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Effect of Face Milling Parameters of Carbon Fiber Reinforced Plastics Composites on Surface Properties

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ABSTRACT
This paper analyses the influence of face milling process parameters on the surface properties of carbon fibre reinforced polymer. The influence of milling speed and feed per tooth on the surface properties was determined. The influence of cutting speed and feed per tooth on surface energy properties was determined. The object of research was a carbon fiber reinforced plastics (CFRP) composites plate made of carbon fibre in epoxy matrix. The tool used in the study was a double-edged end mill. The machining parameters used were variable: cutting speeds of 100 $m \cdot min^{-1}$, 120 $m \cdot min^{-1}$, 140 $m \cdot min^{-1}$ and 160 $m \cdot min^{-1}$, and feeds per tooth of 0.015 mm/tooth, 0.020 mm/tooth, 0.025 mm/tooth and 0.03 mm/tooth. The axial depth of cut and radial depth of cut was a constant parameter. After milling, tests were carried out on the surface contact angle, which was used to determine the surface free energy. Based on the contact angle measurements carried out with the sitting-drop method and the calculation of the surface free energy with the Owens-Wendt model, it was observed, that the increase in the value of the surface free energy is significantly influenced by the increase in the cutting speed.

Keywords: carbon fibre reinforces plastics, face milling, surface free energy, Owens-Wendt model.

INTRODUCTION

Polymer matrix composites have been of immense interest to engineers and researchers alike for the past decade and this interest is still increasing. A carbon fibre reinforced plastic composites consist of carbon fibres as reinforcement and a matrix phase in the form of a polymer resin [1,2]. The fibres are load-bearing and the bonds and protects the carbon fibres with the matrix [3–6]. CFRP composites have excellent properties such as a high stiffness-to-weight ratio and low density, or fatigue and wear resistance. They are also characterised by high corrosion resistance, dimensional stability, and low coefficient of friction and low electrical conductivity, as well as low thermal expansion [7–10]. Fiber reinforced composite materials are used in industry sectors, e.g.: aerospace, yachting, shipbuilding, automotive, sports, medicine as well as biomedical applications [11–14]. The production of the Airbus A350 XWB aircraft is an example of the use of CFRP composites. In this case, CFRP accounts for up to 50% of the total material, and components made from CFRP included wing spars and parts of the fuselage. The unpressurised fuselage, landing gear as well as the trailing edge on commercial aircraft are also produced from CFRP composites [13].

Polymer composites, which are a relatively new type of engineering materials, were subjected to numerous studies. These works mainly focus on the description of their surface quality after machining operations in terms of geometry and surface topography. One of the papers concerning milling of this type of materials was published

by K. Ciecieląg [15], in which the influence of face milling parameters on the surface roughness of glass and carbon fibre reinforced plastics was determined. R. Teti, in his work [16] presents a general description of composites with polymer, metal or ceramic matrices, where he also described the turning, cutting, milling and drilling process of each of these materials.

When machining fibre reinforced composite materials, it is important to use tools with the suitable geometry, which are made of wear-resistant materials [17]. In this study, the materials were prepared by face milling. Polymeric composites are subjected to face milling in many cases, including as a means of surface preparation for adhesive processes, as well as a finishing treatment to remove the allowance created during manufacturing, or just to improve the surface quality [18–20]. The selection of the milling parameters should take into account in particular the structure of the material and the orientation and type of fibres [21]. By reviewing previously published research papers on the milling process of carbon fibre reinforced plastics composites [15, 19, 22–26] it was observed that the cutting speeds used by researchers ranged from 20 to 250 m/min, the feed per tooth in the range of 0.01 to 0.5 mm/blade and the depth of cut from 0.1 to 4 mm. Analysing the research results presented in the above-mentioned works, it can be observed a variety of results and a changeable influence of the applied processing parameters on the surface quality of the obtained surface. However, taking into account the adhesive or energetic properties of the surface, in the current review of literature there were no papers describing the influence of the face milling process of carbon fibre reinforced plastics composites on the value of the surface contact angle and the surface free energy.

Studies of the properties of CFRP composites, including surface energetics, wettability and surface free energy, may prove to be important elements in the assessment of surface properties. Moreover, as A. Rudawska presents in paper [27], the observation and analysis of contact angle values and surface free energy is also important when processing the tested composite materials by adhesion-based processes. Similar observations in other papers are presented by Kłonica and Kuczmaszewski [28, 29] that the energy state of structural materials is particularly important in technologies where adhesion is crucial for process performance. This makes it possible to analyse the adhesive properties of surfaces that are applied to processes such as painting, coating or bonding. Therefore, the aim of this study is to analyse the influence of cutting parameters such as face cutting speed and feed per tooth on the surface energy properties of carbon fibre reinforced plastics composites determined by the contact angle and surface free energy.

RESEARCH METHODOLOGY

Materials used in the study

The material used in the study was CFRP plates. The plates were made using vacuum bag technology with a vacuum pressure of 0.9 bar. The moulds used were two steel plates with a polished surface treated with Frekote 770NC liquid release agent from Loctite Company (Hemel Hempstead, UK) placed in a plastic bag and then electrically resistance welded. The board layers were impregnated layer by layer using the wet method and applying successive layers by hand. The prepared material was cured in an oven at 50° for 4 hours, followed by an 8-hour heat treatment at 110°C. The material was then left to cool down spontaneously. After the plates were de-moulded, their edges were CNC machined to obtain the final dimension. The final thickness of the CFRP sheets was 9.5 mm.

A carbon fibre fabric in an epoxy matrix was used to manufacture the CFRP composites

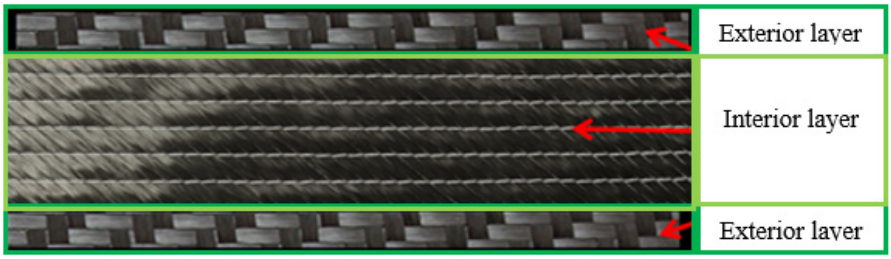


Fig. 1. Structure of the material layers in the CFPR composite

plates. The entire panel consisted of 11 layers. The outer layers of the board were two layers of 2X2 twill CF fabric by 245 g/sq. 3K threads. The stacking sequence of the exterior layers was [0/90/±45]. In interior of the CFRP plates was used ±45 biaxial CF by 300 g/sq, type CF-BI-300-127. The stacking sequence of the layers was [±45]. MGS® RS-L 285 epoxy laminating resin and Hardeners RS-H 286 catalyst from Lange-Ritter GmbH (Gerlingen, Germany), were used as matrices. The mixing ratio of resin and catalyst was 100:40 parts in weight ratio. The stacking sequence of the exterior layers was [0/90/±45]. In interior of the CFRP plates was used ±45 biaxial CF by 300 g/sq, type CF-BI-300-127. A schematic layout of the material layers in the plate structure is shown in Figure 1.

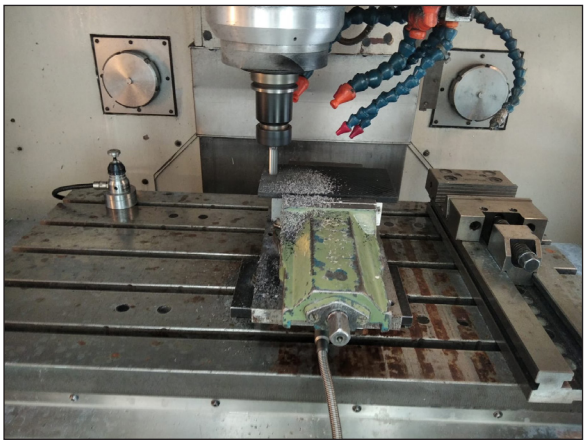


Fig. 2. Test stand with mounted sample

Test stand and tools

The machining of CFRP was carried out on an Avia VMC 800HS vertical machining centre. Specimens were clamped in a vice on the machine's milling table. A view of the station and specimen clamping is shown in Figure 2.

The tool used in this study to machine the CFRP surface was an end milling cutter dedicated to machining composites (shown in Figure 3). The Seco cutter has a diameter of ø12mm and is fitted with two teeth and is commercially available as EDP 65056.

Fig. 3. The milling cutter used in the machining

Table 1. Technological parameters of the face milling process of CFRP composites

Marking	Radial depth of cut a_e, mm	Axial depth of cut a_p, mm	Cutting speed v_c, m·min^{-1}	Feed per tooth f_z, mm/ostrze
Milling 1	12	1	100	0.015
Milling 2	12	1	100	0.02
Milling 3	12	1	100	0.025
Milling 4	12	1	100	0.03
Milling 5	12	1	120	0.015
Milling 6	12	1	120	0.02
Milling 7	12	1	120	0.025
Milling 8	12	1	120	0.03
Milling 9	12	1	140	0.015
Milling 10	12	1	140	0.02
Milling 11	12	1	140	0.025
Milling 12	12	1	140	0.03
Milling 13	12	1	160	0.015
Milling 14	12	1	160	0.02
Milling 15	12	1	160	0.025
Milling 16	12	1	160	0.03

During the concurrent face milling of the CFRP composites, the constant parameters were the axial depth of cut and radial depth of cut. The variable parameters were cutting speed and feed per tooth. The machining parameters used in the study are presented in Table 1.

Test stations and computational methods

After the face milling process contact angles were measured, which were then used to determine the surface free energy (SFE), which was determined using the Owens-Wendt model. The Owens-Wendt model is based on the direct measurement of the contact angle using two measuring fluids (non-polar - diiodomethane CH_2J_2 and polar - distilled water), whose value is known for the polar and dispersive components of the SFE, which are presented in Table 2. On the basis of the obtained angle values, the polar and dispersive components of the SFE were determined, according to the equation (1) [30–32].

$$\gamma_S = \gamma_S^d + \gamma_S^p \tag{1}$$

where: γ_S - surface free energy, γ_S^d - dispersion component of SFE, γ_S^p - polar component of SFE.

The components γ_S^d and γ_S^p of the SFE of the interfaces can be calculated from the equations (2) i (3):

$$\left(\gamma_s^d\right)^{0.5} = \frac{\gamma_d(cos\theta_d + 1) - \sqrt{\frac{\gamma_d^p}{\gamma_w^p}}\gamma_w(cos\theta_w + 1)}{2\left(\sqrt{\gamma_d^d} - \sqrt{\gamma_d^p\frac{\gamma_w^d}{\gamma_w^p}}\right)} \tag{2}$$

$$\left(\gamma_s^p\right)^{0.5} = \frac{\gamma_w(cos\theta_w + 1) - 2\sqrt{\gamma_S^d\gamma_w^d}}{2\sqrt{\gamma_w^p}} \tag{3}$$

where: γ_d – SFE of diiodomethane, γ_d^d – dispersive component of the SFE of diiodomethane, γ_d^p – polar component of the SFE of diiodomethane, γ_w – SFE of water, γ_w^d – dispersive component of the SFE of water, γ_w^p – polar component of the SFE of water, θ_d – the value of the contact angle measured with diiodomethane, θ_w – the value of the contact angle measured with distilled water.

The droplet volume of the measuring liquids was about 2 µl. Contact angle measurements were carried out at 21±1°C and 30±1% air humidity. PGX pocket goniometer was used for the measurements. Ten repetitions of the measurement were carried out on each sample with each measuring liquid. All results of contact angle measurements, both for water and for diiodomethane, were statistically processed, which became the basis for the determination of the SFE by the Owens-Wendt model.

After the face milling process, control images of the surface structure were also taken with an Alicona InfiniteFocusG5 3D microscope (Raaba, Graz, Austria).

RESULTS AND DISCUSSION

On the basis of the research carried out, values of the contact angle were obtained for the surfaces machined by face milling using the parameters in Table 1. The obtained results were statistically processed and the average values were determined, and the standard deviation was determined. The results are presented in Table 3.

Based on the results presented in Table 3, it can be seen that the contact angle value for water was higher for lower cutting speeds. Similarly for the contact angles measured with diiodomethane, but in this case the range of scatter of the results was not so high. The standard deviation of the obtained results was within the following ranges: for water: 8.3–17.7%, for diiodomethane: 5.1–14.2%. These standard deviations may be due to defects on the processed surface caused by fibres being pulled out

Table 2. Values of polar and dispersive components of the surface free energy of water and diiodomethane [30, 31, 33]

Measuring liquids	Surface free energy of the measuring liquid γ_S	Dispersive component of the surface free energy of the measuring liquid γ^d	Polar component of the surface free energy of the measuring liquid γ^p
Distilled water	72.8 mJ/m²	21.8 mJ/m²	51.0 mJ/m²
Diiodomethane	53.2 mJ/m²	50.8 mJ/m²	2.4 mJ/m²

Table 3. Contact angle value averaged over 10 measurements

Marking	Variable parameter		Contact angle (measuring liquid)			
			(Distilled water) Θ_w [°]		(Diiodomethane) Θ_d [°]	
	Cutting speed v_c, [m·min^{-1}]	Feed per tooth f_z, [mm/tooth]	Average	Standard deviation	Average	Standard deviation
Milling 1	100	0.015	79.4	8.78	48.9	5.87
Milling 2	100	0.02	88.3	7.99	53.3	3.44
Milling 3	100	0.025	85.8	8.26	53.0	3.98
Milling 4	100	0.03	79.3	8.21	49.2	6.98
Milling 5	120	0.015	75.6	7.57	50.7	6.88
Milling 6	120	0.02	73.4	9.76	55.4	2.98
Milling 7	120	0.025	69.5	7.96	55.4	2.92
Milling 8	120	0.03	68.1	8.02	50.5	4.93
Milling 9	140	0.015	60.9	8.86	51.1	2.41
Milling 10	140	0.02	70.2	9.69	48.7	4.64
Milling 11	140	0.025	59.5	4.92	51.2	4.23
Milling 12	140	0.03	58.5	5.86	51.2	5.06
Milling 13	160	0.015	65.5	9.6	49.8	5.97
Milling 14	160	0.02	64.0	10.01	46.9	2.41
Milling 15	160	0.025	67.4	8.59	48.7	4.63
Milling 16	160	0.03	70.5	10.39	46.7	4.18

of the material structure during milling. Examples of the defects formed are illustrated in the photographs of the surface structure taken with a 3D microscope in Table 4. It also shows the droplet obtained during contact angle measurements for a set of technological parameters of face milling of surfaces, for which minimum and maximum of contact angles were obtained.

Analysing the images shown, it can be seen that the machined surfaces exhibited localised pulling out of the fibres of the outer layer of the CFRP composites. In the case of surfaces where

Table 4. Droplets for measuring surface contact angles of CFRP sheet samples after milling and surface structure images

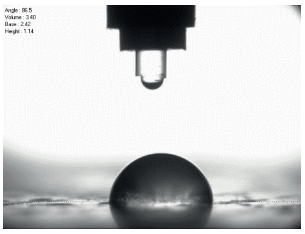
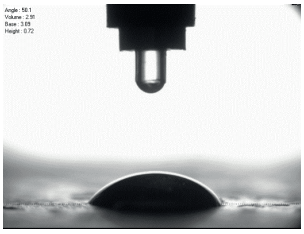
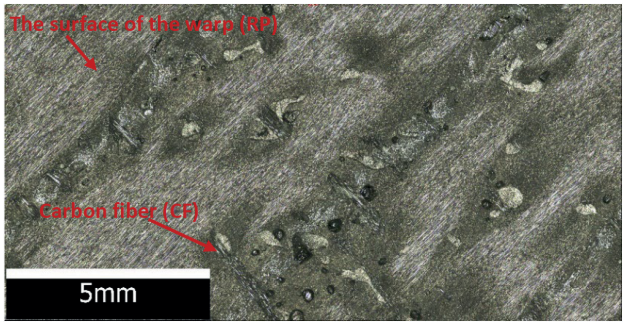
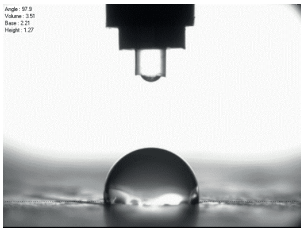
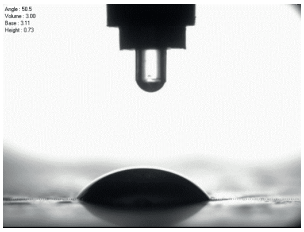
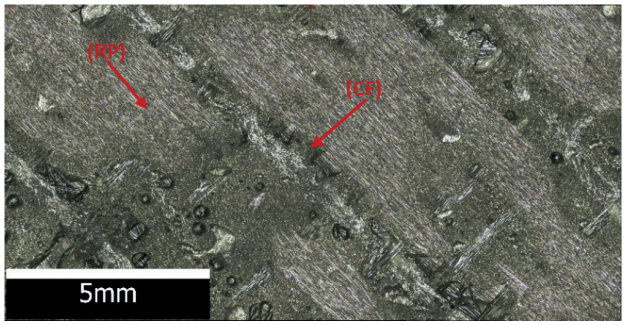
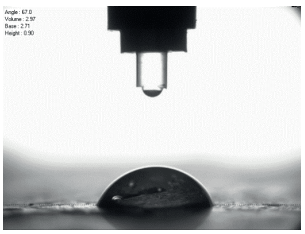
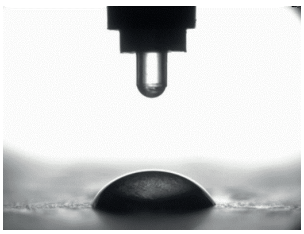
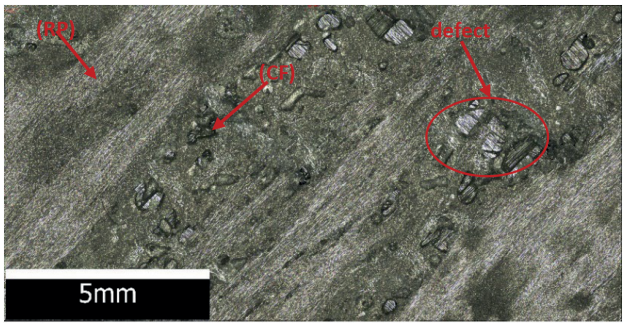
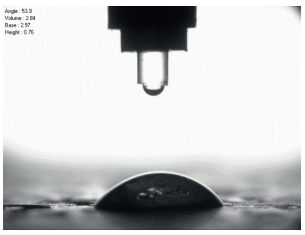
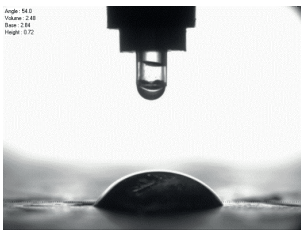
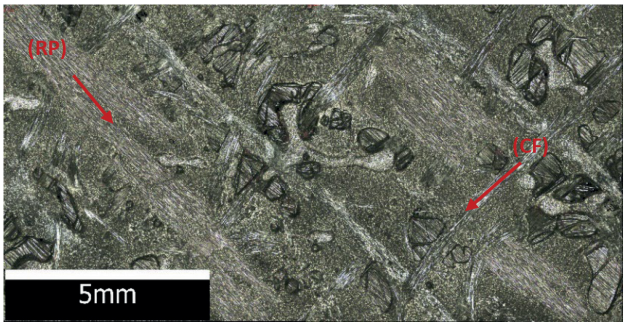
Marking	Contact angle (measuring liquid)	
	(Distilled water) Θ_w [°]	(Diiodomethane) Θ_d [°]
Milling 1	 Θ_w = 79.4°	 Θ_d = 48.9°
		

Table 4. Cont.

Milling 2	 Θ_w = 88.3°	 Θ_d = 53.3°
		
Milling 7	 Θ_w = 69.5°	 Θ_d = 55.4°
		
Milling 12	 Θ_w = 58.5°	 Θ_d = 51.2°
		

larger surface defects were observed (for face milling 7 and face milling 12), the value of the polar liquid contact angle was lower. On the surfaces where the surface defects are smaller, the value of the polar liquid contact angle was higher, which indicates that there was less wetting of the surface by the measuring liquid.

Based on the contact angle values obtained, the SFE components were calculated and the results obtained are shown in the graphs below. Figures 4–7 show the effect of changing the face milling speed (according to Table 1) on the value of SFE.

On the basis of the graphs presented, it can be seen that the value of the SFE increases with an increase in the cutting speed from 100 m·min^{-1} to 160 m·min^{-1}. There is also an increase in the polar component of the SFE, while the dispersion component decreases or remains at a similar level. In each case, regardless of the parameters of machining the

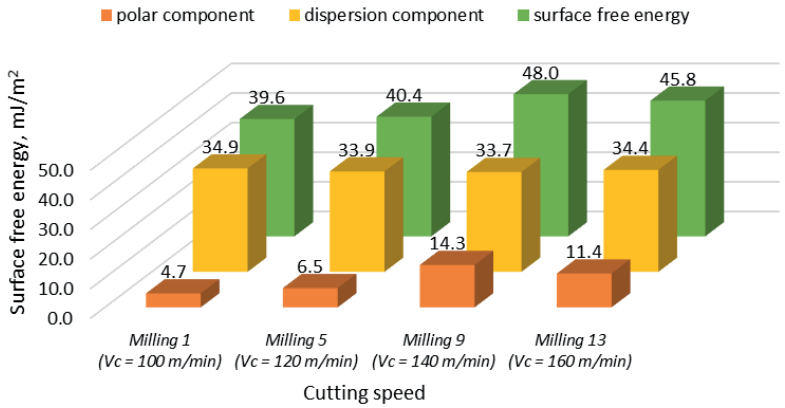


Fig. 4. Relationship between cutting speed and surface free energy at f_z = 0.015 mm/tooth

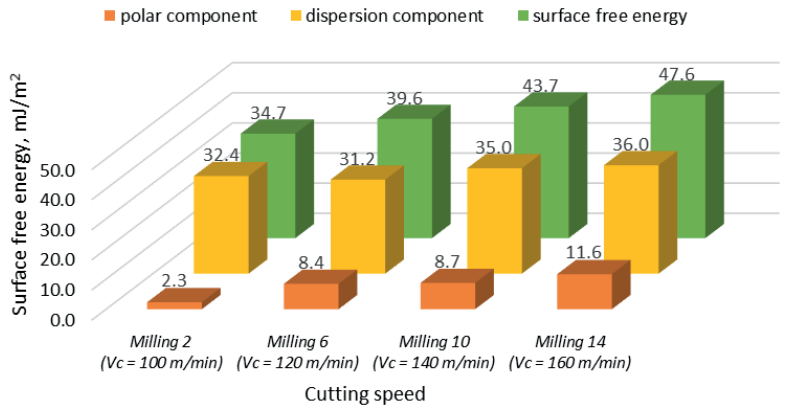


Fig. 5. Relationship between cutting speed and surface free energy at f_z = 0.020 mm/tooth

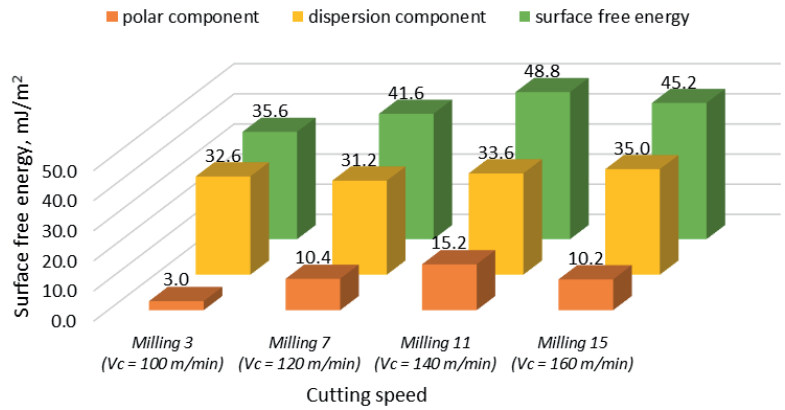


Fig. 6. Relationship between cutting speed and surface roughness parameters at f_z = 0.025 mm/tooth

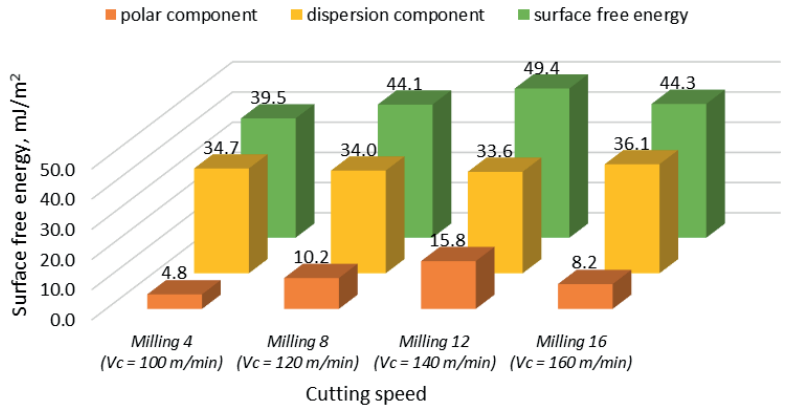


Fig. 7. Relationship between cutting speed and surface roughness parameters at f_z = 0.030 mm/tooth

composites surface, the dispersive component was much higher than the polar component (more than 70–90 % of the total SEP value).

For a more detailed comparison, the effect of changing the feed per tooth on the value of SFE was also evaluated. This comparison is shown in Figures 8–10.

Analysing the influence of the feed per tooth on the value of the SFE, based on the result shown in Figures 8–11, it can be observed that by varying the feed rate per tooth linearly, the value of the SFE does not show a constant characteristic.

However, in order to accurately analyse the results obtained, it is necessary to perform a

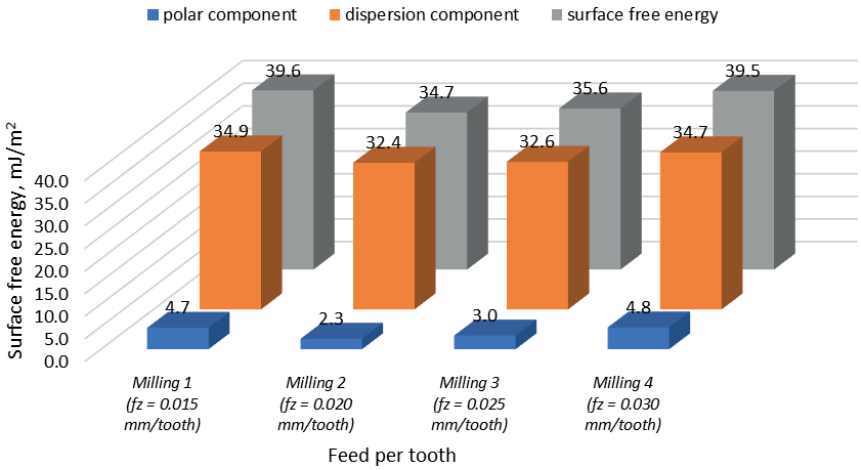


Fig. 8. Relationship between feed per tooth and surface free energy at v_c = 100 m·min^{-1}

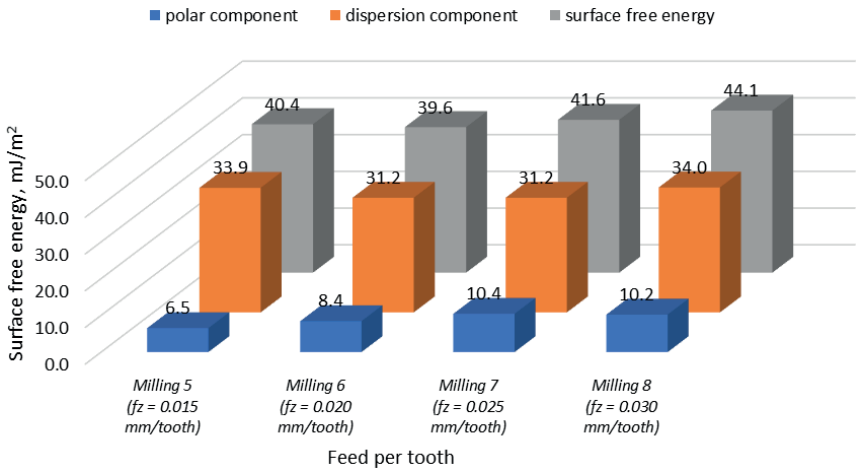


Fig. 9. Relationship between feed per tooth and surface free energy at v_c = 120 m·min^{-1}

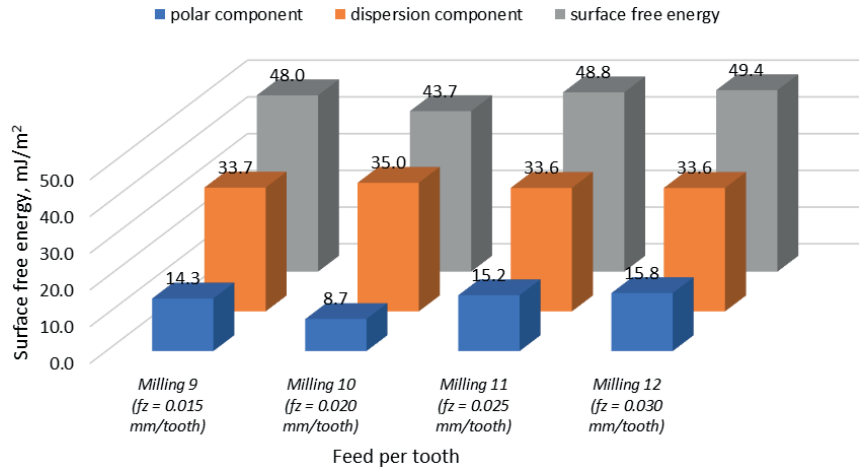


Fig. 10. Relationship between feed per tooth and surface free energy at v_c = 140 m·min^{-1}

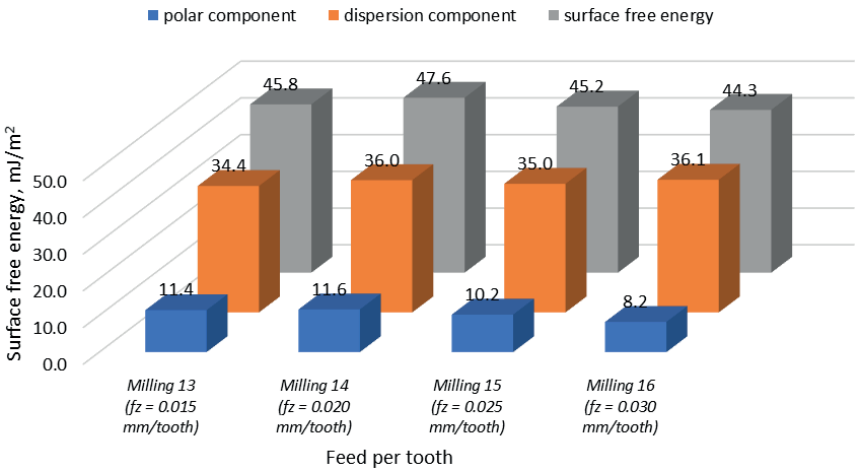


Fig. 11. Relationship between feed per tooth and surface free energy at v_c = 160 m·min^{-1}

statistical analysis using the Statistica programme. The assumption of normality of distribution and equality of variance was fulfilled at the assumed significance level α = 0.05. At first, a correlation study between factors was carried out to determine the influence of machining parameters on the value of SFE of the CFRP composites after face milling. Table 5 summarises the results obtained.

Analysing the results of the correlation tests presented in Table 5, it can be observed that in case of cutting speed, the Pearson correlation coefficient is 0.80, which indicates a strong linear dependence of cutting speed on SFE. The coefficient of determination is 0.64, which means that the change in SFE is explained 64% by the change in cutting speed. The significance level p for the t statistic is less than 0.05, which means that the correlation coefficient is significantly different from 0. When analysing the feed rate per tooth, it can be seen that the correlation coefficient is

Table 5. Results of a study on the correlation of face milling parameters and surface free energy

Parameters	Correlations at a significance level of p < 0.05000					
	Average	Standard deviation	r(X,Y)	r2	t	p
Cutting speed v_c [m/min]	130.00	23.09				
Surface free energy	42.99	4.51	0.80	0.64	4.97	0.00
Feed per tooth f_z [mm/tooth]	0.02	0.01				
Surface free energy	42.99	4.51	0.10	0.01	0.39	0.70

where: r (X,Y) – Pearson correlation coefficients, r2 – coefficient of determination, t – value of the t statistic testing the significance of the correlation coefficient, p – the calculated significance level for the t-test.

only 0.10, so it can be concluded that there is no relationship between the feed rate per tooth and the value of SFE.

In order to illustrate the change in SFE as a function of the change in face milling process parameters, scatter diagrams of the results obtained are shown in Figure 12.

The next step was to evaluate the differences between the obtained the SFE results. In order to find unequivocally which parameters allow to obtain a CFRP composites surface with the lowest SFE, i.e. characterised by hydrophobic properties, an ANOVA analysis was performed. The Tukey test of homogeneous

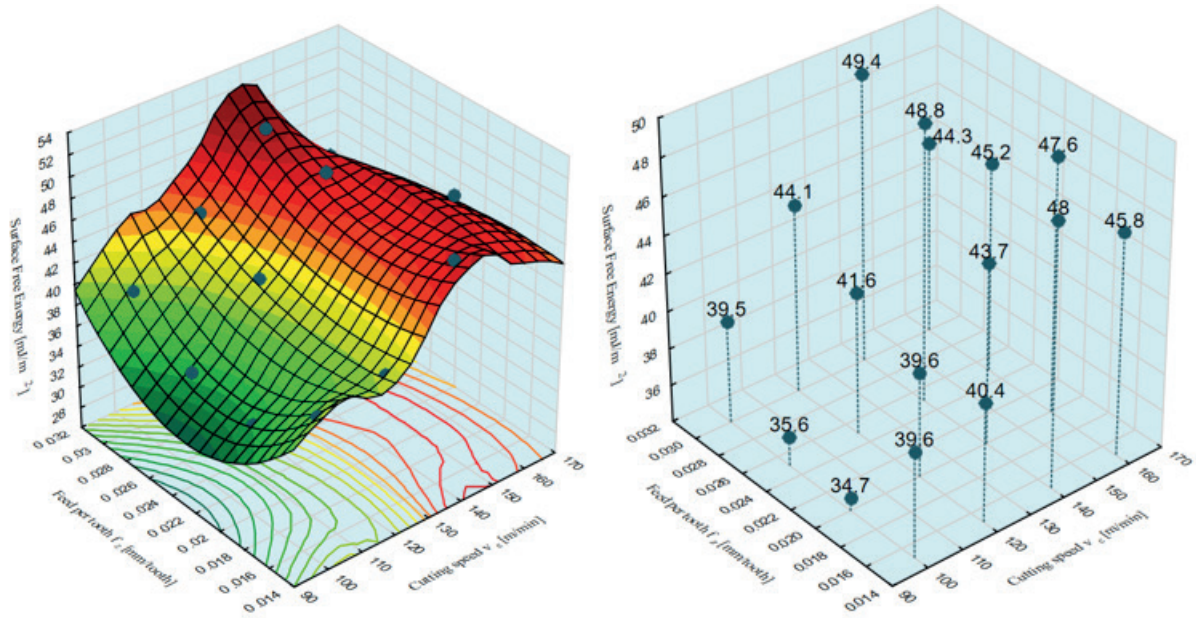


Fig. 12. 3W scatter diagrams: cutting speed v_c [m/min] vs. feed per tooth f_z [mm/tooth] vs. surface free energy [mJ/m^2]

Table 6. Results of the HSD Tukey test of homogeneous groups

Tukey's HSD test Homogeneous groups, alpha = .05000 Error: Between-group MS = 4.7627, df = 12.000						
Marking	Variable parameter		Average Surface Free Energy [mJ/m2]	Homogeneous groups		
	Cutting speed v_c, [m/min]	Feed per tooth f_z, [mm/tooth]		1	2	3
Milling 1	100	0.015	39.6	****		
Milling 2	100	0.02	34.7	****		
Milling 3	100	0.025	35.6	****		
Milling 4	100	0.03	39.5	****		
Milling 5	120	0.015	40.4	****	****	
Milling 6	120	0.02	39.6	****	****	
Milling 7	120	0.025	41.6	****	****	
Milling 8	120	0.03	44.1	****	****	
Milling 9	140	0.015	48.0			****
Milling 10	140	0.02	43.7			****
Milling 11	140	0.025	48.8			****
Milling 12	140	0.03	49.4			****
Milling 13	160	0.015	45.8		****	****
Milling 14	160	0.02	47.6		****	****
Milling 15	160	0.025	45.2		****	****
Milling 16	160	0.03	44.3		****	****

groups was performed. The test results are presented in Table 6.

When machining CFRP composites, it is desirable to obtain the highest possible value of the polar liquid contact angle and, at the same time, the lowest value of the SFE when considering the acquisition of hydrophobic properties. When face milling of a composites is used as a surface preparation treatment for further operations, it is expected to increase the surface wettability [27]. According to the results presented in Table 6, it can be observed that lower cutting speeds produce a surface characterised by a lower value of SFE. The results obtained at cutting speeds of 100 m/min and 120 m/min place them in one homogeneous group. The last homogeneous group contains the results obtained at the highest of the used cutting speeds, 140 m/min and 160 m/min.

CONCLUSIONS

Carbon fibre reinforced plastic composites, are characterised by excellent properties and therefore attract the attention of researchers and are very popular in numerous engineering applications such as automotive, aerospace, biomedical applications, sports items, robot cells, etc. The knowledge of the surface properties of engineering materials is very important for the preparation of the surfaces of components, for further operation, as they influence all the operations involved in the joining, painting or coating process, as well as the resistance to external factors.

In this paper, the influence of cutting parameters such as cutting speed and feed per tooth on the surface energy properties of CFRP was evaluated. For this purpose, the contact angle values were measured with two measuring liquids: polar - distilled water, and dispersive - diiodomethane. On the basis of the obtained values, the SFE was calculated using the Owens-Wendt model. On the basis of the results obtained, the following conclusions were formed. The contact angle values for both measuring liquids were higher for lower cutting speeds. In the case of angle measurements with a dispersion liquid, the scatter of results was lower. For both water and diiodomethane contact angle measurements, the standard deviation did not exceed 15%. Differences between contact angle measurements within one surface could be due to surface defects caused by fibres being pulled out of the CFRP plate structure during milling. On surfaces with less surface defects, the values of the contact angles measured with the polar liquid were higher, which may consequently result in less wetting of the surface by the measuring liquid. Such surfaces show hydrophobic properties. As the cutting speed increases, the value of the surface free energy increases. There is also an increase in the polar component of the surface free energy, while the dispersion component decreases or remains at a similar level. Regardless of the CFRP composites surface machining parameters, the dispersion component was significantly higher than the polar component (more than 70–90 % of the total SEP value).

There is a strong linear correlation between the cutting speed and the surface free energy, as shown by the Pearson correlation coefficient of 0.80, while there is no correlation between the feed per tooth and the surface free energy, with a correlation coefficient of only 0.10. Lower cutting speeds on the CFRP composites allow surfaces with lower surface free energy to be obtained, and the results obtained at cutting speeds of 100 $m \cdot min^{-1}$ and 120 $m \cdot min^{-1}$ fall into one homogeneous group. These parameters should be used when the machining objective is to obtain hydrophobic properties of the surface. Higher cutting speeds for face milling of the CFRP composites produce surfaces characterised by higher surface free energy values. The results obtained at the highest of the applied cutting speeds, 140 $m \cdot min^{-1}$ and 160 $m \cdot min^{-1}$, fall into one homogeneous group. These parameters should be used when the machining objective is to increase the surface wettability and improve the surface adhesion properties.

It can be seen that the surfaces tested in this study, irrespective of the face milling parameters, are characterized by a rather significant value of the SFE, being in the range of 34.7–49.4 mJ/m^2. Since the SFE of polymeric plastics according to various sources is usually between 20 and 56 mJ/m^2 these are therefore average and one of the higher values of the SFE, which means in case of lower values better hydrophobic properties, and in case of higher values better adhesive properties. The information presented can have a significant impact on the planning of the surface machining of CFRP composites. Further research is planned to compare the value of surface free energy with the parameters of roughness and geometric structure of the surface after face milling. It is also planned to check the correlation of face milling process parameters on surface energy properties, using other end milling cutter.

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