Pertanika J. Sci. & Technol. 23 (1): 61 - 72 (2015)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Optimization of Drilling Parameters for Delamination Associated with Pre-drill in Chopped Strand Mat Glass Fibre Reinforced Polymeric Material

T. Panneerselvam* and S. Raghuraman

School of Mechanical Engineering, Shanmugha Arts, Science, Technology and Research Academy (SASTRA University), Thanjavur - 613 401, Tamil Nadu, India.

ABSTRACT

Glass fibre reinforced polymeric (GFRP) composites are used in various applications such as aircraft, marine and automobile industries because of their high specific strength, high specific stiffness, light weight, corrosion resistance and non-magnetic properties. They also replace traditional materials in many critical applications. Nonetheless, the machining behaviour of GFRP material is still a challenge to the researchers due to its complicated interaction between fibre and matrix material. On machining, this kind of material suffers by surface delamination, fibre peel up, fibre push up, fibre pull out, fibre fracture, and matrix breaking. With an objective to minimize delamination, an investigation was carried out on Chopped Strand Mat GFRP (CSMat GFRP) material by studying the effects of drill diameter and drill diameter ratio besides spindle speed and feed rate. The experiments were designed by L_{18} Orthogonal Array and conducted by using standard High Speed Steel tools. The obtained results were analyzed by Signal-to-Noise ratio and Analysis of variance. Based on the Signal-to-Noise ratio analysis, drill diameter of Ø8mm, drill diameter ratio of 0.8, spindle speed of 3000rpm and feed rate of 50mm/min were identified as optimal parameters for drilling CSMat GFRP material with minimum delamination. The ANOVA table results reveal that drill diameter, drill diameter ratio, spindle speed and feed rate have shown statistical significance on delamination.

Keywords: CSMat GFRP, Delamination, Orthogonal Array, Signal-to-Noise ratio, ANOVA.

INTRODUCTION

The light weight materials are becoming emerging materials for many applications to save energy consumption. GFRP is used in structural components for automobile, aircraft, marine industries, etc. In drilling Glass Fibre Reinforced Polymer, delamination

Article history:
Received: 19 April 2013
Accepted: 5 February 2014

E-mail addresses:
tpansel@mech.sastra.edu (T. Panneerselvam),
raghu@mech.sastra.edu (S. Raghuraman)
*Corresponding Author

ISSN: 0128-7680

is the major and critical damage. The rejection of parts in the aircraft industry was mostly reported due to drilling- induced delamination during final assembly (Stone & Krishnamurthy, 1996). It could also be seen from the earlier studies that the main objective was to minimize the drilling-induced delamination of composite laminates through delamination-free drilling experiments (Hocheng & Tsao, 2005; Enemuoh *et al*., 2001; Tsao, 2006). The effects of input variables such as feed rate, cutting speed and point angle of twist drill on drilling-induced delamination have been studied by many researchers. It was reported that the observed drilling-induced delamination increases with feed rate at any different cutting speeds for various drill bits due to the increase of thrust force during drilling of composite laminates. Khashaba *et al*. (2010) reported in their work that delamination decreased with cutting speed during conventional drilling of woven-ply GFRP composite laminates. Gaitonde *et al*. (2008) also noticed a similar inference that drilling-induced delamination decreased with cutting speed during high speed drilling of CFRP composite laminates. Karnik *et al.* (2008) have studied and inferred that the tendency of delamination increases with the increase of point angle of twist drill during both conventional drilling and high speed drilling of woven-ply CFRP composite laminates.

Won and Dharan (2002) conducted drilling experiments on carbon fiber-reinforced composite laminates to study the effects of the chisel edge on the thrust force and the effects of pre-drilling the laminate with a pilot hole. Their results showed a large reduction in the thrust force by the use of pilot hole, which in effect, removes the chisel edge contribution on delamination. Jain and Yang (1993) concentrated to establish an analytical model to predict thrust force and feed rate which avoid delamination in drilling polymeric composite and the chisel edge width has been identified as an important factor that contributes the thrust force and delamination. Tsao and Hocheng (2003) studied the effects of chisel edge length and pilot hole diameter on delamination in drilling woven carbon/epoxy composite. Their experimental results showed that the critical thrust force could be reduced with pre-drilled hole by cancelling the chisel edge effect on delamination. Tsao (2007) proposed an analytical approach to identify the role of the pilot hole on drilling woven carbon fibre reinforced plastics in order to reduce the thrust force-induced delamination during saw drilling. The experimental results with saw drill showed that the increase in pilot hole ratio could potentially attribute to reduce thrust force and delamination. Tsao and Hocheng (2004) studied the delamination factor of carbon fibre reinforced plastics with the objective to establish a correlation by multi-variable linear regression and the model values were compared with experimental results. Tsao (2008a, 2008b) selected orthogonal array of L_{18} to study the effects of diameter ratio, feed rate and spindle speed on induced delamination for various step core drills and he found the best combination of parameters for all step core drills within the tested range. He also studied the effects of thrust force of step core drill with drilling parameters. L_9 Orthogonal array and Signal-to-noise ratio were applied to optimize the levels of parameters for minimum delamination in drilling CSMat GFRP material (Panneerselvam & Raghuraman, 2012). Aji *et al*. (2013) investigated the hybridized kenaf (bast)/ pineapple leaf fibre (PALF) bio-composites with an objective of improving tensile property and the results obtained were analyzed statistically at 95% confidence level.

This paper investigates the way to use conventional tool for minimum delamination in drilling CSMat GFRP material. The influences of drill diameter, drill diameter ratio, spindle speed, and feed rate on delamination were studied with the objective to select the optimal conditions for minimum delamination.

EXPERIMENTAL DETAILS

Material and Method

The material specimen used in this work is a laminated slab of 300mm x 300mm x 23mm, and it was fabricated from the hand lay-up process. The material has chopped strand mat glass fibre in isophthalic polyester resin. It contains 40% glass fibre with a density of 1.5Mg/m^3. It has the heat resistance up to 175°C and its tensile strength and compressive strength are 140MPa and 170MPa, respectively.

This work is planned with Taguchi method of approach. The Taguchi method provides a special design to set the process parameters with minimum number of experiments by saving time and resources. The method also combines the experimental design theory and the quality loss function concept in order to solve the problem of industrial product quality and reliability. Thus, Taguchi's experimental design, a L_{18} (2×3^7) orthogonal array, was selected in this work to study the effect of drill diameter and drill diameter ratio separately, along with spindle speed and feed rate on delamination. The factors and their levels considered in conducting the experiments are listed in Table 1 and Table 2.

TABLE 1: Factors and levels (to study the effects of drill diameter on delamination)

Symbol	Factor	Level 1	Level 2	Level 3
A	Drill diameter (mm)	8	15	-
B	Spindle speed (rpm)	1000	2000	3000
C	Feed rate (mm/min)	50	150	250

TABLE 2: Factors and levels (to study the effects of drill diameter ratio on delamination)

Symbol	Factor	Level 1	Level 2	Level 3
A	Drill diameter ratio	0.8	0.53	-
B	Spindle speed (rpm)	1000	2000	3000
C	Feed rate (mm/min)	50	150	250

Machining and Measuring Equipment

MCV- 400 machining centre, with a workspace of 600 x 415 x 460 mm and a speed range of 60 – 6000 rpm, was used to perform drilling operations on CSMat GFRP material. The effect of drill diameter on delamination was initially studied by using standard High Speed Steel (HSS) twist drill of Ø8 mm and Ø15mm. Later, the drilled Ø8mm holes were subsequently drilled by Ø10mm and Ø15mm according to L18 Orthogonal Array design to study the effect of drill diameter ratio on delamination. The drilled holes used for the delamination studies are shown in Fig.1.

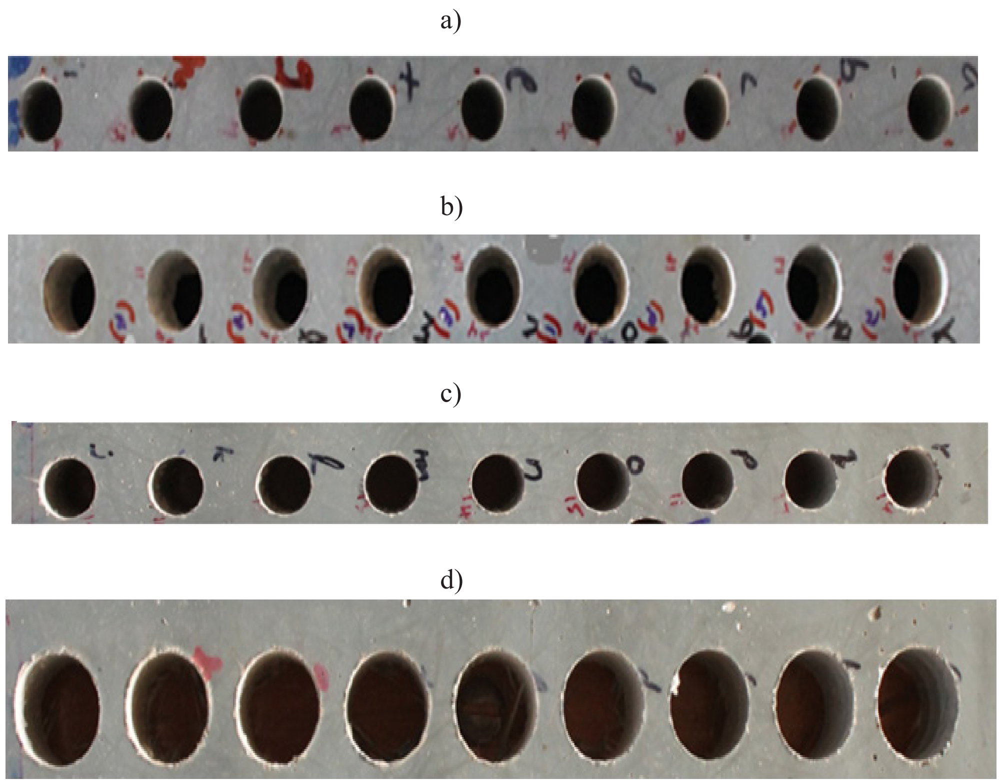

Fig.1: Drilled holes for delamination studies; a) Ø8mm drilled holes, b) Ø15mm drilled holes, c) Ø10mm holes obtained by drill diameter ratio of 0.8 and d) Ø15mm hole obtained by drill diameter ratio of 0.53

Delamination is a physical separation of constituent materials which gives a serious problem in the fibre reinforced composite materials at the entry and exit of holes. This can be evaluated by tool maker's microscope, profile projector or image processing analyzer. In this work, DYNASCAN Profile Projector, model PT 400 EM, was used with a magnification of 20X for an accuracy of 0.001mm. It is capable of measuring 200mm × 150mm in X/Y axis. The maximum diameter in the delaminated area was measured as the scheme shown in Fig.2.

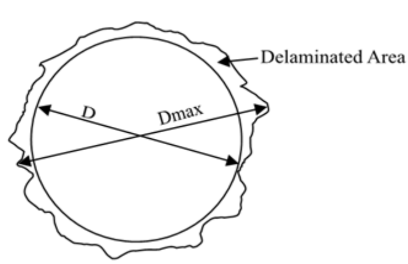

Fig.2: A scheme of measurement for maximum diameter in the delaminated area

The delamination factor was determined by the ratio between the maximum diameter in the damaged zone and the drill diameter, i.e.

$$F_d = \frac{D_{max}}{D} \qquad \text{Equation 1}$$

where Dmax – Maximum diameter measured in the delaminated area and D – Drill diameter

RESULTS AND DISCUSSION

Signal-to-noise Ratio

A Taguchi approach, Signal-to-Noise (S/N) ratio, was used to measure the quality characteristics which deviate from the desirable value. In the Signal-to-Noise ratio, the term 'Signal' represents the desirability of response parameters and the term 'Noise' represents the undesirability for the response parameters. The objective of the work was to identify the factors and their combination that influence the drilling process and to minimize the delamination. For minimum delamination, the smaller-the-better quality characteristic was used to calculate S/N ratio and S/N ratio is determined by:

$$\text{S/N ratio} = -10 \times \log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \qquad \text{Equation 2}$$

where n is the number of measurements in a trial/row, in this case, n = 2 and y_i is the i^{th} measured value in a run.

The results of the delamination factor and the corresponding calculated S/N ratio values are given in Table 3 to study the effects of drill diameter and the effects of drill diameter ratio on delamination during drilling CSMat GFRP material. In order to study the drill diameter effect and drill diameter ratio on delamination, the main effects plots were drawn with the help of Minitab16, and these are shown in Fig.3 and Fig.4.

From Fig.3, it can be seen that the increasing drill diameter, decreasing spindle speed and increasing feed rate have demonstrated the increasing delamination. The reduction in the delamination observed for small drill diameter is due to the fact that decreasing drill diameter actually has the effect to reduce the delamination by reducing the cutting torque and thrust force. The authors of many research papers have investigated that cutting torque and thrust force are the contributing parameters in increasing the delamination values (see Stone & Krishnamurthy, 1996; Tsao, 2007; Tsao, 2008b). The mechanism which is capable of reducing cutting torque and thrust force can reduce delamination and hence small drill diameter has the effect to reduce the delamination value.

A reduction in delamination was also observed for the use of pre-drill and the higher drill diameter ratio was shown to have reduced delamination (Fig. 4). This is due to the fact that the use of pre-drill has an effect to reduce the chisel effect, cutting torque, thrust force and

TABLE 3: L_{18} (2×3^7) Orthogonal Array design, Delamination factor (Fd) and Signal-to-noise (S/N) ratio

Trial No.	A	B	C	To study the effect drill diameter		To study the effect of drill diameter ratio	
				Fd	S/N ratio (dB)	Fd	S/N ratio (dB)
1	1	1	1	1.034	-0.292	1.025	-0.211
2	1	1	2	1.079	-0.663	1.061	-0.514
3	1	1	3	1.094	-0.783	1.088	-0.733
4	1	2	1	1.026	-0.227	1.024	-0.207
5	1	2	2	1.066	-0.559	1.053	-0.449
6	1	2	3	1.091	-0.755	1.066	-0.558
7	1	3	1	1.025	-0.218	1.021	-0.183
8	1	3	2	1.058	-0.491	1.042	-0.355
9	1	3	3	1.061	-0.515	1.058	-0.492
10	2	1	1	1.079	-0.657	1.038	-0.324
11	2	1	2	1.084	-0.704	1.071	-0.597
12	2	1	3	1.100	-0.825	1.099	-0.819
13	2	2	1	1.073	-0.614	1.036	-0.307
14	2	2	2	1.088	-0.734	1.070	-0.588
15	2	2	3	1.092	-0.766	1.079	-0.663
16	2	3	1	1.070	-0.590	1.034	-0.290
17	2	3	2	1.072	-0.600	1.053	-0.446
18	2	3	3	1.087	-0.725	1.074	-0.616

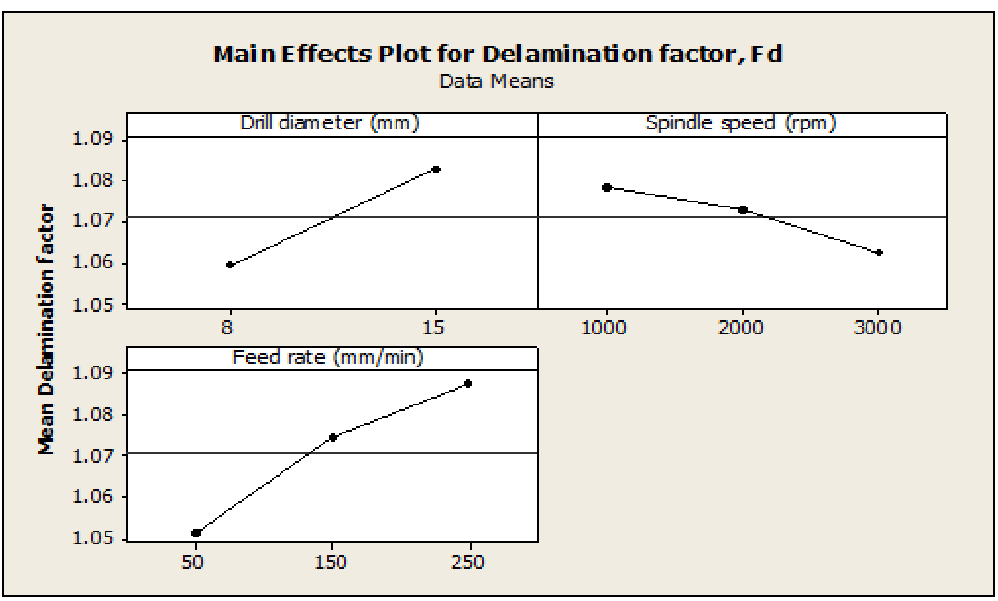

Fig. 3: The main effects plot for Delamination factor (effect of drill diameter)

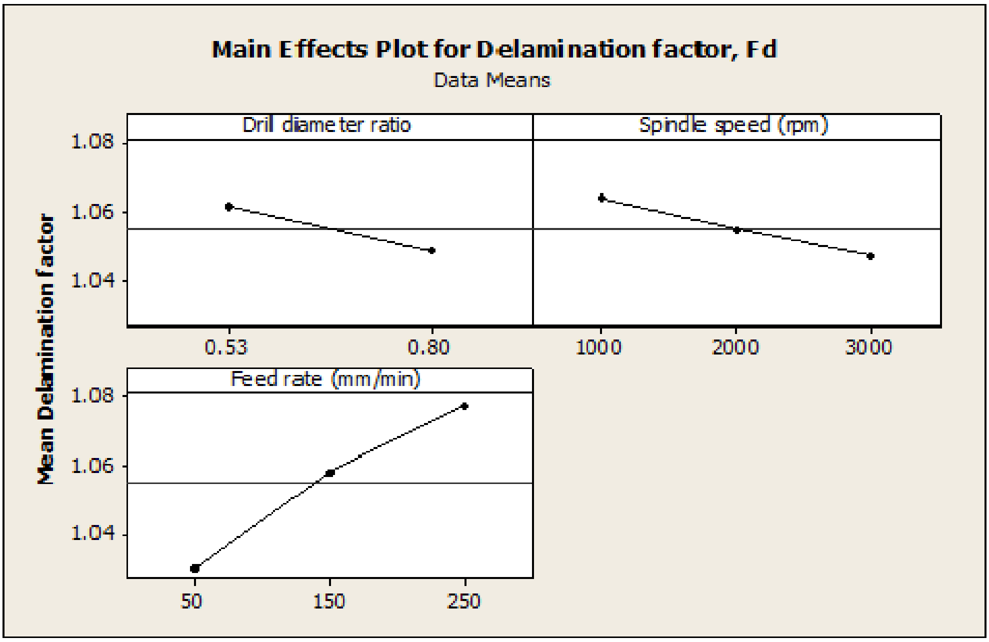

Fig.4: The main effects plot for Delamination factor (effect of drill diameter ratio)

the amount of material removed (Won & Dharan, 2002; Tsao & Hocheng, 2003; Tsao, 2006; Tsao, 2007) and hence, reduced delamination was observed for higher drill diameter ratio. Meanwhile, it is also noted that the use of pre-drill with higher drill diameter ratio permits to go for higher diameter drilling of CSMat GFRP material with minimum delamination. The main effect plots of both also reveal that the increasing spindle speed and decreasing feed rate have the effects in reducing delamination. This is due to the fact that the cutting torque and thrust force contributions are reduced by the increasing spindle speed and decreasing feed rate (Khashaba *et al*., 2010). Hence, delamination is reduced for higher spindle speed and lower feed rate (Panneerselvam & Raghuraman, 2012).

TABLE 4: S/N Response table for delamination factor (effect of drill diameter)

Levels	Factor		
	A	B	C
1	-0.5	-0.654	-0.433
2	-0.691	-0.609	-0.625
3	---	-0.523	-0.728
Max-min	0.191	0.131	0.295
Rank	2	3	1

The study of the S/N response (Table 4) and S/N response graph (Fig.5) for the effects of drill diameter indicates that drill diameter and feed rate are the significant factors for minimum delamination and the slope gradient is larger for drill diameter and feed rate. The optimal

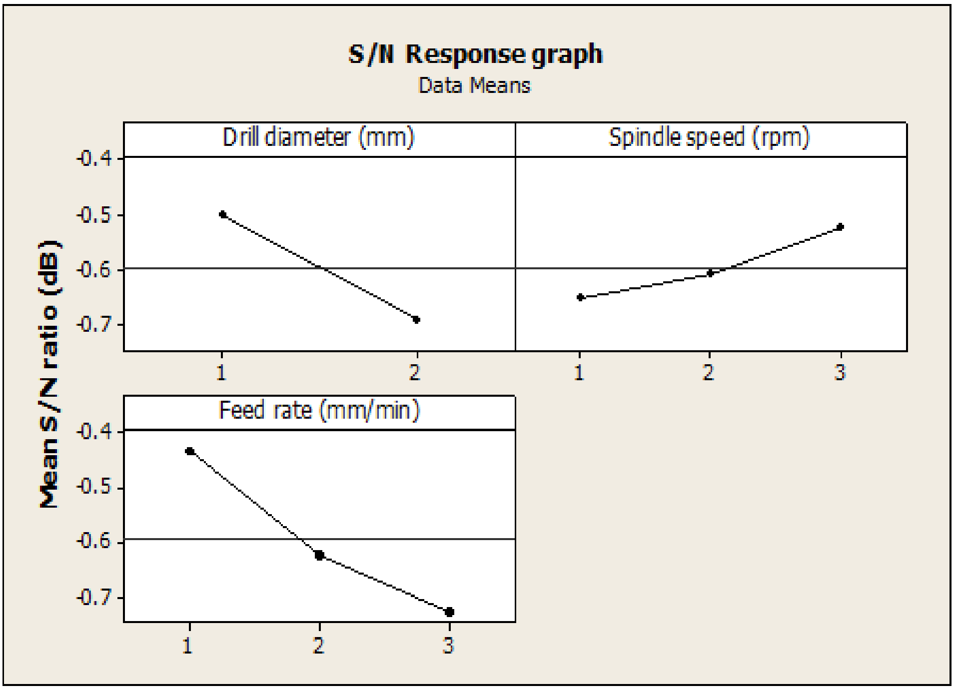

Fig.5: S/N Response graph for Delamination factor (effects of drill diameter)

cutting conditions leading to the minimum delamination were identified based on the parameter settings which have the highest S/N ratio as the highest S/N ratio always gives optimum quality with minimum variance. Accordingly, it is evident from Table 4 and Fig.5 that level 1 of drill diameter (Ø8mm), level 3 of spindle speed (3000rpm) and level 1 of feed rate (50mm/min) have the highest S/N ratio. These levels of combination are determined as the optimal levels for minimum delamination for drilling CSMat GFRP material.

Similarly, the study of the S/N response (Table 5) and the S/N response graph (Fig.6) for the effects of drill diameter ratio indicates that drill diameter ratio, spindle speed and feed rate are the significant factors for minimum delamination. From Table 5 and Fig.6, the optimal parameter combination corresponding to level 1 of drill diameter ratio (0.8), level 3 of spindle speed (3000rpm) and level1 of feed rate (50mm/min) are determined to get the minimum delamination for drilling CSMat GFRP material.

TABLE 5: S/N Response table for delamination factor (Effects of drill diameter ratio)

Levels	Factor		
	A	B	C
1	-0.411	-0.533	-0.254
2	-0.517	-0.462	-0.492
3	---	-0.397	-0.647
Max-min	0.106	0.136	0.393
Rank	3	2	1

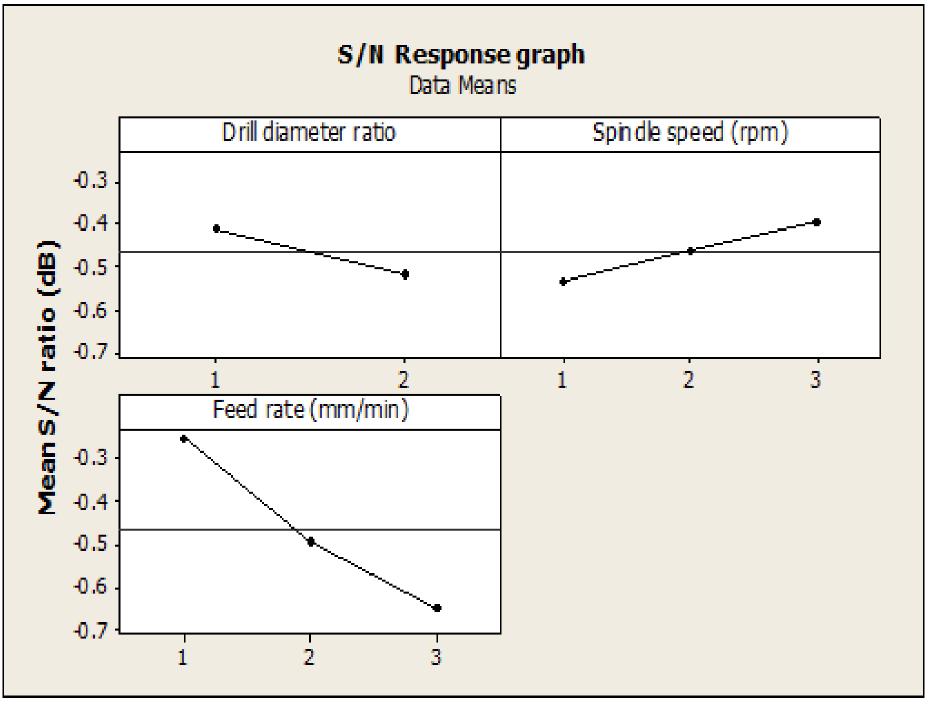

Fig.6: The S/N Response graph for Delamination factor (effect of drill diameter ratio)

Analysis of Variance

The purpose of the analysis of variance is to find the parameter's significance on the quality characteristics. The ANOVA results developed for this experimental work are summarized in Table 6 and Table 7. It can be seen from Table 6 that drill diameter and feed rate have shown statistical significance on the delamination factor. In addition, both have 27.72% and 45.85% of contributions on total variation, respectively.

TABLE 6: ANOVA for Delamination factor (Effect of drill diameter)

Source	SS	DOF	MS	F_{cal}	F_{table}	C %
A*	0.163	1	0.163	19.136	4.75	27.72
B	0.053	2	0.027	3.127	3.89	9.06
C*	0.270	2	0.135	15.826	3.89	45.85
Error	0.102	12	0.009	---	---	17.38
Total	0.588	17	---	---	---	100.00

*Significant

SS- Sum of Squares, DOF- Degrees of Freedom, MS – Means of Square, F_{cal} – F-distribution value calculated, F_{table} – F-distribution value from table at 5% significant level, C – contribution in total variations

TABLE 7: ANOVA for Delamination factor (Effect of drill diameter ratio)

Source	SS	DOF	MS	F_{cal}	F_{table}	C %
A*	0.050	1	0.050	22.836	4.75	8.29
B*	0.056	2	0.028	12.689	3.89	9.22
C*	0.471	2	0.235	107.591	3.89	78.14
Error	0.026	12	0.002	---	---	4.36
Total	0.602	17	---	---	---	100.00

*Significant

SS- Sum of Squares, DOF- Degrees of Freedom, MS – Means of Square, F_{cal} – F-distribution value calculated, F_{table} – F-distribution value from table at 5% significant level, C – contribution in total variations

The results of ANOVA (Table 7) indicate that drill diameter ratio (8.29%), spindle speed (9.22%) and feed rate (78.14%) have the statistical significance on the delamination factor. In both the ANOVA tables, it is observed that feed rate plays a major contribution in controlling the delamination factor, apart from the other drilling parameters.

CONCLUSION

The experimental studies on delamination associated with drill diameter, drill diameter ratio, spindle speed and feed rate in drilling CSMat GFRP material are presented in this work. The following conclusions are drawn from this investigation: in the first set of the experiment, the effect of drill diameter was considered and it is seen that Ø8mm HSS twist drill offers minimum delamination compared to Ø15mm HSS twist drill. The delamination increases with increase in drill diameter; in the second set of the experiment, the effect of diameter ratio was considered, and it is observed that drill diameter ratio of 0.8 offers the minimum delamination compared to drill diameter ratio of 0.53. Delamination decreases with the increase in drill diameter ratio; the results also show that the increase in spindle speed and decrease in the feed rate reduced the delamination value; based on the S/N response table and S/N response graph for the study on the effect of drill diameter, drill diameter of Ø8mm, spindle speed of 3000rpm and feed rate of 50mm/min were found as the optimal parameter combination for drilling CSMat GFRP material with minimum delamination. Similarly for the study on the effect of drill diameter ratio, the drill diameter ratio of 0.8, spindle speed of 3000rpm and feed rate of 50mm/min were identified as the optimal parameter combination for minimum delamination; the ANOVA results for the study on the effects of drill diameter reveal that the drill diameter and feed rate have statistical significance on delamination factor, while the ANOVA results for the study on the effect of drill diameter ratio reveal that drill diameter ratio, spindle speed and feed rate have the statistical significance on delamination factor; and in the ANOVA analysis, it is also noted that feed rate has more percentage of contribution on total variation for both the studies on the effects of drill diameter and the effects of drill diameter ratio on delamination.

REFERENCES

Aji, I. S., Zinudin, E. S., Khairul, M. Z., Abdan, K., & S. M. Sapuan, S. M. (2013). Induced Tensile Properties With EB- Cross Linking of Hybridized Kenaf/Palf Reinforced HDPE Composite. *Pertanika Journal of Science and Technology, 21*(1), 135 – 140.

Enemuoh, E. U., El-Gizawy, A. S., & Okafor, A. . (2001). An approach for development of damage-free drilling of carbon fiber reinforced thermosets. *International Journal of Machine Tools & Manufacture, 41*, 1795–1814.

Gaitonde, V. N., Karnik, S. R., Campos Rubio, J., Esteves Correia, A,, Abrao, A. M., & Paulo Davim, J. (2008). Analysis of parametric influence on delamination in high-speed drilling of carbon fiber reinforced plastic composites. *Journal of Material Processing Technology, 203*,431–438.

Hocheng, H. & Tsao, C. C. (2005). The path towards delamination-free drilling of composite materials. *Journal of Material Processing Technology, 167*, 251–264.

Jain, S. & Yang, D. C. H. (1993). Effects of Feed rate and Chisel Edge on Delamination in Composites Drilling. *ASME Journal of Engineering for Industry, 115*, 398- 405.

Karnik, S. R., Gaitonde, V. N., Campos Rubio, J., Esteves Correia, A., Abrao, A. M., & Davim, J. P. (2008). Delamination analysis in high speed drilling of carbon fiber reinforced plastics (CFRP) using artificial neural network model. *Material and Design, 29,* 1768–1776.

Khashaba, U. A., EI-Sobaty, I. A., Selmy, A. I., & Megahed, A. A. (2010). Machinability analysis in drilling woven GFR/epoxy composites: part I – effect of machining parameters. *Composites: Part A, 41*, 391–400.

Panneerselvam,T. & Raghuraman, S. (2012). Experimental Investigations on Delamination to improve the hole quality in Chopped Strand Mat GFRP Material during Drilling Operation. *Journal of applied sciences, 12*(10), 1063-1066.

Stone, R. & Krishnamurthy, K. (1996). A neural network thrust force controller to minimize delamination during drilling of graphite-epoxy laminates. *International Journal of Machine Tools & Manufacture, 36,* 985–1003.

Tsao, C. C. (2006). The effect of pilot hole on delamination when core drill drilling composite materials. *International Journal of Machine Tools & Manufacture, 46*, 1653–61.

Tsao, C. C. (2008a). Investigation into the effects of drilling parameters on Delamination by various step-core drills. *Journal of Material Processing Technology, 206,* 405-411.

Tsao, C. C. (2007). Effect of pilot hole on thrust force by saw drill. *International Journal of Machine Tools & Manufacture, 47*, 2172–2176

Tsao, C. C. (2008b). Experimental study of drilling composite materials with step-core drill. *Materials and Design, 29*, 1740-1744.

Tsao, C. C. & Hocheng, H. (2003). The effect of chisel length and associated pilot hole on delamination when drilling composite materials, *International Journal of Machine Tools & Manufacture, 43*, 1087–1092.

Tsao, C. C. & Hocheng, H. (2004). Taguchi analysis of delamination associated with various drill bits in drilling of composite material, *International Journal of Machine Tools & Manufacture, 44,* 1085-1090.

Won, M. S. & Dharan, C. K. H. (2002). Chisel Edge and Pilot Hole Effects in Drilling Composite Laminates. *ASME Journal of Manufacturing Science and Engineering, 124*, 242-247.