possible to establish a clear relationship between RMS and tool condition.

By combining acoustic emission signals and vibration signals, to identify tool condition with reliability is possible. Each of these signals provide complementary results, in different spectral bands and with a clearly differentiated nature. Therefore, use of these complementary signals is more relevant for monitoring systems than an individual use. This type of control is essential in operations where very high value parts and tools are involved, such as milling of very thick-very large steel sheets.

Although this paper is not focused in applying fusion technology or artificial intelligence to combine both types of signals in a unique system, we consider a very promise line of working in a near future.

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References

Andrade, L.H., Abrao, A.M., Vasconcelos, W.L., Sales, W.F., Macahdo, A.R., 2015. A new approach for detection of wear mechanisms and determination for tool life in turning using acoustic emission. Tribol. Int. 92, 519–532.

Bhuiyan, M.S.H., Coundhury, I.A., Dahari, M., 2014. Monitoring the tool wear, surface roughness and chip formation occurrences using multiple sensors in turning. J. Manuf. Syst. 33, 476–487.

Bisu, C.F., Zapciu, M., Cahuc, O., Gerard, A., Anica, M., 2011. Envelope dynamic analysis: a new approach for milling process monitoring. Int. J. Adv. Manuf. Technol. 62 (5-8), 471–486.

Childs, T.H.C., Maekawa, K., Obikawa, T., Yamane, Y., 2000. Metal Machining Theory and Applications. Arnold, London.

Diniz, A.E., Liu, J.J., Dornfeld, D.A., 1992. Correlating tool life, tool wear and surface roughness by monitoring acoustic emission in finish turning. Wear 152 (2), 395–407.

González-Laguna, A., Barreiro, J., Fernández-Abia, A., Alegre, E., González-Castro, V., 2015. Design of a TCM system for metal turning based on vibration signals. In: Proceedings of the 6th Manufacturing Engineering Society International Conference, Barcelona, pp. 264–270.

Lamroui, M., Thomas, M., El Badoui, M., 2014. Cyclostationarity approach for monitoring chatter and tool wear in high speed milling. Mech. Syst. Signal Process. 44 (1-2), 177–198.

Lauro, C.H., Brando, L.C., Baldo, D., Reis, R.A., Davim, J.P., 2014. Monitoring and processing signal applied in machining processes - A review. Measurement 58, 73–86.

Lu, C., 1992. Study on prediction of surface quality in machining process. J. Mater. Process. Technol. 29 (1-3), 3–13.

Lu, P., Chou, Y.K., 2013. Analysis of acoustic emission signal evolution for monitoring diamond-coated tool delamination wear in machining. Machining and Machine-Tools. Woodhead Publishing, pp. 1–28.

Marinescu, I., Axinte, D.A., 2015. A critical analysis of effectiveness of acoustic emission signals to detect tool and workpiece malfunctions in milling operations. Int. J. Mach. Tools Manuf. 48 (10), 1148–1160.

Mix, P.E., 2005. Introduction to Nondestructive Testing. Wiley Interscience, New Jersey.

Orhan, S., Osman, A., Camuscu, N., Aslan, E., 2007. Tool wear evaluation by vibration analysis during end milling of AISI D3 cold work tool steel with 35 HRC hardness. NDT E Int. 40 (2), 121–126.

Rehorn, A.G., Jiang, J., Orban, P.E., 2005. State-of-the-art methods and results in tool condition monitoring: a review. Int. J. Adv. Manuf. Technol. 26, 693–710.

Zeng, S., Wan, X., Li, W., Yin, Z., Xiong, Y., 2012. A novel approach to fixture design on suppressing machining vibration of flexible workpiece. Int. J. Mach. Tools Manuf. 58, 29–43.

Zhong, W., Zhao, D., Wang, X., 2010. A comparative study on dry milling and little quantity lubricant milling based on vibration signals. Int. J. Mach. Tools Manuf. 50 (12), 1057–1064.