International Journal of Applied Research in Mechanical Engineering

Volume 2 | Issue 4 Article 6

April 2013

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EXPERIMENTAL AND ANALYTICAL STUDIES ON THE DETERMINATION OF HOLE QUALITY IN DRY DRILLING OF GFRP COMPOSITES

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Abstract- In this investigation nonlaminated Glass Fiber Reinforced Plastic (GFRP) composite rods made by pultrusion method with high fiber weight fraction was drilled with a special geometry coated carbide drill. The ovality of the drilled holes were measured using CMM. Taguchi's orthogonal array and analysis of variance (ANOVA) were employed to study the influence of process parameters such as feed and spindle speed on ovality. The optimum level of process parameters towards minimum ovality were obtained to achieve defect controlled drilling of pultruded GFRP composite rods. Correlation for ovality with process parameters were established using a statistical software MINITAB 16 and found not to be fit. The influence of feed was insignificant and that of speed was significant on ovality of the drilled holes. The optimal process parameter levels within the range examined was identified as 0.05 mm/rev feed and 1000 rpm speed for drilling pultruded GFRP composite rods using 10 mm ratio drill. The influence of process parameters on hole quality in nonlaminated composite rods differs from that of in laminated composites.

Keywords*-GFRP composite rods; drilling; ovality; Taguchi method; ANOVA; S/N analysis*

I. INTRODUCTION

Glass fiber reinforced plastic (GFRP) composites are most widely used in aerospace, automobile, marine, electronic industries, construction of military vehicles, machine tools, robots and sports equipment owing to their multi potential properties such as high strength to weight ratio, high specific stiffness, high damping, high fracture toughness, good dimensional stability and excellent corrosion resistance [1,2]. Accordingly, the need for accurate machining of composites has increased enormously. Intricacy in the product design necessitates development of the composite product in parts, which are finally assembled. Hole making thus becomes an integral part of the product development cycle.

During drilling of fiber reinforced composites, the work material experiences delamination, fiber breakage, matrix cracking, etc. [3,4]. Among these defects caused by drilling, delamination which occurs both at the entrance and exit planes of the workpiece is most critical, since it can result in lowering of bearing strength and thereby reduces service life of the component [3,5,6]. Hence, utmost care is to be exercised to attain defect controlled drilling performance. The fastening efficiency is largely dependent on the bearing strength which defines the quality of machined holes. Many researchers have proposed that the quality of machined holes is strongly dependent on process parameters such as feed and spindle speed [2,3,7-10] which have great influence on the thrust force and torque. Many attempts have been made by various researchers in drilling laminated GFRP composites. They are briefly presented here. Malhotra [1] and Arul et al. [2] stated that carbide tipped drill performs much better than HSS drill with GFRP. Caprino et al. [4] stated that the type of damage induced in glass/polyester composite materials during drilling is strongly dependent on the feed rate. Di Ilio et al. [7] characterized the interaction between the twist drill and the composite during machining. Paulo Davim et al. [8] employed a statistical technique, using orthogonal arrays and analysis of variance, to investigate the influence of cutting parameters in machining Glass Fiber Reinforced Plastics (GFRPs) manufactured by hand lay-up. Mohan et al. [9] analyzed the influence of machining parameters on thrust force and torque during drilling glass fiber reinforced polyester composite materials.

König et al. [11] stated that cutting forces such as thrust force and torque which depend on cutting parameters affects the surface quality. Wen-Chou Chen [12] correlated the delamination factor with the average thrust force for the drilling of uni-directional and multidirectional composite materials. Enemuoh et al. [13] proposed an approach combining Taguchi's technique and multi-objective optimization criterion to select global optimum drilling parameters for damage-free drilling in carbon fiber reinforced epoxy composite materials. Tsao et al. [14] predicted and evaluated delamination factor in drilling carbon fiber reinforced plastics (CFRPs) based on Taguchi's method and the analysis of variance (ANOVA). Ogawa et al. [15] stated that the mean value (static component) of the thrust force influences on a cutting phenomenon occurring at the chisel edge of the drill and the magnitude of variation (dynamic component) of the thrust force influences on a cutting phenomenon occurring at the major cutting edge of the drill. Singh and Bhatnagar [16] drilled UD-GFRP laminates with different drill geometries and concluded that drilling-induced damage is not only dependent on thrust force alone but also on torque. They also found that the damage is maximum at higher cutting speeds and minimization of thrust force and torque during drilling can lead to minimal damage of the hole. Ramesh and Elayaperumal [17] stated that feed is only significant in influencing thrust force and torque and obtained optimal process parameter levels for drilling high fiber volume fraction nonlaminated composite rods.

However, literature on the drilling of composite materials with special geometry and that on the drilling of nonlaminated composite materials is scarce. Also many researchers have worked towards attaining hole quality considering only damage/delamination around the drilled hole. This work differs from the previous works by machining a higher order fiber weight fraction glass/epoxy nonlaminated composite rods, with a special geometry carbide drill (Ratio drill).

In ballistic applications mostly nonlaminated composites with higher percentage of fiber weight fraction is used to ensure higher order energy absorption. The research interest in the present study was to investigate the influence of drilling process parameters such as feed and spindle speed on ovality of the drilled holes and attaining optimal process parameter levels in the selected range for hole quality considering ovality of the drilled holes in nonlaminated GFRP composite rods as a criteria.

This paper presents the application of Taguchi's orthogonal array and analysis of variance (ANOVA) to study the relative influence of process parameters and analysis of Signal-to-Noise ratio for attaining optimal parameter levels. If ovality (hole diameter accuracy) of the drilled holes can be minimized, the bearing strength of the drilled holes and the service life of the assembled components can be substantially increased.

II. EXPERIMENTAL DETAILS

Pultruded rod which is a GFRP polymeric (epoxy) nonlaminated composite (Fig. 1) with maximum fiber weight fraction was taken as workpiece. Pultruded rod was made using E-CR glass directional roving fibers of 4800 tex with 80 % fiber weight fraction and has 20 mm length and 25 mm diameter. The E-CR glass fibers are of ASTM 578 section 4.2.4 standards. In the pultruded rod the orientation of glass fibers is parallel to the axis of drill.

Figure 1. Photograph of the GFRP rod manufactured by pultrusion process

The micrographs of GFRP composite rod obtained through Scanning Electron Microscope (SEM) is shown in Fig. 2. The composition of GFRP composite rod obtained through Energy Dispersive X-ray Spectrometry (EDX) is found to be Carbon - 62.69 %, Oxygen -16.88 %, Magnesium - 0.22 %, Aluminium - 0.73% and Silicon -2.33 %. Ratio drill (Guhring No. 02475), a drill with special geometry, made of tungsten carbide of grade K/P was used in this work to produce through holes (Fig. 3).

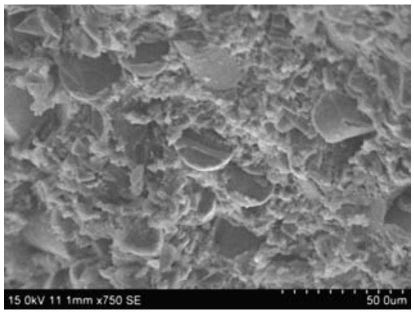

Figure 2 SEM images of pultruded rod

Figure 3. Photograph of Ratio drill (make Guhring) used in the tests

The physical properties of the pultruded rod and specification of the drill is given in Tables 1 and 2 respectively. CNC machining center (ARIX VMC 100) was used to perform the drilling operations (Fig. 4).

TABLE I. PROPERTIES OF GFRP COMPOSITE ROD

Properties	Value
Young's modulus (MPa)	49881.52
Ultimate stress (MPa)	1004.89
Elongation (%)	36.40
Density (kg/m^3)	212.52
Specific gravity	2.15
Water absorption (%)	0.0001
Diameter of glass fiber (µm)	24.8
Shore 'D' hardness	74-76

TABLE II. DETAILS OF THE RATIO DRILL

Drill standard	DIN 6537K R-RT1
Drill type	RT 100F
Shank type	Cylindrical
Drill diameter (mm)	10
No. of flutes	2
Helix angle	30^0
Point angle	140^0
Point geometry	Relieved cone
Overall length (mm)	89
TiN+TiAlN coating (µm)	7-8

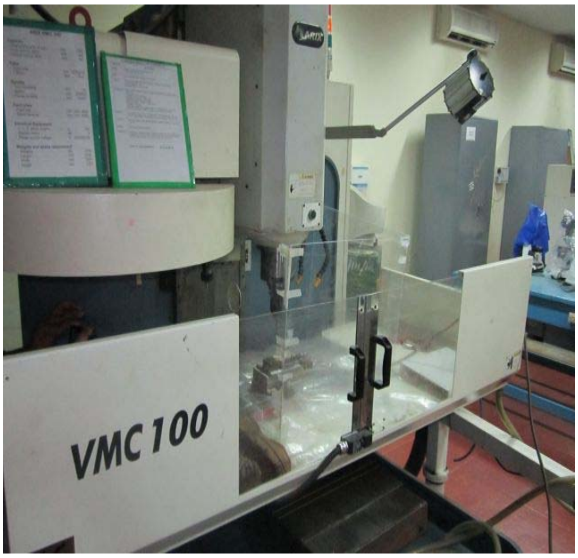

Figure 4. Photograph of the experimental setup used for drilling GFRP composite rods

Fixture consisting of V-jaws between which the GFRP rod held was specially designed. The GFRP solid round rod was mounted on the fixture which in turn was mounted on the table of CNC machining center (Fig. 5). The schematic representation of experimental setup is shown in Fig. 6. Vacuum cleaner was used to remove powdery chips away from the cutting zone.

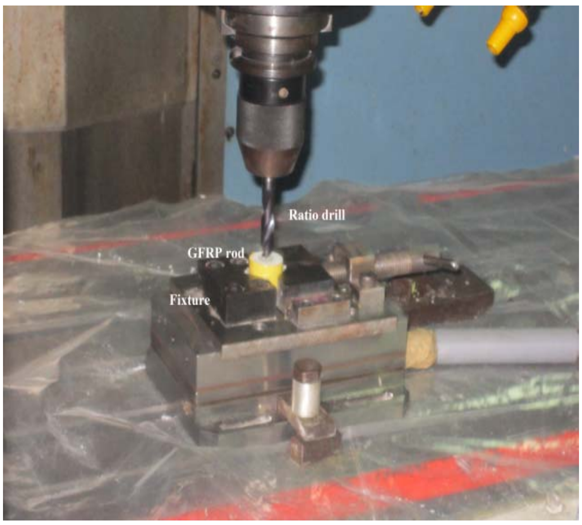

Figure 5. Close-up photograph of the experimental setup

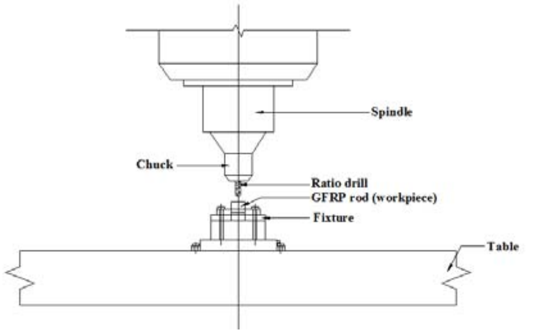

Figure 6. Schematic representation of experimental setup

The ovality of the drilled holes was measured using coordinate measuring machine (CMM) Tesa Micro-Hite 3D 474 (Fig. 7) which uses Tesa-Reflex MH3D software and adjustable trigger force as probe head.

Figure 7. Photograph of CMM used for measuring ovality of drilled holes

A. Plan of Experiments

The experiments were conducted with selected cutting conditions [16] without using coolant. The process parameters and their levels selected for drilling GFRP composite rods are presented in Table 3. The orthogonal array L_9 as shown in Table 4 was selected for this work.

TABLE III. PROCESS PARAMETERS AND THEIR LEVELS IN DRILLING

Symbol	Process parameter	Level 1	Level 2	Level 3
F	Feed (mm/rev)	0.05	0.10	0.15
S	Spindle speed (rpm)	750	1000	1250

This investigation is carried out in nonlaminated composite rods to optimize the process parameter levels within the selected range to attain minimum drilled hole ovality and thereby to attain defect controlled drilling which leads to high hole quality. Each test was repeated thrice and an average was taken for analysis. Analysis of variance (ANOVA) were calculated for the experimental data obtained for average of ovality to study the relative significance of process parameters in nonlaminated composite rods. In Taguchi method, S/N ratio is the measure of quality characteristics and deviation from the desired value. In this investigation, "smaller the better" characteristic has been applied to determine the S/N ratio for average ovality as it is to be minimized. A higher the value of S/N ratio means the better the fit for the combined objective. The ovality was measured many times at the entry, middle and exit of the drilled holes and an average was taken for analysis.

TABLE IV. $L_9(3^2)$ ORTHOGONAL ARRAY WITH THE ASSIGNED VALUES

Exp. No.	Feed F	Speed S	Process parameter F	Process parameter S
1	1	1	0.05	750
2	1	2	0.05	1000
3	1	3	0.05	1250
4	2	1	0.10	750
5	2	2	0.10	1000
6	2	3	0.10	1250
7	3	1	0.15	750
8	3	2	0.15	1000
9	3	3	0.15	1250

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

The influence of process parameters (feed and speed) on ovality is discussed below. Two ratio drills have been used for making 27 holes. The average flank wear of first ratio drill after making 14 holes was 0.011 mm and that of second ratio drill after making remaining holes was 0.0105 mm. This reveals that effect of tool wear on hole quality will be negligible and therefore tool wear is not considered in this study.

A. Ovality

From Fig. 8 it can be realized that the ovality decreases with decrease in feed and speed in general. Also it is observed that lower ovality of the drilled hole can be obtained with higher feed (0.15 mm/rev) and medium speed (1000 rpm). From Table 5, it is observed that experiment no. 8 gives minimum ovality in pultruded rods.

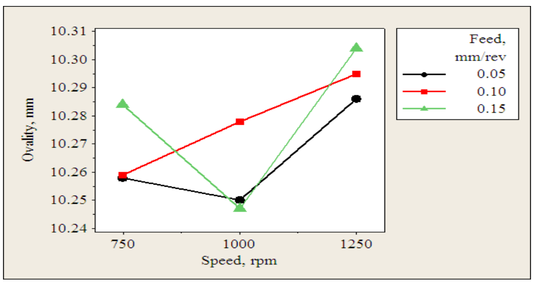

Figure 8. Influence of feed and spindle speed on average ovality

TABLE V. AVERAGE OVALITY VALUES AS A FUNCTION OF PROCESS PARAMETERS

Exp.No.	L_9 Feed mm/rev	L_9 Speed rpm	Ovality mm Pultruded rod
1	0.05	750	10.258
2	0.05	1000	10.250
3	0.05	1250	10.286
4	0.10	750	10.259
5	0.10	1000	10.278
6	0.10	1250	10.295
7	0.15	750	10.284
8	0.15	1000	**10.247**
9	0.15	1250	10.304

B. Analysis of variance (ANOVA) and Signal-to-Noise (S/N) ratio

The analysis of variance of the experimental data was done to statistically analyze the relative significance of process parameters, feed (F) and speed (S), on ovality of the drilled holes. The last column of the ANOVA table indicates the percentage of contribution (ρ) of each parameter to the total variation indicating the influence of each parameter.

From the analysis (Table 6), it is observed that the process parameter F, feed, has no significance and the process parameter S, speed, has statistical (55.90 %) and no physical significance on the ovality (hole diameter accuracy) obtained. The parameters are not physically significant if their variance ratio is less than the pooled error.

TABLE VI. ANOVA TABLE FOR AVERAGE OVALITY

Source	DF[a]	S[b]	V[c]	F[d]	S'[e]	ρ[f] (%)
F	2	0.000	0.000	_	_	_
S	2	0.002	0.001	6.658	0.001	55.90
Error	4	0.001	0.000	1.232	0.000	4.57
(e)[g]	2	0.000	0.000	_	0.001	39.52
Total	8	0.002	0.000	_	_	100

a. degree of freedom. b. sum of squares. c. variance. d. variance ratio. e. pure variation. f. percentage of contribution. g. pooled error

The S/N ratio response graph for ovality is shown in Fig. 9. From Fig. 9 the optimal combination can be concluded as

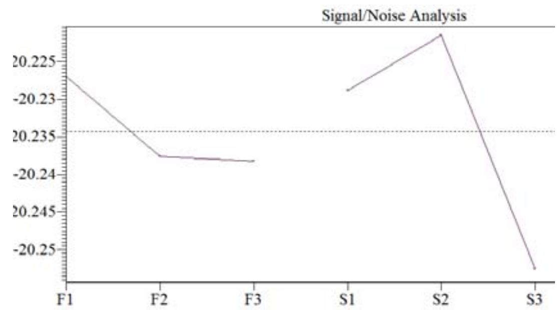

Figure 9. Response graph of ovality for process parameters in drilling nonlaminated GFRP composite rods

0.05 mm/rev feed and 1000 rpm speed which gives lower drilled hole ovality of the order of 10.250 mm.

C. Correlation of ovality with process parameters

In use of nonlinear regression analysis, the correlation for ovality with process parameters in drilling pultruded GFRP composite rods was obtained using statistical software MINITAB 16.

The regression equation is:

Ovality in mm = 10.5 + 0.76 F - 0.000653 S - 2.33 F^2 + 0.000000 S^2 - 0.000160 FS, $R^2 = 0.759$
(1)

where F is feed in mm/rev and S is spindle speed in rpm . In multiple regression analysis, R^2, which is called R-sq, is the regression co-efficient, where $R^2 >$ 0.85 for the models indicates that the fit of the experimental data is satisfactory. Therefore, the model for ovality deems to be not fit. This is because the process parameters are not significant for predicting ovality. This is similar to process parameters that are not significant in predicting damage factor [18] in GFRP rods and differs from laminated composites where the quality of machined holes is strongly dependent on process parameters such as feed and spindle speed [2,3,7-10]. The probable reason may be due to the orientation of glass fibers which is parallel and perpendicular to the axis of drill in nonlaminated and laminated composites respectively.

IV. CONCLUSIONS

The research in the present study was to optimize the process parameter levels within the range examined based on minimum ovality of the drilled hole and thereby attaining high hole quality in drilling nonlaminated GFRP composite rods using a coated solid carbide drill. Based on the experimental results and methodology used, the following conclusions can be drawn for drilling pultruded GFRP composite rods using 10 mm special geometry drill (Ratio drill).

1. The influence of feed on ovality of the drilled holes was insignificant. The influence of speed was significant (55.90 %) on ovality of the drilled hole.

2. The quality of drilled holes in nonlaminated composite rods is not dependent on process parameters such as feed and spindle speed whereas it is not the same in laminated composites. The probable reason for the process parameters being not significant in influencing ovality of the drilled holes in nonlaminated composite rods may be due to the orientation of glass fibers which are parallel to the axis of drill.(In laminated composites the orientation of glass fibers are perpendicular to the axis of drill).

3. The optimal process parameter levels to attain lower ovality of the drilled hole and thereby producing high quality holes in pultruded GFRP composite rods was identified as 0.05 mm/rev feed and 1000 rpm speed within the range examined. This optimal process parameter level combination gives ovality of the drilled hole in the order of 10.250 mm.
4. The mathematical model developed for ovality of the drilled hole deems to be not fit, as the process parameters are not significant.

ACKNOWLEDGMENT

The authors are grateful to M/s. Sunrise Fibre Glass Industries, Bangalore, India for supplying the composite materials for experimentation. The authors are thankful to Guhring India Pvt.Ltd. for supplying the drill bits used in this experiments. Also the authors are thankful to Opus Precision Instruments Private Limited, Chennai for assisting in taking ovality measurements.

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