A Taguchi Approach in Investigating the Effects of Process Parameters in Drilling of Glass Fibre Reinforced Plastic Composite

RAVI SHANKAR S. N.1 SURJYA K. PAL2 AND ARUN K. SAMANTARAY3

1DEPARTMENT OF MECHANICAL ENGINEERING, MALNAD COLLEGE OF ENGINEERING, HASSAN, KARNATAKA, INDIA
2DEPARTMENT OF MECHANICAL ENGINEERING, INDIAN INSTITUTE OF TECHNOLOGY KKHARAGPUR, WEST BENGAL, INDIA
Corresponding author:1ravishivara@yahoo.com

Abstract. Glass fibre reinforced plastic (GFRP) composite has found an important place in the industries replacing many metals and alloys. The joints formed are found to be the weakest portions of the assembled GFRP parts. Conventional drilling is the most widely adapted manufacturing process for an efficient assembly. Moreover, drilling of glass fibre reinforced plastics is difficult to carry out due to the anisotropic, non-homogeneous structure and high abrasiveness of the glass fibre and the complex geometry of the drill. For these reasons, the damage gets induced to the hole/workpiece and the cutting tool. In this study, Taguchi approach is employed to analyse the drilling process. An L25 orthogonal array, signal to noise S/N ratio and analysis of variance (ANOVA) are used to identify the effects of process input parameters on the output factors. The process input parameters are drill diameter, cutting speed and feed rate. The output factors/responses are the thrust force, torque, power, temperature, tool life, surface roughness, deviation from dimensional parameters of the holes, peel-up and push-out delaminations. In every set of experiment, an exhaustive work has been carried out till each drill bit reached its tool life. Optimal process parameters are available from the S/N ratio plots whereas ANOVA has identified the significant input factors and their percentage contribution on the responses.

Keywords: Drilling, Glass fibre reinforced plastic (GFRP), Delamination, Design of experiments (DOE), Taguchi approach, Analysis of variance (ANOVA)

Nomenclature

\begin{align*}
D & \quad \text{Drill diameter, mm} \\
f & \quad \text{Feed rate, mm/rev} \\
F_{\text{cal}} & \quad \text{Test of significance, calculated} \\
F_d & \quad \text{Push-out delamination} \\
F_p & \quad \text{Peel-up delamination} \\
F_{\text{tab}} & \quad \text{Test of significance, tabulated} \\
F_z & \quad \text{Thrust force during drilling, N} \\
M_z & \quad \text{Drilling torque, Nm} \\
P & \quad \text{Power, W} \\
R_a & \quad \text{Surface roughness, } \mu \text{m} \\
T & \quad \text{Average chip temperature, } ^\circ \text{C} \\
t_t & \quad \text{Tool life, s} \\
V_b & \quad \text{Tool flank wear, } \mu \text{m} \\
v_c & \quad \text{Cutting speed, m/min} \\
V_f & \quad \text{Fibre volume fraction} \\
\Delta_c & \quad \text{Deviation from cylindricity, mm} \\
\Delta_d & \quad \text{Deviation from nominal diameter, mm} \\
\Delta_o & \quad \text{Deviation from circularity, mm} \\
\theta & \quad \text{Fibre orientation angle}
\end{align*}
1. Introduction

Glass fibre reinforced plastic (GFRP) composite material is used extensively in the industries nowadays due to its high strength to weight ratio, stiffness to weight ratio, rigidity, low thermal expansion, high specific modulus of elasticity, flexibility in design, parts consolidation, dimensional stability and low tooling costs. Their application is in the area of aerospace, marine, automotive, electronic industries, transportation industries, military vehicles and sports equipments. Because of electrical insulating properties, GFRP is widely used in appliances, tools and machinery. Corrosion resistant glass fibre reinforced tanks and pipes offer extended service life as compared to metals. A GFRP composite provides protection against biological agents, nuclear radiation and resists the degradation caused by chemicals. Hole making is the most important secondary manufacturing process to give final shape to the assembled GFRP component. Efforts have been made by various researchers in the recent past to optimize the process parameters to minimize the drilling induced damages. Among the damages, peel-up and push-out delaminations are found to be the most critical, since they reduce the structural integrity and long term performance of the GFRP material.

Godwin et al. [1] have reviewed the strength of the joints in fibre reinforced plastics (FRPs). Konig et al. [2-3] have produced keynote papers on machining of FRPs and reviewed quality definition and assessment in drilling of fibre reinforced thermostets. Teti [4] has reviewed machining of composite materials. Singh et al. [5] attempted to review the status of the work done in drilling of composite materials with emphasis on damage mechanisms and reported initial experimental findings on drilling of GFRP composite laminates. Hocheng et al. [6] have reviewed the path towards delamination-free drilling of composite materials. Abrao et al. [7], in their review, have found that the phenomena associated with shearing of polymeric composite materials require additional studies, in order to allow a better understanding of the behavior of polymeric composites when subjected to cutting.

Tagliaferri et al. [8] has worked on the effect of drilling parameters on the finish and mechanical properties of GFRP composites. They have found that the damage zone width is correlated to the ratio between drilling speed and feed rate, Vr/ Vt; in particular, higher the Vr/ Vt value, better is the cut quality. For a definite value of Vr/ Vt, the damage zone decreases to a minimum value, beyond which the damage stays constant. Malhotra [9] found that the flank wear is higher than chisel edge wear. Drilling was interrupted at preset depths to study the quality of the cut surface and the damage development during drilling GFRP by Caprino and Tagliaferri [10]. According to that study, damage induced in the form of delamination is strongly dependent on the feed rate. Khashaba [11] experimentally investigated the influence of drilling and material variable on thrust force, torque and delamination of GFRP composites. Variable feed technique was used to achieve delamination free drilling. Sonbaty et al. [12] made an experimental study on drilling glass fibre reinforced epoxy composites. They found that cutting speed has insignificant effect on the thrust force and surface roughness of epoxy resins whereas increase in feed, drill size, and fibre volume fractions led to increase in the thrust force and torque. Drill diameter combined with feed has a significant effect on surface roughness. Experimental investigation by Arul et al. [13] on the influence of tool material on the dynamics of drilling GFRP composites has revealed that defect-tolerant drilling can be attained by proper selection of cutting parameters and tool material. Monitoring of flank wear, hole shrinkage and acoustic emission during drilling substantiates this finding. Khashabaet al. [14] analysed drilling of chopped composites. Their observations revealed no clear effect of the cutting speed on delamination size, while the delamination size decreased with the decrease in feed. They commented that delamination free drilling of chopped composites, with high fibre volume fraction, remained as a problem for further investigation. A finite element (FE) approach was proposed to study the drilling characteristics of UD-GFRP composite laminates in Singh et al. [15]. Rao et al. [16] have studied the effect of drilling induced damage on notched tensile and pin bearing strengths of woven GFR-epoxy composites. They concluded that the feed rate is found to be the major contributing factor on drilling damage. The effect of cutting tools with four different geometries and composition on thrust force and delamination were studied by Abrao et al. [17]. In contrast to other reports, a direct relationship between thrust force and delamination was not observed, since the drill responsible for the highest
thrust force was also responsible for the smallest delamination. Hence it is concluded that the relationship between thrust force and delamination is not straightforward. Mathew et al. [18] have used DOE technique to investigate the effect of geometry of a trepanning tool on the thrust and torque during drilling of GFRP. It is revealed that the performance of the trepanning tool is superior to that of conventional twist drills in terms of thrust, torque and hole quality. Low production cost and ease of regrinding are its major additional advantages due to its simple geometry. Davim et al. [19] evaluated the cutting parameters (cutting velocity and feed) and the influence of the matrix under specific cutting force, delamination factor, and surface roughness in two types of matrix (Viapal VUP 9731 and ATLAC 382-05) by DOE technique using carbide drills. From their investigation it was concluded that the specific cutting force decreases and the delamination factor increases with both the cutting parameters (cutting velocity and feed); whereas the surface roughness increases with the feed and decreases with the cutting velocity. A correlation between the cutting velocity and the feed rate with the specific cutting pressure, thrust force, damage factor and surface roughness in a GFRP material was established by Davim et al. [20]. The analysis of variance (ANOVA) was performed for the investigation of the cutting characteristics of GFRPs by using cemented carbide (K10) drills with appropriate geometries. The objective of the experiment was to establish a correlation between the cutting velocity and the feed rate with the specific cutting pressure, thrust force, damage factor and surface roughness. A study on the influence of process parameters on the cutting force and torque during drilling of glass fibre polyester reinforced composites by using Taguchi method has been attempted by Mohan et al. [21]. They reveal that the speed and drill (carbide) size have more significant influence on the cutting thrust force than specimen thickness and feed rate. Study of the response table indicated that the specimen thickness and drill size are significant and dominant parameters on torque than any other combination. Al-Sulaiman et al. [22] investigated the use of electrical power for online monitoring of tool condition and found that the differential electrical power is a better indicator of tool wear than conventional mechanical power method. Delamination analysis in the drilling process of GFRP using carbide drills by Mohan et al. [23] reveals that the specimen thickness and cutting speed have significant influence on peel up delamination and the specimen thickness and feed have more significant influence on push out delamination. DOE, Taguchi method and ANOVA have been adapted for the study. The residual strength of drilled UD-GFRP has been investigated by using Taguchi method in Kishore et al. [24]

2. Plan of experiments

Design of experiments is a statistical technique used to study the effects of multiple variables (also called factors or parameters) simultaneously. DOE is highly effective wherever and whenever it is suspected that the performance of a part or process is controlled by more than one factor. The Taguchi technique or Taguchi approach is an experimental strategy in which a modified or standardized form of DOE is utilized. The Taguchi approach, which is a form of DOE with special application principles, is chosen for the present study [25].

| Process parameters | Factors assigned | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|--------------------|-----------------|--------|--------|--------|--------|--------|
| Drill diameter (D), mm | A | 6 | 7 | 8 | 9 | 10 |
| Cutting speed (v_c), m/min | B | 1.6 | 9.2 | 16.8 | 24.4 | 32 |
| Feed rate (f), mm/rev | C | 0.02 | 0.09 | 0.16 | 0.23 | 0.3 |

The process parameters selected for the present study were chosen from the range of process parameters opted by earlier researchers. A few trial experiments were conducted initially. The results were compared with earlier reports for confirmation. The planning of experiment for the drilling of GFRP composite was based on Taguchi L_{25} orthogonal array (Table 3). The orthogonal array was formed by selecting three factors/parameters and five levels as shown in Table 1. Accordingly, a total number of 25 sets of experiments were carried out. In each set of experiment, the drill bit was examined for the wear measurement in the Leica inverted microscope at regular intervals after drilling.
The regular intervals were after drilling the first hole, third hole, fifth hole, eighth hole, eighteenth hole and so on, further maintaining a constant interval of ten holes till the drill bit reached the end of its tool life; the tool life criteria being 300 µm flank wear ($V_b$). Some drill bits had short life, i.e., they reached their tool life criteria after drilling only 18 or less holes. On the other hand one of them showed a long life by reaching its tool life criteria after drilling in between 228 to 238 holes. Hence the number of experiments carried out, varied between 18 and 238. A total number of 2175 experiments were conducted in the present work. The input factors (process parameters) are the drill diameter ($D$), cutting speed ($v_c$) and feed rate ($f$). The responses measured are the thrust force ($F_t$), torque ($M_z$), power ($P$), temperature ($T$), tool flank wear ($V_b$), tool life ($t_i$), peel-up delamination factor ($F_p$), push-out delamination factor ($F_d$), arithmetic mean value of the surface roughness ($R_a$), deviation from the nominal diameter ($A_d$), deviation from circularity ($A_c$) and deviation from cylindricity ($A_t$).

3. Experimental setup and procedure

The schematic diagram of the experimental setup along with various sensors and the data acquisition system are shown in Fig. 1. Glass fibre reinforced plastic (GFRP) whose mechanical properties shown in Table 2, was supplied by Sunrise FRP Ltd, Bangalore, India. It was prepared by passing glass fibre mat (woven roving of Vetrotex) through a hot press lamination process using two rollers. Then a hot cure epoxy was applied on the glass mat. The epoxy resin used was Araldite LY-556 with hardener HT-972. The whole set was cured under high temperature ranging from 120 - 140 °C. The laminate so cured was cut to the required size of 100mm x 50mm and 9 mm thickness. The fibre orientation ($\theta$) was 0/90 with a fibre volume fraction ($V_f$) being 65-68%.

The workpiece was held in the fixture to avoid any displacement due to shock and vibration during drilling. A CNC vertical machining center BFW Agni (BMV 45 T20) of 16 kVA capacity having a maximum spindle speed of 10000 rpm and a maximum feed rate of 10000 mm/min was used for drilling the GFRP work material. Standard HSS twist drills of regular geometry and point angle of 118° were used to generate holes in the GFRP composite. The work which was held in the fixture was mounted on the KISTLER® dynamometer (type 9272A). The thrust force and the torque during drilling were measured from the drilling dynamometer which was connected to the charge amplifier (5070A). Machining center’s main power supply cables were made to pass through the arrangement made in the Hall effect Monotronix power sensor PS 100-DGM for measurement of power.

Table 2. Mechanical Properties of GFRP Work Material

| Property            | Value       | Unit  |
|---------------------|-------------|-------|
| Specific gravity    | 1.65-1.75   |       |
| Glass content       | 65-68       | % weight |
| Water absorption    | 0.07-0.08   | % weight |
| Tensile strength    | 2.35-2.74   | N/mm² |
| Flexural strength   | 2.94-3.09   | N/mm² |
| Compressive strength| 3.33-3.72   | N/mm² |
| Impact strength     | 300-310     | KJ/m² |
| Fiber orientation   | 0/90        | deg   |

Temperature in the machining zone was measured by an Omega temperature sensor (model OS 523-3). The charge amplifier, power sensor and temperature sensor were all connected to the data acquisition card (NI 6210 card 2). This NI DAQ card, which gave the output signals in volts, was interfaced with an IBM PC. The acquired data was processed and stored with the help of LabVIEW software (Version 7.1). Actual values of thrust force, torque, power and temperature were later converted to their respective units of measurement by the corresponding conversion factors.

Drill wear was monitored by withdrawing the drill bit at regular intervals between the experiments. The drill flank wear was measured in the Leica DMILM type inverted microscope. Once the drill bit
reached its tool life, the corresponding hole drilled in the GFRP workpiece was examined for its peel-up and push-out delaminations in the Leicastero zoom microscope. Thus the delamination factors were determined. Surface roughness of the hole was measured three times for each test in the Mitutoyo SJ-201P surface roughness tester. The cut-off length selected was 0.8 mm with 5 samplenumbers. The deviations from the nominal diameter, circularity and cylindricity, all related to the geometrical parameters of the hole were measured in the TESA micro-hite DCC 4-7-4 coordinate measuring machine.

![Figure 1. Schematic diagram of the experimental set up.](image)

4. Analysis of experimental results

Taguchi $L_{25}$ orthogonal array and experimental results are given in Table 2. A statistical analysis was performed using the commercial software package MINITAB 15\textsuperscript{\textregistered} on each response to study the effect of the drill diameter, cutting speed and the feed rate. Hence the analysis consists of calculation of signal to noise (S/N) ratio values and analysis of variance (ANOVA) test for each response factor. The S/N ratio is the mean square deviation of the data set plotted in a log (to the base 10) scale with a -10 multiplier which changes the desirability from smaller is better to larger is better model. Higher the S/N ratio better is the result.

In the smaller the better model,

$$S/N \text{ ratio} = -10 \log \frac{1}{n} \left[ \sum_{i=1}^{n} Y_i^2 \right] \quad (1)$$

where, for Y observed data, n is the number of observations.

For larger the better model,

$$S/N \text{ ratio} = -10 \log \frac{1}{n} \left[ \sum_{i=1}^{n} \frac{1}{Y_i^2} \right] \quad (2)$$

The designed parameter is considered as a significant factor if test $F_{\text{cal}}$ is greater than $F_{\text{tab}}$. Test $F_{\text{cal}}$ is the ratio of mean of squared deviations (MS) to the MS error and $F_{\text{tab}}$ and istaken from the statistical table. The percentage contribution of the factors (shown in Table 4) in influencing the response is the percentage ratio of sum of squares to the total sum of squares, where the used variable...
Degrees of freedom (DF) = Number of levels – 1

The delamination factor is the ratio of the maximum diameter \(D_{max}\) of the damage zone measured, to the nominal hole diameter \(D\). Peel-up delamination \(F_p\) and push-out delaminations \(F_d\) were determined by using Eq. (4) after measuring the outer diameters \(D_{max}\) of both the delaminations, respectively.

\[
\text{Delamination factor} = \frac{D_{max}}{D}
\]

5. Results and discussion

Main effect plots of signal to noise ratios of the entire responses versus the process parameters are shown in Fig. 2. For better productivity, it is desirable to have minimum thrust force, torque, power, temperature, surface roughness, deviations from the geometrical parameters, peel-up and push-out delaminations but maximum tool life. Therefore the calculation of S/N ratio follows smaller the better model for all the responses except tool life for which the calculation of S/N ratio follows larger the better model. An increase in S/N ratio indicates the decrease in thrust force, torque, power, temperature, surface roughness, deviation from nominal diameter, deviation from circularity, deviation from cylindricity, peel-up and push-out delaminations. But for tool life, an increase in S/N ratio indicates longer life. From the results, it is found that increase in tool diameter has increased the thrust force. This may be due to the increase in the length of the chisel edge and the increase in depth of cut. Since test \(F_{cal} > F_{tab}\), as seen in the ANOVA Table 4 the drill diameter is a significant factor influencing the thrust force. But the percentage contribution is only 11.49. There is a slight reduction of thrust force with increase in cutting speed.

Table 3. Orthogonal Array \(L_{25}\)

| \(L_{25}\) test | \(A\) | \(B\) | \(C\) |
|---------------|-------|-------|-------|
| 1             | 1     | 1     | 1     |
| 2             | 1     | 2     | 2     |
| 3             | 1     | 3     | 3     |
| 4             | 1     | 4     | 4     |
| 5             | 1     | 5     | 5     |
| 6             | 2     | 1     | 2     |
| 7             | 2     | 2     | 3     |
| 8             | 2     | 3     | 4     |
| 9             | 2     | 4     | 5     |
| 10            | 2     | 5     | 1     |
| 11            | 3     | 1     | 3     |
| 12            | 3     | 2     | 4     |
| 13            | 3     | 3     | 5     |
| 14            | 3     | 4     | 1     |
| 15            | 3     | 5     | 2     |
| 16            | 4     | 1     | 4     |
| 17            | 4     | 2     | 5     |
| 18            | 4     | 3     | 1     |
| 19            | 4     | 4     | 2     |
| 20            | 4     | 5     | 3     |
| 21            | 5     | 1     | 5     |
| 22            | 5     | 2     | 1     |
| 23            | 5     | 3     | 2     |
| 24            | 5     | 4     | 3     |
| 25            | 5     | 5     | 4     |
The matrix material may have been softened due to the rise of cutting temperature with the increase in the cutting speed. But the contribution is a mere 4.17% and is not a significant factor. Feed rate is highly significant in influencing the thrust force with a 77.97% contribution. This may be due to the increase in shear area as the tool encounters more material per revolution.

The trend observed in the effects of process parameters on torque is almost similar to the thrust force. Though all the process parameters are significant, feed rate is the more significant factor with 64.04% contribution. This is due to the increase in cross-sectional area of the undeformed chip [8]. There is a steep rise in power consumption with the increase in both the cutting speed and feed rate, as can be
seen in Fig. 2. They are very significant in influencing the power consumption with a contribution of 44.2% and 42.81%, respectively. The measurement of electrical power has indicated the increase in power with the increase in spindle motor rpm. The increase in the feed rate increases the power consumption because the tool encounters more work material (with the increase in shear area) during cutting.

Table 4. Analysis of Variance (ANOVA) for the Responses

| Response | Source | DF | Seq SS | Adj MS | F_cal | F_tab | % Contribution |
|----------|--------|----|--------|--------|-------|-------|---------------|
| $F_c$ | $D$ | 4 | 55912 | 13978 | 5.41 | 3.26 | 11.49 |
| | $v_c$ | 4 | 20316 | 5079 | 1.97 | 3.26 | 4.17 |
| | $f$ | 4 | 379522 | 94880 | 36.74 | 3.26 | 77.97 |
| | Error | 12 | 30990 | 2582 |
| | Total | 24 | 486739 |
| $M_c$ | $D$ | 4 | 0.61462 | 0.15365 | 10.73 | 3.26 | 19.13 |
| | $v_c$ | 4 | 0.36868 | 0.09217 | 6.44 | 3.26 | 11.48 |
| | $f$ | 4 | 2.05711 | 0.51428 | 35.92 | 3.26 | 64.04 |
| | Error | 12 | 0.17180 | 0.01432 |
| | Total | 24 | 3.21221 |
| $P$ | $D$ | 4 | 95.5 | 23.9 | 0.11 | 3.26 | 0.47 |
| | $v_c$ | 4 | 9033.6 | 2258.4 | 10.60 | 3.26 | 44.20 |
| | $f$ | 4 | 8748.6 | 2187.1 | 10.26 | 3.26 | 42.81 |
| | Error | 12 | 2557.3 | 213.1 |
| | Total | 24 | 20435.0 |
| $T$ | $D$ | 4 | 520.0 | 130.0 | 0.47 | 3.26 | 4.36 |
| | $v_c$ | 4 | 5440.3 | 1360.1 | 4.90 | 3.26 | 45.63 |
| | $f$ | 4 | 2631.1 | 657.8 | 2.37 | 3.26 | 22.07 |
| | Error | 12 | 3332.0 | 277.7 |
| | Total | 24 | 11923.4 |
| $F_p$ | $D$ | 4 | 0.011110 | 0.002778 | 2.33 | 3.26 | 29.83 |
| | $v_c$ | 4 | 0.004697 | 0.001174 | 0.98 | 3.26 | 12.61 |
| | $f$ | 4 | 0.007134 | 0.001783 | 1.50 | 3.26 | 19.15 |
| | Error | 12 | 0.014308 | 0.001192 |
| | Total | 24 | 0.037249 |
| $F_d$ | $D$ | 4 | 0.095819 | 0.023955 | 3.97 | 3.26 | 42.27 |
| | $v_c$ | 4 | 0.008694 | 0.002174 | 0.36 | 3.26 | 3.84 |
| | $f$ | 4 | 0.049753 | 0.012438 | 2.06 | 3.26 | 21.95 |
| | Error | 12 | 0.072417 | 0.006035 |
| | Total | 24 | 0.226683 |
| $t_i$ | $D$ | 4 | 4.9488E+10 | 1.2372E+10 | 0.78 | 3.26 | 5.72 |
| | $v_c$ | 4 | 5.9776E+11 | 1.4944E+11 | 9.48 | 3.26 | 69.12 |
| | $f$ | 4 | 2.8412E+10 | 7102933832 | 0.45 | 3.26 | 3.29 |
| | Error | 12 | 1.8921E+11 | 1.5767E+10 |
| | Total | 24 | 8.6486E+11 |
| $R_a$ | $D$ | 4 | 4.6543 | 1.1636 | 1.25 | 3.26 | 12.33 |
| | $v_c$ | 4 | 15.8939 | 3.9735 | 4.26 | 3.26 | 42.11 |
| | $f$ | 4 | 6.0064 | 1.5016 | 1.61 | 3.26 | 15.91 |
| | Error | 12 | 11.1921 | 0.9327 |
| | Total | 24 | 37.7466 |
| $A_d$ | $D$ | 4 | 0.0222776 | 0.0055694 | 6.97 | 3.26 | 53.14 |
| | $v_c$ | 4 | 0.0070614 | 0.0017654 | 2.21 | 3.26 | 16.84 |
| | $f$ | 4 | 0.0030001 | 0.0007500 | 0.94 | 3.26 | 7.16 |
| | Error | 12 | 0.0095835 | 0.0007986 |
| | Total | 24 | 0.0419226 |
| $A_s$ | $D$ | 4 | 0.0038669 | 0.0009667 | 2.03 | 3.26 | 32.51 |
| | $v_c$ | 4 | 0.0009548 | 0.0002387 | 0.50 | 3.26 | 5.00 |
| | $f$ | 4 | 0.0013532 | 0.0003383 | 0.71 | 3.26 | 11.38 |
| | Error | 12 | 0.0057209 | 0.0004767 |
| | Total | 24 | 0.0118958 |
| $A_e$ | $D$ | 4 | 0.0105614 | 0.0026403 | 3.82 | 3.26 | 41.53 |
| | $v_c$ | 4 | 0.0018466 | 0.0004616 | 0.67 | 3.26 | 7.26 |
| | $f$ | 4 | 0.0047330 | 0.0011832 | 1.71 | 3.26 | 18.61 |
| | Error | 12 | 0.0082897 | 0.0006908 |
| | Total | 24 | 0.0254306 |
Temperature rises with the increase in cutting speed, which is the only significant factor with a contribution of 45.63%. This may be due to high friction at higher cutting speeds and more heat generation while shearing more work material with high feed rate. The chips produced at low feed rates were of ribbon type and were winding themselves to the drill bit for a while before getting separated. This sometimes blocked the new chips from getting exposed to the sensor. Hence the average temperature recorded may not be consistent for few readings.

It is seen that an increase in drill diameter and cutting speed reduces the peel-up and push-out delaminations. But an increase in feed rate has increased the delaminations. This may be due to the increase in thrust force with the increase in feed rate. The trend in both the cases appears to be the same. In the case of peel-up delaminations, as the test $F_{cal}$ is less than $F_{tab}$ for all the process parameters, they are less significant in influencing the delaminations. But the test $F_{cal}$ is greater than $F_{tab}$ for drill diameter in the case of push-out delaminations and is a very significant factor in influencing the delaminations.

$Larger the better$ model is chosen for the tool life $S/N$ ratios. Figure 2 shows an increase in tool life with increase in drill diameter, but decrease in tool life with increase in cutting speed and feed rate. Though the drill diameter and feed rate are not the significant factors, the cutting speed appears to be very significant in influencing the tool life. This may be due to the increase in temperature at the elevated speeds which may have affected the tool material as well as the matrix in the composite. Increase in drill diameter and cutting speed increased the surface roughness, whereas increase in feed rate decreased the surface roughness. From the ANOVA results, cutting speed seems to be a very significant factor in influencing the surface roughness, making the other two factors less significant. Increase in surface roughness may be attributed to the thermal softening of the matrix which becomes sticky because of rise in temperature at higher speeds.

Deviation from the nominal diameter has decreased with increase in drill diameter and feed rate. This may be due to the same amount of fibre pullouts irrespective of the drill diameter since it is a very significant factor. Though there is an increase in deviation with increase in cutting speed, both the cutting speed and feed rate are not significant in influencing the deviation from the nominal diameter. With the increase in the cutting speed, the deviation from circularity increases and the deviation from cylindricity decreases. But this is the least significant factor for both the deviations. Though the trends of drill diameter and feed rate are similar in both the cases, they are inconsistent. Though none of the factors are significant in the case of deviation from circularity, drill diameter is a significant factor in influencing the deviation from cylindricity.

| Table 5. Optimal Parameter Settings of Input Factors |
|-----------------------------------------------|
| **Physical requirement**                  | **Optimal combinations** |
|                                      | Drill diameter | Cutting speed | Feed rate |
| Minimum thrust force                   | 7             | 32           | 0.02      |
| Minimum torque                        | 6             | 32           | 0.02      |
| Minimum power                         | 6             | 1.6          | 0.02      |
| Minimum temp                          | 7             | 1.6          | 0.02      |
| Maximum tool life                     | 10            | 1.6          | 0.23      |
| Minimum peel-up delamination          | 9             | 24.4         | 0.09      |
| Minimum push-out delamination         | 9             | 9.2          | 0.09      |
| Minimum surface roughness             | 6             | 1.6          | 0.3       |
| Minimum deviation from nominal hole diameter | 10       | 16.8         | 0.3       |
| Minimum deviation from circularity    | 10            | 1.6          | 0.23      |
| Minimum deviation from cylindricity   | 7             | 32           | 0.23      |
6. Conclusions

In the present work, Taguchi method with ANOVA identified the significant input factors and their percentage contribution on the responses. The results are obtained after all the drill bits reached their tool life. The increase in thrust force is mainly due to the feed rate and drill diameter to a smaller extent. The torque also increases considerably with increase infeed rate but effects of drill diameter and cutting speed were also found to be significant. The power increases significantly with the increase in cutting speed and feed rate whereas the drill diameter has the least significance. Cutting speed and feed rate are the most significant factors in influencing the temperature. Moreover, cutting speed is also a significant factor in decreasing the tool life and interestingly increasing the surface roughness. None of the factors are significant in case of peel-up delamination but drill diameter is a significant factor for the push-out delamination. Drill diameter is a significant factor for both deviation from the nominal diameter and deviation from cylindricity whereas there are no significant factors for deviation from circularity. The optimal process parameters available from the S/N ratio plots are shown in Table 5.

References

[1] E. W. Godwin, F. L. Matthews, (1980), “A review of the strength of joints in fibre-reinforced plastics,” Composites, pp. 155-160.
[2] W. König, Ch. Wulf, P. Grab, H. Willerscheid, (1985), “Machining of fibre reinforced plastics,” Annals of the CIRP, Vol. 34, no.2, pp. 537-548.
[3] W. König, P. Grab, (1989), “Quality definition and assessment in drilling of fibre reinforced thermosets,” Annals of the CIRP, Vol. 38, no. 1, pp. 119-124.
[4] R. Teti, (2000), “Machining of Composite Materials,” CIRP Annals – Manufacturing Technology, Vol. 51, pp. 611-634.
[5] I. Singh, D. Nayak, R. Saxena, N. Bhatnagar, (2004), “Drilling induced damage in FRP composite laminates,” Institution of Engineers, Vol. 85, pp. 37-40.
[6] H. Hocheng, C. C. Tsao, (2005), “The path towards delamination-free drilling of composite materials” Journal of Materials Processing Technology, Vol. 167, pp. 251-264.
[7] A. M. Abrao, P. E. Faria, J. C. Campos Rubio, P. Reis, J. Paulo Davim, (2007), “Drilling of fiber reinforced plastics: A review,” Journal of Materials Processing Technology, Vol. 186, pp.1-7.
[8] V. Tagliaferri, G. Caprino, A. Diterlizzi, (1990), “Effect of drilling parameters on the finish and mechanical properties of GFRP composites,” Int J Mach. Tools Manufact, Vol. 30, no.1, pp. 77-84.
[9] S. K. Malhotra, (1990), “Some studies on drilling of fibrous composites,” Journal of Materials Processing Technology, Vol. 24, pp. 291-300.
[10] G. Caprino, V. Tagliaferri, (1995), “Damage development in drilling glass fibre reinforced plastics,” Int J Mach Tools Manufact, Vol. 35, no. 6, pp. 817-829.
[11] U. A. Khashaba,(2004), “Delamination in drilling GFR-thermoset composites,” Composite Structures, Vol. 63, pp. 313–327.
[12] E. Sonbaty, U. A. Khashaba, T. Machaly, (2004), “Factors affecting the machinability of GFR/epoxy composites,” Composite structures, Vol. 63, pp. 329-338.
[13] S. Arul, L. Vijayaraghavan, S. K. Malhotra, R. Krishnamurthy, (2006), “Influence of tool material on dynamics of drilling of GFRP composites,” Int J AdvManufTechnol, Vol. 29, pp. 655-662.
[14] U. A. Khashaba, M. A. Seif, M. A. Elhamid, (2007), “Drilling analysis of chopped composites, Composites: Part A, Vol. 38, pp. 61-70.
[15] I. Singh, N. Bhatnagar, P. Viswanath, (2008), “Drilling of uni-directional glass fiber reinforced plastics: Experimental and finite element study,” Materials and Design, Vol. 29, pp. 546-553.
[16] B. SrinivasRao, R. Rudramoorthy, S. Srinivas, B. NageswaraRao, (2008), “Effect of drilling induced damage on notched tensile and pin bearing strengths of woven GFR-epoxy composites,” Materials Science and Engineering A, Vol. 472, pp. 347–352.
[17] A. M. Abrao, J. C. Campos Rubio, P. E. Faria, J. P. Davim, (2008), “The effect of cutting tool geometry on thrust force and delamination when drilling glass fibre reinforced plastic composite,” Materials and Design; Vol. 29, pp. 508–513.
[18] J. Mathew, N. Ramakrishnan, N. K. Naik, (1999), “Investigations into the effect of geometry of a trepanning tool on thrust and torque during drilling of GFRP composites,” Journal of Materials Processing Technology, Vol. 91, pp. 1-11.
[19] J. P. Davim, P. Reis, C. C. António, (2004), “Drilling fiber reinforced plastics (FRPs) manufactured by hand lay-up: influence of matrix (Viapal VUP 9731 and ATLAC 382-05),” Journal of Materials Processing Technology, Vol. 155-156, pp. 1828-1833.
[20] J. Paulo Davim, P. Reis, C. António, (2004), “Experimental study of drilling glass fiber reinforced plastics (GFRP) manufactured by hand lay-up,” Composites Science and Technology, Vol. 64, pp. 289–297.
[21] N. S. Mohan, A. Ramachandra, S. M. Kulkarni, (2005), “Influence of process parameters on cutting force and torque during drilling of glass–fiber polyester reinforced composites,” Composite Structures, Vol. 71, pp. 407–413.
[22] F. A. Al-Sulaiman, M. A. Baseer, A. K. Sheikh, (2005), “Use of electrical power for online monitoring of tool condition,” Journal of Materials Processing Technology, Vol. 166. pp. 364–371.
[23] N. S. Mohan, S. M. Kulkarni, A. Ramachandra, (2007), “Delamination analysis in drilling process of glass fiber reinforced plastic (GFRP) composite materials,” Journal of Materials Processing Technology, Vol. 186, pp. 265–271.
[24] R. A. Kishore, R. Tiwari, A. Dvivedi, I. Singh, (2009), “Taguchi analysis of the residual tensile strength after drilling in glass fibre reinforced epoxy composites,” Materials and Design, Vol. 30, Issue 6, pp. 2186-2190.
[25] Ranjit K Roy, (2002), “Design of experiments using the Taguchi approach”, John Wiley & Sons. Inc.