Factor Analysis of Machining Parameters On Surface Integrity of CFRP Composites Based On A Microscopic Finite Element Cutting Model

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Factor analysis of machining parameters on surface integrity of CFRP composites based on a microscopic finite element cutting model

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Abstract

In the paper, a three-dimensional (3D) micromechanical finite element (FE) cutting model with three phases was developed to study the surface integrity of CFRP composites. The surface roughness and the depth of subsurface damage were predicted by using the FE cutting model, which were used to characterize the surface integrity. The machined surface observations and surface roughness measurements of CFRP composites at different fiber orientations were also performed for model validation. It is indicated that the 3D micromechanical model is capable of precisely predicting the surface integrity of CFRP composites. To investigate the complex coupling influences of multiple machining parameters on the surface integrity, the factor analysis of multiple machining parameters was performed, and then the effects of these machining parameters on the surface roughness and subsurface damage depth were obtained quantitatively. It was found that the fiber orientation angle and cutting speed are the most significant factors affecting the surface roughness, and the fiber orientation and edge radius are the main factors affecting the subsurface damage depth. The results also reveal that coupling effects of depth of cut and edge radius should be considered for

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improving the surface integrity of CFRP composites.

Keywords Carbon fiber-reinforced polymer (CFRP) composites; Surface integrity; Microscopic finite element cutting model; Factor analysis; Machining parameters

1 Introduction

Carbon fiber-reinforced polymer (CFRP) composites with high strength, light weight and fatigue and corrosion resistances, which consist of various polymer matrices and fibers. Owing to their excellent mechanical properties, CFRP composites are becoming the promising solutions to various industrial applications, especially used as structural components in the weight-critical aerospace industry [1, 2]. Despite the fact that composite parts are fabricated near-net shape, machining operations such as trimming and drilling are still required in order to achieve close fit tolerances and finalize part sizes. The surface integrity of a machined component after such machining operations needs to be investigated for assembly purpose, which including surface roughness, subsurface damage and residual stresses [3, 4]. Considering the surface integrity has an important effect on the performance of the structural parts, it is of great technological and practical interest to study the surface integrity in machining CFRP composites.

Workpiece surface integrity and functional performance of CFRP composites have been the focus of a great many publications over the last decade. Significant efforts were made to investigate the quality of the machined surface in terms of surface topography as well as the subsurface layer. Çolak et al. [5] measured the 3D surface

topography of a machined CFRP surface and evaluated the influences of fiber orientation on the surface quality. Pecat et al. [6], Rajasekaran et al. [7], Schorník et al. [8], Lissek et al. [9] and Abhishek et al. [10] studied the influence of cutting parameters on the surface quality of CFRP by using an experimental approach. Konneh et al. [11], Haddad et al. [12] and Voß et al. [13] investigated the surface damage on the machined surface under various tool geometries and cutting parameters. To examine the detail information of subsurface damage, various experimental observation technologies have been used, such as the application of the optical and electron microscopy techniques [14-16]. On the other hand, as the development of modeling tools, prediction of machining-induced damage in composite cutting has been commonly achieved using finite element method (FEM). Wang et al. [17] studied the influences of machining parameters on surface subsurface damage by using the finite element modeling in CFRP cutting. Ghafarizadeh et al. [18] built a finite element model to investigate the machining damage and chip formation mechanism for the flat end milling of unidirectional CFRP. Zenia et al. [19, 20] proposed a finite element model for the prediction of machining damage under the machined surface. Calzada et al. [21] developed a microstructure-based finite element model for CFRP machining to describe the fiber failure mode in the chip formation process. Although the subsurface damage in composite cutting have been analyzed with the simulation tools, the detail information of microstructure influences the machined damage has been neglected as well as the surface topography in these models.

The surface integrity can be investigated by using the experimental tests, however,

the research on CFRP composites machining is not only expensive and time-consuming, but also the carbon chips are dangerous for human health. In addition, there still is a big challenge to obtain the good surface integrity of CFRP composites under different cutting conditions. The present work is devoted to develop a 3D micromechanical FE model with considering the microstructure to study the surface integrity of CFRP composites. Based on the simulation results, the surface integrity can be characterized by the surface roughness and subsurface damage depth. The multi-factor analysis is further done to study the effect of multiple machining parameters on the surface integrity of CFRP composites, so as to determine the most important machining parameters and give a quantitative comparison of their influences. At the same time, the observations and roughness measurements of the machined surfaces at different fiber orientations were also performed for the validation of the FE model.

2 Experiment setup of CFRP composites trimming

The CFRP composites used in our tests were fabricated from the IMS/X850 prepregs with T800 carbon fiber of 65%. Four types of unidirectional laminae with 6 mm of thickness were selected in the experiments, in which the fiber orientations are 0°, 45°, 90° and 135°, respectively. The experimental setup and the geometry feature of the cutting tool are shown in Fig. 1. The milling process was performed by using a diamond coated and cemented carbide multi-edge milling cutter with a 10 mm diameter, 36 mm cutting length, 12 teeth and 15° helix angle. The workpiece was fixed by the fixture mounted on a Kistler 9272 dynamometer, which was used to measure the cutting force.

The machining conditions which cutting speed is 157 m/min, radial depth of cut is 1 mm and axial depth of cut is 6 mm. To evaluate the machined surface quality of the workpiece samples after milling experiment, the machined surfaces were observed by a Hitachi S-3400N scanning electron microscope (SEM). And then the machined surface roughness of the composite workpiece was measured by MAHR-Perthometer M1 instrument. Each measurement was repeated five times and the average value was taken as the effective one.

3 FE modelling of CFRP composites

3.1 Description of 3D cutting FE model

Considering the microstructure of three individual phases (i.e., fiber, matrix and the interphase between the fiber and matrix) of the CFRP composites, a 3D micromechanical finite element cutting model was established for CFRP composites, as shown in Fig. 2. The orthogonal cutting simulation was carried out by using the explicit module of the general finite element software ABAQUS/Explicit. The tool was assumed to be a rigid body. The nose radius of the tool is 5 μm and the rake and relief angles are 25° and 10° , respectively. The tool was given a constant cutting velocity in the x direction during the cutting process, the movement of which in the y direction was constrained in the model. The size of model was adopted as $215 \times 215 \times 50 \mu\text{m}$. The model was meshed with 8-node brick elements with reduced integration (C3D8R) and there are about 100,000 elements with a minimum element length of 0.5 μm along the cutting path. The displacements were constrained in three directions (x , y and z) at the

bottom surface of the model and the longitudinal displacement (U_y) was restricted at the left-hand surface of the model. The fiber in the composite model has a hexagonal array arrangement based on the actual measurement. The fiber orientation angle θ was defined relative to the cutting path in a clockwise direction. The thickness of interphase was evaluated as 0.5 μm based on the fiber diameter. A kinematical contact definition was applied between the tool surface and workpiece based on the penalty-function principle. A self-contact condition was adopted for each phase of the composites to avoid penetration among deleted elements during cutting process.

The friction between the cutting tool and fiber plays an important role in the machining of composites. The Coulomb friction law is applied to various contact surfaces. The coefficient of friction at the tool and chip interface in the present micromechanical model was taken as 0.68, 0.84, 0.63, and 0.96 for the 0° , 45° , 90° and 135° fiber orientations, which was based on the orthogonal machining tests [22], respectively. The material properties of the fiber and matrix provided by [2, 23] were given in Table 1.

3.2 Material modelling

1) Fiber and matrix models

The 3D micromechanical cutting model was built with consideration of the three constituents of the CFRP composites, i.e., fiber, interphase and matrix. The carbon fiber is assumed to be an elastic and anisotropic material and can be fully characterized by the anisotropic elasticity moduli of the fiber (E_f). It has been observed that the carbon fiber has not significant plasticity before failure. Therefore, the carbon fiber is assumed

to fail at the onset of the stress of the fiber exceeding the maximum stress in either tension or shear, i.e., the element will be immediately deleted when the stress reaches the ultimate strength of fiber.

The epoxy matrix of the composite is modeled as an isotropic and elasto-plastic material, the elastic behavior of which is characterized by the elastic modulus (E_m) and the Poisson ratio (ν_m) and the plastic behavior is described by von Mises yield criterion and isotropic hardening. The damage is assumed to occur when the stress reaches the ultimate tensile or compressive strength of matrix.

2) Interphase model with damage failure

The interphase is defined as a transversely isotropic materials (the elastic modulus is denoted by E_i). A progressive damage happens at the maximum normal and tangential stress ($\sigma_{\max}$ and $\tau_{\max}$). The normal damage behavior of the interfacial elements is modeled with a tensile progressive damage model, which describes the normal separation of the interface. After damage initiation occurs, the degree of damage can be fully characterized by a scalar damage variable (d_i). As the normal strain increases, the current state of damage exhibits itself in the form of a decrease modulus of elasticity (E_i^d) as shown below:

$$E_i^d = (1 - d_i) E_i \quad (1)$$

where E_i^d is the damaged elastic modulus of interphase. The material stiffness is equal to zero when the damage variable is equal to unity which means that the material fully reaches fracture. The damage variable is then said to linearly evolve according to:

$$d_i = \frac{L_e}{u_f^{pl}} \bar{\varepsilon}^{pl} \quad (2)$$

where L_e is the characteristic element length, $\bar{\varepsilon}^{pl}$ is the equivalent plastic strain and u_f^{pl} is the equivalent plastic displacement at failure which is expressed as

$$u_f^{pl} = \frac{2G^f}{\sigma_y} \quad (3)$$

where G^f is the fracture energy of the material, and σ_y is the static yield stress before the initiation of damage.

4 surface integrity analysis and validation

Surface integrity plays a predominant role in determining the machining accuracy of CFRP composites, which is resulted from material removal with the combination of bending, crushing and shearing, and depends on the cutting condition. In the present work, a simulation investigation was carried out to study the surface integrity of CFRP composites, in which the surface roughness and subsurface damage depth were analyzed.

4.1 Surface roughness analysis

The comparisons of the simulated and experimental results of machined surface of CFRP at $\theta=0^\circ$ were presented in Fig. 3, in which the material and cutting conditions adopted in FE simulation were the same as those used in the tests (Table 1). The fibers on the machined surface are laid in parallel to the cutting direction (see Fig. 3a and c), and two different material fracture mechanism occurs for the fiber orientation of 0° , in which the crushing-dominated failure happens in the tool-fiber contact zone and the

bending-dominated failure occurs beyond the cutting zone. To characterize the surface roughness, the machined surface profile was then numerically distinguished according to FE results, as shown in Fig. 3b. The arithmetical mean surface was regarded as a reference surface, and the arithmetic mean of the departures of roughness profile was further obtained to evaluate the machined surface roughness R_a . The fibers were only cracked and peeled off along the trimming path, and cause the machined surface smoothly. As shown the experimental observation in Fig. 3d, the machined surface is mainly composed of bare fibers and resin ridges at 0° , which is consistent with the simulation results (Fig. 3c).

For the case of 45° , the crushing governs the fracture of the fibers become a more dominated mechanism [24, 25], as shown in Fig. 4. It can be seen that most of the fibers fractured quickly due to the high stress concentration in the tool-fiber contact zoon. As a result, a machined surface with wave fracture shape was obtained, as shown in Fig. 3a and c. The machined surface is relatively smooth at the 45° fiber orientation, and the debonding between fiber and matrix can be found in the surface, which is caused by the failure of interphase. The measurement of machined surface is mainly composed of coated resin, and low damage is found on the surface at 45° which also match well with the simulation, as shown in Fig. 4d.

For the case of 90° (Fig. 5), the fiber fracture mechanism is more complex: the crushing-dominated failure and the bending-dominated failure are occurring at the same time. It can be seen that most of the fibers are sheared and bended, which induced a machined surface with transverse fracture, as shown in Fig. 5a and c. The depth of the

interphase debonding and fiber fracture increases by comparing with the result at 45° , as shown in Fig. 5b. Some small pitting damages were found in the observation of 90° , which are the ends of carbon fiber bundles on the machined surface, and in good agreement with the simulations, as shown in Fig. 5d.

Fig. 6 shows the simulation result of machined surface in cutting CFRP composite at $\theta=135^\circ$. Due to the bending-dominated fiber failure in the cutting case of 135° , large fragment formed ahead of the cutting edge, which leads to most of the fibers fracture under the cutting surface. It can be seen that a poor machined surface with large subsurface damage is obtained at 135° , as shown in Fig. 6a and c. In addition, a bouncing back of fiber was observed in simulation, which causes brushing between the relief surface of tool and the machined surface, as shown in Fig. 6b. From the Fig. 6d, the damage such as big pits of carbon fiber bundles and resin ridges were obviously observed at 135° , which is also consistent with the simulation results.

The surface roughness from simulations and experiments in the cutting of CFRP are presented in Fig. 7. It is indicated from the figure that the simulation predictions match well with the measured values of surface roughness at different fiber orientation angles. The surface roughness is greatly influenced by the fiber orientations, which increases with increasing the fiber orientation, and the surface roughness is minimum at 0° while maximum at 135° . There is a variation between the measured roughness and the simulation prediction at 0° , because the fibers and matrix fragments often adhere to the surface in experiment. To further understand the surface topography, a cross-sectional examination of the finished workpiece is performed in next section.

4.2 Subsurface damage analysis

To further clarify the surface topography, the subsurface layer was investigated by observing the cross-sections of the machined surface. Fig. 8 shows the numerical depths of the subsurface damage, which reveal that the damage layer on the machined surface is dependent on the fiber orientation. It is shown from the figure that the experimental depths of subsurface damage (L_d) are in good agreement with the predictions by the FE modelling, as shown in Fig. 9. When the fiber orientation was 135° (Fig. 8d), fiber fracture was dominated by fiber bending as the tool ploughed into the workpiece and formed deepest damage in subsurface layer with $40\text{ }\mu\text{m}$. These subsurface damages decreased to $29\text{ }\mu\text{m}$ as the fiber orientation decreased to 90° (Fig. 8c). When the fiber orientation was 45° , the subsurface damage significantly decreased to $18\text{ }\mu\text{m}$ with mic-cracks caused by the crushing-dominated fracture. At the fiber orientation of 0° , the minimum damage depth was found, which was $11\text{ }\mu\text{m}$ in simulated cutting, respectively.

5. Factor analysis of multiple parameters on surface integrity

It is well known that the surface integrity of CFRP composites is affected by many factors during the machining process. To provide a better understanding of the optimized machining quality, the significance of multiple machining parameters was studied based on the statistical method. By using the approach of factor analysis, the dominant machining parameters and coupling of double parameters affecting the surface roughness and subsurface damage depth were determined by quantitative comparison.

5.1 Implementation of factor analysis

Factor analysis is a mathematical statistics method used to study whether one or more control variables of different levels has a significant effect on the observed variable. And factorial experiments need be done to provide basic data for factor analysis. The precise evaluation of the main effects and interactions of various factors may be acquired by full factorial experiments, but it needs a large number of experimental data with expending lots of time and cost. Therefore, fractional factorial experiments are generally adopted to obtain a few key factors by requiring fewer experimental data. In this study, the two-level fractional factor analysis is adopted and implemented based on FE simulation results, which can be expressed as 2_R^{k-p} (here k is the number of factors; p is the number of full factorial experiments dichotomized; R is the resolution level). According to the FE cutting simulation of CFRP composite as presented in the above section, a fractional factorial experiment of 2_{III}^{6-3} was finally taken to analyze the effects of six factors (i.e., fiber orientation angle, fiber volume fraction, cutting speed, depth of cut, rake angle and edge radius) on the machined surface integrity.

The different levels of machining parameters used in factor analysis are shown in Table 2. The cases of fractional factorial experiment design are shown in Table 3, in which the central value of each factor is given to check the nonlinearity in the influencing relationship of each factor, and four such same cases are included to reflect the discretion error of factorial simulation cases.

5.2 Results of multi-factor analysis

In this paper, a series of simulations were performed to provide the sample data needed in the factor analysis, so as to investigate the effects of machining parameters and coupling of double parameters on the surface roughness and subsurface damage depth. The factor analysis is performed by the Minitab software, in which the confidence level of 95% was used, i.e., the critical P value is 0.05.

The main effects of single machining parameters on the surface roughness were obtained, as presented in Fig. 10. It can be seen from Fig. 10b that the surface roughness gradually decreases with the increase of cutting speed, and this decreasing trend exists for all the fiber orientations. While the surface roughness increases with the increase of the other machining parameters in the studied range. It is known that the surface roughness increases with fiber orientation from 45° to 135° , as shown in Fig. 10a. A linearly increase in surface roughness was found when the depth of cut increases from 30 to $70\text{ }\mu\text{m}$ (Fig. 10c), which implies that larger depth of cut is not preferred for higher surface quality in machining CFRP composite. These simulated results are in good agreement with the results in experiment [26, 27]. In addition, the specific relationships of the surface roughness and the other three factors are presented in Fig. 10d, e and f, respectively. It is revealed that the effect of the three factors on the surface roughness is approximately linear, this indicates that high value of fiber volume fraction, rake angle and edge radius may not good for improving the surface quality.

The quantitative comparison of multiple machining parameters and their coupling effects on the surface roughness was obtained, as shown in Fig. 11. The results of

multi-factor analysis of variance for surface roughness are listed in Table 4. It was found that fiber orientation angle (θ) and cutting speed (V_c) are the most significant factors affect the surface roughness. The depth of cut and edge radius are the next significant factors. Furthermore, the coupling effect of fiber orientation and cutting speed is more significant than the other interactions. It may be concluded that the surface roughness becomes low with the lower value of fiber orientation particularly with the higher cutting speed.

At the same time, the main effects of single factor on the subsurface damage depth were also obtained, as shown in Fig. 12. It can be known that the results of the maximum subsurface damage depth are observed at 135° while the lowest subsurface damage depth at 45° as shown in Fig. 11a, and the subsurface damage depth is almost linearly increasing with the edge radius in Fig. 12b. It is found from Fig. 12e that the subsurface damage depth decreases with increasing cutting speed, which indicates that the higher cutting speed is good for machined surface of CFRP. These results are in good agreement with the observed trend in different studies which deal with the subsurface damage [15, 17, 20, 28]. Moreover, the relations of subsurface damage depth versus the fiber volume, depth of cut and rake angle were plotted in Fig. 12c, d and f. It is showed that the effect of the three factors on the subsurface damage depth is also approximately linear, this indicates that high value of fiber volume fraction, rake angle and depth of cut may not prefer for higher surface quality.

As shown in Fig. 13, the quantitative comparison of multiple machining parameters and their coupling effects on the subsurface damage depth was presented. The results of

multi-factor analysis of variance for subsurface damage depth are given in Table 5. The fiber orientation and edge radius are the main factors affecting the response followed by the tool rake angle. Furthermore, a more significant interaction was found between fiber orientation and edge radius, which indicates the subsurface damage depth becomes large with the higher value of fiber orientation couple with edge radius.

6 Conclusions

This paper studied the effects of multiple machining parameters on the surface integrity of CFRP composites based on a 3D micromechanical FE cutting model with consideration of the microstructure of composites. The experimental observations of machined surface were carried out for the validation of FE results. And then the factor analysis was used to make a quantitative comparison of the influences of multiple machining parameters. The main conclusions have been summarized as follows:

(1) The proposed FE cutting model of CFRP composites can be used to reliability characterize the surface integrity of machined CFRP composites, in which the surface roughness and subsurface damage depth predicted in the FE simulations show a very good agreement with the experimental results. The cutting model can be further applied to improve the optimal solution of surface integrity of other composites.

(2) It has been noticed that there is significant coupling effect of fiber orientation and cutting speed on the surface roughness, and a more important interaction was found between fiber orientation and edge radius for the depth of subsurface damage. The coupling effects of depth of cut and edge radius should also be considered for improving

the surface integrity of CFRP composites.

(3) The fiber orientation in the CFRP composites proves to be the most important factor affecting the surface roughness and the subsurface damage depth. The next significant factors are the cutting speed and depth of cut for the surface roughness, while edge radius and rake angle for the subsurface damage depth.

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Declarations

a. Conflicts of interest/Competing interests

The authors declare no competing interests.

b. Availability of data and material

The raw/processed data required to reproduce these findings cannot be shared at this time as they will be used in an ongoing study.

c. Code availability

Not applicable (minitab 19 design of experiments “free version”).

d. Ethics approval

This study complies with the ethical standards set out by Springer. All the authors read and approved the final manuscript.

e. Consent to participate

All the authors consent to participate.

f. Consent for publication

All the authors consent to publication.

g. Authors' contributions

All the authors have their contributions on the modelling, experiment measure and data processing.

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Table 1 Properties of the three phases used in the cutting simulation of CFRP composite

Constituents	Properties	Values
Carbon fiber	Longitudinal elastic modulus, E_{f1} (GPa)	294
	Transverse elastic modulus, E_{f2} (GPa)	15
	Poisson's ratio, ν_{f12}	0.3
	Tensile Strength, X_f (GPa)	5.49
	Shear Strength, S_f (GPa)	0.38
	Diameter, d_f (μm)	7
	Fiber volume fraction, V_f (μm)	65%
	Density, ρ_f (g/cm^3)	1.81
Epoxy	Elastic modulus, E_m (GPa)	4
	Poisson's ratio, ν_m	0.4
	Tensile Strength, X_m (MPa)	85
	Shear Strength, S_m (MPa)	70
	Density, ρ_m (g/cm^3)	1.26
Interphase	Longitudinal elastic modulus, E_{i1} (GPa)	83.9
	Transverse elastic modulus, E_{i2} (GPa)	7.03
	Poisson's ratio, ν_{i12}	0.37
	Tensile Strength, X_i (MPa)	167.5
	Shear Strength, S_i (MPa)	25
	Thickness, t_i (μm)	0.5
	Density, ρ_i (g/cm^3)	1.41

Table 2 The different levels of machining parameters used in factor analysis

Factors	Symbols	Low level (-1)	High level (+1)	Central value (0)
Fiber orientation ($^\circ$)	θ	45	135	90
Fiber volume fraction (%)	V_f	40	80	60
Cutting speed (m/min)	V_c	60	300	180

Depth of cut (μm)	a_c	30	70	50
Rake Angle ($^\circ$)	α_t	5	25	15
Edge radius (μm)	r_t	1	20	10

Table 3 Scheme of the basic cases for fractional factor analysis

Number	θ	V_f	V_c	a_c	α_t	r_t	Surface roughness R_a (μm)	Subsurface damage depth L_d (μm)
1	-1	-1	-1	1	1	1	5.2	20
2	1	-1	-1	-1	-1	1	4.8	19
3	-1	1	-1	-1	1	-1	5.3	20
4	1	1	-1	1	-1	-1	4.5	19
5	-1	-1	1	1	-1	-1	3.1	12
6	1	-1	1	-1	1	-1	5.5	22
7	-1	1	1	-1	-1	1	3.5	14
8	1	1	1	1	1	1	6.8	27
9	0	0	0	0	0	0	4.9	19
10	0	0	0	0	0	0	5.4	20
11	0	0	0	0	0	0	4.7	20
12	0	0	0	0	0	0	4.5	18

Table 4 Results of the analysis of variance for surface roughness

Machining parameters	Sum of squares (SS_B)	Degrees of freedom	Mean square (MS_B)	F-value	p-value
Fiber orientation angle (θ)	9.46	2	4.73	3.63	0.000
Cutting speed (V_c)	5.66	2	2.83	2.17	0.000
Depth of cut (a_c)	4.94	2	2.47	1.90	0.000
Edge radius (r_t)	3.82	2	1.91	1.46	0.000
Rake angle (α_t)	3.12	2	1.56	1.20	0.000
Fiber volume fraction (V_f)	2.24	2	1.12	0.86	0.001
Interaction ($\theta \times V_c$)	1.6	2	0.80	0.62	0.002
Interaction ($\theta \times a_c$)	1.22	2	0.61	0.47	0.002
Interaction ($V_c \times a_c$)	0.6	2	0.30	0.31	0.002

Table 5 Results of the analysis of variance for subsurface damage depth

Machining parameters	Sum of squares (SS_B)	Degrees of freedom	Mean square (MS_B)	F-value	p-value
Fiber orientation angle (θ)	10.02	2	5.01	20.33	0.000
Edge radius (r_t)	6.04	2	3.02	12.25	0.000
Rake angle (α_t)	5.77	2	2.885	11.71	0.000
Fiber diameter (V_f)	5.70	2	2.85	11.57	0.000
Depth of cut (a_c)	5.09	2	2.545	10.33	0.000
Cutting speed (v_c)	4.68	2	2.34	9.49	0.000
Interaction ($\theta \times r_t$)	3.83	2	1.915	7.77	0.000
Interaction ($\theta \times \alpha_t$)	2.03	2	1.015	4.12	0.001
Interaction ($r_t \times \alpha_t$)	1.82	2	0.91	3.7	0.002

Figures:

Fig. 1 Experimental setup in CFRP composites trimming

Fig. 2 3D microscopic FE model of orthogonal cutting for CFRP composites ($\theta=45^\circ$)

Fig. 3 Simulation results and observation of machined surface at $\theta=0^\circ$

Fig. 4 Simulation results and observation of machined surface at $\theta=45^\circ$

Fig. 5 Simulation results and observation of machined surface at $\theta=90^\circ$

Fig. 6 Simulation results and observation of machined surface at $\theta=135^\circ$

Fig. 7 Comparison of average surface roughness between simulation and measurement for CFRP at different fiber orientations

Fig. 8 Depth of subsurface damage in simulation for (a) 0°, (b) 45°, (c) 90° and (d) 135° fiber orientation

Fig. 9 Comparison of depth of subsurface damage between simulation and measurement for CFRP at different fiber orientations

Fig. 10 Dependence of surface roughness on machining parameters

Fig. 11 Quantitative comparison of the contribution of different machining parameters to surface roughness

Fig. 12 Dependence of subsurface damage depth on machining parameters

Fig. 13 Quantitative comparison of the contributions of different machining parameters to subsurface damage depth