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CORRELATION BETWEEN MECHANICAL VIBRATION AND WORKPIECE SURFACE QUALITY IN THE GRINDING PROCESS

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Abstract. *Grinding is a machining process that produces components with high-quality surface finishing. The mechanical vibration and machining parameters, such as, feed and ratio between wheel and workpiece velocity have also influence on the surface roughness of the workpiece in the grinding process. In this context, the objective of this work is to analyze the influence of the feed and workpiece velocity on the mechanical vibration and surface roughness of the product generated by the grinding process. For this analysis, the grinding process of a shaft was monitored with the feed of 0.15 mm/rotation and 0.374 mm/rotation in the ratio velocity of 15 and 35 - 150 rpm and 375 rpm respectively. During the machining, the mechanical vibration was measured with two accelerometers mounted on the machine tool. In the analysis the vibration data, it was used the Power Spectrum (PS) and the Continuous Wavelet Transform (CWT) applied to the signals in the time domain. After the signal processing, the PS and CWT of the vibration signals were correlated with roughness parameters Ra, Rz and Rt used for evaluating of the surface finish of the workpieces. The results proved that CWT of vibration signals had a good correlation with the roughness parameter Rt, hence, it would be possible to monitor the quality surface finish in the grinding process by using this signal processing tool.*

Keywords: *continuous wavelet transform, external cylindrical grinding, power spectrum, surface finish, vibration signals*

1. INTRODUCTION

Grinding process is a machining process used to produce workpiece with high surface quality. Usually, in the grinding process, the surface roughness is smaller when compared to the milling or turning process. There are several factors that have influence on the workpiece surface quality, such as, the workpiece and wheel velocity, feed, and mechanical vibration generated during the machining process. From a mechanical vibration point of view, it is interesting to study ways to control this influence in order to improve the final product surface finishing. Because of the difficulty of modelling the mechanical vibration produced during the grinding process, usually, engineers and researchers analyze the measured vibration data during the machining process in order to mitigate this effect on the part surface quality (Diniz and Hassui 2003; Fang et al., 2015).

The final product surface quality may be quantified by the measurement of workpiece surface profile and calculation of roughness parameters, as for example, the Ra, Rz and Rt. Unfortunately, in the on-line production process, the direct measurement of the roughness parameters is impracticable. In this context, the on-line monitoring techniques of the piece surface finishing should be used with the purpose to optimize the product quality control process. Therefore, it is necessary to investigate and research the influence of the mechanical vibration generated by grinding process on the behavior of the roughness parameters measured in the workpiece surface.

Zeng and Forsberg (1994) were the pioneers in the study of correlation between the mechanical vibration and the workpiece surface roughness in the grinding process. They used the RMS value and the Spectral analysis of the vibration signals to correlate with the piece surface quality in the grinding. Guimarães et al. (2008) applied the Power Cepstrum to the vibration signals measured in the milling process in order to correlate to the parameter Ra of the machined workpiece. Santos et al. (1998) have applied band pass filtering to vibration signals measured in the milling process in order to monitoring the Ra roughness parameter of machined pieces. In the grinding process, Diniz et al. (1998) have investigated the wear of the grinding wheel using the vibration signals analysis and acoustic emission techniques. Subsequently, Diniz and Hassui (2003) have researched the influence of the mechanical vibration on the piece surface roughness in plunge cylindrical grinding of steel by using the Root Mean Square (RMS) technique. Asiltürk et al. (2012) have modelled an intelligent system for predicting the vibration and piece surface roughness in the cylindrical grinding process by using the Fuzzy Logic and Artificial Neural Network. Fang et al. (2015) have modelled the effect of the mechanical vibration on the piece surface roughness using an analytical approach and experimental validation. Ding et al. (2023) applied the recurrence analysis to correlate the piece surface roughness in the burnishing process and the mechanical vibration generated during the machining.

Although the abovementioned works are important contributions in this field, more recently, more advanced techniques for the signal processing, such as, the Continuous Wavelet Transform and Hilbert-Huang Transform have also been used in the vibration signal analysis measured in the machining process. Usually, the conventional techniques, as for example, Power Spectrum and Root Mean Square (RMS) are not able to extract the transient vibration components generated by the metal cutting process. In this context, Lopes et al. (2018) studied the self-excited mechanical vibration in the grinding process by using the time-frequency analysis applied to acceleration signals measured during the machining process. In this work, they have applied the Short Time Fourier Transform (STFT) to the vibration data to analyze the transient components caused by the self-excited vibration phenomena. Hubner et al. (2020) have applied time-frequency analysis and artificial neural network to the classification task of the burn phenomena in the grinding process. Liao et al. (2021) have modelled the mechanical vibration of machining process by means of time-frequency representations and deep neural networks.

The objective of this work is to study the correlation between the mechanical vibration generated in the cylindrical grinding process and steel shaft surface quality (roughness) by using the conventional techniques of signal processing and time-frequency analysis. For the estimation of the piece surface quality, it was used Ra, Rz and Rt roughness parameters. In this work, the acceleration vibration signal will be measured close to the spindle of the tool machine and subsequently, they will be processed by using Power Spectrum (PS) and the Continuous Wavelet Transform (CWT). The Power Spectrum (PS) was applied to extract the frequency components of the vibration data and the Continuous Wavelet Transform (CWT) was used in order to generate the time-scale map of the transient vibration components generated by the grinding process. For the measuring of the mechanical vibration during the grinding process, it was used a cylindrical tool in the rotation of about 5100 rpm with the roughness parameters Ra, Rz and Rt measured in the machined part surface. In experiments, it was used the feed values of 0.15 and 0.374 mm/rotation with the ratio velocity between wheel and workpiece de 15 and 35 times which is equivalent to workpiece rotation of 150 and 375 rpm respectively.

2. MECHANICAL VIBRATION GENERATED IN THE GRIDING PROCESS

Mechanical vibration produced during the grinding process depends on the irregularities from grinding wheel, workpiece and the mass, stiffness and damping parameters from machine tool vibration model. In addition, cutting parameters, as for example, grinding wheel and workpiece rotation, feed, workpiece material has also influence on the mechanical vibration generated during the machining process. In the turning process, since the contact between the tool and workpiece is continuous during the machining process, the vibration signals measured usually do not have pulses or transient components generated by events with short time. In a general way, in the grinding process, the mechanical vibration measured during the metal removal process has also several harmonics components without the presence of transient signals largely as a function of the random distribution of abrasive grains and their binder protusion, deflection machine and wheel and others (Figure 1). However, if the grinding wheel or if the workpiece has failures, no dynamic balance or geometrical irregularities, transient vibration component may be present in the measured signals during the process.

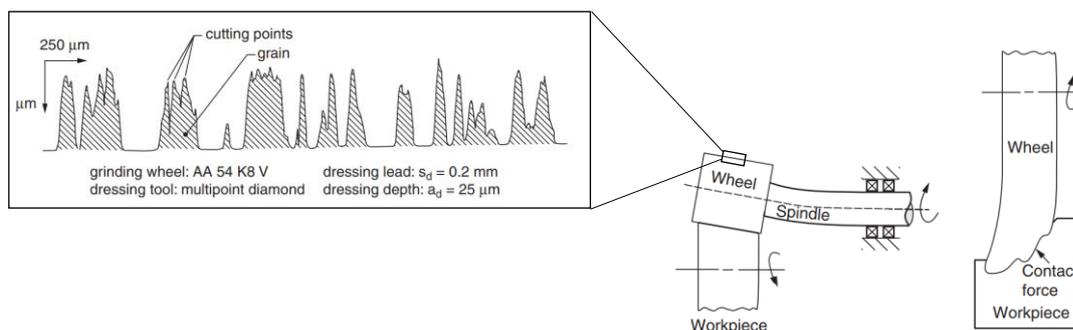


Figure 1. Aspects associated with grinding process cause part inaccuracies (adapted from Makin, et al. 2008).

In the measurement of the signals generated by the grinding process, self-excited vibration components may appear in the analysis of the results (Lopes et al., 2018). During the machining, small waves or irregularities present on the workpiece surface may generate signals components due to the self-excited vibration phenomena (Lopes et al., 2018). In this case, time-frequency analysis tools, such as, the Short Time Fourier Transform (STFT), Continuous Wavelet Transform (CWT) and Hilbert-Huang Transform may be used to detect these transient components (Hubner et al., 2020). Moreover, the noise produced by the vibration of several sources, as for example, mechanical vibration of electrical motor and gearbox from machine tool may also difficult the analysis and extraction of the vibration components produced by the grinding process. In this way, the accelerometers to be used in the acquisition of vibration signals should be placed in order to minimize the influence of the external sources of noise.

3. TOOLS FOR SIGNAL PROCESSING AND WORKPIECE SURFACE ROUGHNESS IN THE GRINDING PROCESS

3.1 Power Spectrum and Continuous Wavelet Transform

The Fourier Transform (TF) can be defined using the correlation concept of the signal. In the traditional spectral analysis, the vibration signal in the time domain is compared with harmonic functions. In this way, by using the Fourier Transform (TF), the vibration signal could be decomposed in the individual frequency components. Since the objective is to extract the global frequency energy density, the TF will be used in this work in the vibration analysis of the grinding process. The TF of the vibration signal measured during the grinding process is defined by (Randall, 2011):

$$X(f) = \int_0^{\infty} x(t)e^{-j2\pi ft} dt \quad (1)$$

where $x(t)$ is the vibration signal in the time domain measured in the machining process, f is the frequency in Hz, j is the pure imaginary and $X(f)$ is the signal in the frequency domain. In the practice, for the Spectral Analysis of the grinding process, it will be used the magnitude from signal squared, $X(f)^2$ or Power Spectrum (PS) in order to extract the frequency energy density. Therefore, by using the $X(f)^2$, the signal analyst may verify what signal components have more energy in the frequency domain (Randall, 2011).

Although the FT is a powerful tool in the signal processing context, its main disadvantage is that the transient vibration signals caused by the metal removal process may not be easily extracted by the conventional spectral analysis. Since that the window in the time domain used in the FT has infinity duration, it is not possible to extract neither when the transient component has occurred and nor its duration in the time-frequency plane (Cohen, 1995). A simple way of identifying when and how the frequencies components from signal are changing with respect to the time is to break up $x(t)$ into small time segments and to apply the FT in each time segment (Cohen, 1995). This concept is used in the definition of the Short Time Fourier Transform (STFT):

$$STFT(t, f) = \int_0^{\infty} x(\tau)h(\tau - t)e^{-j2\pi f\tau} d\tau \quad (2)$$

where $h(\tau-t)$ represents a window function used to break up the signal, $x(t)$, into segments of finite time duration. Although the STFT be a useful signal processing tool, the duration in the time and bandwidth of the window used in the time-frequency map is constant in the analysis. Hence, the time-frequency resolution has obtained in the processing of the vibration signal will not represent all details of the transient components generated by the grinding process.

In the CWT, a correlation between the vibration signal, $x(\tau)$ and functions previously chosen by the signal analyst, known as mother wavelet, is computed during its processing. In this work, it will be applied the Continuous Wavelet Transform (CWT) to the vibration signals measured in the grinding process. The main advantage of the CWT when compared the Short Time Fourier Transform (STFT) is the multiresolution analysis used in the decomposition of the vibration signal. For the vibration components with high frequency is used a mother wavelet with short duration; otherwise, for the signal components with low frequency, the mother wavelet used in the analysis has long time duration. The CWT to be used in this work is defined by (Randall, 2011):

$$CWT(t, a) = \frac{1}{\sqrt{|a|}} \int_0^{\infty} x(\tau)\psi^*(t - \tau)d\tau \quad (3)$$

where ψ is the mother wavelet, which is compared with signal in the time domain, $x(t)$, a is a scale factor used in the dilation of $\psi(t)$ and τ is the delay time used in the convolution integral from CWT. In practice, there exist different types of mother wavelet that can be used in the correlation with $x(t)$. In this work, it will be used the Morlet Wavelet for the extraction of the features of transient vibration produced by the grinding process.

3.2 Roughness of the Workpiece Surface

The machined workpiece surface finishing may be quantified by means of the roughness. In the case of the grinding process, the parameters commonly used are Ra, Rz or Rt. By using the device for measurement of workpiece surface profile, it is possible to compute the parameters Ra, Rz and Rt based on the heights of the irregularities present in the workpiece surface. During the measuring, the device has a tip that moves in the longitudinal direction on the piece surface and the peaks and valleys are recorded for the processing according to the Ra, Rz and Rt parameters concepts.

The Ra parameter is extensively used to qualify the machined workpiece surface finishing. The first step to be used in the calculation of Ra parameter is to compute the mean of the workpiece surface profile heights, named Center Line Average (y_{CLA}). Subsequently, the absolute value of the difference among the measured heights and the y_{CLA} is calculated. In this way, the parameter Ra, called Roughness Average is the mean of the absolute values of the heights with respect the Center Line Average (Carpinetti et al., 2020):

$$R_a = \sum \frac{y_i}{n} \quad (4)$$

where n is quantity of points of the measured coordinates y_i inside of piece surface cut off length.

The Rz parameter may also be used to quantify the workpiece surface finishing in the grinding process. In practice, the calculation of Rz parameter is also based on the average of the measured heights on the piece surface profile. The main different between the Ra and Rz is the number of points used in the mean process. In the calculation of the Ra parameter, all measured heights on the piece surface profile are considered in the average process. On the other hand, in the calculation of the Rz, the cut off length is divided in 5 samples and the highest pick with the lowest valley are recorded by the measurement device. Subsequently, the difference between the highest pick and lowest valley, z, is calculated and the average process is applied to these values (Carpinetti et al., 2020):

$$R_z = \frac{z_1 + z_2 + z_3 + z_4 + z_5}{5} \quad (5)$$

Instead of considering the mean process of the measured heights on the workpiece surface profile, the calculation of the Rt parameter is based on the difference between the highest peak with the lowest valley inside the cut off length. In a similar way to the Rz parameter, the first step is to divide the total cut off length in 5 samples. Then, the device for measurement of roughness records the highest peak and the minor valley inside of each sample used in the discretization of the points. By using this idea, the Rt parameter is defined by:

$$R_t = \max(y_i) - \min(y_i) \quad (6)$$

In this work, the Ra, Rz and Rt parameters measured in the specimens after the grinding process will be correlated with the workpiece rotation and grinding wheel feed. Moreover, the CWT and PS of the mechanical vibration signals measured during the grinding process will be analyzed with the respect to the workpiece rotation and feed of the wheel.

4. MATERIALS AND METHODS

4.1 Grinding Process and Roughness Parameters

The cylindrical grinding experiments were carried out using a grinding machine from Nardini S.A. manufacturer, Nodulos 220.B model. The tests have been done in the machine tool available in Machining Laboratory from Federal University of Triângulo Mineiro by using a grinding wheel in rotation of 5100 rpm. It was carried out 4 tests with tool feed of 0.15 and 0.374 mm/rotation and workpiece rotation of 150 and 375 rpm. Figure 2 displays an image of the grinding machine and cylindrical workpiece.



Figure 2. Image of the machine tool and part used in the grinding tests.

After the machining from parts, the roughness parameters Ra, Rz and Rt were measured in the cylindrical workpiece surface by using profilometer model Form Talysurf 5.0. The parameters values Ra, Rz and Rt was calculated by using a

software available by the manufacturer. In order to improve the results accuracy, the cylindrical specimen surface profile was measured for 3 different angles, 0°, 120° and 240°, respectively. Subsequently, the average roughness Ra, Rz and Rt was calculated based on the roughness values have obtained in each angle. The Table 1 summarizes the results obtained for each test condition.

Table 1. Roughness Ra, Rz and Rt have obtained in each test of the grinding process.

Roughness Parameter	Test 1 Feed: 0.15 mm/rot Rotation: 150 rpm	Test 2 Feed: 0.15 mm/rot Rotation: 375 rpm	Test 3 Feed: 0.375 mm/rot Rotation: 150 rpm	Test 4 Feed: 0.375 mm/rot Rotation: 375 rpm
Measurement for Angle of 0°				
Ra [μm]	0.6	0.68	0.7	0.76
Rz [μm]	4.2	6.0	4.7	5.4
Rt [μm]	6.3	7.5	5.9	6.6
Measurement for Angle of 120°				
Ra [μm]	0.64	0.64	0.74	0.82
Rz [μm]	5.1	5.3	5.5	5.7
Rt [μm]	6.0	6.7	6.5	8.2
Measurement for Angle of 240°				
Ra [μm]	0.66	0.64	0.76	0.86
Rz [μm]	5.8	5.2	6.4	6.6
Rt [μm]	7.5	5.9	8.4	9.2
Mean of Roughness Parameters				
Ra [μm]	0.63	0.65	0.73	0.81
Rz [μm]	5.03	5.5	5.53	5.9
Rt [μm]	6.6	6.7	6.93	8.0

In all tests, it was used a cutting fluid in order to reduce the friction and the temperature of the workpiece surface during the grinding process in 5% concentration, measured by refractometer.

4.2 Measurement of the Vibration Signals

The mechanical vibration signals in the time domain were measured for each condition described in Table 1. Since the external noise due to the electrical motor, pump of the cutting fluid and gearbox used to drive the spindle from grinding machine is high, it was used 3 accelerometers placed on different positions, as can be seen in the Fig. 2. The objective of using 3 accelerometers is to identify the measurement point with the minimum external noise. In this study, it was applied the Power Spectrum has defined in the Eq. (1) to the vibration data in the time domain in order to detect the components caused by the griding process and by the external noise sources. In all tests, the sampling frequency was 12800 Hz and the total duration of the vibration signals measured during the metal removal process was 40 s. The accelerometers used in the measuring of data are from PCB Piezotronics manufacturer, PCB 352C22 model. Table 2 describes the sensitivity values of each accelerometer used in the acquisition of the vibration signals.

Table 2. Sensitivity parameters of each accelerometer used for the acquisition of vibration signals.

Sensitivity of accelerometer 1 [mV/m/s²]	Sensitivity of accelerometer 2 [mV/m/s²]	Sensitivity of accelerometer 3 [mV/m/s²]
0.988	1.099	1.05

For the analysis of influence of the external noise on the vibration data, the signals were measured during the grinding process and for the condition of no machining. After the signal analysis in the frequency domain, it was verified that the accelerometer placed on tool holder is able to measure the vibration data with minor level of noise when compared to the signals measured by the others accelerometers. In the processing of CWT from vibration signals, it was used the scales of 1 until 100 in order to maintain, as the high frequency vibration components, as the low frequency vibration components. At same way, the global vibratory energy level produced by the grinding process was also computed from the time-scale map provided by the CWT.

5. ANALYSIS OF THE RESULTS

Figure 3(a) illustrates the vibration signals measured in the grinding process for feed of 0.15 mm/rot and workpiece rotation of 375 rpm. By analyzing the signals in the time domain, the amplitude of is about 4 m/s^2 for both cases, condition of machining and no machining. The Power Spectrum of vibration signals from Fig. 3(a) is illustrated in the Fig. 3(b). Although the amplitude of the signals shown in the Fig. 3 is the same (4 m/s^2), the signal components in the frequency domain measured during the grinding process are higher than signal components in the situation of no machining. In the low frequency region, there are several harmonics components from grinding wheel rotation of 85 Hz ($5100/60$) for both cases. However, the amplitude of the signal components measured in the grinding process are higher when compared the vibration signal in the frequency domain for the situation of no machining. The mechanical vibration for no machining condition corresponds to the external noise caused by the electrical motor, cutting fluid pump and gearbox used in the driving of the grinding machine spindle.

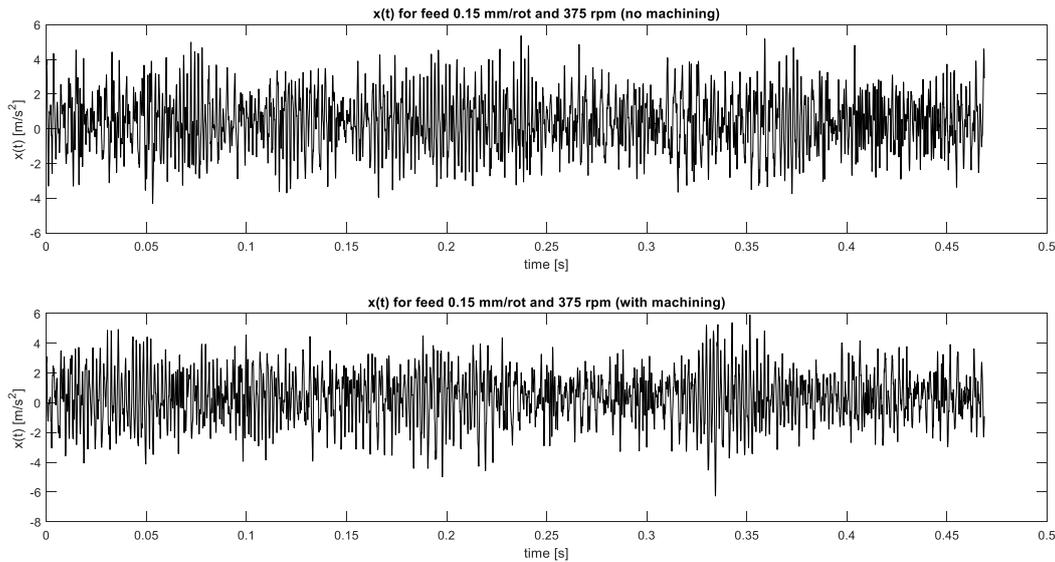


Figure 3(a). Vibration signals in the time domain for feed of 0.15 mm/rotation, workpiece rotation of 375 rpm in the conditions of machining and no machining.

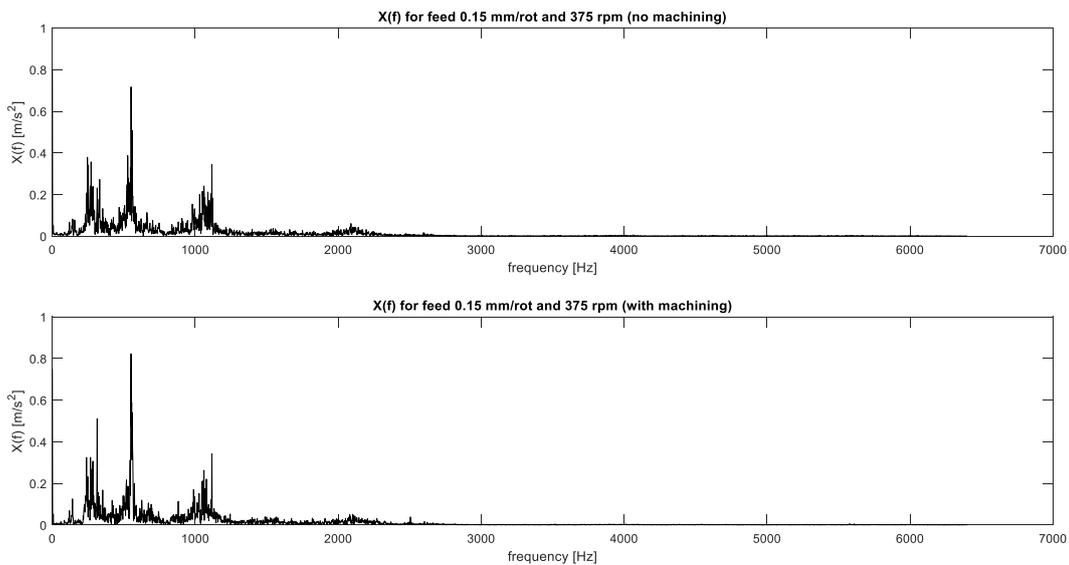


Figure 3(b). Power Spectrum of the vibration signals for feed of 0.15 mm/rotation, workpiece rotation of 375 rpm in the conditions of machining and no machining.

Figure 3(c) shows the Continuous Wavelet Transform (CWT) of the vibration signals measured during the grinding machine operation without machining (external noise) and for grinding process of the cylindrical shaft. In two situations, the time scale maps provided by the CWT illustrates vibration components in the scale range of about 18 until 60.

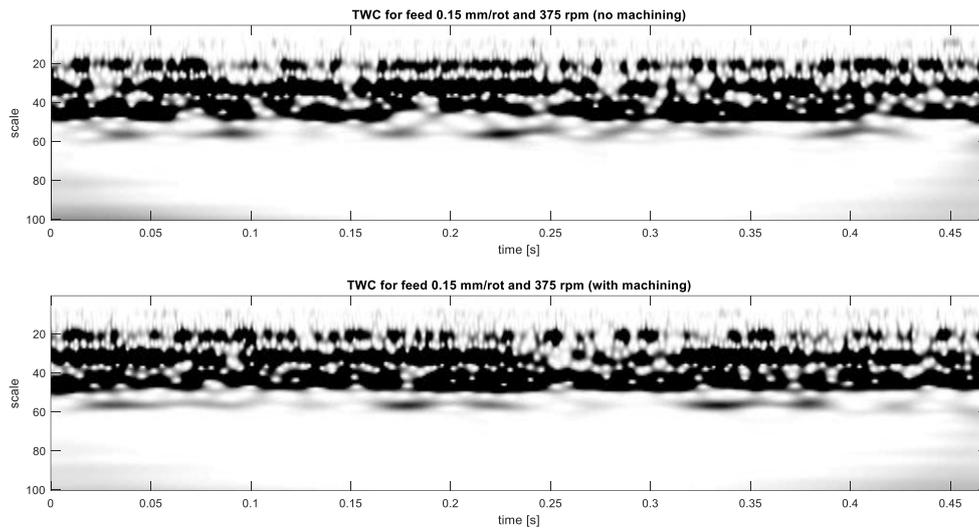


Figure 3(c). CWT of the vibration signals for feed of 0.15 mm/rotation, workpiece rotation of 375 rpm in the conditions of machining and no machining.

The vibration components in the scale of 60 are caused by the harmonics of the rotation frequency from grinding wheel and the components present in the scale of 18 until 40 due to the high frequency vibration generated by the grinding process. By comparing the time scale energy distribution given by the maps in the Fig. 3(c), it is verified that the time scale vibratory energy level has observed for two situations (machining and no machining) are approximately the same. Nevertheless, when the grinding wheel feed and workpiece rotation increases, the time scale energy density of the vibration signals also increase, as can be seen in the Figs. 4(a), 4(b) and 4(c). Figures 4(a), 4(b) and 4(c) compares the behavior of the roughness parameters, Ra, Rz and Rt and the time scale energy level (CWT) of the mechanical vibration generated during the grinding process by changing the grinding wheel feed and workpiece rotation.

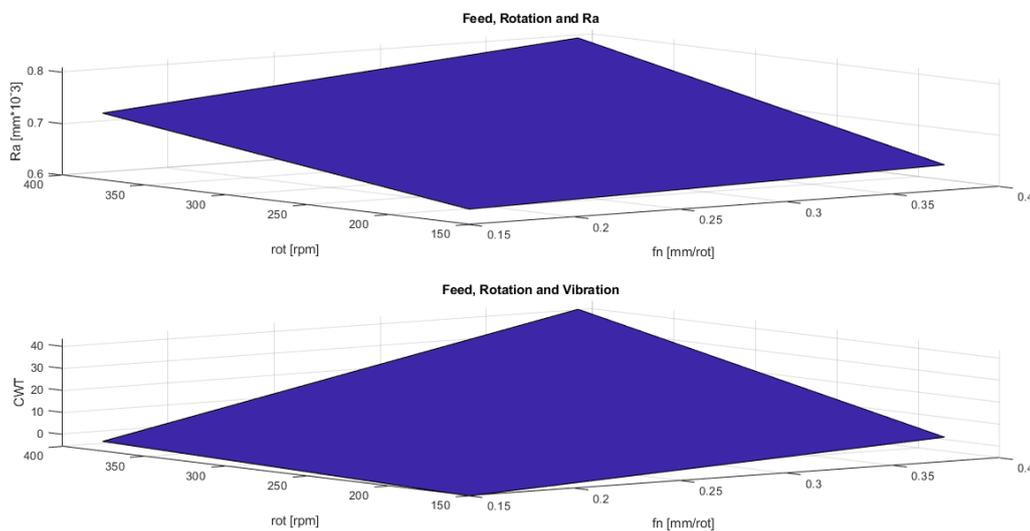


Figure 4(a). Roughness parameter, Ra, and CWT of the vibration signal measured during the grinding process by the changing the wheel feed and workpiece rotation.

For the calculation of the response surfaces provided by the CWT shown in the Figs. 4(a), 4(b) and 4(c), the time scale energy density from vibration signal measured in the grinding process was compared with the vibration signal for the condition of no machining (noise generated by the machine tool operation). In the 3 situations, as the Ra, Rz and Rt roughness parameters, as the time scale energy level from CWT increase when the grinding wheel feed and workpiece rotation increase.

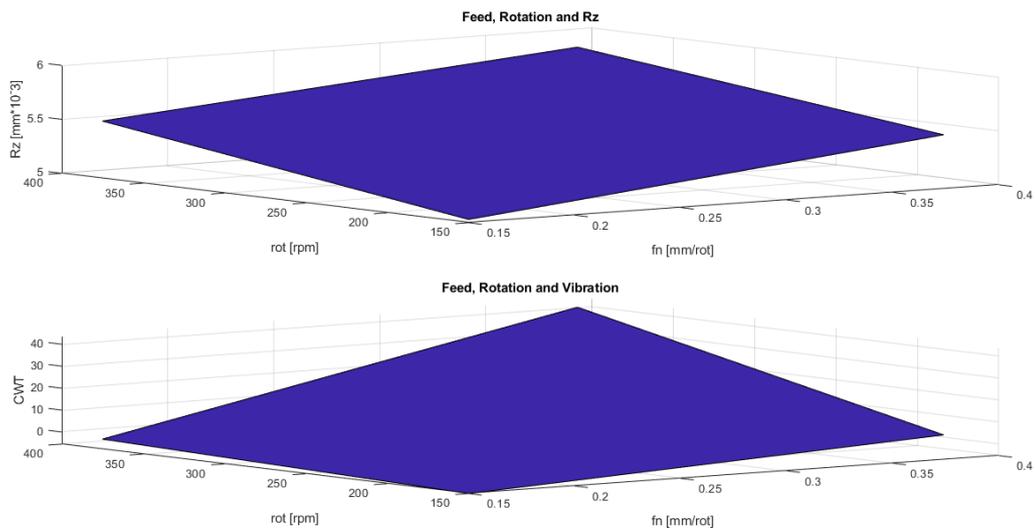


Figure 4(b). Roughness parameter, Rz , and CWT of the vibration signal measured during the grinding process by the changing the wheel feed and workpiece rotation.

Indeed, by the comparing the shape of the response surface of the Ra , Rz and Rt roughness and the energy density of CWT, it is observed that they are similar, by the analysis of the Figs. 4(a), 4(b) and 4(c). However, from a visual point of view, it was verified that for the response surface of Rt roughness parameter fits better to the CWT data, as illustrated in the Fig. 4(c). Therefore, based on the results obtained in this work, it was concluded that the Rt parameter could be used to monitor the workpiece surface quality in the cylindrical grinding process, by the measurement of the vibration signals during the metal removal process.

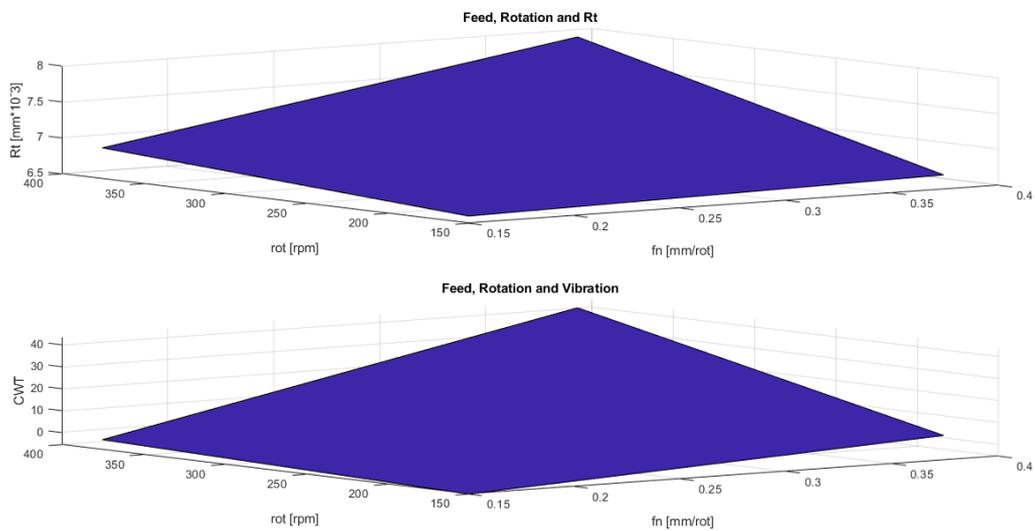


Figure 4(c). Roughness parameter, Rt , and CWT of the vibration signal measured during the grinding process by the changing the wheel feed and workpiece rotation.

6. CONCLUSIONS

It was researched, in this paper, the correlation between the Ra , Rz and Rt roughness parameters of machined workpiece in the cylindrical grinding process and mechanical vibration generated during the metal removal process. In the experiments, the grinding wheel rotation was of 5100 rpm by considering the workpiece rotation of 150 and 375 rpm and tool feed of 0.150 and 0.374 mm/rotation. The mechanical vibration produced in the grinding process was measured with 3 accelerometers placed on the machine tool. After the measuring, it was applied the Power Spectrum (PS) and

Continuous Wavelet Transform (CWT) as vibration signal processing tools. By using the PS, it was possible to select the best measurement point for the acquisition of the vibration data with minor influence of external noise. Furthermore, it was possible to extract the frequency components of the signals caused by the mechanical vibration in the grinding process, as well as, the transient vibrations produced by the material removal process using the CWT.

The response surface for the Ra, Rz and Rt roughness parameters and for CWT from vibration signals was also computed for the results analysis. By the analysis of the response surface of the vibration signal CWT and Ra, Rz and Rt roughness parameters, it was verified that Rt parameter surface behavior is similar to the shape of CWT surface. Hence, in cylindrical grinding process, the Rt roughness parameter and the vibration signal CWT could be used as tools for the on-line monitoring of the workpiece surface finishing for this machining process. In future, it is intended to investigate the influence of different values of wheel rotation and workpiece feed on the roughness parameters and vibration signals measured in the grinding process. In addition, by using the results of this research, it is intended to apply the machine learning techniques, as for example, Artificial Neural Networks in order to monitoring and validating the workpiece surface roughness in the grinding process using the analysis of the vibration signals measured in the machining process.

7. ACKNOWLEDGEMENTS

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