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# Analysis of forces and vibrations during milling of a metal-ceramic composite

## Analiza sił oraz drgań podczas frezowania kompozytu metalowo-ceramicznego

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Presented is the analysis of the cutting forces and vibrations during milling of the F3S.10S Duralcan™ metal-ceramic composite, using milling cutters made of two materials: PCD and CBN. The test was carried out with variable milling parameters, i.e. cutting speeds  $v_c$  and feed  $f_z$ . Measurements of vibrations and forces were made in three directions: feed ( $F_t$ ,  $A_t$ ), feed normal ( $F_{FN}$ ,  $A_{FN}$ ), and resistant ( $F_p$ ,  $A_p$ ). The root mean square values were determined from the received forces and vibrations. The analysis was made both as a function of time and frequency. The analysis mainly concerned the impact of the cutting speed and the feed on the level of the amplitudes of the vibrations and forces. An additional frequency analysis was carried out.

**KEYWORDS:** milling, composite, forces, vibrations

In many fields of industry, newer construction materials are being sought after. The most intense group developed among them are composites composed of two or more materials. They combine different matrix and reinforcement properties [2].

Among metal composite materials, more and more important in research and implementation works is attributed to casted composites with a matrix of aluminum alloys (Al-Si) reinforced with graphite, SiC and Al<sub>2</sub>O<sub>3</sub> ceramic particles [1, 7, 9].

The properties of composite materials depend on their intended use [5, 7]. Currently, the most composites are used in the transport industry [7].

Machining of MMC (metal matrix composites) composite is a major challenge because it causes rapid tool wear and costs are high. The cracking and detachment of the reinforcing particles affects the efficiency of the tool, therefore the prediction of the cutting force and vibrations can be used to evaluate the cutting process [3, 6].

The article [3] presents the energy-based force model, developed for orthogonal cutting of MMC composites. The results showed compatibility between the predicted and measured cutting forces. The proposed model is based on the quantification of various energy inputs used during the cutting process [3].

In turn, the author of the work [8] proposed an exact model of cutting force applied to finishing milling with a ball end milling cutter. In addition to forces, the analysis of mechanical vibrations seems to be an important aspect. The work [4] shows an experimentally tested system to demonstrate the reduction of dynamic force as a result of vibration. Extensive testing has been carried out to validate system performance in terms of practical performance parameters such as improving surface finish and increasing tool durability.

The literature review shows that little research on the machining of MMC composites focuses on the analysis of dynamics during precision milling. Therefore, in this work, the components of total force and vibrations were evaluated, taking into account statistical measures and spectral analyzes of the signal.

### Aim, scope and methodology of research

The purpose of the work was the analysis of forces and vibrations during milling of a metal-ceramic composite for various milling parameters.

The work material was an aluminum-ceramic composite F3S.10S by Duralcan with a matrix of aluminum reinforced with SiC particles. The most useful features of these composites are their high strength, stiffness and abrasion resistance.

The method of fixing the workpiece material is shown in fig. 1. The tests were carried out on the DECKEL MAHO three-axis milling center model DMC 70V Hi-Dyn with a maximum rotational speed  $n = 30,000$  rpm.

The change of forces and vibrations was measured depending on the speed and feed rate, and their values used during milling are shown in the tab. I and tab. II.

As cutting tools, two monolithic end mills (tab. III) were mounted in a shrink-fit holder. The measurement of the components of the total force was made using a three-component dynamometer platform connected to the load amplifiers, an analog-digital converter and a PC equipped

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with a program for acquisition and overweighting data. The vibration was measured with a three-component piezoelectric accelerometer attached to the workpiece. The vibration measurement station is equipped with a vibration sensor, a Brüel & Kjær charge amplifier and a PC computer.



Fig. 1. Way of fixing the workpiece

TABLE I. Parameters adopted during milling at a constant feed per tooth  $f = 0.1$  mm/rev

PCD CBN	$v_c$ , m/min	$n$ , obr/min	$v_f$ , mm/min
1	50	1 591	159
2	100	3 182	318
3	200	6 364	636
4	300	9 546	955
5	400	12 728	1 273
6	500	15 910	1 591
7	600	19 093	1 909
8	700	22 275	2 227

TABLE II. Parameters adopted during milling at constant cutting speed  $v_c = 500$  m/min

PCD CBN	$f$ , mm/obr	$f_z$ , mm/ostrze	$v_f$ , mm/min
1	0,01	0,0049	159
2	0,03	0,015	477
3	0,06	0,03	955
4	0,09	0,045	1 432
5	0,12	0,06	1 910
6	0,18	0,09	2 865
7	0,30	0,15	4 775
8	0,50	0,25	7 958

TABLE III. Applied cutters

Carbide milling cutter with PCD diamond coating: $d = 10$ mm $z = 6$	
CBN cutter from regular boron nitride: $d = 10$ mm $z = 2$	

During the tests, the cutting depth values  $a_p$  and the cutting width  $a_e$  were constant and amounted to:  $a_p = 10$  mm,  $a_e = 0.3$  mm. Measurements of vibrations and forces were made in three directions: feed ( $F_t$ ,  $A_t$ ), feed normal ( $F_{tN}$ ,

$A_{tN}$ ) and resistant ( $F_p$ ,  $A_p$ ). From the received forces and vibrations, statistical measures were determined, such as mean square root RMS values (root mean square). The analysis was made as a function of time and frequency. The analysis mainly concerned the impact of cutting speed and feed on the level of amplitudes of the vibrations and forces.

Test results

■ **Graphs as a function of time.** The results were presented in the form of graphs of forces and vibrations as a function of time.

Fig. 2 shows a graph of the  $F_{tN}$  component with a selected time interval corresponding to one tool revolution. In turn, fig. 3 shows the graph of the course of force components  $F_p$  at different cutting speeds for the PCD cutter. Amplitudes of the component forces were read in each interval in time for a given cutting speed.

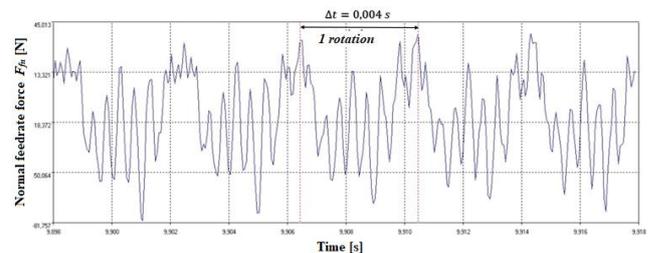


Fig. 2. Plot of normal federate force  $F_{tN}$  in a narrowed range of time at feed  $f = 0.01$  mm/rev

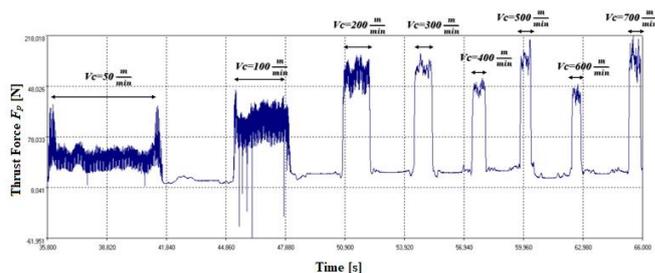


Fig. 3. Graph of thrust force component  $F_p$  for PCD cutter at different cutting speeds (fixed parameters:  $a_e = 0.3$  mm,  $a_p = 10$  mm,  $f = 0.1$  mm/rev,  $f_z = 0.02$  mm/tooth)

■ **Mean square values of forces and vibrations.** The received values of forces and vibrations are presented in figs. 4-9.

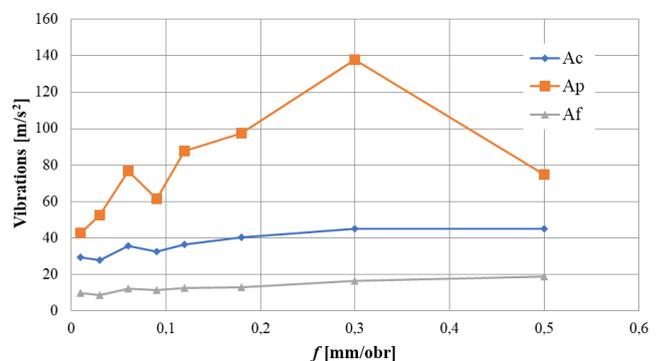


Fig. 4. Diagram of mean square values for PCD cutter at constant cutting speed

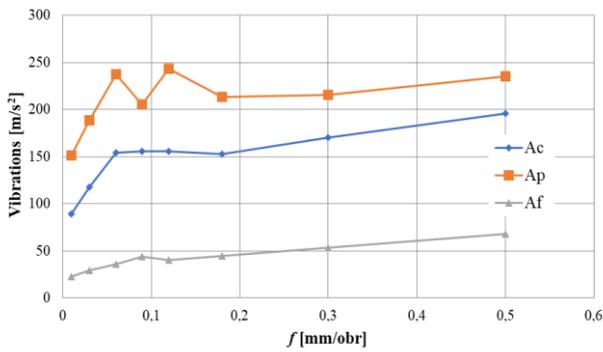


Fig. 5. Diagram of mean root vibration values for a CBN cutter at a constant cutting speed

It can be seen that the smallest vibration amplitude values occur when machining with a PCD diamond-coated cutter. The same applies to the CBN regular nitride cutter. However, fig. 5 shows that along with the increase in feed, the vibration values reach much higher amplitudes than in the PCD cutter. The largest amplitudes are for vibrations in the thrust direction. The smallest values, in the same way as for the PCD cutter, occur in the direction Y - feed  $A_f$ .

As with variable feed, also at variable cutting speeds (fig. 6 and fig. 7), the vibration amplitude is lower for the PCD cutter as compared to the CBN cutter. In the case of a PCD cutter for  $v_c = 300$  m/min, self-excited vibrations appeared, which resulted in a several-fold increase in amplitudes.

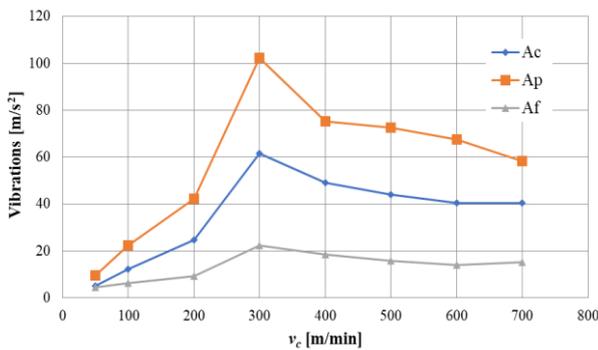


Fig. 6. Graph of mean square values for PCD cutter with constant feed per revolution

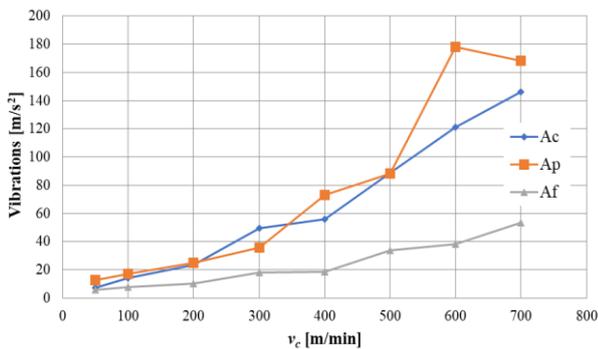


Fig. 7. Graph of mean square vibration values for a CBN cutter with constant feed per revolution

Fig. 8 and 9 show examples of average-square values for components of total force. Together with the increase in the feed per revolution, the value of the forces monotonically increases, which is in line with the theoretical models. In addition, the values of the total force components are significantly higher compared to the results for a PCD cutter.

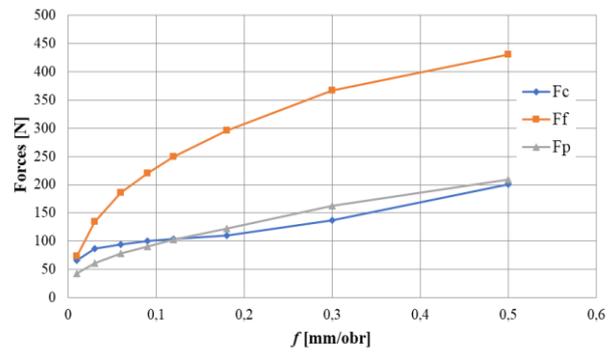


Fig. 8. Graph of the mean square values of forces for a CBN cutter with constant feed per revolution

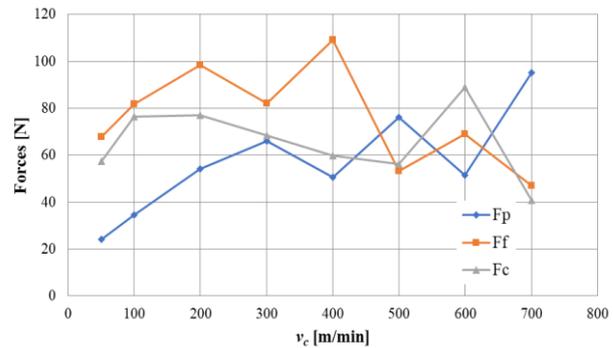


Fig. 9. Graph of the mean square values of forces for a CBN cutter at a constant cutting speed

At the change of cutting speed (fig. 9), non-monotonic changes of amplitudes for all components were noted. The same trend occurred for the PCD cutter, i.e. the non-monotonic waveforms and amplitude values were much smaller than for the CBN.

**Frequency analysis.** Fig. 10 shows the amplitude-frequency characteristics of  $F_{IN}$  force for PCD cutters at constant cutting speed and load. The amplitudes of individual bands are several times smaller for PCD cutter compared to CBN cutter, as confirmed by the prior analysis of RMS values in the time domain. In turn the nature of the spectrum is closely correlated with the two basic frequencies:

- $f_0$  - the frequency associated with the speed  $n$ ,  $f_0 = n / 60$ ,
- $f_{0z}$  - frequency of the milling process  $f_{0z} = f_0 \times Z$ .

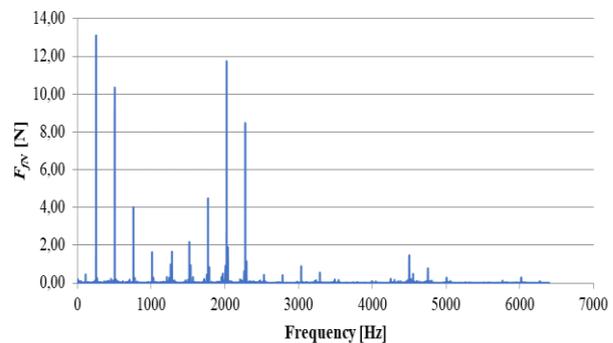


Fig. 10.  $F_{IN}$  component for PCD cutter at constant cutting speed and feed  $f = 0.01$  mm/rev

In all the analyzed power spectra and vibration accelerations, the largest amplitudes occur for the signal components  $f_0$  and  $f_{0z}$  and their harmonic frequencies, which indicates the determination of the basic kinematics of the milling process.

## Conclusions

- In all amplitude parameters considered vibrations for the feed direction  $A_f$  are the smallest.
- Milling with a CBN cutter gives higher vibration amplitudes compared to a PCD cutter.
- Increase in the cutting speed caused a slight decrease in the values of forces  $F_f$  and  $F_{TN}$ . In the case of  $F_p$ , a slight increase in force was observed with increasing cutting speed.
- When changing the feed while maintaining a constant speed, a significant effect on the increase of all components of the total force is visible.
- Frequency analysis showed that the waveforms (signals) of the components of the total force and the components of the vibration accelerations are determined mainly by the kinematics of the milling process.

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