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Surface Roughness Analyses in Drilling of CFRP Composite

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Abstract

Drilling is a commonly used machining process in carbon fiber reinforced polymer (CFRP) composite laminates in industries. The surface roughness while drilling of composite laminates is one of the generally used parameters for measuring the quality of the drilled holes. The present work aims to examine the consequences of process/cutting parameters such as spindle speed, drill diameter, feed rate and point angle on surface roughness while drilling of bi- directional carbon fiber reinforced polymer (BD CFRP) composite with TiN coated solid carbide tools. Taguchi design of experiments (DOE) is used for conducting the experiments and the Taguchi method is used for predicting the surface roughness. The study shows that the experimental and the predicted results of surface roughness are closely matches with each other and drill diameter has a maximum contribution on surface roughness, followed by spindle speed and feed rate. The point angle has an insignificant contribution on surface roughness. The study also shows that surface roughness decreases with increase in spindle speed, decrease in drill diameter and feed rate during drilling of composite. The minimum values of surface roughness (0.927 and 0.945) deduced in drilling of BD CFRP composite, indicating that TiN coated carbide tools can be used for drilling better quality of holes for structural applications.

Keywords: surface roughness; drilling; carbide tools; composite material; anisotropy; fiber pull-out; Taguchi design of experiments.

INTRODUCTION

In the recent years, CFRP composites are extensively used in aircraft, space structures, automobiles, sports, medical devices etc., owing to their good mechanical properties such as high specific modulus, high strength and stiffness, high damping capacity and low thermal expansion, light weight and high resistant to corrosion [1,2]. CFRP composites are also used for machine tool spindles and power transmission shafts of ships due to their energy saving capacity and trouble-free maintenance [3-6]. Drilling, cutting, grinding etc. are the several machining processes which are necessary for preparing structural elements [7, 8]. Among these processes, drilling is the most repeatedly used machining process in CFRP composites. However, the machining of CFRP composites varies significantly from machining of conventional metals and alloys owing to their unique attributes such as non-homogeneity, anisotropy and abrasiveness [9].

In order to evaluate the surface quality while machining, it is quite important for composite materials to measure the surface roughness and estimate the damaging factors. Due to the non-homogeneity in their structures and variation in damages, it is difficult to measure precise and reliable surface roughness of composite material. Cutting mechanism and surface roughness varies depending upon the fiber orientation and machining direction [10-13]. The different defects generally occur while machining of CFRP composites are fiber pull-out, delamination, matrix cracking, fiber matrix de-bonding and surface roughness and these defects/damages can greatly influence on the fatigue life and strength of the components. Therefore, it is essential to minimize these problems to have better assembly strength and tolerance of the finished components. The consequences of machining parameters on roughness and failure stresses in edge trimming of carbon fiber reinforced polymer were also highlighted by Gidossi [14]. It was noticed that the lowest failure stresses were glimpsed on specimen machined at the highest cutting speed.

The study of surface roughness for various combination of cutting parameters during drilling of CFRP composite laminates is important for microscopic analyzes of delamination, fiber pull-out, de-bonding of fibers etc., encountered in drilling and to establish the correlation between these defects and the surface roughness values. In the present work, author's aims to evaluate the effect of cutting parameters on surface roughness in drilling of BD CFRP composite material with TiN coated solid carbide drills and to determine the optimum cutting parameters required for minimum surface roughness. The choice of BD CFRP is based on the fact that it has a better interface between the lamina due to fiber orientation in both X and Y direction and normally it has higher strength compared to that of UD CFRP composite. Generally, TiN coated solid carbide tools produces lesser thrust force and torque while drilling due to less friction generated between the tool and the work piece. The reduction in thrust force and torque reduces the surface roughness of the drilled holes.

MATERIALS AND METHODS

Material fabrication

The hand lay-up process is used for fabricating BD CFRP composite of 4 mm thickness. The resin used in the fabrication of the composite is Bisphenol A 520 and the resin content is maintained at 45 weight %. The hardener used is Amino K-6 and the bi-directional plain weave type carbon fiber is used as reinforcement. The resin mixture is applied on different layers of the carbon fiber and it is then pressed in the compression moulding machine with a pressure of 0.5 MPa for about 24 hours. The post curing of the composite is carried at 80°C for about eight to ten hours. The sample of the fabricated composite laminate is shown in Fig. 1 and its mechanical properties are given in Table 1.

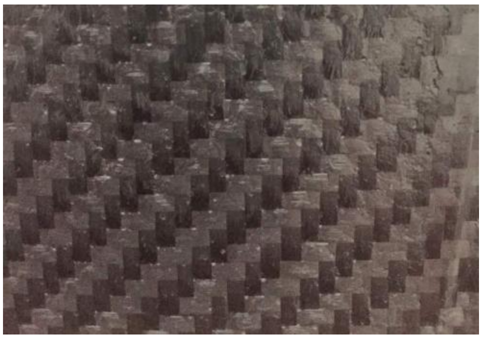


Figure 1: BD CFRP composite

Measurement of surface roughness

The Taguchi L_{27} orthogonal array (L_3^4 i.e, three levels and four factors shown in Table 2) is used for conducting experiments. The MINITAB software (Version 15) is used for analyzing the results of surface roughness [15]. The signal-to-noise ratio, smaller the better is used for selecting the optimum cutting parameters and is given by the equation:

$$S/N = -10 * \log 1/n ((\Sigma Y^2) \quad (1)$$

where, n is the number of remarks and y is the observed data.

Table 2: Factors and levels

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 operation is carried out using CNC vertical machining centre. The drill bits of different sizes used in the current work and the CNC vertical machining centre is shown in Fig. 2 and 3 respectively.

Table 1: Mechanical properties of BD CFRP composite

Material	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)
55-45 wt.%	1.295 (1.30)*	23.34	424.25	131	7.37	8.86	12.29	104.1	801.97	14.42

*Theoretical density

(a) (b) (c)

Figure 2: TiN coated carbide drills (a) 4 mm (b) 6 mm and (c) 8 mm.

Figure 3: Vertical Machining Center

The Taylor Hobson Surtronic machine, shown in Fig. 4 is used for measuring the surface roughness (R_a) of the drilled holes and R_a values are calculated using the equation:

$$R_a = 1/3\Sigma x_i \quad (2)$$

where, Σx_i is the total number of trials.

Figure 4: Taylor Hobson surtronic machine

RESULTS AND DISCUSSION

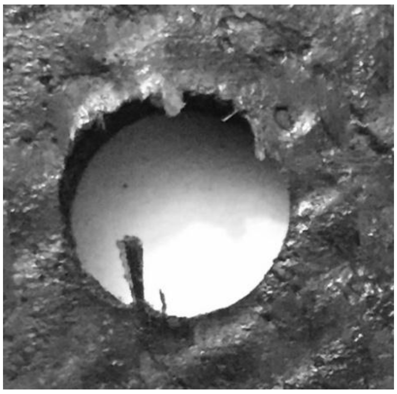
Analyses of surface roughness

The results of surface roughness during drilling of BD CFRP composite are shown in Table 3. From the Table 3, it is observed that the percentage error of surface roughness between the experimental and the prediction by Taguchi is in the range of -0.0267 to 4.5963. Since the percentage of variation or error of surface roughness is less than 5%, the results of surface roughness deduced by Taguchi L_{27} orthogonal array is very much within the acceptable limit of accuracy for any prediction system. It is also observed from the Table 3 that the experimental and the predicted values of surface roughness of BD CFRP are less than 1.7660 and 1.7977 respectively. These minimum values of surface roughness produced by the TiN coated tools is due to the fact that they produce lesser thrust force and torque due to less friction generated during drilling. Decrease in friction between the tool and the work piece may be due to higher heat dissipation rate, lesser wear and tear of solid carbide tools and the better lubricating ability of the TiN coating in the solid carbide drills [16, 17].

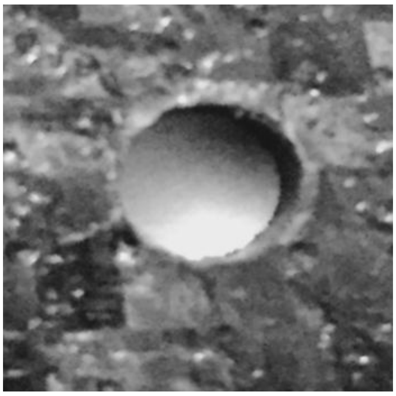
Table 3: Results of surface roughness in drilling of BD CFRP composite

Trial No.	Experimental R_a	Predicted R_a	Error % Experimental over Taguchi
1	1.152	1.1645	-1.0810
2	1.229	1.2069	1.8286
3	1.483	1.4657	1.1803
4	1.168	1.2182	-4.1255
5	1.482	1.4119	4.9627
6	1.683	1.6837	-0.0415
7	1.358	1.3635	-0.4099
8	1.599	1.6075	-0.5343
9	1.766	1.7977	-1.7633
10	1.014	1.0500	-3.4322
11	1.045	1.0760	-2.8846
12	1.395	1.3738	1.5424
13	1.122	1.1650	-3.6942
14	1.381	1.3813	-0.0267
15	1.653	1.5828	4.4345
16	1.082	1.1627	-6.9407
17	1.448	1.4003	3.4012
18	1.674	1.6218	3.2180
19	1.003	0.9553	4.7557
20	1.013	1.0040	0.8923
21	1.193	1.2314	-3.1246
22	1.016	0.9770	3.9875
23	1.063	1.1327	-6.1534
24	1.296	1.3654	-5.0883
25	1.043	1.0067	3.4803
26	1.189	1.2280	-3.1790
27	1.468	1.4884	-1.3759

It is apparent from the Table 3 that the minimum R_a of 1.003 is obtained at spindle speed of 1800 rpm, drill diameter of 4 mm and feed rate of 10 mm/min and point angle of 118°. Hence, it is concluded from the study that R_a is minimum with minimum feed rate and drill diameter and maximum spindle speed. The minimum surface roughness at minimum feed rate is due to the reason that at low feed rate, the rate of strain developed is less and therefore, the fracture is less aggressive and more controllable [18]. The decrease in surface roughness with increase in spindle speed may be due the fact that at higher spindle speed, built up edge (BUE) vanishes and chip fracture decreases and thus, the roughness decreases. This demonstrated that higher cutting speed is appropriate for drilling of composites for getting excellent surface finish. The minimum surface roughness at minimum drill diameter is also may be due to less formation of BUE and less cutting forces generated while drilling of composite [19]. The scanned images of drilled hole obtained from a high resolution scanner (Model: HP Scan jet G4010, Hewlett-Packard Company, USA) for maximum and minimum surface roughness is also shown in the Fig. 5(a, b).



(a)



(b)

Figure 5: Scanned images of the BD CFRP composite for (a) maximum surface roughness and (b) minimum surface roughness

The Fig. 6 shows the relationship between the experimental and the predicted results of surface roughness. From the Fig. 6, it is seen that there is a very little divergence among these results of surface roughness. Hence, it is concluded from the study that Taguchi method can be efficiently used as a tool for predicting R_a values in drilling of BD CFRP composite with TiN coated carbide tools.

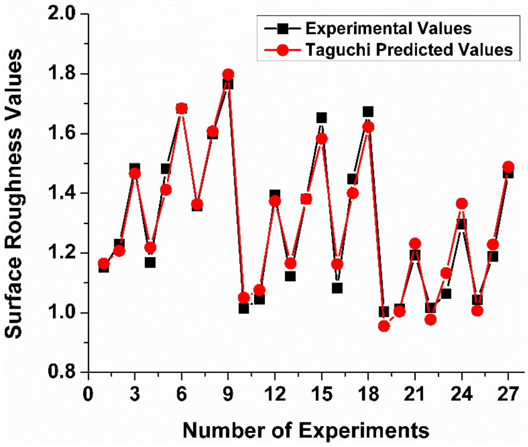


Figure 6: Relationship among the experimental and predicted results of surface roughness

The main effect plot for surface roughness of BD CFRP composite is shown in Fig. 7. From the Fig. 7, it is apparent that drill diameter has a significant contribution on surface roughness compared to that of spindle speed and feed rate as the slope of the drill diameter is more. It is also apparent from the Fig. 7 that the point angle has a negligible influence on surface roughness as the slope of the point angle is almost horizontal. The optimum cutting parameters given by the main effect plot for minimum surface roughness are drill diameter of 4 mm, spindle speed of 1800 rpm, feed rate of 10 mm/min and point angle of 90°.

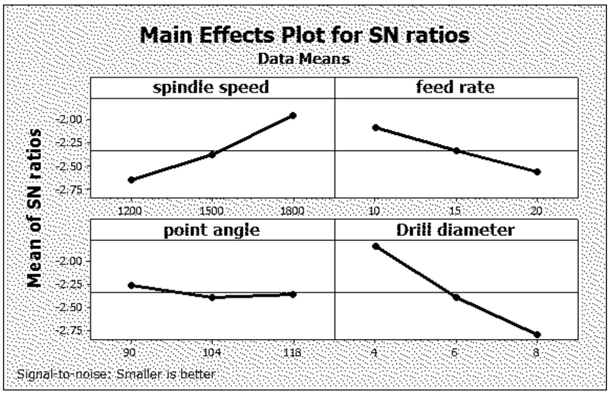
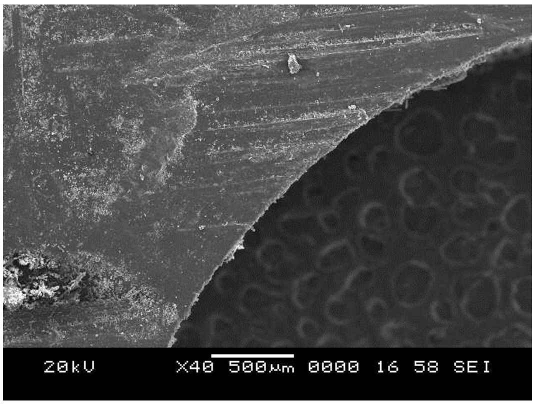


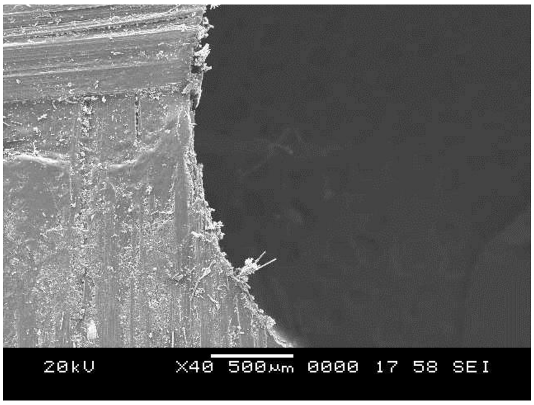
Figure 7: Main effect plot for surface roughness

Microstructure analyses

Delamination and fiber pull-out are considered as the key problems occur during drilling of composites and they greatly affect the quality of the drilled holes. Since these defects has a direct correlation with the surface roughness, decrease in delamination and fiber pull-out decreases the surface roughness. The microscopic level of study of the drilled holes helps for identifying these defects during drilling of composites. The Fig. 8(a) shows the SEM image obtained for minimum (1.003) surface roughness for spindle speed of 1800 rpm, feed rate of 10 mm/min, point angle of 118°, drill diameter of 4 mm and the Fig. 8(b) shows the SEM picture obtained for maximum (1.766) surface roughness value for spindle speed of 1200 rpm, feed rate of 20 mm/min, point angle 118°, drill diameter of 8 mm. It is observed that the delamination and fiber pull-out is very minimum in SEM picture shown in Fig. 8(a) as compared to that shown in Fig.8b. More delamination and fiber pull shown in Fig. 8(b) may be due to the fact that ploughing action is dominating over the cutting action. The ploughing of the fibers may be due to higher friction developed by the heat generated between the work piece and cutting edge of the tool [20].



(a)



(b)

Figure 8: SEM images of BD CFRP composite for (a) minimum surface roughness and (b) maximum surface roughness

Verification test

The result of the verification test carried out for optimal cutting parameters is shown in the Table 4. From the Table 4, it is clear that the experimental result of surface roughness (0.9274) derived 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°) for BD CFRP composite is less than the minimum surface roughness (1.003) obtained from Taguchi L_{27} orthogonal array. This confirms the accuracy of the results obtained from the Taguchi design of experiments. The SEM image shown in the Fig. 9, also substantiate the result of the confirmation test. From the SEM image (Fig. 9), it is apparent that the damages like delamination and the fiber pull-out are less as compared to the damages observed in the SEM image shown in the Fig. 8a. From the Table 4, it is also clear that there is a very close convergence between the experimental and the Taguchi predicted result of surface roughness with less than 2% deviation.

Table 4: Verification test results of surface roughness

Optimum cutting parameters	Experimental R_a	Prediction R_a	% of agreement
$A_3 B_1 C_1 D_1$	0.9274	0.9449	98.14%

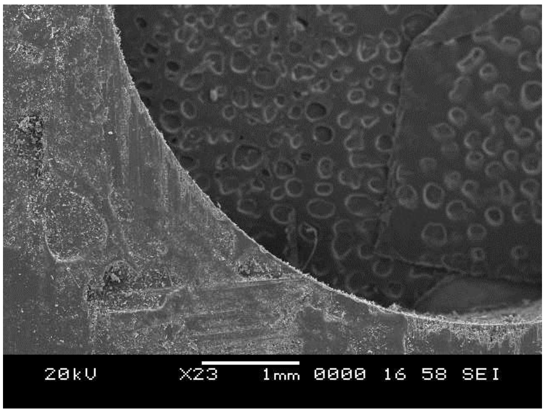


Figure 9: SEM image of the hole drilled for optimum cutting parameters

CONCLUSIONS

1. The study indicating that the Taguchi DOE can be used as a tool for obtaining and evaluating the influence of cutting parameters on surface roughness in drilling of BD CFRP composite using TiN coated soild carbide drills.
2. The experimental and the Taguchi predicted results of surface roughness are perfectly matches with each other. Therefore, it is concluded that Taguchi method can be efficiently used for predicting the roughness values in drilling of BD CFRP composite.
3. The investigation reveals that the optimal cutting parameters required for minimum surface roughness are drill diameter of 4 mm, spindle speed of 1800 rpm, feed rate of 10 mm/min and point angle of 90° and drill diameter has a considerable influence on surface roughness compared to the effect of spindle speed, feed rate and the point angle.

4. The confirmation test shows the truthfulness of the experimental results obtained from Taguchi L_{27} orthogonal array.
5. The minimum delamination and the fiber pull-out shown by the SEM pictures indicating that TiN coated solid carbide drills can be used for drilling quality holes in composites.
6. The study reveals that the surface roughness has a direct relationship with feed rate and drill diameter and has an inverse relationship with the spindle speed. The point angle has a very little impact on surface roughness.
7. Since the fabricated BD CFRP composite laminate shows good mechanical properties, it can be used for structural applications in industries such as aerospace, automobile, marine, space, naval, sports, transportation etc.

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