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Optimization of delamination factor in drilling of carbon fiber filled compression molded GFRP composite

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Abstract

The objective of the present work is to improve the drilled hole quality of compression molded glass fiber reinforced polymer composite (GFRP) by reducing the delamination occurs in drilling. The three process parameter namely % of carbon fiber as filler, spindle speed and feed rate of drilling. The experiments in the present work were carried out as per the Taguchi L9 orthogonal array to study the influence of various combinations of process parameters on hole quality. Analysis of variance (ANOVA) was performed on the raw data of delamination factor and signal to noise (S/N) ratios to find the significance of process parameters. It was observed that feed arte is the most significant factor that effect the delamination factor in drilling of compression molded GFRP composite. The optimal values of control factors for optimum delamination 2.58 µm were found as carbon fiber 20 % spindle speed 1000 and feed rate 150 mm/min.

Keywords: Carbon fiber, filler, compression molding, delamination

Introduction

Some machining processes is almost always required to applied over composite materials for their use in specific engineering application. Drilling is the most frequently used operation for assembly of structures or components but the composite damage called delamination is also associated with drilling composite laminates [1]. Delamination is one of the major problems encountered in drilling of composite laminates as compared to that of metals. It is generally regarded as a resin or matrix dominated failure [2]. This failure of composites is an inter-ply failure during drilling which leads due to the multi-phase structure and non-homogeneity nature of the composites [3]. 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] The structural integrity is strongly depends on fiber matrix interfacial interactions, fiber orientations, cutting directions and tool wear. Khashaba et al. [4] reported that catastrophic shear failure of the composite layers has been done due to the higher feed rates and cutting temperatures resulting poor surface integrity, lower bearing strength of machined holes while GFRP composite drilling. Arul et al. [6] have utilized acoustic emission technique to improve the quality and surface integrity of the machined hole during drilling on woven glass fabric/epoxy composite laminates. Murugesh and Sadashivappa [7] used filler material TiO_2 and Graphite and found that the values of thrust and delamination factor can be reduced during drilling with the increase of filler %. Gupta et al.(2014)[8] investigated the effect of $CaCO_3$ on hand layup GFRP composite tensile strength. Gupta et al.(2015) [9]used bagasse fiber, carbon black and $CaCO_3$as filler in pultruded glass reinforced polymer composite and optimize the tensile strength. Gupta et.al. (2016)[10] develop hybrid filler for optimizing the flexural strength of pultruded jute fiber reinforced composite.

Material used and Method:

Material used for manufacturing of GFRP composite with carbon fiber as filler by compression molding process is as follows

1. Fiber for Reinforcement: Milled fiber glass
2. Filler: Milled carbon fiber
3. Matrix: Epoxy resin
4. Hardener:6-tetrahydrophthalic anhydride

The specimen for performing the drilling operation were made by compression molding, the steel die is used for compression molding is shown in figure 1.

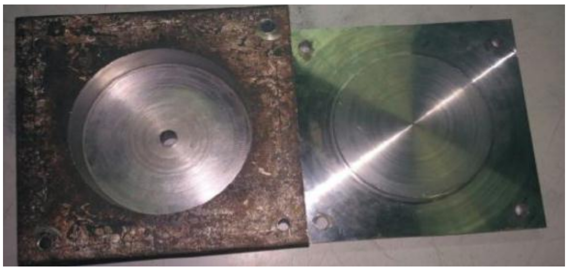

Figure 1: Die for compression molding of composite

The following steps were followed to prepare the specimen

1. The 10 % hardener of resin weight was mixed in the epoxy resin.
2. The milled glass and milled carbon fiber was mixed in the epoxy as per design of experiments (DoE). But the total fiber % (carbon Fiber+glass fiber) was kept 70 % of resin weight.
3. The bulk molding compound developed in the second step was poured into the die cavity to fill the same and then the die was closed and subjected to the compression pressure on UTM.
4. The die was kept under pressure for 4-5 hours so the natural curing of composite takes place.
5. After curing of specimen the die was opened and a specimen was drawn out from die.

After developing the specimens the drilling operation was performed on the developed specimens as per the DoE on CNC vertical milling center. The drilled specimen of carbon filled GFRP composite are shown in figure2.

Figure2: Drilled compression molded carbon filled GFRP specimen

Experimentation:

To examine the effect of carbon fiber and drilling parameters on delamination of drilled hole the three parameters were selected on the basis of literature survey and there levels were decided by performing pilot experiments. The three selected parameters and their levels are given in the table1.

Table1: Selected process parameters and their levels

Parameter	Level 1	LEVEL 2	LEVEL 3
Carbon Fiber % (A)	10	15	20
Spindle speed RPM (B)	1000	2000	3000
Feed rate mm/min (C)	150	200	250

The drilling of holes in specimens were conducted as per Taguchi L9 orthogonal array after preparing the specimen as per same scheme of experiments. The experimental scheme as per Taguchi L9 orthogonal array is given in the table 2.

Table 2: Experimental scheme as per Taguchi L9 orthogonal array

Experimental Run	Carbon fiber %	Spindle speed(rpm)	Feed rate (mm/min)
1	10	1000	150
2	10	2000	200
3	10	3000	250
4	15	1000	200
5	15	2000	250
6	15	3000	150
7	20	1000	250
8	20	2000	150
9	20	3000	200

After drilling the die penetration test were performed on the drilled compression molded carbon fiber filled GFRP composites. The steps for die penetration test were as follows:

The GFRP composite laminates were cleaned using cleaner of dye penetrations test kit, checkmate make, type CL-96.

Checkmates make, Type PT-97A, red dye was applied by spraying to the areas all around the hole. This dye penetrates into the micro cracks due to its low molecule nature.

Once the dye settle into any delamination the excess dye was washed away and again cleaned with cleaner to remove the excess penetrant.

Developer, Checkmate make, Type DV-98, was applied as a spray. Excess amount of the developer may wash the penetrant out of the damaged zone.

The ultra violet light source was switched on before starting the dye penetrant test to allow the light to warm up to maximum brilliance. The composite laminates were inspected under the UV light and the information interpreted. A clear damage zone was visible all around the drilled hole.

This damge zone was measured with the help of toolmakers microscope. The delamination factor was determined by equation1.

$$F_d = \frac{D_{max}}{d} \quad \text{…(1)}$$

Where, Fd= Delamination Factor, Dmax = Maximum Diameter of drill damaged zone and d =diameter of drill bit.

The delamination zone is shown in figure 3 after dye penetration test applied on specimen

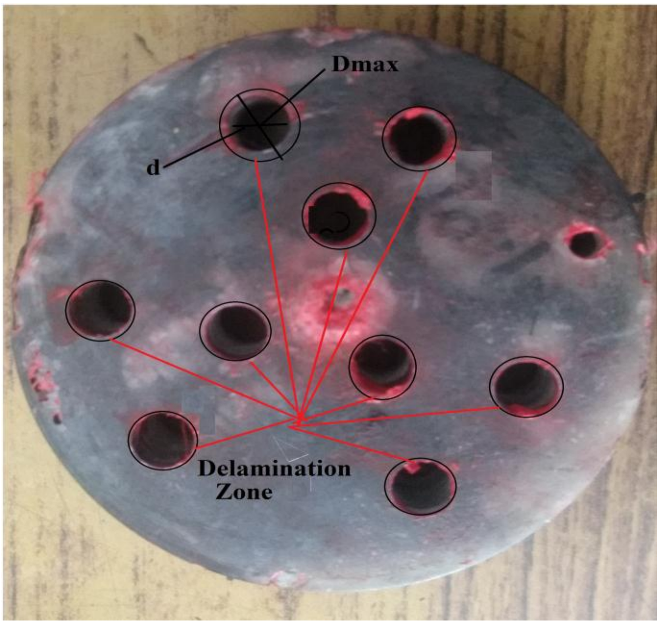

Figure 3 showing delamination zone after dye penetration test

Result and Discussion:

The delamination factor calculated for different composite specimen are given in table 3 along with the calculated S/N ratio. As the delamination factor is a lower the better type response so the S/ N ratio is calculated on the equation 2

$$\eta = -10 \log_{10}\left[\left(\frac{1}{n}\right)\sum_{i=1}^{n} y_i^{\,2}\right] \quad \ldots(2)$$

The experimental run as per Taguchi L9 orthogonal array along with calculated delamination factor are given in table 3

Table3: Taguchi L9 OA with responses (raw data and S/N ratios).

Run	R1 Delamination factor	R2 Delamination factor	R3 Delamination factor	Mean	S/N Ratio
1	1.028	1.028	1.028	1.028	-0.24
2	1.119	1.138	1.138	1.131	-1.07
3	1.183	1.183	1.183	1.183	-1.46
4	1.101	1.101	1.101	1.101	-0.84
5	1.128	1.119	1.119	1.122	-1.00
6	1.110	1.110	1.110	1.110	-0.91
7	1.046	1.037	1.046	1.043	-0.36
8	1.018	1.018	1.018	1.018	-0.16
9	1.110	1.110	1.119	1.113	-0.93

The average values of delamination factor raw data and S/N ratio for each parameter at level L1, L2 and L3 were calculated and are given in Table 4. These values have been plotted in Figure 4.

Table 3: S/N ratio values for the three levels

Response Table for Tensile strength and S/N ratio						
	Carbon fiber %		Spindle speed		Feed rate	
LEVEL	Raw data	S/N	Raw data	S/N	Raw data	S/N
L1	1.12	-0.92	1.06	-0.48	1.05	-0.43
L2	1.11	-0.91	1.09	-0.74	1.12	-0.95
L3	1.06	-0.48	1.14	-1.10	1.12	-0.94
Difference	0.06	0.82	0.08	0.62	0.06	0.51
Rank	1	1	2	2	3	3

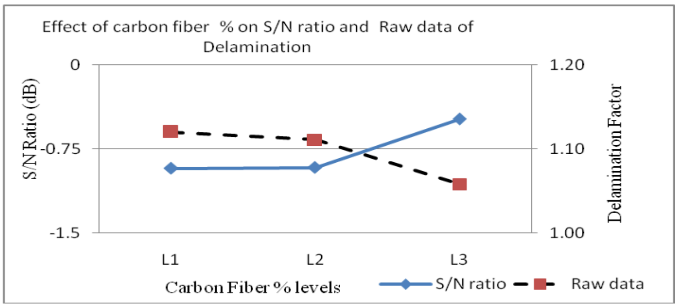

Figure 4(a)

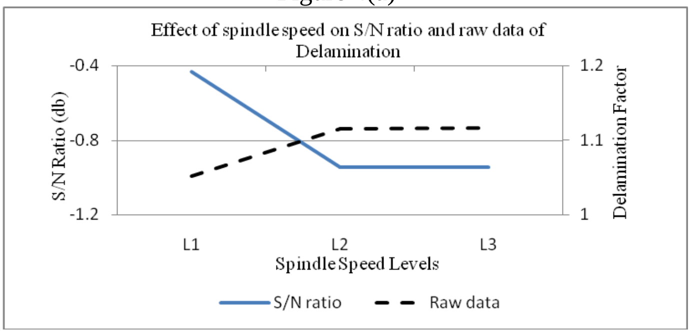

Figure 4(b)

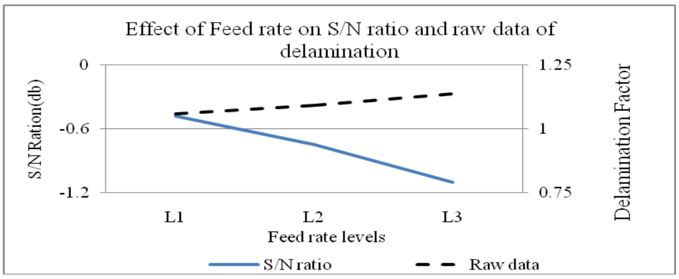

Figure 4(c)

Figure 4 Effect of process parameters on delamination raw data and S/N ratio (main effects). (a) Effect of carbon fiber % on raw data and S/N ratio; (b) Effect of spindle speed on raw data and S/N ratio and (c) effect of feed rate on raw data and S/N ratio

From figure 4(a) it is evident that the delamination of drilled hole reduced as the % of carbon fiber increased in carbon fiber filled GFRP composite. Although is reduction delamination is very less when carbon fiber % increased from 10 to 15% but reduced significantly as carbon % increases from 15 to 20 %.

It was found that the delamination of drilled hole first increases as the spindle speed increases from 1000 rpm to 2000 rpm and delamination further remains almost constant when spindle speed increases from 2000 rpm to 3000 rpm as shown in Figure 4(b).

Experiments also reveals that the delamination of drilled hole in carbon filled GFRP composite increases with the increases of feed rate and this can be seen in the figure 4(c).

ANOVA for S/N data and the raw data for delamination factor are given in Tables 5 and 6 respectively. As the F calculated is greater than F table for ANOVA of raw data and S/N ratio, so it is clear that carbon fiber %, spindle speed , and Feed Rate significantly affect both the mean and the variation in the delamination of hole.

Table5: analysis of Variance for delamination factor (Raw Data)

Source	Seq SS	DOF	Variance	P (%)	F-Ratio	F-table
Carbon fiber %	0.0052	2	0.0026	7.35	26.12	3.49
Spindle speed	0.0048	2	0.0024	6.67	23.70	
Feed Rate	0.0593	2	0.0297	83.17	295.56	
Error	0.0020	20	0.0001	2.81		
T	0.0713	26	*	100.00		
* significant factors at confidence level 95%, F-Ratio Table=3.49						

Table6: analysis of Variance for delamination factor (S/N ratio)

Source	Seq SS	DOF	Variance	P (%)	F-Ratio	F-table
Carbon fiber %	0.3787	2	0.1894	25.25	27.16	19
Spindle speed	0.5846	2	0.2923	38.97	41.93	
Feed Rate	0.5228	2	0.2614	34.85	37.49	
Error	0.0139	2	0.0070	0.93		
T	1.5001	8		100.00		
* significant factors at confidence level 95%, F-Ratio Table=19						

Optimum performance characteristics estimtion:

The optimum value of delamination was predicted at the selected levels of significant parameters A3, B3 and C1. The estimated mean of the response i.e. delamination factor was determined (Ross, 1988; Roy, 1990) as delamination factor sile strength =A3+ B1 +C1 -2 T=1.03

where

T : Overall mean of tensile strength = 1.09

A3: Average delamination factor at the third level of carbon fiber % = 1.06

B1 : Average delamination factor at the first level of spindle speed = 1.06

C1 : Average delamination factor at the first level of feed rate = 1.05

Substituting the values of various terms in the above equation, The 95% confidence interval of confirmation experiments (CICE) and of population

(CIPOP) was calculated by using the following equations:

$$CI_{CE} = \sqrt{F_{\alpha}(1, f_e)V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \quad \ldots(3)$$

And

$$CI_{POP} = \sqrt{\frac{F_{\alpha}(1, f_e)V_e}{n_{eff}}} \quad \ldots(4)$$

where,

Fα(1, fe): The F ratio at the confidence level of (1 – α) against DOF 1 and error DOF fe

N: Total number of results = 27 (treatment = 9, repetition = 3)

R: Sample size for confirmation experiments = 3

Ve: Error variance = 0.0001 (Table 5), fe = error DOF = 20 (Table 5).

$$\eta_{eff} = \frac{N}{(1 + \text{DOF associated in the estimate of mean response})}$$

=3.86

$F_{\alpha}(1,20) = 3.49$ (Tabulated F value; Roy, 1990)[11]

CICE = ± 0.014 and CIPOP = ± .01

Therefore, confidence interval of predicted mean at 95% confidence level is:

Mean delamination factor -CICE< delamination factor <Mean delamination factor + CICE

=1.046 < delamination factor < 1.074

Confidence interval of the population at 95% confidence level is:

Mean delamination factor _ CIPOP< delamiation factor <Mean delamination factor +CIPOP

=1.05< delamination factor < 1.07

The optimal values of process parameters for the predicted ranges of delamination factor are as follows:

Third level of carbon fiber % = 20%

First level of Spindle speed = 1000rpm

Ffirst level of Feed rate = 150 mm/min

Confirmation Experiments

Three confirmation experiments were conducted at the optimum setting of the process parameters. The average delamination factor was found 1.055 MPa, which was within the confidence interval of the predicated optima of delamination factor.

Conclusion

The effect of three process parameter Carbon fiber %, spindle speed and feed rate on delamination factor of drilled hole in carbon filled GFRP composite was investigated. The following conclusions can be drawn from the study:

1. The predicted optimal range for delamination factor is CIPOP: 1.05< tensile strength<1.07

2. The 95% confidence interval of the predicted mean for delamination factor is 1.046< tensile strength<1.074
3. The delamination factor in drilled hole of composite reduces with the increase carbon fiber % from level 1 to 3.
4. The optimum delamination factor was obtained when spindle speed and feed rate are at their first level.
5. The optimum parameter setting for lower delamination factor within the parameter range was found as 20% carbon fiber as filler in GFRP composite, spindle speed and feed are in drilling a hole as 1000 rpm and 150mm/min respectively.

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