Effects of Tool State on the Output Parameters of Front Milling Using Discrete Wavelet Transform

B. S. Sória, M. R. Policena, A. J. de Souza

Abstract**—**The state of the cutting tool is an important factor to consider during machining to achieve a good surface quality. The vibration generated during material cutting can also directly affect the surface quality and life of the cutting tool. In this work, the effect of mechanical broken failure (MBF) on carbide insert tools during face milling of AISI 304 stainless steel was evaluated using three levels of feed rate and two spindle speeds for each tool condition: three carbide inserts have perfect geometry and three other carbide inserts have MBF. The axial and radial depths remained constant. The cutting forces were determined through a sensory system that consists of a piezoelectric dynamometer and data acquisition system. Discrete Wavelet Transform was used to separate the static part of the signals of force and vibration. The roughness of the machined surface was analyzed for each machining condition. The MBF of the tool increased the intensity and force of vibration and worsened the roughness factors.

Keywords**—**Face Milling, Stainless Steel, Tool Condition Monitoring, Discrete Wavelet Transform.

I. Introduction

STAINLESS steel milling is a subject matter of considerable interest in the industry because it is a material widely used to manufacture parts. This material is characterized by high oxidation resistance and good mechanical resistance. However, austenitic stainless-steel poses considerable difficulty during machining because it undergoes plastic deformation and has lower thermal conductivity than carbon steel [1]. The wear on stainless steel milling tools has been investigated by many researchers [2-5].

The monitoring of machining process signals is important for the detection of premature tool failure or poor surface quality. Different types of machining process signals are used in machining research [6]. The use of machining force signal is widely used in research to characterize the process [7-9].

II. Discrete Wavelet Transform

Discrete wavelet transform (DWT) is used to detect failure and wear in cutting tools through the analysis of signal strength or the identification of some instability in the process with time [10-12].

The authors used the DWT to detect chatter vibration, which indicates instability in the process that can cause violent vibration, directly affecting the integrity, tool life, and surface quality and compromising the productivity of machining [13-15].

The DWT uses the multiresolution analysis method developed by Stephane Mallat and Yves Meyer [16]. After several mathematical processes, each signal level is divided into approximations (A) and details (D). The filtering process is illustrated in Fig. 1. Thereby, approximations have a high scale factor but have low-frequency components, whereas details have a low scale factor but have high-frequency components. The process resembles the high-pass and low-pass filters. For each level or step, the force signal captured by the sensor in the process is filtered by frequency. In the next level, the previous approximation signal is filtered successively on other levels of approximation and detail up to the desired frequency signal.

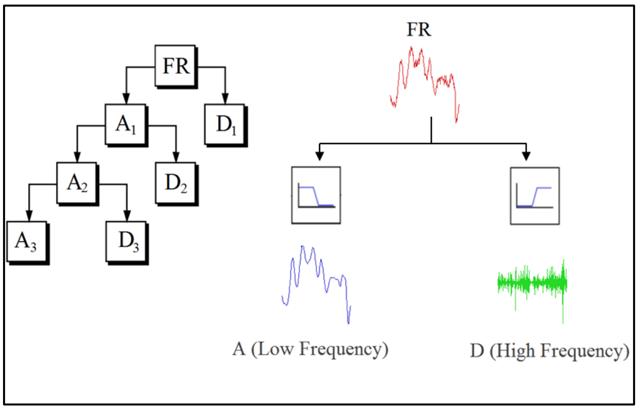

Fig.1 Wavelet multiresolution process

III. Experimental Procedure

TABLE. I

The front milling characteristics are presented in Table I

Workpiece	AISI 304 stainless steel; 100 mm x 90 mm x 5 mm
Tool	Coated Carbide (PVD (Al,Ti)N) Diameter 20 mm with 3 inserts
Depth of cut	0,5 mm
Tooth feed rate	0.04–0.07–0.10 mm/rev
Spindle Speed	477 and 716 rpm

To assess the influence of the tool condition on the output parameters of the process, an end mill with diameter of 20 mm and three TiAlN + Al_2O_3 PVD-coated carbide inserts with tip radius of 0.8 mm were used. Thus, six different inserts were used: three in each tool life condition. First, three new inserts (without wear or failure) and three other inserts with mechanical broken failure (MBF) were used. The difference between each insert is denoted by the area (A) measured under a microscope. Fig. 2 characterizes the state of carbide inserts with MBF. Visual analysis was also made through images taken by the Dino-Lite AM413ZT USB digital microscope with a resolution of 1,024 × 768 and a magnification of ×50.

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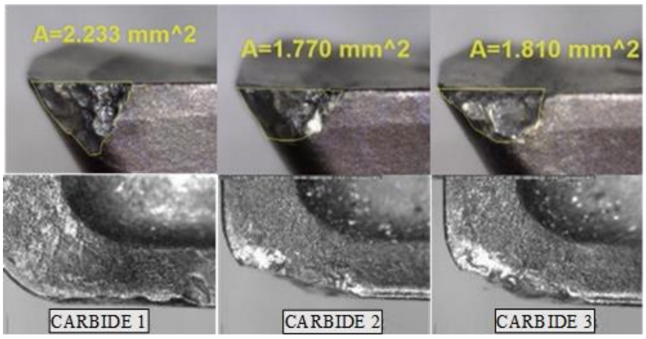

Fig.2 Measured mechanical broken failure

During machining, a CNC ROMI Discovery 308 machining center with a maximum power of 5.5 kW and a maximum spindle speed of 4,000 rpm was used. On the machining center table, a set composed of AISI 304 stainless steel specimens was established. The experiments were performed on rectangular sheets (100 mm × 90 mm × 6 mm) properly mounted on a Kistler model 9129AA piezoelectric platform, which is capable of measuring forces in the *x*, *y*, and *z* axes. An acquisition rate of 2 kHz was used. The signal was sent by cable to a Kistler 5070A signal conditioner. The data acquisition board used was a Measurement Computing model PCIM-DAS1602/16 with 16-bit resolution. Fig. 3 shows the experimental system used during face milling.

Each specimen was subjected to six machining passes. The machining conditions are shown in Table II. For all conditions, the axial depth of cut was set and kept at 0.5 mm and the pass was done with the radial depth equal to the milling cutter diameter (i.e., 20 mm). Machining was done without cutting fluids (i.e., dry machining).

TABLE II
MACHINING PARAMETERS SETS

Cutting conditions	Tooth Feed rate [mm/rev]	Spindle Speed [rpm]
1	0,04	480
2	0,07	480
3	0,10	480
4	0,04	720
5	0,07	720
6	0,10	720

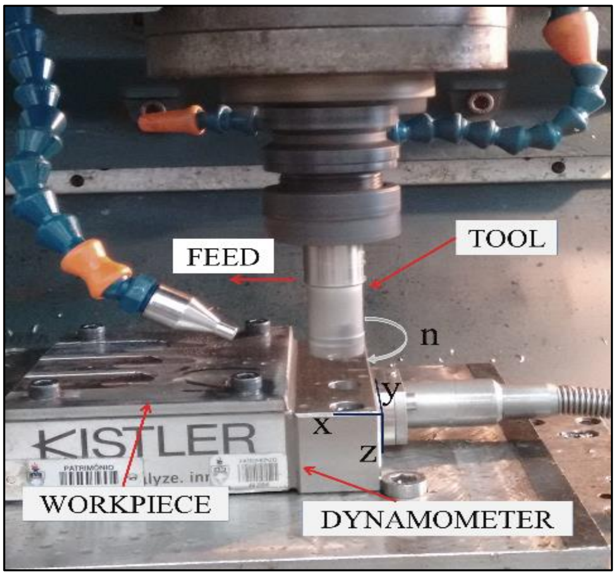

Fig.3 Experimental system used

DWT was used to analyze the signals of force and vibration for each condition. In doing so, we extracted the resultant force (F_R) from the vector sum of the three orthogonal components of machining force (Fx, Fy, Fz). The resultant force was calculated using Eq. (1):

$$F_R = \sqrt{(F_x)^2 + (F_y)^2 + (F_z)^2} \qquad (1)$$

The Daubechies wavelet with six vanishing moments (db6) with three levels, which presented a better match of the signals, was used. Fig. 4 shows the multiresolution process of F_R with three levels. The approximation A3 has the smallest filtered frequency of the original signal with large amplitude. By contrast, the detail D1 shows the signal with high frequency and low amplitude.

Thereby, similar to the output parameter, the RMS value of the third approximation (A3) was calculated to characterize the machining force and the first level of detail (D1) was calculated to characterize the vibration. For the calculation, a stable interval (center zone of pass) of F_R was considered for 10,000 points at a spindle speed of 480 rpm and 15,000 points at a spindle speed of 720 rpm. This procedure is intended to consider only the process, thereby disregarding the force and vibration as the input and output of the tool on the workpiece at the beginning and end of the machining pass.

After machining of the samples, the roughness of each machined surface per pass was measured to assess the influence of the input parameters on this output parameter. This was accomplished using a Mitutoyo SJ-201P portable roughness tester, with a sampling length (le) of 0.8 mm and an evaluation length of 4 mm. The roughness was characterized by the following output parameters: average roughness (Ra) and total roughness (Rt). Ra represents the arithmetic average of the absolute values of the profile height derivations from the mean line of measure. This information can characterize the medium roughness profile of the material removal process. Meanwhile, Rt represents the distance between the highest asperity (peak or summit) and the lowest valley. These two parameters can be used to complement each other to characterize the machined surface.

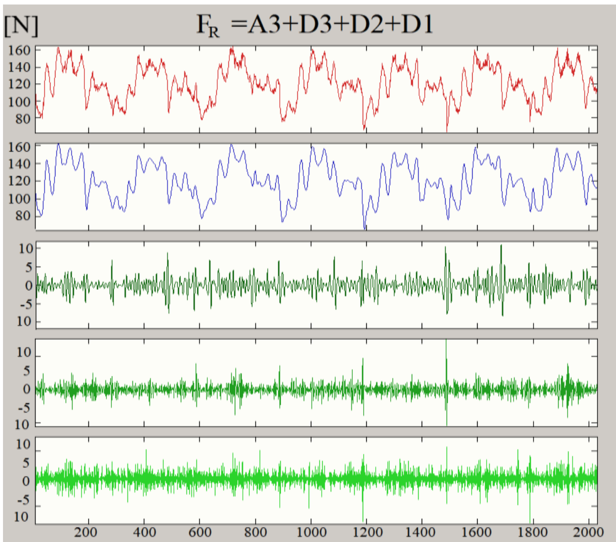

Fig.4. Multiresolution process of resultant force

IV. Static Force—Approximation 3

The last level of approximation (A3) represents the oscillations with low-frequency and high-amplitude signal. Therefore, A3 can be used to analyze the strength of the signal intensity because it represents the filtered signal without the high frequencies. The calculated RMS values of the third approximation in Newton are shown in Fig. 5.

This level of approximation showed that the tool without damage (new) exhibited a lower magnitude of force than the MBF tool. This indicates that chip removal occurs easily during machining. The sharp edge reduces the amplitude of the force.

In the MBF, the fracture of the cutting edge altered the geometry, causing the increase in the magnitude of force during cutting. The analysis of the results indicated that the increase in the tooth feed rate during milling causes the proportional increase in machining force, which can be attributed to the modification of the cross-sectional area with high chip thickness. Under the two spindle speed conditions, the strength slightly increases with the increase in machining rotation.

V. Vibration—Detail 1

Vibration is related to the variation of the oscillation speed of a particle around the equilibrium position over time. According to Newton's second law, the force may be related to the acceleration. In the DWT process, the first level of detail (D1) can be related to the highest frequency and vibration. Fig. 6 shows the D1 RMS value calculated for each cutting condition.

The results show that the influence of vibration (D1) was affected by the rotation of the spindle of the machining center. For the rotation speed of 480 rpm, the cutting tool with new geometry presented slightly higher vibration levels. However, there was a slight variation. For the higher cutting speed, the overall vibration level increased slightly, with visible influence of the feed increment. When the tooth feed rate is increased, the vibration increases.

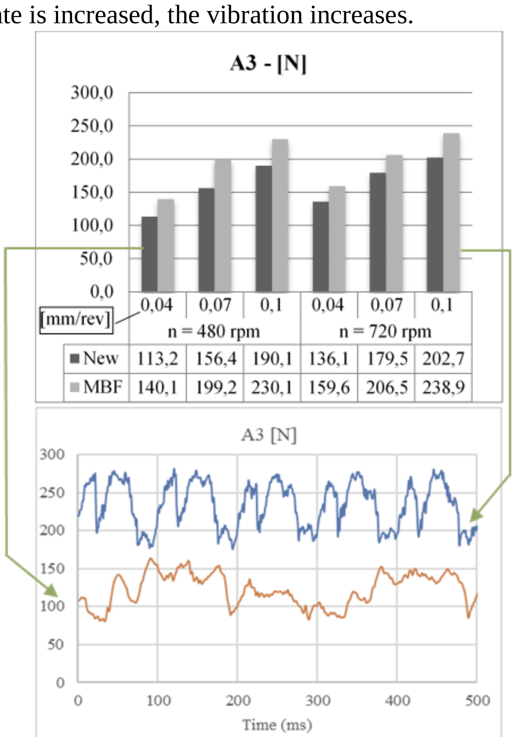

Fig.5. Approximation 3 for each cutting condition

Of all the conditions tested in the experiment, the one with the highest levels of D1, reaching approximately 2.9 N of variation, was the condition of greater advance and higher cutting speed with MBF. The two conditions with higher and lower vibration are shown in Fig. 6 on the same scale of variation.

The two conditions shown in Fig. 6 are, in the first graph of D1, the new cutting tool, with the rotation speed of 480 rpm and tooth feed rate of 0.04 mm/rev. Meanwhile, the second graph of D1 shows the variation of vibration for the MBF condition, with the rotation speed of 720 rpm and tooth feed rate of 0.1 mm/rev.

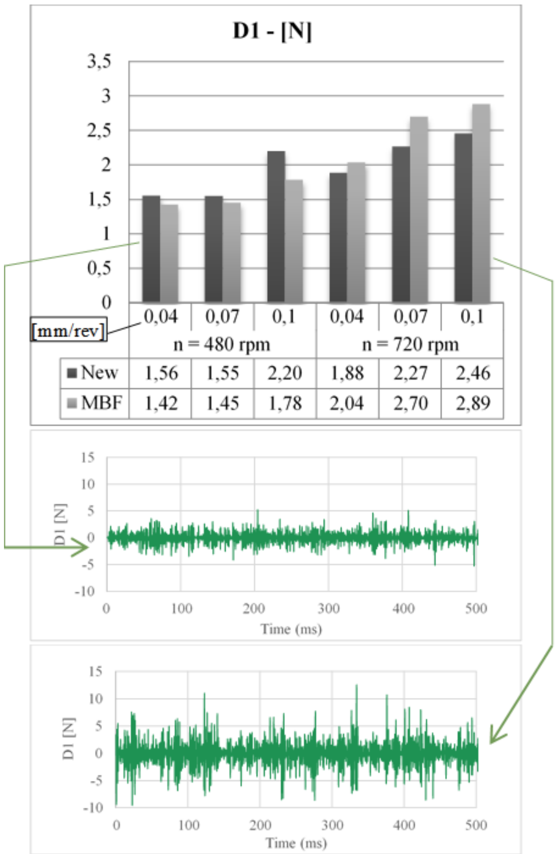

Fig.6. Detail 1 for each cutting condition

VI. Roughness

Surface quality is an important output parameter of the machining process that characterizes the material. The vibration generated in the process can have a direct influence on the quality of the work. Fig. 7 shows the results obtained by measuring the roughness of each machined surface per pass.

Notably, the final roughness of the MBF tool changed for almost all machining conditions, once the cutting edge has an irregular geometry between each insert. The increased tooth feed rate tends to increase the Ra and Rt roughness values in most conditions, which are affected by the increase in peaks and valleys, resulting from the greater spacing in the direction of cutting between each tooth during rotation of the cutter.

As shown in Fig. 7, the increase in cutting speed during the process improved both of the roughness parameters measured for the condition of the new tool. As for the tool with MBF, the increase in the rotation speed in some cases worsened the parameters of medium roughness Ra. This may be related to poor chip formation due to an altered and imprecise geometry. Austenitic stainless steel has a certain plasticity with localized hardening and may, with the formation of the chip, have affected the machined surface, which is unevenly detached or scratched during the process.

Regarding the Rt parameter, the discrepancy between different cutting geometry conditions is visible. Given that Rt is a parameter related to the amplitude of the roughness profile, the poor formation of the chip may have caused higher peaks and valleys because of surface fastening and/or scratching by the chip itself, thus causing this amplitude.

(a)

(b)

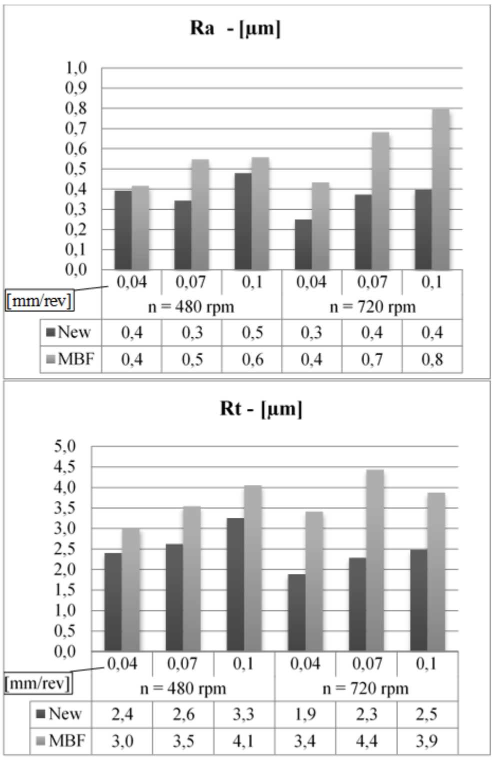

Fig.7 Roughness: (a) average roughness (Ra) and (b) total roughness (Rt)

VII. Conclusion

On the basis of the performed tests and analyses, we can conclude that the tool condition affects both the amplitude of the force of vibration during the process and the roughness of each machined surface per pass. The tooth feed rate increased proportionally with the strength and vibration and, generally, worsened the surface quality. The increase in spindle speed had no evident influence on the static force, with a slight increase in the vibration process and a slight worsening in Ra and Rt roughness for low feeds values (Fz = 0.04 and 0.07 mm/rev).

The DWT can be used in the study of machining for specific purposes, in which one looks for a certain effect of a phenomenon denoting the signals captured with specific frequencies (i.e., high and low frequencies) of performance, depending on what is intended to be evaluated.

Therefore, the MBF presented irregularities between the cutting edges of the carbide inserts, causing difficulty during cutting of the material and influencing the strength of the static part of the signals of force and vibration, which is reflected by the surface quality.

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References

[1] J.L. Endrino, G.S. Fox-Rabinovich, C. Gey, “Hard AlTiN, AlCrN PVD coatings for machining of austenitic stainless steel”, Surface & Coatings Technology 200 (2006) 6840–6845.

[2] W.Y.H. Liewa, X. Ding, “Wear progression of carbide tool in low-speed end milling of stainless steel”, Wear 265 (2008) 155–166.

[3] J. Gu, G. Barber, S. Tung, R.-J. Gu, “Tool life and wear mechanism of uncoated and coated milling tools”, Wear 225 (1999) 273–284.

[4] M. Nouari, A. Molinari, “Experimental verification of a diffusion tool wear model using a 42CrMo4 steel with an uncoated cemented tungsten carbide at various cutting speeds”, Wear 259 (2005) 1151–1159.

[5] J. Gu, G. Barber, S. Tung, R.-J. Gu, “Tool life and wear mechanism of uncoated and coated milling tools”, Wear 225 (1999) 273–284.

[6] R. Teti, K. Jemielniak, G. O’Donnellc, D. Dornfeld, “Advanced monitoring of machining operations” CIRP Annals - Manufacturing Technology 59 (2010) 717–739

[7] Zhu, K., & Zhang, Y. (2019)., “A generic tool wear model and its application to force modeling and wear monitoring in high speed milling”. Mechanical Systems and Signal Processing.

[8] Gajrani, K. K., Suvin, P. S., Kailas, S. V., & Sankar, M. R., “Hard machining performance of indigenously developed green cutting fluid using flood cooling and minimum quantity cutting fluid.” Journal of Cleaner Production. (2019).

[9] Wan, M., Li, S. E., Yuan, H., & Zhang, W. H., “Cutting force modelling in machining of fiber-reinforced polymer matrix composites (PMCs): A review”. Composites Part A: Applied Science and Manufacturing. (2019).

[10] B. Y. Lee, Y. S. Tarng, “Milling cutter breakage detection by the discrete wavelet transform”, Mechatronics 9 (1999) 255-234.

[11] F. Klocke, M. Reuber, H. Kratz, “Application of a wavelet-based signal analysis for evaluating the tool state in cutting operations”, Industrial Electronics Society, IECON 2000, in: Twenty-sixth Annual Conference of the IEEE, vol. 3, 22–28 October 2000, pp. 1967–1972.

[12] Y. Choi, R. Narayanaswami, A. Chandra, “Tool wear monitoring in ramp cuts in end milling using the wavelet transform”, International Journal of Advanced Manufacturing Technology 23 (2004) 419–428.

[13] Samik Dutta, Surjya K. Pal, Ranjan Sen, “Progressive tool flank wear monitoring by applying discrete wavelet transform on turned surface images”, Measurement 77 (2016) 388–401

[14] B.S. Berger, I. Minis, J. Harley, M. Rokni, M. Papadopoulos, “Wavelet based cutting state identification”, Journal of Sound and Vibration 213 (5) (1998) 813–827.

[15] S. Tangjitsitcharoen, “Analysis of Chatter in Ball End Milling by Wavelet Transform”, Journal of Intelligent Manufacturing. Vol:6, No:11 (2012).

[16] S.G. Mallat, “Theory for multiresolution signal decomposition: The wavelet representation”, IEEE Transactions on Pattern Analysis and Machine Intelligence,11(7), (1989), 674-693.

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