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MACHINE TOOL

Influence of machining cycle of horizontal milling on the quality of cutting force measurement for the cutting tool wear monitoring

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Abstract The cutting tools are today used a lot by industry and they are expensive, so it was interesting to optimize their use, by developing a predictive method of their wear, particularly, the flank wear V_b. For this task, the flank tool wear was measured in off-line using a binocular microscope, whereas, the cutting forces are recorded by means of a dynamometer (Kistler 9255B). The acquired signatures are analyzed during the milling operation throughout the tool life. In this paper, we are interested in the extraction of the appropriate indicators which characterize the tool wear by temporal and frequential analyses of the cutting force signals; and highlighting the influence of the clamp holes and the machining cycle to the quality of the measurements.

Keywords Flank wear Cutting forces · Milling · Signal processing · Monitoring

List of symbols

a	depth of cut (mm)
C_w	the edge force constant (N/mm^2)
F_a	axial force (N)
F_r	radial force (N)
F_{RR}	resultant force (N)
K_s	specific cutting pressure of workpiece material (N/mm^2)
S_t	feed rate per tooth (mm/tooth)
V_b	the flank wear width (mm)
K_t	the crater wear depth (mm)
V_f	feed speed (m/min)
V_c	cutting speed (m/min)
S_s	spindle speed (rpm)
R_1, R_2	force ratio constant

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1 Introduction

Milling is one of the main methods in the manufacturing. Therefore, the detection of tool wear is essential to improve manufacturing quality and to increase productivity.

A successful on-line monitoring system for machining operations has the potential to reduce cost, to guarantee consistency of product quality, to improve productivity, and to provide a safer environment for the operator [1, 2].

Wear of the cutting tool in milling is a complicated process that requires a reliable technique for monitoring and control of the cutter performance.

In most approaches, proposed for the tool wear monitoring area, several parameters can be measured, such as forces, vibrations, and acoustic emission, which are directly correlated with tool wear. Furthermore, these parameters are measured on-line during the machining process [3, 4].

Several studies have focused their effort on the detection of tool breakage. The effect of tool breakage is usually revealed through an abrupt change in the processed measurements showing a value which is in excess of a threshold value.

Tansel et al. [5] used acoustic emission (AE) signal to detect the tool breakage. We can see in Fig. 1a the AE signal corresponding to the fresh new cutting tool and in

Fig. 1b the AE signal where a significant impulse is produced at the moment when the tool was broken.

In another case, Romero-Troncoso René de Jesus et al. [6] exploited the current driver monitoring to examine the tool failure (Fig. 2).

The cutting force signal is considered to be the most suitable signal for tool failure detection in milling operations because the cutting force signal can offer a clear feature for the detection of tool failure/wear.

Different models of the wear laws have been established, Taylor was the first researcher who proposed in 1907 a mathematical model relating the effective cutting duration (lifetime) of the tool to the cutting parameters. Gilbert (1950) proposed the generalization of Taylor's model, taking into account the tool geometry and the chip. Another mathematical model, developed by Golding (1958–1960), considers the negative curve based on polynomial forms. The complexity of such a model makes it far to be exploitable. Koning-Deperieux (1969) proposed a model which enables a correct representation of the wear law, whose type is exponential and is in agreement with the experimental curves which determine the tool wear. Currently, the simple model of Taylor is sufficiently representative; it is usually used today for all materials of tools [7]. In practice, and also theoretically, the flank wear V_b follows the pattern represented by Fig. 3 and presents three wear phases: (1) Break-in, (2) Normal wear, (3) Severe wear.

Arshinov and Alekseev proposed a model binding the flank wear V_b and the cutting forces as represented by the following equations [8]:

$$F_a = K_s a S_t \sin(\theta) + a C_w V_b \quad (1)$$

$$F_r = R_1 K_s a S_t \sin(\theta) + R_2 a C_w V_b \quad (2)$$

$$F_{RR} = \sqrt{F_a^2 + F_r^2} \quad (3)$$

Figure 4 show that, only the odd harmonics followed the theoretical pattern of wear.

In the present work, we are interested in measuring the cutting forces to predict the state of wear process of milling cutter. For this purpose, we used spectral and temporal analysis.

2 Experimental setup

An experimental setup was carried out on a horizontal high speed milling machine (PCI Meteor 10). The cutting force was measured by a dynamometer (Kistler 9255B) and the measured force was amplified using a charge amplifier (Kistler 5011). The dynamometer was used to measure the cutting forces in three mutually perpendicular directions: *X*-, *Y*- and *Z*-axis. During the milling, the *Z*-axis cutting force component contained little information, but the *X*- and *Y*-axis cutting forces allowed modelling of the process.

The dynamometer was clamped between the workpiece and the table (or pallet), as shown in Fig. 5**.** In this study, we have used cutter milling type RT130408R-31 with diameter of 25 mm and a workpiece material type 40CMD8+S.

The cutting force signal is sampled at frequency of 12 KHz. The milling operations were conducted without

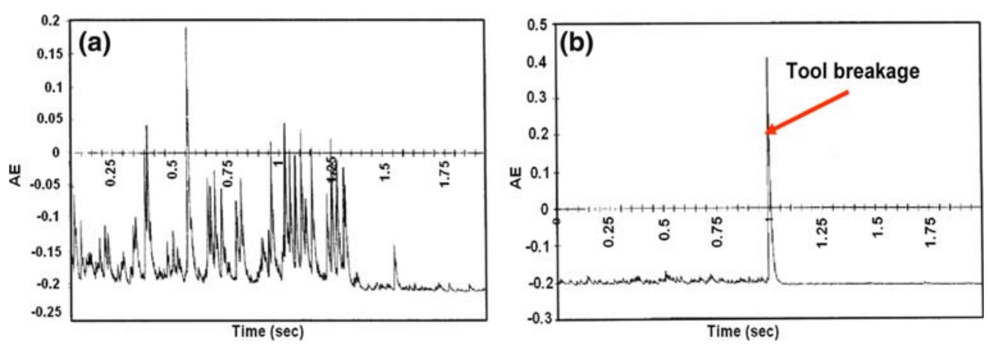


Fig. 1 Detection of tool breakage by AE signal [5]

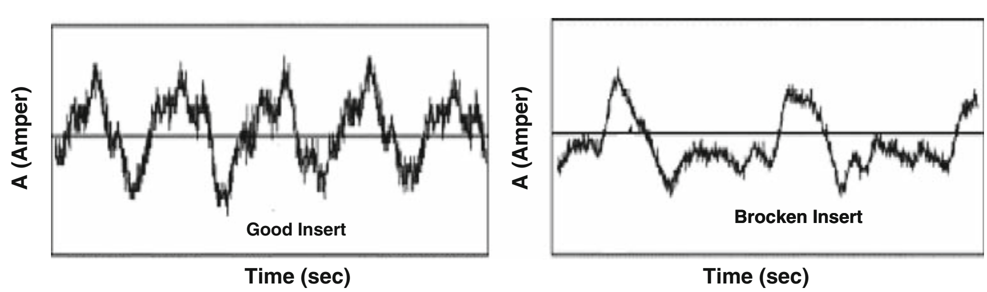


Fig. 2 Detection of tool breakage by current driver [6]

applying any coolant, and all cutting testes were performed at the following cutting conditions (Table 1), with a single insert.

The workpiece is machined on its length with catch of measurement at the beginning of race. Figure 6 illustrates the machining cycle.

3 Results and discussion

In the first stage, to have extra-information about the cutting force, we focus on the “force signal part”; whereas the other parts give information about natural frequencies of the studied system. Windowing the parts of the signal corresponding to the passing of the tool by clamp holes and the tool entry as illustrated in Fig. 7.

Thirty-nine recordings were collected during our experimental test that enabled us to follow the evolution of tool wear during machining time. Figures 8 and 9 show the evolution of flank wear V_b and crater wear K_t during the test.

The off-line measurement of V_b and K_t has been done by means of an electronic microscope which is specially conceived to this kind of tasks.

It can be seen on Fig. 8 that flank wear V_b follows the theoretical pattern and presents the three stages of wear, characterized by a change of slope.

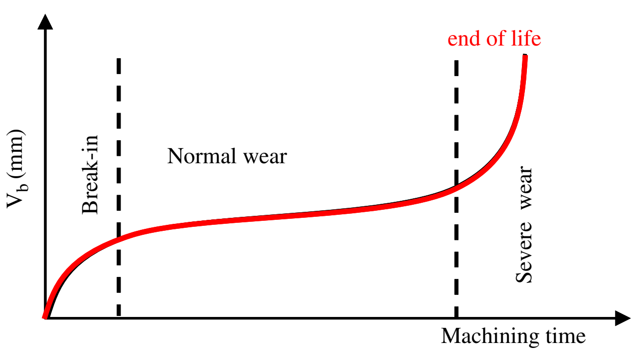


Fig. 3 Theoretical tool wear

3.1 Temporal analysis

The temporal analysis of cutting force signal is presented in the following Figs. 10, 11, 12. Using such statistical parameters as mean, root mean square and variance, it can be observed that the variance values provided more

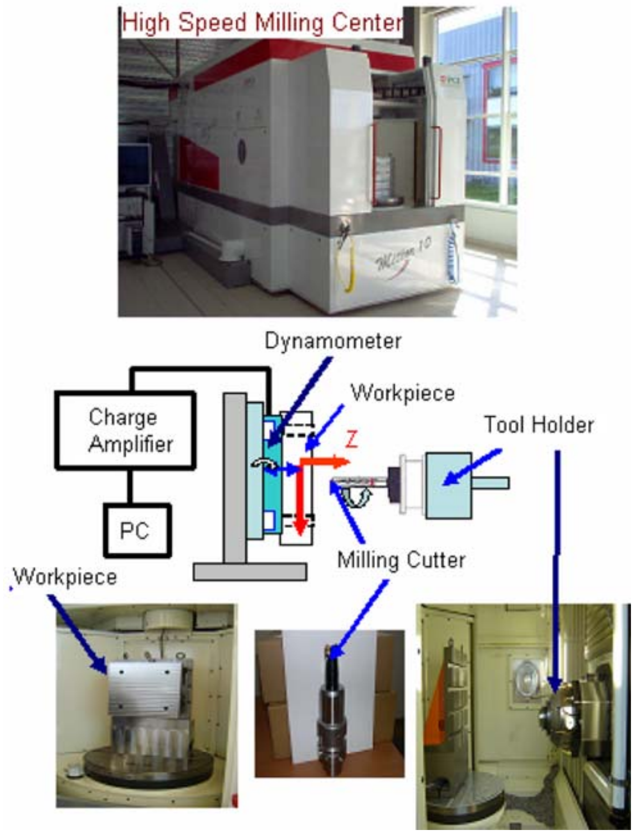
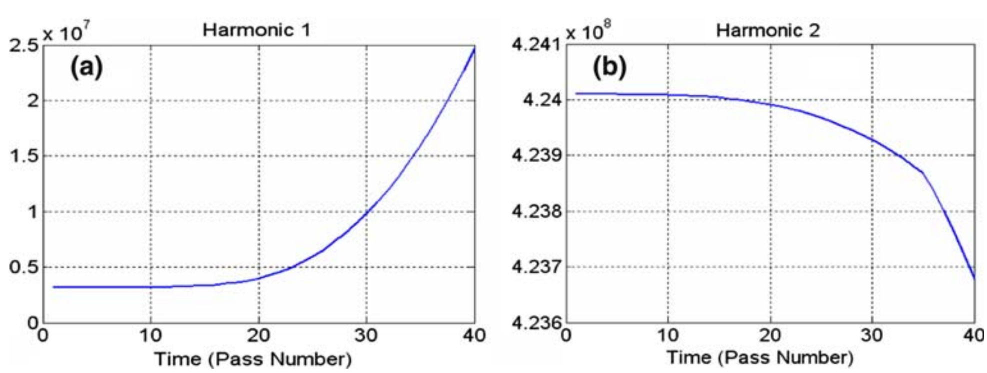


Fig. 5 Illustration of experimental setup

Table 1 Cutting conditions

S_s	V_c	S_t	a
3647 rpm	280 m/min	0.15 mm/tooth	2 mm

Fig. 4 Harmonics evolution. **a** First, **b** second



relevant information on the evolution of the milling cutter wear than the values of other parameters[8, 9].

The variance evolution (Fig. 12) has certain characteristics on the 15th ($t = 300$ s) and the 30th passes ($t = 600$ s) which represent the change of the machining cycle of the workpiece.

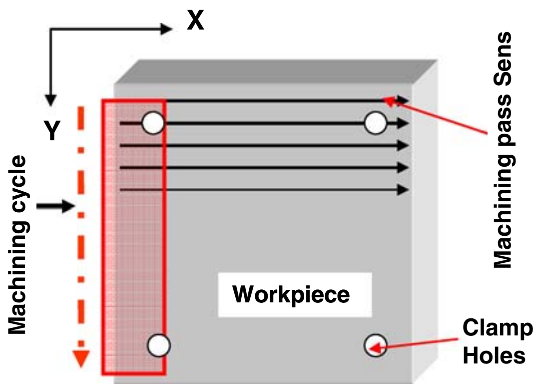


Fig. 6 Machining procedure

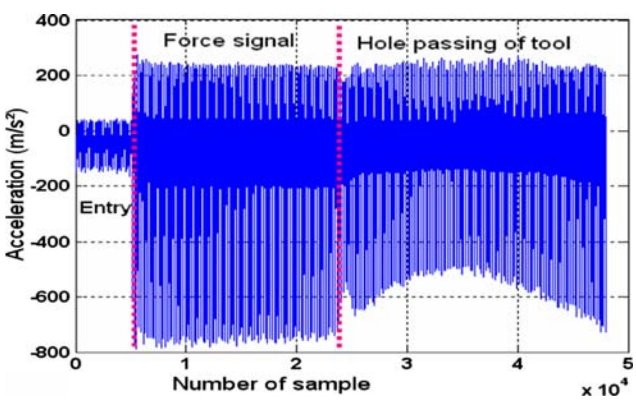


Fig. 7 Cutting force signals acquired according to the *X*-axis

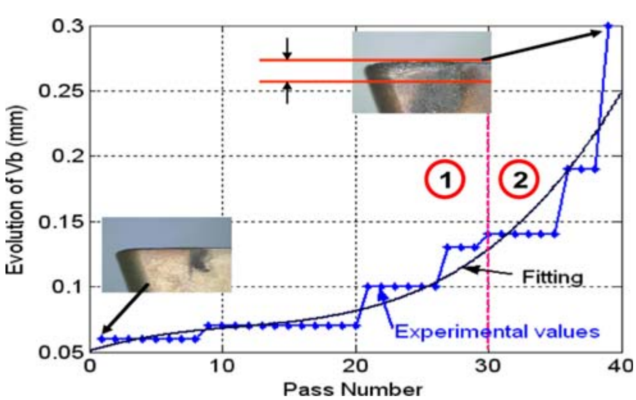


Fig. 8 Evolutions of Flank wear V_b

On the other hand, the transition between the second phase (2) and the third phase (3) is characterized by a peak at the 30th pass ($t = 600$ s).

3.2 Frequential analysis

Our study is limited to the evolution of the first six harmonics corresponding to the three cutting forces (radial,

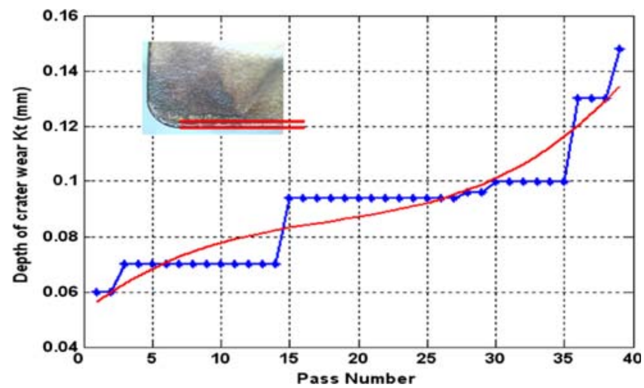


Fig. 9 Evolutions of crater wear K_t

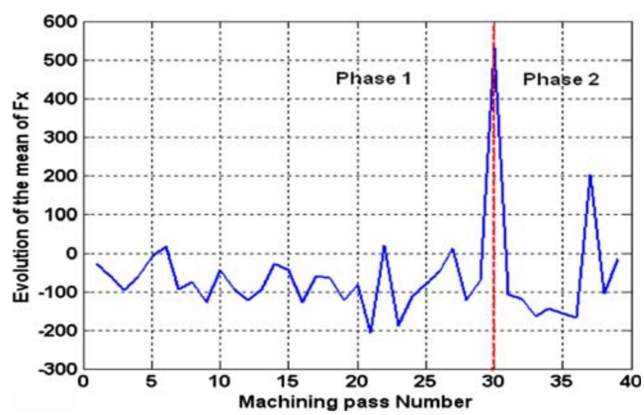


Fig. 10 Evolution of the mean of F_x

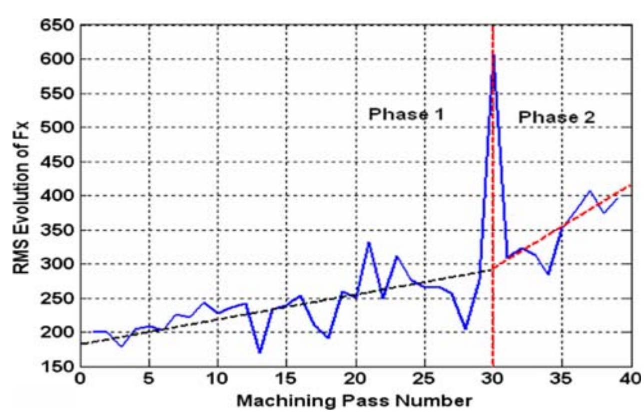


Fig. 11 Evolution of the RMS of F_x

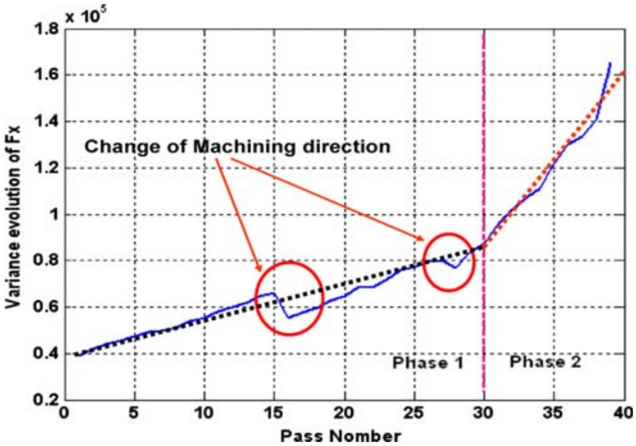


Fig. 12 Evolution of the variance of F_x

axial and resultant) during the machining process, and we observed that the axial force F_x gives best results than the others.

Under a normal cutting condition in the milling process, the dominant frequency components in the spectrum graph are around the tooth passing frequency (TPF), the spindle rotating frequency and their harmonics (Fig. 13). TPF is determined using the following equation:

$$\mathrm{TPF} = (S_s N)/60(\mathrm{Hz}) \tag{4}$$

where S_s is the spindle rotating velocity (rpm), N is the number of teeth of the cutter. In this study TPF = 60.78 Hz

In Fig. 14, it can be seen that the magnitudes of certain cutting harmonics increased significantly with flank wear while other harmonics are unaffected.

Furthermore, we have remarked that the first harmonic of the axial force was the most sensitive to the variation of tool wear (Fig. 15). In contrast to the variance plot, the harmonic's evolution has certain characteristics only on the 15th pass ($t = 300$ s), representing the change of the machining cycle of the workpiece but not on the 30th one ($t = 600$ s). Consequently, we deduce that any change of the cutting conditions or the tool performance leads to changes in the amounts of flank wear and then in the significant cutting forces harmonics [8, 10].

3.3 Influence of machining cycle and the holes on the measurements' quality

The particular shape of the evolution of harmonics 11 to 15 (Fig. 16a) shows the presence of a cyclic phenomenon. This latter simply corresponded to the machining cycle that is confirmed by the skewness graph (Fig. 16b) and the variance evolution of M_x, M_y, and M_z graph (Fig. 17a). Indeed, the dynamometer and the workpiece being positioned vertically, the influence of their weights modifies the

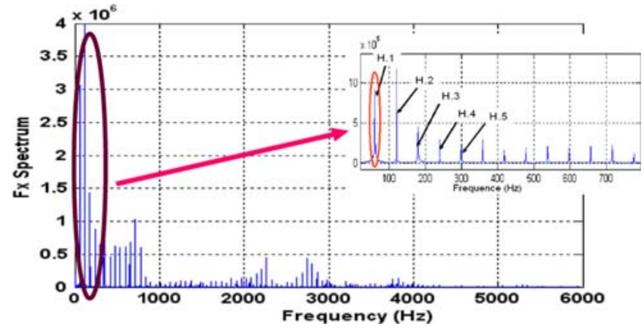


Fig. 13 F_x spectrum

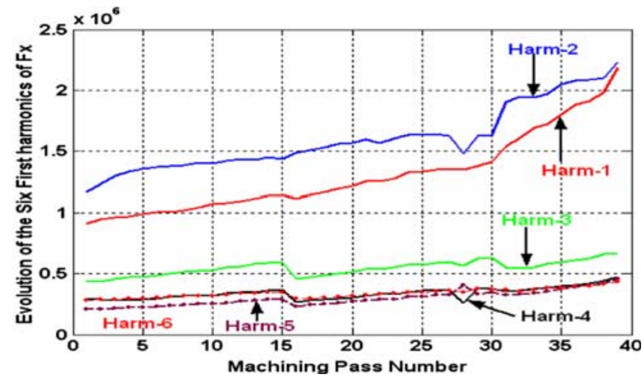


Fig. 14 Evolution of the first six harmonics of F_x

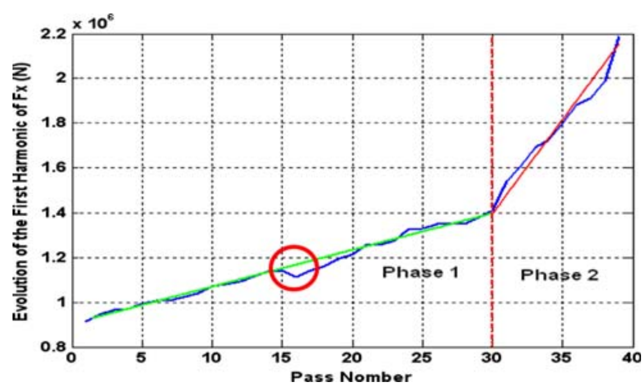


Fig. 15 Evolution of the first harmonics of F_x

measurements when they are carried out at the top or the bottom of the workpiece.

This mechanism can be explained by the following: the distance between the sensors and the gravity centre of the workpiece creates a momentum which increases the efforts on the sensors present at the bottom of the dynamometer and limits the efforts on those placed at the top of it (Fig. 17b).

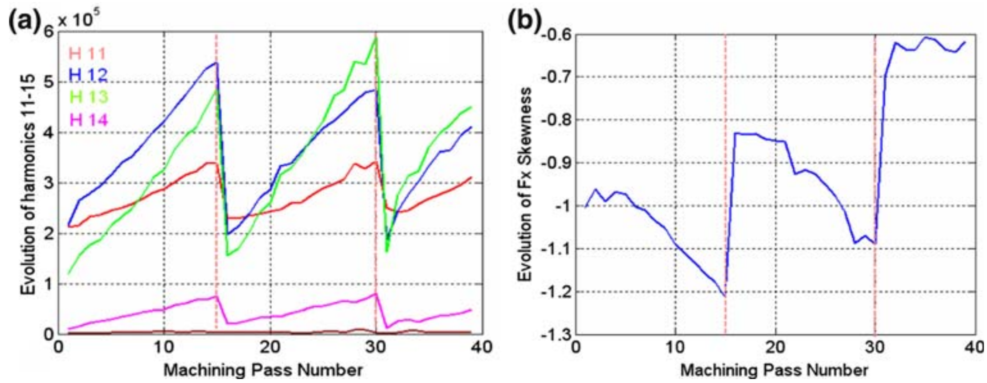


Fig. 16 Evolution of the **a** 11–15 harmonic of F_x, **b** skewness of F_x

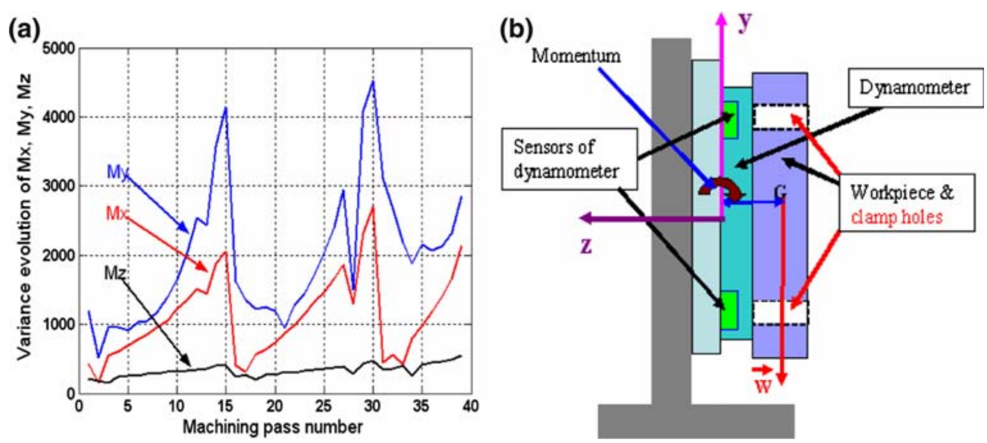


Fig. 17 **a** Variance evolution of M_x, M_y, and M_z. **b** Position of sensors and workpiece

In order to determine the response of the dynamometer we carried out another series of tests. For this reason we proceeded as follows:

- We made a grid on the workpiece (300 × 300 mm) in 25 points to which we realized a drilling.
- The drilling is carried out with new insert at each point.
- The cutting conditions are constant, Just the position of the tool which changes from a test to another.

One of the tables represent the positions of the holes to which drilling is carried out (Table 2) and the second shows the maximum, mean, and RMS values of the cutting force signals according to the X-axis (Table 3)

It is obvious that the effort exerted at the passage of the cutting tool by a hole decreases and is characterized by descending peaks on the evolution graphs of the variance and the first harmonic, for this reason, it would be significant to know the position of these holes and that of the

Table 2 Position of holes (red points)

(0,0) — Y (mm), X (mm)

(30,-30)	(90, -30)	(160, -30)	(230, -30)	(290,-30)
(30, -90)	(90, -90)	(160, -90)	(230, -90)	(290, -90)
(30, -160)	(90,-160)	(160,-160)	(230,-160)	(290,-160)
(30, -230)	(90, -230)	(160,-230)	(230,-230)	(290,-230)
(30,-290)	(90,-290)	(160,-290)	(230,-290)	(290,-290)

Table 3 Values of RMS (red), mean (black), maximum (blue)

194.3041 -51.451 338.562	198.5715 -54.6795 335.022	193.1468 -40.5116 349.243	200.1473 -56.7494 340.942	189.7744 -51.7218 345.764
185.7165 -46.682 316.772	195.6482 -46.3577 339.885	191.5114 -52.1134 319.885	208.1901 -50.9222 356.75	187.6113 -44.1834 330.566
195.8676 -52.4227 321.533	213.1295 -65.6228 336.731	196.149 -47.592 382.813	204.3501 -56.9728 332.947	193.6272 -53.0128 318.848
203.0352 -61.2844 320.496	190.8006 -42.2731 334.106	209.069 -64.8099 318.665	204.3441 -58.9787 317.566	202.9742 -58.4125 319.702
174.6772 -48.8212 281.677	174.2301 -43.6901 284.668	179.6188 -42.9364 292.908	176.0725 -49.7629 276.306	165.8215 -51.7486 310.791

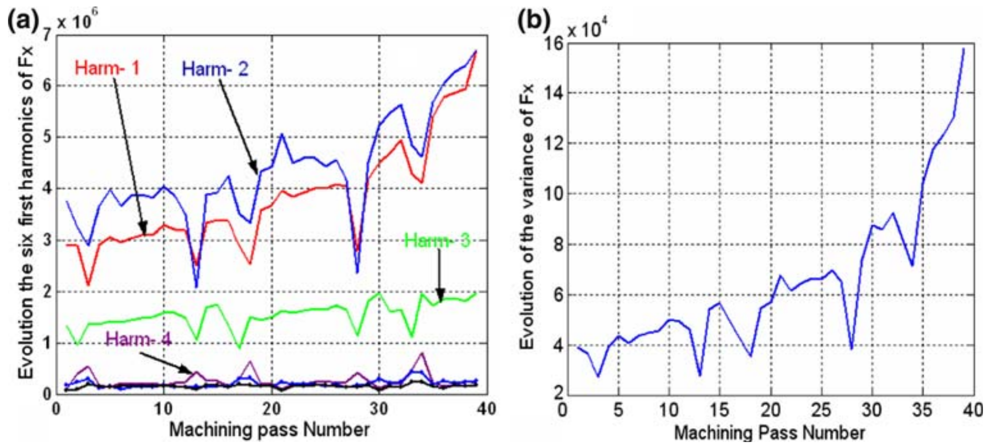


Fig. 18 Evolution of **a** 1–6 harmonic, **b** the variance of F_x

cutting tool to establish a good treatment of the signals (Fig. 18).

4 Conclusions

This study investigated the use of cutting force signal measurements to improve the on-line tool wear detection and monitoring of coated tools in milling process by developing a predictive method of their wear. To achieve this goal, we have used the cutting force analysis to establish a relationship between the wear evolution and the cutting force variations.

Indeed, we observed some values on the evolution curves of the variance and of the first harmonic that show a change in the nature of the efforts. This change becomes more significant and is characterized by an increase in slope of the evolution curve; it is also directly linked to the transition from the normal phase of the cutting tool wear to the severe phase. We stressed on the influence of the machining cycle and the weights of the dynamometer and the workpiece on the quality of measurements. This phenomenon should be well taken into account during any measurement of the cutting forces, specially, in horizontal milling.

An automatic monitoring system of tool wear based on neural networks can be implemented using the cutting condition, the insert type, the values of the variance, and the first harmonic of the cutting force as input vectors to estimate the tool wear.

It was shown that it is possible to repeat this study on a large scale, by dressing a data base of many inserts. This would make it possible to get knowledge about the tool life for each insert type under various cutting conditions and help to avoid the wasting of inserts because their use time would be optimized. The economic impact of this optimized use would be obviously very significant for industries which use a large quantity of this type of tools.

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