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AN ANALYSIS OF VIBRATION AND WORKPIECE SURFACE QUALITY IN THE MILLING PROCESS

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Abstract. *The workpiece surface quality in the milling process depends on the mechanical vibration generated during the machining and the cutting parameters. In this work, it was studied the relationship between the aluminum workpiece surface roughness, feed and the mechanical vibration produced in the milling process. In this analysis, it was used several values for feed in the range of 0,33 mm/rotation until 8 mm/rotation during the metal cutting process. The mechanical vibration was measured with two accelerometers has mounted in the machine-tool close to the cutting edges. After the acquisition of the vibration data, the Root Mean Square (RMS) and the Continuous Wavelet Transform (CWT) were applied to the signals in the time domain in order to identify some amplitude modulation source caused by the milling process. For the measuring of the vibration during the machining, it was used a tool with 1 and 2 inserts and the roughness parameters Ra and Rq were used in the analysis. The results proved that the RMS value and CWT of the vibration signals measured during the process had a good correlation with the roughness parameter Rq for two cases, a tool with 1 and 2 inserts.*

Keywords: *continuous wavelet transform, milling, root mean square, surface finish, vibration signals*

1. INTRODUCTION

Milling is a machining process extensively used in the production of the slots, tears and holes in the workpiece. Therefore, it is interesting to control the surface quality (roughness) of the workpiece for the final product meets the design requeriments. The mechanical vibration generated during the machining and cutting parameters, such as, feed and cutting speed have also influence on the workpiece roughness (Jáuregui et al., 2017). In this way, the study of the finishing end milling operation is important, since one of the ways to obtain lower roughness is by using inserts with wiper geometry in conjunction with inserts of standart geometries, Figure1, mounted simultaneously on the cutter holder (Altintas, 2000).

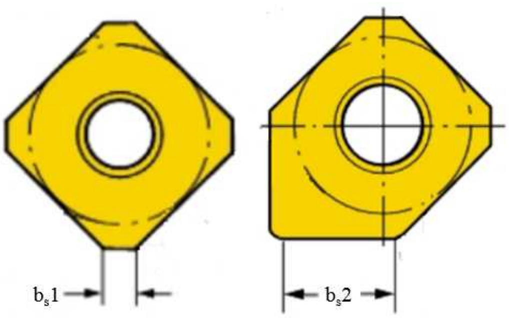

Figure 1. Difference of the wiper edge length of the Standard insert (b_s1) to the Wiper insert (b_s2) (Lins et.al., 2023).

The smoothing insert, as it has a higher plane phase (bs), removes the portion of material left by the other inserts and smoothes the roughness peaks to a point called the saturation point, which is equivalent to saying that the maximum ratio bs/Fz was obtained for which has the lowest roughness values (Altintas, 2000). According to Sandvik Coromant (2010) wiper inserts work more efficiently with high feed per revolution fn, in milling cutters of larger diameters with extra fine pitch.

The mechanical vibration also depend on the tool wear, geometry of the workpiece and tool and the parameters of the mass, stiffness and damping of the machining tool. (Sick, 2002). Then, it is possible to monitor and optimize the product surface quality generated in the milling process from the control the mechanical vibration produced during the machining process.

In the literature, most of works investigate the correlation between the mechanical vibration and the tool wear based on the vibration signal analysis measured during the milling process (Sousa, 1998; Silva et. al, 1998; Sick, 2002). In this context, several techniques, such as, signal processing in the domains of the time, frequency and time-frequency have been applied in the estimation of the tool wear and life. (Sousa, 1998; Sick, 2002, Guimarães et al., 2008). Furthermore, the soft computing techniques, as for example, the Artificial Neural Networks and Fuzzy Logic have also been used for the estimation of the tool wear and life (Sick, 2002).

In a production line, the estimation of the workpiece roughness may be carried out by using a device for measurement of the workpiece surface profile and processing the roughness parameters, such as, Ra (mean roughness) and Rq (root mean square roughness). Unfortunately, this surface quality off-line estimation process is impracticable and unfeasible since is very time consuming. In this sense, the on-line monitoring techniques may be used in the surface quality control of the final product (Sick, 2002). Asiltürk et al. (2023) have investigated the correlation between the surface quality of the piece (Ra parameter) in the turning process and the cutting parameters using vibration signals, acoustic emission and the machining learning techniques. Zahaf and Benghersallah (2021) have studied the influence of the cutting speed, feed and cutting depth with respect to the piece surface Ra parameter and vibration generated in the end milling of annealed and hardened bearing steel. In this work, they modelled and optimized the best conditions of speed, feed and cutting depth in this specific milling process. In most works have published in the literature, the piece surface quality in the milling process is estimated based on the Ra roughness parameter

The objective of this work is to study the correlation between the mechanical vibration generated in the end milling and AA6063-T6 aluminum alloy workpiece surface quality (roughness) by using the Ra and Rq parameters. 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. In this work, the vibration signal will be processed by using the parameters Root Mean Square (RMS) and the Continuous Wavelet Transform (CWT) in order to extract the vibration energy density caused by the workpiece roughness. For the measuring of the vibration during the machining, it was used a tool with 1 and 2 inserts and the roughness parameters Ra and Rq were used in the analysis. In all tests, it was used several values for feed in the range of 0,33 mm/rotation until 8 mm/rotation during the metal cutting process.

2. CHARACTERISTICS OF THE VIBRATION SIGNALS MEASURED IN THE MILLING PROCESS

Figure 2. Image of the end milling process (Mapal, 2023).

The vibration generated during the metal machining is highly nonlinear with several frequency components (Sick, 2002). Usually, the vibration signals measured during the machining process depends on the cutting parameters, as for example, cutting speed, feed, workpiece material, etc. Moreover, the mass, stiffness and damping parameters of the machine tool vibration model have also influence on the vibration signal measured during the machining process. Most of machining process produces vibration amplitude modulation components caused by the contact between the cutting tool and the metal piece (Sick, 2002). For example, 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. On the hand, in the milling process, the tool edge rotation movement produce vibration pulses due to material removal process in the machining. Hence, the vibration signals measured in the milling process are ciclostationary, since that the pulses have a repetition pattern (Jáuregui et al., 2017). Figure 2 illustrates an image of the inserts and cutting tool in the end milling process of an aluminum alloy workpiece.

In this work, it will be studied the repetition pattern of the amplitude modulation components in the milling process by using the Continuous Wavelet Transform (CWT) and the Root Mean Square (RMS) applied to vibration signal in the time domain. After the vibration amplitude modulation components analysis caused by the milling process by using the CWT, the roughness parameters, Ra and Rq measured in the workpiece surface will be correlated with the RMS and CWT from vibration signals measured during the milling process. Moreover, the noise produced by the vibration of several sources, as for example, the tool rotation, feed and vibration of electrical motor and gearbox may also difficult the analysis and extraction of the amplitude modulation patterns produced during the milling 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 THE VIBRATION SIGNALS ANALYSIS AND MEASURING OF WORKPIECE SURFACE ROUGHNESS IN THE MILLING PROCESS

3.1 Root Mean Square

The Root Mean Square value (RMS) of a signal in the time domain represents the energy density in the time domain (Randall, 2011). By using the RMS value is possible to estimate if the vibration signal measured during the milling process has high or low energy. Unfortunately, the RMS is a global measure of the vibration energy level in the time domain. Hence, if the RMS value is calculated, the mean energy density of all vibration components is estimated. If the signal analyst is interested in computing the energy level of each component, he should use others techniques, such as, the Power Spectrum of vibration signal in the frequency domain. In this context, the mean value of vibration signal, x(t), is defined by:

$$x_m(t) = E\left[x(t)\right] \tag{1}$$

where the symbol E[] is the expected value of the vibration signal in the time domain, x(t), and $x_m(t)$ represents the mean value. Of this way, if the dc level from vibration signal is zero, the mean value is also equals to zero. In order to measure the energy density from signal in the time domain, it more convenient to use the RMS value given by (Randall, 2011):

$$x_{rms} = \sqrt{E\left[x^2(t)\right]} \tag{2}$$

where x_{rms} represents the RMS value of signal in the time domain. In this work, the RMS parameter will be used to estimate the vibration energy level associated with the workpiece surface roughness generated in the milling process.

3.2 Continuous Wavelet Transform

The Fourier Transform (TF) and the Continuous Wavelet Transform (CWT) could 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. Although the FT is a powerful tool in the signal processing context, its main disadvantage is that the transient vibration signals caused by the pulses during the milling process could 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 (Randall, 2011). In this case, appropriate techniques of the non-stationary signal analysis should be used for this purpose.

In the CWT, a correlation between the vibration signal, x(τ) 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 milling process of the workpiece. 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):

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

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 end milling process. Furthermore, the CWT will be also used to estimate the time-frequency energy level caused by the transient vibration components produced during the workpiece milling process.

3.3 Roughness of the Workpiece Surface

After the milling process, workpiece surface quality may be quantified by means of the roughness. In the literature, there are several roughness parameters, as for example, R_a, R_q or R_t. For the milling process, the more recommended parameters are R_a and R_q. The idea is to measure the workpiece finishing profile by using a device and to compute the parameters R_a and R_q. During the measuring, the device has a tip that moves in the longitudinal direction, and the heights of the irregularities are measured according to the peaks and valleys present in the workpiece surface. The Figure 3 shows the random pattern of the workpiece surface after the machining.

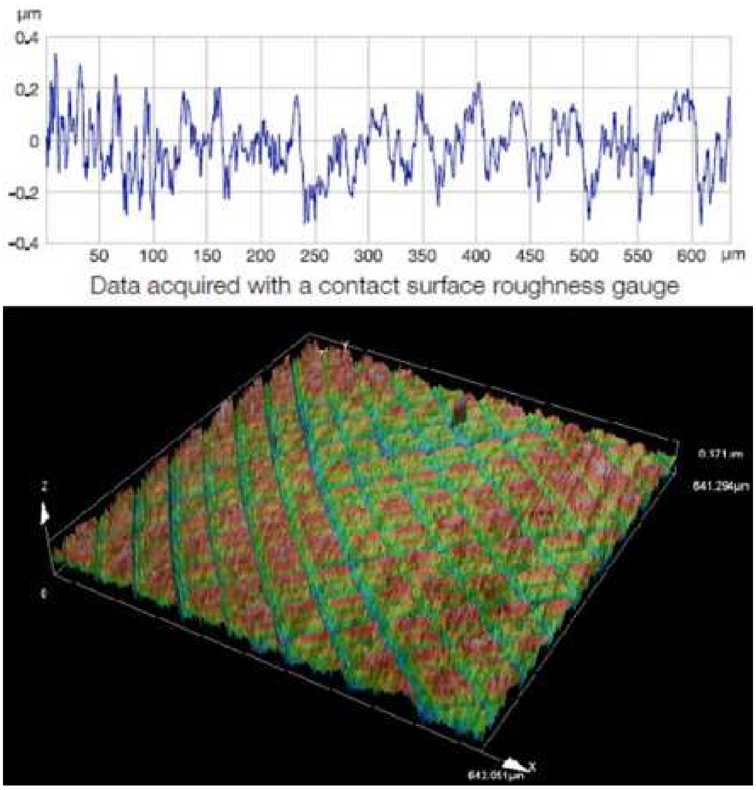

Figure 3. Example of workpiece surface roughness (Olympus, 2023).

The Ra is a common parameter used to quantify the workpiece roughness. The Brazilian standardization recommends this parameter to the qualify the piece surface finishing depending on the machining process. After the acquisition of the coordinates y of the workpiece surface profile, the Center Line Average (y_{CLA}) is calculated using the mean of the measured heights inside of cutting of length. Then, the absolute values of the difference among the measured heights and the y_{CLA} is calculated. In this way, the parameter R_a, called Roughness Average is the mean of the absolute values of the heights with respect the Center Line Average (Carpinetti et al., 2020):

$$R_a = \sum \frac{|y_i - y_{CLA}|}{n} \tag{4}$$

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

Another way of quantify the workpiece surface quality is to use the parameter R_q. The concept of R_q is similar to the RMS value used in the vibration signal processing in the time domain. Instead of using recorded vibration signal, x(t), the Root Mean Square of the coordinates y is calculated after the measuring of the piece surface finishing pattern. Hence, the Rq named Root Mean Square roughness is defined by the equation (5) (Carpinetti et al., 2020):

$$R_q = \sqrt{\frac{1}{n}\sum y^2} \quad (5)$$

In this work, both parameters, R_a and R_q will be applied in the analysis of the workpiece surface quality in the end milling process. In the practice, Ra and R_q are estimated based on the average of the positive values of the coordinates y of the workpiece surface finishing profile. For the calculation of the R_a and R_q, the Ra parameter applies the absolute value operation to the coordinates y measured in the workpiece surface and R_q compute the squared heights of the peaks and valleys present in the workpiece surface finishing pattern.

4. MEASUREMENT AND ANALYSIS OF THE VIBRATION SIGNALS AND SURFACE QUALITY IN THE MILLING PROCESS

4.1 Milling Process and Machining Parameters

The end milling tests were carried out in a Machining Center from Federal University of Triângulo Mineiro. The Machining Center used in all experiments is from ROMI manufacturer, model 1250 D with mechanical power of 18 KW and spindle maximum rotation of 12000 rpm. The workpiece material is AA 6063-T6 aluminum alloy. More details of the chemical composition and mechanical properties of this alloy may be found in Lins et al. (2023). Figure 4 displays an image of the machine tool, as well as, the mounting of the specimen and the insert tool used during the end milling process.

The Table 1 describes the feed values used in the end milling tests. In all experiments, the cutting speed was 1100 m/min and the cutting deep was 0.5 mm. The cutting fluid used in the tests was MV AQUA 180 from VCI manufacturer. During the machining, the spindle was mounted with 6 insert tools of SANDIVIK manufacturer model 345R-1305E-KLH13A. Initially, it was used 1 (one) wiper insert for all feeds condition has described in the Table 1. Subsequently, the tests set was repeated by using 2 (two) wiper inserts. The wiper insert has used in these experiments is from SANDIVIK manufacturer model 345N-1305E-KW8H13A.

Table 1. Feed values and roughness Ra and Rq have obtained in each end milling test (Lins et al., 2023).

Feed [mm/rot]	0.30	0.54	0.84	1.20	1.38	1.98	3.36	4.48	5.52	7.20	8.10
Ra [µm] (1 wiper insert)	0.179	0.279	0.333	0.253	0.350	0.374	0.863	1.800	1.970	1.069	1.993
Rq [µm] (1 wiper insert)	0.165	0.307	0.329	0.398	0.352	0.366	0.617	0.924	0.940	0.205	0.307
Ra [µm] (2 wiper inserts)	0.152	0.147	0.190	0.274	0.287	0.343	0.422	0.430	0.452	0.444	0.414
Rq [µm] (2 wiper inserts)	0.132	0.125	0.164	0.242	0.262	0.425	0.454	0.442	0.532	0.719	0.689

Before the start of the tests, the axial and radial runout of the inserts were evaluated for each configuration of the cutter set, using a digital comparator Pressetting with a resolution of 0.001 mm. All inserts had radial runout equal to 0.000 mm. Table 3 shows the axial deviation values measured in millimeters.

The position of the Wiper insert in the B assembly was chosen at random with an axial runout of 0.073 mm. In assembly C, the first wiper insert was placed in the same position used in assembly B and the second wiper insert was placed at 180° from the first, axial runout of 0.037 mm.

After the end milling tests, the surface quality from machined specimens have estimated by using the parameters R_a and R_q. Table 1 describes the roughness values R_a and R_q have obtained in each test (Lins et al., 2023). For the measurement, it was used a profilometer model Form Talysurf 5.0. The parameters values R_a and R_q was calculated by using a software available by the manufacturer. The cut off length used for the measuring of the R_a and R_q was 0.8 mm and a Gaussian filter was applied in order to smooth the irregularities present on the workpiece surface.

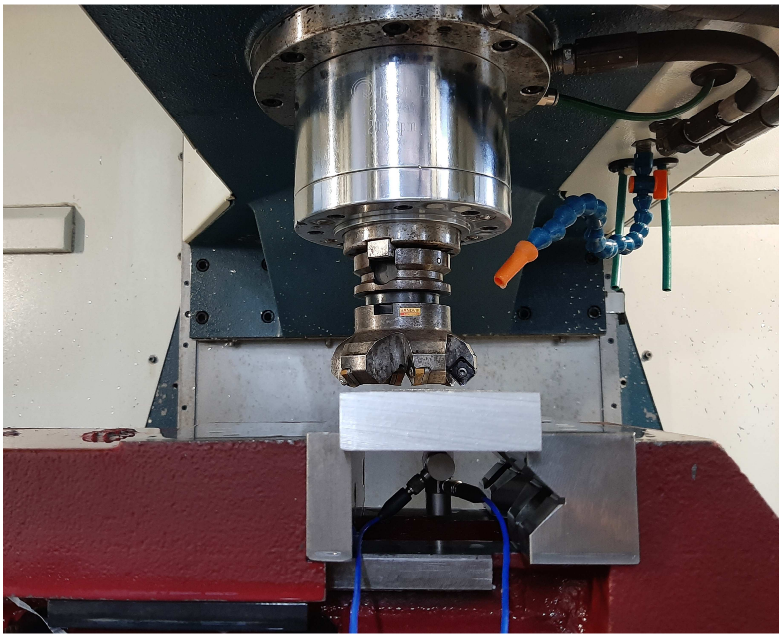

Figure 4. Image of the machine tool, specimen and accelerometers for measuring of the vibration signals during the end milling tests.

4.2 Measurement of the Vibration Signals

During the end milling tests, the vibration signals were measured by using two 352C33 model accelerometers from PCB Piezotronics® manufacturer. Table 2 describes the parameters values used for measuring the vibration data in the time domain. It was not necessary to use a signal conditioning unit since this accelerometer has an integrated signal pre-amplifier for increasing the output signal gain. In all experiments, it was used 1 (one) accelerometer placed in the radial direction and 1 (one) accelerometer fixed in the axial direction, as can be seen in the Figure 4, shows that the 2 accelerometers were mounted in the specimen inferior face. In this way, because the vibration sensors were placed near from cutting process, the influence of the noise was minimized. Subsequently, the software MATLAB® 2018 with a toolbox integrated to the software Labview® was used to save the data file in a txt format.

Table 2. Parameters values used for measuring of the vibration signals in the end milling tests.

Sampling frequency [Hz]	Number of points	Duration of the signals [s]	Sensitivity of accelerometer in the radial direction [mV/m/s^2]	Sensitivity of accelerometer in the axial direction [mV/m/s^2]
51200	6000	0.11	10.44	10.38

The vibration data in the time domain were processed by using the RMS and CWT defined in the Equations (2) and (3), respectively. For the signal processing, it has been used algorithms for calculation of RMS and CWT according to Randall (2011) have implemented in MATLAB® language. Hence, it was possible to analyze the repetition pattern of the transient vibration components caused by the cutting process in the end milling by using the time-scale energy distribution provided by the CWT. Moreover, the vibratory energy measured during the end milling process by using the RMS and CWT will be also compared with the roughness parameters, Ra and Rq, by changing the feed of the cutting tool.

In the processing of the RMS level, the global energy density in the time domain was calculated for all components of vibration signal. In this way, no filtering procedure was applied to the vibration measured during the end milling. On the other hand, for the processing of the CWT, the low frequency vibration components have been filtered, since that these components are not caused by the vibration due to the milling process. In this case, the vibration energy density by using the CWT was computed for the scales of 1 until 50 in order to maintain the high frequency vibration components.

5. ANALYSIS OF THE RESULTS

Figure 5 shows the vibration signal in the time domain for the end milling with feed of 0.3 mm/rotation and the time-scale map provided by the CWT. For the feed of 0.3 mm/rotation, the vibration pulses caused by the metal cutting process are clearly seen, as in the signal in the time domain, as the time scale representation of the CWT. The same pattern of repetition of the transient components can be also seen for the vibration measured in the end milling process with feed of 1.38 mm/rotation have illustrated in the Fig 6. For the signals in the time domain, it is possible to visualize the period between two consecutive pulses which are associated with the spindle rotation and the quantity of inserts (6 inserts) used in the milling process. In the CWT of the vibration signals, it is possible to analyze the duration of each vibration pulse, the period of the repetition pattern and the frequency band excited by the impulsive forces caused by the cutting process of the inserts in the end milling.

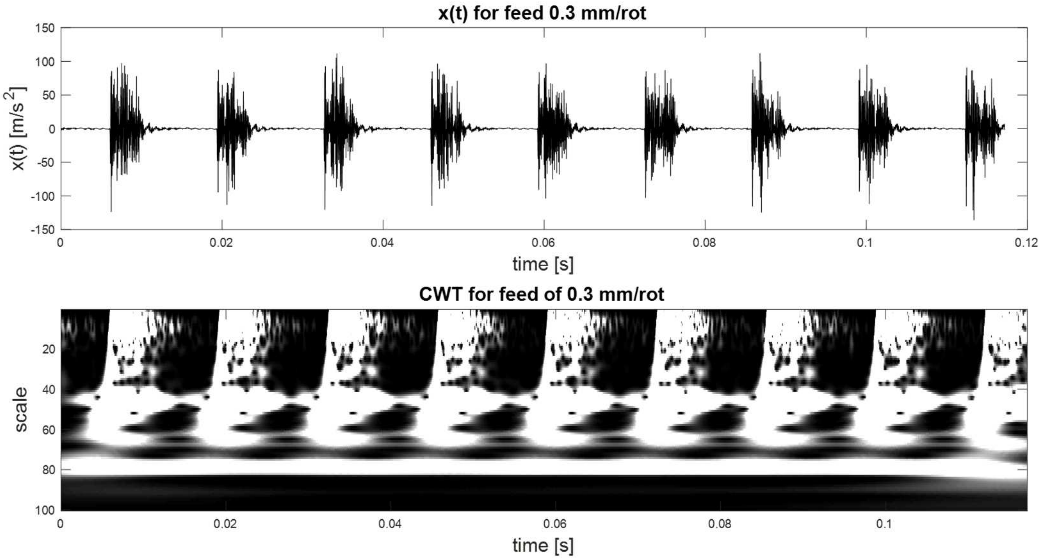

Figure 5. Vibration signal in the time domain and CWT for milling process with 1 wiper insert and feed of 0.3 mm/rot.

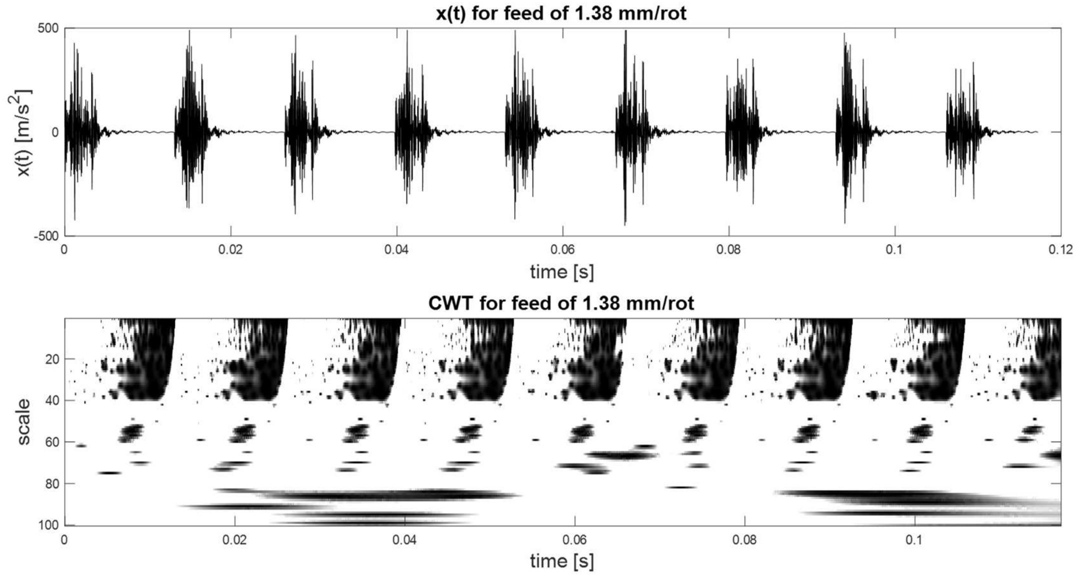

Figure 6. Vibration signal in the time domain and CWT for milling process with 1 wiper insert and feed of 1.38 mm/rot.

Figures 7 and 8 illustrate the vibration signals in the time domain and CWT for the end milling process with 2 wiper inserts. In this condition, the signals show two consecutive pulses because of the cutting process caused by 2 wiper inserts. It is interesting to note that transient component amplitude has low vibratory energy (about 100 m/s^2) when compared to the amplitude of the pulses for the situation of 1 wiper insert (about 400 m/s^2). Furthermore, the transient vibration components for the case of 1 wiper insert excite a wide frequency band (scale of 1 until 42) and for the situation with 2 wiper inserts the impulsive forces in the milling process produce acceleration vibration transient components with a narrow frequency band (scale of 18 until 30).

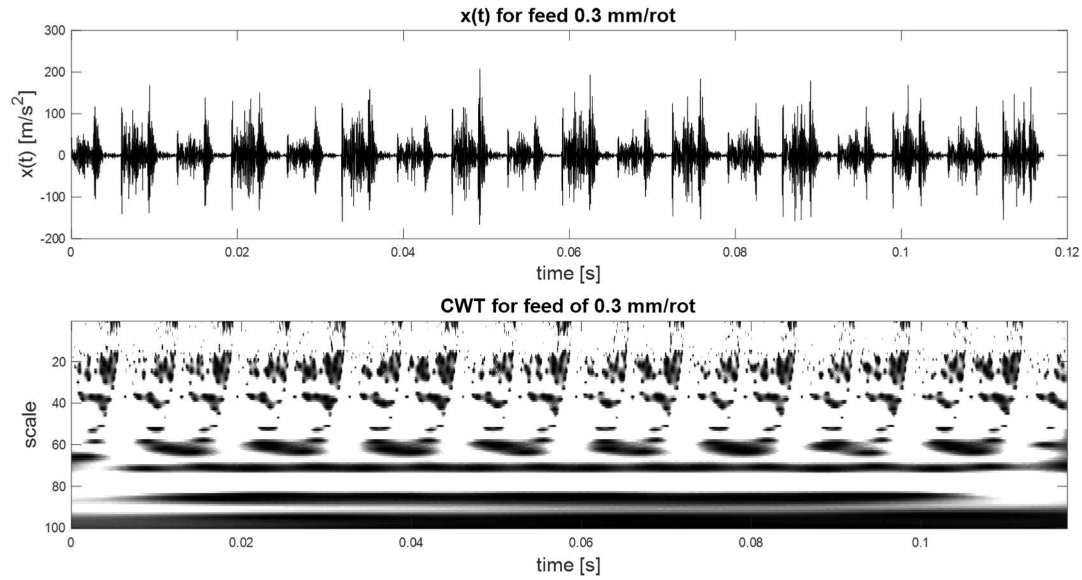

Figure 7. Vibration signal in the time domain and CWT for milling process with 2 wiper inserts and feed of 0.3 mm/rot.

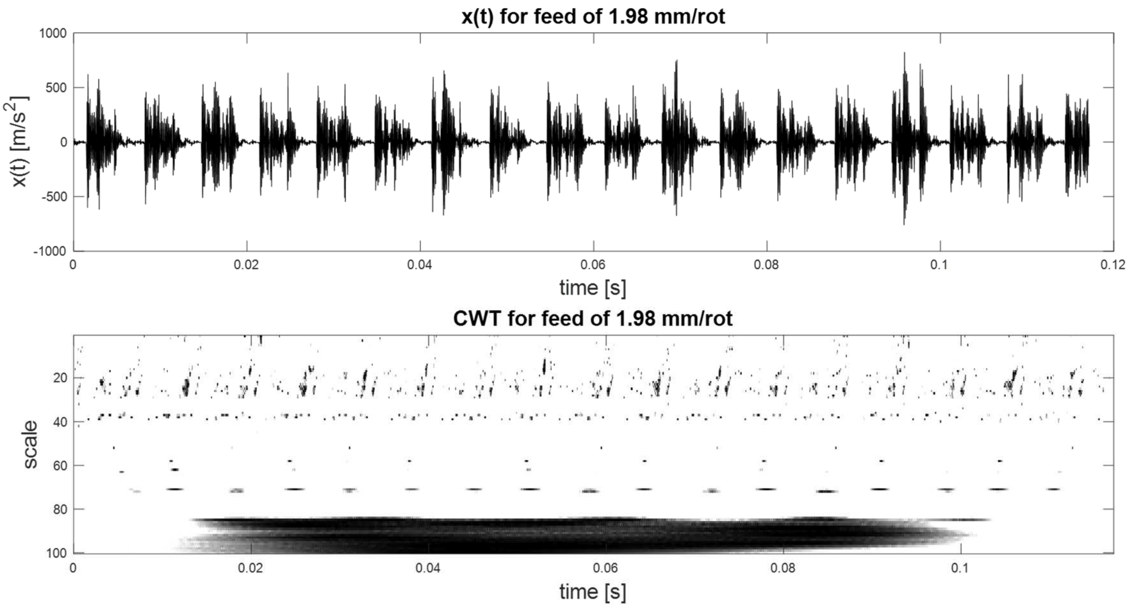

Figure 8. Vibration signal in the time domain and CWT for milling process with 2 wiper inserts and feed of 1.98 mm/rot.

After the measuring and processing of the vibration signals for the conditions of 1 and 2 wiper inserts, the RMS value and CWT were compared with the parameters R_a and R_q have obtained in the end milling tests for each feed condition. By analyzing the behavior of the RMS value and CWT with respect to the feed values used in each experiment, and, the parameters R_a and R_q for each feed, it was observed that the graphics of R_q and CWT are similar. Indeed, Figs. 9 and 10 illustrate a similar tendency if the R_q parameter is compared with the CWT of vibration signals by changing the feed of the tool used in the tests.

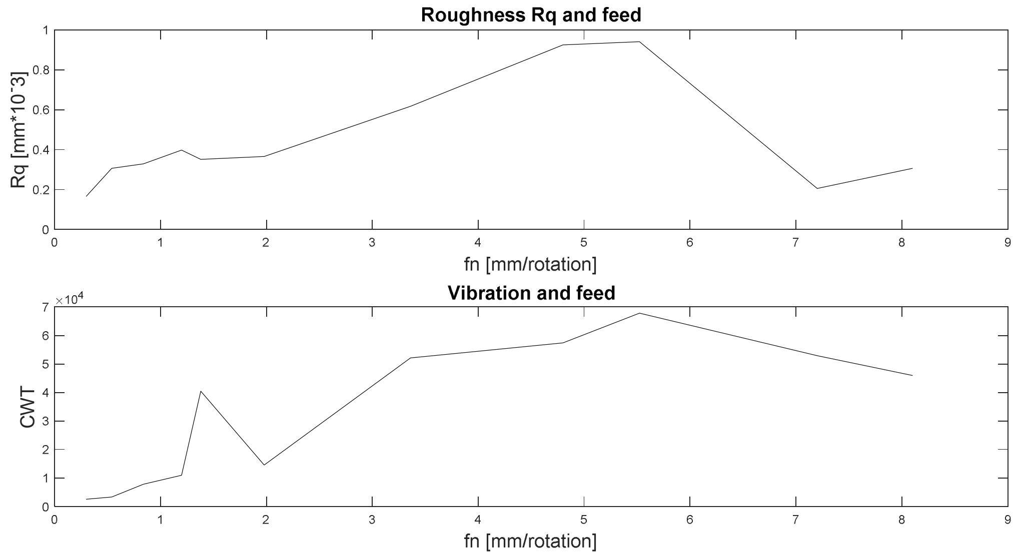

Figure 9. Roughness R_q, CWT of the vibration signal and feed for the condition of 1 wiper insert.

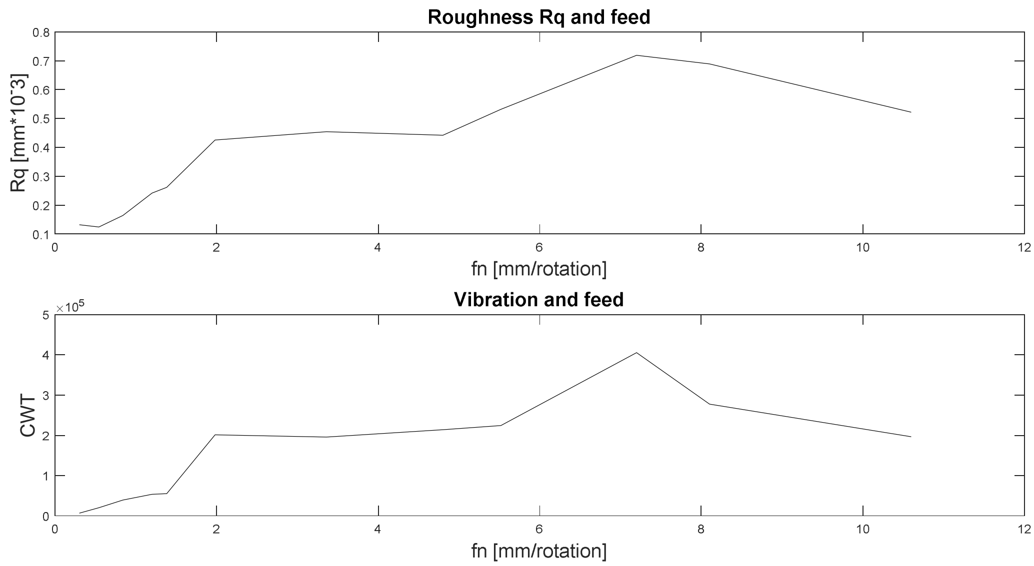

Figure 10. Roughness R_q, CWT of the vibration signal and feed for the condition of 2 wiper inserts.

For the test condition with 1 wiper insert shown in Fig. 8, the end milling process by using a feed of 5.52 mm/rotation produced the worse workpiece surface finishing (Rq equals to 0,940 µm). In the same way, for the tool feed of 5.52 mm/rotation, the vibration measured in the end milling process was also higher by generating a machined workpiece with low surface quality. This same tendency has been also observed in the end milling experiments carried out with 2 wiper inserts, as illustrated in Fig. 10.

By the comparison of the results of present paper with Zahaf and Benghersallah (2021), it was observed that the specimen surface Ra parameter the mechanical vibration measured during the end milling process increased with the cutting tool feed. In the work of Zahaf and Benghersallah (2021), it was not highlighted the vibration signals processing tools used in the analysis. In this work, it was applied, as the conventional techniques of the signal processing (RMS level) as the time-frequency analysis (Continuous Wavelet Transform) which allowed the vibration transient components generated by the milling process was extracted in the analysis process. Another contribution of this work was the comparison between the Ra and Rq parameters measured in the machined specimen surface and the mechanical vibration produced in the end milling process. Indeed, it was concluded that the Rq parameter had a better correlation with the mechanical vibration measured in the end milling. In this way, in the piece surface quality off-line estimation process using the mechanical vibration, the Rq parameter could be a better choice when compared the Ra parameter.

6. CONCLUSIONS

In this work, it was studied the correlation between the mechanical vibration generated in the end milling process and the machined workpiece surface quality. In order to quantify the surface finishing level, it was measured the Ra and Rq parameters of the machined specimens after the machining process. Moreover, it was used in the experiments tools with 1 (one) wiper insert and 2 (two) wipers insert in order to improve the workpiece surface finishing. Since the mechanical vibration generated during the end milling process have transient components with amplitude modulation, it was applied the Root Mean Square (RMS) and the Continuous Wavelet Transform (CWT) as signal processing tools. By changing the tool feed, the objective was to analyze the behavior of the machined workpieces roughness, as well as, the RMS value and CWT of acceleration vibration signals with the respect to the tool feed.

By the analysis of the graphics of the RMS, CWT, Ra and Rq with respect to the feed, it was observed that Rq parameter and the CWT from vibration signals had a similar tendency, from a visual point a view. The parameter Ra and the RMS value have displayed a different behavior with respect to the cutting tool feed. In this way, it is possible to predict the workpiece surface quality (Rq parameter) for the end milling process studied in this work using only the CWT of vibration signal measured during the machining. For this purpose, another possibility is to apply an Artificial Neural Network in order to estimate the workpiece surface finishing by using the CWT from vibration signal as the input parameters.

7. ACKNOWLEDGEMENTS

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