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INVESTIGATION OF DRILLING IN [(0/90)/0]S GLASS FIBRE REINFORCED PLASTICS USING TAGUCHI METHOD

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Abstract:
Fibre Reinforced Plastics (FRPs) are extensively used these days due their superior mechanical properties like high strength to weight ratio, high stiffness to weight ratio, better impact characteristics, corrosion resistance and design flexibility. Usually FRP products are made to a near net shape by primary manufacturing process like hand lay up process and filament winding. As the product complexity increases, the products are produced in parts and are then finally assembled. The secondary manufacturing in terms of drilling thus becomes unavoidable in order to facilitate the assembly operations. However, this leads to drilling induced damage resulting in high rejection rate. Researchers are trying world wide to minimize this damage by adopting different approaches. The present study is an attempt to investigate experimentally the significance of the drill point geometry and the operating variables on the drilling forces and the drilling induced damage.

Key Words: Drilling, GFRP, Operating Variables, Damage, Taguchi method

1. INTRODUCTION

Fibre Reinforced Plastic (FRP) is composite material comprising of a polymer matrix reinforced with fibres. FRPs are typically organized in a laminate structure, such that each lamina (or flat layer) contains an arrangement of unidirectional fibres or woven fibre fabrics embedded within a thin layer of light polymer matrix material. Fibre Reinforced Plastics (FRPs) are being used widely today, owing their use to superior mechanical properties like high strength to weight ratio, high stiffness to weight ratio, better impact characteristics, corrosion resistance and design flexibility. The tremendous increase in the application areas of FRPs has necessitated the development of high quality and cost-effective manufacturing techniques that will enable them to compete with the conventional materials economically. The manufacturing of FRPs can be broadly categorized into primary and secondary manufacturing. The primary manufacturing processes, such as pultrusion and filament winding are well developed and mostly automated. The products made by primary manufacturing are generally to the near-net shape, but sometimes due to complexity in the product design, the product has to be manufactured in parts. Secondary manufacturing, in terms of drilling thus becomes unavoidable to facilitate the assemble operations of the parts to get the final product. The drilling of laminated FRPs is a process substantially different from drilling of conventional materials such as steel and wood. The drilling induced damage is also an area of paramount importance, as various types of damage forms, such as delamination, fibre pull-out, matrix burning, chipping have already been reported. The research efforts have been put worldwide to minimize the drilling induced damage with a fair degree of success. The drilling induced damage has been quantified using different methods, such as, computerized tomography and C-scan [1], digital image analysis [2] and a shadow moiré laser based imaging technique [3]. Hocheng and Tsao [4] have reviewed the research efforts put in the direction of delamination free drilling of composite materials. Abrao et *al.* [5] also reviewed the work done in the field of drilling of fibre reinforced plastics. The tool material and the tool point geometry are important in terms of making a damage free hole in composite materials. It is an established fact by now that High Speed Steel (HSS) drills should be avoided for drilling of composite materials as greater number of holes to failure are drilled with carbide drills with highest quality [6, 7]. The standard twist drill that is used for making holes in metals can not be used in drilling of composite materials owing to substantial material damage [8]. With increasing wear ratio of the drill the critical thrust force is higher and delamination becomes more likely to occur [9]. The 'Brad & Spur' drill point results in better quality holes as compared to the 'Straight shank' and 'Stub length' drill point geometries [10, 11]. The effect of eccentricity of twist drill and candle stick drill and the effect of chisel edge length on delamination has also been reported [12, 13]. It was found that 8-facet and the Jodrill are the most suitable for making holes in composite laminates. There have been other studies on the modification of the drill point geometry for minimizing the drilling induced damage [14-18]. The cutting velocity and the feed rate are the two most important operating variables in the drilling process. These variables are under the direct control of the operator. Both these variables are to be optimized to make a good quality hole. The type of damage induced in a composite material during drilling is strongly dependent on the feed rate. When the feed rates are high, the failure modes show the features typical of the impact damage [19]. The feed rate is identified as the most critical parameter that influences damage [20]. Increasing feed rate leads to increased drill thrust and torque, smaller entrance and exit burrs, reduced damage width and increased number of holes drilled, whereas increasing speed leads to increased tool wear, larger entrance and exit burrs, larger damage rings and decreased number of holes drilled [6]. The cutting velocity has the highest physical as well as the statistical significance on damage and the surface roughness in drilling of Glass Fibre Reinforced Plastic (GFRP) material [11]. An intelligent machining system has been proposed for delamination free drilling of composite laminates [21]. Sardinas *et al.* [22] used an optimization procedure using genetic algorithm to choose the more adequate solution for drilling laminated composite materials. Although a number of general approaches have been employed to minimize the drilling induced damage, a wide variety of material combination possible within the family of laminated composite materials necessitate the need to examine experimentally their machining or drilling characteristics. The basic understanding of the process can help subsequently to develop more generic approaches for minimizing the drilling induced damage.

The present experimental investigation is an attempt to study the influence of drill point geometry, the cutting speed and the feed rate on the drilling forces and the drilling induced damage. A novel approach of quantifying the drilling induced damage using the non-destructive dye penetrant testing in combination with the digital image processing has been employed.

2. EXPERIMENTAL SET- UP

2.1 [(0/90)/0]s laminate specimen preparation

The FRP laminates used in the present investigation were manufactured using the hand lay-up technique. The E-glass fibre was used as reinforcement in the epoxy matrix (Araldite make LY-556 with hardener HY-951). A flat plate mold was used for laminating and the laminates were left for 24 hours for room temperature curing. The fibre volume fraction was found to be 0.60 by burn-off method.

2.2 Experimentation

A schematic diagram of the experimental set-up is shown in Figure 1. As has been reported by Ramulu *et al.* [14], carbide drills give better surface finish and more number of holes to failure; HSS drills were ruled out from the scope of this study. The range for the spindle speed and the feed rate was selected after a pilot experimentation, wherein the minimum damage using visual examination was used as the selection criteria. The spindle speed selected was 750, 1500, and 2250 rpm for a drill diameter of 8mm and the feed rate was 10, 15, 20 mm/min. The cutting forces, torque (*T*) and thrust (*F*) were recorded using the drill dynamometer (Kistler, type 9272). The methodology employed to quantify the drilling-induced damage used a non-destructive dye penetrant test in combination with digital image processing to quantify the drilling-induced damage at the exit side of the hole. Image segmentation and thresholding principles that work on the difference in the gray scale values of image pixels were used to distinguish the damaged area around the drilled hole.

The damaged area (including the hole area) around the drilled hole was quantified and was divided by the hole area to get the damage factor.

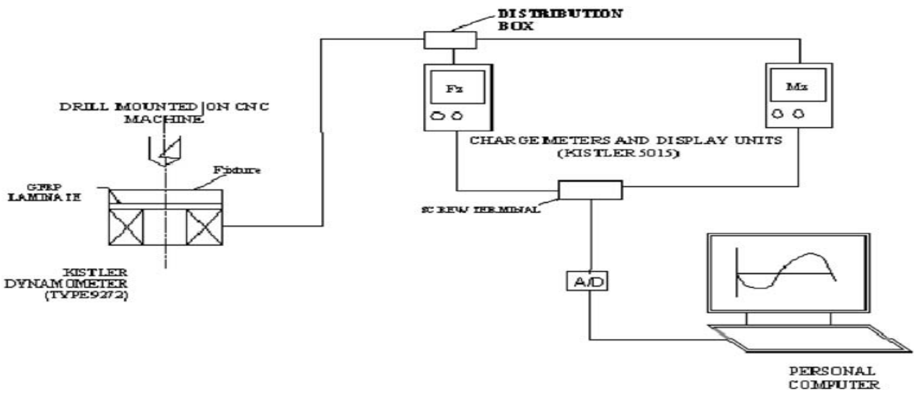

Figure 1: Experimental Set-up [23].

3. TAGUCHI METHOD

The two major tools used in the Taguchi method are the orthogonal array (OA) and the signal to noise ratio (S/N ratio). OA is a matrix of numbers arranged in rows and columns. Each row represents the level of factors in each run and each column represents a specific level for a factor that can be changed for each run. S/N ratio is indicative of quality and the purpose of the Taguchi experiment is to find the best level for each operating parameter so as to maximize (or minimize) S/N Ratio. The S/N ratio characteristics can be divided into three categories.

Smaller the better characteristic: $S/N = -10 \log \frac{1}{n}(\sum y^2)$

Larger the better characteristic: $S/N = -10 \log \frac{1}{n}(\sum 1/y^2)$

Nominal the best characteristic: $S/N=10 \log (\bar{y}/s^2_y)$

where $\bar{y}$ is the average of observed data, s^2_y is the variation of y, n is the number of observations, and y is the observed data.

The general steps involved in the Taguchi Method are as follows:

- STEP 1

Define the process objective, or more specifically, a target value for a performance measure of the process. The objective of the present work is to minimize the thrust force, torque and drilling induced damage i.e. damage factor. Ideal target values for the thrust force and torque is taken as zero. While in case of damage factor, this value is unity.

- STEP 2

Determine the design parameters affecting the process. Parameters are variables within the process that affect the performance measure that can be easily controlled. The number of levels that the parameters should be varied at must be specified. For the drilling of [(0/90)/0]s laminates typical control factors include drill point geometry, feed rate and cutting speed (Table I). Three levels of drill point geometry taken were 8-facet drill point, 4-facet drill point, and Jodrill. Levels of feed rate taken were 10 mm/min, 15 mm/min, and 20 mm/min and cutting speeds were 750 rpm, 1500 rpm and 2250 rpm. These factors and their levels are shown in Table I.

Table I: Levels of the variables used in the experiment.

Variables / Levels	**A: Drill Point Geometry**	**B: Feed Rate (mm/min.)**	**C: Cutting Speed (rpm)**
1	8-facet drill	10	750
2	4-facet drill	15	1500
3	Jodrill	20	2250

- STEP 3

Create suitable orthogonal arrays (OA) for the parameter design indicating the number of and conditions for each experiment. In the present case, there are three parameters, each having three levels. Therefore, the L9 OA (inner array in Table II) was selected for the investigation according to the Taguchi method.

Table II**:** The L9 Orthogonal array.

Number	**P1**	**P2**	**P3**	**P4**	**S/N**
1	1	1	1	1	S/N1
2	1	2	2	2	S/N2
3	1	3	3	3	S/N3
4	2	1	2	3	S/N4
5	2	2	3	1	S/N5
6	2	3	1	2	S/N6
7	3	1	3	2	S/N7
8	3	2	1	3	S/N8
9	3	3	2	1	S/N9

- STEP 4

Conduct the experiments indicated in the completed array to collect data on the effect on the performance measure. The measured experimental results of critical thrust force and the corresponding S/N ratios for each experimental trial are shown in Table III. Table V indicates the experimental torque and corresponding S/N ratio. Damage factor and its S/N ratio are shown in Table VII.

- STEP 5

Complete data analysis to determine the effect of the different parameters on the performance measure. The ANOVA technique is used to predict the relative significance of the process factors and to estimate the experimental errors. It gives the percentage contribution of each factor and provides a better feel for the relative effect of the different factors on experimental responses. Table IV, Table VI and Table VIII show ANOVA for thrust force, torque and damage factor. Response graphs Figures 2, 3, 4 for each significant factor are drawn. The horizontal axis shows the different levels of the each significant factor. The vertical axis shows the corresponding values of the S/N ratio. The lines represent the trend of each factor with respect to different levels.

Table III: Experimental critical thrust force.

Experiment no.	Experiment Condition				Critical Force	
	Matrix				Mean (N)	S/N (dB)
1	1	1	1	1	40.30	-32.10
2	1	2	2	2	34.50	-30.75
3	1	3	3	3	32.40	-30.21
4	2	1	2	3	37.45	-31.46
5	2	2	3	1	33.15	-30.40
6	2	3	1	2	60.25	-35.59
7	3	1	3	2	22.25	-26.94
8	3	2	1	3	34.15	-30.66
9	3	3	2	1	37.35	-31.44

Table IV: ANOVA table for thrust force.

	Factor	Level	S/N (dB)	Degrees of freedom	Sum of squares	Mean squares	Main effect %	F
A.	Drill Point geometry	8-facet	-31.03	2	11.85	5.926	32	5
		4-facet	-32.50					
		Jodrill	-29.69					
B.	Feed	10	-30.18	2	8.451	4.225	23	3
		15	-30.61					
		20	-32.42					
C.	Speed	750	-32.80	2	19.65	9.829	53	8
		1500	-31.23					
		2250	-29.19					

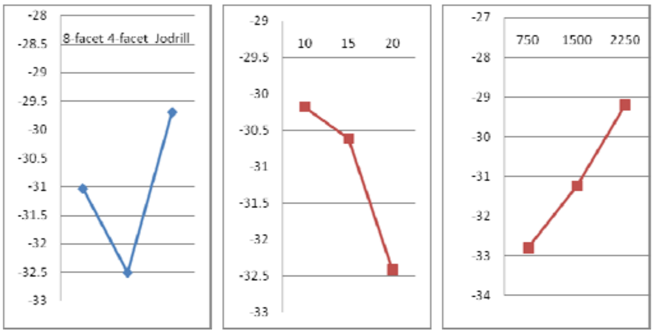

Figure 2: The main effects plot of S/N for thrust force.

The analysis of average performance shows that the optimum condition for minimum thrust force is A3B1C3 (i.e. drill point geometry: Jodrill, feed rate: 10mm/min and cutting speed: 2250 rpm).

Table V: Experimental torque.

Experiment no.	Experiment Condition				Torque	
	Matrix				Mean (N-cm)	S/N (dB)
1	1	1	1	1	13.45	-22.57
2	1	2	2	2	11.40	-21.13
3	1	3	3	3	11.60	-21.28
4	2	1	2	3	10.20	-20.17
5	2	2	3	1	13.45	-22.57
6	2	3	1	2	11.06	-20.87
7	3	1	3	2	10.35	-20.30
8	3	2	1	3	9.150	-19.22
9	3	3	2	1	12.50	-21.93

Table VI: ANOVA table for torque.

	Factor	Level	S/N (dB)	Degrees of freedom	Sum of squares	Mean squares	Main effect %	F
A.	Drill point geometry	8-facet	-21.67	2	2.084	1.042	25	1
		4-facet	-21.21					
		Jodrill	-20.50					
B.	Feed	10	-21.12	2	0.2678	0.1339	3	-
		15	-21.12					
		20	-21.12					
C.	Speed	750	-21.12	2	0.3662	0.1831	4	-
		1500	-21.12					
		2250	-21.12					

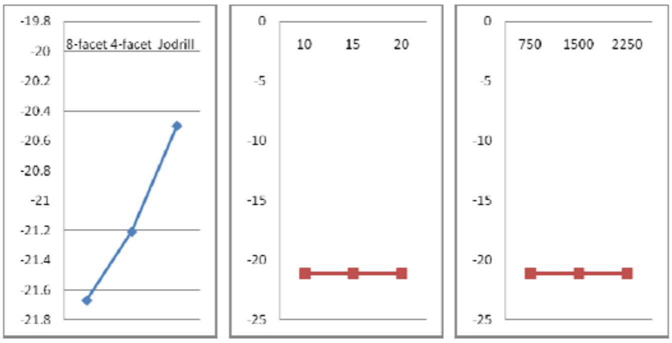

Figure 3: The average effects plot of S/N for torque.

The analysis of average performance shows that the optimum condition for minimum torque is A3B0C0 (i.e. drill point geometry: Jodrill). Minimum torque is found to be independent of the speed and feed rate. Therefore any one the three levels of these two factors can be selected.

Table VII: Drilling induced damage.

Experiment no.	Experiment Condition				Damage Factor	
	Matrix				Mean (N)	S/N (dB)
1	1	1	1	1	2.265	-2.041
2	1	2	2	2	2.365	-2.702
3	1	3	3	3	2.44	-3.167
4	2	1	2	3	2.585	-4.000
5	2	2	3	1	2.535	-3.722
6	2	3	1	2	2.321	-2.421
7	3	1	3	2	2.593	-4.047
8	3	2	1	3	2.344	-2.568
9	3	3	2	1	2.365	-2.702

Table VIII: ANOVA table for damage factor.

	Factor	Level	S/N (dB)	Degrees of freedom	Sum of squares	Mean squares	Main effect %	F
A.	Drill Point geometry	8-facet	-2.64	2	0.8618	0.4309	22	45
		4-facet	-3.39					
		Jodrill	-3.11					
B.	Feed	10	-3.37	2	0.5498	0.2749	14	28
		15	-3.00					
		20	-2.77					
C.	Speed	750	-2.35	2	2.574	1.287	65	133
		1500	-3.14					
		2250	-3.65					

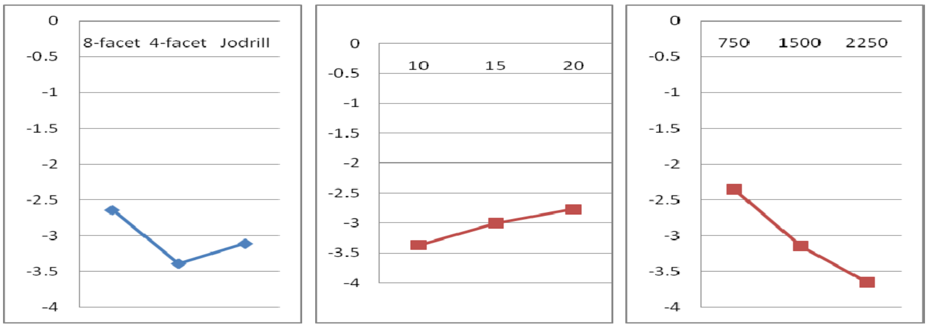

Figure 4: The average effects plot of S/N for damage factor.

The analysis of average performance shows that the optimum condition is A1B3C1 (drill point geometry: 8-facet, feed: 20mm/min and cutting speed: 750 rpm).

- STEP 6

Finally, the experimental validations of optimum value of the objective function were done as the optimum run may not be necessarily among the many experiments that were already carried out. Table IX shows the results of confirmation experiments with initial condition A2B2C2 for all cases.

Table IX: Confirmation tests.

Variables	Conditions	S/N ratio	
		Estimation	Confirmation
Force	Optimal condition	-26.92	-27.00
	Initial condition	-32.20	-32.10
	Gain	5.28	5.10
Torque	Optimal condition	-20.5	-18.02
	Initial condition	-21.20	-21.14
	Gain	0.7	3.12
Damage factor	Optimal condition	-1.67	-1.79
	Initial condition	-3.44	-3.35
	Gain	1.77	1.56

4. CONCLUSIONS

The drilling of [(0/90)/0]s GFRP laminate has been investigated using the Taguchi method. Three important parameters, that is the drill point geometry, the cutting speed and the feed rate have been studied. The following conclusions can be drawn from the investigation:

- The optimum levels of the drill point geometry, the cutting speed and the feed rate have been established for making damage free holes in [(0/90)/0]s GFRP laminates.
- The optimum thrust force is recorded with Jodrill drill at cutting speed of 2250 rpm and feed rate of 10 mm/min.
- The drill point geometry has maximum influence on the torque in [(0/90)/0]s GFRP laminates. Jodrill results in minimum torque as compared to 8-facet and 4-facet drills.
- It is also observed that minimum drilling induced damage is recorded with 8-facet drill at cutting speed of 750 rpm and feed of 20mm/min. The minimum recorded drilling induced

damage at the highest feed rate indicates that if woven layers are added at top and bottom, higher feed rates may be employed with minimum damage.

- It may further be concluded that although the drilling forces are minimum for Jodrill, the drilling induced damage is minimum for 8-facet drill point. It clearly puts forward an important point that the understanding of the tool-work interaction is very important for minimizing the drilling induced damage.
- Confirmation tests were carried out to verify the predicted optimal conditions. Values of estimation gain and confirmation gain were found close each other.
- The experimental results established as a part of this investigation are useful in laying a platform for design and development of optimal drill point geometry for damage free drilling of GFRP laminates.

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