21st International Conference on Composite Materials
Xi'an, 20-25th August 2017

OPTIMIZATION OF CUTTING TOOL GEOMETRIC PARAMETERS IN MILLING OF CFRP LAMINATES

S. Waqar[1], Y. He[2*], C.A. Abbas[3], and A. Majeed[4],

[1, 2, 4]School of Mechanical Engineering, Northwestern Polytechnical University, Xi'an,
[3]School of Mechanical Engineering, Shandong University, Jinan, China

[1]saadwaqar@mail.nwpu.edu.cn, [2]heyl@nwpu.edu.cn, [3]chasad573@yahoo.com,
[4]amajeed@mail.nwpu.edu.cn,

Keywords: CFRP, Milling optimization, Tool Geometry, Cutting Force, Surface Roughness

ABSTRACT

The general trend in the manufacturing of CFRP components is to fabricate near net shape components, however machining is often required as well as desirable to produce bores, notches and to enhance the surface quality. The conventional machining operations used for CFRP components are Turning, Milling and Drilling. Among these conventional machining operations, milling still lacks its due attention because of the complex nature of the process. In the presented study, experiments according to Taguchi's Design of experiments technique were conducted to optimize end mill's geometric parameters in milling of Multidirectional CFRP laminates. The geometric parameters considered for optimization are Rake Angle, Helix Angle and Clearance angle. The optimization was done to minimize both the cutting force generated during the milling and the surface roughness of the machined surface. The optimal combination for Cutting force was found to be 9° rake angle, helix angle of 60° and clearance angle of 10°. For surface roughness, rake angle of 5°, helix angle of 60° degree and clearance angle of 10° was the optimal tool geometric parameters combination. Validation tests were then conducted to check the validity of the selected approach.

1 INTRODUCTION

Carbon Fibre reinforced plastics CFRPs are often considered as high performance materials for lightweight applications in aviation, automobile, marine, medical and sports industries [1-3]. Their high specific strength and high specific stiffness are among the characteristics, which make them attractive for these industries[4]. Although CFRP components are manufactured near to their final shape, they often require machining operations such as milling and drilling, for dimensional accuracy, assembly and geometrical requirements[5]. However, these machining operations can lead to various surface defects such as increased surface roughness, matrix smearing, cracking, delamination and fibre protrude etc. [6]. These machining defects such as fibre pull out, matrix smearing, cracking even delamination may occur due to the overlarge machining force or the resultant force with improper direction during drilling and milling of CFRP. Various researchers have worked on the milling of metallic and other homogeneous materials however, the findings of those researchers cannot always be applicable while working on CFRP[7, 8]. Few experimental studies have been done to study the influence of combination of cutting tool geometric parameters and machining process parameters on surface quality in drilling and orthogonal cutting of CFRP [9-11]. However comparatively less attention was given to the influence of cutting tool geometric parameters and machining process parameters in milling of CFRP. Karpat et al[12] proposed a model based on fibre orientation for the prediction of cutting force. Hagino performed experiments with variable helix cutting tools while keeping rake and clearance angle constant and stated that axial force increases with high helix cutting tools[13]. Koplev et al [14] studied the influence of clearance angle on cutting forces and found that increasing clearance angle has a positive influence on the cutting forces. Rusinek [15, 16] studied the effect of feed rate and rotational speed on cutting force during milling of EPMC with the objective to develop a new mathematical model of the composite material cutting process. Chao and Hwang [17] conducted experiments in milling CFRP composites and found that the best operating condition was the combination of factors and levels that produced the minimum cutting force. Chao studied the influence of relief angle, feed rate and depth of cut through Taguchi experimental design. Davim [6] performed milling experiments on CFRP and found that two flute cutting tool produces better surface finish and less deamination as compared with 6 flute cutting tool. In the summary, it was found that the influence of macro level cutting tool geometric parameters on cutting force and surface roughness was not well researched.

In the presented study, experiments according to Taguchi's Design of experiments technique were conducted to optimize end mill's geometric parameters in milling of multidirectional CFRP laminates. End Mill's Rake Angle, Helix angle and Clearance angle were selected as factors for optimization based on literature review and industrial input. The optimization was done to minimize both the cutting force generated during the milling and the surface roughness of the machined surface.

2 EXPERIMENTAL SETUP

A set of cutting experiments were conducted on YHVT 850Z multi axis milling center with maximum achievable cutting speed of 8000 mm/min and maximum spindle power of 5.5 kW. All cutting tests were performed on uniform machining parameters i.e. feed per tooth of 0.02 mm, spindle speed of 2500 rev/min and depth of cut of 2 mm. Figure 1 illustrates the experimental setup and milling center used for experimentation. Cutting tools used are 4 flute, K40 carbide, uncoated end mills with 10 mm diameter manufactured by OSL ltd.

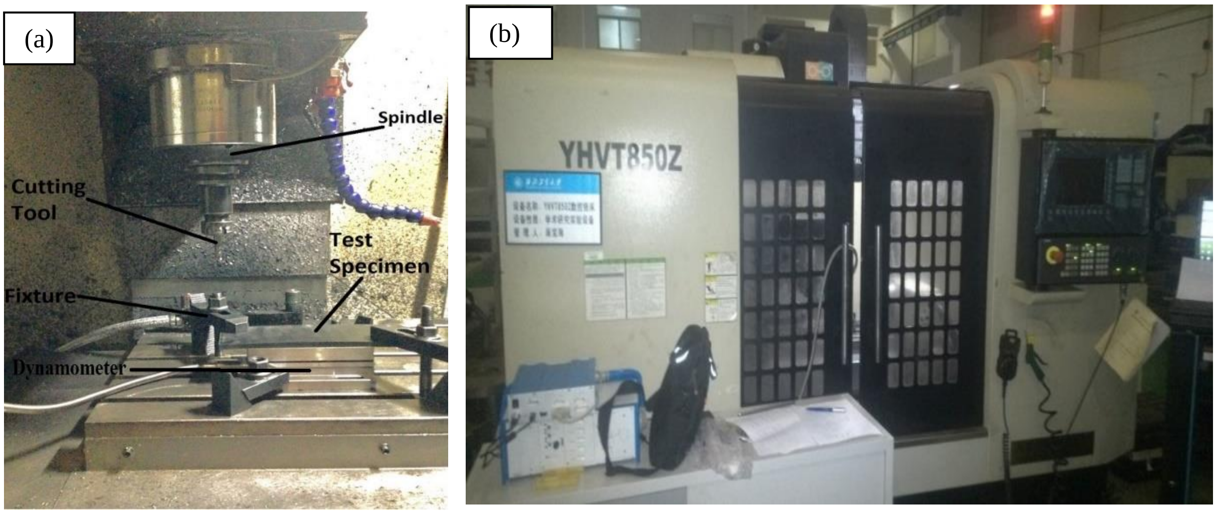

Figure 1: (a) Experimental Setup, (b) YHVT 850Z Milling Center

Test specimen for cutting experiments was aerospace grade T300 multidirectional CFRP laminates with layup sequence of $0^0/90^0/45^0/-45^0$. Table 1 states the properties of CFRP laminates used. Each experiment was repeated twice with new tool for each cut to minimize any error or uncertainty of the results.

Properties	Description
Resin Type	Epoxy Resin
Resin Content	33%
Fibre Content	66%
Tensile Strength	3530 MPa
Tensile Modulus	230 MPa
Specific Heat Capacity	0.19 Cal/g.oC
Resistivity	1.7x10-3 Ohm.cm

Table 1: Mechanical Properties of CFRP Laminates.

In this study, relationship between cutting tool geometric parameters and cutting force , surface roughness in milling of multi directional CFRP laminates were discussed in order to achieve optimal cutting tool geometric parameters combination. Three Cutting tool geometric parameters namely rake angle, helix angle and clearance angle are selected with three levels denoted as 1, 2, and 3 in table 2. These cutting tool geometric parameters and their levels were selected based on previous experimental studies. Taguchi's orthogonal array L9 was selected as Experimental design array. The Experimental design array in terms of levels of selected parameters is given in table 3.

Parameter	Level		
	1	2	3
Rake Angle	5◦	7◦	9◦
Helix Angle	30◦	45◦	60◦
Clearance Angle	6◦	8◦	10◦

Table 2: Selected cutting tool geometric parameters and their levels.

Experiment No	Tool Geometry Parameters		
	Rake Angle	Helix Angle	Clearance Angle
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 3: Taguchi's Experimental Design, L9 Orthogonal Array with levels of selected parameters.

The average lateral cutting force and axial cutting force were measured with a Kistler dynamometer (Model 9255B), respectively. The net cutting force acting for each experiment was then calculated as the resultant of these average lateral and axial forces. The surface roughness parameter used in this paper is the arithmetic mean surface roughness R_a. The surface roughness of machined surfaces was measured by surface profilometer mar surf 2.0 m, made by Mahr Co. Ltd. Surface roughness was measured at three points i.e. near the start , mid and end of cut. Average of these three values was considered for further analysis.

3 RESULTS AND DISCUSSION

3.1 Analysis of Signal to Noise (S/N) Ratio

In Taguchi's method, S/N ratio represents the performance characteristics. There are three different models for S/N ratio calculation. Smaller the better model, larger the better model and nominal the better model. Relationships to calculate S/N ratio for these models are given by eq 1,2and 3.

Larger the better model:

$$\frac{S}{N} = -10log_{10}\left[\frac{1}{n}\left(\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right)\right] \quad (1)$$

Smaller the better model:

$$\frac{S}{N} = -10log_{10}\left[\frac{1}{n}\left(\sum_{i=1}^{n} {y_i}^2\right)\right] \tag{2}$$

Nominal the better model:

$$\frac{S}{N} = -10log_{10}\left[\frac{1}{n}\left(\sum_{i=1}^{n}(y_i - y_o)^2\right)\right] \tag{3}$$

Table 4 presents the average experimental results, and S/N ratio of cutting force and surface roughness. As smaller values of both cutting force and surface roughness are desirable, hence a smaller the better model was selected for the calculation of S/N ratio. A large S/N ratio value states that response is closer to the expected performance. According to table 4, experiment number 8 has the largest value of S/N ratio for cutting force so among the experimental array the optimal tool geometric parameters combination is 9^0 rake angle, 45^0 helix angle and 6^0 clearance angle for cutting force. For Surface roughness, the largest S/N ratio was found for experiment number 3. Hence, the optimal cutting tool geometric parameters are rake angle of 5^0, helix angle of 60^0 and clearance angle of 10^0 among the experimental array.

Experiment No	Tool Geometry Parameters			Responses			
	Rake Angle	Helix Angle	Clearance Angle	Cutting Force (N)	S/N Ratio	Ra (um)	S/N Ratio
1	5	30	6	152.375	-43.6583	0.6117	4.26923
2	5	45	8	136.649	-42.7121	0.5307	5.50302
3	5	60	10	132.137	-42.4205	0.4642	6.66590
4	7	30	8	148.639	-43.4427	0.6408	3.86555
5	7	45	10	136.101	-42.6772	0.5734	4.83085
6	7	60	6	133.802	-42.5293	0.5417	5.32482
7	9	30	10	111.518	-40.9469	0.7053	3.03252
8	9	45	6	99.576	-39.9631	0.6217	4.12838
9	9	60	8	102.184	-40.1877	0.5807	4.72096

Table 4: Experimental Design, Results and S/N ratio for Cutting force and Surface roughness.

The response table gives the mean S/N ratio of each level of each factor. The response tables for Cutting force and Surface roughness are given in table 5 and table 6 respectively.

Factor	Mean S/N ratio of Level			Max - Min
	1	2	3	
Rake Angle	-42.93	-42.88	***-40.37***	2.56
Helix Angle	-42.68	-41.78	***-41.71***	0.97
Clearance Angle	-42.05	-42.11	***-42.01***	0.10

Table 5: Response table of S/N ratio for cutting force.

Factor	Mean S/N ratio of Level			Max - Min
	1	2	3	
Rake Angle	***5.47***	4.67	3.96	1.51
Helix Angle	3.72	4.82	***5.57***	1.84
Clearance Angle	4.57	4.69	***4.84***	0.26

Table 6: Response table of S/N ratio for surface roughness.

Min effects Plot of S/N ratio for Cutting force and surface roughness are given in Figure 2 and figure 3 respectively.

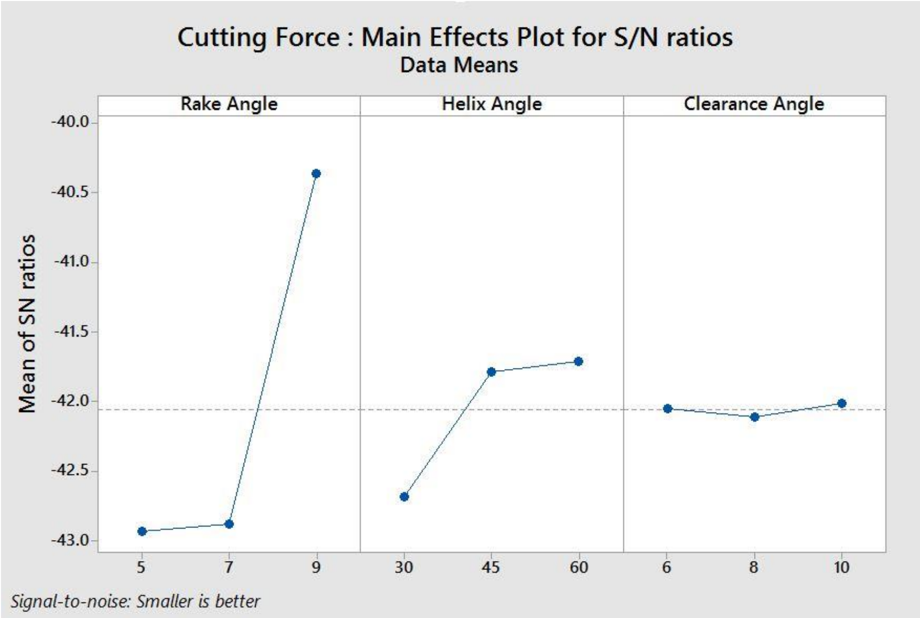

Figure 2: Main effects plot of S/N ratio of cutting force.

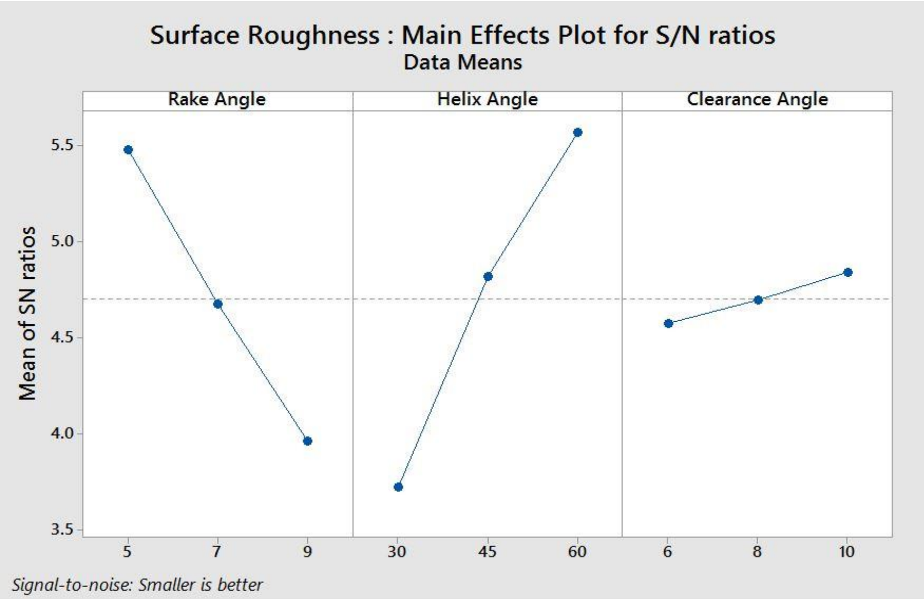

Figure 2: Main effects plot of S/N ratio of Surface roughness

As higher value of S/N ratio shows that at that level response is closer to the expected performance, thus for a specific factor, level with largest value of S/N ratio is the optimal level. For Cutting Force, the optimal cutting tool geometric parameters according to mean S/N ratio analysis given in table 4 are Rake angle 9^o, Helix angle 60^o and clearance angle 10^o. For Surface Roughness, The optimal cutting tool geometric parameters are 5^o Rake angle, 60^o Helix angle and 10^o clearance angle.

3.3 Analysis of Variance (ANOVA)

Analysis of variance is used in this study to elucidate cutting tool geometric parameters significantly affecting Cutting Force and Surface Roughness. ANOVA analysis was done on the experimental data collected Experimentation using Statistical Analysis Package MINITAB. Higher percentage contribution corresponds to the higher importance of factor in affecting performance characteristics.

Table 7 and table 8 shows the ANOVA results for Cutting Force and Surface Roughness respectively. For Cutting Force the percentage contribution of rake angle, helix angle and clearance angle were 87.47%, 11.87% and 0.10 % respectively. According to the ANOVA results, Rake angle and helix angle significantly influence the cutting force, Rake angle being the most influential parameter. Clearance angle was found to be negligibly significant for cutting force.

For Surface roughness, the percentage contributions for rake angle, helix angle and clearance angle were 38.89 %, 58.20 % and 1.22 % respectively. Factors significantly influencing surface roughness are also rake angle and helix angle, helix angle being the most influential parameter.

Source	DF	SS	MS	F Value	% Contribution
Rake Angle	2	12.9146	6.4572	159.46*	87.47%
Helix Angle	2	1.7535	0.8767	21.65*	11.87%
Clearance Angle	2	0.0152	0.0076	0.19	0.10%
Error	2	0.0810	0.0405		
Total	8	14.764300			

*Significant at 95% confidence level Cutting Force

DF = Degree of freedom, SS = Sum of Squares, MS = Mean Sum of Squares

Table 7: ANOVA for cutting force.

Source	DF	SS	MS	F Value	% Contribution
Rake Angle	2	3.4642	1.7321	23.19*	38.89 %
Helix Angle	2	5.1841	2.5920	34.71*	58.20 %
Clearance Angle	2	0.1088	0.0543	0.73	1.22 %
Error	2	0.1494	0.0746		
Total	8	8.9065			

*Significant at 95% confidence level Surface Roughness

DF = Degree of freedom, SS = Sum of Squares, MS = Mean Sum of Squares

Table 8: ANOVA for surface roughness.

4 VALIDATION

After the selection of Optimal cutting tool geometric parameters, next step is to predict and validate the improvement in performance characteristic i.e. decrease in cutting force and surface roughness, using the optimal cutting tool geometry. The estimated Value of S/N ratio can be calculated by the following relationship

$$\sigma = \sigma_t + \sum_{i=1}^{n}[\sigma_m - \sigma_t] \qquad (4)$$

Whereas σ_t is the total mean of S/N ratio, σ_m is the mean of S/N ratio at optimum level, and n is the number of significant factors. The optimal cutting tool geometric parameter combination by S/N ratio analysis for cutting force was 9o rake angle, 60o helix angle and 10o clearance angle so cutting force for a cutting tool with this tool geometric combination were regarded as validation test. Based on above mentioned equation, the estimated value of S/N ratio for optimal combination can be obtained. The optimal combination for surface roughness was found to be 5o rake angle , 60o helix angle, and 10o clearance angle. This optimal tool combination is also among the 9 combination of Taguchi's design i.e. experiment 3 and also shows smallest surface roughness. Therefore validation of optimal cutting tool geometric parameter for surface roughness was not done separately.

	Cutting Force		
	Initial Geometric parameter Combination	Optimal Geometric parameter combination	
		Prediction	Experiment
Parametric Combination	Rake Angle 9° Helix Angle 45° Clearance Angle 6°	Rake Angle 9° Helix Angle 60° Clearance Angle 10°	Rake Angle 9° Helix Angle 60° Clearance Angle 10°
S/N Ratio	-39.9631		-39.5381
Cutting Force	99.576 N	97.501 N	94.821 N

Table 9: Validation of Optimal Cutting tool geometric parameters for cutting force

5 CONCLUSION

In this paper the influence of cutting tool geometric parameters on cutting force and surface roughness of the machined surface was studied based on Taguchi's DOE method. Taguchi's S/N ratio was used to minimize both cutting force and surface roughness. Based on Taguchi's S/N ratio response table, optimal cutting tool geometric parameters combination were determined for smaller cutting forces and surface roughness. The Conclusions were summarized as follows.

1. Taguchi's S/N ratio was used to minimize both cutting force and surface roughness. From results of S/N ratio analysis, it was concluded that optimal cutting tool geometric parameters combination for decreasing cutting force was 9o rake angle, 60o helix angle and 10o clearance angle. Similarly, for surface roughness optimal combination was found to be rake angle of 5o, helix angle of 60o and clearance angle of 10o.
2. From the Analysis of Variance results, Rake angle showed greatest influence on cutting force, followed by helix angle. The percentage contribution of rake angle, helix angle and clearance angle is 87.47 %, 11.87%, 0.10% respectively.
3. From ANOVA for surface roughness, helix angle was found to be the most influential factor, followed by rake angle. Clearance angle was found to be least influential factor. Percentage contribution of each factor is 38.89% for rake angle, 58.20% for helix angle, and 1.22% for clearance angle.
4. The effectiveness of the selected approach was verified by the results. A decrease in cutting force was observed for the optimal tool geometric parameters combination. The optimal combination for surface roughness was also observed to produce smallest surface roughness.

6. ACKNOWLEDGMENT

The authors wish to acknowledge Science Foundation of Northwestern Polytechnical University for Financial Support through Grant No 3102105JCS05009.

7. REFERENCES

[1] R. Teti, "Machining of composite materials," *CIRP Annals-Manufacturing Technology*, vol. 51, pp. 611-634, 2002.

[2] C. S. Chang, "Turning of glass–fiber reinforced plastics materials with chamfered main cutting edge carbide tools," *Journal of materials processing technology,* vol. 180, pp. 117-129, 2006.

[3] A. W. Zia, Y. Q. WANG, and S. Lee, "Effect of Physical and Chemical Plasma Etching on Surface Wettability of Carbon Fiber–Reinforced Polymer Composites for Bone Plate Applications," *Advances in Polymer Technology,* vol. 34, 2015.

[4] K. Dransfield, C. Baillie, and Y.-W. Mai, "Improving the delamination resistance of CFRP by stitching—a review," *Composites Science and Technology,* vol. 50, pp. 305-317, 1994.

[5] W. Hintze, D. Hartmann, and C. Schütte, "Occurrence and propagation of delamination during the machining of carbon fibre reinforced plastics (CFRPs)–An experimental study," *Composites Science and Technology,* vol. 71, pp. 1719-1726, 2011.

[6] J. P. Davim and P. Reis, "Damage and dimensional precision on milling carbon fiber-reinforced plastics using design experiments," *Journal of materials processing technology,* vol. 160, pp. 160-167, 2005.

[7] J. Ferreira, N. Coppini, and G. Miranda, "Machining optimisation in carbon fibre reinforced composite materials," *Journal of materials processing technology,* vol. 92, pp. 135-140, 1999.

[8] N. Hu and L. Zhang, "Some observations in grinding unidirectional carbon fibre-reinforced plastics," *Journal of materials processing technology,* vol. 152, pp. 333-338, 2004.

[9] M. Henerichs, R. Voß, F. Kuster, and K. Wegener, "Machining of carbon fiber reinforced plastics: Influence of tool geometry and fiber orientation on the machining forces," *CIRP Journal of Manufacturing Science and Technology,* vol. 9, pp. 136-145, 2015.

[10] E. Brinksmeier, S. Fangmann, and R. Rentsch, "Drilling of composites and resulting surface integrity," *CIRP Annals-Manufacturing Technology,* vol. 60, pp. 57-60, 2011.

[11] L. M. P. Durão, D. J. Gonçalves, J. M. R. Tavares, V. H. C. de Albuquerque, A. A. Vieira, and A. T. Marques, "Drilling tool geometry evaluation for reinforced composite laminates," *Composite Structures,* vol. 92, pp. 1545-1550, 2010.

[12] Y. Karpat, O. Bahtiyar, and B. Değer, "Mechanistic force modeling for milling of unidirectional carbon fiber reinforced polymer laminates," *International Journal of Machine Tools and Manufacture,* vol. 56, pp. 79-93, 2012.

[13] M. Hagino and T. Inoue, "Effect of carbon fiber orientation and helix angle on CFRP cutting characteristics by end-milling," *International Journal of Automation Technology,* vol. 7, pp. 292-299, 2013.

[14] A. KoPlev, A. Lystrup, and T. Vorm, "The cutting process, chips, and cutting forces in machining CFRP," *composites,* vol. 14, pp. 371-376, 1983.

[15] R. Rusinek, "Cutting process of composite materials: An experimental study," *International Journal of Non-Linear Mechanics,* vol. 45, pp. 458-462, 2010.

[16] R. Rusinek, K. Kecik, and J. Warminski, "Dynamics of composite materials cutting," *Advances in Manufacturing Science and Technology,* vol. 35, pp. 31-37, 2011.

[17] P. Chao and Y. Hwang, "An improved Taguchi's method in design of experiments for milling CFRP composite," *International journal of production research,* vol. 35, pp. 51-66, 1997.