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Optimization of Process Parameters in Drilling of Glass Fiber Reinforced Epoxy Resin Composites using Taguchi Method

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Abstract— Glass fiber reinforced epoxy resin composites are widely used in the manufacturing of printed circuit boards. Drilling is used to provide the holes for the electronic components to be placed on printed circuit board surfaces. Drilling of these composite materials is different from metallic materials due to surface delamination and surface roughness of drilled holes. The objective of the present work is to optimize process parameters namely cutting speed, feed rate, drill diameter and thickness of workpiece in drilling of glass fiber reinforced epoxy resin composites. The experiments were designed by using Taguchi's L_{27} orthogonal array with factor 4 and 3 level. Analysis of variance test was conducted to determine the significance of each quality characteristic on drilling. The results indicate that feed rate is the most influential factor on the delamination followed by cutting speed, drill diameter and thickness of workpiece, and for surface roughness the most influential factor is feed rate followed by drill diameter, thickness of workpiece and cutting speed. This work is useful in determining optimum values of process parameters to minimize delamination and surface roughness in drilling of glass fiber reinforced epoxy resin composites.

Keywords—Taguchi Method; Optimization; Drilling; L_{27} Orthogonal Array.

I. INTRODUCTION

Fiber reinforced composite materials have successfully substituted the traditional materials in several light weight and high strength applications. Applications of such materials are observed in automotive, aircraft, sea vehicles industries, military and defense, transportation, etc. [1]. Another relevant application of fiber reinforced composite materials (especially glass fiber reinforced epoxy resin composites) is in electronic industry for producing printed circuit boards. Drilling of these composite materials can be considered as a critical operation due to their tendency to delaminate when subjected to drilling stresses. With regard to the quality of drilled holes, the principle drawbacks are related to delamination, fiber/resin pullout and surface roughness of the hole wall. In order to overcome these difficulties it is necessary to select appropriate drilling process parameters such as tool geometry cutting speed, feed rate, drill diameter, thickness of workpiece etc. [2]

The analysis in drilling of fiber reinforced composite material was carried out by many researchers. Rubio et al. (2008) [3] investigated the effect of high speed in the drilling of glass fiber reinforced plastic (GFRP) on delimitation factor. It was concluded that delamination decreases as the spindle speed is elevated. At 40,000 rpm delamination was minimum, irrespective of the feed rate.

Kilickap (2010) [4] carried out the drilling of the GFRP composites to optimize the cutting parameters on delamination. It was concluded that low feed rates provide minimum damage. The point angle 118° drill produces less damage than the point angle 135° drill. The optimal parameters found were, cutting speed 5 m/min. and feed rate 0.1 mm/rev. Vasudevan et al. (2014) [5] carried out drilling of GFRP/Epoxy composite using desirability and Taguchi method. In this study, various drilling parameters with multiple performance characteristics were optimized. Desirability indices of each performance measures, viz. surface roughness, thrust force and delamination are converted into an overall desirability, and then optimized with Taguchi method. Karpat et al. (2015) [6] investigated comparative analysis of polycrystalline diamond (PCD) drill design during drilling of carbon fiber reinforced plastic (CFRP) laminates. This experimental study shows the importance of drill geometry specific to the CFRP laminates being drilled. Parida et al. (2015) [7] conducted the drilling experiments on GFRP composite based on the Taguchi L_{27} orthogonal array. Process parameters for minimum surface roughness were optimized and concluded that surface roughness increases with the spindle speed. The response surface model for surface roughness was developed from the observed data. Melentiev et al. (2016) [8] investigated effect of tool geometry and process parameters on delamination in CFRP drilling. It was concluded that feed rate has strongest influence on delamination. Low value of feed is recommended when drilling CFRP using a standard twist drill. Low feed rate together with high cutting speed can reduce delamination.

The objective of the present work is to optimize the process parameters in the drilling of glass fiber reinforced epoxy resin composite using Taguchi method and to find significant process parameters using analysis of variance (ANOVA).

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II. METHODOLOGY

A. Taguchi Method

In the Taguchi method a special design of orthogonal arrays is used to study the entire parameter space with a small number of experiments only. Then, the experimental results are converted into signal to noise (S/N) ratios. Signal refers to desirable value and noise refers to the undesirable value. The purpose of adopting S/N ratio is a measure of performance to develop products and processes insensitive to noise. The level of the process parameter with the highest S/N ratio always yields the optimum quality characteristics with minimum variance. The S/N ratios were calculated using the condition smaller is the better. The signal-to-noise ratios were calculated by applying the equation given below:

$$S/_N = -10log\left[\frac{1}{n}\sum_{i=0}^{n} x_i^2\right]$$

x_i = Observed value of the response characteristics.

n = Number of repetitions.

B. Selection of Process Parameters

In this study, four drilling parameters were used as control factors and each parameter was designed to have three levels as shown in table 1.

Table 1: Different Input Parameters and Their Levels

Input Parameters	Levels		
	Level-1	**Level-2**	**Level-3**
Cutting Speed (rpm)	600	1200	1800
Feed Rate (mm/min)	50	150	250
Drill Diameter (mm)	5	7	9
Thickness of Work-Piece (mm)	1.5	2.5	3

According to Taguchi's design of experiments, for four parameters and three levels L_{27} Taguchi orthogonal array was selected.

C. Analysis of Variance

Analysis of variance (ANOVA) method was used to investigate the statistical significance of the process parameters affecting the responses. ANOVA method was applied to signal to noise ratios of results obtained from the experiments. F-test is performed to judge the significant parameter affecting the response parameter. The larger F-value affects more on the performance characteristics. Minitab 18.1 statistical analysis software was used for the Taguchi Analysis and ANOVA analysis and also to establish regression models.

D. Experimental Work

In this study, E-glass fiber reinforced epoxy resin composite laminate specimens were used as the workpiece material. The drilling experiments are conducted on glass fiber reinforced epoxy resin composites in computer numeric control (CNC) vertical machining center (VMC) model super VF-2 (HASS, USA make). The machining center has a maximum spindle speed of 12000 rpm with a table size of 914 x 356 mm. It has maximum feed rate of 35.6 m/min, travels 762 x 406x 508 mm and inline direct-drive. The experiments have been carried out using high speed steel twist drill of three different diameters. The view of the computer numeric control (CNC) vertical machining center (VMC) used for conducting experiments is represented in fig. 1. Twenty seven trials were performed as per L_{27} array based on Taguchi method. All the drilled holes were examined with coordinate measuring machine, surftest SJ-201 and profile projector. The experimental setup used in the drilling operation is shown in fig. 2.

Fig. 1: CNC Vertical Machining Center (VMC) Model Super VF-2

Fig. 2: Experimental Setup

III. RESULTS AND DISCUSSIONS

The results and S/N ratios of delamination and surface roughness of each sample are shown in table 2. The main effect plots for mean S/N ratios of delamination are plotted in Fig. 3. Response values for S/N ratios for delamination are given in Table 3. Fig. 3 and Table 3 show the influence of process parameters on the delamination. The optimum process parameters on the delamination are obtained as cutting speed at level 3 (1800 rpm), feed rate at level 1 (50 mm/min.), drill diameter at level 1 (5 mm) and thickness of workpiece at level 3 (3 mm). Fig. 3 shows that in drilling of composites delamination decreases with increase in cutting speed. This is due to the reason that increase of cutting speed increases

Table 2: Experimental Results and Corresponding S/N Ratios

Exp. No.	A	B	C	D	Response parameters		S/N ratio	
	Cutting Speed (rpm)	**Feed Rate (mm/min)**	**Drill Diameter (mm)**	**Thickness (mm)**	**Delamination**	**Surface roughness (µm)**	**Delamination**	**Surface roughness**
1	1	1	1	1	1.065	0.70	-0.547	3.098
2	1	1	2	2	1.073	0.88	-0.612	1.11
3	1	1	3	3	1.068	1.08	-0.571	-0.668
4	1	2	1	2	1.106	1.01	-0.875	-0.086
5	1	2	2	3	1.108	1.15	-0.891	-1.214
6	1	2	3	1	1.119	1.16	-0.977	-1.289
7	1	3	1	3	1.134	1.37	-1.092	-2.734
8	1	3	2	1	1.132	1.42	-1.077	-3.046
9	1	3	3	2	1.128	1.55	-1.046	-3.807
10	2	1	1	2	1.032	0.69	-0.274	3.223
11	2	1	2	3	1.035	0.84	-0.299	1.514
12	2	1	3	1	1.041	0.92	-0.349	0.724
13	2	2	1	3	1.071	0.88	-0.596	1.11
14	2	2	2	1	1.078	0.91	-0.652	0.819
15	2	2	3	2	1.073	0.90	-0.612	0.915
16	2	3	1	1	1.103	1.25	-0.852	-1.938
17	2	3	2	2	1.115	1.46	-0.946	-3.287
18	2	3	3	3	1.118	1.67	-0.969	-4.454
19	3	1	1	3	1.018	0.72	-0.155	2.853
20	3	1	2	1	1.027	0.81	-0.231	1.83
21	3	1	3	2	1.03	0.93	-0.257	0.63
22	3	2	1	1	1.062	0.92	-0.522	0.724
23	3	2	2	2	1.051	1.05	-0.432	-0.424
24	3	2	3	3	1.048	1.27	-0.407	-2.076
25	3	3	1	2	1.092	1.30	-0.764	-2.279
26	3	3	2	3	1.095	1.35	-0.788	-2.607
27	3	3	3	1	1.103	1.32	-0.852	-2.412

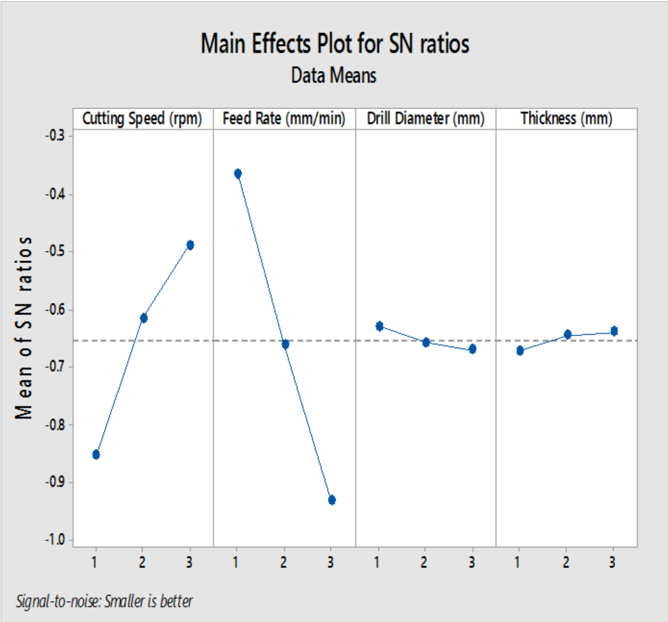

Fig. 3: Main Effect Plots for Delamination

Table 3: Response Table for Mean S/N Ratios of Delamination

Level	Cutting Speed	Feed Rate	Drill Diameter	Thickness
1	-0.8543	-0.3661	-0.6308	-0.6732
2	-0.6164	-0.6627	-0.6587	-0.6464
3	-0.4899	-0.9317	-0.6711	-0.6409
Delta	0.3644	0.5656	0.0403	0.0323
Rank	2	1	3	4

the temperature produced in drilling of composites, which softens the matrix material and inducing less delamination. It is observed that the delamination increases frequently with increase in feed rate. With the increase in feed rate, thrust force increased resulting in increase in the delamination. It is observed that the increase of drill diameter increases the delamination.This is due to the reason that increase of drill diameter increases the contact area between the workpiece and drill, which increases the thrust force.

It is found that the delamination decreases with the increase of thickness of workpiece in the drilling of composites. Table 4 shows the result of ANOVA for delamination. The purpose of analysis of variance is to identify the parameters that significantly affect the quality characteristics. It can be observed from the table that for delamination the factors feed rate and cutting speed are significant as p value is less than 0.05 whereas drill diameter and thickness of work piece are insignificant as p value is greater than 0.05. The larger F-value affects more on the quality characteristics; therefore feed rate is the most influential factor for delamination.

The main effect plots for mean S/N ratios of surface roughness are plotted in Fig. 4. Response values for S/N ratios for surface roughness are given in Table 5. Fig. 4 and Table 5 show the influence of process parameters on the surface roughness. The optimum process parameters on the surface roughness are obtained as cutting speed at level 2 (1200 rpm), feed rate at level 1 (50 mm/min.), drill diameter at level 1 (5 mm) and thickness of workpiece at level 1 (1.5 mm). Fig.4 shows that in drilling of composites surface roughness first decreases and then increases as cutting speed is increased from 600 rpm to 1200 rpm and further to 1800 rpm. The surface roughness was improved by increasing cutting speed due to the reason that increase of cutting speed decreases the thrust force. It is observed that the surface roughness increases with increase in feed rate, drill diameter and thickness of workpiece. This result was due to the increasing of thrust force and torque.

ANOVA table for S/N ratios of surface roughness is given in Table 6. ANOVA table indicates the significance of various input process parameters.

Table 4: Analysis of Variance for S/N Ratios of Delamination

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed	2	0.616	0.616	0.308	95.12	0
Feed Rate	2	1.44078	1.44078	0.72039	222.48	0
Drill Diameter	2	0.00766	0.00766	0.00383	1.18	0.329
Thickness	2	0.00537	0.00537	0.00269	0.83	0.452
Residual Error	18	0.05828	0.05828	0.00324		
Total	26	2.12809				

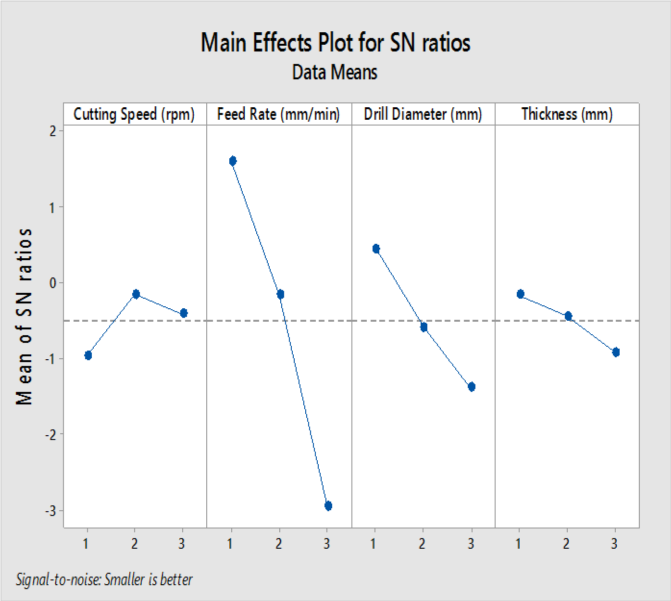

Fig. 4: Main Effect Plots for Surface Roughness

Table 5: Response Table for Mean S/N Ratios of Surface Roughness

Level	Cutting Speed	Feed Rate	Drill Diameter	Thickness
1	-0.9596	1.5906	0.4412	-0.1654
2	-0.1526	-0.1689	-0.5892	-0.4449
3	-0.4176	-2.9515	-1.3818	-0.9195
Delta	0.807	4.5421	1.8231	0.7541
Rank	3	1	2	4

Table 6: Analysis of Variance for S/N Ratios of Surface Roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed	2	3.046	3.046	1.5229	3.19	0.065
Feed Rate	2	94.408	94.408	47.2041	98.93	0
Drill Diameter	2	15.041	15.041	7.5204	15.76	0
Thickness	2	2.616	2.616	1.3082	2.74	0.091
Residual Error	18	8.589	8.589	0.4771		
Total	26	123.7				

It is observed from the table that for surface roughness the factors feed rate and drill diameter are significant as p value is less than 0.05 whereas cutting speed and thickness of workpiece are insignificant as p value is greater than 0.05. The F-value is largest for feed rate; therefore feed rate is the most influential factor for surface roughness.

To verify the normality assumption of the residuals the model adequacy checking was conducted. The normal probability plots of the residuals for delamination and surface roughness are shown in Fig. 5 and Fig. 6 respectively. It is evident from the normal probability plots of residuals that the residuals lie reasonably close to a straight line implying that errors are distributed normally. This work will be useful for industries in the selection of process parameters to improve the quality of drilled holes of glass fiber reinforced epoxy resin composites.

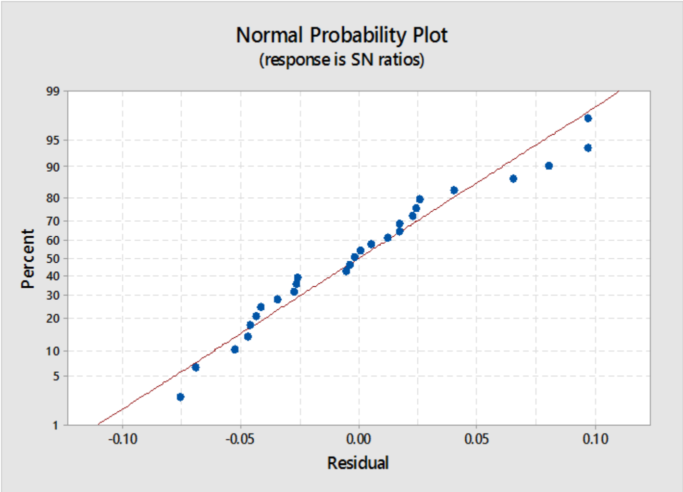

Fig. 5: Normal Probability Plot for Delamination

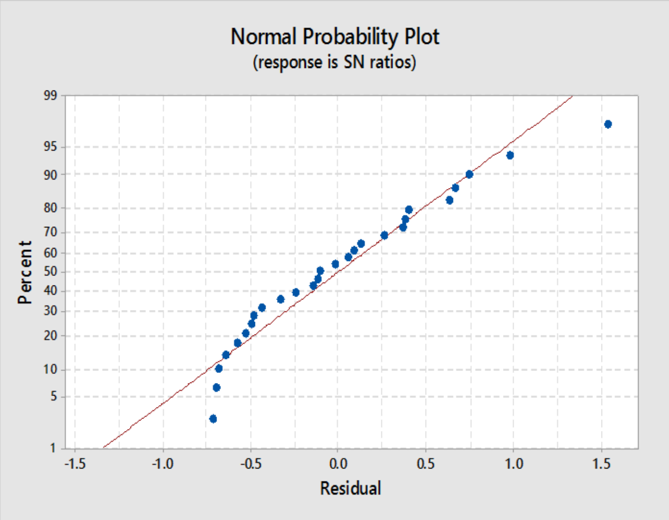

Fig. 6: Normal Probability Plot for Surface Roughness

IV. CONCLUSIONS

In this study the optimization of drilling process parameters viz. cutting speed, feed rate, drill diameter and thickness of workpiece in drilling of glass fiber reinforced epoxy resin composites (GFREC) using Taguchi method. The results are given below:

The optimum process parameters in drilling of GFREC are:

- Cutting speed of 1800 rpm, feed rate at 50 mm/min, drill diameter of 5 mm and thickness of workpiece at 3 mm for delamination.
- For surface roughness cutting speed of 1200 rpm, feed rate at 50 mm/min, drill diameter of 5 mm and thickness of workpiece at 1.5 mm.

The ANOVA results reveal that feed rate is the most influential factor on the delamination and surface roughness in drilling of GFREC.

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