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Experimental Investigations on Delamination to Improve the Hole Quality in Chopped Strand Mat GFRP Material During Drilling Operation

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Abstract: Fiber Reinforced Composite materials have an increased applications in recent days due to its enhanced structural properties and in turn mechanical and thermal properties. The heterogeneous nature of this kind of material makes complications in machining operation. However, drilling is a common machining practice for assembly of components. The quality of holes produced in Chopped Strand Mat Glass Fiber Reinforced Plastic (CSMat GFRP) material is severely affected by internal delamination besides with entry and exit delamination. The objective of the study was to apply the Taguchi methods to achieve an improved hole quality considering minimum delamination through proper selection of drilling parameters. A plan of experiments based on orthogonal main effect design has been used to get data for analysis. The signal to noise ratio and the analysis of variance are employed to investigate the drilling characteristics of CSMat GFRP material using high speed steel drills.

Key words: CSMat GFRP, drilling, delamination, orthogonal design, signal to noise ratio, analysis of variance

INTRODUCTION

The use of composite material is being increased in recent years, because of their special mechanical, thermal and structural properties. Most of the researchers have used Glass Fiber Reinforced Polymers for their studies. GFRP material is being inexpensive material compared to other composite material and having wider industrial applications. The drilling operation is an important machining process required for fastening the components in an assembly. To establish the better quality of hole made by drilling operation, the hole must be free from any damages like delamination etc. It is quiet difficult to generate hole without any damage, however changing the influencing machining parameters can minimize the same. The hole surface quality mainly depends on cutting parameters, like tool material, tool geometry, cutting forces etc. (Hocheng and Puw, 1992; Chen, 1997; Lin and Chen, 1996; Piquet *et al*., 2000). The influence of the cutting parameters in damage around the drilled hole with different tool geometry has been studied on discs made of GFRP (Polyester matrix reinforced with 65% of glass fiber) produced by hand lay-up (Davim *et al*., 2004). Enemuoh *et al*. (2004) have studied the application of Taguchi and a multi-objective optimization criterion and reported that it is possible to achieve cutting parameters that allow the absence of damage in drilling of fiber reinforced plastics. Using High Speed Steel (HSS) drill, a series of vibratory drilling experiments have been conducted to assess the delamination factor and it was found that vibratory drilling is a promising machining technique (Arul *et al*., 2006).

Delamination is being the most critical defect, among the defects caused by drilling operations. Delamination lowers the bearing strength thereby reducing the structural integrity of the material (Won and Dharan, 2002; Caprino and Tagliaferri, 1995). Davim and Reis (2003) have studied the drilling of laminated composite materials by conventional tools and concluded that the quality of cut surfaces depend on the cutting parameters, tool geometry and tool material. A comparative study aiming to evaluate the influence of the drill geometry on unidirectional laminate glass reinforced plastics (Bhatnagar *et al*., 2004; Singh and Bhatnagar, 2006). Khashaba (2004) has investigated the machining of GFRP composites produced by different matrix materials and different reinforcing shapes and concluded that the composite with cross winding had a surface without delamination and the woven composite with different matrix materials had a negligible effect on thrust. Hocheng and Tsao (2006) have studied the delamination using specially designed drills and established a relationship between feed rate, cutting speed and drill diameter. Kurt *et al*. (2009) have applied Taguchi methods

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and optimized the cutting parameters for surface finish and hole diameter accuracy in dry drilling operation.

The delamination of FRP composites under machining plays a vital role in determining the machining quality. In this research, an attempt is made to study the internal delamination that cause poor surface quality of hole during drilling of CSMat GFRP apart from entry and exit delamination. The work is carried out based on a statistical based approach namely, Design of Experiments (DOE). The standard HSS twist drills are used in this experimental work to investigate the internal delamination of CSMat GFRP material under various influencing parameters such as drill diameter, spindle speed and feed rate.

MATERIALS AND METHOD

Material and machine used: The specimen material made from the Chopped Strand Mat Glass Fiber Reinforced Plastic of size of a slab of 300×300×23 mm was used for the experiments. The physical properties of CSMat GFRP materials are highlighted in the Table 1. The drilling experiments were conducted in dry condition and at room temperature on MCV-400 with a workspace of 600×415×460 mm and the machine has a speed range of 60-6000 rpm.

Experimental design: The design of experiments is an effective tool to optimize the various machining parameters. In this study, a three level L_9 orthogonal main effect design was used. This design has an advantage of reducing the number of experiments. The identified parameters were drill diameter, spindle speed and feed rate. The factors and the levels of factors used are listed in the Table 2.

Determining delamination value: The damage around the holes was measured with 3D Coordinate Measuring Machine (SPECTRA Model) by the procedure: the diameter of the hole in the damage zone is measured for four times and the maximum value was recorded as D_{max} value. The delamination factor was determined by the ratio of maximum diameter (D_{max}) of the damage zone to the hole diameter (D). Therefore, the equation used to determine the delamination factor is:

$$F_d = \frac{D_{max}}{D} \quad (1)$$

where, F_d is the delamination factor, D_{max} is the maximum diameter of the damage zone in mm and D is the diameter of the hole in mm.

Table 1: Properties of CSMat GFRP material

Property	Range
Glass content	25-40 by wt %
Coefficient of thermal conductivity	0.2-0.23 W/m°C
Heat resistance	Up to 175°C
Density	1.4-1.5 Mg m^{-3}
Tensile strength	63-140 MPa
Tensile modulus	6-12 GPa
Compressive strength	130-170 MPa
Compressive modulus	6-9 GPa

Table 2: Levels of factors

Level	Drill diameter (mm)	Spindle speed (rpm)	Feed rate (mm min^{-1})
1	08	1000	050
2	15	2000	150
3	25	3000	250

Table 3: Experimental results for delamination factor and S/N ratio

Expt. No.	Drill dia (mm)	Spindle speed (rpm)	Feed rate (mm min^{-1})	F_d	S/N ratio (dB)
1	8	1000	50	1.008	-0.069
2	8	2000	250	1.018	-0.120
3	8	3000	150	1.007	-0.065
4	15	1000	250	1.044	-0.302
5	15	2000	150	1.029	-0.241
6	15	3000	50	1.021	-0.179
7	25	1000	150	1.036	-0.282
8	25	2000	50	1.035	-0.302
9	25	3000	250	1.037	-0.314

The experiments were replicated for two times and the average values of the delamination factor obtained were tabulated in Table 3. The results were analyzed using S/N ratio and ANOVA analysis.

Analysis of drilling parameters

Analysis of S/N ratio: S/N ratio is applied to measure the quality characteristic deviating from the desired value. The term signal represents the desirable value of the response variable whereas the term noise represents the undesirable value of the response variable. The S/N ratio η is defined as:

$$\eta = -10 \log (MSD)$$

where, MSD is the mean square deviation for the response characteristics.

To obtain optimal drilling performance, the-lower-the-better quality characteristic for delamination was taken. The MSD for the-lower-the-better quality characteristic can be given as:

$$MSD = (1/n) \Sigma F_{di}^2 \; ; \; i = 1,\ldots,n$$

where, n is the number of repeated experimental run and F_{di} is the value of delamination factor for the ith test.

The experimental results for delamination factor and the corresponding S/N ratio are shown in the following Table 3.

Table 4: S/N response table for delamination factor

	Mean S/N ratio (dB)				
Factor	Level 1	Level 2	Level 3	Max-min	Rank
Drill diameter	-0.085	-0.241	-0.299	0.214	1
Spindle speed	-0.218	-0.221	-0.186	0.035	3
Feed rate	-0.183	-0.196	-0.245	0.062	2

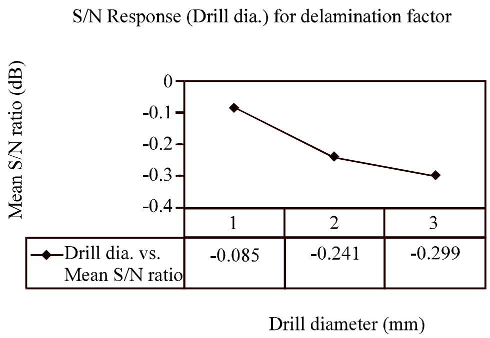

Fig. 1: S/N response (Drill dia.) for delamination factor

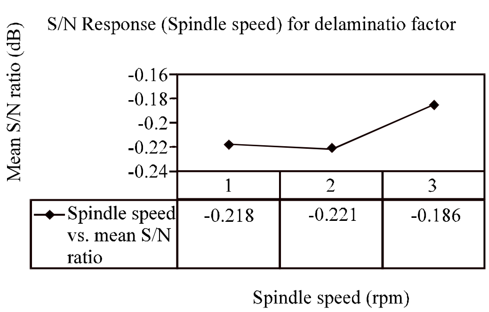

Fig. 2: S/N response (Spindle speed) for delamination factor

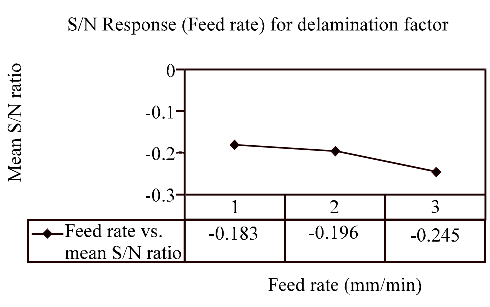

Fig. 3: S/N response (Feed rate) for delamination factor

The S/N response table and S/N response chart for delamination factor are given in Table 4 and in Fig. 1 to Fig. 3.

It is observed that higher S/N ratio for drill diameter is at the first level (Fig. 1), higher S/N ratio for spindle speed is at the third level (Fig. 2) and higher S/N ratio for feed rate is at the first level (Fig. 1).

Table 5: Results of ANOVA for delamination factor

Source of variation	Sum of squares	Degrees of freedom	Mean square	F-ratio	$F_{0.05,2,2}$	Contribution (%)
Drill diameter	0.0739	2	0.03695	56.85	19	88.19
Spindle speed	0.0022	2	0.0011	1.69	19	02.62
Feed rate	0.0064	2	0.0032	4.92	19	07.64
Error	0.0013	2	0.00065	-	-	01.55
Total	0.0838	8	-	-	-	100.00

Based on the analysis of S/N ratio and from S/N Response Table, the optimal drilling performance which will minimize the delamination factor was found as 8 mm drill size (level 1), 3000 rpm spindle speed (level 3) and 50 mm min^{-1} feed rate (level 1).

Analysis of variance: The analysis of variance is extensively used to investigate the design parameters, which significantly affect the quality characteristics. For this, 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, is partitioned into contribution by each of the design parameter and the error, i.e.,

$$SS_T = SS_{drilldia} + SS_{spindle\ speed} + SS_{feed\ rate} + SS_{error}$$

To perform the F-test, the mean of squared deviations is calculated from the sum of squared deviations of design parameter divided by the degrees of freedom associated with the design parameter. Then, the F-value for each design parameter is the ratio between the mean squared deviations and the mean squared error. The F-ratio corresponding to 95% confidence level from statistical table is used to compare the F-value calculated for each design parameter. The percentage contribution by each of the design parameters in the total sum of squared deviations SS_T is a ratio between the sum of squared deviations of each design parameter and the total sum of squared deviations SS_T.

Table 5 shows the results of ANOVA for delamination factor. Drill diameter has a significant effect on the delamination value. The percentage contribution of each parameter on total variation is 88.19, 2.62, 7.64%, respectively.

Confirmation test: Using the aforementioned data, one can predict the minimum delamination value using the optimal level of the design parameters selected. To verify the predicted results, a confirmation test was conducted at the first level of drill diameter (A1), the third level of spindle speed (B3) and the first level of feed rate (C1). Table 6 shows the comparison of predicted value with experimental value of delamination along with S/N ratio, good agreement being observed.

Table 6: Confirmation results

	Optimal drilling parameters	
	Prediction	Experiment
Level	A1B3C1	A1B3C1
Delamination	1.002	1.005
S/N ratio (dB)	-0.038	-0.043

CONCLUSIONS

The out come of research work are listed below:

- It is found that the Taguchi method of approach using L9 orthogonal arrays could be used to analyze the delamination of CSMat GFRP material under drilling operations
- Signal to Noise ratio analysis has been used to find the optimal drilling parameters suitable for minimal delamination which in turn improves the hole quality in drilling
- It is experimentally found that the optimum parameters for the drilling are identified from the S/N response table as 8 mm drill size, 3000 rpm spindle speed and 50 mm/min feed rate
- It is observed from the ANOVA table that the drill size plays a significant role in determining the delamination value rather than the other parameters considered in this work
- ANOVA results also show the percentage contribution of the drill diameter, spindle speed and feed rate on total variation by 88.19, 2.62 and 7.64%, respectively
- The experimental results have good agreement with the predicted results obtained from the confirmation tests

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