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THE ANALYSIS OF SPECIFIC CUTTING FORCES AT MACHINING OF COMPOSITE MATERIALS

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Abstract: This paper deals with the analysis of specific cutting forces acting on the carbide milling cutters deposited by AlTiN, nACo and diamante coating. Glass-polyester and carbide-epoxy composite materials were chosen as the workpiece material. Glass and carbon fibers are now most common types of reinforcement in composite materials. Each tested milling cutter performed twenty-one passes through workpiece material to reduce the influence of irregular structure of tested composite materials, especially glass-polyester composite. The milling process was carried out without using process liquid, so it was dry machining. The development of specific cutting forces with the changing of cutting condition and increasing wear of the tested milling tools were monitored simultaneously. Dynamometer Kistler was used for measuring of force loading, obtained data was reconverted to specific cutting forces for comparison of milling cutters with different geometry of cutting edges. The evaluation of milling tools surfaces were performed on an electron microscope.
Keywords: specific cutting force, flank wear, composite material, milling cutter

1. INTRODUCTION

In view of the increase in the use of composite part in the aerospace and automotive industry, it is becoming important to study the machinability of these materials. Composite materials offer high strength/weight ratio, good damage tolerance, excellent fatigue resistance and corrosion resistance, which make them highly competitive against conventional materials [1,2]. On the other hand composite materials are highly abrasive and hard. The cutting tool materials must by chosen attentively to minimize wear of the cutting tools during the machining process [3].

Many studies have been made focus on machining of composite materials reinforced by glass and carbon fibres. Ramulu [4] and Koplev et al. [5] have shown that the fiber orientation is relevant factor in explaining cutting edge failure and materials defect [6]. Following this research another experimental works were made to study delamination and effect of tool wear during drilling [3,7,8], milling [9,10] and orthogonal cutting [11]. For example, current studies deal with analysis of vibrations [12,13], FEM simulation models [14,15] or online monitoring during machining of composite materials [16].

2. THEORY OF THE CUTTING TEST

The performance of a cutting tool can be evaluated either in terms of tool life as decided by tool wear or performance indicators such as machining forces (specific cutting force), temperature and related features.

There are several models suggested by a number of authors, which could be tested against the acquired data. They have many common aspects and most of them include some very specific particularities. First models proposed a direct relation between forces and the chip cross sectional area (Kronenberg 1966 and Ehmann et al. 1997), in general equations like:

$$\mathrm{F_c} = \mathrm{k_c} \cdot \mathrm{A_D} \tag{1}$$

where k_c is the specific cutting force and A_D is the chip cross sectional area. This equation came from observations that there seems to be an approximate linear relation between force and area in some experimental data, mainly from turning. Later on, it was found that k_c is not constant, but rather a function of process parameters, such as chip thickness and rake angle, for example. Kronenberg (1966), proposed a more detailed equation for k_c, which was:

$$k_c = \frac{C_p}{A_D^{zp}} \tag{2}$$

where C_p was a Cutting Force Coefficient to a unity of cutting force and the exponent zp is an experimental value depending on tool-workpiece pair. Following on, many other researchers proposed equations for $\mathrm{k_c}$ even including some other parameters, such

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as feed and depth of cut. Every new parameter seems to have added more complexity to the equation and little more accuracy on the prediction of experimental data [17].

3. EXPERIMENTAL PROCEDURE

Glass-polyester and carbon-epoxy composites were used for the experimental measurements. Glass-polyester composite material is composed of matrix (polyester resin – 60%) and reinforcements (glass fibers – 40%) covered with a protective polyethylene foils. Carbon-epoxy composite is consisted of matrix (epoxy resin – 32%) and reinforcements (carbon fibers – 68%). Details about the structure of composite materials can be found in [18]. Dimensions of the glass-polyester were 220x110x12 mm and 120x50x1.4 mm. The structure of the materials is shown in Figure 1 and Figure 2 and mechanical properties are shown in Table 1 and Table 2.

Table 1: Mechanical properties of glass-polyester composite material [18].

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

Table 2: Mechanical properties of carbon-epoxy composite material [18].

Material	Tensile strength [MPa]	Tensile modulus [GPa]	Coefficient of thermal expansion [mm/K]	Density [kg/m^3]
Carbon-epoxy	3000	155	$6 \cdot 10^{-6}$	1.6

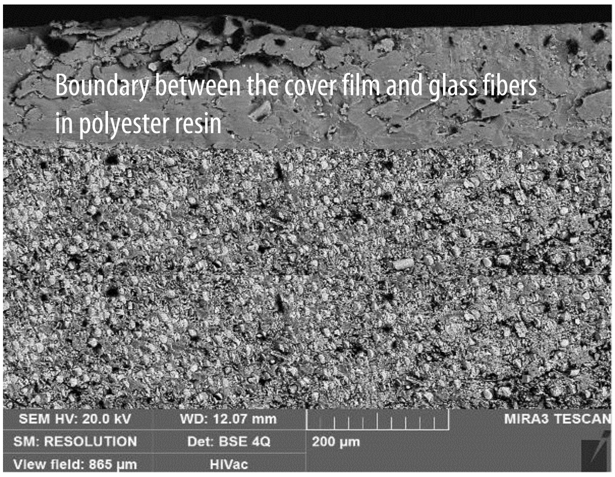

Figure 1a: Cross-section of the glass-polyester composite material with marked boundary between the individual layers

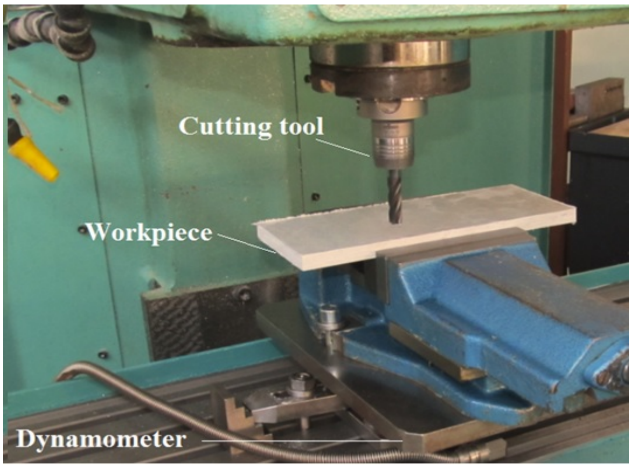

Figure 1b: Experimental set up of cutting tool and workpiece

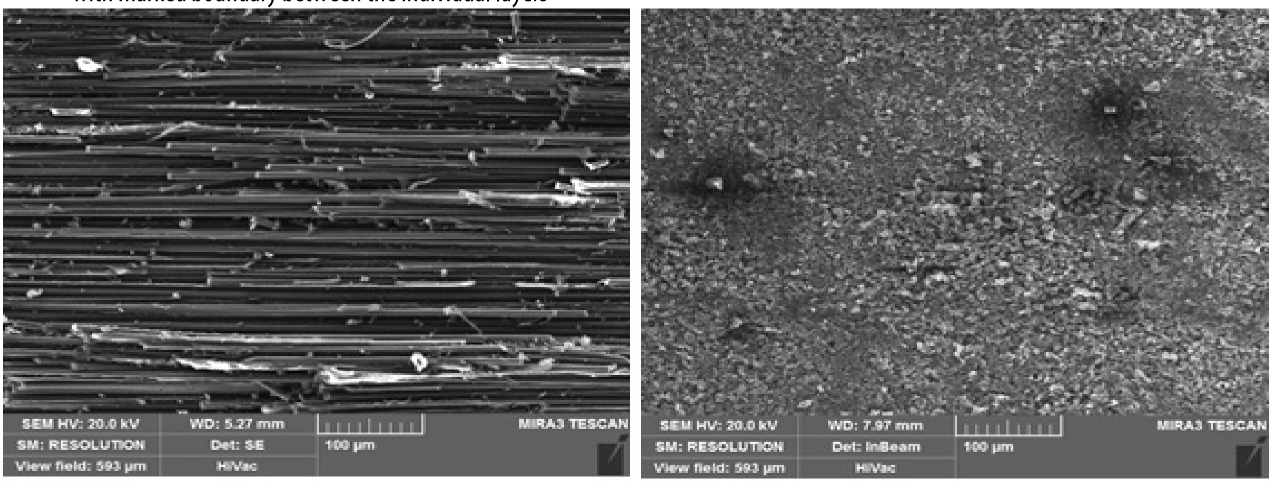

Figure 2: Cross-section of the carbon-epoxy composite material in the direction of the fibers (left) and perpendicular to the fiber direction (right)

Table 3: Mechanical properties of PVD.

Milling cutter	Uncoated (tool A)	AlTiN (tool B)	nACo (tool C)	DLC (tool D)
Hardness [GPa]	2125	3300	2510	9000
Maximal working temperature [°C]	800	900	1200	800

Carbide end 4-edges milling cutters (φ10x80 mm, producer Carbide, s. r. o., Měřín) were used for face milling of the composite materials. Type of the tested carbide tools was K05, helical angle 60° and composition was 94% WC and 6% Co. Three tools were deposited by PVD coatings (AlTiN, nACo and DLC) and one tool was uncoated. Mechanical properties of used coatings are shown in Table 3 and geometry in Figure 3.

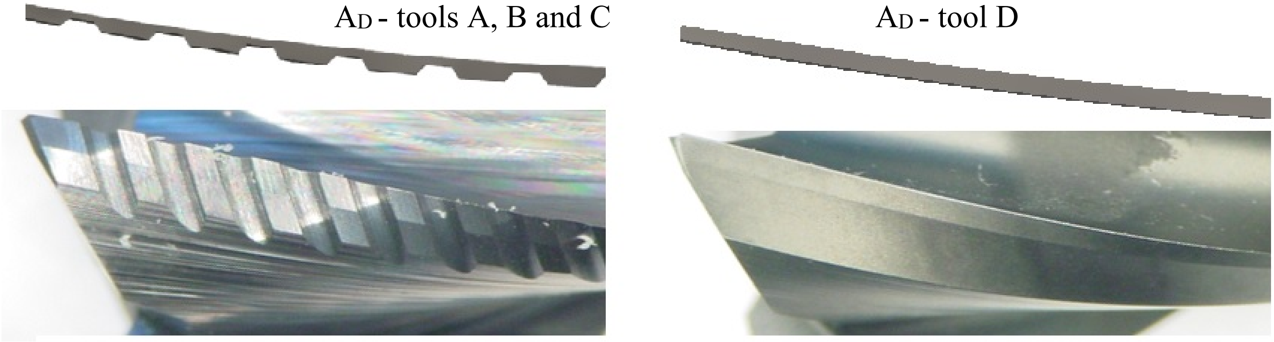

Figure 3: The geometry of tested milling cutters and examples of calculated chip-cross sections

The milling cutters A, B and C were fitted by chip breaker, which has a major impact on the chip-cross sections. Different chip-cross sections caused different values of the cutting tool force loading for tools fitted by chip breaker. The cutting forces cannot be compared directly, due to the different cutting conditions and chip cross sections, so the specific cutting force was used for comparison the forces acting on the milling tools. The chip-cross sections were calculated by Autodesk software for different cutting conditions. The force load of cutting tools was measured by piezoelectrical dynamometer Kistler 9257B, equipped with the charge amplifier 5070A and Dynoware software was used for data processing. The specific cutting forces values were calculated by equation (2).

Table 4: Cutting conditions used for experimental milling.

Material	Cutting speed v_c [m/min]	Feed per tooth f_z [mm]	Axial depth of cut a_p [mm]	Radial depth of cut a_e [mm]
Glass-polyester	63	0.1	5	10
		0.35		
Carbon-epoxy		0.1	1.4	
		0.35		
Glass-polyester	31	0.1	5	
	126			
Carbon-epoxy	31		1.4	
	126			
Glass-polyester	63	0.1	5	
			14	

The experimental slot milling was performed for fiber orientation 0° and 90° (fiber orientation was parallel to the feed rate and perpendicular to the feed rate direction). Machining was carried out in dry conditions, the walls between two straight passes were 5 mm. Cutting conditions are shown in Table 4. Each milling cutter carried out twenty passes through material. Then one control measurement was performed for all cutting tools with the same cutting conditions as in the first pass through material, for elimination of tool wear factor on values of the specific cutting forces.

4. RESULTS

The values of specific cutting forces were statistically evaluated by Statistica software v. 10 with medians and appropriate data dispersions. Examples of the experimental measurement results are shown in Figure 4a and Figure 4b. Two passes through workpiece material were performed for each set of the cutting condition to verify obtained data and eliminate possible errors. The maximal value of the feed per tooth was established 0.35 mm, because when the set value was higher, the pieces of composite material were started to break off. The boundary for cutting speed was set up 126 m/min (4000 rev/min), because higher cutting speed led to unstable machining.

The control measurements of k_c for all milling cutters showed, that the increase of median values at the end of experimental machining is not exceed 10% of values reached from beginning of machining for coated tools, but for uncoated cutting tool it was almost 25%.

Lowest values of the specific cutting forces were observed for machining with milling cutter deposited by DLC coating – in 19 cases lowest, but in 1 case was k_c value highest (probable caused by irregular structure of composite material). While the highest values of k_c were determined for machining with cutting tool deposited by nACo coating – in 12 cases highest, in 6 cases second highest and in 2 cases third highest k_c values. That was due to the increase of force loading acting on uncoated milling tool with growing of the tool wear. The flank wear of tested milling cutters is shown in Figure 5.

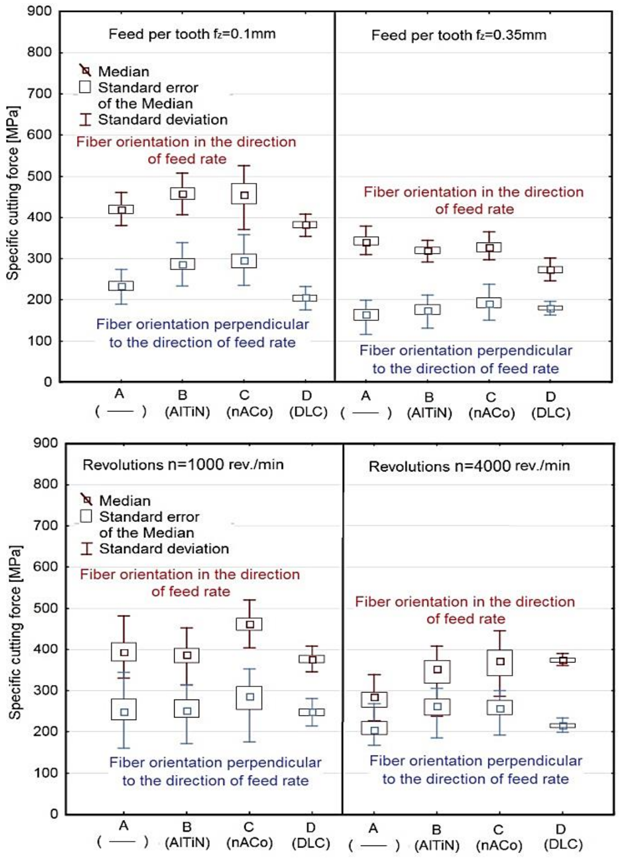

Figure 4a: The specific cutting forces at machining of glass-polyester composite.

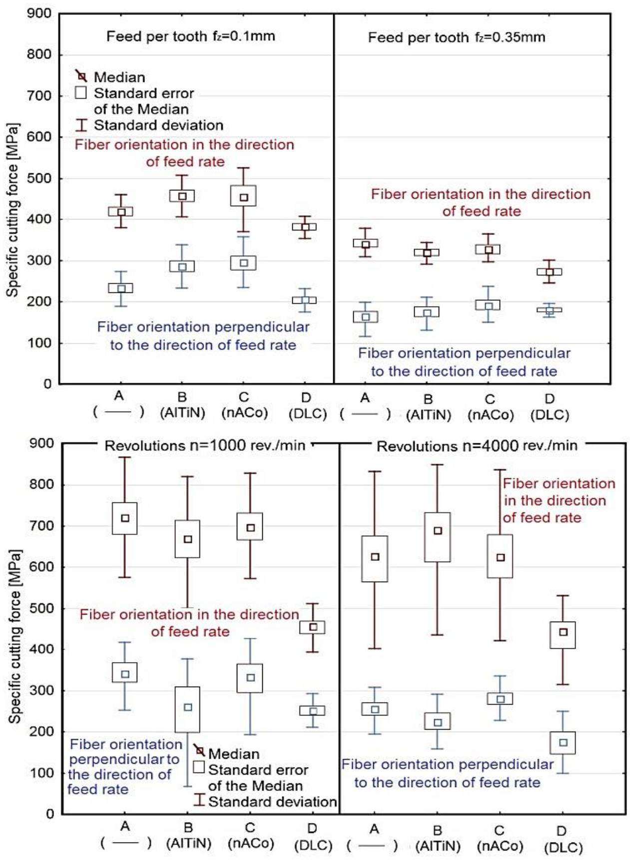

Figure 4b: The specific cutting forces at machining of glass-polyester composite.

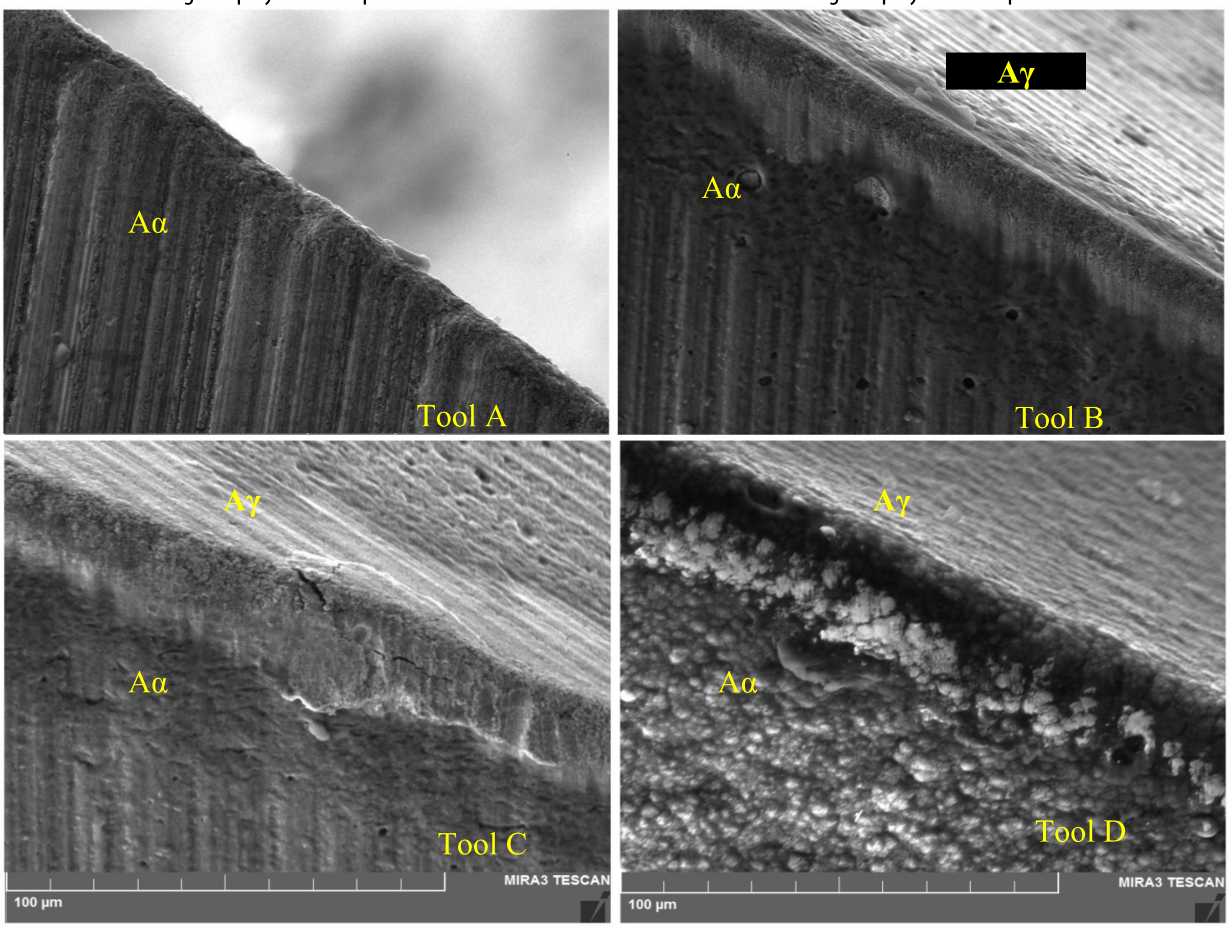

Figure 5. Cutting tools edges magnified on electron microscope TESCAN after experimental machining

5. CONCLUSION

The carbide milling cutter deposited by DLC coating has not only longest life time, but also the specific cutting force has lowest value during machining process. Therefore it may be concluded, that the carbide tool deposited by DLC is the most appropriate for machining of composite materials.

The deposition of carbide tool extended tool life, however in same cases led to increase of specific cutting force acting on the cutting tool (tool deposited nACo coating). The analysis of tested milling cutters on the electron microscope showed, that AlTiN and nACo coatings were removed from cutting edges after twenty passes through composite materials and same errors of the cutting edges occurred.

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