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Correlation between surface roughness and AE signals in ceramic grinding based on spectral analysis

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Abstract. The study and monitoring of the workpiece surface roughness is one of the most important parameters of the grinding process. This paper proposes a method for analysing the surface condition of ground ceramic components by means of the acoustic emission (AE) signal analysis along with frequency domain techniques. Tests were performed using a surface-grinding machine equipped with a resin-bond diamond grinding wheel, where signals were collected at 2 MHz. Alumina workpieces were machined under six different depth of cut values, covering slight, medium and severe grinding conditions. Frequency content was studied in order to select bands closely related to the process conditions. An analysis of the root mean square values (RMS) of the signals was performed, seeking for a correlation with the surface roughness. Digital filters were applied to the raw signals. The RMS values filtered for two frequency bands presented a better fitting to the linear regression, which is highly desirable for setting a threshold to detect the workpiece surface conditions and implementing into a monitoring system. Results showed that the amplitude of the signals presented different characteristics in the frequency domain according to the workpiece surface condition. It was also observed a higher spectral activity in the severe grinding conditions.

1 Introduction

The grinding process is located in the final stage of the machining process and is performed by a cutting tool known as grinding wheel. The cutting tool is composed of many tiny, irregularly shaped, randomly positioned and oriented abrasive grains held together in a bond material [1]. It is known that the performance of the grinding process basically depends upon the operator's skills as well as the dressing condition of the grinding wheel. The optimization of the machining operation can be done by changing the process input parameters [2]. The interest in the use of advanced ceramics has increased in the recent years due to their unique physical and mechanical properties such as low density, chemical stability, high hardness and strength at elevated temperatures. Grinding is considered the most efficient technique in machining brittle materials [3]. However, machining of advanced ceramics is extremely difficult and time-consuming due to their low fracture toughness and thermal shock resistance [4]. Some studies that deal with the advanced ceramics grinding process can be cited, such as, the vibration signal application for diagnosing the grinding parameters and the workpiece surface [5] and the modelling of surface roughness [6]. The efficient grinding of advanced ceramics requires a careful selection of the machining parameters in order to maximize the material removal rate without compromising the quality of the workpiece surface [7]. One of the main grinding parameters used to study the process mechanics is the equivalent chip thickness (heq), which represents the thickness of the ceramic layer that is pulled out by the grinding wheel in a complete revolution. The equivalent chip thickness is a measure of the grinding condition and proportional to the depth of cut and workpiece speed, and inversely proportional to the peripheral grinding wheel speed. In other words, it allows to quantify a working condition from the input parameters [8].

The surface roughness is one of the most important parameters in the evaluation of the surface quality of a ground ceramic component [9]. It can be defined as the average value of the deviations of the surface profile heights with respect to a midline [10]. In the machining process, a reduction in production costs and an improvement in the quality of the machined workpieces are expected; automated detection of machining defects has become of great interest among scientists and machining users from industries [11]. Monitoring methods can be classified into two categories: direct and indirect methods. Direct measurement uses optical methods and requires the machine to be stopped and the workpiece removed (and latter placed back) for visual inspection, resulting in downtime and high costs. Indirect methods monitor grinding without interrupting the production process and are generally performed through the acquisition of signals coming from sensors [12]. Some of the main signals used for the monitoring the grinding process is the acoustic emission (AE). The advantage of using AE to monitor the grinding process is that the frequency range of the AE signal is much higher than the frequencies of machine vibrations and environmental noises and does not interfere with the grinding operation [13]. Some studies that have used AE sensors to monitor the grinding process can be cited, such as, detection of the grinding wheel wear [14] and the thermal damage detection [15].

This paper proposes a method for analyzing the surface condition of ground ceramic components by means of the AE signal analysis along with frequency domain techniques. Six depth of cut values were varied to reproduce different grinding conditions. This paper is distinguishable from other works in terms of selecting specific frequency bands of the raw AE to infer about the surface roughness, i.e., monitoring the quality of the workpiece surface described by this important parameter. This work presents a preliminary study on the aforementioned topic and may be useful as a start point for future studies, which can also be implemented with different types of sensors, materials and statistics.

2 Methodology

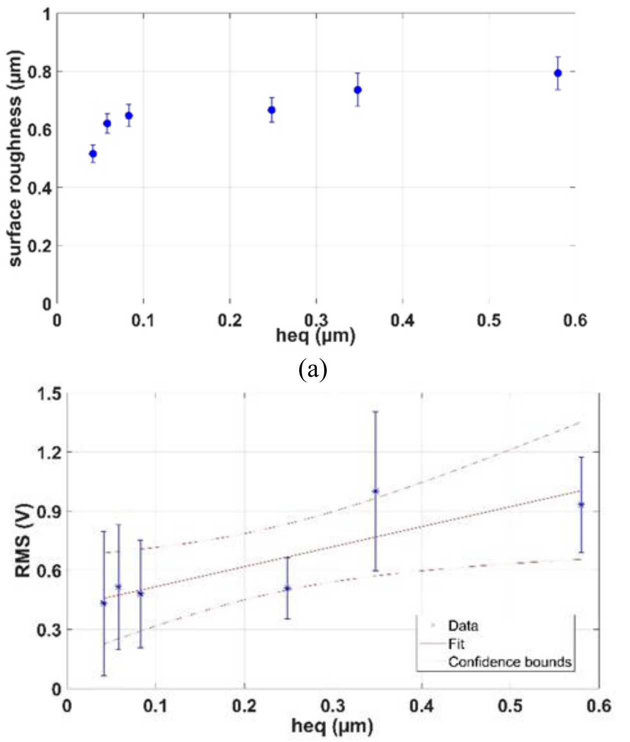
Ceramic alumina workpieces (96% aluminum oxide and 4% of other oxides) with 20 mm length x 7 mm width and Vickers microhardness of 1339 ± 47 HV1 (JIS R1610-1991 standard) were machined under six different depth of cut values in a surface-grinding machine. The cutting tool was a resin-bond diamond grinding wheel, with designation SD126MN50B2, from Dinser manufacturer. Each test consisted of a single grinding pass across the workpiece length at a given grinding condition. Prior to the test 1, a conglomerate type dresser performed the dressing of the grinding wheel to guarantee its best grinding performance. The six depth of cut values were: 25 μm, 35 μm, 50 μm, 150 μm, 210 μm, 350 μm, corresponding to the equivalent chip thickness: 0.0414 μm, 0.0580 μm, 0.0829 μm, 0.2486 μm, 0.3480 μm, 0.5800 μm, respectively. An AE sensor and a processing signal unit, from Sensis manufacturer, model DM-42, were employed in the tests. The sensor was fixed to the workpiece holder and properly calibrated for good signal sensitivity and saturation properties.

An oscilloscope, model DL850, from Yokogawa, collected the AE raw signal at a sampling rate of 2 MHz. The tests were performed in presence of a cutting fluid (Emulsion water-oil of 4%) at a flow rate of 27.5 l/min and pressure of 0.02 MPa. The following grinding parameters were kept constant in all the tests: cutting speed= 33 m/s; workpiece speed= 58 mm/s; grinding wheel diameter= 350 mm and wheel width= 15.5 mm. After the grinding tests, all the samples were evaluated in terms of surface roughness (Ra parameter) with aid of a Taylor Hobson Surtronic 3+ portable stylus instrument. A sampling length of 0.8 mm and a cut-off of 0.25 mm were used. Each workpiece surface length was equally divided into five regions and three surface roughness measurements were taken from each region. Thus, the mean value and the standard deviation of the three surface roughness measurements of each region were calculated, allowing the assessment of the ground workpiece regarding this important parameter.

The data sets from the tests were digitally processed in MATLAB. A study of the raw signals spectra was performed in order to identify frequency bands more strongly related to the surface condition of the workpiece. Thus, three different conditions were selected, representing a slight, medium and severe grinding process. The frequency spectrum of each signal was obtained by using an 8192-block fast Fourier transform and Hanning window at three equidistant central points along the grinding pass. The mean value of the three spectra was considered for analysis. The selection of suitable frequency bands for monitoring the quality of the workpiece is a very important process that depends on the grinding parameters chosen, as well as the type of material, dimensions of the workpiece, grinding wheel and sensor used in data acquisition. The optimum bands are not necessarily around the highest spectra peaks. Therefore, the criterion used in the selection of the frequency band was based on the search for frequency windows that presents significant differences of magnitude related to the workpiece conditions. In addition, a minimum of overlap between the three condition spectra was sought. The Butterworth digital filters, order 10, for each previously selected frequency band, were applied to the raw signals and, therefore, new filtered vectors were generated. After filtering, the new signals vectors were divided into 2048 points windows, which correspond to about 1 ms time intervals from the total grinding pass section. The mean value and standard deviation for each test were obtained, considering only the grinding pass interval.

3 Results and discussions

In this section, the results and discussion for grinding of alumina workpieces with diamond grinding wheel are presented to demonstrate the proposed method. All RMS results were normalized with the aim of equalizing amplitudes and facilitating their comparison. Figure 1a shows the surface roughness and standard deviation for each workpiece machined with its respective depth of cut. Each value represents the average value of roughness measured transversally along the workpiece length.



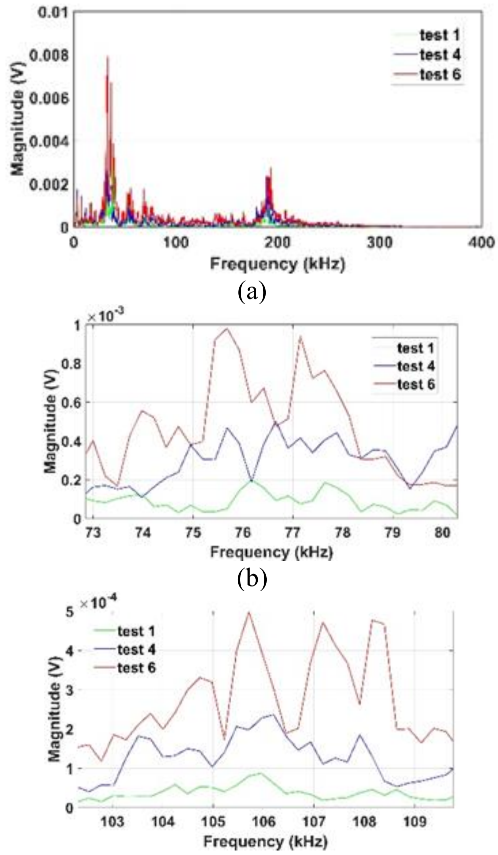
(a)

(b)

Figure 1. (a) Surface roughness for each workpiece. (b) RMS values without filtering.

It can be seen that roughness increases as the grinding conditions become more severe (increase in depth of cut). In addition, the standard deviation values for workpieces 1-3 are small and they increase with the depth of cut, resulting in higher standard deviation values for workpieces 5 and 6. According to [16], for tests to be considered successful, roughness values for ceramic grinding cannot exceed 1.6 µm. Thus, it can be seen that all results are in general below this stipulated criterion, Figure 1b shows the RMS values in function of the equivalent chip thickness for the raw unfiltered AE signal. The continuous line of the figure represents the regression line of the data and the dashed outer lines represent the 95% confidence limit, which helps to better visualize the behavior of the RMS signal prior to the application of filters. It can be observed that AE RMS values without the application of filters in the raw signal presents an increasing tendency as the condition of the process becomes more severe. However, the data behavior does not properly fit the linear regression shown in the red line (R-Squared value of 0.727) and the confidence interval. The characteristics of the mean values of the AE RMS signal are somewhat correlated with the surface roughness as shown in Figure 1a.

Figure 2a shows the frequency spectrum of the AE sensor for three different grinding conditions. It can be seen that the AE signal has a frequency range of 1-300 kHz. It can be observed that the amplitude of the signals presented different characteristics in the frequency domain according to the workpiece surface condition. There was greater spectral activity in the severe grinding conditions. On the other hand, the opposite behavior can be observed in the slight grinding conditions. The magnitude of the signals plays a key role in selecting the best frequency bands related to the process condition. The frequency bands of 74-79 kHz and 103-108 kHz were chosen. Figure 2b and 2c show a magnification of the frequency bands. It should be noted that there are other frequency bands that could have been investigated; this bands, however, may be considered for future studies. It can be clearly seen in Figure 2b and 2c that the magnitude of the signal is higher for severe grinding conditions, and a minimum of overlap is observed.



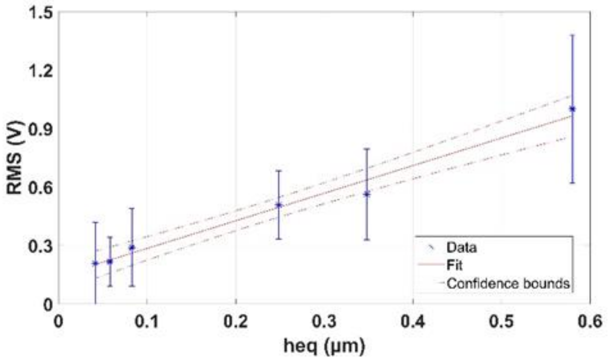
(a)

(b)

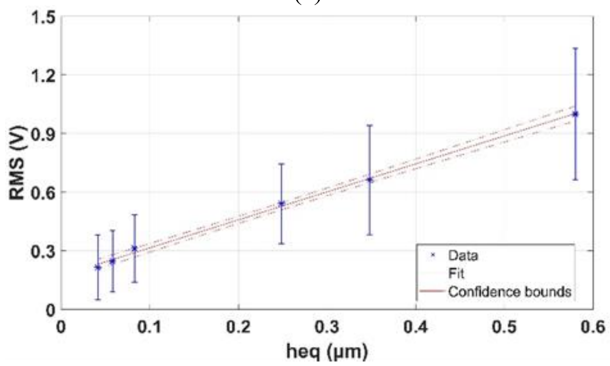
(c)

Figure 2. (a)AE spectra. Magnification for AE signal. (b) 74-79 kHz. (c) 103-108 kHz.

Figure 3 shows the filtered RMS values for the two chosen frequency bands. It can be seen that the RMS values for both filtered signals fit much better in their respective linear regression line, which is a very desired behavior for the process, since a limit can be easily established to distinguish the surface conditions of the workpieces. The R-squared for the linear regression is 0.983 for band 74-79 kHz and 0.998 for band 103-108 kHz. It can be clearly observed that there is a linear behavior between the mean RMS values and the heq when the signal is filtered. Additionally, the confidence interval narrowed, which indicates a good fit of the coefficients.



(a)



(b)

Figure 3. RMS values for filtered signal. (a) 74-79 kHz. (b) 103-108 kHz.

The standard deviation values were found to increase as the condition of the process becomes more severe. The RMS unfiltered results did not fully represent the conditions of the process; in contrast, the filtered signals showed a significant improvement for the two bands. Based on the observations, the results presented almost linear behavior when filtered in frequency bands, which makes them more attractive for monitoring the surface condition of the workpieces. Thus, the characteristics of the sensor demonstrated the importance of finding frequency bands that best represent each surface condition.

4 Conclusions

This work presented a method to monitor the grinding process by means of acoustic emission signals in order to relate the workpiece roughness with the signals acquired during the process. The method consists in the selection of frequency bands of the AE signals related to the process conditions and the subsequent application of the RMS parameter in the filtered AE signals. From the mean and standard deviation of the RMS signals, a linear regression and the compute of the R-squared value were performed in order to help in the identification of roughness variations and consequently the severity of the process. The results of the measured roughness showed the expected behavior, that is, the surface roughness values of the workpiece increased as the grinding condition becomes more severe. It can be clearly seen that RMS values filtered in frequency bands have a better fit in the linear regression. Also, it was observed that the standard deviations RMS values are more related to the process severity and the increase of the workpiece surface irregularities when filtered. The AE RMS values presented the same behavior as the measured average surface roughness. The successful results of the tests and signal processing demonstrated the reliability of the method for the proposed test bench. The approach reported in this article is initial and, for the method validation under other conditions (other sensors, materials and signal statistics), additional studies are necessary.

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