Effect of the standard and special geometry design of a drill body on quality characteristics and multiple performance optimization in drilling of thick laminated composites

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Abstract

The process parameter effects on quality characteristics of standard and special geometry design of a drill body in dry drilling of Sheet Moulding Compound (SMC) composites which are extensively utilized in structural applications, instrument bases and automotive load floors have been discussed in this report. The drilling experiments using carbide drills were conducted using Response Surface Methodology (RSM). Standard geometry (twist) drill performs better than special geometry (ratio) drill. The optimal process parameter levels were determined as 0.074 mm/rev feed and 750 RPM spindle speed for twist drill and that for ratio drill as 0.091 mm/rev feed and 1250 RPM spindle speed.

Keywords: SMC composite; laminated; twist drill; ratio drill; ANOVA; response surface methodology.

1. Introduction

Glass Fibre Reinforced Epoxy (GFRE) composites are most widely utilized in aerospace, automotive, marine, process industries, construction of military conveyances and machine implements owing to their multi potential properties such as high vigour to weight ratio, high fracture toughness and good dimensional stability [1,2].

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Consequently, the desideratum for precise machining of composites has incremented enormously. Intricacy in the product design necessitates development of the composite product in components, which are conclusively assembled. Thus making holes forms an essential part in product development.

The workpiece is subjected to delamination, fibre breakage, matrix cracking, etc. while drilling fibre reinforced composite materials [3]. Among these defects caused by drilling, delamination which occurs both at the ingestion and exit planes of the work piece is most vital, since it can result in lowering of bearing vigour and thereby reduces accommodation life of the component [3-5]. Bearing strength gets affected by surface roughness of the side walls of the drilled hole. Hence, utmost care is to be worked out to procure defect controlled drilling performance. The fastening efficiency is mostly hooked on the bearing strength which limits the quality of machined holes. Many researchers have suggested that the quality of machined holes is vigorously dependent on process parameters such as feed and spindle speed [2,3,6-9] which have big influence on the thrust force and torque. Therefore, to attain maximum hole quality it is essential to optimize the drilling process parameter levels.

Many endeavours have been established by sundry researchers in drilling laminated glass fibre reinforced composites. They are briefly presented below. Durao et al. [10] drilled unidirectional carbon fibre/epoxy laminates plates with different tool geometries and found a carbide twist drill performs better towards minimum delamination and higher bearing strength at a lower feed rate. They [11] also found that low feed rates reduces the axial thrust force and consequently the risk of delamination onset. Durao et al. [12] made holes in carbon fibre reinforced laminates with different tool geometries and compared the damage based on data extracted from radiographic images. They also compared damage results with mechanical test results. Durao et al. [13] stated that a proper combination of all the factors involved in drilling operations, like tool material, tool geometry and cutting parameters, such as feed rate or cutting speed, can lead to the reduction of delamination damage. They also found that WC tools are more favourable than PCD tools for small series of holes. When GFRP composites are machined, it is clearly seen that the fibres cut across and along their lay direction, leaving deformed projections and partially disclosed fibres on the machined surface [14]. Ogawa et al. [15] verbalized 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 entirely dependent on thrust force alone but additionally on torque. They too establish 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. Singh et al. [17] verbalized the desideratum for a controller which can control thrust force, torque, cutting speed and feed rate to have damage free drilling in polymer matrix composites. De Albuquerque et al. [18] evaluated the drilling delamination caused in laminate plates from radiographic images by employing a novel solution based on artificial neural network. Khashaba et al. [19] considered the effects of feed, drill diameter and cutting speed on thrust force, delamination size and surface roughness while drilling GFRE composites. They constitute that the increase in the feed also increases the thrust force which in turn increases the surface roughness and delamination damage and subsequently low bearing strength. Rajamurugan et al. [20] verbally expressed that feed rate is the ingredient which has great influence on the thrust force followed by the drill diameter in machining GFRP composites.

The literature review indicates that many researchers have worked towards procuring hole quality considering thrust force, torque, surface roughness and damage/delamination around the drilled hole in thin laminated composites. Yet, literature on the drilling of thick laminated composites and that on the drilling of composites with special geometry is scarce. Thus the research interest in the present work is to investigate the relative influence of drilling process parameters (feed and spindle speed) on quality characteristics (thrust force, torque, surface roughness and ovality) for standard and special geometry design of a drill body. Also to procure optimal process parameter levels in the culled range for aperture quality considering minimum of all the quality characteristics together utilizing Response Surface Methodology (RSM). If quality characteristics shall be improved, the bearing strength of the drilled holes and thereby the service lifetime of the assembled components can be substantially incremented. This investigation will be useful for the fabrication industry working with Sheet Moulding Compound (SMC) composites. SMC composites finds application in building products, automotive load floors, water tanks, structural applications, public transport seats, stadium seats, complex ribbed parts such as automobile front-end panels, business-machine housing, instrument bases and many other innovative new products.
2. Experimental details

SMC bar which is a GFRE laminated composite with maximum fibre weight fraction was chosen as the workpiece. SMC bar was made by compression moulding utilizing epoxy resin and E-CR (electrically insulated and corrosive resistant) glass two directional woven rovings with 70 % fibre weight fraction (59% fibre volume fraction) and has 170 mm length, 55 mm width and 20 mm thickness. Like sheet metal, composite materials having more than 6 mm thickness can be classified as thick composites. The mechanical properties of the workpiece have been found out by various tests and are presented in Table 1.

Table 1. Mechanical properties of GFRE composite

<table>
<thead>
<tr>
<th>Properties</th>
<th>ASTM standards</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>D638</td>
<td>MPa</td>
<td>410</td>
</tr>
<tr>
<td>Tensile modulus</td>
<td>D638</td>
<td>MPa</td>
<td>3215</td>
</tr>
<tr>
<td>Tensile elongation</td>
<td>D638</td>
<td>-</td>
<td>17.30 %</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>D695</td>
<td>MPa</td>
<td>314</td>
</tr>
<tr>
<td>Compressive modulus</td>
<td>D695</td>
<td>MPa</td>
<td>10130</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>D790</td>
<td>MPa</td>
<td>58</td>
</tr>
<tr>
<td>Double shear strength</td>
<td>D2344</td>
<td>MPa</td>
<td>204</td>
</tr>
</tbody>
</table>

Fig. 1. SEM image of workpiece.

Fig. 2. (a) twist drill; (b) ratio drill.

Fig. 3. Experimental setup.

The micrograph of GFRE composite obtained through a Scanning Electron Microscope (SEM) is presented in Fig. 1. The elemental composition of SMC composite in weight % obtained through Energy Dispersive X-ray
Spectrometry (EDX) with a spot size of 350 is found to be Carbon – 67.30 %, Oxygen – 29.04 %, Sodium - 0.17 %, Magnesium - 0.07 %, Aluminium – 0.68 %, Silicon – 1.69 %, Chlorine – 0.22 %, Potassium – 0.10 %, Calcium – 0.72 % and Titanium – 0.02 %. Twist drill (standard geometry, Sandvik No. R840 1000 A1A) and Ratio drill (Special geometry, Guhring No. 02475), constructed of tungsten carbide of grade K, was utilized in this study (Fig. 2) to engender through holes. The name ratio drill arises due to cross shaped web thinning form which is similar to ratio cross. For the same coating, the difference in the colours of drills is due to the difference between drill companies in applying the same. The designation of the drills is given in Table 2. CNC machining centre (ARIX VMC 100) was acclimated to perform the drilling operations. The GFRE composite was mounted on the fixture which in turn was mounted on a dynamometer on the table of CNC machining centre (Fig. 3).

### Table 2. Specification of the drills

<table>
<thead>
<tr>
<th>Specification</th>
<th>Twist drill</th>
<th>Ratio drill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill standard</td>
<td>DIN 6537</td>
<td>DIN 6537K R-RT1</td>
</tr>
<tr>
<td>Shank type</td>
<td>Cylindrical</td>
<td>Cylindrical</td>
</tr>
<tr>
<td>Coolant type</td>
<td>Internal</td>
<td>External</td>
</tr>
<tr>
<td>Point geometry</td>
<td>Standard (Conical)</td>
<td>Special (Relieved cone)</td>
</tr>
<tr>
<td>Chisel</td>
<td>Bow shaped (nonlinear)</td>
<td>Sharp edged (linear)</td>
</tr>
<tr>
<td>Cutting lip</td>
<td>Straight, sharp</td>
<td>Concave, honed</td>
</tr>
<tr>
<td>Drill diameter (mm)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>No. of flutes</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Helix angle</td>
<td>30°</td>
<td>30°</td>
</tr>
<tr>
<td>Point angle</td>
<td>140°</td>
<td>140°</td>
</tr>
<tr>
<td>Overall length (mm)</td>
<td>89</td>
<td>89</td>
</tr>
<tr>
<td>Coating (6 – 8 μm)</td>
<td>TiN/TiAlN</td>
<td>TiN + TiAlN</td>
</tr>
</tbody>
</table>

2.1. Thrust force, torque, surface roughness and ovality measurement

The axial thrust force and torque during drilling were quantified utilizing a piezoelectric dynamometer (Kistler make, Model No. 9257B). Dynamic component of thrust force was taken into consideration for minimizing the damage of the hole [15]. The vacuum cleaner was habituated to abstract powdery chips away from the cutting zone. The average surface roughness (Ra) of the side walls of the drilled holes were measured along the feed direction (i.e. across the lay) using a portable surface roughness measuring instrument, Surftest SJ-201P, whose stylus is of 6 mm height and 3.5 mm width and having a tip radius of 5 μm. The surface roughness instrument was set to a cut off length of 0.8 mm, traverse speed of 1 mm/sec and an evaluation length of 4 mm. R //<span class="subscript">a</span>// was used primarily to monitor production processes where gradual changes in surface finish due to cutting wear can occur. The ovality (imperfectness of circularity) of the drilled holes was quantified utilizing coordinate measuring machine (CMM), Tesa Micro-Hite 3D 474, which uses Tesa-Reflex MH3D software and TESASTAR probe head with adjustable trigger force. The surface roughness (R //<span class="subscript">a</span>//) and ovality were measured many times at the entry, middle and exit of the drilled holes and an average was taken for analysis. The average maximum flank wear of the drills was measured using 2D vision measurement machine (Model OL-2515) having a resolution of 1 μm.

2.2. Plan of experiments

The RSM is a collection of mathematical and statistical procedures, used for the analysis of problems in which the desired response is affected by several parameters and for optimizing the process parameter levels considering multiple responses together [21]. The experiments were designed by applying RSM with selected cutting conditions [16]. The process parameters and their levels selected for the experiments are shown in Table 3. In applying RSM, central composite face centred (CCF) design was utilized which fits the second order response surfaces very accurately. The above matrix requires three levels of each parameter and yields 13 experiments (standard order) for two parameters. All the coefficients were obtained by applying CCF design utilizing the Design-Expert statistical software package (version 7). After finding out the paramount coefficients (at 95% confidence level), the final
models were developed utilizing only these coefficients for the quality characteristics of dry drilling in SMC composites. Each experiment has been reiterated three times and average values of the dynamic component of thrust force, mean torque, surface roughness ($R_a$) and ovality were taken to consider the comparative significance of process parameters and to procure optimal parameter levels.

### Table 3. Process parameters and their levels in drilling

<table>
<thead>
<tr>
<th>Std.</th>
<th>Run</th>
<th>Process parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Feed (mm/rev)</td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0.15</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>0.05</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>0.15</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>0.10</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>0.10</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>0.10</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>0.10</td>
</tr>
<tr>
<td>11</td>
<td>12</td>
<td>0.10</td>
</tr>
<tr>
<td>12</td>
<td>11</td>
<td>0.10</td>
</tr>
<tr>
<td>13</td>
<td>13</td>
<td>0.10</td>
</tr>
</tbody>
</table>

### 3. Experimental results and discussions

Two twist drills have been utilized for making 29 holes. The average maximum flank wear of first twist drill after making 15 holes and that of second twist drill after making remaining holes was negligible. Two ratio drills have been utilized for making 29 holes. The average maximum flank wear of first ratio drill after making 15 holes was 0.029 mm and that of second ratio drill after making remaining holes was also 0.029 mm. The maximum flank wear for reconditioning of tool [22] is 4% of the tool diameter (i.e. 0.4 mm in this case). Therefore the effect of 0.029 mm flank wear on hole quality will be negligible and hence tool wear is not considered in this study. From Fig. 4, a plot of experimental results, it is observed that twist drill gives minimum values for the quality characteristics (thrust force, torque and surface roughness) than that of ratio drill within the range examined, which is desirable towards defect controlled drilling. The decrease in thrust force, torque and surface roughness observed in the case of twist drill can be attributed to its standard geometry.

When surface roughness considered separately, ratio drill performs better than twist drill at higher feed and speed values. As feed increases with speed, thrust force and torque increases for both the drills. This may be due to the incrementing cross-sectional area of the undeformed chip [23]. As speed increases with feed, thrust force and torque almost remains constant for both twist and ratio drills.

As feed and speed increases, surface roughness ($R_a$) increases for a twist drill whereas for ratio drill, surface roughness decreases as feed increases with speed and stays near constant as speed increases with feed. At high feed values the abstraction of fibre from the matrix is partially sheared leading to comparatively high surface roughness. In contrast, at lesser feeds a consummate shearing of the fibre was occurring, resulting in a relatively good surface finish [19]. Therefore, it can be concluded that the special geometry design of ratio drill produces a complete shearing of fibre even at higher feeds. As feed increases with speed, ovality decreases for both the drills. As speed increases with feed, ovality almost remains constant for both the drills. Ratio drill gives much lesser ovality than a twist drill because of its special point geometry (relieved cone). It is observed that for both the drills, the quality of machined holes is vigorously dependent only on the process parameter feed. Figure 5 is a typical example for response of quality characteristics with process parameters.
Fig. 4. Response graph of quality characteristics with process parameters.

Fig. 5. Response surface of surface roughness for (a) twist drill; (b) ratio drill.
3.1. Adequacy analysis of the model using ANOVA

The following response surface models with significant model terms were obtained by using RSM.

**Twist drill:**

\[
\text{Thrust force} = + 64.72026 + 684.06667 \times \text{Feed} \tag{1}
\]

\[
\text{Torque} = + 0.058462 + 2.46667 \times \text{Feed} - 6.66667E-05 \times \text{Speed} \tag{2}
\]

\[
\text{Surface roughness} = - 9.80048 + 12.8 \times \text{Feed} + 0.020862 \times \text{Speed} - 9.47429E-06 \times \text{Speed}^2 \tag{3}
\]

\[
\text{Ovality} = +11.08209 - 3.30264 \times \text{Feed} + 0.020862 \times \text{Speed} - 9.47429E-06 \times \text{Speed}^2 \tag{4}
\]

**Ratio Drill:**

\[
\text{Thrust force} = + 105.02359 + 1493.53333 \times \text{Feed} \tag{5}
\]

\[
\text{Torque} = + 0.2759 + 2.86667 \times \text{Feed} - 9.33333E-05 \times \text{Speed} \tag{6}
\]

\[
\text{Surface roughness} = + 4.76923 - 16.2 \times \text{Feed} \tag{7}
\]

\[
\text{Ovality} = +10.35948 - 4.95714 \times \text{Feed} + 3.33333E-05 \times \text{Speed} + 18.81905 \times \text{Feed}^2 \tag{8}
\]

The adequateness of the response surface models (1) - (8) was tested utilizing the Analysis of Variance (ANOVA) technique and the results of the regression model (1) fitting in the form of ANOVA is given in Table 4 as a typical example for adequate analysis. As per this technique, the computed value of F-ratio of the developed model should be more than the tabulated value of the F - table, for 95% confidence level, for the model to be adequate.

Table 4. ANOVA results for the thrust force with a twist drill

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F Value</th>
<th>p-value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>7019.21</td>
<td>1</td>
<td>7019.21</td>
<td>81.26</td>
<td>&lt; 0.0001</td>
<td>significant</td>
</tr>
<tr>
<td>Feed, F</td>
<td>7019.21</td>
<td>1</td>
<td>7019.21</td>
<td>81.26</td>
<td>&lt; 0.0001</td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td>950.14</td>
<td>11</td>
<td>86.38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of fit</td>
<td>950.14</td>
<td>7</td>
<td>135.73</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pure error</td>
<td>0.000</td>
<td>4</td>
<td>0.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected total</td>
<td>7969.35</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Standard Deviation</th>
<th>9.29</th>
<th>R²</th>
<th>0.8808</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>133.13</td>
<td>Adjusted R²</td>
<td>0.8699</td>
</tr>
<tr>
<td>Coefficient of variation %</td>
<td>6.98</td>
<td>Predicted R²</td>
<td>0.8556</td>
</tr>
<tr>
<td>PRESS</td>
<td>1150.60</td>
<td>Adequate Precision</td>
<td>18.765</td>
</tr>
</tbody>
</table>

The Model F-value of 81.26 for thrust force implicatively insinuates the model is consequential. There is just a 0.01% probability that a "Model F-Value" this immensely colossal could occur due to noise. Values of "Prob > F" less than 0.05 designate model terms are consequential. For thrust force F (feed) is a consequential model term. Lack of fit is not paramount as it is desired. A relatively lower value of the coefficient of variation betokens amended precision and reliability of the conducted experiments.

The determination coefficient (R²) betokens the goodness of fit of the model, i.e. it denotes the acquiescent between experimental and predicted values. The determination coefficient betokens that only remaining % of the
total variations is not expounded by the model. The obtained $R^2$ value of 0.8808 indicates a more preponderant fit of the model. The "Pred R-Squared" of 0.8556 is in plausible accordance with the "Adj R-Squared" of 0.8699. "Adeq Precision" measures the signal to noise ratio. A ratio more preponderant than 4 is desirable. The obtained ratio of 18.765 indicates an adequate signal. Therefore, the model (1) for thrust force in terms of the actual factors is adequate and can be habituated to navigate the design space. Similarly, the regression models (2) – (8) have been checked and found to be adequate.

3.2. Adequacy analysis of model using response surface graphs

The accuracy of the models obtained for quality characteristics with twist drill and ratio drill have been checked by the residual analysis [21]. It is essential that residuals should be normally distributed in order to ascertain the validity of the regression analysis. The obtained normal probability plots of the residuals for the quality characteristics with twist drill and ratio drill reveals that the residuals are closely falling on the straight line, which denotes the errors are distributed normally [24] and adequately support the least square fit.

Residuals with reverence to the experimental runs for quality characteristics with the two different drills have been examined. The residuals do not show any conspicuous pattern and are distributed in both positive and negative directions. This implicatively insinuates that the models are adequate and there is no reason to suspect any contravention of the independence. The scatter correlation graphs obtained for quality characteristics with the two different drills clearly shows that the prognostications made by the mathematical model are in good accordance with the experimental values. Figure 6 is a typical example for adequacy analysis of model using response surface graphs.

![Residuals vs. Run](image)
3.3. Optimizing the process parameter levels in drilling SMC composites

RSM is utilized to determine the optimal set of process parameter levels that engender a maximum or minimum value of the response [25]. In the present investigation the process parameter levels corresponding to the minimization of all the quality characteristics together are considered as optimal. The desirability graph (Fig. 7a) shows that the process parameter level combination (0.074 mm/rev feed and 750 RPM spindle speed) having the
highest desirability of 0.615 is optimum for drilling SMC composites with twist drill of diameter 10 mm. The above optimal parameter levels for a twist drill predicts 115.22 N, 0.19 Nm, 1.46 μm and 10.608 mm as thrust force, torque, surface roughness and ovality respectively. Similarly the desirability graph for ratio drill (Fig. 7b) reveals that the process parameter level combination (0.091 mm/rev feed and 1250 RPM spindle speed) having the highest desirability of 0.573 is optimum for drilling the composites. The above optimal parameter levels for ratio drill predicts 241.09 N, 0.42 Nm, 3.29 μm and 10.106 mm as thrust force, torque, surface roughness and ovality respectively.

3.4. Validation test

The intention of the validation test is to attest conclusions drawn during the analysis [26]. In one case the model fit and predicted values at optimal levels has been arrived, the last step is to affirm the agreement of regression model results with experimental values and thereby guarantee the betterment of the quality characteristics at these levels. Two experimental runs with three trials each were conducted at the corresponding optimal values of process parameters. The obtained results of both experimental and predicted values show the same results within ±10% error. Hence, the above response surface models demonstrate a feasible and an efficient means for the evaluation of quality characteristics within the chosen range of parameter levels in drilling SMC composites.

The average experimental values of quality characteristics obtained during optimal drilling of SMC composites using twist drill and ratio drill is shown in Fig. 8. It is observed that twist drill gives minimum value for all the quality characteristics (except ovality) than ratio drill. Thrust force, torque and surface roughness have been reduced by 50.47 %, 53.49 % and 53.22 % respectively in the optimal drilling of SMC composites using a twist drill as compared to that of ratio drill. Likewise, it is observed that ovality of the drilled holes obtained through twist drill is slightly greater (5.1 %) than that of ratio drill. It can be understood from the confirmation experimental results that the quality characteristics has greatly been amended by the optimal drilling parameter levels. The average range of surface roughness in drilling is 1.6 – 6.3 μm [27] and the value of surface roughness obtained with optimal process parameter levels falls well within this average range.

4. Conclusions

This paper has described the utilization of Response Surface Methodology (RSM) to investigate the comparative influence of drilling process parameters on quality characteristics of standard and special geometry design of a drill
body, adequacy analysis of response surface models and to procure optimal process parameter levels in the selected range for hole quality. Drilling experiments were carried out utilizing coated tungsten carbide drills (twist drill and ratio drill) of diameter 10 mm in SMC composites having a maximum fibre weight fraction (70%) and of 20 mm thick. From this investigation, the following paramount conclusions were derived:

- Standard geometry (twist) drill performs better than special geometry (ratio) drill in drilling SMC composites.
- It is observed that for both twist drill and ratio drill, feed is more consequential in influencing the quality characteristics.
- For ratio drill in contrast with the twist drill surface roughness of the drilled hole walls decreases as feed increases with speed and this is because of its special point geometry (relieved cone).
- Ratio drill gives lesser ovality (imperfectness of circularity) than a twist drill because of its special point geometry (relieved cone).
- The process parameter level combination (0.074 mm/rev feed and 750 RPM spindle speed) having the highest desirability of 0.615 is optimum for drilling SMC composites with a twist drill. Likewise the process parameter level combination (0.091 mm/rev feed and 1250 RPM spindle speed) having the highest desirability of 0.573 is optimum for drilling the thick laminated GFRE composites with ratio drill.
- Thrust force, torque and surface roughness have been reduced by 50.47 %, 53.49 % and 53.22 % respectively in the optimal drilling of SMC composites utilizing a twist drill as compared to that of ratio drill.
- At optimal drilling parameter levels, ovality of the drilled holes obtained through twist drill is slightly greater (5.1 %) than that of ratio drill.
- The developed response surface models can be effectively applied to anticipate the quality characteristics within the chosen range of parameter levels.

Acknowledgements

The authors are grateful to M/s. Sunrise Fibre Glass Industries, Bengaluru, India for providing the composite materials for this research study.

References