

# Investigation of Milling of Carbon Fiber Reinforced Plastic

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## Abstract

The use of fiber-reinforced plastics has increased significantly in the past decades. Consequently, the demand for finishing and machining of such materials has also escalated. During machining, the fiber-reinforced materials exhibit machining problems dissimilar to the problems of metals. These are fiber pull-out, fiber breakage in the cutting zone, matrix smearing and delamination. The purpose of this experiment is to investigate the characteristics of the resultant force ( $F_e$ ) during the milling of carbon fiber reinforced plastic as a function of input machining parameters. For the force measurements, CFR with perpendicular ( $0^\circ$ – $90^\circ$ ) fiber orientation was machined. The experimental design involved the central composite design method. To analyze and evaluate the measurements, we applied the response surface methodology.

**Keywords:** milling, cutting force, central composite design, RSM method.

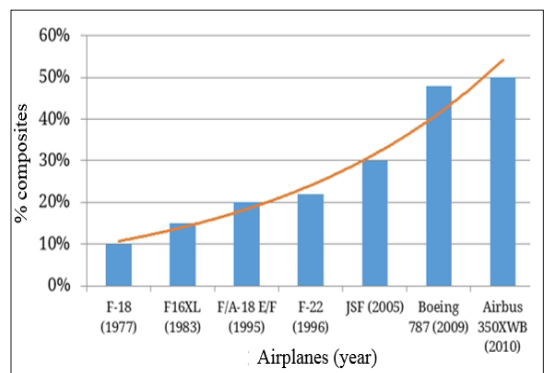
## 1. Introduction

Fiber-reinforced composites belong to a new generation of engineering materials. Thanks to their excellent mechanical properties, the use of fiber-reinforced materials (e.g. glass or carbon fiber) is increasing rapidly. One of the greatest users is the aviation industry. **Figure 1.** shows the increasing amount of carbon fiber reinforced composites used in the airframes of airplanes **[1]**. Next generation airplanes will be designed to have more than 50% composites. This reduces fuel consumption and carbon dioxide emissions by 20–25% **[2]**.

The final step in producing a carbon fiber reinforced composite product may be machining. During preliminary process planning it is important to know what cutting forces will be encountered as a function of cutting parameters, and how these forces will affect the part and the tool. For this reason, the cutting of carbon fiber-reinforced plastics is a much-researched topic.

Meltem and Hasan wrote a comprehensive study on the machinability of carbon fiber reinforced polymers **[3]** in 2018. They reviewed recent publications on the traditional machining techniques of composites (turning, milling, drilling etc.). Based on the literature, they drew the following conclusions:

- increased feed rate results in greater force;
  - the least amount of delamination can be achieved with a low cutting speed and a low feed rate;
  - for the lowest average surface roughness, a high cutting speed and a low feed rate are required.
- Mathivanan et al. **[4]** examined the machinability of glass fiber reinforced (GFRP) and carbon fiber reinforced (CFRP) plastics while closed groove milling. The fibers were laid perpendicular to each other in the workpiece. In the cutting experiment (nine measurement points) they used



**Figure 1.** The proportion of composites in the airframe of airplanes

Ø 10 mm K10 hard metal milling tool, and varied cutting parameters (cutting speed and feed per tooth) on three levels. They investigated the resultant force and found that feed increased it most. They recommend low feed and high cutting speed for the cutting of such materials.

Haijin et al. [5] milled carbon fiber reinforced plastic. They measured the force and temperature during cutting. They used the central composite design method, and applied the response surface methodology (RSM) in the analysis of the results. Their input parameters were cutting speed, feed rate and depth of cut. They found that resultant force was most influenced by feed rate, while temperature is most affected by cutting speed.

Çolak and Sunar [6] milled a carbon fiber reinforced composite consisting of 32 laminated layers. They used a  $\phi$  10 mm PCD tool and varied cutting speed on two levels (50 m/min and 100 m/min), and feed per tooth on five levels (0.050, 0.075, 0.100, 0.125 and 0.150 mm). In the experiments, they measured all three force components and surface roughness. They found that a smaller cutting force can be achieved with higher cutting speeds and lower feed rates, while surface roughness (Ra) is impaired as feed rate is increased and cutting speed is lowered.

Yanli et al. [7] examined the force during milling and delamination as a function of fiber orientation, cutting speed and feed rate. They milled a composite reinforced by 43 layers of unidirectional carbon fiber (TC35-12K / 150) at 0, 45, 90 and 135 degrees. The thickness of the laminated composite was 6 mm and the volume fraction of the fibers was approximately 60%. They varied cutting speed and feed rate on three levels. An  $\phi$  8mm milling tool was used in the experiments. They analyzed how cutting force components depend on fiber orientation. They also investigated delamination in detail.

Erol Kiliçkap et al. [8] milled a composite reinforced with 16 layers of carbon fiber. The fibers were perpendicular to each other. They used two hard metal milling tools (3-tooth and 4-tooth). They used three cutting speeds (31.4, 62.8 and 94.2 m/min) and three feed rates (100, 150 and 200 mm/min), while they kept depth of cut at a constant 1.5 mm. During milling, they measured the force components, the surface roughness of the milled surfaces and delamination phenomena on the surface. They found that as feed increases, the resultant force increases too. They got better results with the tool with 4 teeth.

Geier N. and Szalay T. [9] drilled and spiral milled

a carbon fiber reinforced composite. The drill bit was a special SECO SD205A-11.138-53-12R1-C1, diamond-coated bit, while they performed milling with a TIVOLY 8236651 1000 hard metal end mill. They measured the force components during cutting, and also the milled surfaces and the surface roughness of the holes. They also examined delamination on the machined surfaces. They used a design of experiments and did 13 drilling and 20 milling experiments. They analyzed the results with the ANOVA method. They varied the process parameters of cutting on five levels in the case of both cutting processes. Cutting speed in drilling was 50, 65, 100, 135 and 150 m/min and feed per tooth was 0.035, 0.043, 0.064, 0.078 and 0.093 mm. During milling, cutting speed was 50, 70, 100, 130 and 150 m/min) feed was 0.020, 0.028, 0.040, 0.051 and 0.060 mm, and pitch for milling was 0.100, 0.068, 1.550, 2.410 and 3.000 mm). They determined the ideal process parameters, and also found that a hard metal milling bit produced better quality bores than a diamond-coated bit.

We milled a carbon fiber reinforced composite and measured the force components, and analyzed the resultant force. We examined the effect of cutting process parameters on the resultant force.

We built a predictive model, with which the resultant force can be estimated with adequate accuracy in preliminary process planning, as most defects and the properties of the part (e.g. delamination, dimensional inaccuracy, fiber breakage in the cutting zone, fiber pull-out, surface roughness values) greatly depend on cutting force.

## 2. Materials and methods

### 2.1. The material and tool used in the experiment

We milled a 26-layer (10 mm thick) carbon fiber reinforced composite produced by vacuum infusion. The carbon fiber was Zoltek Panex 35. Its aerial density is 400 g/m<sup>2</sup>, its tensile strength is 4137 MPa, its modulus of elasticity is 242 GPa, and the diameter of the fibers is 7.2. The epoxy resin used was Araldite LY 1564, and the curing agent was Aradur 3487. Their proportion was 100 g resin/34 g curing agent.

The composite was cross-ply laminated (Figure 2.). We used a  $\phi$  10mm D-POWER GUF40100 end mill, which is specially designed to mill fiber-reinforced composites. A great advantage of this tool is that it reduces the moving of layers away from each other.

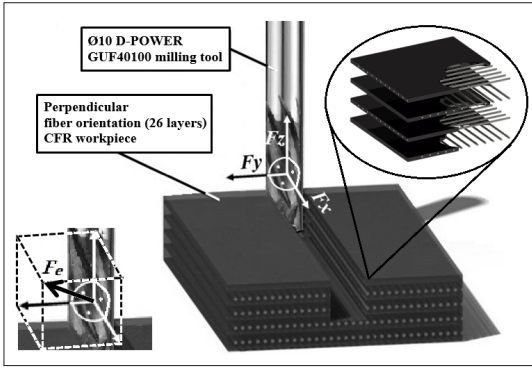


Figure 2. Layout of the cutting experiment, and the direction of the force components

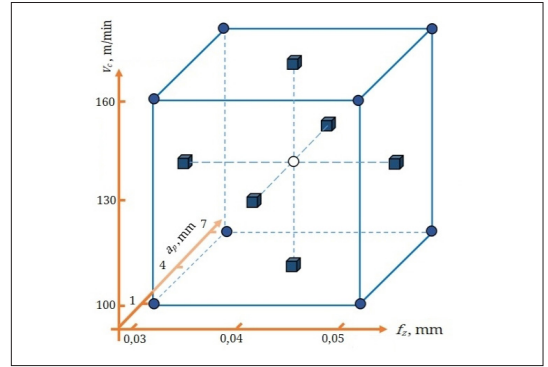


Figure 3. The points of experiment in the cutting parameter space

2.2. The measuring instruments used and the measured parameters

We performed the milling experiments on a Mazak Nexus 410A-II machining center. Force was measured with a piezoelectric KISTLER 9257b dynamometer. We measured the  $F_x$ ,  $F_y$  and  $F_z$  force components. The range of the dynamometer is  $F_x = F_y = -5...5$  kN, and  $F_z = -5...10$  kN. The measured force components were analyzed with the Kistler DynoWare software. The tool and the workpiece are affected by the resultant force (Figure 1.), therefore we examined the resultant force ( $F_e$ ):

$$F_e = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{1}$$

2.3. The Design of Experiments

We used the central composite design method in the milling experiments. Input variables (cutting speed and feed per tooth, depth of cut) were varied on three levels. We evaluated the data with the response surface methodology. The levels are equidistant from each other (Table 1., Figure 3.). The measured output variable is the resultant force ( $F_e$ ). We sought to find a relationship between the independent input variables  $x_1$ ,  $x_2$ ,  $x_3$  and the dependent output variable  $Y$ :

$$Y = \Omega(x_1, x_2, x_3) \tag{2}$$

Table 1. The values of input parameters

Process parameters		Level		
		-1	0	1
$x_1$	cutting speed – $v_c$ , m/min	100	130	160
$x_2$	feed – $f_s$ , mm	0.03	0.04	0.05
$x_3$	depth of cut – $a_p$ , mm	1	4	7

where  $\Omega$  is the response function, which can be written in the following general form:

$$Y = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 + b_{11} \cdot x_1^2 + b_{22} \cdot x_2^2 + b_{33} \cdot x_3^2 + b_{12} \cdot x_1 \cdot x_2 + b_{13} \cdot x_1 \cdot x_3 + b_{23} \cdot x_2 \cdot x_3 + \epsilon \tag{3}$$

where  $b_0$ ,  $b_i$  and  $b_{ij}$  are the calculated coefficients,  $x_1$ ,  $x_2$  and  $x_3$  are the input variables and  $\epsilon$  is the error. Model (3) takes into account input process parameters, their second-order components, and if they have a significant effect, then the cross-effects of the input process parameters as well.

2.4. The measurement points of the design of experiments

We set the cutting parameters and their level based on the literature and the recommendations of the tool catalogue (Table 1.).

Figure 3. shows the measurement points on the cutting parameter range based on Table 1. Based on the design of experiments, we milled the specimen at the factorial points and axis points of the cube once, and six times with the process parameters at the center of the cube.

The points of experiment and their parameters can be found in Table 2.

3. Results

3.1. The effect of cutting process parameters on the resultant force

Figure 4. shows the main effect plots obtained from the results.

The main effect plots show that increasing feed per tooth and increasing depth of cut increase the resultant force.

**Table 2.** The calculated and measured resultant forces in the 20 measurement points

Experimental runs	$v_c$ m/min	$f_z$ mm	$a_p$ mm	$F_e^e$ N (measured)	$F_e^c$ N (calculated)
1.	100	0.03	1	26.57	22.83
2.	160	0.03	1	18.95	21.70
3.	130	0.04	1	21.03	26.07
4.	100	0.05	1	33.95	30.45
5.	160	0.05	1	31.17	29.32
6.	130	0.03	4	99.32	97.04
7.	100	0.04	4	117.31	123.17
8.	160	0.04	4	114.24	122.04
9.	130	0.04	4	133.70	122.61
10.	130	0.04	4	131.05	122.61
11.	130	0.04	4	127.07	122.61
12.	130	0.04	4	122.48	122.61
13.	130	0.04	4	118.16	122.61
14.	130	0.04	4	124.19	122.61
15.	130	0.05	4	142.72	148.18
16.	100	0.03	7	173.24	172.38
17.	160	0.03	7	174.36	171.25
18.	130	0.04	7	208.12	219.14
19.	100	0.05	7	267.26	267.03
20.	160	0.05	7	273.99	265.90

**3.2. A predictive model to estimate the resultant cutting force**

**Table 3.** shows which cutting parameters had a significant effect on the resultant force (the linear components of input process parameters re-main in the model irrespective of their significance).

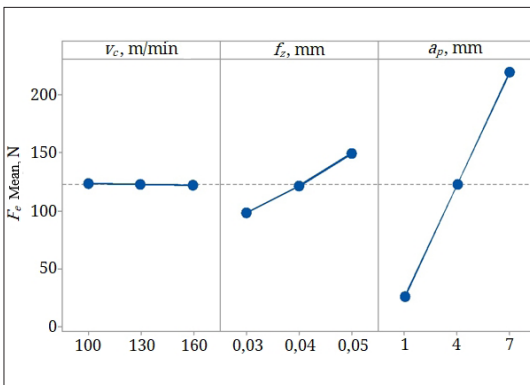
**Table 3.** The result of the significance test (✓ – the process parameter has a significant effect on the resultant force, ✗ – the process parameter does not affect the result-ant force)

Cutting parameters	
$v_c$	✓
$f_z$	✓
$a_p$	✓
$v_c^2$	✗
$f_z^2$	✗
$a_p^2$	✗
$v_c \cdot f_z$	✗
$v_c \cdot a_p$	✗
$f_z \cdot a_p$	✓

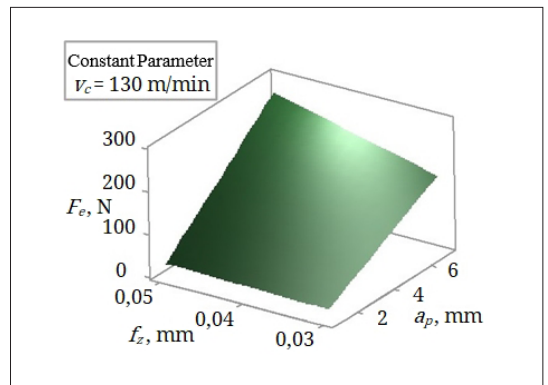
After the significance test, we built the following predictive model from the factors affecting the resultant cutting force:

$$F_e = 10,1 - 0,0188 \cdot v_c - 344 \cdot f_z + 3,17 \cdot a_p + 725,2 \cdot f_z \cdot a_p \tag{4}$$

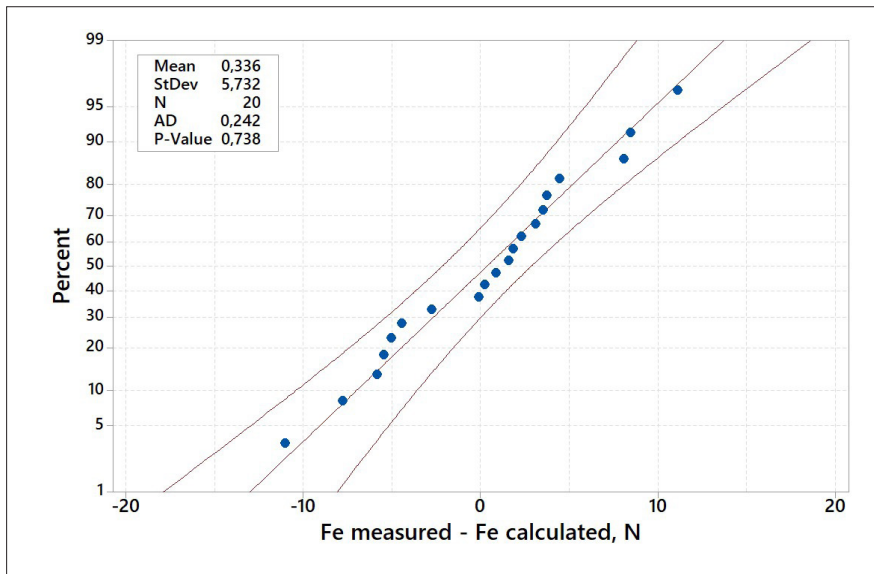
**Figure 5.** shows the effects of process parameters on the resultant force graphically. It clearly shows that minimal cutting force is obtained when feed and depth of cut are lowest.



**4. ábra.** A forgácsolási folyamatváltozók hatása az eredő erőre



**Figure 5.** The graphical representation of the predictive model (4)



**Figure 6.** The residuals of measured and calculated results on the probability plots

The predictive model can be considered adequate in preliminary process planning if the expected value of the residuals (the difference between the measured and calculated values) are near zero and the standard deviation of the residuals is as low as possible. **Figure 6.** shows the differences of the measured and calculated results on a probability plots. It is clearly visible that in estimating the resultant force, the expected value of the errors is near zero, the distribution of the errors approximates normal distribution well and their standard distribution is  $\pm 5,7$  N.

#### 4. Conclusions

We investigated the milling of a carbon fiber reinforced composite with the central composite design method. We used three levels of the cutting process parameters (cutting speed, feed per tooth and depth of cut), measured the cutting force components and examined the resultant force. We analyzed the effect of the cutting process parameters on the examined characteristics with main effect plots and made a predictive model to estimate the resultant cutting force as it can help preliminary process planning. Based on our experiments, we can draw the following conclusions:

- cutting speed has the least (negligible) effect on the resultant cutting force;
- increasing feed and depth of cut increases the resultant cutting force;

- depth of cut has the greatest effect on the resultant cutting force;

We built a predictive model to estimate the resultant force in the examined range of cutting process parameters. The model can estimate the resultant force with a standard deviation of  $\pm 5,7$  N.

#### Acknowledgements

The authors would like to thank KANDSI Kft. (AKO-BEZ) for providing the custom-made specimens, and GranTOOL Kft. for providing the tool for the tests. This project was supported by the New National Excellence Program (ÚNKP-2018-1-I) of the Ministry of Human Resources.

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