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Temporal and frequential analysis of the tools wear evolution

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1. Introduction

For the optimization of machining process, the tools wear study represents one of the major factors to guarantee the quality of manufactured product. One of the serious consequences of a brutal wear is the stop of the cutting process, causing the tool breakage and the premature wear of the mobile bodies of the machine, even the productivity fall. A monitoring system of the machining process, based on reliable techniques such as cutting forces and vibration signals analyses, must be used. In the literature, Jemielniak and Otman [1] employed a statistical algorithm using some indicators, such as root mean square (RMS), skew (SB) and kurtosis (KB) of the acoustic emission (AE) signals for the detection of the cutting tools damage. The results show that the skew and the kurtosis can be better indicators of the tool brutal failure than the RMS values. Jae-seobkwak [2] proposed the discrete wavelet decomposition of cutting force signals for the detection of the tool failure. The analysis shows than the chattering vibration phenomenon occurred just before the tool failure. The proposed method gives better results than the use of the fast Fourier transform (FFT). Cemal cakir and Yahya [3, 4] calculated the exit value to indicate the tool wear with a warning system. The experimental results proved that the variations of the cutting force decrease uniformly when the tool breaks. Xiaozhi and Beizhi [5] proposed to use the wavelet analysis of AE signals. The experiments proved that the standard of the wavelet resolution coefficients can be a good criterion for the monitoring of the tool state. Arnaud [6] developed software allowing the optimization of the cutting conditions, the limitation of the tests' number, and the machining process monitoring.

The approach proposed in this article consists in using numerical and experimental methodology based on the analysis of the cutting force and vibration signals. Any changes in the measured signals (cutting forces, accelerations) are then closely related to the change of the cutting insert state in the turning operation.

2. Cutting tools monitoring and signals processing

The monitoring of the tool state allows maximizing the product and improving its quality. To this end, reliable signal processing techniques is necessary to follow up the machining process. The extraction of useful information built-in in these signals allows the identification of the tool wear through the application of several methods in time or frequency domain. The time domain approach consists in using the statistical analysis by the scalar indicators (RMS, Energy, Power...). In the frequency based analysis, Fourier transform is the most used method. Advanced analysis methods such as wavelet transform can also be used.

2.1. Static and dynamic forces

For each cutting test, the static force (average) value was calculated starting from the taken cutting force, as well as an indication of the variation of the dynamic force. The component of the static force $\widetilde{F}$ was calculated like the average value of the taken data F_i. Consequently, the static variation of the average value was included in the following analysis, and justified by the experimentation process. The static force being known for each cutting operation, the dynamic component of the variable force for each bench mark could be given.

2.2. Scalar indicators

The vibration monitoring in the time domain consists in computing the scalar indicators. These ones associate to a vibratory signal a number or a scalar. The simplest approach of the use of scalar indicators consists of the calculation of RMS. Several other parameters were largely used, such as the energy and the power [7].

Because of mask effects, whose origins are varied, the useful information is drowning in disturbances. Background noise and other machine components pollute the signal and make detection difficult, even impossible. The scalar indicators being limited, several signals denoising methods were proposed to improve their sensitivity.

2.3. Wavelet multiresolution analysis

The wavelet transform is a mathematical transformation which represents a signal $s(t)$ in term of shifted and dilated version of singular function called wavelet mother $\psi(t)$. The family of wavelets has the form [8]:

$$\psi_{a,b}(t)=\frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right). \tag{1}$$

With a and b the scale and the translation parameters, respectively. Noting by $\psi^*(t)$ the conjugate of $\psi(t)$, the continuous wavelet transform (CWT) of the signal $s(t)$ is defined by [8]:

$$CWT(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty}s(t)\psi^*\left(\frac{t-b}{a}\right)dt. \tag{2}$$

The discrete wavelet transform (DWT) is a discretization of the continuous wavelet transform (*CWT*). By replacing a and b by 2^m and $n2^m$, respectively, the above expression becomes [8]:

$$DWT(m,n) = 2^{\frac{-m}{2}} \int_{-\infty}^{+\infty} s(t)\psi^*(2^{-m}t - n)dt\,, \tag{3}$$

where m and n are integers.

A practical version of this transform, called wavelet multiresolution analysis (WMRA), was introduced for the first time by Mallat [9] in 1989, it consists to introduce the signal $s(t)$ in low-pass (L) and high-pass (H) filters. In this level, two vectors will be obtained, cA_1 and cD_1. The elements of the vector cA_1 are called approximation coefficients, they correspond to the low frequencies of the signal, while the elements of the vector cD_1 are called detail coefficients and they correspond to the highest of them. The procedure can be repeated with the elements of the vector cA_1 and successively with each new vector cA_j obtained. The process of decomposition can be repeated n times, with n the number of levels. Fig. 1 represents an example of waterfall decomposition for n = 3 [8].

During the decomposition, the signal $s(t)$ and vectors cA_j undergo a downsampling, this is why the approximation cA_j and detail cD_j coefficients pass through two new reconstruction filters (LR) and (HR). Two vectors result; A_j called approximations and D_j called details, satisfying the relation:

$$\left.\begin{aligned} A_{j-1} &= A_j + D_j\,; \\ s &= A_j + \sum_{i \le j}^{n} D_i\,, \end{aligned}\right\} \tag{4}$$

where i and j are integers.

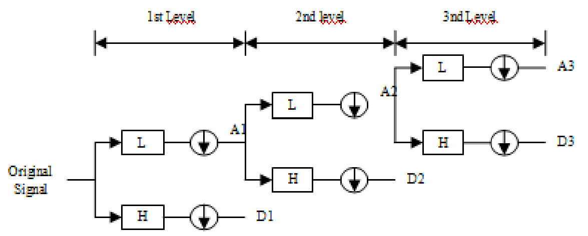


Fig. 1 Waterfall decomposition at three levels

3. Experimental part

3.1. Experimental conditions

The machining operations are ensured by a TOS TRENCIN SN40C type lathe, with spindle power of 6.6 KW. Not coated carbide cutting insert (S40T) of square form is used. The milled steel is of X200Cr12 type (according to AFNOR Z200Cr12), with high chromium content. It has an excellent behavior with wear (high wear resistance). The workpiece is 480 mm long and 62 mm in diameter. The tool holder is of CSBNR2525M12 designation, with active part geometry characterized by the following angles: χ = 75°; α = 6°; γ = -6°; λ = -6° [10]. The machining tests were carried out without lubrication and under the following cutting conditions: feed rate f = 0.12 mm/rev, cutting speeds Vc = 100, 135, 190 m/min, and two depths of cut a_p = 0.5 and 1 mm. A Surftest 301 Mitutoyo type roughness meter was used for roughness measurement (*Ra*, *Rz* and *Rt*). To measure the flank wear, we used an optical microscope of HUND W.AD model (Fig. 2). The insert is placed under the microscope on a cross motion table equipped with two drums with an accuracy of 0.001 mm.

Fig. 2 Photo of the optical microscope HUND W.AD

Fig. 3 Measuring equipment of acceleration and cutting force signals

3.2. Signals acquisition

In this study, the acquisition of the signals generated in machining was carried out using a KISTLER dynamometer model 9257 B, which makes it possible to record the cutting forces in real time according to three principal directions. This device is composed of a platform, signals amplifier, and a PC with DYNOWARE software. Acceleration signals are measured using bi-channel B&K 2035 type analyzer with a standard piezoelectric accelerometer B&K 4384 with sensitivity of 0.99 PC/ms^{-2}. The experimental scheme is illustrated by Fig. 3.

4. Results and discussion

4.1. Evolution of the roughness and the static force according to flank wear

The analysis of the roughness according to the wear shows that the increase in flank wear *VB* involves a degradation of the machined surface quality (where the characterization of the machined surface quality was limited to the criteria of arithmetic mean roughness *Ra*, total *Rt* and average heights of the irregularities *Rz*) (Fig. 4).

In this context, it should be specified on this level that, as long as irregular wear does not exceed the allowable value (*VB* = 0.3 mm), roughness *Ra* evolves very slowly and the surface quality remains acceptable. Beyond this value, roughness undergoes an abrupt increase.

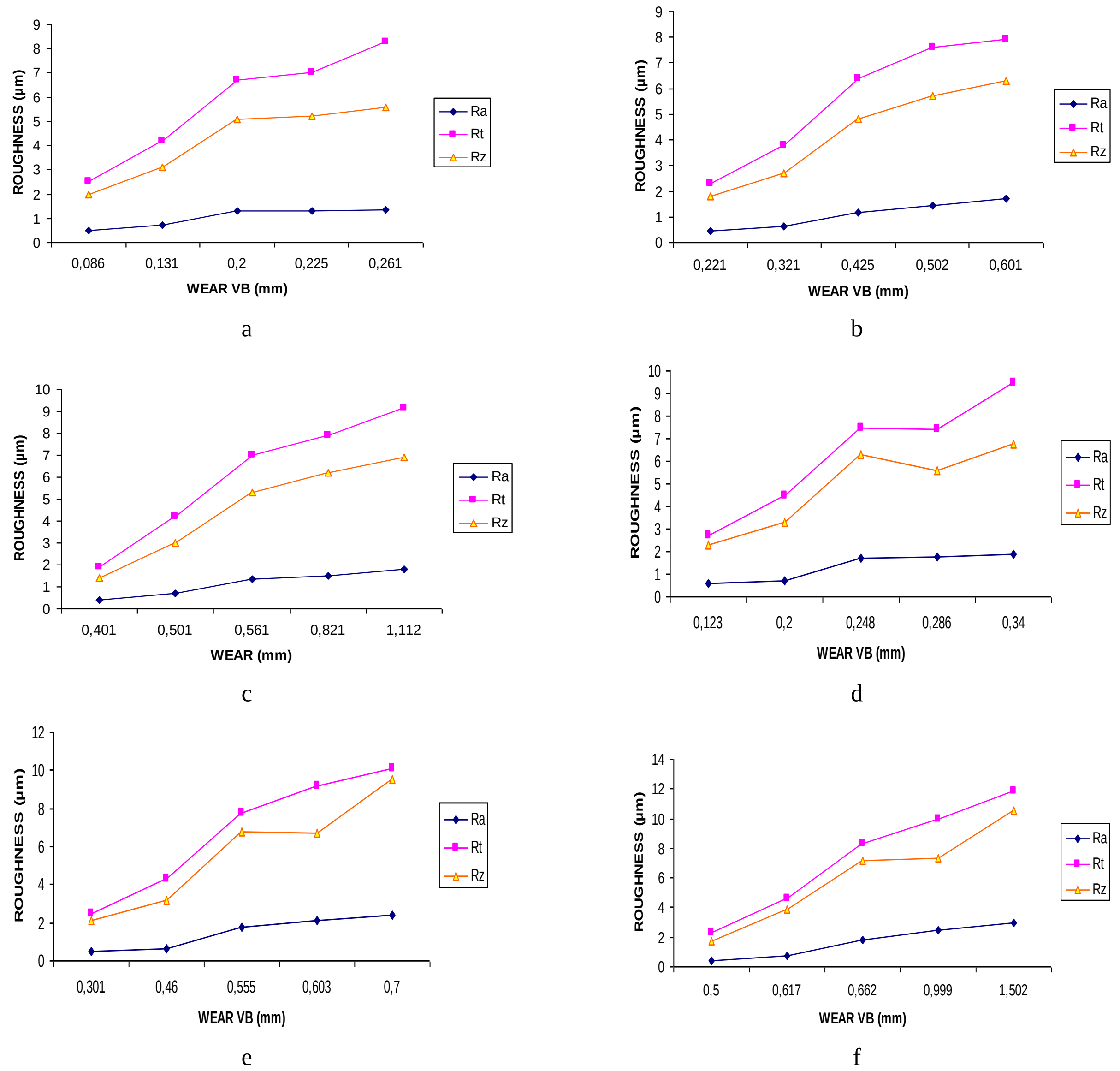


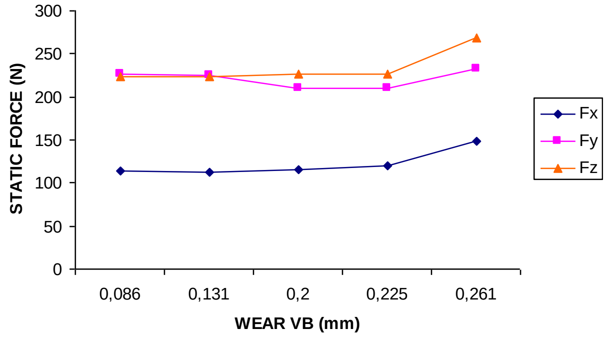
Fig. 4 Evolution of roughness according to flank wear: a) V_c = 100 m/min, a_p = 0.5 mm, f = 0.12 mm/rev; b) V_c = 135 m/min, a_p = 0.5 mm, f = 0.12 mm/rev; c) V_c = 190 m/min, a_p = 0.5 mm, f = 0.12 mm/rev; d) V_c = 100 m/min, a_p = 1 mm, f = 0.12 mm/rev; e) V_c = 135 m/min, a_p = 1 mm, f = 0.12 mm/rev; f) V_c = 90 m/min, a_p = 1 mm, f = 0.12 mm/rev

The three roughnesses present a growth at the cutting time of a high alloy steel. It is noted that for high speed *Vc* = 190 m/min, the degradation of the machined surface is too fast beyond the allowable wear criterion with values of R_t > 11 µm. These results also show that the choice of the allowable wear criterion is well adapted to describe in a suitable way the tool life.

The static force was calculated in all the studied cases. The results presented in Fig. 5 for the three cutting speeds and the two depths of cut, show that the static force increases slightly with flank wear for the first two speeds (100 and 135 m/min). Whereas for speed 190 m/min its variation becomes significant, it passes from 250 N for *VB* = 0.4 mm to 355 N for *VB* > 1 mm.

On the other hand, the increase of depth of cut a_p causes a gradual increase in the static cutting force and flank wear. Depth of cut increases the roughness, but less significant than the cutting speed especially for relatively long machining time.

The micrographs of flank wear for different cutting conditions are presented in Fig. 6. We can also see that the flank wear evolution is regular. The variation of flank wear *VB* according to machining time for three speeds shows that the cutting speed has a significant influence on the wear of the tested cutting material. *VB* wear is considerably high in a cutting speed of 190 m/min compared to those obtained for cutting speeds 100 m/min and 135 m/min. Moreover, the increase of the cutting speed causes a significant decrease in the tool life. During these cutting conditions the machining becomes unstable, it is accompanied by vibration increase, which results in limiting the range of cutting speeds. The increase in depth of cut $a_p = 1$ mm causes wear increase from 0.086 mm to 0.123 mm. We note that the effect of a_p is less important than the cutting speed.



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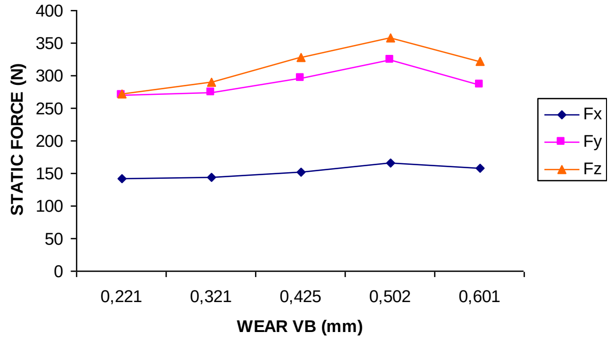

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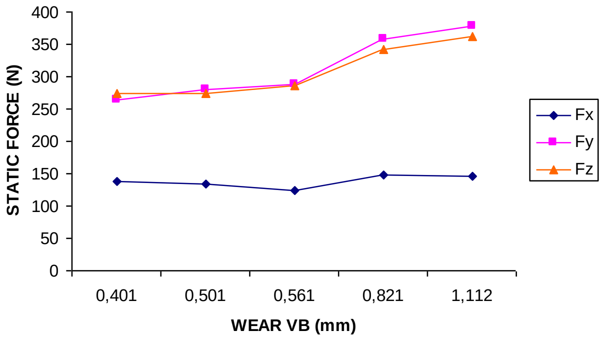

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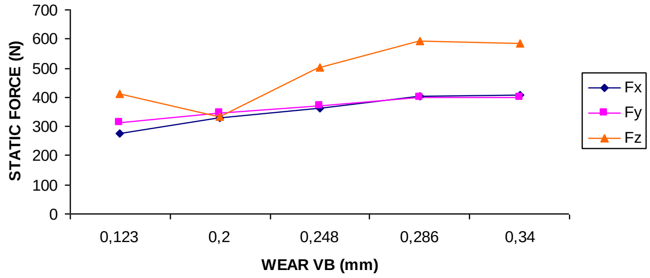

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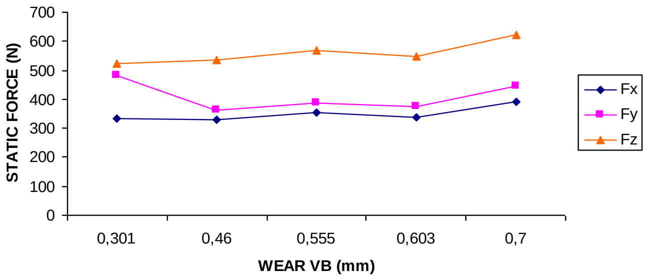

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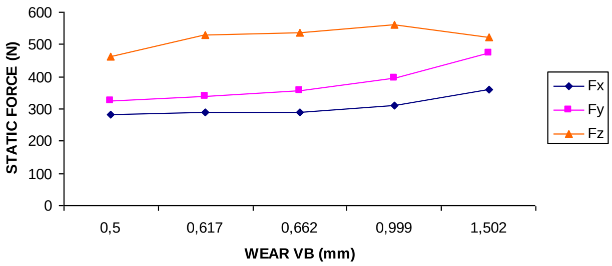


f

Fig. 5 Evolution of the static force according to flank wear: a) $V_c = 100$ m/min, $a_p = 0.5$ mm, $f = 0.12$ mm/rev; b) $V_c = 135$ m/min, $a_p = 0.5$ mm, $f = 0.12$ mm/rev; c) $V_c = 190$ m/min, $a_p = 0.5$ mm , $f = 0.12$ mm/rev; d) $V_c = 100$ m/min, $a_p = 1$ mm, $f = 0.12$ mm/rev; e) $V_c = 135$ m/min, $a_p =$ mm, $f = 0.12$ mm/rev; f) $V_c = 190$ m/min, $a_p = 1$ mm, $f = 0.12$ mm/rev

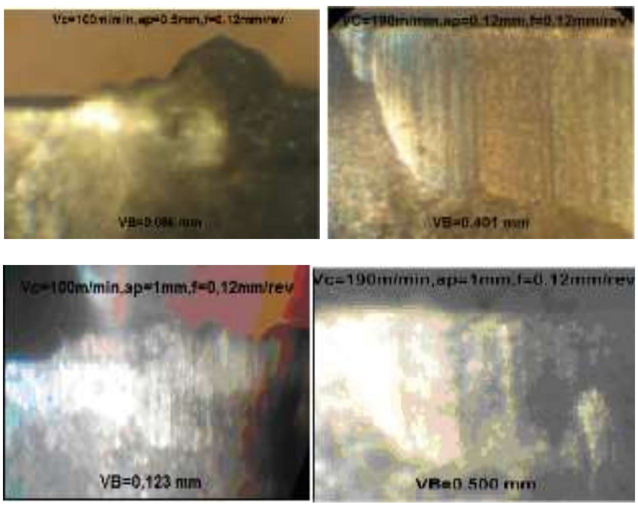
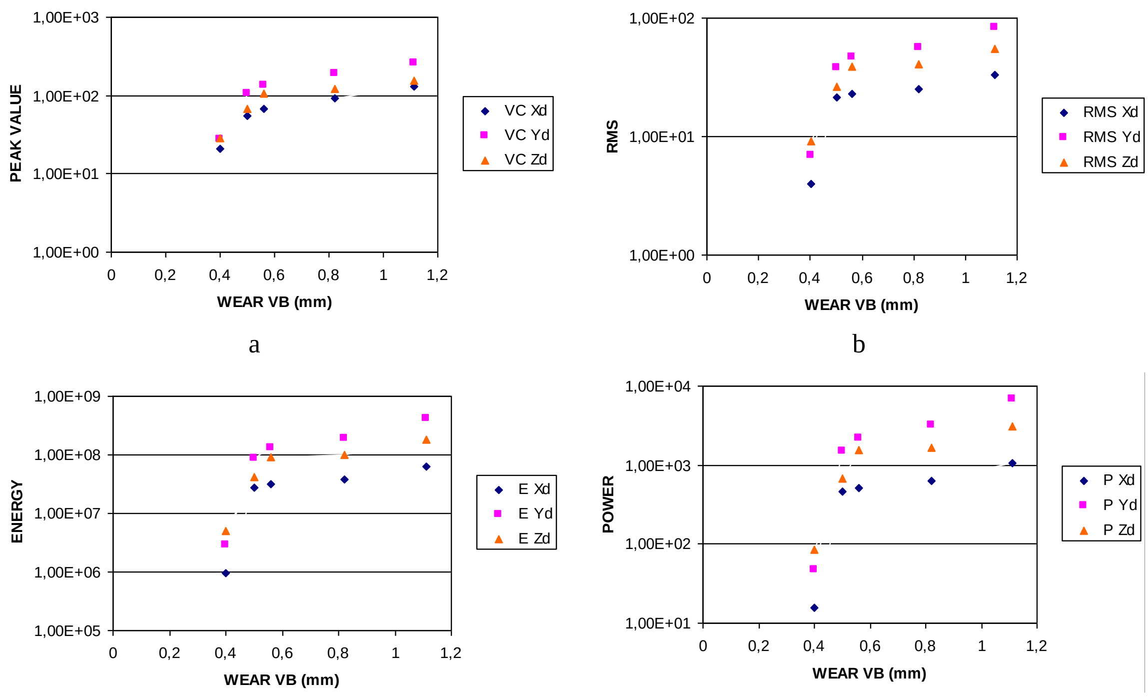


Fig. 6 Micrographs of flank wear for different cutting conditions

4.2. Evolution of the scalar indicators according to flank wear

Fig. 7 represents the semi log of the scalar indicators according to flank wear *VB*. It shows an apparent increase of these indicators for $VB \geq 0.5$ mm.

Beyond this value one notes that this increase becomes progressive, which can be explained by the cutting edge rupture. It is also noted that the scalar indicators of the radial component of the cutting force signals are more important than those of the two other components. Thus, one can conclude that the radial component is most sensitive to the wear that the two other components especially with the increase of the cutting speed.



a b c d

Fig. 7 Semi log of the scalar indicators according to flank wear at V_c =190 m/min; a_p = 0.5 mm; f = 0.12 mm/rev: a) peak value; b) RMS; c) energy; d) power

4.3. Frequential analysis

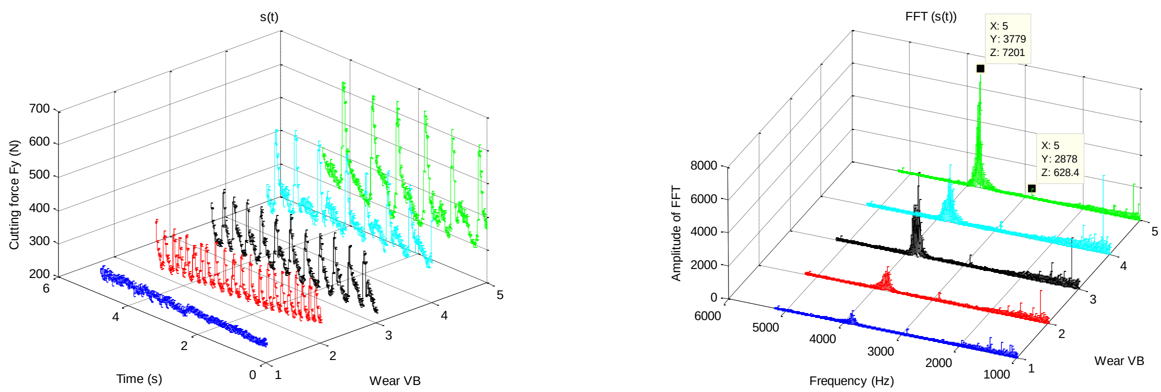
The cutting force signals and spectra analyses in the radial direction, which cover all the tool life since the first test until the fifth test, show (Fig. 8):

- A significant increase in the signals amplitude from a stage to another with the wear increase.

- The radial component of the cutting force reveals a peak of 4000 Hz corresponding to the tool natural frequency.

- Appearance of some low frequency peaks up to 2000 Hz which can be due to the wear phenomenon. The amplitudes of these peaks are very significant compared to the natural frequency amplitude.

- Wear appearance and increase are well shown by the very significant increase of the tool natural frequency amplitude.



a b

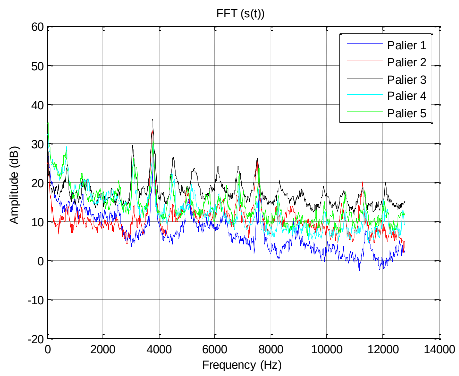
Fig. 8 Signals and spectra of the radial force according to flank wear at V_c = 190 m/min; a_p = 0.5 mm; f = 0.12 mm/rev: a) measured signals; b) spectra

The analysis of acceleration spectra (Fig. 9) shows that:

– For a speed of 190 m/min (Fig. 9, a), wear appears starting from the first stage with a value higher than 0.4 mm. The spectrum level increases to stage 3 (where *VB* is equal to 0.561 mm). One can notes the appearance of a great number of peaks corresponding to the chattering phenomenon which causes the tool nose rupture, therefore a retreat of this last compared to the workpiece (reduction of the depth of cut). This is expressed by a reduction in the acceleration spectra levels in high frequencies.

– Concerning the tangential acceleration (Fig. 9, b), one notes the appearance of peaks corresponding to the tool natural frequencies as for the first stage (very severe machining conditions). An increase of the spectrum level over all the frequency bands with the increase of the cutting speed and wear is also noted. Moreover one notes, on the stage three and five, the appearance of peaks corresponding to the tool nose rupture.

– Principally on the tangential component, one notes the appearance of two natural frequencies; the first related to the tool natural frequency in the axial direction and the second related to the tool torsion mode [11].



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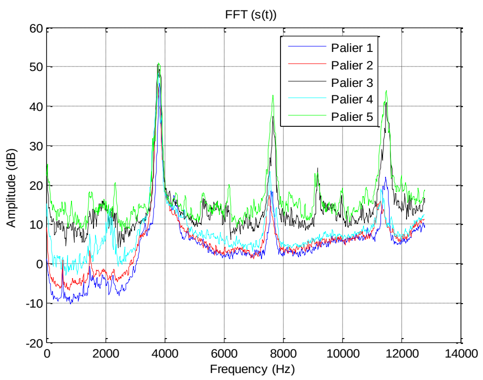


b

Fig. 9 Spectra of accelerations according to flank wear at V_c = 190 m/min; a_p = 0.5 mm; f = 0.12 mm/rev: a) radial acceleration; b) tangential acceleration

4.4. Wavelet analysis

Wavelet Transform is new signal processing method that was applied with great success to the monitoring of the machining process. The wavelet multiresolution analysis (WMRA) was proposed to improve the monitoring of the cutting process by filtering the random noise and other machine components to have only the signatures of the cutting tool variation.

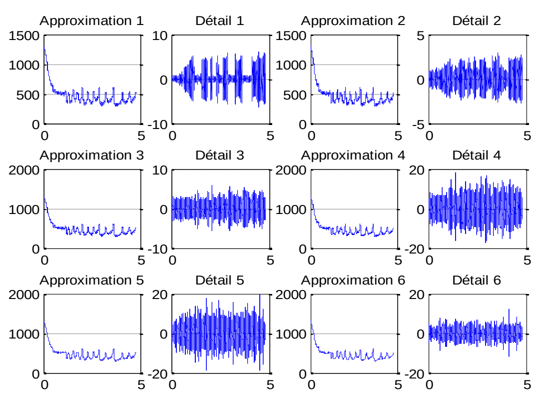
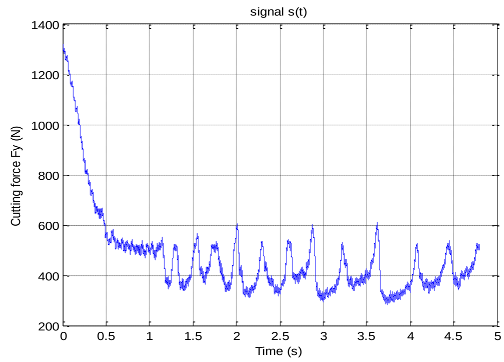


Fig. 10 Various details and approximations resulting from the wavelet multiresolution analysis of the radial force signal at V_c = 190 m/min; a_p = 1 mm; f = 0.12 mm/rev

Fig. 10 represents the various details and approximations resulting from the six level wavelet decomposition of the radial component of the cutting force. The profiles of the measured signals are very disturbed by the severe cutting conditions. The increase of the cutting speed, the thermal and mechanical solicitations become significant and lead to a catastrophic wear that causes the rupture of the cutting edge. The wear evolution leads to the collapse of the cutting tool edge, followed by a reduction in the cutting forces (Fig. 11, a) due to the reduction of the cut depth caused by the retreat of the cutting edge compared to the workpiece.

Note that the wear evolution deserves a particular attention since it affects the surface quality and the dimensional accuracy of the workpiece. To this end the analysis of the wear results shows that the influence of the cutting speed is significant. Indeed its increase involves a clear reduction in the tool-life.



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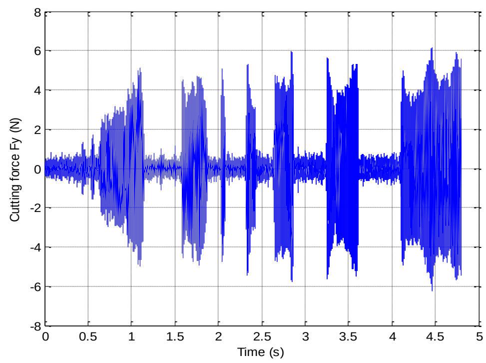

b

Fig. 11 Measured and reconstructed signals of Fy at V_c = 190 m/min; a_p = 1 mm; f = 0.12 mm/rev: a) measured signal; b) reconstructed signal $D1$

The machining during these cutting conditions becomes unstable; it is accompanied by increase in the vibrations. It becomes thereafter almost impossible and lead to limit the band of the cutting speeds. Fig. 11, b shows the reconstructed signal $D1$ that shows the phenomenon of chattering. This one is due to the appearance of certain zones of the machining instability.

4.5. Highlighting the chattering phenomenon

The tangential acceleration is very alarming; it gives information on the existence of impact on the measured or on the reconstructed signals (Fig. 12). Figs.12, a, b show the measured signal (tangential acceleration) and the reconstructed signal, respectively, extracted starting from the detail 3 $D3$ that shows abrupt changes synonymy of an unstable machining over all the period of measurement. According to the reconstructed signal $D3$ envelope one can clearly note a periodicity of $\Delta t = 0.0022$ s corresponding to a frequential component of 480 Hz that appears clearly on the envelope spectrum (Fig. 12, c). In this case the phenomenon of chattering is established over all the machining period.

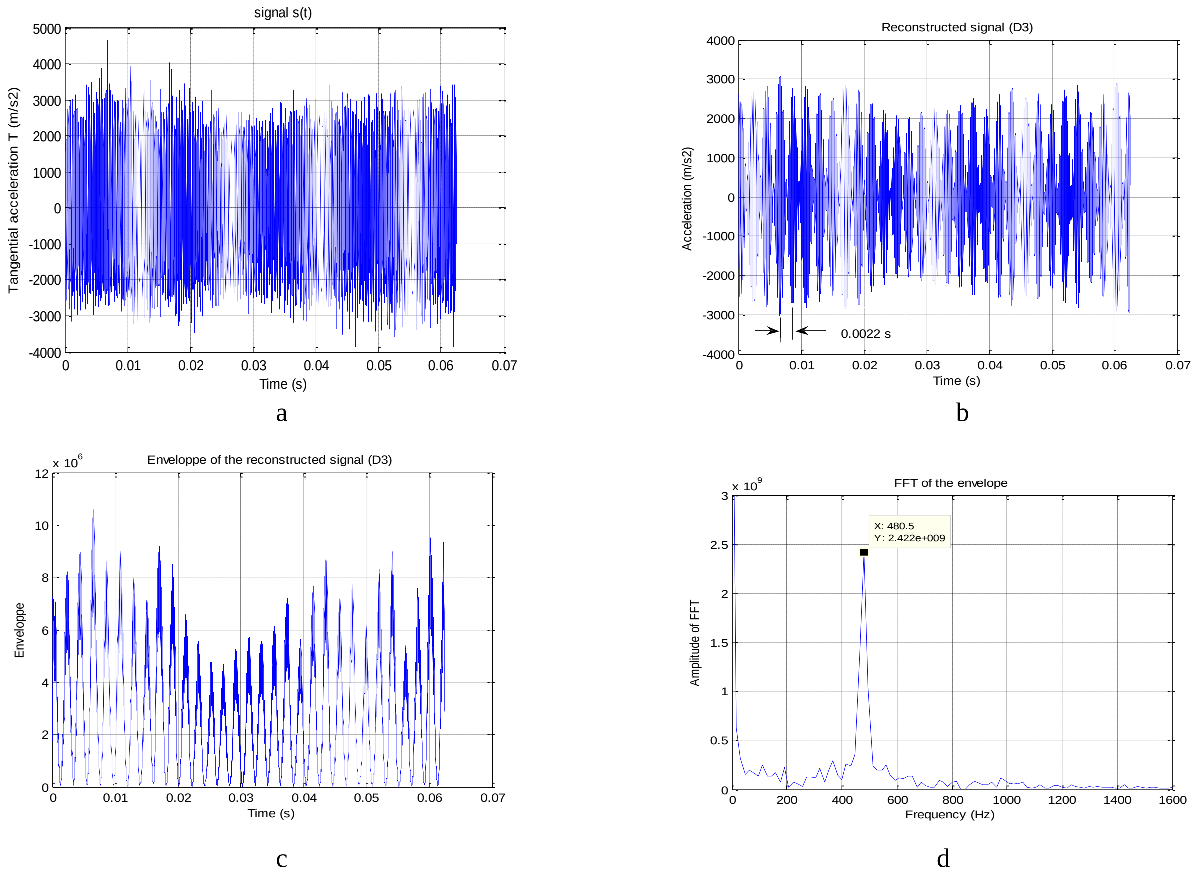

Fig. 12 WMRA of tangential acceleration signal at $V_c = 190$ m/min; $a_p = 1$ mm; $f = 0.12$ mm/rev: a) measured signal; b) reconstructed signal $D3$; c) envelope of the reconstructed signal and d) envelope spectrum of the reconstructed signal $D3$

To highlight the denoising capacity of the wavelet multiresolution analysis, one calculated the kurtosis and the peak value of the original and the reconstructed signals. The kurtosis of the radial acceleration signal increases from 6.1622 to 12.9635 for a wear $VB = 0.401$ mm, while the peak value of the reconstructed signals (radial acceleration) passes from 26.7592 m/s^2 for a flank wear $VB = 0.086$ mm to 109.8105 m/s^2 for $VB = 0.221$ mm and to 346.8968 m/s^2 for $VB = 0.401$ mm. The amplitudes of the radial and tangential acceleration increase with the increase of flank wear.

5. Conclusion

The monitoring of machining process requires the installation of an effective follow-up in particular that the phenomenon of wear is very complex to follow during the various phases of cutting operation. In this context, the approach suggested in this study consists in determining several wear indicators like the vibratory level and the abrupt changes that can detect the brutal damage of the cutting tool. In order to evaluate wear starting from the collected signals, the adopted strategy is based on a statistical and frequency domain analyses, this last allowed the extraction of relevant wear descriptors. Several parameters were studied such as the direct control of the cutting tool and the workpiece by measuring flank wear and roughness, the cutting force and the vibratory response. However, one showed that the scalar indicators (RMS, Power, etc.) of the cutting force signals increase gradually according to flank wear, this is explained by the rupture of the tool nose. One also noted that the radial component of the cutting force is most sensitive to the variation of wear; this result is confirmed by the frequential analysis.

One showed that the spectral analysis of acceleration and cutting force signals is limited to follow the evolution of wear, because the spectra are very disturbed especially at low frequency which is the favorable place of the wear detection. The only manner allowing the follow-up of the wear by the spectral analysis is the variation of the first tool natural frequency amplitudes that increase with the wear increase. The wavelet multiresolution analysis allows clear representation and seems more sufficient for the tools wear follow-up in particular the presence of the phenomenon of chattering. The results showed that the phenomenon of chattering appears for the two cutting speeds (190 and 135 m/min) on the two acceleration components, and for two depth of cut (0.5 and 1 mm). However, for the cutting speed of 100 m/min this phenomenon is missed.

The analysis presented in this work is an attempt to extract the maximum of information necessary to the establishment of an on-line monitoring system of the wear phenomenon. It is essential to supervise considering its importance in the machining process.

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ĮRANKIŲ DILIMO EVOLIUCIJOS LAIKINĖ IR DAŽNINĖ ANALIZĖ

R e z i u m ė

Apdirbimo proceso monitoringas vaidina didelį vaidmenį prognozuojant nepageidaujamus reiškinius, tokius kaip įrankio dilimas ir lūžimai. Šiame straipsnyje pritaikyta efektyvi technika pagrįsta pjovimo jėgos ir virpesių signalų matavimų įvairiomis pjovimo sąlygomis analize. Pasiūlyta metodika pasitelkia tokią signalų apdorojimo techniką, kaip laikinė, dažninė ir banginė analizė. Šio darbo tikslas yra parodyti iš vienos pusės skaliarinių rodiklių jautrumą užpakalinio paviršiaus dilimo pokyčiams ir iš kitos pusės įvertinti užpakalinio paviršiaus įtaką apdirbimo metu sukeltiems signalams. Šiame kontekste dilimo vertinimo rezultatai leidžia nustatyti netikėtus pokyčius, kurie susiję su įrankio apgadinimu.

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TEMPORAL AND FREQUENTIAL ANALYSIS OF THE TOOLS WEAR EVOLUTION

S u m m a r y

The machining process monitoring plays a very significant role in the prevention of non-desired phenomena, such as excessive wear and the tool rupture. In this article, we use effective techniques based on the analysis of cutting force and vibratory signals measured for various cutting conditions. The proposed methodology uses some signal processing techniques, such as temporal, frequential approaches and the wavelet analysis. The objective of this work is to show, on one hand, the sensitivity of the scalar indicators to the flank wear variation, and on the other hand the determination of the influence of flank wear on the signals produced during a machining process. In this context the wear evolution results allow determining the abrupt changes that can detect the cutting tool damage.

Keywords: wear, cutting forces, vibration signatures, scalar indicators, wavelet analysis.

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