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Digital signal processing of acoustic emission signals using power spectral density and counts statistic applied to single-point dressing operation

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Wenderson Nascimento Lopes[1], Fabio Isaac Ferreira[1] ✉, Felipe Aparecido Alexandre[1], Danilo Marcus Santos Ribeiro[1], Pedro de Oliveira Conceição Junior[1], Paulo Roberto de Aguiar[1], Eduardo Carlos Bianchi[2]

[1]*Department of Electrical Engineering, São Paulo State University, Av. Eng. Luiz Edmundo C. Coube 14-01, Bauru, Brazil*
[2]*Department of Mechanical Engineering, São Paulo State University, Av. Eng. Luiz Edmundo C. Coube 14-01, Bauru, Brazil*
✉ *E-mail: fab.kf@hotmail.com*

Abstract: Dressing is an important operation for the grinding process. Its goal is to recondition the wheel tool to re-establish its cutting characteristics, owing to the wear produced after successive passes. Monitoring systems that use acoustic emission (AE) have been studied to correlate the signals with several tool conditions. This study brings a new approach of processing AE signals with the purpose of identifying the correct moment to stop the dressing, which is essential in an automatic control system. From the AE signals collected in dressing tests with aluminium oxide grinding wheel and single-point dresser, spectral analysis was made through power spectral density, selecting frequencies bands that best characterise the process. The statistical parameter 'counts' was applied to the raw signal unfiltered and filtered in the selected bands in order to identify the tool condition and, in turn, towards a monitoring system implementation. Results showed an expressive relation between tool cutting conditions and processed signals in the selected bands. There was a great disparity of the filtered signals in the selected bands and signals unfiltered, reflecting that the filtered ones were more efficient in terms of process automation.

1 Introduction

Grinding is usually the final process in the manufacturing chain, in which the main goal is to deliver high finish quality and precision to the parts [1]. The process is highly complex, mostly due to the fact that it is influenced by many factors such as the workpiece, the grinding machine and the grinding wheel [2]. The grinding wheel is one of the factors that differentiates the grinding process from other machining processes. This tool is composed of many tiny, irregularly shaped, and randomly positioned and oriented abrasive grains bonded by a cement matrix to form a solid circular shape [3]. The grinding wheel topography and its conditions in which it is prepared play an important role in the performance of the grinding process [4].

According to [5], the grinding community sustained the slogan 'Grinding is dressing' because of the significance of the dressing on the quality of the grinding process. The dressing operation consists in conditioning the grinding wheel surface when the tool loses its cutting capacity and original shape during the grinding process. In the case of aluminium oxide grinding wheel, the dressing operation is the cleaning, truing and conditioning in which the main goal is to produce appropriate topography of the grinding wheel. This operation should be carried out from time to time, ensuring sharp-edged grains to be produced on the wheel surface for machining.

Dressing depends directly on the effective contact width (bd) of the dresser that increases as the dresser diamond wears out. In this paper, this variable is very important because it is proportional to the overlap ratio, which is defined by equation

$$Ud = \frac{bd}{Sd} \quad (1)$$

where Sd is the dressing feed rate per revolution of the wheel [6]. The overlap ratio determines the contact frequency of a point on the peripheral face of the grinding wheel with the dresser. To fill the entire wheel surface with the dresser, this parameter should be at least equal or superior to one [7]. The overlap ratio is directly related to the sharpness that the dressing operation produces on the grinding wheel.

Although there have been many important advances in machining processes, a significant number of existing problems still need to be solved such as machine downtime and financial losses. In general, an operator, who stops the process to verify the conditions, performs the direct tool wear monitoring. In most industries that depend on the grinding process, the dressing operation is carried out from the operator sensitive information such as change in acoustic noise or colouration of the part and tools. Thus, automatic systems with indirect monitoring are of great importance to the solution of existing problems, avoiding damages to the parts machined and then leading to a successful machining process. As a result, an increase in productivity and a decrease in production costs are achieved [8].

Indirect monitoring methods rely on some sensors, digital signal processing techniques and computational intelligence, for instance, artificial neural network [9]. In applications involving machining processes, such as grinding, dressing, turning, milling, among others, the use of acoustic emission (AE) sensors has been shown an effective alternative to monitor features of the processes. Studies such in [1, 8, 10–15] among others have demonstrated effectiveness of the AE signals. In [16], an AE monitoring technique was successfully used to recognise the wear mechanisms during mechanical processes. In [17], a complete review is conducted about sensor applications in tool condition monitoring in machining, including AE sensors. The authors affirm that an effective tool condition monitoring system based on AE sensor is efficient to monitor the tool wear, keeping the cutting tool under surveillance to safeguard the cutting tool and protecting the workpiece from damage.

According to [18], AE signal can be defined as transient elastic waves generated by the rapid release of energy within a material. When the structure underwent an external stimulus such as load, pressure or temperature, localised sources trigger the release of

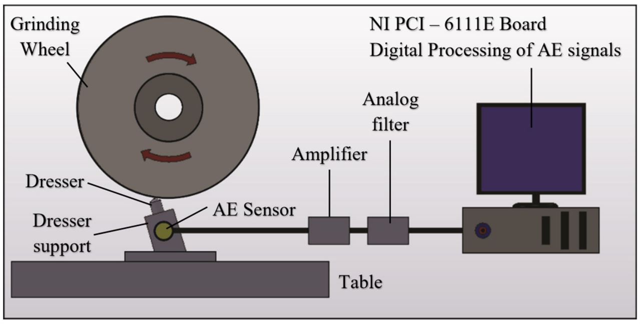

Fig. 1 *Setup for grinding tests and acquisition of AE signal*

energy, in the form of stress waves, which propagate to the surface and are detected by piezoelectric transducers responsible to convert mechanical energy into electrical signals.

According to [19], the major advantage of using AE to monitor the tool condition is that the frequency range of the AE signal is much higher than that of the machine vibrations and environmental noises. The AE signals from the machining processes are very stochastic and they contain a wide range of frequencies from different sources. Due to their complexity, they need to be processed and in turn features obtained. These features are used to correlate the tool wear, cutting condition and other process phenomena of interest.

Monitoring of the dressing process has the purpose of increasing quality control, reducing the costs and improving productivity. It is known that changes of the wheel topography influence directly on the results of the grinding process. On the other hand, an obstacle for monitoring the dressing process still consists in the lack of a reliable method to estimate the wear of the dresser and the sharpness of the wheel in real time. Several studies with the goal of evaluating single-point dresser were performed, as presented in [13, 20–23]. They have obtained successful results using statistics as root mean square (RMS) and ratio of power from the AE signals associate with artificial neural networks.

In many cases, spectral analysis of digital signals allows for extracting relevant information that are not visible in the time-domain spectrum. Frequency content of signals can be obtained using fast Fourier transform (FFT), which consists in an efficient algorithm of implementation of discrete Fourier transform (DFT). The main advantage of using FFT is that it requires a low computational power and is executed in a short processing time [24].

On the other hand, power spectrum density (PSD), obtained through the Welch's method, is a function that represents energy distribution in the frequency domain of random or periodic signals [25]. Applications such as speech recognition and sonar systems for locating submarines use this spectral analysis as a preliminary step to perform a reduction of the bandwidth and, posteriorly, an acoustic processing [26]. Similarly, throughout the dressing process, many frequencies with distinct magnitudes are generated, which can be studied when they are divided into bands using these tools. From the signal filtered in bands, several statistical parameters can be applied in order to obtain important information during the tests. According to [27], the statistic 'counts' is the number of times that a signal crosses a threshold per unit of time. The author still emphasises that this statistical parameter may be used to quantify the acoustic activity of a signal.

As this paper includes information about sharpness of the wheel, which was measured during the tests, a brief description of the used method is provided next. According to [11], the sharpness of the wheel is of utmost importance, because it is a determining factor of the cutting forces, heating generation, superficial integrity and other relevant characteristics of the grinding process in manufacturing a workpiece. The authors use a simple method, called the ground disc that is described by Coelho [28], in which a fixed disc (without rotation), made of an appropriated material to be worn, is pressed against the wheel with a constant normal force. The wheel displacement against the fixed disc is recorded for a certain period of time. Then, regression and transformation are applied and the sharpness of the wheel (K) is determined by the expression

$$K = \frac{2b\sqrt{8r}}{3F_n}(a_1)^{2/3} \tag{2}$$

where b and r are the width and radius of the disc, respectively, F_n is the normal force and a_1 is the gradient of the regression line obtained from the experimental characteristic of displacement versus $(t)^{2/3}$.

This study uses the PSD to analyse the frequencies, in order to verify the bands related to the tool condition of the wheel as the dressing process takes place. Furthermore, the study applies the statistic 'counts' to observe behaviour of signals during the tests. The purpose was to compare the result of digital processing for filtered signals in the best frequency bands with the result obtained for the entire frequency spectrum (no filtering). The present work has an unprecedented approach because, differently from other researches previously executed about the process, AE signal is investigated for bandwidth more related to the cutting tool (wheel). It aims to propose a stopping criterion for the dressing process through digital processing of AE signals for a potential automatic system. Thus, by using this method, it is possible to identify bands that best characterises the process, aiming its optimisation through an efficient and autonomous system.

2 Material and Methods

Setup was developed and configured to allow the analysis of cutting conditions of the grinding tool (wheel) from spectral contents of raw AE signals. The dressing tests were performed using a conventional type 38A220KVS aluminium oxide grinding wheel, with dimensions of 355.6 × 12.7 × 127 mm^3, manufactured by NORTON. The grinding wheel was installed in a surface grinding machine RAPH-1055 model, manufactured by Sulmecanica. The parameters of the dressing operation were controlled, ensuring the quality of data acquisition at different cutting conditions of the grinding wheel. Cutting fluid emulsion type was used at a controlled concentration of about 4% per volume of water. It was also used a single-point dresser with a synthetic diamond. Three tests were performed in order to ensure repeatability and a new grinding wheel and a new dresser were used for each test.

An AE system was used, which consisted of a broadband sensor, with a frequency range of 0–300 kHz, and an amplifier, DM 42 model, manufactured by Sensis. The sensor was fixed on the dresser holder using a suitable screw recommended by the manufacturer. To collect the raw AE signal, a data acquisition board, manufactured by National Instruments, PCI–6111E model, was used and set to a sampling frequency of 1 million samples per second.

Fig. 1 shows the setup employed in the tests. Three tests were performed and, before each test, the grinding wheel was worn during the grinding of a steel SAE 1020 workpiece, in severe cutting conditions, without the use of cutting fluid, until the occurrence of visible burn on its surface. This allowed for clogging the wheel with chips, which characterises a grinding wheel very worn and, consequently, the need of dressing.

An analogue filter was used after the AE sensor and amplifier module, which has the following characteristics: low-pass, Butterworth type, second-order and 300 kHz cutoff frequency. This filter was used to avoid the effect of aliasing. Each test consisted of 22 dressing passes along the width of the wheel, with constant cutting depth (ad) of 10 µm, for different effective widths of the dressing tool (bd) and different overlap ratios (Ud). The parameters used in the tests are presented in Table 1, where the traverse dresser speed across the grinding wheel is Vd, the rotational speed of the grinding wheel is n, and the diameter of the grinding wheel is ds. It was attempted to use the same parameters for the three tests to ensure repeatability.

Each test was divided into three conditions during the grinding passes, according to the grinding wheel surface condition: (i)

Table 1 Dressing tests parameters

	Test 1	Test 2	Test 3
Ud	2.0	1.5	1.0
ad, µm	10	10	10
bd, µm	152.3	132.3	165.0
Vd, m/s	2.29	1.65	4.95
n, RPM	334	386	714
ds, mm	314.5	314.3	314.0
number of passes	22	22	22

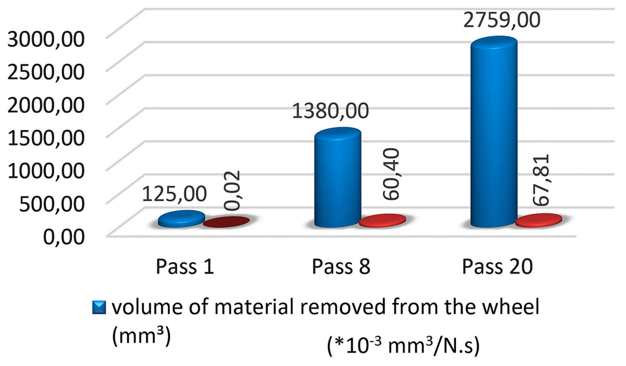

Fig. 2 *Grinding wheel sharpness and volume of material removed – Test 1*

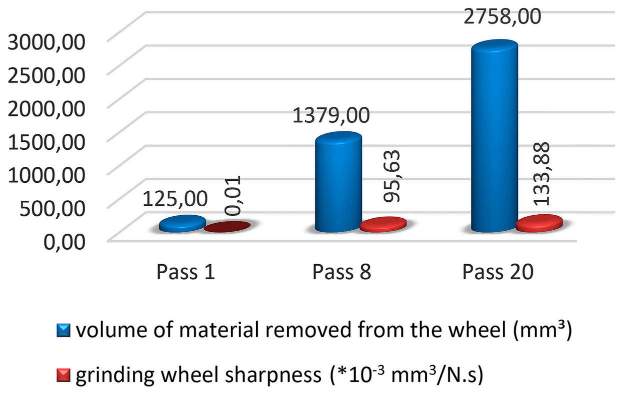

Fig. 3 *Grinding wheel sharpness and volume of material removed – Test 2*

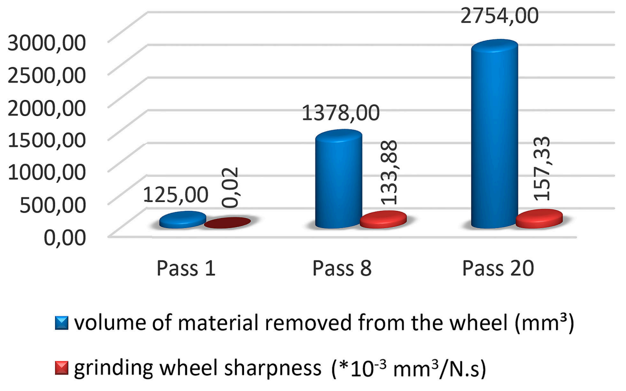

Fig. 4 *Grinding wheel sharpness and volume of material removed – Test 3*

grinding wheel without cutting capacity, i.e. it is clogged (with chips) and its surface is smooth and dark-coloured; (ii) grinding wheel with an average cutting capacity, i.e. an intermediary condition, where the worn grains are being detached and new sharp grains are exposed on the surface; and (iii) grinding wheel with full cutting capacity, i.e. it is clean and dressed, the chips were removed and the grains are sharp and ready for turning back to the grinding process.

For obtaining the AE signal spectra, the following steps were conducted: First, it was used a digital band-pass filter of Butterworth type with cutoff frequency of 50–200 kHz, order 5, implemented in MATLAB to eliminate frequencies out of this range, according to the spectra presented in [10]. Second, signal section of the wheel-dresser contact (pass of dressing) was extracted. Nine equally spaced points in the grinding pass were selected. Then, PSD using the Welch's method of length 8192 for DFT, no overlapped samples, Hanning window, was computed for nine locations along the pass. Finally, an average spectrum was computed for each wheel condition (pass 1: without cutting capacity; pass 8: average cutting capacity; pass 20: full cutting capacity).

For each dressing test, the AE frequency spectrum was analysed and two frequency bands were selected so that there would not be overlap of the spectra for these different conditions (passes 1, 8 and 20), in which each spectrum represented a given grinding wheel condition. In other words, the signal magnitude increased as the grinding wheel condition was more severe, according to the passes 1, 8 and 20. Then, a band-pass digital filter, order 5, Butterworth type was used in the AE raw signals in the MATLAB software. This digital filter showed better frequency responses with low harmonic distortion in the frequency bands considered.

Next, the statistical parameter counts were computed for each 1024 samples (∼1 ms) from the raw signal filtered and, thresholds to attain the three grinding tests were chosen. Hence, the mean and standard deviation of each dressing pass were obtained. In addition, the sharpness of the grinding wheel was measured using the ground disc method described previously at three dressing test moments: After the dressing passes 1, 8 and 20. Also, the volume of material removed was determined by the difference in diameter of the grinding wheel.

3 Results and discussion

3.1 Analysis of the grinding wheel sharpness

The sharpness of the grinding wheel was measured three times for each dressing test: at the beginning, in the middle and at the end of the test. The grinding wheel sharpness and volume of material removed are shown in Figs. 2–4 for the dressing tests 1, 2 and 3, respectively.

It can be observed in Figs. 2–4 that the grinding wheel restores its cutting capacity as the material is removed from the grinding wheel surface by the dressing process. As can also be seen in these figures, the cutting capacity of the wheel is fully restored to a volume of about 1379 mm^3 of material removed, because there is no significant change in grinding wheel sharpness after this pass. Thus, it can be considered that, from test 8 on, the grinding wheel is fully dressed.

In the beginning of each dressing test, the level of sharpness was essentially low, due to the grinding wheel being clogged (with chips). This also makes the AE signal level low because the friction with the diamond tip is small. As the wheel is dressed along a test, its sharpness increases and chips are removed. The cutting wheel topography is restored because its worn grains are detached and other grains recover the sharp edges. As the surface becomes less smooth, i.e. with more cutting edges, friction is bigger and hence AE level is higher.

3.2 AE signal spectrum performance

The AE signals spectra were analysed, as described in the previous section. Fig. 5 shows the best frequency bands selected. The frequency bands were chosen observing the ranges in which the magnitudes of the energy had distinct levels for the different conditions. For each test, the top row in Fig. 5 shows the spectra of the AE raw signal without filter; the centre row shows the spectrum magnification of the AE raw signal filtered in the frequency band 1 (126–133 kHz); and the bottom row shows the spectrum magnification of the AE raw signal filtered in the frequency band 2 (141–146 kHz).

The chosen bands showed different AE energy levels for different grinding wheel cutting conditions. As can be seen, the signal curves that represent the grinding wheel without cutting capacity (pass 1) has lower energy levels during all grinding tests in both bands. However, tool condition with full cutting capacity

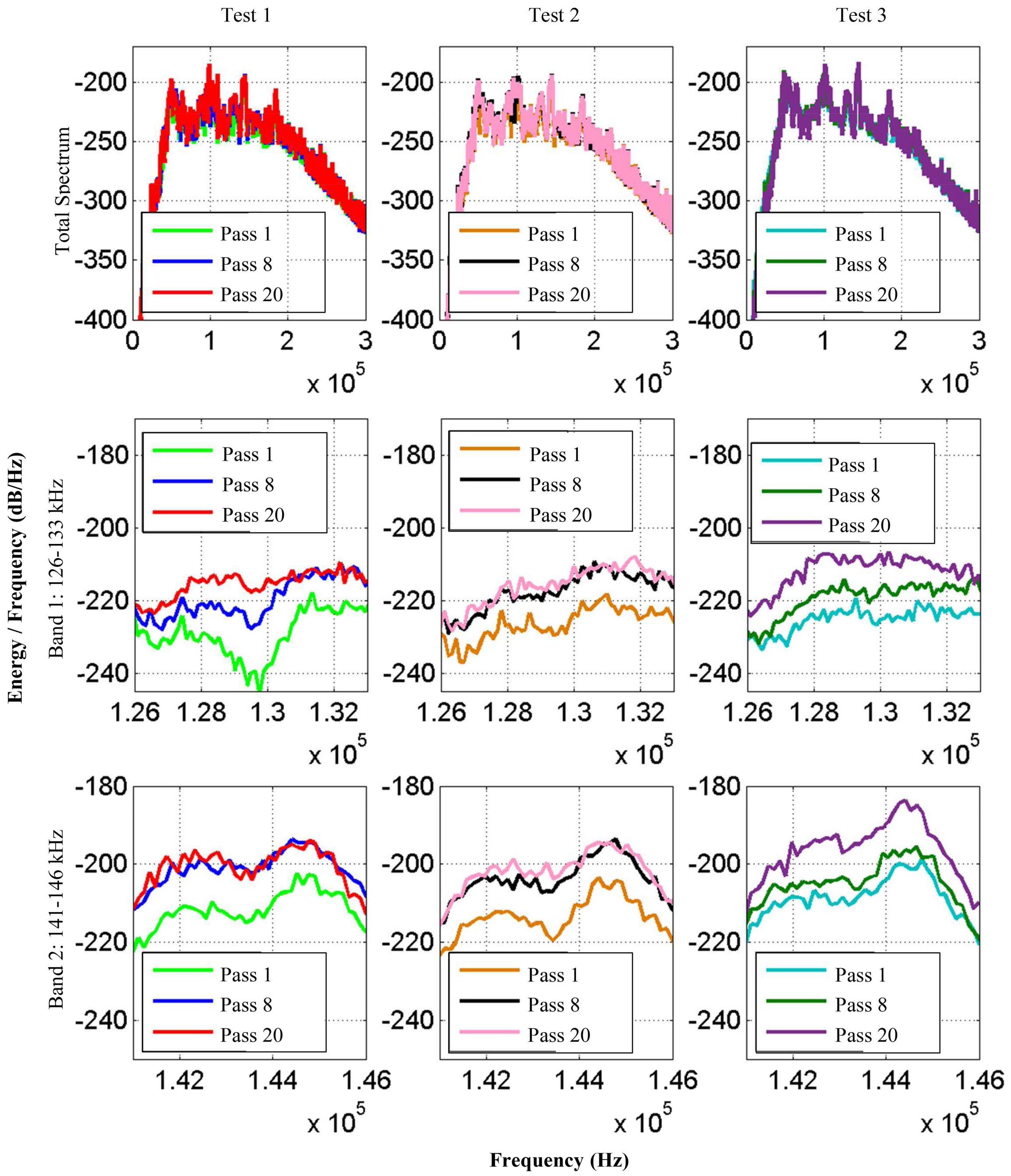

Fig. 5 *Frequency spectra of the raw AE signals for tests 1, 2 and 3*

(pass 20) has the highest signal amplitude for all spectra. This study shows the behavioural differences of AE signals, according to the different grinding wheel conditions. When the grinding wheel is at full cutting capacity, friction generated between the abrasive grains of the grinding wheel and the dresser produces a higher AE level. This is because the edges of the abrasive grains are exposed, and consequently a larger friction occurs between the grinding wheel and dresser.

It is also possible to observe that there are some crossings occurring between the dressing passes 8 and 20 for test 1 in the frequency band 1 and tests 1 and 2 in the frequency band 2. This occurs because there is a small variation in friction between the grinding wheel and the dresser from the pass 8. Besides, the grinding wheel sharpness presents no significant variation from the pass 8 according to Figs. 2–4, explaining the overlap of spectra in the passes 8 and 20.

3.3 Applying count rate statistic

The statistic ‘*count rate*’ was applied to the AE signals without band selection and also for bands 1 and 2. It was empirically found a threshold of 0.0035 V for signals without filtering. A threshold of 0.0005 V was chosen for the filtered signals. Fig. 6 shows the mean values of the count rate for the three tests, where the unit is threshold crossings per millisecond. However, Fig. 6 shows the normalised values obtained from the maximum value of each test. Comparative analyses were performed for each test over the statistics obtained without the application of filters and for the signals filtered in two selected bands.

It can be noted in Fig. 6 that as the grinding wheel restores its sharpness along the tests, there are changes in the acoustic activity mean values of the filtered signals, generating a satisfactory result within regard to the identification of the grinding wheel condition. However, the acoustic activity presents an oscillatory behaviour for the signals not filtered, becoming difficult to set a threshold to define the condition of the grinding wheel in terms of having or not its cutting capacity restored, and then ready to be used in the

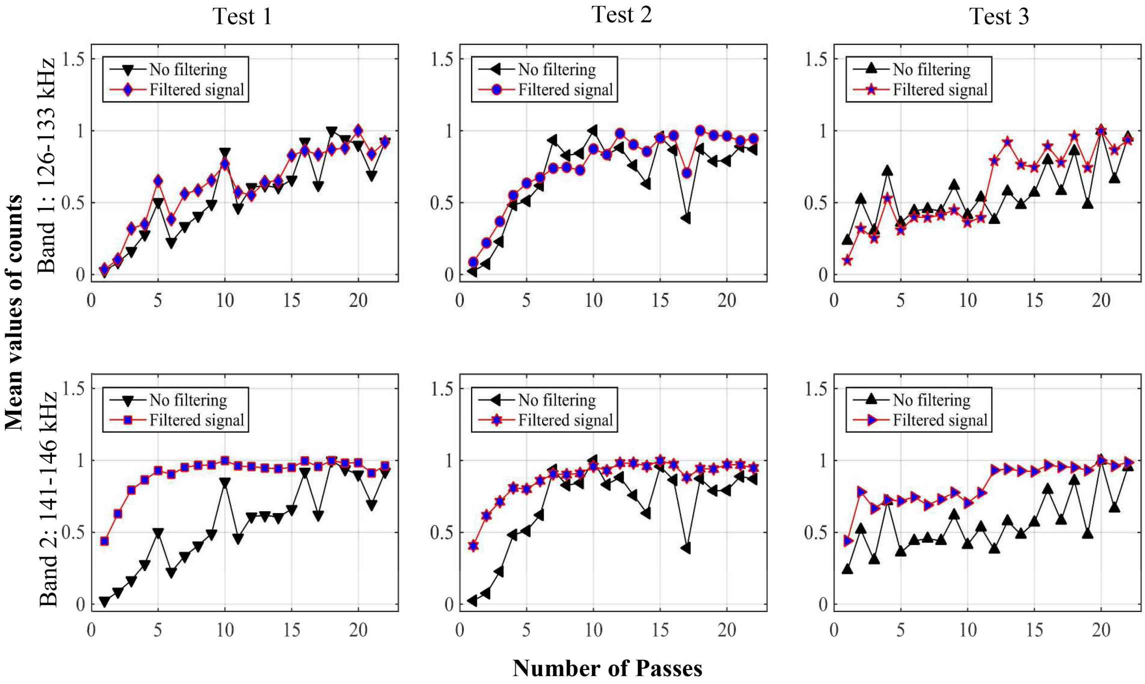

Fig. 6 *Mean values of normalised count rate*

grinding process. On the other hand, the filtered signals show less scattered behaviour and, therefore, a threshold to indicate the sharpness of the wheel can be established easily. This can be explained in function of the frequency content of the filtered raw signal, which is more related to the wheel surface conditions when compared to the unfiltered raw signal.

It is also noted that the acoustic activity is low for unfiltered and filtered signals in the beginning of each test. Throughout the dressing operation, there is a significant increase of acoustic activity up to approximately pass 10, for filtered signals in the bands 1 and 2. This behaviour can be better observed for tests 1 and 2. From pass 10 on, there is a uniform behaviour of the count rate values for the bands 1 and 2. In test 3, there is; however, a scattered increase, but it is also observed a uniform behaviour of the values from the pass 10. This reinforces that the count rate statistic can be considered an alternative method for automatic monitoring of the dressing operation.

4 Conclusion

This paper presented a study of the grinding wheel cutting condition after the process of dressing. The sharpness of the grinding wheel measured by the ground disc method was correlated with the signals of AE acquired by a passive sensor. The signals were digitally processed in order to find information and characteristics related to the process.

By using the Welch's method for analysing the power spectral density of the signals, it was possible to choose frequency bands that were more efficient in the characterisation of the three grinding wheel conditions studied along the tests, i.e. grinding wheel without cutting capacity, medium cutting capacity and full cutting capacity. Next, the AE signals were filtered in the selected bands and the statistical parameter *counts* was computed. The aforementioned results about *counts* for the selected bands were compared with the results without band selection.

It was observed that characteristics describing the sharpness of the grinding wheel could be obtained by using PSD and count rate applied to the AE signals acquired along the dressing tests. It can also be noticed that important features for monitoring this operation are highlighted by filtering the signals in frequency bands more related to the sharpness of the grinding wheel. On the other hand, the wheel cutting conditions cannot be related to the AE counts rate quite well when unfiltered raw signal is used.

The frequency bands of 126–133 and 141–146 kHz were best found to relate the grinding wheel cutting condition to the AE signal. From the dressing pass 10, the grinding wheel can be considered sharped, that is, with full cutting capacity, and then ready to get back to grinding, as its sharpness measured is nearly unchanged. Therefore, the presented method has shown satisfactory results and it can be used to characterise the grinding wheel condition during the dressing process.

5 Acknowledgements

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