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EXPERIMENTAL ANALYSIS ON DRILLING OF GLASS FIBER REINFORCED PLASTICS (GFRP) MANUFACTURED BY HAND LAY-UP

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ABSTRACT

Drilling of glass fibre reinforced plastic (GFRP) composite is substantially different from metallic materials due to its mechanical properties. The drilling of this material may generate delamination of drilled holes on the workpiece. The purpose of this paper is to investigate the influence of the drilling parameters, such as cutting speed, feed rate and drill diameter on delamination produced when drilling a GFRP composite. Drilling is a frequently practiced machining process in industry due to the need for component assembly in mechanical pieces and structures. Hence it is essential to obtain optimum drilling parameters minimizing delamination at drilling of GFRP composites. A plan of experiments, based on the techniques of Taguchi, was established considering drilling with prefixed cutting parameters in a hand lay-up GFRP material. The analysis of variance (ANOVA) was performed to investigate the drilling characteristics of GFRP's using twist drills with appropriate geometries. The optimum drilling parameter combination was obtained by using the analysis of signal-to-noise ratio.

Keywords: *GFRP, Delamination, Feed rate, Cutting speed, Drill diameter, ANOVA and Taguchi*

1. Introduction

Recently the use of composite materials increases in various areas of science and technology due to their special properties. Glass fiber reinforced plastics (GFRP) are the most commonly used in mechanical joints in pieces and structures in industry. However the mechanical joints require good surface quality holes for bolts and rivets. The dominant problem faced by industries while drilling GFRP composite panels is the delamination that reduces the accuracy of the drilled holes. The parameters of quality and machining characteristics are analyzed under varying cutting speed (500, 1500, 2500 rpm), feed rate (100, 300, 500 mm/min) and drill diameter (8, 10, 12 mm).The experimental trials are conducted based on L_{27} orthogonal array and analysis of variance (ANOVA) is employed to study the influence of performance characteristics in drilling operation of GFRP composites using HSS twist drill bit. The key drilling parameters that affect the performance in drilling operation can be determined that will be of industrial importance in terms of applications. The confirmation tests with optimum level of drilling parameters are carried out in order to illustrate the effectiveness of taguchi optimization method.

2. Literature Review

Lakshmi Narayanan [4] et al., reported a study on GFRP matrix composites. In this method delamination, thrust force, tool wear is measured before and after machining weight tool material difference. Tool makers microscope was used for measuring delamination.

Kilickap [5] et al., investigated on the influence of the cutting parameters, such as cutting speed and feed rate, and point angle on delamination produced when drilling a GFRP composite. The conclusion revealed that feed rate and cutting speed were the most influential factor on the delamination, respectively.

Kishore [6] et al, made a study on the effect of the cutting speed, the feed rate and the drill point geometry on the residual tensile strength of the drilled uni-directional glass fiber reinforced epoxy composite using the Taguchi method and suggests the optimal conditions for maximum residual tensile strength.

Mustafa [7] et al., utilized Taguchi methods to optimize surface finish and hole diameter accuracy in the dry drilling of Al 2024 alloy.

The parameters of hole quality are analyzed under varying cutting speeds, feed rates, depths of drilling and different HSS Twist type drilling tools with a 118° point angle. Orthogonal arrays of Taguchi, the signal-to-noise (S/N) ratio, the analysis of variance (ANOVA), and regression analyses are employed to find the optimal levels and to analyze the effect of the drilling parameters on surface finish and hole diameter accuracy values.

Shyha [8] et al., utilized an L_{12} Taguchi fractional factorial orthogonal array with analysis of variance (ANOVA) employed to evaluate the effect of drill geometry and drilling conditions on tool life and hole quality.

Karin [9] et al., achieved the best cutting conditions for minimizing surface roughness in a turning process of ferritic stainless steel, grade AISI 12L14. The orthogonal array L18 with five replicates, the signal-to-noise ratio (SNR) and the analysis of variance (ANOVA) were deployed to determine the optimal conditions for obtaining the desired surface roughness.

Gaitonde [10] et al., presented the methodology of Taguchi optimization method for simultaneous minimization of delamination factor at entry and exit of the holes in drilling of MDF panel. The utility concept has been employed for the multi-performance characteristics optimization using Taguchi design.

Tsao [11] et al., made a study on the prediction and evaluation of thrust force and surface roughness in drilling of composite material using candle stick drill. The approach was based on Taguchi method and the artificial neural network.

Gaitonde [12] et al., applied Taguchi optimization method for simultaneous minimization of burr height and burr thickness influenced by cutting conditions and drill geometry. In the present work, optimal values of cutting speed, feed, point angle and lip clearance angle are determined for selected drill diameter values to minimize burr height and burr thickness during drilling of AISI 316L stainless steel work pieces using Taguchi method.

Tsao [13] et al., presented a study on taguchi optimization method. In this study orthogonal array of L_{18} (2×37) was selected to realize the effects of the drilling parameters (diameter ratio, feed rate and spindle speed) on induced- delamination for various step-core drills.

Lee [14] et al., explored how the different parameters such as drill shape and friction angle, friction contact area ratio, feed rate, and drilling speed would affect the response parameter for Austenite stainless steel (AISI 304) using Taguchi method.

Basavarajappa [15] et al., discussed the influence of cutting parameters on drilling characteristics of hybrid metal matrix composites. The Taguchi design of experiments and analysis of variance (ANOVA) are employed to analyze the drilling characteristics of these composites. The experiments were conducted to study the effect of spindle speed and feed rate on feed force, surface finish and burr height using solid carbide multifaceted drills of 5mm diameter.

Pawade [16] et al., analyzed the nature of deformation beneath the machined surface and arrives at the thickness of machining affected zone (MAZ). The residual stress analysis, micro hardness measurements and degree of work hardening in the machined sub-surfaces were used as criteria to obtain the optimum machining conditions that give machined surfaces with high integrity using Taguchi method.

Nalbant [17] et al., employed Taguchi method to find the optimal cutting parameters (insert radius, feed rate, and depth of cut) for surface roughness in turning. The orthogonal array, the signal-to-noise ratio, and analysis of variance are employed to study the performance characteristics in turning operations of AISI 1030 steel bars using TiN coated tools.

Basavarajappa [18] et al. used a plan of experiments based on Taguchi technique to acquire the data in a controlled way. An orthogonal array and analysis of variance was employed to investigate the influence of wear parameters like as normal load, sliding speed and sliding distance on dry sliding wear of the composites.

Tang [19] et al., fabricated a mould that produced a thin plate made of plastic material. The product was used for warpage testing on the effective factors in warpage problem by applying the experimental design of Taguchi method.

Tsao [20] et al., presented a study using Taguchi method wherein the thrust force of core drill with varying conditions in drilling carbon fiber reinforced plastic (CFRP) was experimentally investigated.

Mohan [21] et al., reported the effects of parameters such as speed, feed rate, and drill size and specimen thickness in a CNC drilling process. A series of experiments were conducted using TRIAC VMC CNC machining center to relate the cutting parameters and material parameters on the cutting thrust and torque. The measured results were collected and analyzed with the help of the commercial software package MINITAB14. An orthogonal array, signal-to-noise ratio were employed to analyze the influence of these parameters on cutting force and torque during drilling.

Tsao [22] et al., presented a method on prediction and evaluation of delamination factor in use of twist drill, candle stick drill and saw drill. This approach was based on Taguchi's method and the analysis of variance (ANOVA). The objective was to establish a correlation between feed rate, spindle speed and drill diameter with the induced delamination in a CFRP laminate. The correlation was obtained by multi-variable linear regression and compared with the experimental results.

Paulo Davim [23] et al., made a study of the cutting parameters (cutting velocity and feed rate) under specific cutting pressure, thrust force in Glass Fiber Reinforced Plastics (GFRP's). The objective was to establish a correlation between cutting velocity and feed rate with the specific cutting pressure, thrust force, damage factor and surface roughness in a GFRP material.

Paulo Davim [24] et al., studied the influence of cutting parameters (cutting velocity and feed rate) and cutting time on drilling metal-matrix composites. The objective was to establish correlation between cutting velocity, feed rate and the cutting time with the evaluator the tool wear, the specific cutting pressure and the holes surface roughness.

Tsann [25] et al., utilized a experimental design using the Taguchi method to optimize the cutting parameters (cutting speed, feed, depth of cut). An orthogonal array, the signal to noise ratio, and the analysis of variance were employed to study the performance characteristics in face milling operation.

Thus from literature review it is observed that research activities have been reported in the field of drilling GFRP composites, but very rarely few works reported the influence of drill diameter in drilling of GFRP laminates. In case of design for assembly, the hole diameter play a vital role. In industrial applications many of the process engineers tend to use smaller holes for assembly of laminate panels for the very purposes of easy process stability control and achievement of accurate assembly of panels. Hence, in this work, drill diameter is included along with other standard parameters cutting speed and feed rate. This work is attempted to study the effects of cutting speed, feed rate and drill diameter on delamination while drilling GFRP composite panels.

3. Experimental Set Up

3.1 Fabrication of GFRP

The key properties expected of a matrix are good binding properties, heat resistance, low moisture absorption, light weight, non toxic etc. Others like good toughness, good impact strength and low density provide additional motive for choice of the material. There are many manufacturing processes for GFRP composite like resin transfer molding, pultrusion etc. The GFRP composite material considered in this project comprises of matrix system that consists of general purpose epoxy resin and a room temperature curing accelerator catalyst MEKP (Methyl Ethyl Ketone Peroxide)] hardener. The reinforcement system consists of chopped mats of E-glass fibers. The glass fiber composites have obtained wide acceptance because of their high specific strengths and non-metallic characteristics. The preparation of the specimen using Hand lay-up molding method is shown figure 2 and figure 3.

Raw materials used to make GFRP specimen is releasing agent (Polyvinyl Alkaline), Matrix (Epoxy resin + Hardener), Reinforcement (E Glass), and Hardener MEKP (Methyl Ethyl Ketone Peroxide).

Die used for molding GFRP specimen is Padock wood of size 600mmx300mmx50mm and it is finished by pocket milling operation. The finished pocket size is of 300mmx100mmx10mm. After the completion of laminate construction the laminate is kept in the atmosphere for 2 to 3 hours for curing. The equipment used for compaction of matrix and fibers by hand roller and the post curing is done in the room temperature.

The procedure to make GFRP composite panel by using hand layup techniques is described below.

3.1.1 Surface preparation and bonding

A key component to a successful lamination is the bonding process of the layers. There are three basic components, which make up the bonding process. First is the surface preparation of the laminae, which improves the substrate's ability to accept and adhere to an adhesive. Surface preparation varies depending on material type. Composites use sanding and grinding, surface texturing, or solvent cleaning. The second component is the adhesive itself, including epoxies, urethanes, phenolics, polyesters, solvents, acrylics and others. Each adhesive has its attributes depending on substrate type, in use requirements and process constraints. As a general rule, a maximum bond is achieved for a given substrate type when the material itself fails during an ultimate strength test. The maximum lap shear strength of an adhesive is achieved when the adhesive exhibits a cohesive failure in the bond line. The third component of lamination is the process by which the materials are bonded together. This involves a host of parameters primarily time, heat pressure, mixture, moisture and catalysts (initiators). It is important that the three basic components of bonding are properly employed to achieve a successful lamination. The surface preparation and gel coating is shown in figure 1 (1).

3.1.2 Laminate construction

There are three types of laminated construction. These include sandwich lamination consisting of at least two high stiffness and strength outer layers connected by a core, all laminated construction consisting of relatively high stiffness and strength layers and a third type consisting of a structural member that is reinforced on the tensile or compression or both sides of a flexural beam.

Sandwich lamination constructions are found in many applications from satellite structures to snow skis. Although both applications may utilize a sandwich approach, satellite applications generally require stiffness, strength and extreme lightweight, while the snow ski requires the laminated beam or composite structure to withstand large deflections and dynamic performance requirements. In addition the ski structure is integrated with thermoplastic surfaces and metal components. Typically metal and composite materials are applied to these sandwich structures. Even complex shapes can be achieved by using composite prepregs and wet lay-ups. The typical laminate construction is shown in figure 1 (2).

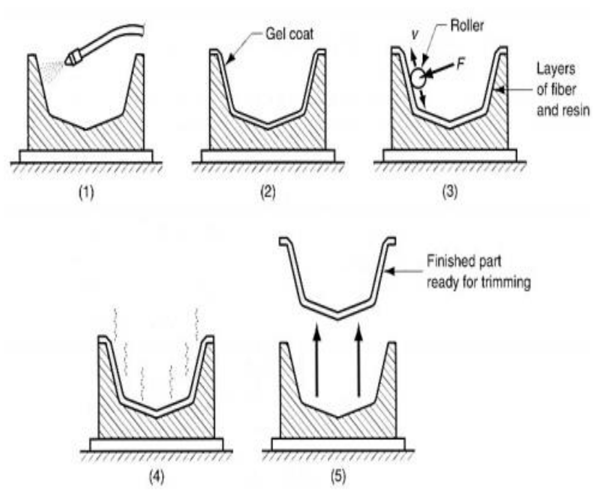

Fig. 1 Hand Layup Molding Method

3.1.3 Stacking of layers

After completing the laminate construction compress the resin and fibre evenly so as to seating all directions in the entire area of the die as shown in figure 1 (3). Stack the number layers up to the required thickness repeat the above steps for each staking.

3.1.4 Curing and releasing of GFRP composite

Finally leave to the atmosphere certain time interval of 2 to 3 hours for avoiding the acceleration of hardener and releasing agent. It is heated up automatically due to chemical reaction between GFRP mate and resin and the metallurgical structure changing then it cools to the room temperature at last. It is shown in figure 1 (4). This can be removed from the die by using the leaver or separate equipments as shown in figure 1 (5).

Fig. 2 Fabrication of GFRP Drilling Specimen

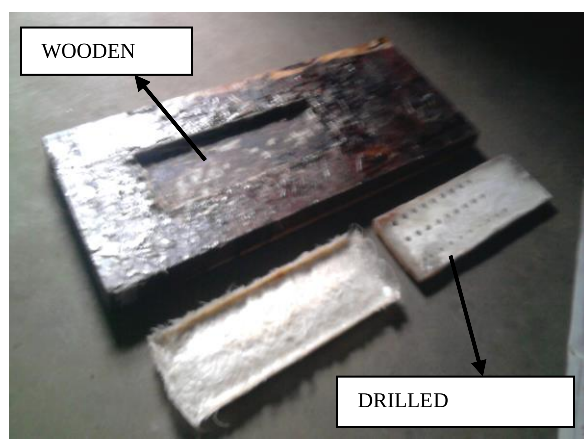

Fig. 3 Wooden Die and Drilled Specimen

3.2 Drilling method

The holes are drilled in the GFRP composite specimen using Arix VMC 100 CNC machine and high speed steel (HSS) twist drill bit. The GFRP laminates were approximately 10mm thick consisting of 24 plies made by hand layup technique and had a 55% cured fiber volume fraction specimen size of 300mm x 100mm x 10mm.

3.3 Delamination

After drilling, it is necessary to define criteria for the comparison of the delamination caused by different drilling parameters, even though they can only be applied to composites with the same stacking sequence and reinforcement fiber in nature and volume fraction. Several ratios were established for damage evaluation, One of them is delamination Factor (Fd) as displayed in Eq. (1), a ratio between the maximum delaminated diameter (D max) and hole nominal diameter (D).the method for measurement of delamination is shown in figure (4). The figure (5) shows the schematic view of a Tool maker's microscope with which delamination was measured.

$$F_d = D_{max}/D \qquad (1)$$

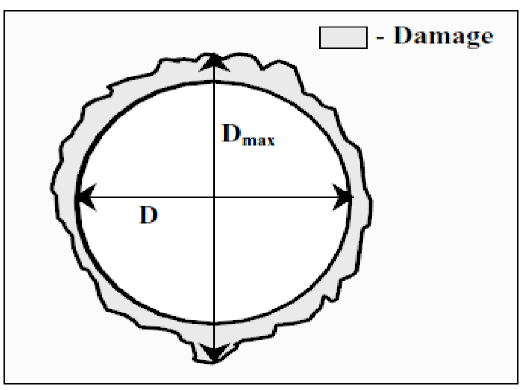

Fig. 4 Measurement of Delamination

Fig. 5 Tool Maker's Microscope

3.4 Experimental Trials

The experimental trials were performed based on L27 orthogonal array. Each experimental trial was performed twice and the average Dmax value is shown in table 2. The various drilling parameters considered in this work is shown in table table 1. For each experimental trial a new drill bit was used to overcome the problem of worn out tool. The randomization process was employed while conducting experimental trials and the sufficient time was spent to overcome machine related errors such as setup error. No coolant was used and the experiments were conducted in dry condition. The experimental result of delamination was measured using tool maker's microscope. The details of experimental trials and the measured delamination values are shown in the table 2.

Table: 1 Parameters and their Levels

Cutting speed(rpm)	500	1500	2500
Feed rate (mm/min)	100	300	500
Drill diameter(mm)	8	10	12

4. Result and Discussion

4.1 Response table for signal to noise ratios

The S/N ratio was calculated using lower the better (LB) characteristic of taguchi parametric design and the formula is given in equation (2).

$$\text{LB}: \quad \eta = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} yi^2 \right] \qquad (2)$$

Where yi is the experimentally observed value and n is the repeated number of each experiment. The S/N ratio plots were obtained using the statistical software MINITAB 14.The response values are tabulated in Table 3. The influence of various process parameters on delamination and contribution of each factor was analyzed using ANOVA and the results are shown in the Table 4.

Table: 2 Experimental Trials

Trial	Drill dia. mm	Cutting Speed rpm	Feed rate (mm/ min)	Dmax	Delamination factor (F_d)	S/N Ratio
1	8	500	100	8.080	1.001	-0.0086
2	8	500	300	15.896	1.987	-5.9639
3	8	500	500	14.400	1.800	-5.1054
4	8	1500	100	8.096	1.012	-0.1036
5	8	1500	300	8.120	1.015	-0.1293
6	8	1500	500	11.824	1.478	-3.3934
7	8	2500	100	10.400	1.300	-2.2788
8	8	2500	300	11.208	1.401	-2.9287
9	8	2500	500	11.304	1.413	-3.0028
10	10	500	100	14.000	1.400	-2.9225
11	10	500	300	14.130	1.413	-3.0028
12	10	500	500	14.620	1.462	-3.2989
13	10	1500	100	16.750	1.675	-4.480
14	10	1500	300	17.050	1.705	-4.6344
15	10	1500	500	18.130	1.813	-5.1679
16	10	2500	100	11.560	1.156	-1.2591
17	10	2500	300	16.900	1.690	-4.5577
18	10	2500	500	17.680	1.768	-4.9496
19	12	500	100	18.816	1.568	-3.9069
20	12	500	300	20.268	1.689	-4.5525
21	12	500	500	17.976	1.498	-3.5102
22	12	1500	100	17.736	1.478	-3.3934
23	12	1500	300	23.616	1.968	-5.880
24	12	1500	500	33.396	2.783	-8.8902
25	12	2500	100	22.440	1.870	-5.4368
26	12	2500	300	14.832	1.236	-1.8403
27	12	2500	500	34.752	2.896	-9.2359

F_d : Delamination Factor S/N: Signal to Noise

Table: 3 Response Table

Level	Drill diameter	Cutting speed	Feed rate
1	-2.546	-3.586	-2.643
2	-3.808	-4.008	-3.721
3	-5.183	-3.943	-5.173
Delta	2.637	0.422	2.529
Rank	1	3	2

Table: 4 ANOVA Table for Delamination Factor

Source	DoF	Adj SS	V	I	P%
Drill Diameter	2	1.1928	0.062	S	22.6
Cutting Speed	2	0.0778	0.775	NS	1.40
Feed rate	2	1.1257	0.069	S	24.4
Drill diameter *Speed	4	0.7604	0.353	S	14.40
Speed* Feed rate	4	0.4249	0.603	S	8.08
Drill diameter *Feed rate	4	0.4906	0.543	S	9.33
Error	8	1.1846	-	NS	19.70
Total	26	5.2568	-	-	100

DoF : Degrees of freedom S : Significant
NS : Non significant V : Variance
P% : Percentage contribution I : Inference

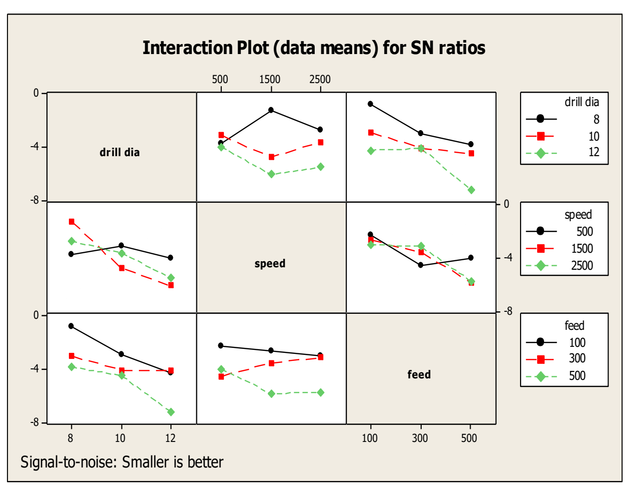

Fig. 6 Interaction Plot (Data Means) For SN Ratios

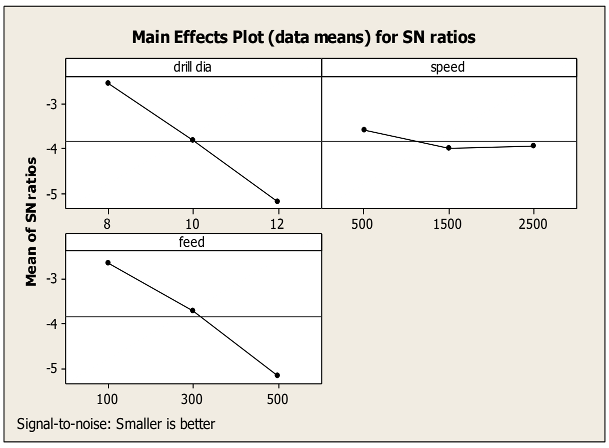

Fig. 7 Main Effect Plot For SN Ratios

4.2 S/N Ratio Plots obtained using MINITAB 14

The figure (6) shows the interaction plot between drill diameter Vs cutting speed, drill diameter Vs feed rate and cutting speed Vs feed rate. The figure (7) depicts the main effect plot for S/N ratio for three levels and three factors.

5. Conclusion

i. GFRP composite specimen of size 300mm x 100mm x 10mm are fabricated by using hand layup method.
ii. The Delamination factor in drilling of GFRP composite has been investigated. The following conclusions are drawn from the investigation.
   a. The feed rate contributes 24.4% and drill diameter contributes 22.6% for delamination factor of GFRP composites.
   b. The optimum drilling parameters are identified as drill diameter 8 mm, spindle speed 500 rpm, and feed rate 100 mm/min.
   c. With respect to interacting parameters it is evident from interaction plot that drill diameter - cutting speed and cutting speed - feed rate are the vitally influencing the delamination of GFRP composites.

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