ON THE ANALYSIS OF THE SOUND SPECTRUM AT MACHINING OF THE GLASS-POLYESTER COMPOSITE MATERIAL

Zdenek Fiala, Miroslav Piska, Ales Jaros
Brno University of Technology
Faculty of Mechanical Engineering
Department of manufacturing technology

e-mail: fialaml@centrum.cz

This paper deals with analysis of the machining process sound spectrum at milling of the glass-polyester composite material. The development of intensities of the machining process with a growing flank wear has been observed during the experimental machining. High speed steel cutting tools deposited by (Al,Ti,Cr)N coating were used for experimental machining.

The goal of this article is identifying relations between the sound generated by the milling process with respect to other measurable variables, which include flank wear of cutting tool and cutting force (or the specific cutting force). The results were compared with results reached during similar milling of the hardened steel DIN EN 10 277 (1.8159).

Keywords:
Sound spectrum, dominant frequency, composite material, specific cutting force, flank wear, cutting tool

1. Introduction

The measuring of sound signals provides significant informations about the state of cutting process [Altintas 2000]. The measurement of the sound can be divided into two areas:

- the first area deals with the stability of a cutting process. The machining sound emerging from the mechanical vibrations produced in the interaction zone between the cutting tool and the workpiece has also been used to detect chattering and vibrations [Altintas 2000]. A microphone is suitable sensor for this purpose and comparisons with other sensors such as dynamometer, accelerometer and displacement probe [Peigne 2006];
- the second area is engaged in monitoring of the cutting tool wear. Sadat found that the noise sound level stemming from friction between the cutting tool and the workpiece was the 0.73~3.5 kHz through many experiments for a sharp tool. The worn cutting tool generates approximately 15 dB higher sound intensity. Lee has found that in most of the workpiece material combinations and operating conditions, a cutting noise of the characteristic frequency about 4~6 kHz can be found, and its sound pressure level has a good correlation with the tool wear [Sadat 1997, Teti 2010].

2. Theory of the experimental measurement

The time domain signals can be transformed to frequency domain signal by Fast Fourier Transform (FFT). In the frequency domain of the sound of the cutting process spectrum the analyzed changes are the sound pressure intensities and frequencies. FFT can be derived from the Fourier transform equation for each component in a form

$$X(f) = F\{x(t)\} = \int_{-\infty}^{\infty} x(t) \cdot e^{-j2\pi 2} dt \qquad (1)$$

Where *X(f)* is the FFT, *F{x(t)}* is the time domain signal and *f* is the frequency to analyze [Wanigarathne 2005].

The intensity and frequency of the sound generated by a cutting process depend on the cutting tool design and physical properties. Forces acting during machining provide information about the machine tool vibration, tool wear and also the machining accuracy, etc. Value of the cutting force Fc depends mainly on the chip cross-section A_D and the specific cutting force k_c [Wanigarathne 2005].

$$F_c = A_D \cdot k_c \qquad (2)$$

The formulation of the cutting force F_c does not include the effect of the tool wear as a function of the cutting time. Equations (3-6) show extended equation (2) with an effect of the wear [Wanigarathne 2005, Forejt 2006].

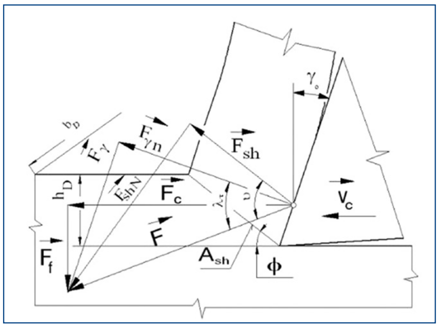

Figure 1. *A force resolution [Piska 2011].*

$$F_c = F_{c0} + F_{cw} \qquad (3)$$

$$F_{c0} = A_D \cdot k_c = a_0 \qquad (4)$$

$$F_{cw} = a_1 .t + a_2 .t^2 \qquad (5)$$

$$F_c = a_0 + a_1 .t + a_2 .t^2 \qquad (6)$$

Where F_{co} represents the cutting force for a sharp cutting edge and F_{cw} includes the effect of tool wear on the cutting force. According to our previous works, polynomial functions reflect the wear phenomena for all measured components in the cutting time as a common function very relevantly. Specific cutting force as a function of cutting time can be defined by the general equation (7) [Piska 2011].

$$k_c = \frac{F_c}{A_D} = \frac{a_0 + a_1 \cdot t + a_2 \cdot t^2}{A_D} \qquad (7)$$

3. Experimental procedure

3.1 The aim of the experimental work

The primary aim of this experiment was to find a relationship between sound generated by machining process and other variables including wear of the cutting tool and specific cutting force when milling of the glass-polyester composite material. High speed steel cutting tools deposited by (Al,Ti,Cr)N coating were used for experimental machining. Fiala investigated sound acoustic pressure frequency correlation with flank wear of cutting tool at machining of steel DIN EN 10 277 (1.8159) [Fiala 2012]. Part of the work is a comparison of results for both types of the workpiece materials.

3.2 Cutting tool

HSSE-PM end milling cutter (Ø16x92 mm; producer ZPS-FN, Zlín, Czech Republic) was used for face milling – Fig. 2. The tool was deposited by PVD coating with (Al,Ti,Cr)N monolayer (producer Liss-Platit, share

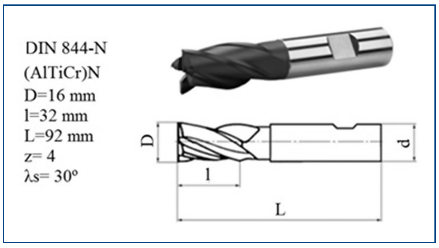

Figure 2a. *HSSE-PM end milling cutter deposited by (Al,Ti,Cr)N [Fiala 2012].*

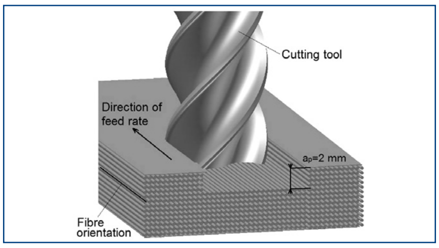

Figure 2b. *The fiberglass orientation.*

Structure	Hardness [GPa]	Max. working temperature [°C]	Coefficient of friction [μm]	Thickness [μm]
Monolayer	40	900	0.55	2 – 4

Table 1. *Characteristics of the (Al,Ti,Cr)N coating [Jaros 2012].*

company, Rožnov p. R., Czech Republic). The coating was synthesized by a cathodic-arc deposition process using Al,Ti and Cr elemental cathodes. The temperature of deposition of the process was about 450°C. Thickness of coating was 2.5-3.2 μm verified by the kalotest. Properties of monolayer (Al,Ti,Cr)N coating are shown in Table 1.

The coated HSSE-PM milling cutter was chosen, because a high flank wear rate was assumed. The high flank wear rate enabled fast and distinct measurement of the flank wear values.

3.3 Workpiece material

Glass-polyester composite material was used for the experiment. This material is composed of matrix (polyester resin – 60%) and reinforcements (glass fiber – 40%) covered with a protective polyethylene foils. Details about the structure of composite material can be found in [Filip 2013]. Dimensions of the workpiece were 220x110x12 mm. The structure of the material is shown in Fig. 3 and mechanical properties are shown in Table 2.

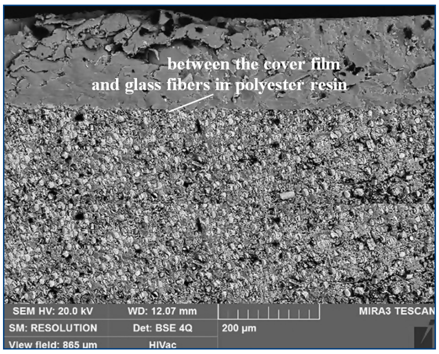

Figure 3. *Cross-section of the glass-polyester composite material with marked boundaries between the individual layers.*

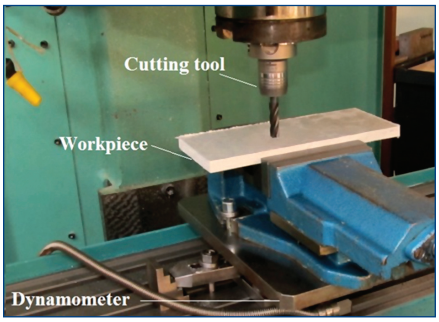

Figure 4. *Experimental set-up of cutting tool and workpiece.*

The results were compared with results obtained during milling low-alloy constructional steel DIN EN 10 277 (1.8159) [Jaros 2012] which is usually called as a spring steel. Dimensions of the workpiece were 200x90x30 mm. Mechanical properties are shown in Table 3.

The experiment was carried out at the three-axes milling machine FV 25 CNC with the control system HEIDENHEIN iTNC 530 – Fig. 4.

3.4 Cutting conditions

Cutting conditions are shown in Table 4. The Fig. 4 shows the milling experiment. All machining were carried out in dry conditions, the walls between two straight passes were kept 5 mm. Five minute intervals were made between individual passes to cool down the cutting tool and to measure the flank wear.

Cutting speed v_c=35 m/min was used for both materials of workpiece, glass-polyester composite material and low-alloy constructional steel. Cutting speed v_c=50 m/min was used only for machining composite material.

Material	Strength in the longitudinal direction [MPa]			Strength in the transverse direction [MPa]			Shear strength [MPa]
	Tensile	Compressive	Flexural	Tensile	Compressive	Flexural	
Glass-polyester composite	240 – 700	240 – 450	240 – 1000	60 – 95	150 – 170	190 – 220	21

Table 2. *Mechanical properties of glass-polyester composite material [Filip 2013].*

Re_{min} [MPa]	Rm [MPa]	A min. [%]	Z min. [%]	Kv [J]
800	1000 – 1200	10	45	30

Table 3. *Mechanical properties of low-alloy constructional steel [Jaros 2012].*

Cutting speed v_c [m/min]	Feed speed v_f [mm/min]	Feed per tooth f_z [mm]	Radial depth of cut a_e [mm]	Axial depth of cut a_p [mm]	Diameter of tool D [mm]
35	280	0,1	16	2	16
50	400	0,1	16	2	16

Table 4. *Cutting conditions.*

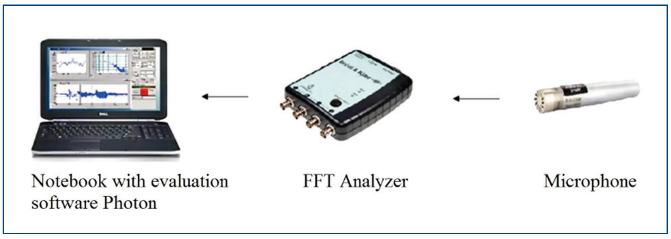

***Figure 5.** The Kistler data acquisition and processing for sound spectrum [Fiala 2012].*

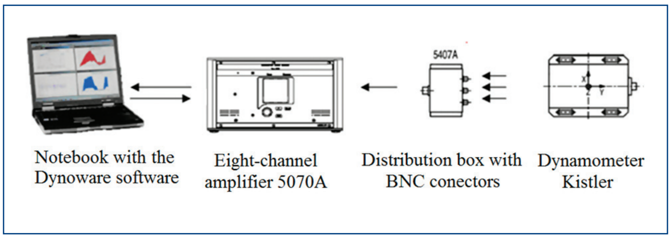

***Figure 6.** The Kistler data acquisition and processing [Piska 2010].*

The primary monitored parameter was finding of the dominant frequency of the sound spectrum generated by the milling process. The Brüel&Kjaer equipment (microphone type 4189A, FFT analyzer Photon and computer with evaluating software) was used for the experimental measurements – Fig. 5. By the analyses of the sound spectrum was easy to determine the stability of the milling and higher level of tool wear in the measured signal time series.

The secondary monitored parameter was force loading of the workpiece generated with the cutting tool. Force loading was measured in three axes by the piezoelectrical dynamometer Kistler 9257B, equipped with the charge amplifier 5070A and Dynoware software was used for data processing (see Fig. 6).

4. Results

The first experimental machining of the composite material was carried out with cutting speed v_c=35 m/min. Twenty passes were performed, until flank wear reached 0.21 mm (7.5 min machining time). Dominant frequency with a higher intensity was not observed during the machining of composite material, sound generated by the cutting process had a low intensity and random dominant frequency in comparison with machining of low-alloy constructional steel. The sound was generated mainly by moving parts of milling machine and not by the milling process. For this reason the cutting speed was increased up to v_c=50 m/min (Table 4).

In spite of the first measurement, additional measurement was carried out with higher cutting speed. Cutting tool preformed 13 passes, until flank wear reached 0.23 mm (5 minutes of cutting). Evolution of the dominant frequencies of the milling process is shown in Fig.7. Sound of milling process was not changed in frequency, but the intensities were changed with the growing flank wear. The machining of the low-alloy constructional steel was performed for cutting condition v_c=35 m/min (Table 4). The cutting conditions were set in unstable region, when the cutting tool started machining the vibrations occurred. The unstable machining was accompanied by the intensive sound with one dominant frequency about 750 Hz. Machining process was changed to stable since flank wear value reached VB=0.11 mm (22 passes). Stable machining was observed until milling tool reached flank wear VB=0.14 mm (57 passes). Worn milling cutter produced sounds of higher frequencies (6 kHz). The sound generated by milling process and the dominant frequency were growing up with increasing wear in general. The sound map for machining of low-alloy constructional steel is shown in Fig.8 [Fiala 2012].

The sound intensity values (20 data per each pass) were statistically evaluated by Statistica v.10 software with medians and the

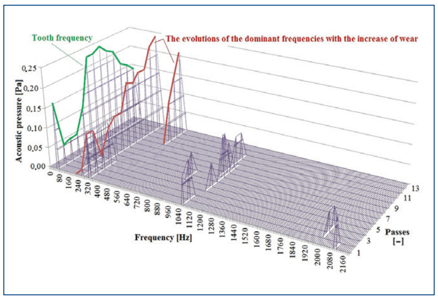

***Figure 7.** Sound map for machining of the glass-polyester composite material.*

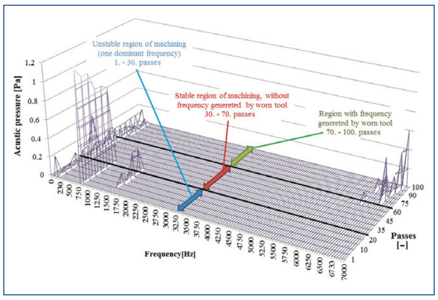

***Figure 8.** Sound map for machining of the low-alloy constructional steel [Fiala 2012].*

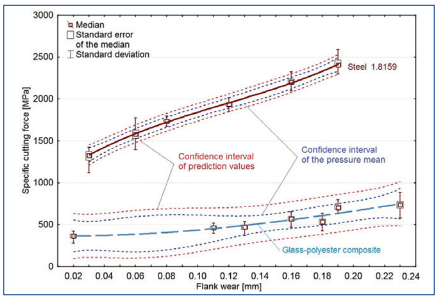

***Figure 9.** The evolution of the specific cutting forces with growing flank wear for both tested materials.*

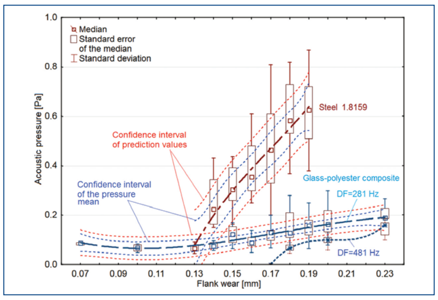

***Figure 10.** Correlation between intensity of the dominant frequency and flank wear for both tested materials.*

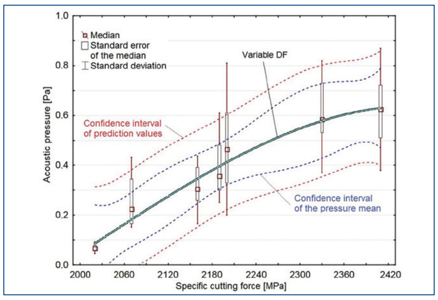

***Figure 11.** Correlation between intensity of the dominant frequency and specific cutting force for steel 1.8159.*

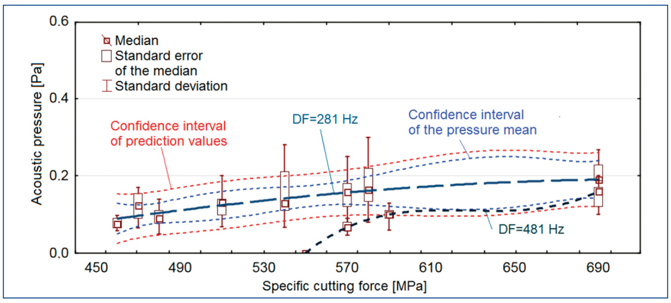

Figure 12. *Correlation between intensity of the dominant frequency and specific cutting force for glass-polyester composite.*

appropriate data dispersions. The values of the specific cutting forces for machining of both tested materials are given in Fig. 9. The specific cutting forces generated during machining of composite material were lower in the interval (71-73%) in comparison with machining of low-alloy constructional steel (see in Fig. 9). The increase of the specific cutting forces was higher for milling of low-alloy constructional steel; with a growing flank wear of the cutting tool. Differences in specific cutting forces standard errors and deviations were not observed.

The evolution of sound intensity generated by milling process for both tested materials is shown in Fig. 10. The sound was caused by a friction between flank of the cutting tool and workpiece material in milling process. The increase of contact area due to flank wear caused the change of the sound intensity. The sound intensity value was higher by 0.02 Pa (in median) at machining of glass-polyester composite material initially for the flank wear 0.13 mm compared to the steel Fig. 10. However, further growth of the sound intensity was lower and the maximal intensity was reached for the flank wear VB=0.23 mm (13 passes, resp.) just 0.16 Pa. The machining of the steel 1.8159 resulted in a faster rise of the sound intensity with increasing flank wear, the maximal intensity was measured 0.43 Pa - for flank wear 0.19 mm (100 passes).

The correlation between the sound intensity and the specific cutting force is shown in Fig.11 for low-alloy constructional steel and in Fig. 12 for glass-polyester composite material.

The experimental machining was accompanied by a variable-dominant frequency for milling of low-alloy steel and constant-dominant frequencies for milling of glass-polyester composite material. The dominant frequencies were increased with tool wear increase in both cases gradually.

5. Conclusions

From the sound spectrum analysis of the experimental milling the following conclusions have been made:

- the development of sound intensity and frequency was measurable just during machining of low-alloy constructional steel when cutting speed was set up v_c=35 m/min (and other cutting conditions);
- the machining of glass-polyester composite material was accompanied by random frequencies with low intensities (under 1.1 Pa), when the same cutting conditions as in machining of low-alloy steel. The sound was generated mainly by moving parts of milling machine and not by the milling process, so it was not possible to find any correlations;
- three dominant frequencies 70 Hz (teeth frequency), 281 Hz (harmonic frequency) and 481 Hz (generated by flank wear) occurred and further developed, when the cutting speed was increased to v_c=50 m/min for machining of glass-polyester composite material;
- a statistically significant correlations were found (p=0.1) between the sound intensity and frequency and the flank wear of cutting tool (or specific cutting force) when machining of low alloy steel with cutting speed v_c=35 m/min.
- other statistically significant correlations were found (p=0.1) between intensity of three dominant frequencies and the flank wear of cutting tool (or specific cutting force) when machining of glass polyester composite with cutting speed v_c=50 m/min;
- the standard deviation of intensity was observed about 200% higher at machining of low-alloy steel.

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Contact

Ing. Zdeněk Fiala
Brno University of Technology
Faculty of Mechanical Engineering
Department of manufacturing technology
Technická 2896/2, 616 69 Brno, Czech Republic
tel.: 775 021 732