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Delamination analysis in drilling process of glass fiber reinforced plastic (GFRP) composite materials

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Abstract

Machining processes are generally used to cut; drill, or contour composite laminates for building products. In fact, drilling is one of the most commonly used manufacturing processes to install fasteners for assembly of laminate composites. The material anisotropy resulting from fiber reinforcement heavily influences the machinability during machining. Machining of fiber reinforced plastic (FRP) components is often needed in spite of the fact that most FRP structures can be made to near-net shape and drilling is the most frequently employed secondary machining process for fiber reinforced materials. Therefore, the precise machining needs to perform to ensure dimensional stability and to obtain a better productivity of the component. The drilling parameters and specimen parameters evaluated were speed, feed rate, drill size and specimen thickness. A series of experiments were conducted using TRIAC VMC CNC machining center to machine the composite laminate specimens at various cutting parameters and material parameters. The measured results of delamination at the entry and exit side of the specimen were measured and analyzed using commercial statistical software MINITAB14. The experimental results indicated that the specimen thickness, feed rate and cutting speed are reckoned to be the most significant factors contributing to the delamination. A signal-to-noise ratio is employed to analyze the influence of various parameters on peel up and push down delamination factor in drilling of glass fibre reinforced plastic (GFRP) composite laminates. The main objective of this study is to determine factors and combination of factors that influence the delamination using Taguchi and response surface methodology and to achieve the optimization machining conditions that would result in minimum delamination. From the analysis it is evident that among the all significant parameters, specimen thickness and cutting speed have significant influence on peel up delamination and the specimen thickness and feed have more significant influence on push down delamination. Confirmation experiments were conducted to verify the predicted optimal parameters with the experimental results, good agreement between the predicted and experimental results obtained to be of the order of 99%.

Keywords: Glass fiber reinforced thermoplastics; Thermoset plastics; Delamination; Contact moulding; Design of experiments; ANOVA

1. Introduction

In recent years glass fibre reinforced plastics (GFRP) have attracted increasing attention for use in load-bearing components, particularly in the aerospace industry. This material has many excellent properties, such as high specific strength, high specific modulus of elasticity, lightweight, good corrosion resistance, etc. [1].

As the fields of application expand, the use of types of machining such as turning, drilling, milling, and cutting-off has increased in GFRP fabrication. However, the glass fibre constituent often renders the machining of GFRP difficult. Machining of composite materials requires a better understanding of cutting processes to achieve accuracy and efficiency [2]. Though near-net shape processes have gained a lot of attention, more intricate and modular products need secondary machining for the final assemblies drilling.

Induced delaminations occur both at the entrance and the exit planes of the work piece and render the work piece less strong. These delaminations could be correlated to thrust force during the approach and exit of the drill. Delamination is one of the major concerns in drilling holes in composite materials especially when the top and bottom surfaces of the work piece are exposed [3].

In order to understand the effects of process parameters on the delamination, a large number of machining experiments have to

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be performed and analyzed mathematical models to be built on the same. Modeling of the formation of delaminations is highly complex and expensive. Hence, empirical/statistical approaches are widely used over the conventional mathematical models. In this paper, an approach based on the Taguchi method is used to determine the desired optimum cutting and material parameters for minimized appearance of delaminations.

1.1. Machining of composite materials

The machining of GFRP is quite different from that of metals and results in many undesirable effects such as rapid tool wear, rough surface finish and defective subsurface layers caused by cracks and delaminations. At the beginning of drilling operation, the thickness of the laminated composite materials is able to withstand the cutting force and as the tool approaches the exit plane, the stiffness provided by the remaining plies may not be enough to bear the cutting force, causing the lamina to separate result in delamination. The delaminations that occur during drilling severely influence the mechanical characteristics of the material around the hole. In order to avoid these problems, it is necessary to determine the optimum conditions for a particular machining operation.

Drilling is a particularly critical operation for fiber reinforced plastics (FRP) laminates because the great concentrated forces generated can lead to widespread damage. The major damage is certainly the delamination that can occur both on the entrance and exit sides of the work piece [4]. The delamination on the exit surface, generally referred to as push down delamination, is more extensive, and is considered more severe. Hocheng and Tsao have beautifully explained the causes and mechanisms of formation of these push down delaminations and they have also reasoned out the dependence of extent of delamiantion on the feed rate [5]. In earlier studies it has been observed that the extent of delamination is related to the thrust force feed, material properties and speed, etc. and that there is a critical value of the thrust force (dependent on the type of material drilled) below which the delamination is negligible [6]. Attempts have been made to model these delaminations considering the axial thrust and that causes in many early investigations and an analytic model proposed to evaluate the critical thrust force is available in literature [7]. Jain and Yang have proposed a theory taking into account the anisotropy of the material and hypothesizing the cracks to be elliptical [8]. They have also noticed that the load of the drill point is mainly due to the chisel edge, while the contribution of the cutting lips in the axial thrust direction is insignificant.

Models, of similar nature are elsewhere available for carbon-fiber composites [9,10] where the size of the delamination zone has been shown to be related to the thrust force developed during the drilling process and observance of a ‘critical thrust force’ below which no damage occurs [11,12]. But a comprehensive study involving a few of these variables simultaneously was thought to be an appropriate and was undertaken in the present work. Realizing that the critical force generated during delamination is influenced by feed rate, spindle speed, tool diameter and materials thickness; an attempt has been made to study the combined effect of these parameters The present work outlines a methodology to optimize process parameters in drilling of glass fiber reinforced polyester for minimum delamination damage. Experimental design as per Taguchi method and analysis of results with ANOVA was resorted to in this study.

2. Experimental set-up and machining conditions

2.1. GFRP specimen preparations

High strength E-glass chopped fiber mat was used as reinforcement in polyester resin to prepare laminate slabs of 200 mm × 200 mm size. Above mat consisted of an E-glass with 72.5 GPa modulus and density of 2590 kg/m^3. The resin polyester possessing a modulus of 3.25 GPa and density 1350 kg/m^3 was used in preparing the specimens with contact moulding process. Required number of mats were stacked to give intended thickness and a fiber volume fraction, which was determined later to 0.63 using weight loss method.

2.2. Machining set-up

The carbide-coated drills bits used in the experiments were of 3, 6, 10 and 12 mm diameter. Dry drilling tests were conducted on CNC TRIAC VMC machining center supplied by Denford, UK. The instrumentation consisted of a force–torque strain gauge drilling dynamometer, fixture, and an amplifier, connecting cables, and an A/D converter a PC for data acquisition. The laminate composite specimen was held in a rigid fixture attached to the dynamometer, which is mounted on the machine table. The experimental set-up is as shown by the schematic in Fig. 1.

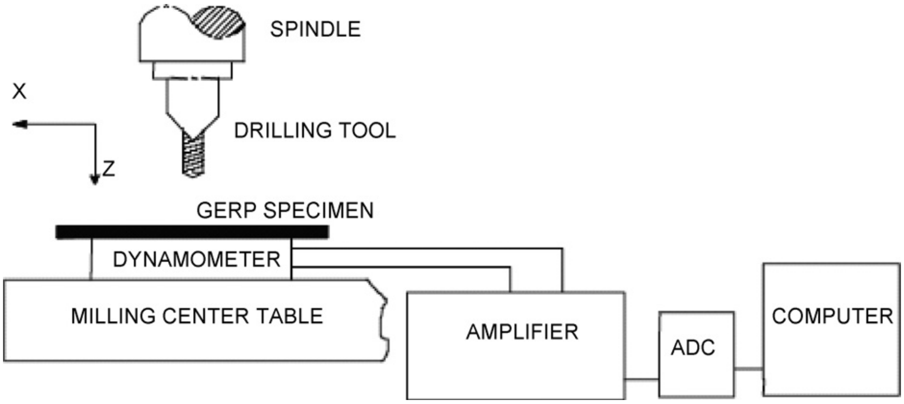

Fig. 1. Schematic diagram of experimental set-up.

Table 1
Levels of the variables used in the experiment

Variables	Lowest	Low	Center	High
Thickness (mm)	3	6	10	12
Speed (rpm)	600	900	1200	1500
Feed rate (mm/min)	50	75	100	125 and 150
Drill size (mm)	3	6	10	12

3. Design of experiment, Taguchi method and experimental details

3.1. Design of experiment

Design of experiments is a powerful analysis tool for modeling and analyzing the influence of process variables over some specific variable, which is an unknown function of these process variables. The most important stage in the design of experiment lies in the selection of the control factors. As many process variables as possible should be included, so that it would be possible to identify the most significant variables at the earliest opportunity. In general, the thrust and torque parameters will mainly depend on the manufacturing conditions employed, such as: feed, cutting speed, tool geometry, machine tool and cutting tool rigidity, etc. In this experiment with four factors at four levels each, the full factorial design was used. Table 1 shows the detail of the variables used in the experiment. A deep analysis of variability associated with such parameters is not the present objective of this work.

3.2. Taguchi method

Robust design is an engineering methodology for obtaining product and process conditions, which are minimally sensitive to the various causes of variation to produce high-quality products with low development and manufacturing costs [13]. Taguchi's parameter design is an important tool for robust design. It offers a simple and systematic approach to optimize design for performance, quality and cost. Taguchi methods which combine the experiment design theory and the quality loss function concept have been applied to the robust design of products and process and have solved some confusing problems in manufacturing. In order to observe the degree of influence with control factors (feed rate, spindle speed, drill diameter and work piece thickness) in drilling, four factors, each at four levels, in full factorial design are considered. Taguchi defines the quality of a product, in terms of the loss imparted by the product to the society from the time the product shipped to the customer. Some of these losses are due to deviation of the product's functional characteristic from its desired value, and these are called losses due to functional variation. The uncontrollable factors which cause the functional characteristics of a product to deviate from their target values are called noise factors, which can be classified as external factors such as temperatures and human factors, etc. Manufacturing imperfections are due to variation of product parameter from unit to unit and product deterioration. The overall aim of quality engineering is to make products that are robust with respect to all noise factors.

Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. The experimental results are then transformed into a signal-to-noise (S/N) ratio. Taguchi recommends the use of the S/N ratio to measure the quality characteristics deviating from the desired values. The S/N ratio for each level of process parameters is computed based on the S/N analysis. Regardless of the category of the quality characteristic, a greater S/N ratio corresponds to better quality characteristics [14]. Therefore, the optimal level of the process parameters is the level with the greatest S/N ratio. Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant. With the S/N and ANOVA analyses, the optimal combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the parametric design.

To summarize, the parameter design of the Taguchi method includes the following steps: (1) identification of the quality characteristics and selection of design parameters to be evaluated; (2) determination of the number of levels for the design parameters and possible interactions between the design parameters; (3) selection of the appropriate orthogonal array and assignment of design parameters to the orthogonal array; (4) conducting of the experiments based on the arrangement of the orthogonal array; (5) analysis of the experimental results using the S/N and ANOVA analyses; (6) selection of the optimal levels of design parameters; (7) verification of the optimal design parameters through the confirmation experiment. Therefore, three objectives can be achieved through the parameter design of the Taguchi method, i.e.: (1) determination of the optimal design parameters for a process or a product; (2) estimation of each design parameter to the contribution of the quality characteristics; (3) prediction of the quality characteristics based on the optimal design parameters.

Usually, there are three categories of quality characteristic in the analysis of the S/N ratio, i.e. the-lower-the-better, the-higher-the-better, and the-nominal-the-better. The S/N ratio characteristics given by Eqs. (1)–(3), when the characteristic is continuous.

Nominal is the best characteristic:

$$\frac{\mathrm{S}}{\mathrm{N}} = 10 \log \frac{\bar{y}}{s_y^2} \tag{1}$$

smaller the better characteristic:

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

and larger the better characteristic:

$$\frac{\mathrm{S}}{\mathrm{N}} = -\log \frac{1}{n} \left(\sum \frac{1}{y^2} \right) \tag{3}$$

where $\bar{y}$ is the average of observed data, s_y^2 the variation of y, n the number of observations, and y is the observed data. For each type of the characteristics, with the above S/N

Table 2
Response for signal-to-noise S/N ratios of peel up and push down delamination for smaller is better

Peel up delamination vs. feed, speed, diameter, and thickness[a]					Push down delamination vs. feed, speed, diameter, and thickness[a]				
Level	Feed	Speed	Diameter	Thickness	Level	Feed	Speed	Diameter	Thickness
1	−1.6936	−1.9524	−2.0693	−3.5526	1	−2.945	−3.320	−4.044	−3.925
2	−1.8760	−2.2659	−1.7576	−2.1303	2	−3.561	−3.868	−4.539	−6.530
3	−2.0767	−1.5709	−2.4170	−1.6509	3	−3.983	−3.679	−3.338	−2.326
4	−2.3793	−2.4210	−1.9662	−0.8760	4	−4.357	−4.595	−3.540	−2.681
5	−2.2371				5	−4.482			
Delta	0.6858	0.8500	0.6595	2.6763	Delta	1.537	1.275	1.201	4.204
Rank	3	2	4	1	Rank	2	3	4	1

[a] Response table for signal-to-noise; smaller is better.

ratio transformation, the higher the S/N ratio the better is the result. Taguchi recommends analyzing the means and S/N ratio using conceptual approach that involves graphing the effects and visually identifying the factors that appear to be significant, without using ANOVA, thus making the analysis simple.

3.3. Delamination factor

The damage generated during drilling was evaluated both in quantitative and qualitative terms. As a quantitative description of peel up and push down delamination, both the upper and lower surfaces of each specimen were scanned using digital scanner. The proper threshold values were determined by examining the histogram of array values and verified by the original and binary images, as shown in Fig. 2. Based on the binary images, the drilling delamination factor is determined by the ratio of the delaminated area (A_{d}) of the delamination zone to the ideal hole area (A). The value of delamination factor F_{d} (4) can be expressed as follows:

$$F_{\mathrm{d}} = \frac{A_{\mathrm{d}}}{A} \tag{4}$$

where the unit of A_{d} and A is the pixel density of the scanned image.

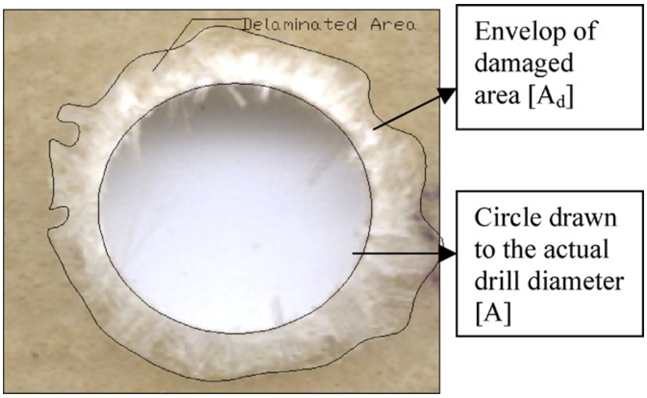

Fig. 2. Scheme of delamination factor using digital scanner.

4. Experimental results and data analysis

4.1. Analysis of S/N ratio

In the Taguchi method, the term ‘signal’ represents the desirable value (mean) for the output characteristic and the term ‘noise’ represents the undesirable value (S.D.) for the output characteristic. Therefore, the S/N ratio is the ratio of the mean to the S.D. Taguchi uses the S/N ratio to measure the quality character deviating from the desired value. The S/N ratio h is defined as

$$\eta = -10\log_{10}(\mathrm{M.S.D.}) \tag{5}$$

where M.S.D. is the mean-square deviation for the output characteristic.

To obtain optimal cutting performance, the-lower-the-better quality characteristics for delamination should be taken for obtaining optimal cutting performance. The optimum process design is achieved when the S/N ratio is maximized. Since −log is a monotonically decreasing the function, it implies that we should maximize. The M.S.D. for the-lower-the-better quality characteristic can be expressed as:

$$\mathrm{M.S.D} = \frac{1}{M}\sum_{i=1}^{m} {F_i}^2 \tag{6}$$

where F_i is the value of delamiantion factor for the ith test and M is the number of tests.

The response obtained from experiments was analyzed using response table and graphical representation of mean effects and interaction effect of parameters on the quality characteristics. Table 2 shows the experimental results for delamination factors of peel up delamination and push down delamination and the corresponding S/N ratio using Eqs. (5) and (6). The S/N response graph for peel up and push down delaminations are shown in Fig. 3. Regardless of the-lower-the-better of the the-higher-the-better quality characteristic, the greater S/N ratio corresponds to the smaller variance of the output characteristic around the desired value (Eqs. (5) and (6)). Therefore, based on the S/N, the optimal parameters for peel up delamination are the feed rate at level 1 (50 mm/mn), the cutting speed at level 3 (1200 rpm),

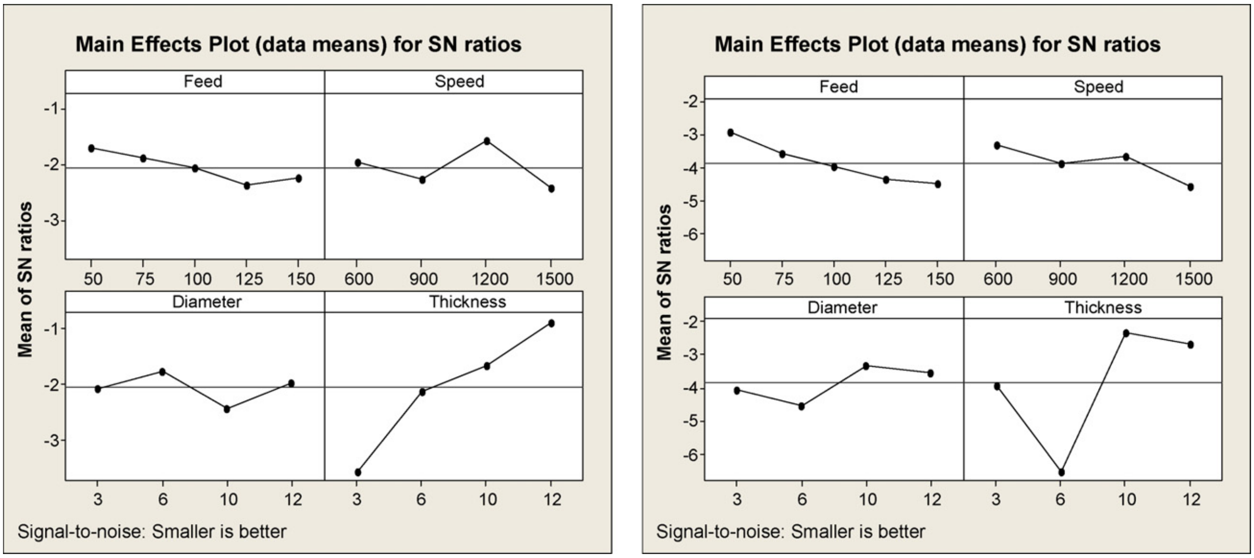

Fig. 3. Peel up and push down delamination main effect plots for S/N ratio.

Table 3
ANOVA response

Analysis of variance for peel up delamination[a]				Analysis of variance for push down delmaination[a]			
Source	d.f.	*F*	*P*	Source	d.f.	*F*	*P*
Feed	4	6.65	0.000	Feed	4	5.25	0.002
Speed	3	10.30	0.000	Speed	3	4.31	0.006
Diameter	3	4.30	0.002	Diameter	3	3.63	0.007
Thickness	3	82.85	0.000	Thickness	3	59.83	0.000
Feed × speed	12	0.83	0.619	Feed × speed	12	0.96	0.484
Feed × diameter	12	1.21	0.276	Feed × diameter	12	1.33	0.199
Feed × thickness	12	0.96	0.485	Feed × thickness	12	0.32	0.985
Speed × diameter	9	5.98	0.000	Speed × diameter	9	5.04	0.000
Speed × thickness	9	4.69	0.000	Speed × thickness	9	0.64	0.761
Diameter × thickness	9	2.74	0.005	Diameter × thickness	9	16.64	0.000

[a] Using adjusted SS for tests.

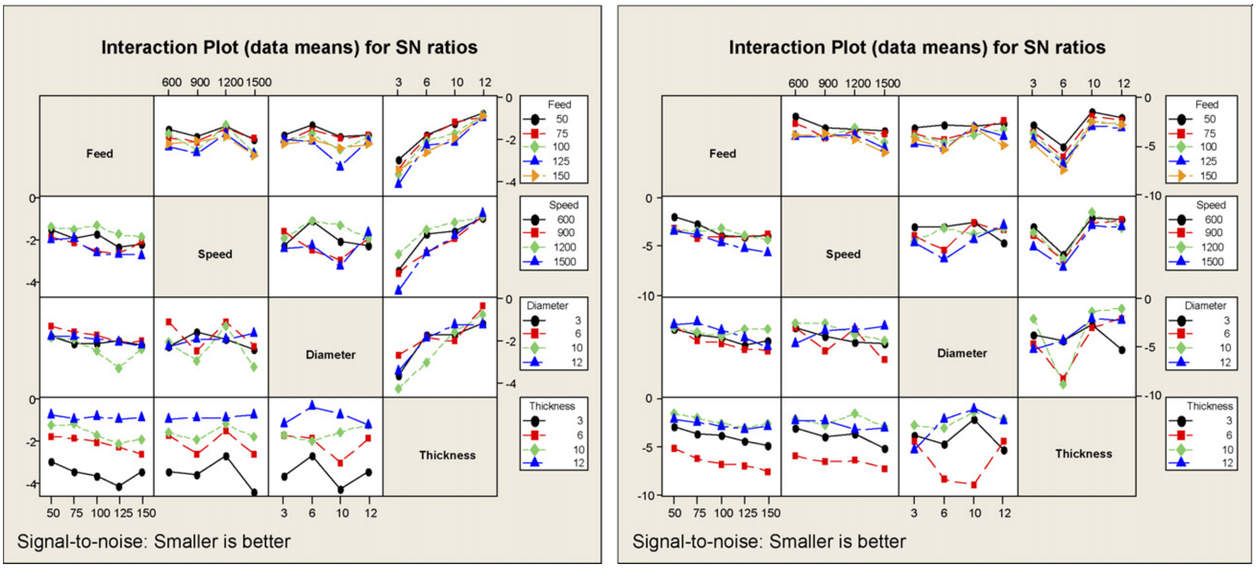

Fig. 4. Peel up and push down delamination interaction plots for S/N ratios.

drill tool diameter at level 2 (6 mm) and the material thickness at level 4 (12 mm). Similarly, the optimum parameters for push down delamination are the feed rate at level 1 (50 mm/min), the cutting speed at level 1 (600 rpm), drill tool diameter (10 mm), and the material thickness at level 3 (10 mm).

4.2. *Analysis of variance*

The purpose of the analysis of variance (ANOVA) is to investigate the design parameters significantly affect the quality characteristic of a product or process. This is accomplished by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean S/N ratio, into contributions by each of the design parameters. Statistically, there is a tool called an *F* test named after Fisher to see which design parameters has a significant effect on the quality characteristic. In performing the *F* test, the mean of squared deviations due to each design parameter needs to be calculated. Then, the *F* value for each design parameter is simply the ratio of the mean of squared deviations to the mean of squared error. Usually, when $F > 4$, it means that the change of the design parameter has a significant effect on the quality characteristic.

From Table 3, which gives ANOVA response results, it can be found that material thickness and cutting speed are the significant parameters affecting the peel up delamination and material thickness and feed rate are the significant parameters affecting the push down delamination. Fig. 4 illustrates the interaction plots for different S/N ratios for peel and push down delmaninations. It can be inferred from the plots that for a particular thickness the influence exercised the different factors are found to be fairly in line with non-interactive.

4.3. *Confirmation tests*

Once the optimal level of the design parameters has been selected, the final step is to predict and verify the improvement of the quality characteristic using the optimal level of the design parameters. The estimated S/N ratio $\hat{\eta}$ using the optimal level of the design parameters can be calculated as:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{m} (\tilde{\eta} - \eta_m) \qquad (7)$$

where η_m is the total mean S/N ratio, $\tilde{\eta}$ the mean S/N ratio at the optimal level, and m is the number of the main design parameters that affect the quality characteristic.

The estimated S/N ratio using the optimal cutting parameters for tool life can then be obtained and the corresponding delamination factor can also be calculated by using Eqs. (5)–(7). Tables 3 and 4 shows the comparison of the predicted delamination factors with the experimental values of delamination factors using the optimal cutting parameters. A good agreement between the predicted and experimental results of delamination factors of an order of 99% being observed. Response surface analysis (Fig. 5) also indicates the minimum peel up delamination at the low level of feed rate, at the high level of material thickness and medium level of cutting speed. Similarly, minimum push down delamination is observed at low level of feed rate, at high level of cutting speed and medium level of drill bit diameter and material thickness.

Table 4
Results of the confirmation experiment for peel up and push down delamination

	Optimal cutting parameters		
	Prediction	Experiment	Agreement with prediction (%)
Opmized condition Level	$F_1N_3D_2T_4$	$F_1N_1D_3T_3$	
Peel up delamination factor	1.032	1.040	99.22
Push down delamination factor	1.015	1.0061	99.12

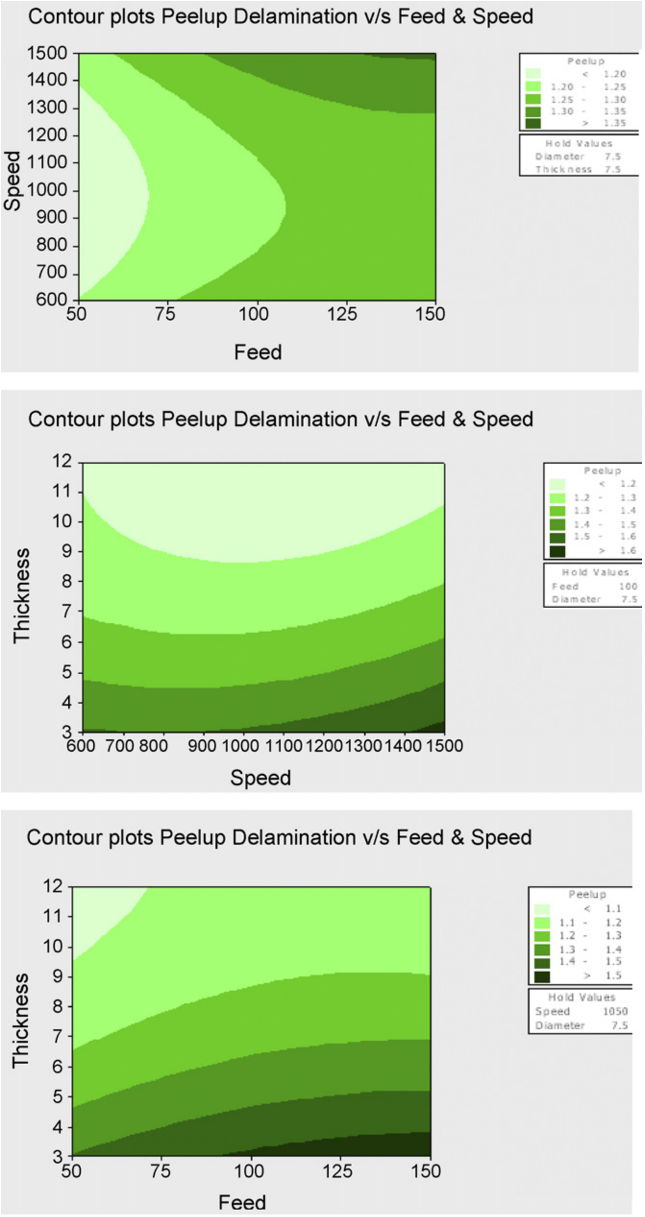

Fig. 5. Response surface plots of peel up and push down delamination.

5. Conclusions

From the analysis of results in drilling of GFRP composite plates using conceptual S/N ratio approach, ANOVA and response surfaces, the following can be concluded from the present study within the range of the experiments.

(1) As seen in this study, the Taguchi method provides a systematic and efficient methodology for the design optimization of the process parameters resulting in the minimum delamination with far less effect than would be required for most optimization techniques.
(2) Based on the S/N, the optimal parameters for the minimum peel up delamination are the feed rate at level 1 (50 mm/min), the cutting speed at level 3 (1200 rpm), drill tool diameter at level 2 (6 mm) and the material thickness at level 4 (12 mm).
(3) Similarly, the optimum parameters for the minimum push down delamination are the feed rate at level 1 (50 mm/min), the cutting speed at level 1 (600 rpm), drill tool diameter (10 mm), and the material thickness at level 3 (10 mm).
(4) The feed rate, cutting speed and material thickness are seen to make the largest contribution to the delamination effect. Generally, the use of high cutting speed and low feed favor the minimum delamination on both entry and exit of the drilling leads to better surface finish and tool life.
(5) The feed rate influences the push down and peel up delaminations next to the material thickness. Therefore, the feed rate seems to be the most critical parameter and should be selected carefully in order to reduce all kinds of damages.
(6) Conceptual S/N ratio and ANOVA approaches for data analysis draw similar conclusion.
(7) The confirmation experiments were conducted to verify the predicted optimal parameters with the experimental results. The comparison of the predicted delamination factor with the experimental values of delamination factors using the optimal cutting parameters, good agreement between the predicted and experimental results of order of 99% being observed.
(8) Response surface analysis reveals the minimum peel up delamination at the low level of feed rate, at the high level of material thickness and medium level of cutting speed. Similarly, for the minimum push down delamination is observed at low level of feed rate, at high level of cutting speed and medium level of drill bit diameter and material thickness.

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