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Interrelationships between cutting force and tool wear in chipboard milling

KRZYSZTOF SZWAJKA[1)], JOANNA ZIELIŃSKA-SZWAJKA [1)]
[1)]Faculty of Wood Technology, Warsaw University of Life Sciences – SGGW

Abstract: Wear of a cutting edge in end-milling is a complicated process that requires a reliable technique for in process monitoring and control of the cutter performance. This paper presents an approach to examine the effect of wear variation on the magnitude of the cutting force harmonics. The results were plotted in time and frequency domains. Cutting forces in process milling were measured using highly sensitive dynamometer which was calibrated in static and dynamic ranges. The tool wear was measured in an off-line manner and interrelationships of cutting force harmonics and tool wear magnitude were constructed. Hence a cutter wear monitoring strategy is constructed.

Keywords: milling, chipboard, cutting force, force sensor

INTRODUCTION

In the study of the relationship between the cutting force harmonics and cutting tool flank wear of a cutting edge in end-milling. Bamdyopadhay et al. [1], found that the amplitude of the dynamic components of the cutting signal are continuously decreasing up to the deterioration stage of the tool flank wear. Lee et al. [2], found that the dynamic components are sharply decreasing at the onset of the accelerated wear zone after a earlier increase. While Zhang and coworkers [3], Elbestawi et al. [4], found that the dynamic cutting components are continuously increasing. The production of an industrial product with high accuracy and surface quality requires control of the tool performance. The development of a fully automated machining system is a practical method to sense the amount of tool wear. Such a development would enhance the quality of the product by insuring that surface and geometrical specifications are within tolerance. In addition, there would be decrease in cutting times, and savings in tool changing times. All of which could result in an estimated overall savings of up to 40% [4]. There are two techniques for tool wear sensing: direct and indirect. The direct technique includes measuring the actual wear, using radioactive analyses of the chip. Indirect technique includes measuring of cutting forces, torque, vibration, acoustic emission (stress wave energy), sound, temperature variation of the cutting tool, power or current consumption of spindle or feed motors and roughness of the machined surface [4-7]. In this study, the cutting forces are used as the indicator of the tool flank wear variation. Finally an on-line flank tool wear monitoring system is constructed.

CUTTING FORCE IN PROCESS MILLING

Investigation of milling process from cutting force point of view begins in year 1941 by M. E. Martellotti and Cincinnati Milling Machine Company. Ten years later (1955) R Pickenbrick investigates cutting forces during face milling. In 1961 Koenigsberger and Sabberwal investigated frequency of cutting forces during face milling with three components dynamometer. Rapid development of measuring instrumentation and computers, in 70 ties investigations rapid increased. Because face milling process is one of the most often used and the most efficient process among high productive machining processes it is logically that the most of the papers and investigations are connected with this machining process. Cutting forces during face machining are investigated intensively analytically and experimentally. Some of previous approaches to cutting forces determination consider only main (tangential) cutting force component, and according this define cutting power. Later attempt consider other cutting force components also. Face milling process particularity like multi tooth that simultaneously cutting and difference in chip cross section that one tooth cut influenced development of variety of models for cutting force calculation. Variation in chip cross section gives difference in intensity of cutting forces and thermal load of single tooth. For easier cutting force model definition usually is considered case of one tooth milling cutter cutting and cutting width is equal to cutter diameter *D*. In this case chip cross section is like it is shown on Fig 1.

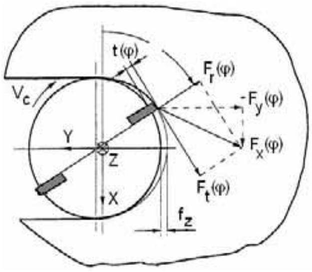

Fig. 1. Cutting forces in milling

$$F_t = F_x \cos\varphi - F_y \sin\varphi \tag{1}$$

$$F_r = -F_x \sin\varphi - F_y \cos\varphi \tag{2}$$

where:
φ-rotation angle, F_t and F_r tangential and radial components of the cutting force, F_x and F_y cutting forces in *X*-, *Y* directions.

The forces are oriented as follows: the "tangential force" is oriented along the feeding direction and has its positive versus in the cutting direction; the "radial force" is oriented perpendicularly to the feeding direction and its verse is positive going inside the surface. Both parallel and normal force are in the same horizontal plane.

FAST FOURIER TRANSFORM (FFT)

An energy-limited signal *f(t)* can be decomposed by its Fourier transform *F( )*, namely

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} F(\omega)\, e^{j\omega t}\, d\omega \tag{3}$$

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)\, e^{-j\omega t}\, dt \tag{4}$$

f(t) and *F( )* are known as a pair of Fourier transforms. Equation (2) implies that *f(t)* signal can be decomposed into a family with harmonics $e^{j\ t}$ and the weighting coefficient F( ) represent the amplitudes of the harmonics in *f(t)*. *F*( ) is independent of time, it represents the frequency composition of a random process, which is assumed to be stationary so that its statistics do not change with time. Fourier transform has been successfully used to process the *AE* signal during turning. In [1], experimental results have shown that the magnitude of the *AE* in the frequency domain was sensitive to the change of tool state. However, the vibration signal is essentially non-stationary. If we calculate the frequency composition of nonstationary signals by using Fourier transform, the results are the frequency composition averaged over the duration of the signal. As a result, Fourier transform cannot describe adequately the characteristics of the transient signal in the lower frequency.

EXPERIMENTAL TEST

The experiments have been performed on the milling center *Busellato JET 130*.

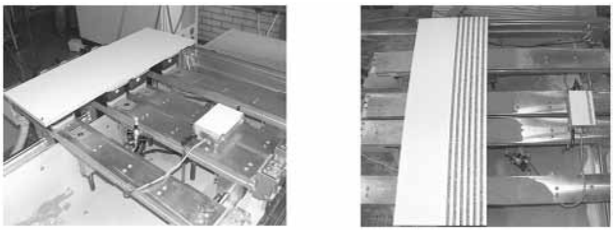

Fig. 2. Milling machine *Buselatto JET 130* and tri-axial dynamometric piezoelectric platform

In experiments was used based-wood materials-laminated chipboard. Dimensions of the specimens which were prepared for the machining were as follows: 900x30x18mm (Fig. 2). The cutting tools was a *DIMAR HW ϕ12 x 51*. In research applications four cutting tools (Test *K1-K4*). The feed speed were constant(11m/min) and the spindle speed was constant (18000min^{-1}). The signals were digitized and stored into a computer using a Computer Boards *NI PCI-6111E* analog-to-digital converter. The piezoelectric sensor *Kistler 5034A3* was clamped between two plates (Fig. 3). VB_{max} was selected as the tool wear measure. The original (F_x and F_y) signals were recorded on a hard disk PC in a digital form. In the course of breaks executable measurements VB_{max} with the of workshop microscope.

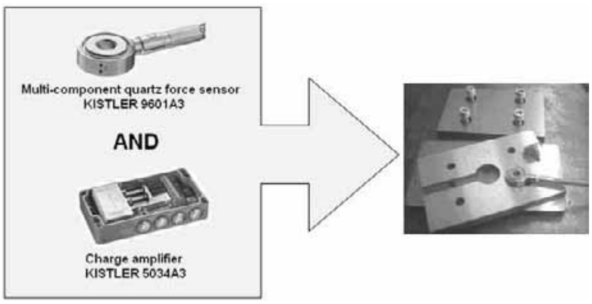

Fig. 3. Multi-component quartz force sensor *KISTLER 9601A3*, charge amplifier *KISTLER 5023A3* and piezoelectric sensors clamped between two plates

The forces acting on the dynamometer were averaged in the time domain while resultant cutting force (F_{RR}) acting on the cutter was calculated by:

$$F_{RR} = \sqrt{F_x^2 + F_y^2} \tag{5}$$

where:
F_{RR} resultant force, F_x and F_y cutting forces in *X*-, *Y* directions.

The literature data concerning the use of spectral analysis to assess the technical condition of machines and devices that signal analysis of cutting forces in the frequency domain is also often used as a signal analysis in time domain. Modern methods of measuring and processing the measurement results significantly facilitate the analysis in the frequency domain. Application of Fast Fourier Transform of a registered, time course of the signal allows for spectral characteristics. Microprocessor engineering meant that practically, this transformation can be carried out in parallel with the measurement of cutting force signal.
Classical spectral analysis is the observation of the frequency spectrum in the entire recorded signal. The choice of these frequencies is one of the most difficult issues. Evaluation of the tool in studies based on tracking the signal resultant force (F_{RR}), at a particular frequency band. Frequency (*f*), however, is dependent largely on the spindle speed (*n*) the number of cutter cutting tools (*z*):

$$f = \frac{n * z}{60} \quad (Hz) \tag{6}$$

After an exchange tools can change both the frequency of the vibrations (the dominant in the spectrum) and the signal level. Based on the survey measurements of the signals of resultant force (F_{RR}), it was observed that with increasing wear of the blade increases the share of energy to high frequencies.
Figure 4 shows the selected courses of the spectrum signals of resultant force (F_{RR}) in the frequency domain. But up to this consumption value of amplitude remains comparable level.

As for the signal, it can be seen a clear increase in amplitude with increasing values of tool wear (Fig. 5). In summary, the spectrum of signal resultant force (F_{RR}) in frequency domain can be used to assess the current state of the tool.

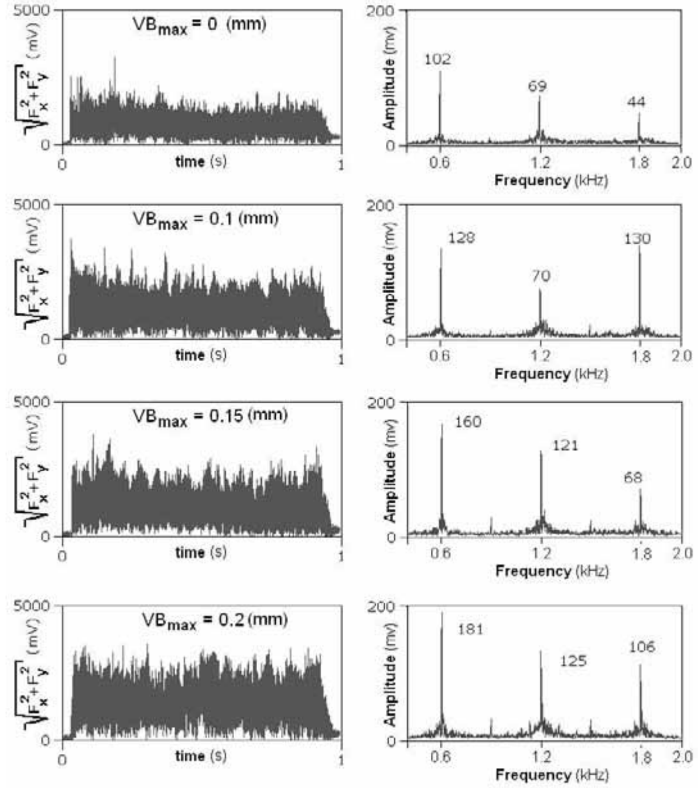

Fig. 4. Representative examples of F_{RR} signal generated for VB_{max}: 0; 0,1; 0,15; 0.2(mm) and FFT

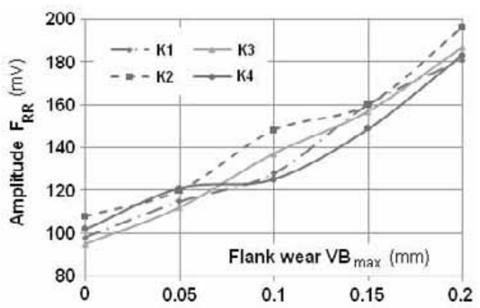

Fig. 5. The relation between change in result force (F_{RR}) first harmonics and tool flank wear for four cutting test

TOOL FLANK WEAR MONITORING STRATEGY

Strategies to increase detection of abnormal wear of the blade used by various manufacturers typically rely on increasing the selected measurement signal (changing with tool wear) accompanying consumption. May be a measure of the average, maximum value of signal strength, a linear combination of signals of cutting forces. Evaluation of measurement chosen is usually performed after the operation. Denote M as a sharp tool of measurement corresponds to the initial value of M_0. During the wear of the blades measure increases, resulting in his dulled (at the end of the cutter life T) value of M_T (Fig. 6). Learning the system is processing the first object with a sharp instrument. At its basis is determined the level of M_T border, on the basis provided by the operator maximum percentage increase in the value of measuring dM_T:

$$M_T = M_0\left(1 + \frac{dM_T}{100\%}\right) \tag{7}$$

$$dM_T = \frac{M_T - M_0}{M_0} \cdot 100\% \tag{8}$$

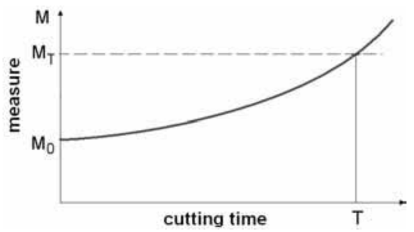

Fig.6. The increase in cutting forces accompanying of the tool wear

Used part of the shelf of the tool life is by definition a linear function of time. It estimates the process on the basis of conduct diagnostic signal which may, but need not be a linear function of time. Based on this simplification, the part of the shelf of the tool life can be set as:

$$\Delta T = \left(\frac{M}{M_0} - 1\right) \cdot \frac{10^4}{dM_T} \tag{9}$$

In conclusion, it is worth noting that the usefulness of the proposed strategy depends on the correlation between signals of cutting forces and of the tool wear. It is of little importance in the workpiece, the material blades or other cutting conditions. The strategy will be effective if accompanied by of the tool wear would be substantial (preferably linear) increase in the signals of cutting forces. But you should remember this, because there are cases where the dependence of w forces the consumption jest too weak to be able to be used if the proposed use and any strategy based on measurements of signals cutting force. Figure 6 shows the results from the developed strategy. As you can see, the estimation of tool wear (ΔT) has been correctly interpreted.

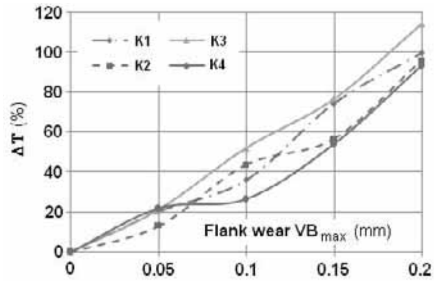

Fig. 6. The used-up portion of the tool life (ΔT=t/T) was used as the tool condition indicator

CONCLUSIONS

This paper has presented the strategy for monitoring the amount of flank wear and interrelationships between cutting force harmonic and tool wear in process milling. Certain harmonics increase significantly with flank wear while other harmonics remain unaffected. An on-line monitoring strategy using the cutting force harmonics magnitudes as indicator to tool flank wear was developed and verified experimentally.

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Streszczenie: *Powiązanie sił skrawania od zużycia narzędzia w procesie frezowania płyty wiórowej* . Zużycie krawędzi tnącej podczas frezowania to skomplikowany proces, który wymaga rzetelnej techniki w procesie monitorowania i kontroli wydajności skrawania. W artykule zaprezentowano metodę określania wpływu zużycia ostrza narzędzia skrawającego na sygnał wypadkowej siły skrawania (F_{RR}) w dziedzinie częstotliwości. Pomiary sił (na kierunku X i Y) przeprowadzono za pomocą siłomierza piezoelektrycznego podczas frezowania płyty wiórowej. Zużycie narzędzi mierzono w sposób off-line.

Corresponding author:

Krzysztof Szwajka,
Warsaw University of Life Sciences,
Faculty of Wood Technology,
02-776 Warsaw
Nowoursynowska 159 str.
Poland
e-mail: kszwajka@poczta.onet.pl