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Experimental Investigation of Machining Parameters on Machinability of Carbon Fiber/Epoxy Composites

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Abstract*— Drilling is one of the most important operations applied in the assembly of composite parts in various industries. The goal of this study is the investigation of the effects of machining parameter and tool geometry (spindle speed, feed rate and tool point angle) during the drilling process of carbon fiber reinforced polymer composites (CFRP) on surface roughness, delamination and thrust force. In this regard, the advantages of statistical experimental design technique, experimental measurements are exploited in an integrated manner. To this end, the experiments on CFRP were conducted to obtain surface roughness, delamination factor and thrust force values based on the full factorial design of experiments, and then analysis of variance (ANOVA) is performed.

Index Terms—**Drilling, Composites, Design of Experiments, Analysis of Variance.**

I. INTRODUCTION

Composites are materials made up of two or several materials. These materials usually consist of two phases: *matrix* which is the weaker phase, and *reinforcement* which comprises the stronger phase. Polymer matrix composites (PMC), metal matrix composites (MMC) and ceramic matrix composites (CMC) represent the three major classes of composites. Reinforcements in the structure of composites are in form of fibers such as glass fibers and carbon fibers, or in form of particles such as ceramic particles, etc. Presenting high strength-to-weight and stiffness-to-weight ratios, fiber reinforced polymers are vastly applied in weight sensitive applications such as aerospace and automobile industries [1, 2]. Herein, epoxy – a class of thermoset polymers – as the matrix and carbon fibers as the reinforcement are highly employed in research and industrial applications [3]. While application of composites in the assembly processes in the aforementioned industries, the drilling process is a significant phase. The drilled holes serve for fasteners such as rivets, bolts and nuts. As a result, the quality of the hole is a significant factor. This factor affects parameters such as surface roughness and delamination [4, 5]. Delamination is considered as a major damage which takes place during machining (especially drilling) of laminated composites. This phenomenon extensively affects the quality of the drilled hole, and results in poor tolerances in assembly. This type of damage occurs in drill entrance and exit, while drilling. The solution of this problem in drill exit is associated with application of smaller thrust force during the operation [6]. On the other hand, the cutting forces in the machining process are a significant element in machine vibrations, chatter and inaccuracy issues. Therefore, reduction of thrust force in the drilling process can lead to better quality of the drilled hole, and finally, reduction of vibration and chatter. Shape accuracy of a component corresponds to machining accuracy. Various factors lead to machining inaccuracy. Herein, the deformation of the machining apparatus under cutting forces is a highly significant element. As for other materials, surface roughness on composites is affected by tool geometry and material properties, cutting kinematics and cutting conditions [7]. Measurement of surface roughness is performed to determine the surface quality of the machined surfaces. Various researches have been conducted to investigate the effect of machining parameters on surface roughness, delamination and thrust force in the drilling process. These parameters include cutting speed, feed rate and tool geometry. For instance, Sonbaty et al. [1] studied the effective factors on machining of GFR/epoxy composites. Their results revealed that with increase in cutting speed, torque and force are decreased, and finally, surface roughness is improved, and also increasing feed rate increases thrust force, and slightly improves surface roughness. Bhatnagar [8] investigated the damage in drilling of glass fiber reinforced plastic composite laminates. His results indicated that the damage area around the drilled hole grows with increase in cutting speed/feed speed ratio, yet the maximum damage was not found at the conditions where maximum thrust force was recorded. They presented some mathematical models for the damages introduced by drilling in terms of cutting speed and feed speed. The delamination occurred in the aftermath of drilling CFRP with helical flute carbide drill was alleviated when drilled making use of a four flute carbide drill. Application of a carbide drill provided higher quality in comparison with that attained taking advantage of a HSS type drill [9]. Tsao and Hocheng [10] unveiled a relationship between spindle speed, feed rate and drill diameter to the induced delamination in a CFRP laminate taking advantage of multiple regression analysis. Khashaba et al. [11] experimentally studied the effect of speed and feed rate on thrust force, torque and delamination in drilling of chopped composites having various fiber volume portions. Based upon their experimental results, the empirical models were developed to come by the best drilling conditions. Enemuoh et al. [12] proposed a method which combined Taguchi's method and the multi-objective optimization criterion to come by the optimum drilling conditions for delamination-free drilling in composite laminates. Davim and Reis [9] also presented a similar methodology taking advantage of Taguchi's method and the analysis of variance (ANOVA) to present a correlation between cutting velocity and feed rate with the delamination in a CFRP laminate. The current study attempts to investigate the effects of machining parameter and tool geometry on machinability in drilling of carbon fiber reinforced thermoset laminates. In order to attain minimum operation numbers and decrease the cost of experiments, an experimental scheme was arranged taking advantage of full factorial design. The considered parameters were cutting speed, feed and tool angle point.

II. EXPERIMENTAL WORK

A. Material

The material used in drilling is CFRP composite material with 50% woven carbon fiber in weight with an orientation of 0/90. The matrix was epoxy (LY564 resin and HY 564 hardener produced by Huntsman Co.). The composite material, with 8±0.1 mm thickness in 32 layers, was made by the Resin Transfer Molding (RTM) technique. The work piece material used was in the form of a 160mm×160mm×8mm sheet, and then cut in the form of bars with 20 mm width for machining operations. The mechanical properties of the composite material have been given in Table 1.

B. Machine Tools

The drilling processes were performed on a vertical computer numerically controlled (CNC) milling machine (SMG-300) with a maximum spindle speed of 5000 rpm.

Table 1. Mechanical Properties of CFRP

Ultimate tensile strength (MPa)	682
Ultimate shear strength (MPa)	31.07
Tensile Modulus (GPa)	68.3
Shear Modulus (GPa)	6.9

The actual machining operation is illustrated in Fig. 1. The experiments have been carried out on composite plate with 8 mm of thickness, using cemented carbide drills, with 5 mm diameter. Cemented carbide drills were manufactured according to standard cemented carbide drills. The point angles of cemented carbide drills were 60, 100 and 140 degree, and are shown in Fig. 2. The point angles were created by grinding operation. The drilled work piece is displayed in Fig. 3.

C. Thrust Force Measurement

In order to measure the axial thrust force, the work piece was mounted on a Kistler 9272 (Switzerland) four-component piezoelectric dynamometer, which in turn was mounted onto the machine's table (see Fig. 1). Data acquisitions were made through the piezoelectric dynamometer by interface RS-232C to load three Kistler 5070A amplifiers and to the PC using the appropriate software DynoWare type 2825 A Kistler®.

D. Surface Roughness Measurement

Surface roughness of machined holes, represented by the parameter R_a, was measured by PERTHOMETER M2 (Mahr, Germany) instrument. The cut-off and traversing length values were 0.8 and 5.5 mm, respectively. For each test, 3 measurements were conducted over the middle of the hole wall and parallel to the hole axis, and subsequently, the results were averaged. In Fig. 4, the employed surface roughness measurement tool is presented.

E. Delamination Factor Measurement

Delamination is the most significant drawback during drilling of enriched plastics and generally in laminated composites. The measuring method implemented to assess this drawback included taking pictures of the component using a microscope with the magnification of 500 on which a camera had been installed; the maximum diameter of the hole was then calculated through image processing in Lab View v.6 software. After measuring the maximum damage diameter, D_{max}, suffered by the material, the damage normally assigned by delamination factor Fd was determined. Delamination factor (F_d) can be define according to the following:

$$F_d = \frac{D_{\max}}{D_0}. \qquad (1)$$

Where D_0 represents the drill diameter.

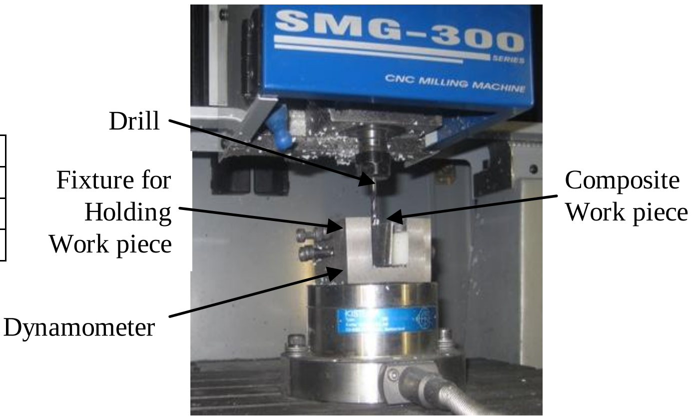


Fig 1. Actual Machining Operation

Fig 2. Cemented Carbide Drills with Different Point Angle

Fig 3. Photograph of Drilled Workspace

Fig 4. The Tool Used For Surface Roughness Measurement

III. DESIGN OF EXPERIMENT

The main objective in design of experiment is to study the relationship between the response and variables. Design of experiment is a method to minimize the number of experiments in order to reach optimum conditions. To explore the relationship between the response and the independent variables, the data required are obtained experimentally. To reduce the number of experiments, the number of data was kept at minimum. In this work, 27 samples based on full factorial design of the experiments employing three-level cutting parameters and three-level angle points are given in Table 2. The parameter levels are chosen based on the primary experiments.

IV. RESULTS AND DISCUSSION

The results of drilling tests allowed for evaluation of the carbon fiber reinforced epoxy composite (CFRP), using cemented carbide drill. The machinability was evaluated by thrust force (TF), delamination factor (F_d) and surface roughness (Ra). Table 3 provides the results as functions of the cutting parameters and tool angle point.

A. Influence of the Machining Parameters on the Thrust Force

The curves of thrust force versus feed rate for various spindle speeds have been shown in Fig. 5 for tool point angle 60, 100 and 140. According to these curves, the thrust force increases with feed rates and decreases with spindle speed. From comparison of the three curves, it can be inferred that increase in the tool angle point increases the thrust force. Thus, the minimum thrust force is obtained in low angle points and feed rates, and high spindle speeds. According to Table 2, the effective factor on the machining force is feed rate.

B. ANOVA for Thrust Force (TF)

Analysis of variance (ANOVA) is a strong method to appoint the conclusion, concerning which parameters affect the response of the inquired process through the series of experimental results. The analysis of variance was employed to investigate the influence of machining parameters on the thrust force (Table 4). These analyses were carried out for a level of significance of 5%, i.e., for a level of confidence of 95%. The last column in Table 5 indicates the percentage of contribution of each factor to the total variation, indicating the degree of influence on the results. From Table 5, it can be revealed that feed rate (66.30%) and spindle speed (20.47%) are significant factors. Fig. 6 shows that the residuals lie reasonably close to a straight line, and no departure points exist. Moreover, it can be concluded that the data follow normal distribution.

C. Influence of Machining Parameter on the Surface Roughness

In Fig. 7, the evolution of surface roughness versus feed rate for the different spindle speed values can be observed. According to these figures, it can be realized that surface roughness increases with feed rate, and decreases with spindle speed. In addition, it can be recognized by comparison of Figs 7a, 7b and 7c that the tool point angle has no clear and considerable effect on surface roughness, so the tool angle with 60 degree has the highest surface roughness, and that with 100 degree has the lowest surface roughness. However, the difference between surface rough nesses for the three tools is not considerable.

D. ANOVA for Surface Roughness (R_a)

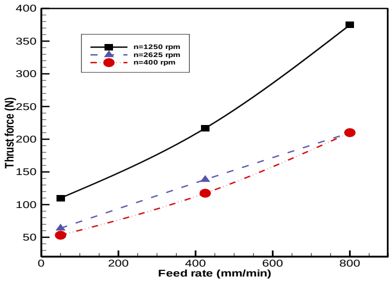
Table 6 displays the ANOVA analysis for surface roughness (R_a). According to Table 5, feed rate (81.49%) is a significant factor. Fig. 8 reveals that the residuals lie reasonably close to a straight line, and no departure points exist. It can be clearly observed that the data follow normal distribution.

Table 2. Levels of Variables

Variables	*Level 1*	*Level 2*	*Level 3*
Spindle speed (rpm)	1250	2625	4000
Feed rate (mm/min)	50	425	800
Point angle	60	100	140

Table 3. Obtained Data from Experiments for Modeling of Machining Process

Test No.	N (rpm)	f ($\frac{mm}{min}$)	Φ (deg.)	TF (N)	F_d	R_a (µm)
1	1250	50	60	110.01	1.02	0.727
2	1250	425	60	216.81	1.11	1.293
3	1250	800	60	374.85	1.182	1.95
4	2625	50	60	63.87	1.03	0.711
5	2625	425	60	138.2	1.07	1.242
6	2625	800	60	209.83	1.128	1.72
7	4000	50	60	53.15	1.026	0.702
8	4000	425	60	117.41	1.048	1.224
9	4000	800	60	210.05	1.102	1.443
10	1250	50	100	124.81	1.05	0.939
11	1250	425	100	285.61	1.18	1.297
12	1250	800	100	426.07	1.24	2.542
13	2625	50	100	69.2	1.04	0.953
14	2625	425	100	169.63	1.12	1.135
15	2625	800	100	306.15	1.66	2.142
16	4000	50	100	61.45	1.02	0.923
17	4000	425	100	153.73	1.08	1.078
18	4000	800	100	249.17	1.26	1.998
19	1250	50	140	143.44	1.08	0.741
20	1250	425	140	326.57	1.24	1.336
21	1250	800	140	499.02	2	1.717
22	2625	50	140	84.32	1.02	0.74
23	2625	425	140	225.25	1.32	1.183
24	2625	800	140	306.88	1.46	1.604
25	4000	50	140	71.66	1.04	0.685
26	4000	425	140	150.02	1.7	1.144
27	4000	800	140	289.47	1.84	1.564



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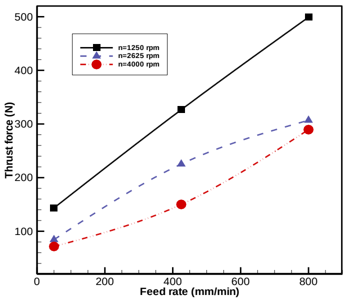

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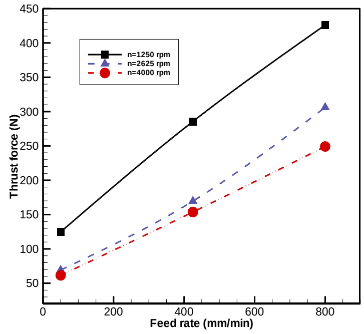


(c)

Fig 5. Thrust force versus feed rate for various spindle speeds: (a) Φ =60 degree, (b) Φ =100 degree, and (c) Φ =140 degree.

Table 4. ANOVA for Thrust Force

Source	*DF*	*Seq ss*	*Ms*	*F*	*P*	*Contribution %*
N (rpm)	2	80470	40235	36.34	0.000	20.47
f (mm/min)	2	255642	127821	115.46	0.000	66.30
Φ (degree)	2	23981	11990	10.83	0.001	5.69
Error	20	22142	1107			5.21
Total	26	382235				

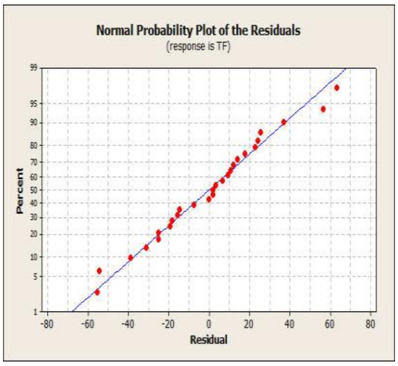
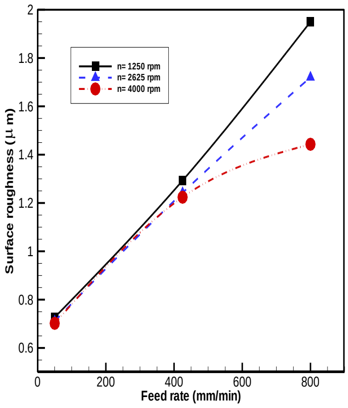


Fig 6. Normal Probability Plot of Residuals for Normal Thrust Force



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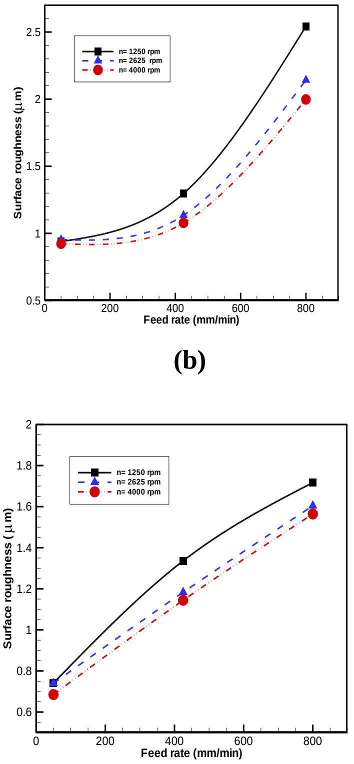


(b)

(c)

Fig 7. Surface roughness versus feed rate for various spindle speeds: (a) Φ =60 degree, (b) Φ =100 degree, and (c) Φ =140 degree.

Table 5. ANOVA for R_a.

Source	*DF*	*Seq ss*	*Ms*	*F*	*P*	*Contribution %*
N (rpm)	2	0.17985	0.08993	3.14	0.065	3.96
f (mm/min)	2	5.14584	2.57292	89.8	0.000	81.49
Φ (degree)	2	0.34543	0.17272	6.03	0.009	6.614
Error	20	0.57301	0.02865			4.25
Total	26	6.24414				

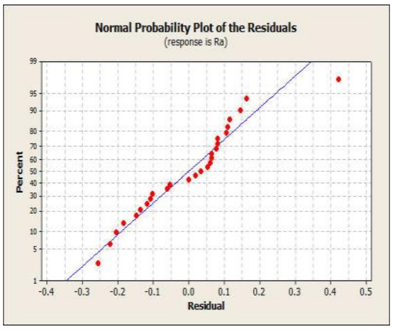


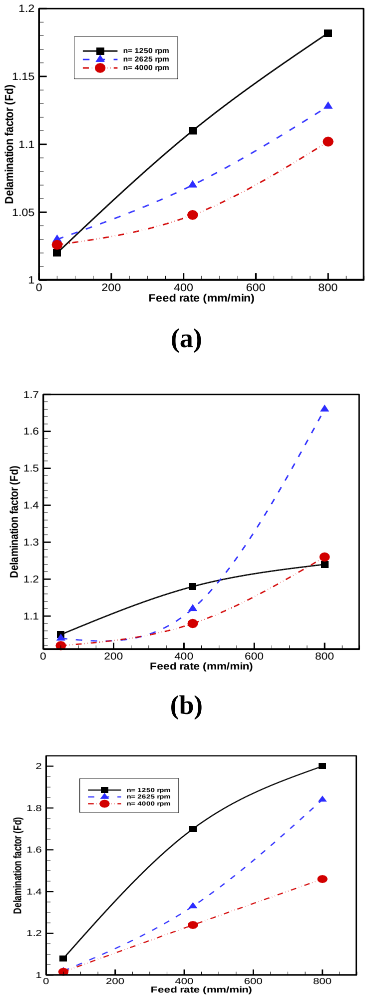
Fig 8. Normal Probability Plot of Residuals for Normal R_a

E. Influence of the Machining Parameters on the Delamination Factor

In Fig. 9, the evolution of the delamination factor (F_d) versus the feed rate for different spindle speed values are illustrated. It can be observed that F_d increases with feed rate, and decreases with spindle speed. Besides, it can be recognized by comparison of the Figs. 9a, 9b and 9c that F_d increases with the tool angle point. Therefore, it can be concluded that F_d is related with thrust force, because increase in the thrust force (increase in feed rate and decrease in spindle speed and tool angle point) leads to increase in F_d.

F. ANOVA for Delamination Factor

The ANOVA analysis results are provided in Table 6. The results show that feed rate (41.14%) and angle point (34.47%) are significant factors. The normal probability plot of residuals is revealed in Fig. 10 which reveals that the residuals lie reasonably close to a straight line, and there are no departure points. Therefore, the data follow normal distribution.



(a)

(b)

(c)

Fig 9. Delamination factor versus feed rate for various spindle speeds: (a) Φ =60 degree, (b) Φ =100 degree, and (c) Φ =140 degree.

Table 6. ANOVA for F_d.

Source	*DF*	*Seq ss*	*Ms*	*F*	*P*	*Contribution %*
N (rpm)	2	0.00506	0.00253	0.07	0.929	5.32
f (mm/min)	2	0.70251	0.35126	10.22	0.001	41.14
Φ (degree)	2	0.51774	0.25887	7.53	0.004	34.47
Error	20	0.68715	0.03436			19.33
Total	26	1.9124				

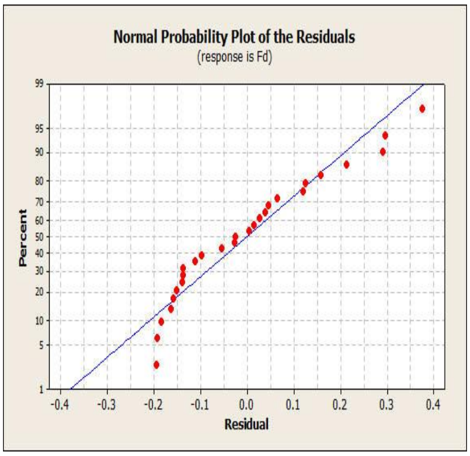


Fig 10. Normal Probability Plot of Residuals for Normal F_d.

V. CONCLUSION

Based on the experimental results presented, the following conclusions can be drawn from drilling of a carbon fiber reinforced epoxy composite (CFRP). Surface roughness increases when the feed increases, and surface roughness decreases when the cutting speed increases; with a higher cutting speed and a lower feed, it is possible to obtain a better surface finish. Thrust forces increase when the feed increases, and increase in cutting speed leads to decrease in thrust forces; i.e. with a higher cutting speed and a lower feed, it is possible to obtain lower thrust forces. Delemination factor increases as the feed rate is elevated and delemination factor decrease when the spindle speed and the tool angle point increase. Increasing the thrust force leads to increase in F_d. Analysis of variance (ANOVA) for thrust force, delamination and surface roughness showed that feed rate is most significant factor.

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