CHAPTER 3

DRILLING ON GFRP COMPOSITE LAMINATES

3.1 INTRODUCTION

During the past one decade the application of FRP composite has been extended widely from a sophisticated airplane fuselage to a simple tennis racket and boat hull. The strength requirement of different part varies and depends on different parameters like fibre proportion, fibre orientation and constituent materials in the composite. In the manufacture of longer structural frames such as an aircraft fuselage, drilling is an essential operation. Aspects of the hole such as waviness/roughness of its wall surface, axial straightness and roundness of the hole cross-section can cause high stresses on the rivet, leading to its failure. The life and proper functioning of the structural joints can be critically affected by the quality of holes, which generally depend upon the appropriate choice of drilling and design parameter. Since drilling is often a final operation during assembly, any defect due to drilling process results in the rejection of the part. The part being rejected at this stage will be an expensive loss. The machining performance can be improved only by proper selection of tool and cutting parameters. However the effect of these parameters mainly depend on the mechanical properties of the composite, which in turn depend on the fibre position and fibre proportion.

This chapter presents an analysis of the drilling operation on unidirectional and bi-directional GFRP composite material using HSS twist
drill at commonly available rotational speeds and feed rates. A little research effort has been expended to determine the optimum cutting parameters for obtaining a satisfactory hole quality in drilling GFRP laminates by conventional methods. Five cutting speeds and three feed rates have been selected. The hole appearance, surface quality and diameter variation at both the sides of the hole were evaluated at all cutting conditions. Optimum cutting parameters producing comparatively excellent quality holes were identified. The comparative effect on the machining performance is discussed.

A drilling experiment to check the effect of pad support and tool diameter variation on the hole quality of the GFRP composite material has been conducted. The peeling up and pushing out actions of the drill tool that cause delamination were found to get restricted by proper pad support. The quality of the holes produced with the use of pad support on either side of the hole has been examined. Quite satisfactory improvement in hole quality with minimum delamination was observed. In another test drilling performance was examined by varying tool diameters. The drill tools with higher diameter produced holes with poor surface quality for a similar cutting condition. Tools with higher diameter require modification to achieve better surface quality if worked at similar cutting condition. The magnitude and direction of the effect of speed, feed rate and fibre proportion on drilling performance has been evaluated using 2k factorial design and analysis of variance a statistical approach. The percentage contribution of the effect of fibre percentage on hole surface quality has been compared with the effect of speed and feed rates.
3.2 OBJECTIVES

□ To fabricate the plate like (flat surface) unidirectional and bi-directional Glass Fibre Reinforced Polymer (GFRP) composite specimens.

□ To perform drilling operation by varying rotational speeds, feed rates, tool diameters and by using pad support while drilling.

□ To analyze the effect of cutting parameters, pad support, tool diameter and design parameter (fibre percentage and position) on hole appearance, surface quality and dimensional deviation.

□ To identify the optimum cutting and design parameters which produce holes with better surface quality.

□ To develop a statistical model using 2k factorial design and regression analysis to evaluate the magnitude and direction of the effect of the cutting and design parameters on the hole surface quality.

□ To compare the machinability of unidirectional GFRP laminates with the bi-directional GFRP laminates.

3.3 EXPERIMENTAL DETAILS
3.3.1. Specimen preparation.
Filament winding and hand lay-up processes were used to prepare the Unidirectional and bi-directional GFRP specimens respectively. E-glass fibre roving were used with polyester resin. Flat unidirectional GFRP specimens of 6mm thick were prepared by filament winding process. A hexagonal shaped wooden mandrel with sun mica sheet on all the six flat surfaces for smooth finish on one side of the specimen was used. The impregnated fibre roving from the creel passing through the resin bath was wounded around the mandrel to the required thickness. The specimens were cured at ambient
temperature for 24 hours. The burning test conducted to check the fibre percentage revealed that the specimens so fabricated possessed 28% of fibre content by volume. One side of the specimen possessed good finish where as the outer surface was corrugated, and hence grounded to make the surface plane and uniform thickness. However the variation in thickness is within the acceptable range [77]. The macroscopic and microscopic tests were carried out to check the presence of voids, delaminations or any other inclusions.

A bi-directional cross woven GFRP specimens of 8mm thickness with varying fibre percentage ranging from 30 to 70% by weight (volume fraction of fibre ranging from 0.19 to 0.44) were prepared by hand lay-up process. Fibre percentage was controlled by controlling the weight of the fibres.(number of layers). Silicon glass (E-glass) fibre cross woven roving mats were used to reinforce unsaturated polyester resin consisting of 33% styrene monomer. Curing agent Methyl ethyl ketone peroxide (MEKP) with accelerator Cobalt Nepthalate was used. Specimens were cured at room temperature for 12 to 24 hours depending on the fibre percentage. Necessary care was taken to remove the entrapped air during the lay-up process. Rollers were used for this purpose. A gel coat was applied on the mould prior to the lay-up process. The specimens were microscopically tested to confirm the absence of defect like voids or delamination. Though few voids and delamination were observed on the planks possessing 60% and 70% fibre percentage, the area free from these defects were cut and selected for drilling experimentation. The specimens prepared by hand lay-up and filament winding process are illustrated in Fig 3.1
The specimen thickness and the range of fibre percentages selected for this analysis are within the allowable/applicable range. The thickness of the specimens were varied in the range of 1.524mm to 25.4mm. Fibre percentages 45% to 65% by weight of woven fabric are used in aircrafts, marine ordinance and electrical applications. Fibre percentage 40 to 70% by weight of woven roving, are used in marines and large container [78].

3.3.2 Drilling experiments and parameter selection
Drilling experiments were performed based on the methods followed by Kobayashi in the drilling performance analysis of pure plastic materials [79].

3.3.2.1 Drilling on UGFRP specimen
In this experiment a unidirectional GFRP composite specimen has been used for drilling. The specimens were drilled dry by using Girard's radial drilling machine. HSS twist drill of 8mm diameter with point angle 118° and helix angle 27° was used. Three feed rates 0.064, 0.25 and 0.64 mm/rev and five
cutting speeds 6.28, 8.92, 12.56, 17.84 and 25.12 m/min were selected in this analysis.

3.3.2.2 Drilling on BGFRP specimen
In this experiment DR 23 type DONAU radial drilling machine was used for drilling BGFRP specimens, five cutting speeds 7.39, 11.81, 15.09, 24.12 and 38.94 m/min, three feed rates 0.075, 0.15 and 0.30 mm/rev were selected as cutting parameters. An HSS drill of 8mm diameter with 75mm long taper shank of one Morse taper, 118°-point angle and 27°-helix angle were chosen. The tool and cutting parameters selected for the present analysis, were based on the ASTME data and hand book of plastic materials [80,81,86].

In both the above experiments three holes were drilled dry for each cutting condition on each specimen. The main problem of drilling FRP is the quality achieved at the tool entry and exit side of the hole. Therefore the hole appearance and the surface roughness are the best indicators for the drilling result. It has to be noticed, however, that the quality and the variation of measured values are highly dependent on cutting parameter, fibre position and fibre proportion. Optical profile projector was used to observe the hole quality at 10X magnification. The average surface roughness (Ra,μm) values of the hole wall surfaces were recorded at random locations using a Surtronic stylus type instrument. Baty's bore gauge instrument having least count of 0.0002mm was used to measure the hole diameters. The hole quality, chip characteristic, hole diameter deviation, effect of tool diameter and the effect of pad support on delamination have been shown by pictorial and graphical representation.
A serious problem of FRP machining is the generation of air borne dust. Glass and carbon fibre compounds usually emit a fine powder like dust, whereas a fibrous dust is typical for the machining of aramids. In any case this dust has to be extracted and filtered carefully, since otherwise serious hazards to health or machine tool damage may occur. Proper care has been taken to overcome this problem. Fans were used to fly the minute chips and dust away from the operator.

3.4 EXPERIMENTAL RESULTS OF DRILLING UGFRP SPECIMEN

3.4.1 Effect of Cutting speed and feed rate on hole quality

Fig.3.2 illustrates the pictorial representation of the appearance of holes drilled at various cutting conditions. It is observed that, the appearance of holes near entry, drilled at 0.064mm/rev feed rate are clean and without any fibres pulled out for all cutting speeds. However a slight fibre pullout was observed at the cutting speeds 8.92 and 17.84 m/min. The lowest feed rate selected 0.064 mm/rev has shown better performance at 12.56 m/min. The hole at this cutting condition was observed to be excellent with minimum hole diameter variation.

At 0.25mm/rev feed a slight delamination with gumming of chips and fibre pullout was observed on both the sides of the hole at all the rotational speeds. Maximum delamination was observed at 12.56 and 25.12 m/min cutting speeds. Also most of the holes drilled at this cutting condition are slightly gummed with chips. At cutting speed 17.84 m/min the hole quality at the entry appears to be good with slightly chips gummed at the exit. At feed
rate 0.64 mm/rev holes on both the sides appear to be damaged with gumming of chips, fibre pullout and delamination at all the rotational speeds.

Fig. 3.2. Appearance of holes drilled at various speeds and feed rates

Fig. 3.3 illustrate the hole quality characterised by different symbols. Based on the appearance of holes, fibre pullout and gumming of chips the hole qualities were classified into five groups, as excellent, good, chips slightly gummed, slightly cone shaped and much delamination and are represented by various symbols. In the present circumstance, the excellent
hole was observed at the cutting condition 0.064 mm/rev feed rate and 12.56 m/min cutting speed. However this characteristic may vary with the other material and tool design.

<table>
<thead>
<tr>
<th>Feed rate (mm/rev)</th>
<th>Entry</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.64</td>
<td>□ Δ Δ X □</td>
</tr>
<tr>
<td>0.25</td>
<td>Δ Δ Δ O Δ</td>
</tr>
<tr>
<td>0.064</td>
<td>O O Θ Δ Δ</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.64</td>
</tr>
<tr>
<td>0.25</td>
</tr>
<tr>
<td>0.064</td>
</tr>
</tbody>
</table>

6.28 8.92 12.56 17.84 25.12

Cutting speed rpm

Figure 3.3. Hole quality at different speed and feed rate

Θ Excellent, O Good Δ Chips slightly gummed
X Slightly cone shape □ Much Delamination

The overall analysis has shown that a relationship between the drill speed and feed rates on hole quality exist, the lowest feed rates has shown better performance at all cutting speeds compare to other feed rates. The increase in torque and thrust force at higher rotational speeds and feed rates
respectively causes a portion of fibre to be pulled out from the surface while cutting. This may result in generating poor surface quality at higher drill speeds and feed rates.

3.4.2. Effect of speed and feed rates on hole diameter variation

Fig. 3.4 (a) and (b) illustrate deviation in diameter at the entry and exit side of the holes respectively at different cutting conditions. Not much deviation was observed at lower cutting speeds (6.28 and 8.92 m/min) for any feed rate. Maximum deviation was observed on holes drilled at cutting speed 25.12 m/min with feed rates of 0.064 and 0.64 mm/rev. Minimum deviation in diameter was observed at feed rate 0.064 mm/rev and cutting speeds 6.28, 8.92 and 12.56 m/min.

Figure 3.4 (a) & (b) Influence of Cutting speed and feed rate on hole dimension at the entry & exit respectively
The holes drilled at cutting speed 25.12 m/min were found enlarged at both minimum and maximum feed rates. As the variation in diameter was found random, no specific relationship between the speed and feed rate with dimensional variation was observed. However in most of the cutting condition the hole diameters at the entry side were found enlarged, probably because of long duration of tool contact with the work material.

![Image of chip characteristics](image-url)

**Figure 3.5. Influence of Cutting speed on chip characteristic**

### 3.4.3 Chip Characteristics

Fig.3.5 illustrate the appearance of chips produced while drilling UGFRP at 0.064mm/rev feed rate by varying cutting speeds. It is observed that at lower cutting speeds 6.28 and 8.92 m/min the chips were found to be continuous and curly like which indicates the formation of fine surfaces. Reduction in chip length with the increase of cutting speed was observed. The chip lengths were varying from 2cm to 4cm. At higher cutting speeds 12.56 to 25.12 m/min
the chips were found to be thin and small segmented like. The chips were so delicate to handle; they got broken into small pieces and powder form while handling.

![Graph showing the influence of cutting speed and feed rate on surface quality.](image)

**3.4.4 Surface quality**

Fig.3.6 illustrate the graphical representation of average surface roughness values (Ra μm) measured at different cutting conditions. Results revealed that, with the increase of cutting speed and feed rate there is an increase in surface roughness values. The average surface roughness (Ra) values measured for a given range of cutting speeds and constant feed rate 0.064mm/rev were found to be 2.49 to 3.98 μm respectively. Similarly for the same range of cutting speeds and at higher feed rate 0.64mm/rev the Ra values are 4.15 to 6.94 μm. These results indicated that fine surface quality was achieved at lowest rotational speeds and feed rates. Minimum and maximum Ra values 2.49 and 6.94 μm were observed at minimum and maximum speed-feed combination respectively. If this quality is within the acceptable range, drilling at higher speed-feed combination considered in this situation is advisable to attain better productivity. However an optimum cutting
parameter selection is essential to minimize the hole dimension deviation and other defects like delamination and fibre pullout.

3.4.5 Effect of pad support on hole quality
In FRP specimens, fibres are arranged layer by layer. While drilling, the drill bit behaves like a screw. As the tool advances it peels up the top layer which has no support, causing the delamination. Similarly on the opposite side of the plate the tool pushes out the bottom layer causing fibres to be delaminated. The specimen was positioned in between the previously drilled 1mm Gi pad
sheets and drilling was carried out after proper alignment as shown in Fig 3.7. Fig 3.8 illustrate the peel-up and push-out action of the drill tool. A thin GI sheet previously drilled was used as pad support. Hocheng and Dharan [34] revealed that the peel up and push out action at the entry and exit of the hole respectively are the main cause for delamination. The peel up force at the entrance is analogous to the action of power screw. The peeling force $F_p$ can be related to the cutting force $F_c$.

$$F_p = F_c / k$$

where $k = f(\mu, \lambda)$  
$\mu =$ Coefficient of friction  
$\lambda =$ Helix angle

It is observed that the pad support used at both the sides reduces the critical forces by restricting the peel up and push-out action causing the reduction in delamination. The holes drilled with and without the pad support on one side and on either sides of the hole are illustrated in Fig.3.9. It is seen that no delamination was observed when pad support was used at both the ends during drilling.
3.5 STATISTICAL ANALYSIS OF DRILLING PERFORMANCE ON UGFRP

3.5.1- $2^k$ Factorial design

Factorial designs [82] are widely used in experiments involving several factors where it is necessary to study the individual and joint effect of the factor on a response. In $2^k$ factorial design $k$ is the factor each at only two levels, low or high. These levels may be qualitative or quantitative. A complete replicate of such a design requires $2 \times 2 \times \cdots \times 2 = 2^k$ observations and is called $2^k$ factorial design. In the present work the $2^k$ factorial design is used to estimate the magnitude and direction of the effects and also to evaluate the percentage contribution of the factor towards the effect.

Table-3.1. Levels of two factors

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>LEVELS</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LOW</td>
<td>HIGH</td>
<td></td>
</tr>
<tr>
<td>Cutting Speed (N) M/min</td>
<td>6.28</td>
<td>25.12</td>
<td></td>
</tr>
<tr>
<td>Feed Rate (F) mm/rev</td>
<td>0.064</td>
<td>0.64</td>
<td></td>
</tr>
</tbody>
</table>

Table-3.2. Treatment combination of the replicates.

<table>
<thead>
<tr>
<th>FACTORS code</th>
<th>Treatment combination</th>
<th>REPLICATES</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>N F</td>
<td>I II III</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>- -</td>
<td>2.49 2.25 2.71</td>
<td>7.45</td>
</tr>
<tr>
<td>'a'</td>
<td>+ -</td>
<td>3.63 3.79 3.98</td>
<td>11.4</td>
</tr>
<tr>
<td>'b'</td>
<td>- +</td>
<td>4.00 4.45 4.15</td>
<td>12.6</td>
</tr>
<tr>
<td>'ab'</td>
<td>+ +</td>
<td>6.67 6.92 7.12</td>
<td>20.71</td>
</tr>
</tbody>
</table>

The factors affecting the machinability considered in the present situation are the drill speed and feed rate and the response will be Surface
Roughness value. The two levels of these two factors are depicted in table-3.1. N and F denote the individual effect of speed and feed rate respectively. NF together represents the combined effect of both the factors on surface roughness values. The treatment combinations of replicates are depicted in table.3.2.

The notation 'a' represents the treatment combination of N at high level and F at low level. 'b' represents N at low level and F at high level and 'ab' represents both the factors N and F at high level. The convention (1) is used to denote both factors at low level.

\[
\text{The main effect of } N = \frac{1}{2} n [ab + a - b - (1)] = +2.01
\]

Similarly \[
\text{the main effect of } F = \frac{1}{2} n [ab - a + b - (1)] = +2.41
\]

The interaction effect NF is the average difference between the effect of N at high level of F and the effect of N at low level of F.

\[
i.e. \quad NF = \frac{1}{2} n [ab - b - a + (1)] = +0.69
\]

The +ve sign of the main effects N, F and NF indicate that in all the cases the effect is to increase the surface roughness value. The magnitude of the interaction effect on surface quality is observed to be least, however the effect of feed rate compared to the effect of other factors is highest.

3.5.2. Regression model

In a \(2^k\) factorial design, an attempt is made to express the results of the experiments in terms of regression model. For example a simple regression model is given by

\[
Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon \quad (1)
\]
Where \( x_1 \) and \( x_2 \) are the coded variables that represents the cutting speed and feed rate respectively and \( \beta \)'s are the regression coefficients. The relationship between the natural variable and coded variable is as follows

\[
X_1 = \frac{N - \frac{N_{\text{low}} + N_{\text{high}}}{2}}{\frac{N_{\text{high}} - N_{\text{low}}}{2}} \quad \text{and} \quad X_2 = \frac{F - \frac{F_{\text{low}} + F_{\text{high}}}{2}}{\frac{F_{\text{high}} - F_{\text{low}}}{2}}
\]

Substituting the high and low level values of \( N \) and \( F \) from the table-3.2 we get

\[
X_1 = 0.00267N - 1.67 \quad \text{and} \quad X_2 = 3.47F - 1.22
\]

\[
\therefore \quad Y = \beta_0 + \beta_1 (0.00267N - 1.67) + \beta_2 (3.47F - 1.22) + \varepsilon \quad (2)
\]

We have the regression coefficients

\[
\beta_0 = \frac{\sum Y}{4n} = \frac{52.16}{4 \times 3} = 4.25
\]

\[
\beta_1 = \text{Main effect of } N / 2 = 2.01 / 2 = 1.005
\]

\[
\beta_2 = \text{Main effect of } F / 2 = 2.41 / 2 = 1.205
\]

Substituting in (1) we get

\[
Y = SR = 4.35 + x_1 + 1.21x_2 \quad (3)
\]

\[
SR = -1.204 + 0.00267N + 4.2F \quad (4)
\]

If the interaction effect is considered the equations will be

\[
Y = SR = 4.35 + x_1 + 1.21x_2 + 0.69x_1x_2 \quad (5)
\]

\[
SR = 2.609 + 0.00047N + 0.203F + 0.0064NF \quad (6)
\]

Fig.3.10 illustrates the relationship between the cutting speed and surface roughness values plotted for different feed rates. Experimental results have been compared with the results evaluated from regression models developed for individual effects and combined effect of the variables (eqn.4 and 6). A linear increase in surface roughness value with the increase of cutting speed and feed rates was observed. Most of the statistical results
have shown good agreement with the experimental results. A slight deviation in the SR values was observed on holes drilled at cutting speeds 8.92 and 17.84 m/min at feed rate 0.25mm/rev. Though, only results at extreme cutting conditions were considered for regression model development, the regression results of middle cutting conditions also were matching well with the experimental results.

![Graph](attachment:image.png)

**Figure 3.10 (a) - (c) Comparison of Experimental and Statistical results.**
### Table 3.3 Analysis of Variance for the drilling experiment on UGFRP.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Sum of Squares SS</th>
<th>Degrees of Freedom, Mean Squares</th>
<th>Variance Ratio F</th>
<th>Percentage Contribution %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>12.1203</td>
<td>1</td>
<td>12.1203</td>
<td>280</td>
</tr>
<tr>
<td>F</td>
<td>17.4243</td>
<td>1</td>
<td>17.4243</td>
<td>373</td>
</tr>
<tr>
<td>NF</td>
<td>1.442</td>
<td>1</td>
<td>1.442</td>
<td>30.89</td>
</tr>
<tr>
<td>Error</td>
<td>0.3734</td>
<td>8</td>
<td>0.04667</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>31.36</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 3.5.3 Analysis of variance

In many experiments involving 2k factorial design, we examined the magnitude and direction of the factors effect to determine which variables are likely to be more effective and important. The analysis of variance was used to confirm this interpretation in the present situation.

Let the Contrast $A = ab + a - b - 1$

$B = ab + b - a - 1$

and $AB = ab + 1 - a - b$

Where $A = N$, $B = F$ and $AB = NF$ these three contrasts are orthogonal and the sum of squares for these contrasts can be computed as follows

\[
SS_{NF} = SS_{AB} = (AB)^2 = 1.4421
\]

\[
SS_N = SS_A = \frac{A^2}{4n} = 12.1203
\]

\[
SS_F = SS_B = \frac{A^2}{4n} = 17.4243
\]

\[
SS_T = \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} Y_{ijk}^2 - \left( \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} Y_{ijk} \right)^2 / 4n
\]

The total sum of squares $SS_T = \frac{258.08 - (52.16)^2}{12} = 31.36$.

The error sum of square $SS_E = SS_T - SS_N - SS_F - SS_{NF} = 0.3734$

These contrast sums of squares completely partition the treatment sum of squares. The tests on the contrasts are usually incorporated in the analysis of
variance as shown in Table-3.3. It is observed that the percentage contribution of the effect of feed rate is high compared to the drill speed. Based on the results of percentage contribution and $F_0$ value it has been concluded that the main effects are statistically significant. This confirms our initial interpretation of the data based on the sign and magnitude of the factor effect.

![Surface roughness values Ra μm](image)

**Figure 3.11** Surface response showing the relationship between Ra value, Cutting speed and feed rate.

3.5.4. The surface response

If several factors in design factorial experiments are quantitative then a response surface may be used to model the relationship between the yield response and the design factors. The regression model in equation (4) can be used to generate surface response plots. Fig.3.11 illustrates the three-dimensional response surface plot of yield (surface roughness values) with respect to drill speed and feed rates. Since the model is first order equation the response surface is a plane. It is observed from the plot that (SR value) yield increases with the increase of drill speed and feed rate. The response
surface could be used to predict the SR values at various speeds and feed rates considered. The response surface is observed to be slightly curved, this is due to a slight interaction effect.

3.5.5 Model adequacy
From the experimental results it is observed that the influence of both the parameters such as drill speed and feed rate cause to increase in SR value. The regression model developed through 2k factorial design is used to identify the magnitude and direction of the effect of individual and combined factors on SR values. Results revealed that influence of both the parameters is on increasing the SR value. However the influence of feed rate in this direction is quite higher than drill speed. Also the interaction effect has shown +ve sign with the magnitude of a small fraction value (+0.69), which indicate that there is a slight increase in SR value.

The regression model can be used to obtain the predicted or fitted value of surface roughness at four points in the design, such as (1), a, b and ab. On substituting -1 and +1 for low and high values of \( x_1 \) and \( x_2 \) in equation (3) we obtain the predicted value of the yield. The difference between the predicted value and the replicate value gives the residuals. Fig.3.12 illustrates the residual plot plotted for residual errors against the fitted values of SR values. From the plot it is observed that the errors are within the range of -2 to +2 and no unusual structure is apparent this revealed that the assumptions made in the analysis are adequate. The equal variance and normality assumptions are easy to check using normal probability plot. Probability plotting is a graphical technique for determining whether sample data conform.
to a hypothesized distribution based on a subjective visual examination of the data.

Fig. 3.12 Residual plot

Fig. 3.13 Probability Plot

Fig. 3.13 illustrate the normal probability plot which shows that the plotted points fall approximately along a straight line. This indicates that the error distribution is normal and the hypothesised model is appropriate. This model will help in selecting the cutting speed and feed rates based on the surface quality requirement.

3.6 RESULTS OF DRILLING EXPERIMENT ON BGFRP SPECIMEN

In this experiment drilling was carried out on bi-directional GFRP specimen by varying cutting speed and feed rate. Specimens with varied fibre percentage
have been selected. The effect of fibre percentage has been compared with the effect of cutting speed and feed rate on the machining performance.

3.6.1. Surface Roughness (SR)

Fig. 3.14 illustrates the effect of cutting speed and fibre volume fraction on surface quality of the holes drilled at 0.075 mm/rev feed rate. A linear increase in surface roughness values with the increase of cutting speed and fibre volume fraction was observed. Minimum surface roughness values ranging from 2.78 to 6.12 μm were observed at lowest cutting speed on specimens with volume fraction ranging from 0.189 to 0.378 respectively. Holes drilled on specimens with fibre fraction ranging from 0.252 to 0.378 at the highest cutting speed 38.94 m/min have shown high surface roughness (Ra) values ranging from 8 to 12 μm respectively. However no much variation on surface quality was observed on specimen with 0.189 volume fraction at this cutting condition.

Fig. 3.15 illustrates the effect of feed rate and fibre volume fraction on surface roughness values. Increase in feed rate and volume fraction cause to increase the surface roughness values, however the extent of increase due to feed rate is comparatively less when compared to the volume fraction. Minimum SR values were observed at 0.075 and 0.15 mm/rev feed rates. On specimen with 0.252 volume fraction the surface roughness values are ranging from 4.17 to 4.62 μm for feed rates ranging from 0.075 to 0.3 mm/rev respectively.
Based on the experimental results the optimum parameters viz. the rotational speed 294 rpm (7.39m/min cutting speed) and feed rates 0.075 to 0.15 mm/rev have shown better results on the specimens with 0.189 and 0.252 volume fraction. On comparing the results of UGFRP & BGFRP laminates, recorded approximately at similar cutting conditions, it is observed that the surface roughness values of bi-directional GFRP specimens were found to be high. As some of the fibres in BGFRP specimens oriented against the direction of cutting edge, these fibres while cutting get bend, compressed and finally sheared, because of which a small fibre portion gets pulled out causing poor surface quality. For better surface quality on BGFRP specimen use of HSS tool with modification or Carbide tool is recommended.
3.6.2. Hole Quality

Fig. 3.16 illustrates the appearance of holes drilled at 0.075 mm/rev feed rate and cutting speed of 7.39 m/min on specimens with fibre volume fraction ranging from 0.189 to 0.441. Upper and lower rows represent the entry and exit side of the holes observed at 10X magnification. Holes drilled on specimens with 0.189 and 0.252 fibre volume fraction have shown better results, however a small amount of gumming at the entrance side of the hole was observed on specimen with 0.189 fibre fraction. Slight delamination and fibre pullout at the entry and exit sides of the hole were observed on specimens of 0.315 and 0.378 fibre volume fraction. Holes drilled on specimen with highest fibre volume fraction 0.441 have shown fuzzy structure with maximum delamination and severe fibre pullout on both the sides.
Fig. 3.17 illustrates the appearance of holes drilled at cutting speed 7.39m/min on specimen with 0.25 fibre volume fraction by varying feed rates. The entry and exit sides of the holes were observed at 10X magnification. A clean hole at the entry with a slight delamination at the exit was observed at feed rate 0.075mm/rev. Holes produced at higher feed rates were found to maximum affected by delamination. Particularly when the uncut portion is small at the entry or exit side of the hole, the outer ply of the composite laminate has got minimum ply support and gets delaminated even with a small thrust force. Proper control in feed rates when the tool approaches near the entry or exit junctions of the hole is required. Much delamination and fibre pullout was observed on holes drilled at feed rate 0.30mm/rev.
3.6.3 Hole diameter variation
Specimens were drilled to produce holes of 8mm diameter. However due to the influence of machining parameters and composite design, a slight variation in hole diameter occur. Excessive variation in hole diameter at the entry to exit creates hole errors like taper or out of roundness.

Fig.3.18 illustrate the effect of drill speed and feed rate on hole diameter variation at the entry and exit side of the holes respectively. No specific relationship was noticed between hole diameter variation and the cutting parameters. However it may be possible to correlate the diameter variation from the entry to exit side of the hole. In most of the cutting conditions the hole size has observed to be enlarged at the entry side.

Fig.3.18 (a) & (b) Influence of Cutting speed on hole dimension at the entry & exit

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**Figure 3.18 (a) & (b) Influence of Cutting speed on hole dimension at the entry & exit**

Fig.3.18 illustrate the effect of drill speed and feed rate on hole diameter variation at the entry and exit side of the holes respectively. No specific relationship was noticed between hole diameter variation and the cutting parameters. However it may be possible to correlate the diameter variation from the entry to exit side of the hole. In most of the cutting conditions the hole size has observed to be enlarged at the entry side.
Probably the longer duration of tool and work contact at this side may be the reason. At feed rate 0.3mm/rev an increase in diameter with the increase of drill speed was observed near the exit, but this trend does not appeared at the entry side. The trends of dimensional fluctuation appear to be varying with the cutting conditions.

Fig 3.19 illustrate the effect of fibre volume fraction and feed rate on hole diameter variation. Though the diameters at the entry side have found to be enlarged, the trend of diameter variation at the entry and exit appears to be somewhat similar. Similarly the specimens with fibre volume fraction 0.189 and 0.441 have shown similar trend of diameter variation, in both the cases.
decrease in diameter with the feed rate was observed. No specific relationship was observed between hole diameter fluctuation with cutting parameters and fibre percentage. However a thorough analysis on this particular aspect may reveal some relationship between dimensional variation with fibre percentage and cutting parameters. The bar diagram revealed that the specimens with fibre volume fractions 0.252 and 0.378 at 0.3 and 0.15 mm/rev feed rates respectively have shown minimum diameter variation. Though 0.02mm reduction in diameter was observed on specimen with fibre volume fraction 0.315, no variation in diameter from the entry to exit side was noticed on the holes drilled at 0.15 and 0.3 mm/rev feed rate.

![Bar diagram showing fibre volume fraction and diameter variation](image)

**Figure 3.20** Effect of fibre volume fraction on chip characteristic

### 3.6.4 Influence of fibre volume fraction on chip characteristic.

**Fig.3.20** illustrate the appearance of chips produced while drilling specimens of various volume fractions at constant cutting speed and feed rate. Minimum cutting speed (7.39m/min) and feed rate (0.076mm/rev) were selected for this analysis. On specimen having volume fraction 0.189 and 0.252, continuous and curly chips were observed. Due to higher percentage of resin in these specimens they deform easily producing continuous chips with smooth...
surface finish. However with the increase of fibre percentage the chips become segmented like with the decrease in length. On specimen with 0.378 fibre volume fraction the chips were in the form of chopped strands and on specimens with 0.441 fibre volume fraction the chips were found to be almost the powdered like. The chip characteristic also is an indicator of surface quality. The results of surface quality are well matching with the chip characteristics. Specimens with fibre fraction 0.189 and 0.252 have shown better results.

3.6.5 Effect of drill tool diameter on surface quality and hole dimension.
Three drill tools of diameters 8mm, 11.5mm and 16mm were used to drill the holes on GFRP composite laminates. The effect of variation in tool diameter on hole surface quality was examined. Surface quality of the holes drilled by bits of smaller diameter was observed to be good. Tools with larger diameter have shown poor surface quality.

![Figure 3.21 Influence of tool diameter and fiber percentage on Surface quality](image)

Fig.3.21 illustrates the effect of tool diameter and fibre percentage on SR values of the holes drilled at 11.81m/min cutting speed, 0.075mm/rev feed
rate by varying tool diameter. The surface roughness values measured on the wall surface of the holes drilled by 8mm-diameter drill bit were ranging from 3.8 to 9.4 μm. However SR values recorded on holes drilled by 11.5mm and 16mm bits were found to be ranging from 7.6 to 14.6μm and 8.4 to 17.4 μm respectively. This indicates that there is deterioration of surface quality with the increase of tool diameter for drilling at same cutting condition.

Figure 3.22 (a-c) Influence of tool diameter on dimensional fluctuation

The variation in cutting speed, which is the function of tool diameter, effects the surface quality. Much variation in SR values of the holes drilled by 8mm and 11.5mm diameter tools was observed. Small variation in surface
quality of the holes drilled on specimens with 0.252 and 0.315 fibre volume fraction was observed. However a sudden increase in SR value was observed on the specimen with 0.315 volume fraction. The trend indicates that the fibre fraction has highest effect on the surface quality than the drill tool diameter.

![Diagram](a) Drill dia = 8mm

![Diagram](b) Drill dia = 11.5mm

![Diagram](c) Drill dia = 16mm

**Figure 3.23 (a-c) Influence of fiber percentage on diameter fluctuation**

Fig. 3.22 illustrate the effect of drill diameter on the hole dimension variation. Except on specimens with fibre volume fraction 0.252 and 0.315 drilled by 16mm diameter bit, no significant variation in hole dimension was
observed. Slight ovality was observed on specimen with 0.315 volume fraction drilled by 11.5mm drill tool. For drilling holes of larger diameter a modification in the drill tool is essential to achieve better surface quality for the same cutting condition.

Fig3.23 illustrates the CMM results measured along the depth of the holes drilled on specimens with varied fiber percentage. The diameters measured on holes drilled by 16mm diameter drill tool with respect to fibre fraction were found to be very close. However slight variation was observed on holes drilled by 8 and 12mm diameter tools.

3.7 STATISTICAL ANALYSIS OF DRILLING PERFORMANCE ON BGFRP

In this analysis a pair of parameters were considered separately to examine the magnitude and direction of individual parameter on the drilling performance. In the first analysis the cutting speed (N) and feed rate (F) were considered and in the second analysis, feed rate(F) and fiber volume fraction (V) were considered. Finally the contribution of the effect of individual parameter on the response were compared. Using the statistical concept, as explained in section 3.5, the magnitudes of the main effects of the variables speed, feed rate and fiber volume fraction have been evaluated. The regression equations obtained for variables speed and feed rate are as follows.

\[
Y = SR = 4.39 + 0.74x_1 + 0.84x_2 \quad --- (7)
\]

\[
SR = 1.92 + 0.0012N + 7.18F \quad --- (8)
\]

Similarly the regression equations for feed rate and fiber percentage are,

\[
Y = SR = 5.22 + 0.84x_1 + 1.59x_2 \quad --- (9)
\]
SR = -0.926 + 7.182 F + 10.61 V \quad \quad (10)

SR = 8.8 F + 11.31V - 3.62FV - 1.24 \quad \quad (11)

The ANOVA contents of the experiments for the variables speed /feed rate and feed rate / fiber volume fraction are depicted in Table 3.4 and 3.5 respectively. The ANOVA results for both the experiments revealed that the main effects are statistically significant for highest confidence level. The interaction effects between the two factors in both the sets of variables are found to be negligible. This confirms to our initial interpretation of the data based on the sign and magnitude of the factor effect.

Table 3.4. ANOVA Table for the variables speed and feed rate

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Sum of Squares SS</th>
<th>Degrees of Freedom,</th>
<th>Mean Squares</th>
<th>Variance Ratio F₀</th>
<th>% Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
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<tr>
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<tr>
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<tr>
<td>Total</td>
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</table>

Table 3.5. ANOVA Table for the variables feed rate and fiber volume fraction

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<tr>
<th>Source of variation</th>
<th>Sum of Squares SS</th>
<th>Degrees of Freedom,</th>
<th>Mean Squares</th>
<th>Variance Ratio F₀</th>
<th>% Contribution</th>
</tr>
</thead>
<tbody>
<tr>
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<td>122.7</td>
<td>21.38</td>
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<tr>
<td>V</td>
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<td>77.23</td>
</tr>
<tr>
<td>FV</td>
<td>0.00134</td>
<td>1</td>
<td>0.00134</td>
<td>0.019</td>
<td>0.0034</td>
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<tr>
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</tr>
<tr>
<td>Total</td>
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</tbody>
</table>
3.8 COMPARISON OF EXPERIMENTAL AND STATISTICAL RESULTS

3.8.1. Cutting Speed and Feed Rate

Fig. 3.24 illustrates the comparison of experimental and regression model results of the experiment when cutting speed and feed rates were varied. In this analysis, effect of two factors cutting speed and feed rate on SR value was examined. From the factorial design, the main effect of cutting speed (N) is +1.475 and the main effect of feed rate (F) is +1.675. Since both these values have positive signs, it is understood that with the increase of any of these factor will increase the yield (SR value). However when compared to the magnitude, it is observed that the magnitude of the effect of feed rate is slightly higher than the magnitude of the effect of drill speed.

The interaction effect has shown –ve sign which indicates that there will be decrease in SR value with the increase of speed and feed rate together, however since the value is found to be very less, the effect has been considered as negligible. Except at cutting speeds 24.12 and 38.94 m/min and 0.15mm/rev feed rate no much variation in results of two models was observed. The trends obtained by regression models as shown in the above figures revealed that there is increase in surface roughness value with the increase of speed and feed rate. At higher speed the tool rotates with higher rotating torque which pulls out the fibre causing a small portion of the fibre extension outside the surface. Also the drill gets worn-out rapidly at higher speed resulting to produce poor surface quality due to inaccuracy in drilling. Similar is the case in the effect of feed rate also. Particularly at the entry and exit side of the hole the top and bottom layers of the laminate get delaminated even at low thrust forces. To achieve fine surface quality it is recommended to
drill at optimized speed and feed rates. Cutting speeds 7.39 and 11.81 m/min have shown better results at all feed rates.

![Graphs showing the correlation between experimental and statistical results for cutting speed and feed rate for different feed rates.](image)

**Figure 3.24** Correlation between Experimental and Statistical results for cutting speed and feed rate

### 3.8.2. Second set of variables (Feed rate F and Fibre Volume V)

In this analysis the effect of two factors like feed rate and fibre volume fraction on SR value was examined. Fig.3.25 (a) and (b) illustrates the comparison between experimental and statistical results on the influence of feed rate and
fiber percentage on surface quality respectively. Except a small variation at feed rate 0.15mm/rev and fibre volume fraction 0.315 most of statistical results are well agreeing with the experimental results. This small variation is mainly because of consideration of extreme results for the statistical analysis. From the main effect values obtained from factorial design, it is observed that in both the cases the values were showing positive sign and the effect of fibre volume fraction was much higher in magnitude when compared to the magnitude of the effect of feed rate. The rate of increase in SR value with the increase of fibre content was observed to be very high. As the glass fibres are abrasive in nature, the tool gets worn out heavily on specimens with higher fibre percentage. The tool has to perform maximum cutting on fibres rather than matrix in the specimen with higher fibre percentage. This might be the cause for poor surface quality on specimens with higher fibre percentage.

![Graph](a) Feed rate mm/rev
Fibre content=30%
Speed=294 rpm
*------- EXPTL
4k Eql.11
... . ... 3.25.(a) & (b) Correlation between Experimental Statistical results for variables feed rate and fiber percentage

![Graph](b) Fiber Volume Fraction
Feed Rate 0.075 mm/rev
Cutting Speed = 7.39 M/min

Figure 3.25.(a) & (b) Correlation between Experimental Statistical results for variables feed rate and fiber percentage
3.8.3. Response surfaces

Fig. 3.26 and 3.27 illustrate the three-dimensional surface responses for variables cutting speed/feed rate and feed rate/fiber volume fraction respectively. The regression equations were used to generate these response surfaces for the first and second set of variables respectively. Since in both the trials the regression equations are first order equation (only the main
effects) the response surfaces are plane. However the interaction effect in first set of variables is \(-0.127\), which is slightly higher than the interaction effect of second. \((-0.072\)). This gives a slightly curved surface in first set of variables. This shows that the interaction effect of first set of variables is more significant than the interaction effect of second set.

From examining the plots we see that yield increases with the increase of drill speed, feed rate and fibre percentage. However the magnitude of the effect of fibre percentage on the yield is very high compared to speed and feed rate. From the over all results it is clear that, along with effect of speed and feed rate, high fibre percentage also plays an important role on surface quality. The percentage of contribution of the effect of fibre content on surface quality is highly significant than the percentage of contribution of the effect of drill speed and feed rate.

![Residual plot for variables speed and feed rate](image1)

![Residual plot for feed rate and fibre percentage.](image2)
3.8.4. Residual plot and model adequacy

Fig. 3.28 and 3.29 illustrate the graphical representation of the residual plots of experiments for variables cutting speed/feed rate and feed rate/fibre volume fraction respectively. From both the plots it is observed that no unusual structure is apparent, hence the assumption made in the analysis are considered to be adequate.

Fig 3.30 and 3.31 illustrate the normal probability plots of the experiments for variables cutting speed/feed rate and feed rate/fibre volume fraction respectively. Taking residuals and normal probabilities along the X and Y co-ordinates respectively plots these graphs. It is observed from the plot that the plotted points approximately fall along a straight line. This indicates that the error distribution is normal and hypothesised model is adequate and appropriate in both the experiments.
CONCLUSION

FRP materials are distinguishably non-homogeneous, anisotropic and often laminated. These factors lead to complexity of developing a sound analysis of the cutting process. The Experimental and the Statistical analysis of the drilling experiments have been carried out on Unidirectional and Bi-directional GFRP composite material with HSS drill tool. The influence of cutting speed, feed rate and fibre volume fraction on surface finish, hole quality and dimensional fluctuation are analysed. The following conclusions are derived from the study.

➢ Higher cutting speeds and feed rates produce high rotational torque and thrust force respectively causing the fibres to be pulled out of the laminate while shearing and results the poor surface quality. Also excessive heat generation at higher drill speeds causes much diameter fluctuation due to hole shrinkage and enlargement.

➢ Excellent surface quality on UGFRP using HSS tool is possible at low cutting speed and feed rate. The optimum cutting parameters for UGFRP specimens based on hole quality and dimensional fluctuation, are 0.064mm/rev feed rate and 12.56 m/min cutting speed. If the surface roughness values recorded in this analysis are within the acceptable range, higher values of cutting speed and feed rate are recommendable for better productivity. However necessary care is essential in selecting the higher values of cutting speed and feed rates to avoid fibre pull out, delamination and thermal degradation.
The delamination can be effectively reduced by proper pad support on either side of the hole while drilling. Resin rich surface could be used on either sides of the laminate to avoid delamination, however cracking around the hole surfaces while fastening is still the limitation. Drill tool modification is required to drill the holes of higher diameter at similar cutting condition.

Based on the extent of the effect, the statistical model developed provides a controlling parameter on which much attention is required in order to improve the machinable characteristic. As in the present model the magnitude of the effect of feed rate is high compare to the effect of cutting speeds, much care is essential on controlling and selecting the feed rates. Most of the regression model results have shown good agreement with the experimental results.

In BGFRP specimen the extent of the influence of fibre volume fraction on surface finish is very high when compared to the influence of drill speed and feed rate. However control over the feed rates near the entry and exit junction of the hole is essential, because these sub-laminates are prone to delaminate even with a small thrust force. The cutting speed 7.39 m/min and feed rate 0.076mm/rev has shown good performance on bi-directional specimens with fibre volume fraction 0.252 and 0.315. Specimen with 0.252 fibre volume fraction has shown good results at all feed rates tested at 7.39m/min cutting speed. As glass fibres are much abrasive in nature, the drill tool get worn out heavily while drilling specimens with higher fibre percentages resulting to produce poor surface quality.
Since the model can give a magnitude and direction of the effect of individual parameters on the surface quality, it would be helpful to an FRP designer in deciding the fibre volume fraction and optimum cutting parameters based on the strength and cut surface quality requirement respectively. The surface response generated using the regression models can give the SR value at any drill speed, feed rate and fibre percentage considered in the present analysis.

On comparing the surface quality of the holes drilled on UGFRP and BGFRP specimens for approximately similar cutting condition, the surface roughness values of the holes drilled on bi-directional GFRP specimens were found to be higher. This is due to the effect of fibre position, as some of the fibres in BGFRP specimens oriented against the direction of cutting edge. During drilling the fibres get bend, compressed and sheared with a portion of fibre pull out causing to produce poor surface.