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Optimization of Process Parameters in Drilling of GFRP Composites Drilled by an End Mill

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***Abstract*— Due to the superior physical and mechanical properties Glass fiber-reinforced (GFRP) composite materials are very attractive for applications like aerospace and air craft structural components. This results a large number of research papers on machining of these composite laminates. Out of all the machining operations, most commonly used operation is drilling. However, drilling operation is hard to carry out due to drilling–induced delamination. To increase drilling efficiency of GFRP composite laminates with the least waste and damages, it is essential to understand the drilling behavior by conducting a large number of drilling experiments and drilling parameters such as feed rate and spindle speed should be optimized. This paper presents delamination study of composite materials by conducting drilling experiments using Taguchi's L_{25}, 5-level orthogonal array and Analysis of variance (ANOVA) was used to analyze the data obtained from the experiments and finally determine the optimal drilling parameters in drilling GFRP composite materials. Experiments were also conducted to determine whether varying feed & spindle speed during drilling could reduce the delamination.**

***Keywords*— Drilling induced Delamination, GFRP composite, L_{25} orthogonal array, Taguchi approach, End mill**

I. Introduction

Recently, the use of composite materials has increased in various areas of science and technology due to their special properties. Fiber reinforced composite laminates commonly used in industries mainly include CFRP (Carbon Fiber Reinforced Polymer) composite laminates, GFRP (Glass Fiber Reinforced Polymer) composite laminates, and fiber metal composite laminates (FMLs). Owing to their considerable advantages, they are being used to replace conventional metallic materials in a wide range of industries including aerospace, aircraft, and defense, which require structural materials with superior properties such as high strength-to-weight, stiffness-to-weight ratios and excellent corrosion resistance.

GFRP (Glass fiber-reinforced polymer) are used in fairings, passenger compartments, storage room doors due to their high mechanical properties.

Drilling using twist drill is the most commonly employed operation of secondary machining for fiber-reinforced materials. However, composite laminates are regarded as hard-to-machine materials, which results in low drilling efficiency and undesirable drilling-induced delamination. For rivets and bolted joints, damaged-free and precise holes must be drilled in the components to ensure high joint strength and precision. However, some special characteristics of composite laminates such as non-homogeneous, anisotropic, and highly abrasive and hard reinforced fibers, result in them difficult to machine. Among the problems caused by drilling, delamination is considered the major damage. It was reported that, in aircraft industry, the rejection of parts consist of composite laminates due to drilling-induced delamination damages during final assembly was as high as 60%.[1]

Defu Liu, Yongjun Tang and W.L Cong mentioned that amongst all machining operations, drilling using twist drill is the most commonly applied method for generating holes [2]. A large number of experiments were conducted by Lee SC, Park J N, Chen W C, Wang X, Davim JP, Tsao CC, Hocheng H to research the influence of input variables (spindle speed, feed rate, and drill bit geometry) on output variables (delamination & thrust force). Park KY, Choi JH & Lee DG firstly introduces grinding drilling to reduce delamination by improving drilling performance [3]. Tsao CC & Hocheng H investigate that delamination is generally regarded as resulting from excessive thrust force & smaller delamination holes can be obtained when grinding drilling composite laminates [4]. A low (<1000 Hz) or high (>1000 Hz) frequency and low amplitude vibration is superimposed on a twist drill bit along the feed direction during drilling. Ramkumar J, Malhothra SK, Krishnamurthy R found that the thrust by (vibration-assisted twist drill) VATD are reduced by 20–30%, compared with conventional drilling [5]. Therefore, VATD is used to reduce the delamination damage during drilling of composite laminates. Unlike conventional drilling operation, high speed drilling operation of composite laminates has to be conducted in a high speed drilling machine system which is very expensive.

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Investigators revealed that the delamination tendency decrease with increase in cutting speed and the combination of low feed rate and point angle is also essential in minimizing delamination during high speed drilling of composite laminates.

H. Hochenga, C.C. Tsao studied about effects of special drill bits on delamination of composite materials and find out that core drill was able to with stand the highest feed rate with reduced delamination [6]. From literature it is clear that twist drill bits made of HSS or carbides are the primary attraction in drilling of composite laminates among various drill bits. However, the applications of other drill bits in drilling of composite laminates are also very extensive to improve machine ability of composite laminates. Most of investigators found that using drill bits with different geometry and materials in drilling of composite laminates find more advantages & beneficiaries.

For practical machining of GFRP, it is necessary to determine the optimal machining parameters to achieve less delamination etc. Optimization of process parameters is the important criterion in the machining process to achieve high quality. Most of the studies on GFRP shows eliminating delamination is very difficult and is to be controlled. K. Palanikumar conducted experiments on GFRP composites using Brad & Spur drill and optimized drilling parameters by using two input variables with four levels and concluded that low feed rate and high spindle speeds are beneficial to reduce delamination [7]. In the present study the experiments are carried out using end mill (Carbide) to find the optimum drilling parameters using Taguchi's L_{25} orthogonal array.

DOE is an important tool for designing processes and products. DOE is a method for quantitatively identifying the right inputs and parameter levels for making a high quality product or service. A proper design of experiments (DOE) is conducted to perform more accurate, less costly and more efficient experiments.

II. Mechanisms Of Delamination

During drilling of composite laminates damages such as delamination, burrs, swelling, splintering and fiber pullout commonly occurs. Delamination is considered as the major concern.

A. Peel-up at entrance

The cutting edge of the drill will first abrade the laminate initially. It then, by moving forward, tends to pull the abraded material away along the flute.

The material spirals up before it is machined completely. This action introduces a peeling force upwards to separate the upper laminas from the uncut portion held by the downward acting thrust force [7].

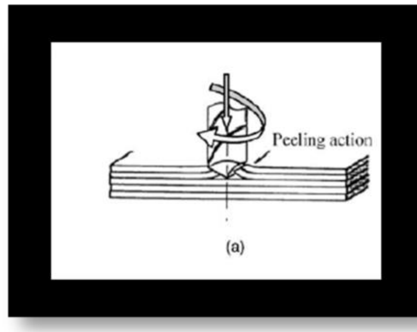

Fig. 1 Peel-up delamination [7]

B. Push-out at exit

In drilling, the drill always exerts a compressive thrust force on the work piece. The laminar under the drill thus tend to be drawn away from the inter-laminar bond around the hole. As the drill approaches the end, the uncut thickness becomes smaller and the resistance to deformation decreases. At some point, the loading exceeds the inter-laminar bond strength and delamination occurs.

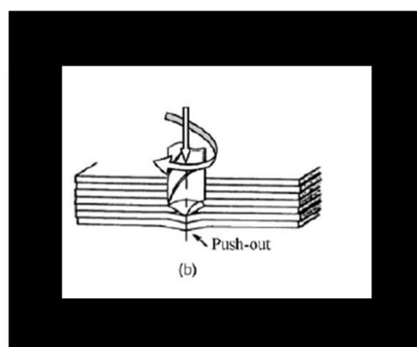

Fig. 2 Push-out delamination [7]

C. Delamination Factor (F_d)

An index or factor called delamination factor (F_d) is used to determinate the extent of delamination [8], [9].

$$F_d = D_{max}/D \text{ [8], [9]}$$

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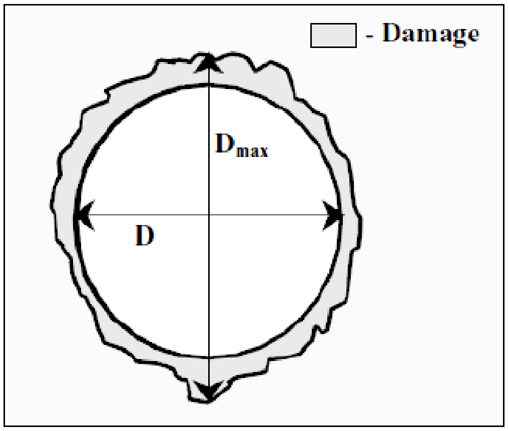

Fig. 3 Diagram of the damage [8], [9]

D *max* is the maximum diameter created due to delamination around the hole and D is the hole or drill diameter. At a critical thickness, the bending stress becomes greater than the inter-laminar strength between the plies and an inter-laminar crack is initiated around the hole. Further pushing down by the drill point causes the crack to propagate and the flexural rigidity of the supporting plies becomes weaker. This leads to fracturing the material below the drill point as the chisel edge proceeds to exit the laminate. The damage at exit plies is shown as spalling that extends beyond the diameter of the hole.

III. Materials & Experimental Procedure

The laminates were composed of 26 layers, laid-up in the symmetrical form [0, 90]. The fibers were unidirectional (UD) E-Glass. The applied resin was of grade L-12 with K-5 hardener. The thickness of the laminate was 6mm. End mill made of Carbide steel with 10 mm diameter is used for the drilling operation, which is shown in fig.4.Drilling experiments are conducted on computer numerically controlled MAKINO S 56 CNC vertical milling machine with maximum rpm of 3000. The experimental set-up is shown in fig.5. Profile projector is used to measure the maximum diameter due to delamination around the hole.

Traditional experimental design methods are too complicate and difficult to use. Additionally, these methods require a large number of experiments, when the number of process parameters increases In order to minimize the number of tests required, Taguchi experimental design method is a powerful tool for designing high quality system was developed by Taguchi.

This method uses a special design of orthogonal arrays to study the entire parameter space with small number of experiments only. In this study, two machining parameters were used as control factors and each parameter was designed to have five levels, denoted 1, 2, 3, 4 and 5 (Table I). Each experiment was repeated twice for getting reliable data. The averages of two tests were taken for determining delamination factor. The experimental design was according to an L25 array based on Taguchi method, while using the Taguchi orthogonal array would markedly reduce the number of experiments (Table II). Minitab software was used for Taguchi analysis. Using Analysis of Variance (ANOVA), the effect of input parameters on delamination factor is studied.

Fig.4 Four Fluted End Mill

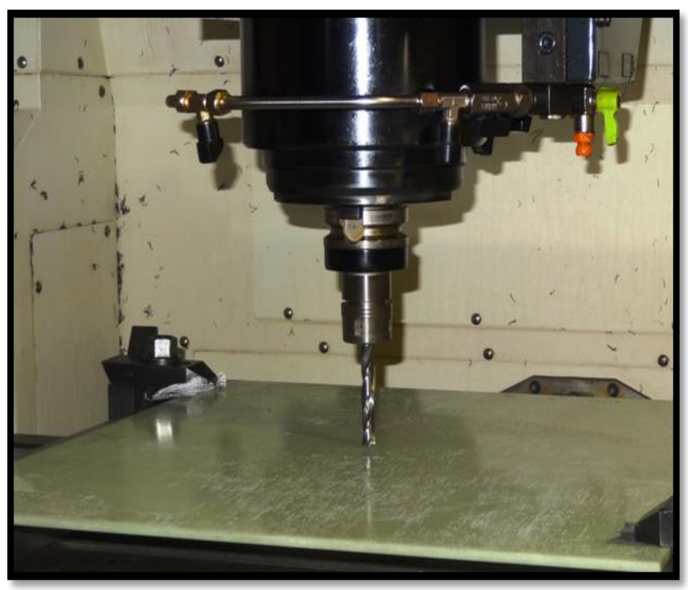

Fig.5 Experimental setup

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TABLE I
DRILLING PARAMETERS AND LEVELS

Process Parameters /Levels	Feed rate (mm/min)	Spindle speed (rpm)
Very low (Level 1)	50	1000
low (Level 2)	100	1500
Medium (Level 3)	200	2000
High (Level 4)	300	2500
Very high (Level 5)	400	3000

TABLE II
ORTHOGONAL ARRAY OF TAGUCHI L25

Experiment No.	Feed rate	Spindle speed
1	1	1
2	1	2
3	1	3
4	1	4
5	1	5
6	2	1
7	2	2
8	2	3
9	2	4
10	2	5
11	3	1
12	3	2
13	3	3
14	3	4
15	3	5
16	4	1
17	4	2
18	4	3
19	4	4
20	4	5
21	5	1
22	5	2
23	5	3
24	5	4
25	5	5

After obtaining the optimized values of process parameters the effect of varying spindle speeds and feed rates during drilling were carried out with the optimum input variables. The input parameters which have been selected for these experiments are shown in the table III.

TABLE III
INPUT PARAMETERS CHOSEN FOR VARYING SPINDLE SPEEDS AND FEED RATES DURING DRILLING

S l No.	Experiments Conducted
1	First 3mm depth* - Speed 2000rpm, Feed 200mm/min- next 3mm depth – Speed 2500 rpm,Feed100 mm/min
2	First 4.5mm depth- - Speed 2000rpm, Feed 200mm/min- next 1.5mm- - Speed 2500 rpm, Feed 100 mm/min
3	First 3mm depth -- Speed 3000rpm, Feed 100mm/min- next 3mm -- Speed 2500 rpm, Feed 50 mm/min
4	First 4.5mm depth -- Speed 3000rpm, Feed 100mm/min- next 1.5mm -- Speed 2500 rpm Feed 50 mm/min

**Total thickness of the plate is 6mm*

IV. Analysis Of Results & Discussion

A drilling test was conducted to evaluate the effect of cutting parameters on the damage at work piece. The damage around the work piece was measured using a profile projector with magnification 20. After measuring the maximum diameter Dmax in the damage around each hole, the delamination factor is determined by utilizing equation as mentioned in the section II. Table IV illustrates the influence of cutting parameters on the delamination factor.

From the table IV it was observed the delamination factor was decreasing with the decrease in feed rate and increase in spindle speed except at feed rate 50mm/min and spindle speed 3000rpm where the highest value of delamination factor was observed as 1.1050. The optimal cutting parameter for the delamination was obtained the feed rate at Level 2 (100mm/min) and the cutting speed at Level 4 (2500rpm).

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TABLE IV
EXPERIMENTAL DESIGN USING L25 ORTHOGONAL ARRAY AND EXPERIMENTAL RESULTS

Test Number	Feed Rate	Spindle Speed	Delamination Factor
1	50	1000	1.0825
2	50	1500	1.0900
3	50	2000	1.0800
4	50	2500	1.1250
5	50	3000	1.0850
6	100	1000	1.0475
7	100	1500	1.0450
8	100	2000	1.0400
9	100	2500	1.0250
10	100	3000	1.0800
11	200	1000	1.0600
12	200	1500	1.0550
13	200	2000	1.0525
14	200	2500	1.0350
15	200	3000	1.0900
16	300	1000	1.0850
17	300	1500	1.0800
18	300	2000	1.0775
19	300	2500	1.0650
20	300	3000	1.0975
21	400	1000	1.1000
22	400	1500	1.0900
23	400	2000	1.0850
24	400	2500	1.0775
25	400	3000	1.1050

The experiments were conducted using Taguchi experimental design methodology & S/N ratio values of each experiment are calculated and tabulated in table V. The signal-to-noise ratios were calculated using the condition smaller is better. The S/N ratio for the delamination is calculated by using the following relation [6]

$$\eta = -10 log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}(F_d - F_1)^2\right]$$

F_d is the measured delamination and $F_1$is the ideal delamination = 1 and n is the number of trials

TABLE V
S/N RESPONSE TABLE FOR DELAMINATION FACTOR

Test Number	Feed rate (mm/min)	Spindle speed(rpm)	Delamination Factor	S/N Ratio
1	50	1000	1.0825	21.6709
2	50	1500	1.0900	20.9151
3	50	2000	1.0800	21.9382
4	50	2500	1.1250	18.0618
5	50	3000	1.0850	21.4116
6	100	1000	1.0475	26.4661
7	100	1500	1.0450	26.9357
8	100	2000	1.0400	27.9588
9	100	2500	1.0250	32.0412
10	100	3000	1.0800	21.9382
11	200	1000	1.0600	24.4370
12	200	1500	1.0550	25.1927
13	200	2000	1.0525	25.5968
14	200	2500	1.0350	29.1186
15	200	3000	1.0900	20.9151
16	300	1000	1.0850	21.4116
17	300	1500	1.0800	21.9382
18	300	2000	1.0775	22.2140
19	300	2500	1.0650	23.7417
20	300	3000	1.0975	20.2199
21	400	1000	1.1000	20.0000
22	400	1500	1.0900	20.9151
23	400	2000	1.0850	21.4116
24	400	2500	1.0775	22.2140
25	400	3000	1.1050	19.5762

From the above table it can be observed that the delamination is increasing with the feed rate and decreasing with the spindle speed except at the feed rates of 50 mm/min and spindle speeds of 3000 rpm. The effects of feed rate and spindle speed on delamination factor are shown in fig.6 and fig. 7.

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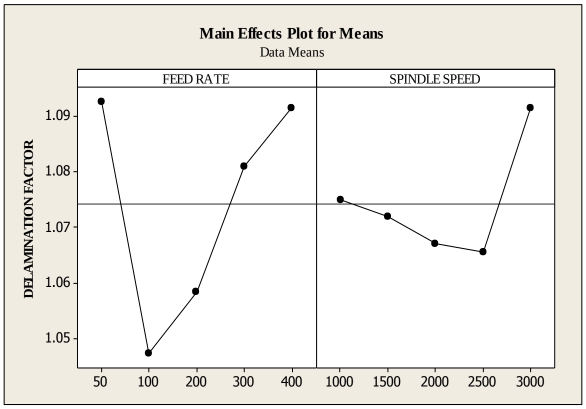

Fig 6: Main effects for means

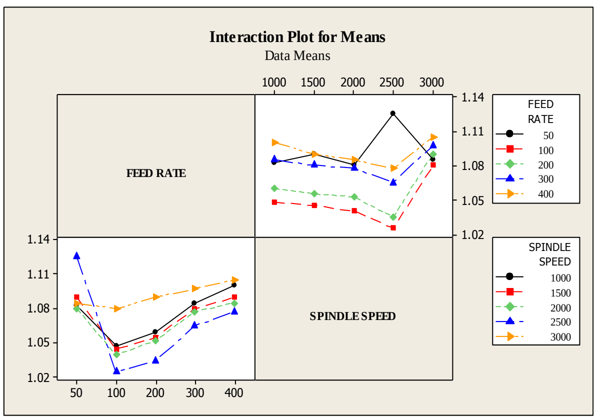

Fig 7: Interaction effects for means

From the graphs it is seen that at 3000 rpm there is a sudden increase in the delamination factor than the excepted value this is due to the reason that when the drill speed increases, the thrust force increases because severe heat generation in the drilling area leads to softening of the fiber and matrix. As a result, fiber cutting becomes harder for the cutting edges of the drill and drilling thrust force increases a small amount. It can also be observed that the feed rate increases from50 mm/min to 100 mm/min, the delamination factor decreases. The reason is that at the feed rate of 50 mm/min, more heat is generated and transferred to the laminate in the drilling area [11]. Further it can be observed from the table IV that lowest delamination is at the spindle speed of 2500 rpm and feed rate of 100mm/min. Table VI and table VII describe the ANOVA of the input parameters and the response table for means respectively.

TABLE VI
ANALYSIS OF VARIANCE FOR MEANS

Analysis of Variance for Means						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Feed Rate	4	0.008199	0.008199	0.002050	9.41	0.000
Spindle Speed	4	0.002162	0.002162	0.000540	2.48	0.086
Residual Error	16	0.003486	0.003486	0.000218		
Total	24	0.013847				

TABLE VII
RESPONSE TABLE FOR MEANS

Response Table for Means		
Level	**Feed Rate**	**Spindle Speed**
1	1.093	1.075
2	1.048	1.072
3	1.059	1.067
4	1.081	1.065
5	1.091	1.091
Delta	0.045	0.026
Rank	1	2

From the Table VII the delta values for feed rate are more compared to the delta value of spindle speed. The rank for feed rate is 1 and that of spindle speed is 2.Thus from the table VI (F value larger) .It is clear that feed rate is mainly affecting the delamination factor compared to spindle speed. Thus from the level 5 experiments it is clear that optimized value or the least delamination factor input parameters are feed rate of 100 mm/min and spindle speed of 2500 rpm.

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Prediction for Optimized Value and Confirmation Test

From S/N analysis and mean response characteristics, the optimum levels of delamination factors were calculated as Level 2 (A_2) for feed rate and Level 4 (B_4) for spindle speed. Hence, the predicted mean of delamination factor is calculated using the equation given below [12].

$$F_{d\ opt} = \bar{y} + (\bar{A}_2 - \bar{y}) + (\bar{B}_4 - \bar{y})$$

Where $\bar{y}$ is the total average of delamination factor (corresponding to all the 25 reading in Table IV), A_2 and B_4 are the average values of the delamination factor with input parameters at their respective optimal levels and $F_{d\ opt}$ denotes the predicted mean of delamination factor at optimum condition. The calculated values of various response averages are $\bar{y} = 1.0742$, $A_2 = 1.048$ and $\bar{B}_4 = 1.065$. So substituting these values in above equation the mean optimum value of delamination factor has been predicted as

$$F_{d\ opt} = 1.0388$$

In Taguchi optimization technique confirmation experiment was required to be conducted for validating of the optimized condition. Table VIII shows the result obtained and compared with the predicted values.

TABLE VIII
RESULTS OF CONFIRMATION EXPERIMENT

Delamination Factor	Replication		Mean
	1	2	
	1.0250	1.0300	1.0275

The next step after obtaining the optimum spindle speed and feed rate is drill the composite with varying spindle speed and feed rate during drilling and to analyze the delamination. The process parameters for these experiments were selected such that during last stage of the drilling (exit) increasing the spindle speed and decreasing the feed rate could reduce the delamination at the exit. The results obtained for these experiments are tabulated in the Table IX

TABLE IX
EXPERIMENTS CONDUCTED BY VARYING SPINDLE SPEEDS AND FEED RATES DURING DRILLING

S l No.	Experiments Conducted	Delamination Factor
1	First 3mm depth* - Speed 2000rpm, Feed 200mm/min- next 3mm depth – Speed 2500 rpm,Feed100 mm/min	1.045
2	First 4.5mm depth- - Speed 2000rpm, Feed 00mm/min-next 1.5mm- - Speed 2500 rpm, Feed 100 mm/min	1.075
3	First 3mm depth -- Speed 3000rpm, Feed 100mm/min- next 3mm -- Speed 2500 rpm, Feed 50 mm/min	1.08
4	First 4.5mm depth -- Speed 3000rpm, Feed 00mm/min- next 1.5mm -- Speed 2500 rpm Feed 50 mm/min	1.1

It has been observed that by varying speed and feed rate the delamination can be reduced to a certain limit. From the results it is clear that lowest delamination factor is at varying input parameters spindle speed 2000 rpm, feed rate 200 mm/min at the entry up to a thickness of 3mm and next 3mm with varying input parameters spindle speed 2500 rpm and 100 mm/min feed rate at the exit, as compared to the other sets of experiments. Varying the speed and feed rates at the depth of 4.5mm has increased the delamination factor; the reason may be due to decrease in uncut thickness at the exit, which is more susceptible for delamination. Thus it is obvious that varying speed and feed rate at the optimized values can reduce delamination. Varying the spindle speed and feed rate during drilling will be more beneficial while drilling higher thicker plates as the savings in drilling time at the same time reducing the delamination.

V. CONCLUSION

This paper has presented an application of the Taguchi method for the delamination study of drilling of GFRP composites. The conclusions of this present study based on results and analysis are drawn as follow:

- The analysis of experimental results is carried out using Taguchi's orthogonal array and analysis of variance. The level of the best of the cutting parameters on the drilling induced delamination is determined by using ANOVA.
- The drilling induced delamination increases with spindle speed (1000rpm-2500rpm) and decreases with feed rate (100mm/min to 400mm/min).
- The results for very low feed rate i.e., 50mm/min and high spindle speed 300rpm show the opposite trend. In both the cases delamination factor increased instead of decreasing.
- The reason for higher delamination at spindle speed 3000rpm may be, when the drill speed increases, the thrust force increases because severe heat generation in the drilling area leads to softening of the fiber and matrix. As a result, fiber cutting becomes harder for the cutting edges of the drill and drilling thrust force increases a small amount causing more delamination.
- The reason for higher delamination at the feed rate 50mm/min may be that at the feed rate of 50 mm/min, more heat is generated and transferred to the laminate in the drilling area. This may be created local thermal destruction of the work piece and made undesirable results on delamination.
- The results of ANOVA revealed that feed rate is the main cutting parameter, which has greater influence on the delamination factor
- Based on the S/N, optimal parameters for the minimum delamination are the spindle speed at Level 4 (2500 rpm) and the feed rate at Level 2 (100mm/min).
- Predicted value of delamination at optimized process parameter is good agreement with the test result.
- By varying the spindle speed and feed rate during drilling with the optimized values of process parameters can reduce the delamination.

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