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Original Article

Optimization of process parameters in drilling of GFRP composite using Taguchi method

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ABSTRACT

The objective of the present work is to optimize process parameters namely, cutting speed, feed, point angle and chisel edge width in drilling of glass fiber reinforced polymer (GFRP) composites. In this work, experiments were carried out as per the Taguchi experimental design and an L9 orthogonal array was used to study the influence of various combinations of process parameters on hole quality. Analysis of variance (ANOVA) test was conducted to determine the significance of each process parameter on drilling. The results indicate that feed rate is the most significant factor influencing the thrust force followed by speed, chisel edge width and point angle; cutting speed is the most significant factor affecting the torque, speed and the circularity of the hole followed by feed, chisel edge width and point angle. This work is useful in selecting optimum values of various process parameters that would not only minimize the thrust force and torque but also reduce the delimitation and improve the quality of the drilled hole.

1. Introduction

Composite materials are increasingly used in various fields of science and engineering due to their unique properties such as high stiffness, lightweight, good corrosive resistance, low thermal expansion, etc. Although most of fiber reinforced composite (FRP) material parts are processed to a near net shape, machining is often necessary, like finishing, trimming, drilling, grinding, etc. Due to these reasons, conventional machining on the FRP composite has gained importance to meet the required dimensional accuracy and good surface quality. Among these machining processes, drilling is frequently used in industries owing to the need for component assembly in mechanical structures [1,2]. Taking into account the wide variety of work material, cutting tool material, cutting conditions and their combinations, becomes difficult to arrive at a generalized equation for prediction of torque and thrust forces, for a complicated process like drilling.

Much of the literature [3–5] reported on drilling of FRP material by conventional tools has shown that the quality of the cut surface is strongly dependent on the cutting parameters, tool geometry, tool material, work piece material, machining process, etc. An improper selection of these parameters can lead

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to unacceptable material degradation, such as fiber pullout, matrix cratering, thermal damage and widespread delamination. Palanikumara and Paulo Davim [6] investigated the influence of cutting parameters namely cutting speed, fiber orientation angle, depth of cut and feed rate on tool flank wear and the results indicated that cutting speed has a greater influence on tool flank wear followed by feed rate. Taguchi proposed that the engineering optimization of a process should be carried out in three step approach: the system design, the parameter design and the tolerance design [7]. The Taguchi method uses orthogonal arrays from design of experiments theory to study a large number of variables with a small number of experiments. The orthogonal arrays reduce the number of experimental configurations to be studied. Furthermore, the conclusions drawn from small scale experiments are valid over the entire experimental region spanned by the control factors and their settings [8]. Orthogonal arrays are not unique to Taguchi [9]. However, Taguchi has modified their use by providing tabulated sets of standard orthogonal arrays and corresponding linear graphs to fit specific projects [10]. The experimental results are then transformed into a signal-to-noise (S/N) ratio. It uses the S/N ratio as a measure of quality characteristics deviating from or nearing to the desired values.

Murthy et al. [11] studied the effect of process parameters like speed, feed, drill diameter, point angle and material thickness on thrust force and torque generated during drilling of GFRP composites using solid carbide drill bit and found the optimum process parameter settings using Taguchi method and response surface methodology. The results revealed that the spindle speed is the main contributing process parameter for the variation in thrust force and drill diameter for torque. The phenomenon of delamination during drilling was identified and analyzed by Hocheng and Tsao [12]. They developed a mathematical model to predict the critical thrust force using various drill bits. Khashaba et al. [13] studied the effect of machining parameters in the drilling of GFR/epoxy composites and they developed a model to predict the critical thrust force during drilling. Mohan et al. [14] optimized cutting process parameters in drilling of glass fiber reinforced composite (GFRC) material and found that speed and drill size are more significant influence factors in cutting thrust than the specimen thickness and the feed rate. Kilickap [15] investigated the influence of cutting parameters, such as cutting speed, feed rate and point angle on delamination produced when drilling a GFRP composite and concluded that feed rate and cutting speed are the most influential factor on the delamination, respectively. A significant amount of research was carried out to find the influence of machining parameters on the delamination of composite laminates using Taguchi and analysis of variance techniques [16–19].

In this work, process parameters are optimized in drilling of GFRP composites using Taguchi design of experimental technique and the results are analyzed using ANOVA technique to know the percentage contribution of each parameter on thrust force, torque, surface finish and circularity of the hole. The main objective of the present work is to optimize the process parameters in the drilling of GFRP composite using Taguchi method design and to find the significance of each process parameter using ANOVA. In the present work, statistical analysis software MINITAB 15 was used for the design and analysis of experiments to perform the Taguchi and ANOVA analysis and also to establish regression models.

2. Methodology

2.1. Taguchi method

Taguchi developed a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. The experimental results are then transformed into a signal-to-noise (S/N) ratio. It uses the S/N ratio as a measure of quality characteristics deviating from or nearing to the desired values. There are three categories of quality characteristics in the analysis of the S/N ratio, i.e. the lower the better, the higher the better, and the nominal the better. The formula used for calculating S/N ratio is given below.

Smaller the better: It is used where the smaller value is desired.

$$\text{S/N ratio}\,(\eta) = -10\log_{10}\frac{1}{n}\sum_{i=1}^{n}y_i^2 \tag{1}$$

where y_i = observed response value and n = number of replications.

Nominal the best: It is used where the nominal or target value and variation about that value is minimum.

$$\text{S/N ratio}\,(\eta) = -10\log_{10}\frac{\mu^2}{\sigma^2} \tag{2}$$

where μ = mean and σ = variance.

Higher the better: It is used where the larger value is desired.

$$\text{S/N ratio}\,(\eta) = -10\log_{10}\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2} \tag{3}$$

where y_i = observed response value and n = number of replications.

Taguchi suggested a standard procedure for optimizing any process parameters [8].

The steps involved are:

- Determination of the quality characteristic to be optimized.
- Identification of the noise factors and test conditions.
- Identification of the control factors and their alternative levels.
- Designing the matrix experiment and defining the data analysis procedure.
- Conducting the matrix experiment.
- Analyzing the data and determining the optimum levels of control factors.
- Predicting the performance at these levels.

2.2. Selection of process parameters

In this investigation, machining process parameters like speed, feed, point angle and chisel edge width of the drill were considered. According to Taguchi's design of experiments, for

Table 1 – Selected variable levels for drilling.

Code	Variable	Level 1	Level 2	Level 3
1	Speed (rpm)	500	1000	1500
2	Feed rate (mm/rev)	0.02	0.04	0.06
3	Point angle (deg)	85	90	95
4	Chisel edge width (mm)	0.8	1.3	1.6

Table 2 – Response table for S/N ratios for thrust force.

Level	Speed	Feed	Point angle	Chisel edge width
1	−11.85	−12.58	−13.66	−14.39
2	−14.14	−15.48	−14.78	−12.30
3	−14.45	−12.38	−12.00	−13.75
Delta	2.59	3.10	2.79	2.09
Rank	3	1	2	4

Table 3 – Response table for S/N ratios for torque.

Level	Speed	Feed	Point angle	Chisel edge width
1	31.63	33.64	32.81	34.81
2	35.99	35.99	33.98	34.81
3	34.81	32.81	35.65	32.81
Delta	4.35	3.18	2.84	2.01
Rank	1	2	3	4

four parameters and three levels L_9 Taguchi orthogonal array [20] was selected. The number of factors and their corresponding levels are shown in Table 1.

2.3. ANOVA

ANOVA is a statistical technique for determining the degree of difference or similarity between two or more groups of data. It is based on the comparison of the average value of a common component. In this paper, Pareto ANOVA [21] was used which measures the importance of each process parameter of the process. Pareto ANOVA is a simplified ANOVA method, which is based on Pareto principle. The Pareto ANOVA technique is a quick and easy method to analyze results of the parametric design. The Pareto ANOVA technique does not need *F*-test. This technique identifies the important parameters and calculates the percentage influence of each parameter on different quality characteristics. The use of both Pareto ANOVA technique and S/N ratio approach makes it less cumbersome to analyze the results and hence, make it fast to arrive at the conclusion [20]. The S/N ratios are calculated for all responses

Table 4 – Response table for S/N ratios for surface finish.

Level	Speed	Feed	Point angle	Chisel edge width
1	−16.26	−14.64	−15.30	−14.99
2	−13.46	−15.73	−12.63	−14.86
3	−13.63	−12.98	−15.42	−13.50
Delta	2.79	2.75	2.79	1.50
Rank	1	3	2	4

Table 5 – Response table for S/N ratios for circularity error.

Level	Speed	Feed	Point angle	Chisel edge width
1	24.68	21.63	23.62	19.40
2	24.91	23.44	20.20	19.89
3	15.59	20.10	21.36	25.87
Delta	9.32	3.34	3.42	6.47
Rank	1	4	3	2

and presented in Tables 2–5. From the S/N ratios, the overall S/N ratio is expressed as

$$\overline{S/N} = \frac{1}{9}\sum_{1}^{9}(S/N)_i \tag{4}$$

where, $\overline{S/N}$ is the overall mean of S/N ratio and $(S/N)_i$ is the S/N ratio for *i*th parameter

The sum of squares due to variation about overall mean is

$$SS = \sum_{i=1}^{9}\left((S/N)_i - (\overline{S/N})\right)^2 \tag{5}$$

where SS is the sum of squares.

For the *i*th process parameter, the sum of squares due to variation about overall mean is

$$SS_i = \sum_{j=1}^{3}\left((S/N)_{ij} - (\overline{S/N})\right)^2 \tag{6}$$

where, SS_i is the sum of the square for *i*th parameter and $(S/N)_{ij}$ is the average S/N ratio of *i*th parameter of *j*th level

$$\%\text{Contribution} = \frac{SS_i}{SS} \times 100 \tag{7}$$

2.4. *Experimental work*

In this study, bi-directional glass fiber reinforced plastic composite laminate specimens with 40% fiber volume ratio were prepared with E-glass fiber using epoxy resin by hand lay-up process. The work piece material specimen size of 40 × 80 × 4 mm was cut from a laminate. The drilling experiments were conducted according to Taguchi's L_9 orthogonal array as shown in Table 6 on GFRP laminates with 10 mm diameter HSS (M2) drill. Each experiment was carried out twice to minimize the experimental error. A computer numerical control (CNC) vertical machining centre (model: Laxmi MV-Junior (VMC)) was used for conducting experiments. A Syscon two-component tube type drilling dynamometer was used to measure the axial thrust force and torque. The proportional charge output from the dynamometer was fed to an amplifier thus produced a scaled voltage output signal proportional to the applied load. Thrust force and torque were continuously monitored and the results were recorded throughout the test by using a digital storage oscilloscope. A Pentium III system with Wave star software was used to interface with the oscilloscope to store the thrust force and torque graphs.

Fig. 1 – Experimental setup used for drilling operation.

The experimental setup used for drilling operation is shown in Fig. 1.

After conducting experiments, the quality of drilled holes was measured in terms of the end surface of the hole using a Surtronic 3 + Taylor Hobson Talysurf surface profilo meter. The circularity and cylindricity errors of the drilled holes were measured using CMM (model: BH 303).

3. Results and discussion

The results of thrust force, torque, surface roughness and circularity of each sample are shown in Table 7. The experimental results were transformed into S/N ratio using Eq. (1). The S/N ratio values for all responses are presented in Tables 2–5, respectively. The main effect for mean and S/N ratio is plotted in Figs. 2–5, respectively.

Table 2 and Fig. 2 show the influence of process parameters on the thrust force. The optimum process parameters on the thrust force are obtained as speed at level 1 (500 rpm), feed at level 2 (0.04 mm/rev), point angle at level 2 (90°) and chisel edge width at level 1 (0.8 mm). Table 3 and Fig. 3 show the effect of cutting parameters on the torque. The optimum process parameters on the torque are obtained as speed at level 1 (500 rpm), feed at level 3 (0.06 mm/rev), point angle at level 3 (95°) and chisel edge width at level 3 (1.6 mm). Table 4 and Fig. 4 show the influence of cutting parameters on the surface roughness. The optimum process parameters on the surface roughness are obtained as speed at level 1 (500 rpm), feed at level 2 (0.04 mm/rev), point angle at level 3 (95°) and chisel edge width at level 1 (0.8 mm). Table 5 and Fig. 5 show the effect of cutting parameters on circularity. The optimum process parameters on the circularity are obtained as speed at level 3 (1500 rpm), feed at level 3 (0.06 mm/rev), point angle at level 2 (90°) and chisel edge width at level 1 (0.8 mm).

The degree of importance of each parameter is considered, namely, speed, feed, point angle and chisel width for each response is given in Tables 8, 9, 10 and 11, respectively. From Table 8, it is found that feed is the major factor affecting the thrust force followed by speed, chisel edge width and point

Table 6 – The basic Taguchi L9 (3^4) orthogonal array.

Expt. No.	Control factors and their levels			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

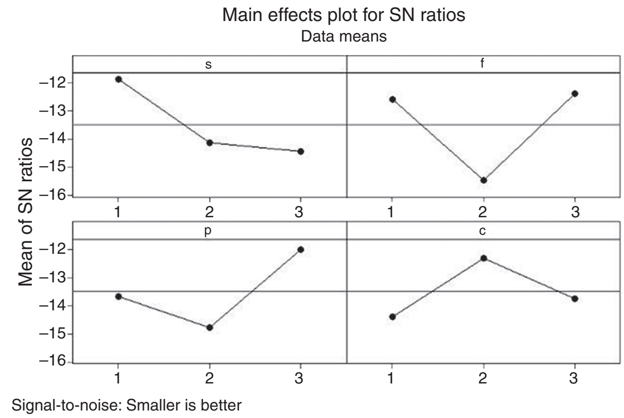

Fig. 2 – Main effects plot for S/N ratio (thrust force).

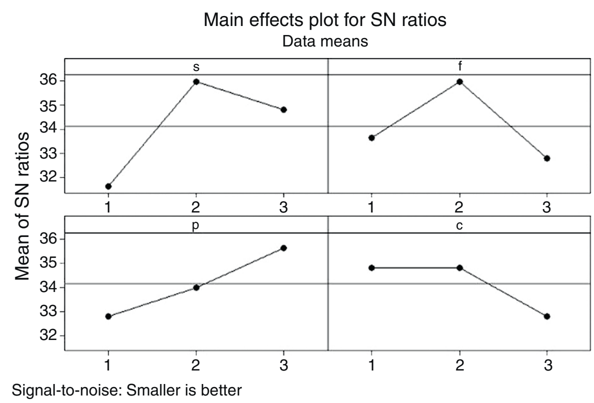

Fig. 3 – Main effects plot for S/N ratio (torque).

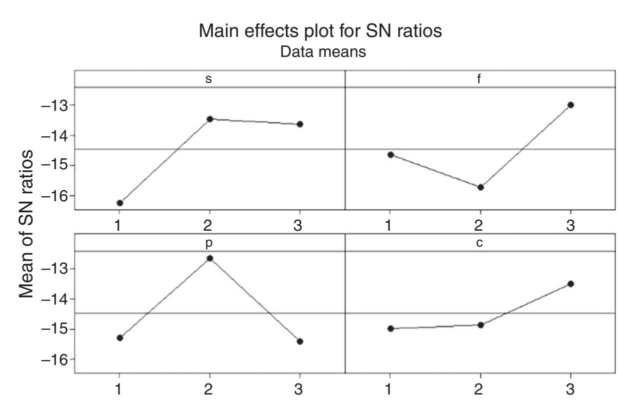

Fig. 4 – Main effects plot for S/N ratio (surface roughness).

Table 7 – Taguchi's L_9 standard orthogonal array with responses.

Ex. No.	Thrust force (kgf)			Torque (kgf m)			Surface roughness (μm)			Circularity (mm)		
	Trial 1	Trial 2	Mean	Trial 1	Trial 2	Mean	Trial 1	Trial 2	Mean	Trial 1	Trial 2	Mean
1	5	3	4.0	0.03	0.03	0.030	8.0	7.6.	7.80	0.064	0.060	0.0620
2	6	4	5.0	0.02	0.02	0.020	6.55	6.25	6.40	0.0720	0.0690	0.0705
3	3	3	3.0	0.03	0.03	0.030	5.8	5.2	5.50	0.065	0.026	0.0455
4	6	5	5.5	0.02	0.02	0.020	3.4	3.6	3.50	0.038	0.047	0.0425
5	7	5	6.0	0.01	0.01	0.010	6.2	6.8	6.50	0.062	0.065	0.0635
6	4	4	4.0	0.02	0.02	0.020	4.7	4.5	4.60	0.079	0.057	0.0680
7	4	3	3.5	0.01	0.02	0.015	6.0	5.5	5.75	0.211	0.222	0.2165
8	8	6	7.0	0.02	0.02	0.020	5.3	5.7	5.50	0.684	0.0676	0.0680
9	4	4	4.0	0.02	0.02	0.020	3.6	3.4	3.50	0.310	0.330	0.3120

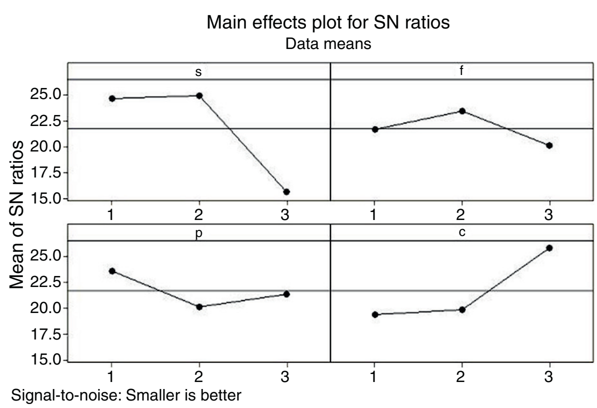

Fig. 5 – Main effects plot for S/N ratio (circularity error).

Table 8 – Contribution of process parameters for thrust forces.

Process parameter	Sum of squares(SS_i)	% Contribution
Speed	3.7222	25.86
Feed	5.5556	38.61
Point angle	2.7222	18.91
Chisel edge width	2.3889	16.62

Table 9 – Contribution of process parameters for torque.

Process parameter	Sum of squares (SS_i)	% Contribution
Speed	0.0001722	53.44
Feed	0.0000722	22.42
Point angle	0.0000389	12.07
Chisel edge width	0.0000389	12.07

angle. In Table 9, speed and feed are found to be the most significant factors affecting the torque followed by point angle and chisel edge width. It can be observed from Table 10 that, feed has the greatest influence on surface finish followed by

Table 10 – Contribution of process parameters for Surface finish.

Process parameter	Sum of squares (SS_i)	% Contribution
Speed	5.6150	35.20
Feed	4.0850	35.61
Point angle	4.3550	27.31
Chisel edge width	1.8950	11.88

Table 11 – Contribution of process parameters for Circularity.

Process parameter	Sum of squares (SS_i)	% Contribution
Speed	0.0392961	55.95
Feed	0.0083371	11.87
Point angle	0.0086317	12.29
Chisel edge width	0.0139611	19.89

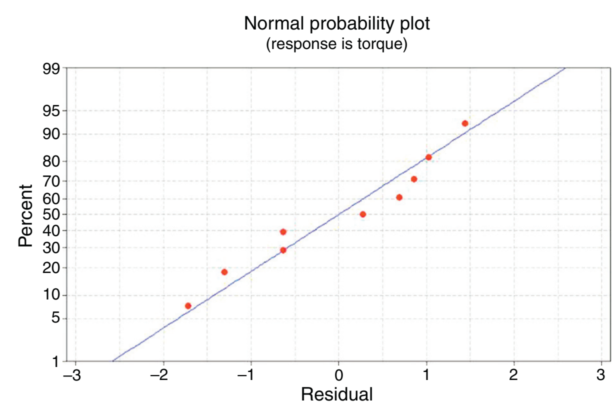

Fig. 6 – Normal probability plot of residuals for thrust force.

speed, point angle and chisel edge width. Table 11 indicates that speed has much influence on circularity error followed by chisel edge width, point angle and feed rate.

The model adequacy checking was conducted after performing an ANOVA analysis to verify the normality

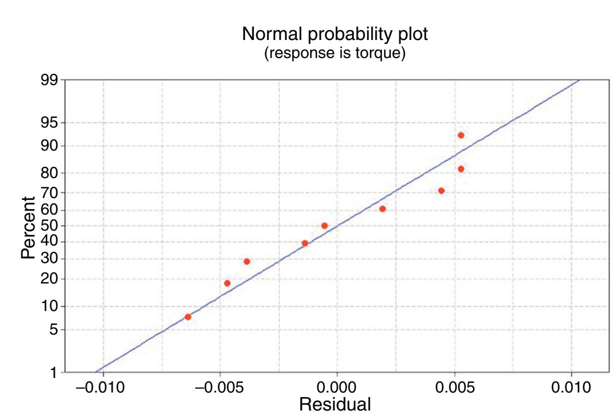

Fig. 7 – Normal probability plot of residuals for torque.

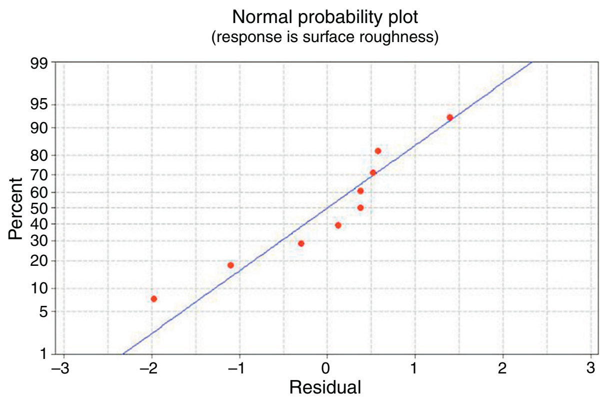

Fig. 8 – Normal probability plot of residuals for surface finish.

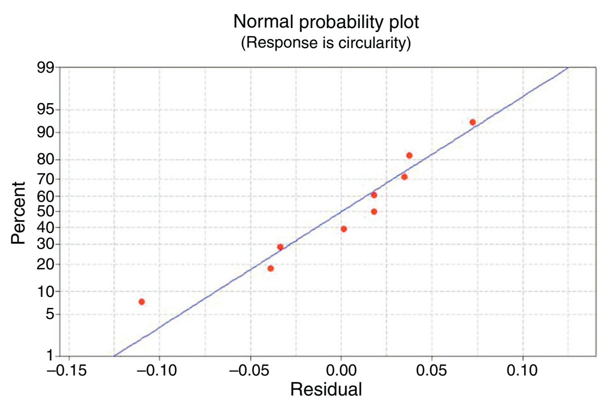

Fig. 9 – Normal probability plot of residuals for circularity error.

assumption of the residual. Figs. 6–9 show normal probability plots of the residuals and these figures reveal that almost all the residuals follow a straight line pattern and this agrees well with the results reported by Davidson et al. [22]. This work will be useful for industries while the selection of process parameters in the drilling of GFRP composite materials, to improve the quality of the drilled holes by reducing the delamination.

4. Conclusions

This paper presents the optimization of cutting process parameters namely, cutting speed, feed, point angle and chisel edge width in drilling of glass fiber reinforced polymer (GFRP) composites using the application of Taguchi and ANOVA analysis. The conclusions drawn from this work are as follows:

The optimum process parameters in the drilling of GFRP composites are:

- Speed of 500 rpm, feed rate at 0.04 mm/rev, point angle at 90° and chisel edge width of 0.8 mm for thrust force whereas for torque, speed at 500 rpm, feed rate of 0.06 mm/rev, point angle at 95° and chisel edge width of 1.6 mm are found to be optimum.
- Speed at 500 rpm, feed rate of 0.04 mm/rev, point angle at 95° and chisel edge width 0.8 mm for surface roughness and for circularity error speed at 1500 rpm, feed rate at 0.06 mm/rev, point angle at 95° and chisel edge width of 0.8 mm are the optimum parameters.

The ANOVA results reveal that feed rate and speed are the most significant influencing on the thrust force, torque and surface finish. Speed and chisel angle width are most influencing on the circularity error of the hole.

Conflicts of Interest

The author declares no conflicts of interest.

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