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Characterization of Machining Parameters on Thrust Force and Surface Roughness in Drilling of 40-60 Wt. % BD CFRP Composite

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Abstract

Thrust force is cited as the main cause for delamination and surface roughness in drilling of carbon fiber reinforced polymer (CFRP) composites. Drilling of CFRP composites is one of the most frequently used machining operations in the modern industries for structural assemblies. The effectiveness of drilling operation is mainly based on delamination and surface roughness. The reduction in thrust force reduces the drilling induced delamination and surface roughness and improves the quality of the drilled holes required for structural joints. The current research aims to analyze the effect of machining parameters (spindle speed, drill diameter, feed rate and point angle) on thrust force and surface roughness in drilling of bi-directional carbon fiber reinforced polymer (BD CFRP) composite with TiN coated solid carbide drills. Taguchi L_{27} orthogonal array is used for formulating the experimental layout and the Taguchi method is also employed for predicting thrust force and surface roughness. The investigation reveals that the experimental and the predicted results of thrust force and surface roughness are in good agreement. It is evident from the study that drill diameter has a significant contribution on thrust force and surface roughness, followed by spindle speed, feed rate and point angle. It is also evident from the study that both thrust force and surface roughness decreases with increase in spindle speed in drilling of BD CFRP composite with TiN coated solid carbide drills. The experimental results show that drill diameter of 4 mm, spindle speed of 1800 rpm, feed rate of 20 mm/min and point angle of 90° are the optimum machining parameters needed for minimum thrust force and surface roughness. The results also show that there is a direct correlation between thrust force and surface roughness developed during drilling of BD CFRP composite.

Keywords: BD CFRP composite; drilling;solid carbide drills; thrust force; surface roughness; delamination; fiber pull-out.

INTRODUCTION

CFRP composites are of considerable interest in the modern industries such as aerospace, automobile, space structures, sports, transportation, marine, medical devices etc., due to their high specific modulus, high strength and stiffness, high rigidity, high damping capacity, low thermal expansion, light weight, high resistant to corrosion as compared to conventional metals and alloys [1-5]. The machining of CFRP composites vary significantly from machining of conventional metals and alloys owing to their unique attributes such as non-homogeneity, anisotropy and abrasiveness [6]. The machining operations such as drilling, cutting, grinding etc., are essential for preparing structural joints. Among these machining operations, drilling is the most commonly used machining operation in the modern industries for finishing composite structures [7-10]. The structures used in aerospace and automotive applications contain drilled holes for different purposes like bolted and riveted joints that are used for transferring load within the structure [11].

The common defects normally occur during drilling of CFRP composite materials are delamination, fiber/resin pullout, de-bonding, surface roughness of the hole wall, and micro-cracking. These defects or damages are mainly due to large difference in properties between the matrix and the fiber as well as excessive tool wear due to strong and hard carbon fibers. Among the defects caused by drilling, delamination is the most critical defect that reduces the fatigue strength of the structural joints. It is an inter-laminar failure in the laminated composite system which usually consider to be a crack propagation between the two adjacent layers [12, 13]. It is well known that higher thrust force generated during drilling of composites induces more extensive delamination and surface roughness of the drilled holes [14]. Therefore, it is essential to minimize the thrust force generated in drilling of composites for minimizing delamination and surface roughness.

The introduction of increased cutting speed and the demonstration of special tools geometry used in the drilling operation has inspired researchers to study the different aspects during drilling of composites, including the correlation between the cutting forces, the quality of the drilled holes and tool wear etc,. High speed cutting appears to be a significant factor in the advanced manufacturing technology for improving production and reducing operating cost. High speed cutting or increasing cutting speed will certainly increase production rate and decreases the cutting forces (thrust force and torque). The decrease in cutting forces will decrease the drilling induced delamination and surface roughness [15]. The thrust force and torque can be minimized to a greater extent by selecting suitable tool geometry and drilling parameters for realizing high performance of composite structures [16].

There is a series of research has been conducted by many authors to determine the effect of cutting forces on process parameters and delamination in drilling of CFRP composite laminates. However, not much work is carried out to analyze the effect of cutting/machining parameters on the thrust force and surface roughness in drilling of composite materials. Therefore, the objectives of the present work are to evaluate the effect of machining parameters on thrust force and surface roughness, to analyze the effect of thrust force on surface roughness and to determine the optimum cutting parameters required for minimum thrust force and surface roughness in drilling of BD CFRP composite with TiN coated solid carbide drills. The selection of BD CFRP composite is due to the fact that it has higher strength and stiffness compared to UD CFRP composite. Since the TiN coated solid carbide tools (4mm, 6mm and 8mm) produces lesser thrust force due to less friction generated between the tool and the workpiece, the authors have decided to use these tools for drilling BD CFRP composite for producing holes of better quality.

MATERIALS AND METHODS

Material preparation

Bi-directional carbon fiber reinforced polymer (BD CFRP) composite of 40-60 wt.% is fabricated by means of hand lay-up process, shown in Fig. 1. The resin (Bisphenol A 520) content of the composite is maintained at 40 wt.%. The hardener, Amino K-6 and 60 wt.% of bi-directional plain weave type carbon fiber is used for the fabrication of 4 mm thickness BD CFRP composite laminate. A brush and a roller is used for applying the resin mixture on different layers of the carbon fiber and then it is pressed in the compression moulding machine with a pressure of 0.5 MPa and kept it for a day at room temperature. The post curing of the composite is carried at 80°C for about eight hours. The Fig. 2 shows the sample of fabricated BD CFRP composite laminate and its mechanical properties are given in Table 1.

Figure 1: Hand lay-up process

Figure 2: BD CFRP composite

Figure 3: Experimental set up

Table 1: Mechanical properties of BD CFRP composite

Density (g/cm^3)	Vickers hardness (H_v)	Tensile strength at break (MPa)	Allowable tensile strength (MPa)	Young's modulus Secant (GPa)	Young's modulus Tangent (GPa)	Elongation at break (%)	Flexural strength (MPa)	Flexural modulus (MPa)	Interlaminar shear strength (MPa)
1.282 (1.30)*	22.34	419.25	124	6.87	7.6	11.24	102.21	798.32	12.56

*Theoretical density

Measurement of thrust force and surface roughness

The Taguchi L_{27} orthogonal array [17] is used for conducting experiments and Taguchi method is employed for predicting thrust force and surface roughness. The MINITAB software (version 15) is used for analyzing the experimental results of thrust force and surface roughness [16]. The Signal-to-Noise (S/N) ratio, smaller the better is used and is given by the equation:

$S/N=-10*\log 1/n\ ((\Sigma Y^2)$ where, n is the number of observations and y is the experimental data. The Table 2 shows the levels and factors used for conducting experiments.

Table 2: Levels and factors

Levels	Spindle speed (rpm) (A)	Feed rate (mm/min) (B)	Point angle (degree) (C)	Drill diameter (D)
1	1200	10	90	4
2	1500	15	104	6
3	1800	20	118	8

The drilling experiments are conducted by using TRIAC vertical machining centre (VMC) and the thrust force developed during drilling is measured by 9257BA KISTLER dynamometer. The Taylor-Hobson Sutronic +3 device is used for measuring the surface roughness (R_a) of the drilled holes. The experimental set up and the drill bits used are shown in Fig. 3 and 4 respectively.

(a) (b) (c)

Figure 4: Solid carbide drill bits (a) 4 mm (b) 6 mm and (c) 8 mm

RESULTS AND DISCUSSION

Analyses of thrust force and surface roughness

The results of thrust force (TF) and surface roughness (SR) of newly fabricated BD CFRP composite are presented in Table 3. It is observed from the Table 3 that the error between the experimental and the predicted results of thrust force and surface roughness is less than 6%. This indicates that the values of thrust force and surface roughness developed during drilling of BD CFRP composite are well within the acceptable limit of accuracy for any prediction system. It is also observed from the Table 3 that the values of thrust force and surface roughness deduced for 40-60 wt.% of BD CFRP composite with TiN coated carbide tools are little more than the values of thrust force and surface roughness derived for 50-50 wt. % of BD CFRP composite presented in the previous published paper [18,19]. Hence, 40-60 wt. % of BD CFRP composite can also be used for structural applications. Lesser thrust force and surface roughness produced by TiN coated solid carbide drills as compared to HSS drills may due to less friction generated during drilling. Decrease in friction while drilling is due to higher heat dissipation rate, less wear and tear of solid carbide drills and the superior lubricating capability of the TiN coating of the carbide tools [19-21].

Table 3: Experimental and predicted results of thrust force and surface roughness

Trial No.	TF(Expt)	TF(Predt)	Error (%)	R_a(Expt)	R_a(Predt)	Error (%)
1	32.50	33.76	-3.88	1.24	1.27	-2.66
2	40.45	38.99	3.61	1.35	1.36	-0.59
3	46.84	45.58	2.69	1.50	1.48	1.53
4	37.53	39.17	-4.37	1.30	1.36	-4.62
5	45.75	45.68	0.15	1.51	1.49	1.46
6	50.26	50.24	0.04	1.69	1.65	2.54
7	41.50	43.45	-4.70	1.42	1.43	-0.49
8	49.86	48.40	2.93	1.65	1.62	1.76
9	52.76	52.16	1.14	1.82	1.83	-0.38
10	30.45	29.83	2.04	1.21	1.19	1.40
11	35.57	35.36	0.59	1.28	1.28	-0.08
12	39.79	40.50	-1.78	1.40	1.40	0.00
13	36.52	35.21	3.59	1.27	1.28	-0.79
14	40.67	40.46	0.52	1.41	1.45	-2.70
15	44.98	45.03	-0.11	1.66	1.63	1.81
16	37.75	36.82	2.46	1.27	1.31	-2.91
17	41.56	42.74	-2.84	1.45	1.46	-0.55
18	46.65	47.94	-2.77	1.69	1.64	2.96
19	26.53	25.88	2.45	1.10	1.08	1.64
20	28.50	30.15	-5.79	1.22	1.21	0.82
21	34.76	35.30	-1.55	1.33	1.35	-1.65
22	28.92	28.59	1.14	1.20	1.13	5.92
23	34.54	34.81	-0.78	1.27	1.25	1.34
24	40.86	40.82	0.10	1.34	1.41	-5.37
25	33.93	32.90	3.04	1.24	1.20	3.63
26	38.85	39.12	-0.69	1.33	1.35	-1.50
27	43.57	42.87	1.61	1.49	1.53	-2.82

It is seen from the Table 3 that thrust force and surface roughness decreases with increase in spindle speed. This is because at higher spindle speed built-up-edge (BUE) may be disappears and chip fracture decreases and hence, the thrust force generated and roughness decreases during drilling of BD CFRP composite [22]. The scanned image of drilled hole obtained from a high resolution scanner (Model: HP Scanjet G4010, Hewlett-Packard Company, USA) for minimum thrust force and surface roughness is also shown in the Fig. 5.

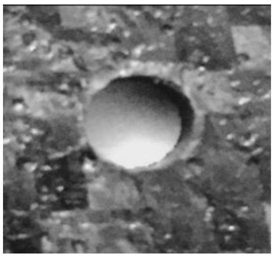


Figure 5: Scanned image of the drilled hole for spindle speed of 1800 rpm, drill diameter of 4 mm, feed rate of 10 mm/min and point angle of 118°

The comparison of experimental and predicted results of thrust force and surface roughness is illustrated in the Figure 6 and 7 respectively. From the Fig. 6 and 7, it is apparent that there is a close approximation among the experimental and the predicted results of thrust force and surface roughness. Hence, it is concluded that Taguchi method can be effectively used as a tool for predicting thrust force and surface roughness in drilling of BD CFRP composite with TiN coated carbide drills.

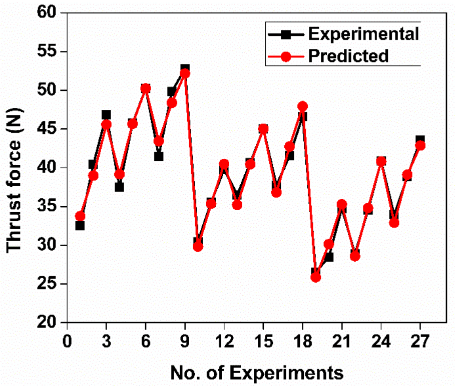


Figure 6: Comparison of experimental and the predicted results of thrust force

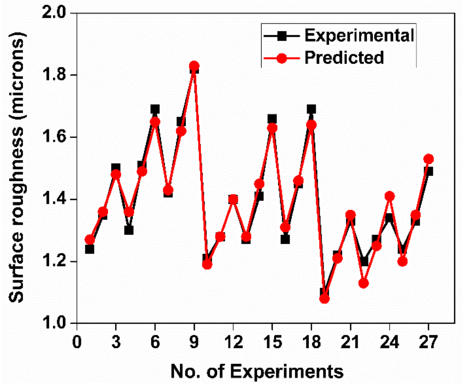


Figure 7: Comparison of experimental and predicted results of surface roughness

The main effect plots for thrust force and surface roughness of BD CFRP composite is shown in Fig. 8 and 9. It is apparent from the Fig. 8 and 9 that drill diameter and spindle speed have a considerable affect on both thrust force and surface roughness compared to the affect of feed rate and point angle on thrust force and surface roughness as the slope of the drill diameter and spindle speed are more. It is also apparent from the Fig.8 and 9 that the point angle has an insignificant influence on thrust force and surface roughness as its slope is almost horizontal. The optimum cutting parameters given by the main effect plots (Fig.8 and 9) for minimum thrust force and surface roughness are drill diameter of 4 mm, spindle speed of 1800 rpm, feed rate of 10 mm/min and point angle of 90°.

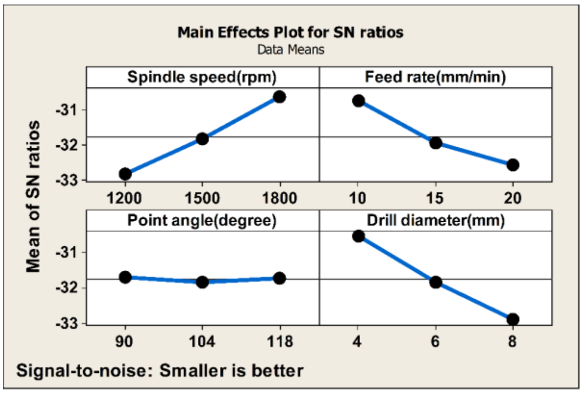


Figure 8: Main effect plot for thrust force

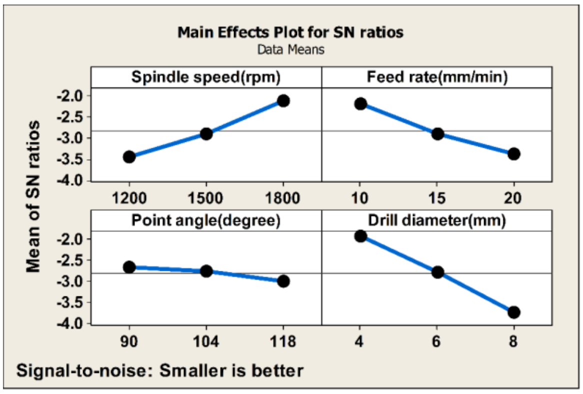


Figure 9: Main effect plot for surface roughness

Effect of thrust force on surface roughness

The thrust force and the surface roughness developed in drilling of composite is the major concern for deciding the quality of the drilled holes. The effect of thrust force on surface roughness in drilling of 40-60 wt. % BD CFRP composite using TiN coated carbide drills is illustrated in Fig. 10. It is evident from the Fig. 10 that there is a direct correlation among the thrust force and the surface roughness developed during drilling of BD CFRP composite. Therefore, the surface roughness of the drilled holes can be minimized by minimizing the thrust force generated in drilling of composite laminates.

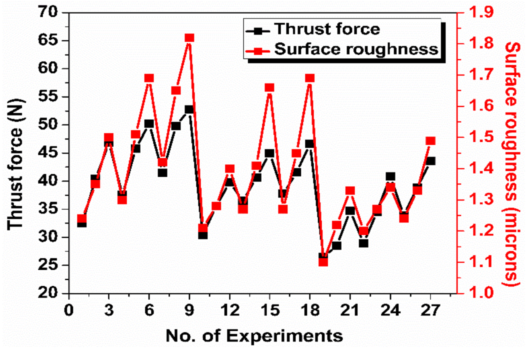
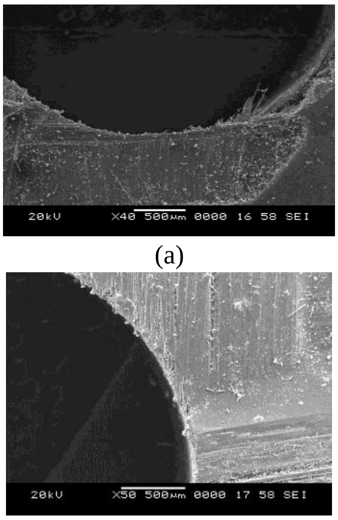


Figure 10: Effect of thrust force on surface roughness

Microstructure analyses

The delamination, fiber pull-out, micro-cracking, de-bonding, fiber breakage, surface roughness etc., are the most common defects occur while drilling of composites. Among these defects delamination is a major problem that affects the quality of the drilled holes. The scanning electron microscopic (SEM) images for spindle speed of 1200 rpm, feed rate of 20 mm/min, point angle 118°, drill diameter of 8 mm (for maximum TF and SR) and for spindle speed of 1800 rpm, feed rate of 10 mm/min, point angle of 118°, drill diameter of 4 mm (for minimum TF and SR) are shown in Fig.11a, b. From the Fig.11a, more delamination and fiber pull-out is observed as compared to the SEM image shown in Fig. 11b. This indicating that higher thrust force produces more delamination and fiber pull-out which leads to higher surface roughness during drilling of composites. Less delamination and fiber pull-out shown in Fig. 11b is may be due to the reason that cutting action is dominating over the ploughing action [23].



(a)

(b)

Fig. 11 SEM images of BD CFRP composite at (a) spindle speed of1200 rpm, feed rate of 20mm/min, point angle of 118° and drill diameter of 8 mm (b) spindle speed of 1800 rpm, feed rate of 10mm/min, point angle of 118° and drill diameter of 4mm

Confirmation test

The confirmation test results of thrust force and surface roughness obtained for optimal cutting parameters (spindle speed of 1800 rpm, drill diameter of 4 mm, feed rate of 10 mm/min and point angle of 90°) are presented in Table 4 and 5. From the Table 4 and 5, it is observed that the experimental result of thrust force (23.45) and surface roughness (1.068) of BD CFRP composite are less than the minimum thrust force (26.53) and surface roughness (1.100) obtained from Taguchi L_{27} orthogonal array. This confirm the truthfulness of the experimental results of thrust force and surface roughness deduced from Taguchi orthogonal array and the optimum cutting parameters given in the Table 4 and 5 can be used for making quality holes for structural assembly. From the Table 4 and 5 it is also observed that there is a very close convergence among the experimental and the predicted result of thrust force and surface roughness with more than 97% and 98% agreement respectively.

Table 4: Confirmation test results of thrust force

Optimum cutting parameters	Experimental Thrust force	Prediction Thrust force	% of agreement
$A_3 B_1 C_1 D_1$	23.45	24.09	97.27

A_3= 1800 rpm, B_1=10 mm/min, C_1=90° and D_1=4 mm

Table 5: Confirmation test results of surface roughness

Optimum cutting parameters	Experimental R_a	Prediction R_a	% of agreement
$A_3 B_1 C_1 D_1$	1.068	1.055	98.78

A_3= 1800 rpm, B_1=10 mm/min, C_1=90° and D_1=4 mm

CONCLUSIONS

The following are the conclusions drawn during drilling BD CFRP composite with TiN coated solid carbide drills:

1. The experimental and the predicted results of thrust force and surface roughness are in good agreement. Hence, Taguchi method can be used as a tool for predicting the thrust force and surface roughness values.
2. The optimal cutting parameters required for minimum thrust force and surface roughness are drill diameter of 4 mm, spindle speed of 1800 rpm, feed rate of 10mm/min and point angle of 90°.
3. The thrust force and surface roughness decreases as the spindle speed increases. This indicating that better quality

of drilled holes can be achieved by using higher spindle speed.

4. The drill diameter and spindle have a significant effect on both thrust force and surface roughness followed by feed rate and point angle.
5. The confirmation results of thrust force and surface roughness confirms the reliability of the experimental results obtained from Taguchi L_{27} orthogonal array and the minimum delamination and fiber pull-out shown in the SEM image indicating that TiN coated carbide tools can be used for making quality holes for structural assembly
6. Since the newly fabricated BD CFRP composite shows good mechanical properties, it can be used in industries like aerospace, automobile, marine, sports, etc. for structural assembly.

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