

Research Article

Experimental Investigation in Drilling of Carbon Fiber Reinforced Polymer Composite using HSS and Solid Carbide Drills

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Abstract

Drilling using twist drills is a frequently employed machining operation in carbon fiber reinforced polymer (CFRP) composite for generating holes for structural assemblies. In the present work, the effect of drill diameter, spindle speed, feed rate and point angle on thrust force and torque during drilling of bi-directional carbon fiber reinforced polymer (BD CFRP) composite using high speed steel (HSS) and solid carbide drills is investigated. The BD CFRP composite is fabricated by hand lay-up process followed by compression moulding technique. Taguchi L₂₇ orthogonal array is used for designing the experimental layout. The response surface methodology (RSM) is employed for predicting cutting forces. The study reveals that the experimental and the predicted results of cutting forces are in good agreement. The investigation shows that drill diameter and spindle speed are the most significant parameters affecting the cutting forces.

Keywords: Drilling, Composite, Thrust force, Torque, Delamination, Anisotropy.

1. Introduction

Carbon fiber reinforced polymer (CFRP) composites are excellent materials which replace many metal structures in aerospace, defense, automobile and marine industries due to their superior mechanical properties such as light weight, high strength and stiffness, excellent fatigue and corrosion resistance, low thermal expansion, and high damping [Guu *et al.*, 2011 and Palanikumar *et al.*, 2008]. Drilling is one of the most frequently used machining operations in CFRP composites for preparing structural joints [Ahmad, 2009]. Machining of CFRP composites differ substantially from machining of conventional metals and alloys due to their special characteristics such as non-homogeneity, anisotropy and abrasiveness [Naveen *et al.*, 2009]. The most common problems that occur during drilling of CFRP composites are fiber breakage, de-bonding, thermal damage, fiber pull-out, micro cracking and delamination at entry and exit layers [Tagliaferri *et al.*, 1989]. Among these problems, delamination is considered to be a major defect in composite structure which reduces the assembly tolerance and strength of the finished component and thus degrades its reliability. Therefore, there is a need for high quality machining to reduce the damage due to delamination which is a consequence of axial thrust

force and torque that the drill tip exerts on the workpiece in drilling [Zitoun and Collombet, 2007].

Higher thrust force and torque generated during drilling of CFRP composite induce more extensive delamination [Hocheng and Tsao, 2003]. Therefore, many researchers have attempted to minimize thrust force and torque while drilling of composites by designing the different types of cutting tools for optimizing the effects of process parameters [Wong *et al.*, 1982]. Tsao and Hocheng [2008] established a number of mathematical models for the step-core special drills to study the inter-relation of thrust force and the drilling-induced delamination. Tsao [2008] demonstrated that diameter ratio and the tool feed rate were the dominant machining parameters influencing the efficiency of the step-core special drills, and that the diameter ratio can be considered a significant parameter for the thrust force generated in drilling using the step-core special drills.

The objective of the present study is to analyze and optimize the effects of process parameters (feed rate, spindle speed, drill diameter and point angle) on thrust force and torque developed while drilling of BD CFRP composite laminate with HSS and solid carbide drills by integrating Taguchi DOE and RSM. The reason for selecting BD CFRP composite is that the fibers in it are oriented in both X and Y directions. Due to this, it has maximum strength and stiffness in all direction. The BD CFRP composite also contains less number of voids which is a significant factor for its higher strength due

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to less stress concentration at voids, when compared to uni-directional carbon fiber reinforced polymer (UD CFRP) composite. This result in higher tensile and flexural properties in BD CFRP composite compared to UD CFRP composite.

2. Experimental

2.1 Fabrication of composite laminate

The BD CFRP composite laminate (200 mm × 200 mm × 4 mm) is fabricated at room temperature by hand lay-up process followed by compression moulding technique (Fig. 1).

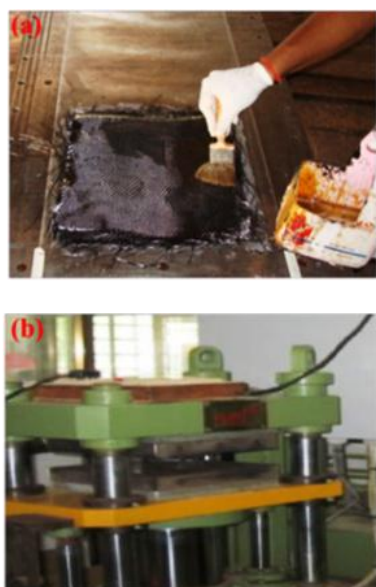


Fig. 1 (a) Hand lay-up process and (b) Compression moulding machine

The resin used for the preparation of matrix is Bisphenol A based epoxy resin L-12, and the hardener used is Amino K-6. The bi-directional plain weave type carbon fiber of areal density 200 g.m⁻² is used as reinforcement. The resin content of the composite laminate is maintained around 50 wt %. A brush and a roller are used for applying the resin mixture onto the different layers of the carbon fiber which is then pressed in the hydraulic compression moulding machine with a pressure of 0.5 MPa for about 24 hours at room temperature. The post curing of the composite laminate is carried out for about eight hours at 80°C. The scanned image of BD CFRP composite is shown in Fig. 2.

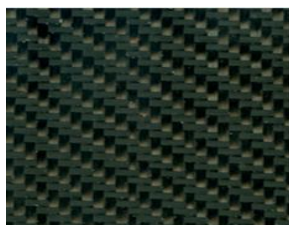


Fig. 2 The scanned image of BD CFRP composite

2.2 Drilling test and statistical tools used for analysis

The drilling experiments are carried out using CNC vertical machine center (TRIAC VMC) with HSS and solid carbide drills. The Kistler 9257 dynamometer is used for measuring thrust force and torque. The Kistler 5070 charge amplifier receives the signals of thrust force and torque in drilling operation which are recorded on a data acquisition device. The experimental set up and the tools used during drilling of BD CFRP composite laminate are shown in Fig. 3.

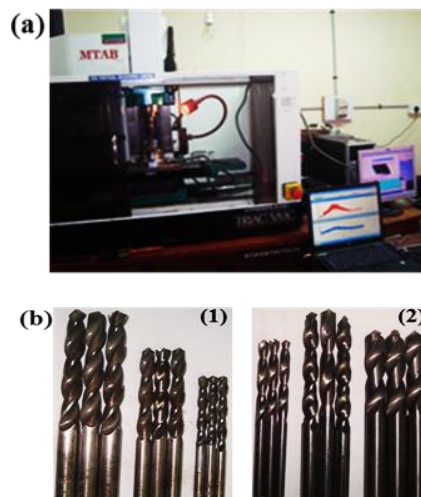


Fig. 3 (a) Experimental set up and (b) Photograph of (1) HSS (2) solid carbide drills

The Taguchi L₂₇ orthogonal array is employed for designing the experimental layout and to identify the optimum design factors for minimizing thrust force and torque developed in drilling of composites [Montgomery, 2005]. The Taguchi analysis is carried out by using the MINITAB 15 software. The RSM is used to evaluate and predict the significance of process parameters on thrust force and torque. The factors and levels chosen for conducting the drilling experiments are summarized in Table 1.

Table 1 Levels and factors

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

3. Results and discussion

3.1 Analysis of thrust force and torque using Taguchi DOE and RSM

In the present work, the central composite design (CCD) of RSM is used for establishing the empirical relationship among the process parameters [Myers and

Montgomery, 1995]. The number of experiments used in this study is 30 and the number of cutting parameters considered is 4. The focus of this study is to minimize thrust force and torque for minimizing the drilling-induced delamination and surface roughness for generating quality holes. The experimental results of thrust force and torque generated in drilling of BD CFRP composite laminate using HSS and solid carbide drills are shown in Fig. 4. It is observed from the figure that there is a drastic reduction in thrust force and torque in solid carbide drills when compared to that in HSS drills. This situation could be attributed to higher hardness, higher resistance to wear, lower thermal conductivity and high heat dissipation rate of solid carbide drills. Due to these reasons, the heat generated between the tip of the tool and the workpiece is less in solid carbide drills which results in less stick-slip friction at the interface of the tool and the workpiece.

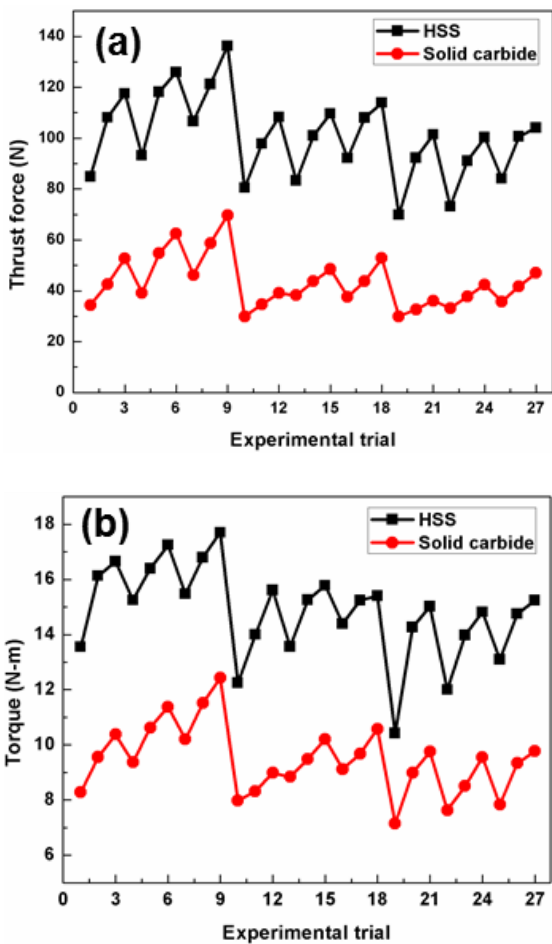


Fig. 4 The experimental results of (a) thrust force and (b) torque in BD CFRP composite using HSS and solid carbide drills

In the present work, RSM is used for predicting the numerical results of thrust force and torque. The comparison of the experimental and the numerical results of thrust force and torque in drilling of BD CFRP composite laminate with HSS and solid carbide drills are shown in Fig. 5 and 6 respectively.

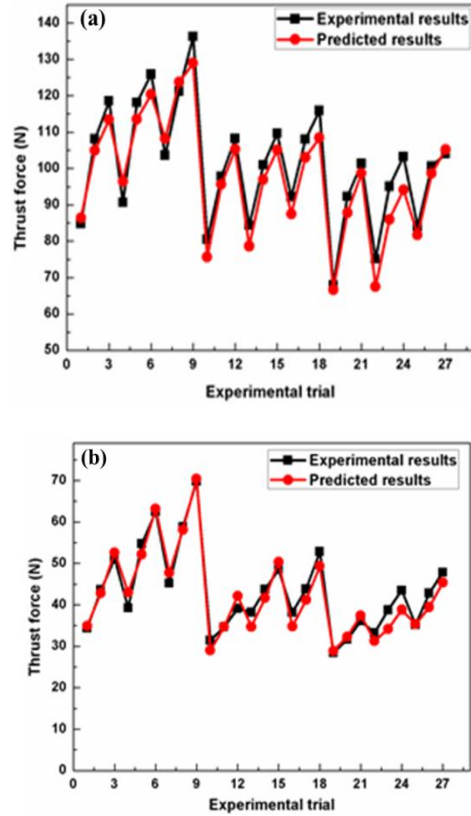


Fig. 5 The comparison of experimental and numerical results of thrust force in (a) HSS and (b) solid carbide drills

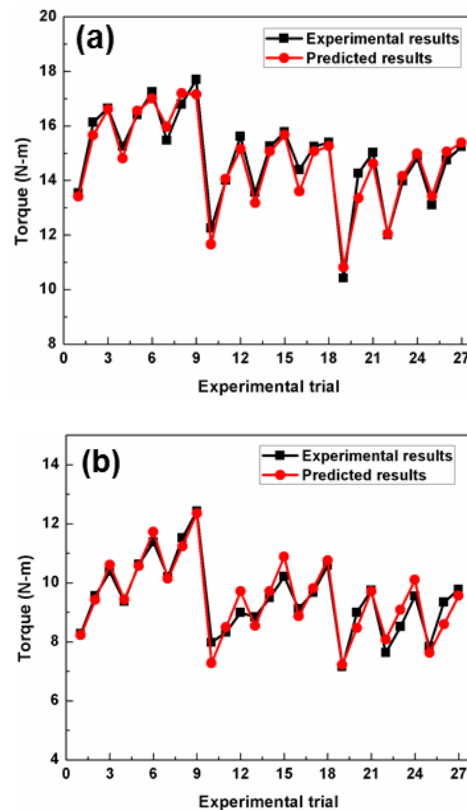


Fig. 6 The comparison of experimental and numerical results of torque in (a) HSS and (b) solid carbide drills

It is observed from figures that the experimental results of thrust force and torque are in good approximation with the predicted results of thrust force and torque as per RSM. Therefore, it is concluded that RSM can be successfully used for predicting the cutting forces during drilling of composites.

The experimental results of thrust force and torque are analyzed through the main effects plot for signal-to-noise (S/N) ratio. The S/N ratio characteristic (smaller the better) is given in Equation 1.

$$\frac{S}{N} = -10 \log \frac{1}{n} (\sum y^2) \tag{1}$$

where, n is the number of observations and y is the observed value of thrust force and torque, S is the signal that represents the desirable value of thrust force and torque, and N is the noise that represents the undesirable value of thrust force and torque. The main effects plot for S/N ratio of thrust force and torque for HSS and solid carbide drills are shown in Fig. 7 and 8. Figures illustrate that drill diameter followed by spindle speed and feed rate are the most significant process parameters which influence thrust force and torque, in both HSS and solid carbide drills as the gradient is more steeper. It is also evident that the point angle is the least contributing process parameter for thrust force and torque as the slope of the graphs is almost horizontal. It is clear from the main effects plots that drill diameter of 4 mm, feed rate of 10 mm/min, spindle speed of 1800 rpm and point angle of 90° are the optimum parametric conditions required for minimum thrust force and torque in drilling of BD CFRP composite laminate using HSS and solid carbide drills.

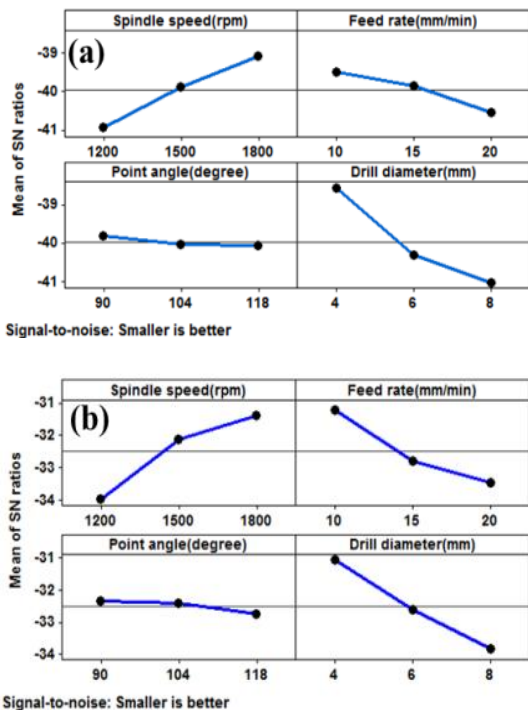


Fig. 7 Main effects plot for thrust force (a) HSS and (b) solid carbide drills

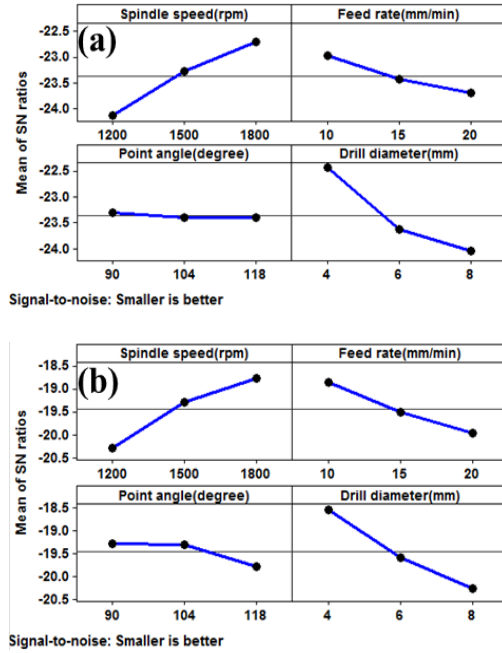


Fig. 8 Main effects plot for torque (a) HSS and (b) solid carbide drills

3.2 The analyses of the influence of machining parameters on thrust force and torque using RSM model

The effects of process parameters are also analyzed using 3D response plot of RSM. Fig. 9 and 10 illustrate the interaction effects of spindle speed and drill diameter on thrust force and torque with feed rate (20 mm/min) and point angle (118°) held constant.

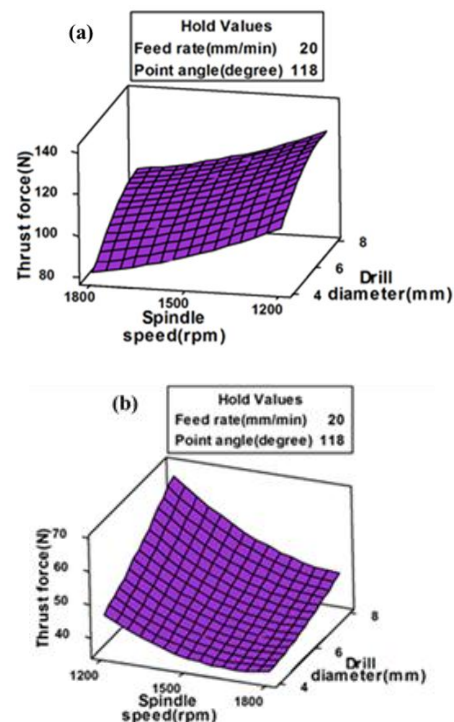


Fig. 9 Interaction effects of spindle speed and drill diameter on thrust force for (a) HSS and (b) solid carbide drills in drilling of BD CFRP composite

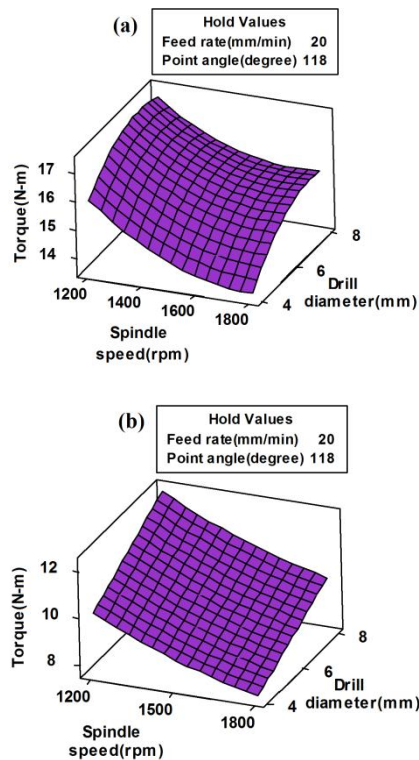


Fig. 10 Interaction effects of spindle speed and drill diameter on torque for (a) HSS and (b) solid carbide drills in drilling of BD CFRP composite

It is observed from the figures that thrust force and torque increase noticeably with increase in drill diameter in both HSS and solid carbide drills. This can be attributed to the increase in contract area of the hole produced due to increase in drill diameter, which increases thrust force and torque generated in drilling of composites [Palanikumar, 2011]. However, thrust force and torque decrease significantly with increase in spindle speed, in both HSS and solid carbide drills. This is due to the fact that the increase in spindle speed increases the heat generated during drilling of composites, which softens and shears the matrix material, thus reducing the thrust force and torque [Palanikumar et al., 2012].

Fig. 11 and 12 demonstrate the effect of feed rate and point angle on thrust force and torque with spindle speed (1800 rpm) and drill diameter (8 mm) held constant. It is observed from the figures that thrust force and torque also increase with increase in tool feed rate both in HSS and solid carbide drills. Since drilling induced delamination is primarily dependent on thrust force and torque, low feed rate usually produces minimum damage due to delamination. This results in better quality of drilled holes in composite materials. The figures also demonstrate that cutting forces generated in drilling of composite are least sensitive to the variation in point angle. From the 3D response plots, it is concluded that the minimum thrust force and torque in drilling of composite are obtained at minimum drill diameter, minimum feed rate, maximum spindle speed and minimum point angle in

drilling of BD CFRP composites using HSS and solid carbide drills.

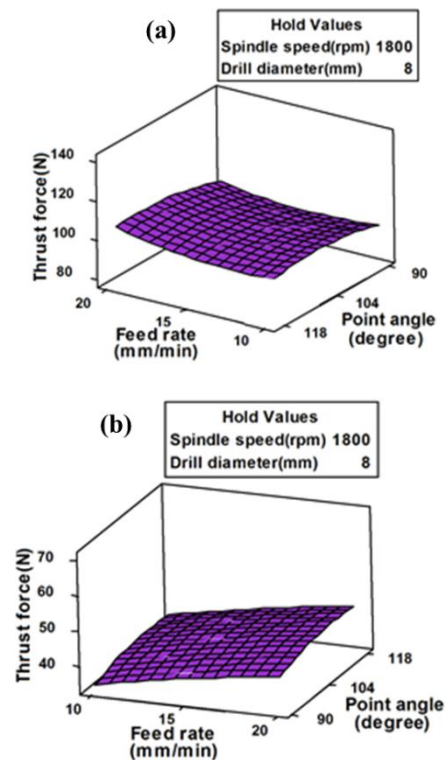


Fig. 11 Interaction effects of feed rate and point angle on thrust force for (a) HSS and (b) solid carbide drills in drilling of BD CFRP composite

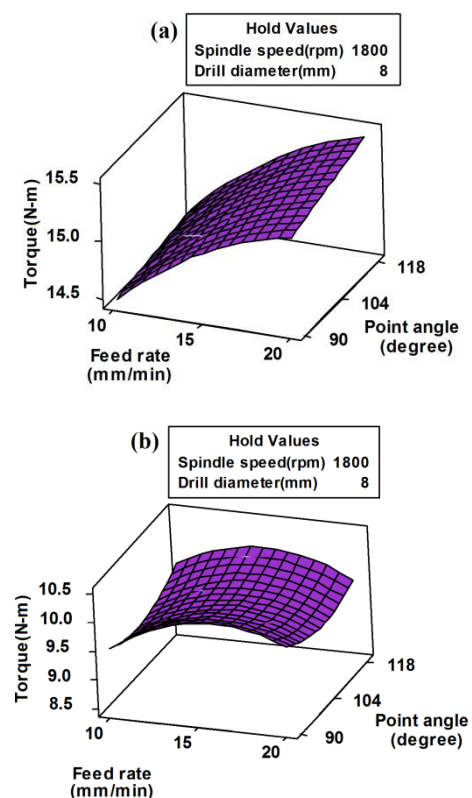


Fig. 12 Interaction effects of feed rate and point angle on torque for (a) HSS and (b) solid carbide drills in drilling of BD CFRP composite

3.3 Material removal mechanism and morphology of the cut surface

Thrust force and torque signals generated in drilling of BD CFRP composite with HSS and solid carbide drills are presented in Fig.13 and 14. From the figures, it is noticed that the variation in thrust force and torque with respect to time is more in HSS drills compared to that of in solid carbide drills.

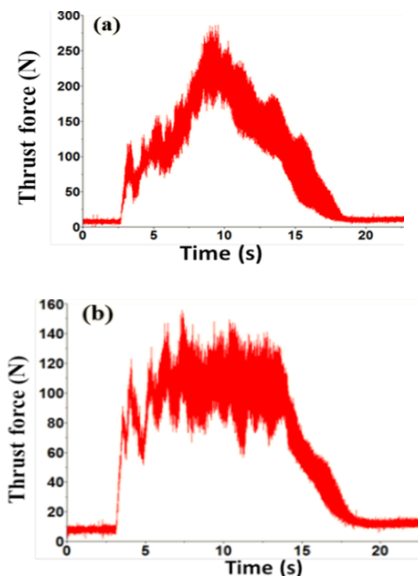


Fig. 13 Thrust force signals for holes drilled by (a) HSS drill and (b) solid carbide drill

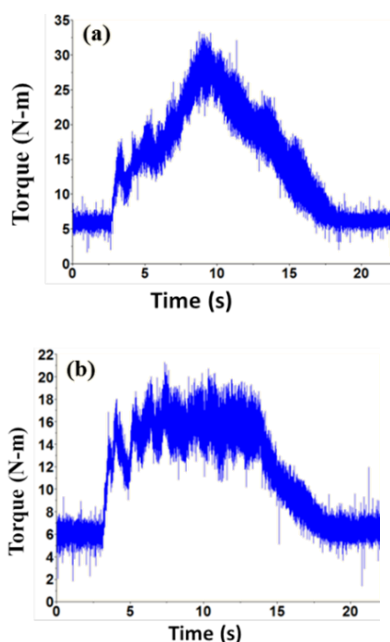


Fig. 14 Torque signals for holes drilled by (a) HSS drill and (b) solid carbide drill

This indicates that the additional thrust force and torque are required for further advancement of HSS drill in the downward direction to overcome the stick-slip friction generated in drilling of BD CFRP

composite. The variation in the signals of cutting forces is may be due to the heterogeneous nature of BD CFRP composite laminate [Bhatnagar et al., 2004].

It is observed from the SEM images (Fig. 15) that the hole drilled by HSS drill has more number of voids compared to that drilled by solid carbide drills in drilling of BD CFRP composite. The fibers at the void surface are dragged by the drill bit while cutting, due to which more pull-out of the fibers from the composite surface takes place in case of HSS drill. This pull-out of the fiber needs additional thrust force and torque in drilling of BD CFRP composite with HSS drill as compared to that in solid carbide drill.

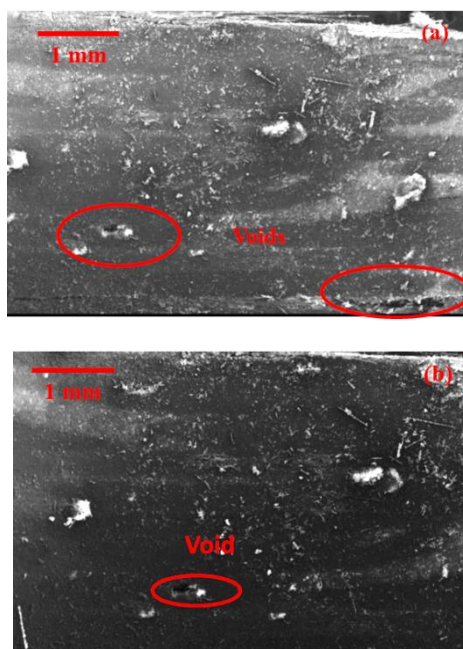


Fig. 15 SEM images of the drilled hole at spindle speed 1200 rpm, 20 mm/min, 118°, and 8 mm for (a) HSS and (b) solid carbide during drilling of BD CFRP composite

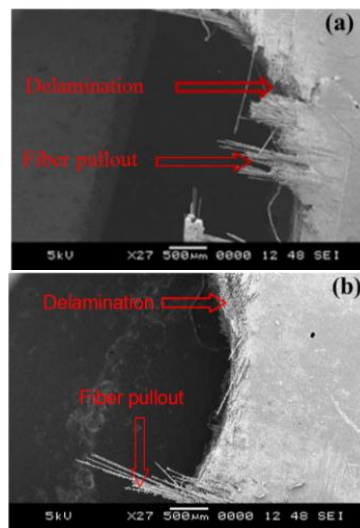


Fig. 16 SEM micrographs showing surface morphology of the drilled hole using (a) HSS drill and (b) solid carbide drill

Fig. 16 depicts the SEM micrographs of the drilled hole of BD CFRP composite at spindle speed of 1200 rpm, feed rate of 20 mm/min, drill diameter of 8 mm, and point angle of 118° using HSS and solid carbide drill.

It is evident from figures that the hole drilled by HSS drill has severely damaged surface compared to that drilled by solid carbide drill. It is due to the fact that there is more fiber pull-out, surface and subsurface cracks in the radial direction, de-bonding of matrix and fibers and delamination as noticed in BD CFRP composite while drilling with HSS drill. These multiple defects are due to the ploughing action rather than the cutting action that degrades the matrix and pulls out the fibers considerably. The ploughing action could be the result of the heating effect which creates friction between the cutting edge of the tool and the workpiece while drilling of BD CFRP composite. Fig. 22 illustrates the SEM image of the BD CFRP composite subjected to tensile loading. Due to higher strength of the BD CFRP composite, pull-out of the fiber at the cutting surface generates less number of cracks in BD CFRP composite laminate. These multiple cracks propagate easily in the plane of lamina and meet together, resulting in delamination and surface roughness.

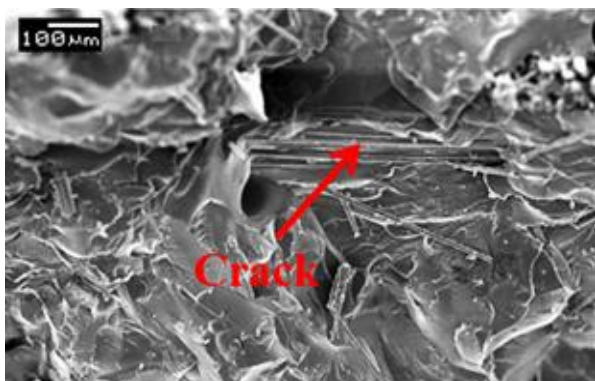


Fig. 17 SEM image of failure surface of BD CFRP lamina subjected to tensile loading

The less number of cracks developed in BD CFRP composite is due to plain weaved structure of reinforced fibers in the composite acts as crack arrester. It is found that the network structure in BD CFRP lamina helps to improve the fracture toughness of the BD CFRP composite.

3.4 Confirmation test for optimum process parameters

The confirmation test results of thrust force and torque obtained for optimum process parameters are presented in Table 2. It is observed from that the values of thrust force and torque obtained for optimum process parameters are lesser than the minimum values of thrust force and torque derived from the Taguchi L_{27} orthogonal array in drilling of BD CFRP composite laminate with HSS and solid carbide drills. It is also observed from Table 2 that there is a good approximation between the experimental and the

predicted results of thrust force and torque with a deviation of less than 2%.

Table 2 Results of confirmation test for optimum process parameters in BD CFRP composite

Tools	Response	Optimum cutting parameters	Experimental	RSM predicted	% of agreement
HSS	Thrust force	$A_3B_1C_1D_1$	65.98	65.54	99.39
Solid carbide			26.35	26.78	98.36
HSS	Torque		10.37	10.57	98.07
Solid carbide			7.11	7.27	97.74

$A_3= 1800$ rpm, $B_1= 10$ mm/min, $C_1= 90^\circ$ and $D_1= 4$ mm

3.5 Validation of experimental results

The validation test is carried out for BD CFRP composite with HSS and solid carbide drills. The results of thrust force and torque obtained from HSS drills along with the experimental results of Taguchi L_{27} orthogonal array are presented in Fig. 18. It is observed that the trend obtained from the validation test fairly matches with those obtained from the integration of Taguchi DOE and RSM. A similar trend is also noticed in drilling of BD CFRP composite laminate with solid carbide drills.

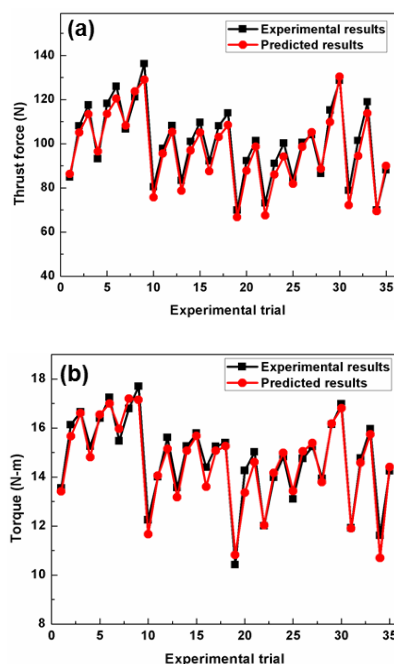


Fig. 18 Comparison of the experimental and the predicted results of (a) thrust force and (b) torque for HSS drills in drilling of BD CFRP composite

Conclusions

The following are the conclusions drawn from the present work while drilling of BD CFRP composite:

- (i) The experimental results show that drill diameter, spindle speed and feed rate have statistical and physical significance on thrust force and torque, for both HSS and solid carbide drills.
- (ii) The study demonstrates that thrust force and torque generated in case of solid carbide drills are less compared to that in HSS drills.
- (iii) The investigation reveals that minimum thrust force and torque are obtained at lower drill diameter, higher spindle speed, lower feed rate and minimum point angle both in HSS and solid carbide drills.
- (iv) The analysis of the study reveals that there is a good match between the experimental results and the RSM predicted results of thrust force and torque. This indicates that the RSM could be effectively used for predicting thrust force and torque.
- (v) The validation test confirms the adequacy of the results of thrust force and the torque obtained from Taguchi DOE.
- (vi) The SEM images depict that the damage caused by HSS drill is more severe compared to that caused by solid carbide drill. This indicates that solid carbide drills could be the preferred choice for generating quality holes for structural applications.

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