A Novel Approach for Reducing Delamination During Drilling of CFRP by Response Surface Methodology (RSM) Integrated with the Taguchi Method

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Abstract Carbon fiber reinforced polymers (CFRPs) laminates are one of the lightweight materials that have been around for a while in the manufacturing sector for its superior properties. However, the aviation industries are considered as the prime shopper of these fibrous composites in building structural parts of airplanes. Despite having some delectable properties like high strength, high fatigue resistant, high stiffness, high resistant to a corrosive environment, etc. it has been kept in the difficult-to-cut category. The machining of the CFRPs is quite tricky due to the anisotropic, heterogeneous, and abrasive nature. Drilling is considered as the final machining operation in the assembly line in most of the cases as holes are the absolute need in assembling purpose. However, the wedge-shaped drill, while cutting high strength fibers, produces various types of damages like delamination, surface roughness, fiber pullout, matrix breakage, etc. Among these, delamination is considered as the most vital and can influence the joint quality for which it needs a more significant concern. In this particular experiment, the drilling experiments have been designed by using Taguchi's L_{18} orthogonal array. The drilled persuaded damage like delamination factor and two sensory output parameters such as thrust force and

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torque has been acquired using data acquisition system and further analyzed and effort has been made to relate with the hole quality. Finally, a multi-objective optimization of the responses was made by utilizing the response surface methodology (RSM) approach. The delamination damages found to be less with a parameteric setting in case of lower feed rate (0.025 mm/rev), small point angle tool (108°), and at a higher spindle speed (3125 rpm).

Keywords CFRP · Thrust force · Torque · Delamination · Radar diagram · RSM

1 Introduction

Composite materials like carbon fiber reinforced polymers (CFRPs) possess superior mechanical and physical properties such as high strength-to-weight ratio, high stiffness, corrosion resistance, fatigue resistance make it as the first choice for structure making industries [1, 2]. However, regardless of its properties, it has been kept in the hard-to-machine category contrary to metal machining. In structure making industries like aerospace, automobile, and sports goods manufacturing units, these composite materials are used in an extensive manner. However, in structure making industries the parts are produced separately and necessitate a secondary machining process for the final assembly. In addition to this, metallic plates are also used with the composite laminate in stack form for providing additional strength to the final product in making various parts of airplane structure to provide extra rigidity [3, 4]. However, in joining several parts in an assembling line by employing riveted or bolted joints that necessitates a hole-making process [1, 5]. The traditional drilling process is considered as the most economical and primary process in making holes [6]. Due to the inhomogeneous and abrasive nature of CFRP, the drilling of these laminates is quite different as compared to the traditional metal machining [7]. Therefore, during drilling these materials drill induced defects like delamination, matrix cracking, fiber pullout that usually occurs [6]. Delamination is the foremost among the flaws occurred during drilling as it directly influences the quality and life of the joints, simultaneously the acceptability of the total product [4, 8, 9]. However, by selecting optimal input parameters and modifying the drill geometry the delamination defects can be minimized rather than completely irradiated [1, 10–13]. Delamination factor defined as the inter-laminar failure due to the separation of the layers while drilling on the upper surface of the composite laminate [14]. The selection of machining input variables, such as feed rate and speed, influence its occurrence that needs attention. However, among the input variables the feed rate is mostly responsible for the occurrence of delamination damages as it directly encompasses in rising the thrust force [10, 12, 15]. The another machining variable, spindle speed also has an effect on the amount of thrust force generated during drilling where higher thrust force causes less amount of delamination defects [6]. Similarly, the geometry of the drill tool also has its consideration in reducing drill hole-related damages like delamination factor. In this regard, a lower point angle tool is preferred as compared to

higher one as it produces lesser thrust force [1]. Therefore, the delamination defect-free hole can be accomplished with a parametric variables setting of lower feed rate and a higher speed along with a low point angle tool while drilling fibrous composite laminates like CFRP. However, for an optimal parametric setting the output response characteristics should be optimized by using a suitable optimization technique.

In recent years, for saving the machining time and to protect against losses, so as to improve the product quality various optimization techniques has been used [8, 16–32]. The response surface methodology (RSM) has been used to analyze the response parameters by which the total improvement of a system has been achieved for getting maximum benefits with minimum effort [17]. This methodology can be applied with a set of input parameters that effects the outputs and can optimize the variables one after another for the best possible outcomes [18].

In this study, Taguchi's L_{18} orthogonal array (total number of 18 experiments) has been used for preparing the experimental design using Min-Tab software. The drilling experiments were performed on a CNC milling center which has been attached with a data acquisition system. The data acquisition system comprises a dynamometer (KISTLER 9257b), an amplifier (KISTLER 5070) along with a personal computer for the storage of the acquired data. The thrust and torque data has been acquired with the help of this data acquisition system at a sampling rate of 1000 Hz. However, the drilling experiments were done on the woven CFRP laminate of 10 mm thickness. The delamination factor has been calculated using optical photographs of the holes, which was taken with help of microscope, was further analyzed using an Image-J software. Finally, the output responses were optimized using the response surface methodology (RSM) optimization technique and the deviation to the experimental output with predicted one has been presented through a radar diagram.

2 Experimental Procedures

2.1 Workpiece and Tool Configuration

The CFRP has various noble properties that suit in designing structural components as enlightened by numerous researchers. Nevertheless, as it has been placed in the category of hard-to-machine material. Therefore, this particular work considered drilling of CFRP laminates as a challenging task regarding and to accomplish some conclusive presumptions regarding drilling of this material. The material used is in the form of a laminate plate of 10 mm thickness which has been made up of by hand lay-up technique. The carbon prepregs having a high tensile strength of 6000 Mpa used in this laminate is of 0.5 mm thickness and alternative stack with epoxy. The reinforcement carbon prepregs have been placed with an orientation of [0°/−45°/90°/45°] [4, 8, 26]. The matrix used in laminate making process is epoxy (type—Araldite LY-556) with hardener (Aliphatic amine HY-95) and the curing of the material was done at ambient temperature. The composite laminate has been cut
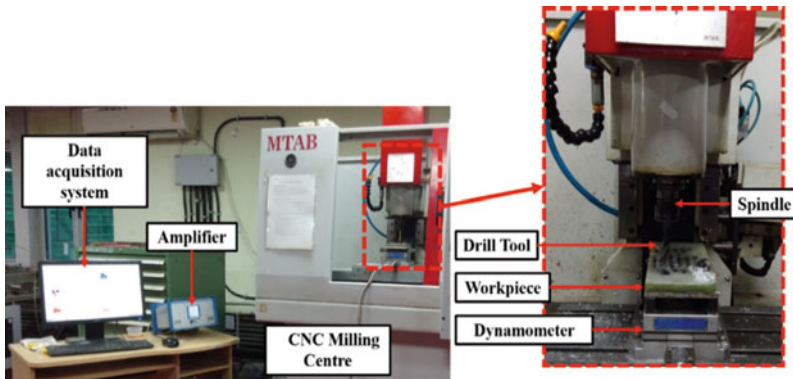
Fig. 1 Experimental setup with the workpiece placed on the dynamometer setting

in the size of 200 mm × 100 mm × 10 mm so that it can be clamped on the fixture designed and placed on the dynamometer, as shown in Fig. 1.

In this experiment, tungsten carbide twist drill bit has been used in drilling with two different point angles (θ) (108° and 118°), keeping other geometrical features constant. However, for reducing man–machine error the drilling experiments were carried out thrice for each parameter setting and the average value was taken for further analysis.

2.2 Machine

The drilling experiments were carried out on a 3-axis milling center (M-Tab) having a maximum speed of 5000 rpm with a vertical feed of 3000 mm/min. however, the machining center has been attached with Dynamoometer (Type—KISTLER 9257b) along with an amplifier (Type—KISTLER 5070) with pre-installed Dynoware software. The real time thrust force and torque data has been stored in a data acquisition system for further analysis. However, for acquiring noise-free data, a sampling rate of 1000 Hz has been chosen.

2.3 Drilling Condition and Input Parameter Setting

The input variables and the levels were selected after performing adequate numbers of trail experiments. The drilling condition has been kept as dry drilling, as the CFRP chips were in the form of powder, and by mixing with the coolant, it may deteriorate the drilled hole surface. However, the drilling of CFRPs with higher feed rates may lead to excessive fiber pullout. Therefore, a moderated range of feed has been selected.

Table 1 Drilling parameters and levels

Level	θ (°)	N (rpm)	f (mm/rev.)
1	108	1125	0.025
2	118	2125	0.05
3	–	3125	0.075

Similarly, high speed suits the drilling quality but extreme spindle speed may lead to fiber-matrix cracking; therefore, a suitable range has been chosen. Likewise, separate drill bits with different point angles have been selected. The experimental design has been prepared with a 2-level of point angle (θ), 3-level of spindle speed (N), and 3-level of feed rate (f) as shown in Table 1. Similarly, for performing the experiment in a well-organized manner the design of the experiment was prepared with a Taguchi's L_{18} orthogonal array prepared using Min-Tab software.

In this study, one-dimensional delamination factor (F_d) only in the entry side has been calculated by the following formula [6]:

$$F_d = D_{max}/D_{min} \tag{1}$$

where

D_{max} the maximum delaminated area diameter
D_{min} the nominal area diameter.

However, in order to reduce the man–machine error for each input variable setting drilling experiments has been performed three times, and the average of the results was taken for further analysis. The delamination factor for each drilled holes has been calculated using the Image-J software of the photographed images using an optical microscope.

2.4 Response Surface Methodology (RSM)

Optimization is a process by which the total improvement of a system has been made for getting maximum benefits with minimum effort [30]. However, the intention behind the optimization process is to find out the condition of a procedure when applied to a system that gives the best likely response. In the early eternities, traditional one variable method was used for optimization, where one variable used to be optimized once. Where the interaction between the variables is found to be missing, on the other hand, it required more time and considered an expensive process [30]. These problems were overcome by adopting a newer multivariate technique called response surface methodology (RSM). RSM methodology is a multi-response variable interactive technique, which utilizes inbuilt mathematics and statistical methods to deal with the experimental responses within a frame of a polynomial equation [17, 18, 30]. This methodology can be applied with a set of input parameters that affects

the outputs and can optimize the variables one after another for the best possible outcomes.

However, before optimizing the process variables, the design of an experiment with all process variables is prepared by adopting a suitable matrix design [30]. Various responses matrix-like full factorial design, central composite design, Box–Behnken design, etc. are executed for quadratic responses. In this particular experiment, a full factorial experimental design matrix has been used for arranging the tests to be performed.

3   Result and Discussions

In this section, the parametric influence of process variable on the output response characteristics such as drilled induced thrust force, torque with process output delamination has been studied in details. The experimental results in the form of sensory data and actual output responses delamination factor have been tabulated in Table 2. However, the real-time signal of thrust and torque acquired during drilling was studied in details and tried to co-relate it with the drilled quality as well as drilled induced defects like delamination factor.

**Table 2** Drilling parameters sequence and respective process outputs

Expt. No.	θ	N	f	F_d	F_z	M_z
1	108	1125	0.025	1.568	32.710	0.590
2	108	1125	0.05	1.731	38.775	0.850
3	108	1125	0.075	1.986	51.356	1.107
4	108	2125	0.025	1.302	28.984	0.510
5	108	2125	0.05	1.336	39.417	0.866
6	108	2125	0.075	1.528	47.813	1.087
7	108	3125	0.025	1.223	28.665	0.669
8	108	3125	0.05	1.426	38.553	0.670
9	108	3125	0.075	1.686	50.545	1.087
10	118	1125	0.025	1.458	29.003	0.582
11	118	1125	0.05	1.752	42.015	0.511
12	118	1125	0.075	1.992	56.562	0.707
13	118	2125	0.025	1.456	32.212	0.796
14	118	2125	0.05	1.758	45.921	0.806
15	118	2125	0.075	1.881	58.580	0.861
16	118	3125	0.025	1.339	29.365	0.698
17	118	3125	0.05	1.659	41.750	0.754
18	118	3125	0.075	1.778	55.289	0.901

3.1 Analysis of Drilled Thrust Force and Torque Acquired During Drilling

A typical thrust force and corresponding drilled persuaded torque signal have been shown in Fig. 2 (Expt. #4). The thrust force in its initial phase starts very smoothly but, as soon as the drill touches (around 4.5 s) the upper surface of the laminates, it rises very stiffly that can be seen from the figure. The corresponding torque also shows the same phenomenon; it also increased very sharply as the drill touches the laminate. The thrust force goes on increasing as long as the drill wedge tip ultimately gets into the laminate, and drilling operation becomes smoother (around 14 s.). Similarly, the torque also goes on rising until it reaches the peak and drops simultaneously as soon as the drilling becomes steady. Hereafter, the drilling becomes steady and it can be noticed from figure until the tip or the chisel edge comes out of the laminate and makes the drilling a bit unsteady. At every moment, a stiff decline in thrust force can be seen. However, there is an increase as the flutes of the drill tries to come out of the laminate.

In this study, regression equation of the second-order polynomial of th0rust force and torque has been developed using the response surface methodology (RSM) optimization technique as given by Eqs. 2 and 3. Besides developing modeled equations, the analysis of variance (ANOVA) technique has also been used to check the adequacy of the models at a 95% confidence level. The R-sq. value, p-value, and F-value (model competence factors) for all the sensory parameters are shown in Table 3, where the R-sq. values found to be more than 85% for all the responses. Similarly, the p-value of all the outputs was found to be less than the standard value of 0.005, which makes all the models acceptable with a higher degree of fitness.

Fig. 2 A typical thrust force and torque signal variation with time
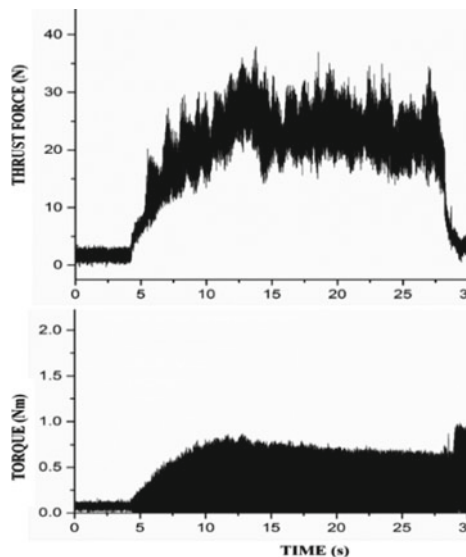
Table 3 Model competency factors of respective process outputs

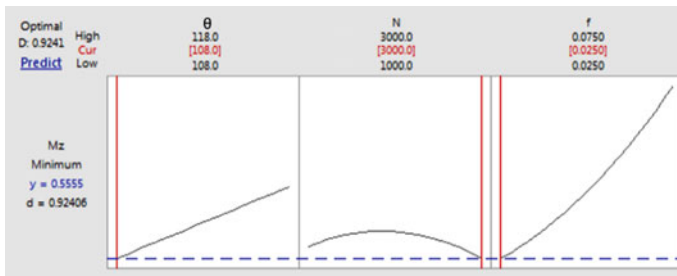| Output responses	R-sq.	R-sq. (adjacent)	F-value	p-value
F_z	98.16%	96.52%	60.02	0.000
M_z	89.38%	79.93%	9.46	0.001

$$F_z = 68.7 - 0.437\theta - 0.0045N - 1206f - 0.000001N * N$$
$$+ 1096f * f + 0.000065\theta * N + 13.66\phi * f + 0.0080N * f \quad (2)$$

$$M_z = -0.28 + 0.0057\theta - 0.000986N + 81.8f - 0.000000N * N$$
$$+ 90.8f * f + 0.000011\theta * N - 0.746\theta * f - 0.00010N * f \quad (3)$$

The response surface plot for the drilled induced thrust force and corresponding torque has been shown in Figs. 3 and 4, distinctly. It can be seen from the optimized surface plot of thrust force (Fig. 3), the feed rate has the substantial impact, followed by the drill spindle speed and the drill tool point angle. The thrust force tends to increase as the feed rate increases and vice versa. Similarly, the point angle also affects the thrust force, as with a higher point angle tool produces greater thrust, as

Fig. 3 Response surface plot for thrust force (F_z)

Fig. 4 Response surface plot for torque (M_z)

Table 4 Model competency factors of delamination factor

Output responses	R-sq.	R-sq. (adjacent)	F-value	p-value
F_d	89.34%	79.86%	9.42	0.001

can be seen from the figure. Nevertheless, the thrust force is seen to be abridged with an increase in drill spindle speed (N).

The variation of torque w.r.t feed, speed, and point angle have been shown in Fig. 4. It can be seen that the feed rate has a maximum impact on the variation of torque, followed by point angle and spindle speed. The optimal parametric setting for minimum thrust force is $\theta = 108°$, $N = 3000$ rpm, $f = 0.025$ mm/rev, and the optimal output for the thrust force is 28.6231 N, which is 0.14% less than that of experimental 28.665 N. Similarly, in the case of torque, the optimal parametric setting for the least torque is 0.5555 Nm, which is 20.33% lower than that of the experimental 0.69 Nm.

3.2 Influences of the Parametric Variables on the Delamination (F_d)

In this particular study, the response surface methodology (RSM) optimization technique was used in developing the regression equation of the second order for the delamination factor (Eq. 4.). The model competence factors like R-sq. value, p-value, and F-value can be seen from Table 4, where the R-sq. values found to be more than 85% for all the responses. Similarly, the p-value of all the outputs was found to be less than the standard value of 0.005, which makes all the models acceptable with a higher degree of fitness.

$$
\begin{aligned}
F_d = \ &3.11 - 0.0129\theta - 0.001448N - 11.4f \\
&+ 0.000000N * N - 16.9f * f \\
&+ 0.000009\theta * N + 0.194\theta * f - 0.00025N * f \quad (4)
\end{aligned}
$$

The variation of delamination factor w.r.t feed, speed, and point angle has been shown in Fig. 5. It can be seen that feed rate has the maximum impact on the delamination defect followed by drill spindle speed and drill tool point angle. The optimal parametric setting for minimum delamination factor has been found at a parametric setting of $\theta = 108°$, $N = 2838.38$ rpm, $f = 0.025$ mm/rev, and the optimal output for the delamination factor is 1.2195, which is 8.2% less than that of experimental 1.223.

In Fig. 6, the interaction effect of delamination defect with various input variables has been plotted in the form of interaction plot. The delamination factor was seen to increase with an increase in point angle significantly. Whereas, the rise in spindle speed reduces the delamination factor as the thrust produced is less. However, if the feed rate has been increased, the delamination defect tends to increase at a constant
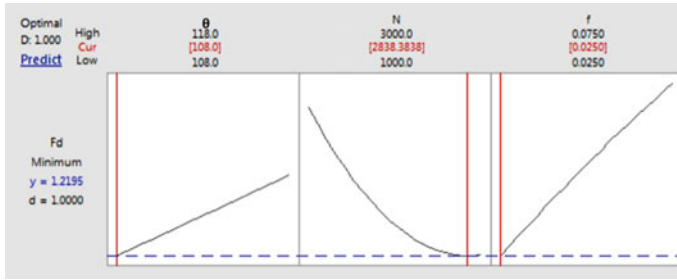
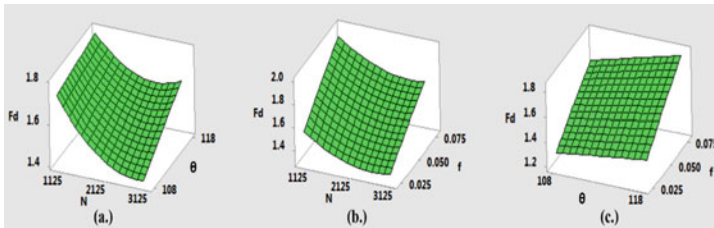**Fig. 5** Response surface plot for delamination factor (F_d)

Fig. 6 Surface response plot of the F_d with f, N, and θ

speed and point angle tool and vice versa. Similarly, the point angle also plays a very crucial role in minimizing the delamination factor, as the higher point angle tool encourages the defects.

The radar diagram has been plotted by taking the experimental data and predicted the value of the respected experiments (Fig. 7). In the figure, the deviation between the two values is seen to be very minimum, proving the accuracy of the model with the experimented value during the drilling process.

Fig. 7 Radar diagram showing the experimental and predicted value for all experiments
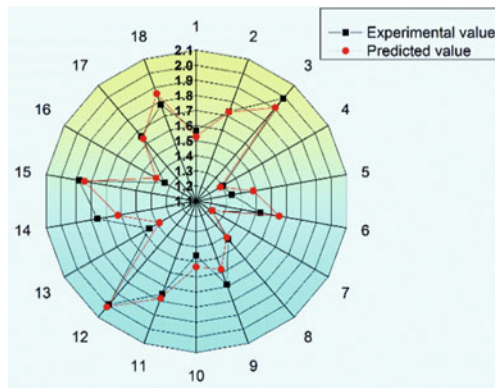
4 Conclusions

In this study, an empirical investigation of drilling in woven CFRP laminates was carried out with various parametric settings and variation in drill tool geometry. The thrust force, as well as torque, were analyzed concerning the hole quality and the following conclusions were made.

- The drilling experiments were conducted with various parametric setting of input variables and the hole surface quality as well as the thrust force and torque can be controlled by a suitable process variable setting.
- It was found that the drilled induced thrust force increases with an increase in feed rate and vice versa, whereas the drill spindle speed increase has an adverse effect on it which also suits the reduction in the delamination factor.
- The selection of the drill tool geometry also has an effect on the hole integrity. It was found that with a lower point angle drill (108°) less drilled induced thrust force was produced in comparison to a higher point angle drill (118°).
- The torque also affects the drill hole quality as it directly influences the stability of the drill.
- In the initial stage of the drilling process due to the presence of the chisel edge in the twist drill produces a higher amount of thrust, which gradually got stable as the drilling progress deep into the laminate.
- The initial stiff rise in thrust force resulted in entry-level delamination damages on the upper piles of the laminate at the initial stage when the drill tries to get into it.
- Delamination factor is the major among all of the defects that occurred in the drilling of fibrous laminates, which directly varies with the thrust force. The higher feed rate produces a higher thrust force, to higher delamination factor.
- Delamination factor found higher in case of higher feed rate (0.075 mm/rev.), higher point angle drill tool (118°) land lower spindle speed (1125 rpm).
- The lowest value of delamination (1.223) was found with the parameter setting of $\theta = 108°$, $N = 3125$ rpm, and $f = 0.025$ mm/rev.
- The response surface analysis optimization integrated with ANOVA has been carried out, the optimal parameter setting for minimum delamination factor has been found at a parametric setting of $\theta = 108°$, $N = 2838.38$ rpm, $f = 0.025$ mm/rev, with an optimal output of 1.2195, which is 8.2% less than that of experimental.
- Thus, it concluded that the optimization process improves the selection of the parametric setting for enhancing the overall drilled hole quality.

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