Optimization of machining parameters on microdrilling of CFRP composites by Taguchi based desirability function analysis

D Rajkumar*a) P Ranjithkumarb & C Sathiya Narayanc

*aDepartment of Production Engineering, JJ College of Engineering and Technology, Tiruchirappalli 620 009, India
bDepartment of Mechanical Engineering, MAM School of Engineering, Sriganur 621 105, India
cDepartment of Production Engineering, National Institute of Technology, Tiruchirappalli 620 015, India

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Microdrilling of CFRP composite materials is a complex process due to its properties and defects occur during the machining process. Optimization of process parameters is important to achieve the desired responses. This paper implies a new approach for optimizing the process parameters on drilling carbon fibre reinforced polymer (CFRP) composites. Optimization of process parameters is done by a method named as desirability function analysis (DFA), which is very useful tool to optimize multiple response problems. In microdrilling process, the feed rate and spindle speed and air pressure are selected as input parameter. Circularity and Feret’s diameter are taken as output parameters. The 0.5 mm solid carbide drill is chosen for microdrilling process. Analysis of variance (ANOVA) is adapted to investigate the performance characteristics of machining parameters. The confirmation tests are conducted to validate the test result. The analysis reveals out that hole quality is mostly influenced by air pressure.

Keywords: CFRP, Solid carbide, Desirability function analysis, ANOVA

Manufacturing is the backbone of any industrialized nation. In the present industries, the miniaturization components production is increases in various fields such as bio-electronics, bio-medical, automotive, aviation. These miniaturized parts and a component are manufactured by micromachining process. The micromachining processes1 are classified as shown in Fig. 1. Among the different micromachining processes, microdrilling is the one of the traditional mechanical micromachining process/tool based micromachining process. Vertical machining center (VMC) is a one of the tool based machining process that is widely used in industries because of its unique capabilities. It can machine any materials irrespective of their mechanical properties2. The advantage of VMC process is that it exerts significantly very small cost comparing to other advanced micromachining process3. The traditional material removal mechanism (VMC) is similar to advanced micromachine. During machining, the spindle speed and feed rate between the tool and work-piece which is separated by micron level metal and flowed out with flute gap, micron level metal removal process takes place. In order to achieve the green machining4,5, dry machining is chosen for this work and few authors used the air pressure is considered as one of the input parameters for small hole fabrication6,7. Therefore, externally compressed air pressure is proposed on machining CFRP composites. Some of the applications parts VMC produces are orifices for biomedical devices, micro-fluidic channels, gas-turbine vents, stylus tips for micro coordinate measurement machines probing heads, and three-dimensional cavities on polycrystalline diamond (PCD)8-10. The characteristic of CFRP composites are light weight, high modulus, specific strength, superior corrosion resistance, high fracture toughness and high resistance to chemical and avoid microbiological attacks.

Hull et al.11 described that these materials have been widely used in variety of applications, such as electronic industries in fabricating printed circuit boards, parts in aircraft brakes, forks in automobile and machine tools in damped structures. In the recent years, while fabricating micro-holes on CFRP material many difficulties have been faced by manufacturing industries. The difficulties faced during drilling of CFRP material such as the deflection of tool, positional accuracy of tool, handling and holding of microtool, requirement of special attachment for tool, improper...
hole dimension, delamination, circularity error and fibre/resin pullout. The drilling of CFRP composite material varies from that of conventional metal machining. Since CFRP material is an abrasive, the tool wear is high. Therefore, Davim et al.\textsuperscript{12} stated that the process parameters are to be carefully selected while machining. Due to its anisotropy and/or in-homogeneity, fixed plastic deformation and abrasive nature, drilling of CFRP composites is a constrained work. In order to overcome these problems and to achieve the desired quality of the machined microhole, it is important to know the cutting mechanisms of material removal, kinetics of machining processes by Sreejith et al.\textsuperscript{13} Precise machining is required to be performed to make sure the dimensional stability and interface quality. However, the structural properties of this material make it difficult in finish machining process.

Madhavan et al.\textsuperscript{14} investigated the influence of drilling geometry on the thrust force and delamination while using different tool materials to machine carbon fibre reinforced epoxy composites. From the experimental results, they found that the minimum thrust force was obtained at low spindle speed, minimum delamination occurs at high speed while using carbide as drill materials. Krishnamoorthy et al.\textsuperscript{15} have used solid carbide tool material having diameter of 4 mm, 8 mm and 12 mm to machine CFRP and developed model for delamination factor using ANN. The error between experimental value and predicted value has been reported to be within the acceptable limit in their work. Krishnaraj et al.\textsuperscript{16} have used 5 mm solid carbide tool material to machine CFRP. The responses thrust force, hole size, circularity, delamination are taken for analysis. From the analysis found that feed rate has a greater influence on thrust force, delamination and hole size and spindle speed is influence the circularity of the drilled hole.

Xu et al.\textsuperscript{17} investigated the machinability of CFRP composite and observed that the minimum hole defects occurred when drilling with higher spindle speed and
lower feed rate. The works of various authors\textsuperscript{18-22} reported that the cutting force, delamination factor and circularity error were strongly depend on cutting parameters, tool material and its geometry. The term feret’s diameter is mostly applied in bio-sensors, bio-electronics and nano-particles analysis field which describes quality the micro-hole. In this case, the circularity and feret’s diameter are considered to analysis the hole performance. From the literatures, it is found that the most of the authors have conducted experiments on CFRP laminates using having diameter more than 1 mm upto 16 mm using carbide tool material. Very few of the authors have involved in drilling micro-hole which are less than 1 mm on the CFRP material. However, they CFRP materials can be used in PCB (printed circuit board) application. The CFRP materials can be used for many applications components such as PCBs, satellite antenna, access doors, pipes, bridges and walkways, panels, wheel chairs and body panels and these components need microdrill in it. Therefore, the microdrilling of CFRP material has been attempted in this work. However, the micro-hole should be with minimum circularity error and feret’s diameters. In order to obtain minimum circularity error and feret’s diameters, it is necessary to use optimization techniques to find optimal machining parameters. Design of experiment is conveniently used for these purposes.

Taguchi method\textsuperscript{23} is practical, economical and user friendly tool for modeling and prediction. Taguchi method is an off-line quality control methodology; it is to be used in many manufacturing industries. Desirability function analysis (DFA) was performed to combine the multiple performance responses in to one numerical value. This value is used to determine the optimal machine parameter settings. Analysis of variance is employed to investigate the most influencing parameters on the circularity and feret’s diameter. This study aims to investigate the impact of three very important machining parameters of CNC VMC (feed rate, spindle speed and air pressure) on the quality of microhole using video measurement system and image processing. Some of the measures to quantify the quality of the microholes are circularity and average diameter at the entrance of the microholes\textsuperscript{24}.

Desirability Function Analysis

DFA\textsuperscript{25} is one of the most widely used methods in industry for the optimization of multi responses problems. Desirability function analysis is used to convert the multi responses problems into single response problems. As a result, optimization of the complicated multi response problems can be converted into optimization of a single response problem termed as composite desirability.

Optimization steps using desirability function analysis

\textbf{Step 1:} determine the individual desirability index \((d_i)\): determine the individual desirability index \((d_i)\) for the corresponding responses using the formula proposed by the Derringer and Suich. There are three expression forms of the desirability functions according to the response characteristics.

**The-nominal-the best:** The desirability function of the nominal-the-best can be written as the term Eq. (1). The value of \(\hat{y}\) is required to achieve a particular target \(T\). When the \(\hat{y}\) equals to \(T\), the desirability value equals to 1; if the departure of \(\hat{y}\) exceeds a particular range from the target, the desirability value equals to 0 and, such situation represents the worst case.

\[
d_i = \begin{cases} 
\frac{(\hat{y} - y_{\text{max}})}{(y_{\text{max}} - y_{\text{min}})}, & y_{\text{min}} \leq \hat{y} \leq y_{\text{max}}, \ s \geq 0 \\
0, & \text{otherwise} 
\end{cases} \quad \text{... (1)} 
\]

where, the \(y_{\text{max}}\) and \(y_{\text{min}}\) represent the upper/lower tolerance limits of \(\hat{y}\) and, \(s\) and \(t\) represent the weights.

**The-larger-the better:** The desirability function of the-larger-the better can be written as the term Eq. (2). The value of \(\hat{y}\) is expected to be the larger the better. When the \(\hat{y}\) exceed a particular criteria value, which can be viewed as the requirement, the desirability value equals to 1; if the \(\hat{y}\) is less than a particular criteria value, which is unacceptable, the desirability value equals to 0.

\[
d_i = \begin{cases} 
0, & \hat{y} \leq y_{\text{min}} \\
\frac{(\hat{y} - y_{\text{min}})}{(y_{\text{max}} - y_{\text{min}})}, & y_{\text{min}} \leq \hat{y} \leq y_{\text{max}}, \ r \geq 0 \\
1, & \hat{y} \geq y_{\text{min}} 
\end{cases} \quad \text{... (2)} 
\]

where, the \(y_{\text{min}}\) represents the lower tolerance limit of \(\hat{y}\), the \(y_{\text{max}}\) represents the upper tolerance limit of \(\hat{y}\) and \(r\) represents the weight.
**The-smaller-the-better**: The desirability function of the-smaller-the-better can be written as the term \( d_i \). The value of \( \hat{y} \) is expected to be the smaller the better. When the \( \hat{y} \) is less than a particular criteria value, the desirability value equals to 1; if the \( \hat{y} \) excess a particular criteria value, the desirability value equals to 0.

\[
d_i = \begin{cases} 
1, & \hat{y} \leq y_{\text{min}} \\
\left(\frac{\hat{y} - y_{\text{min}}}{y_{\text{max}} - y_{\text{min}}}\right)^r, & y_{\text{min}} \leq \hat{y} \leq y_{\text{max}}, \quad r \geq 0 \\
0, & \hat{y} \geq y_{\text{max}}
\end{cases}
\]

where, the \( y_{\text{min}} \) represents the lower tolerance limit of \( \hat{y} \), the \( y_{\text{max}} \) represents the upper tolerance limit of \( \hat{y} \) and \( r \) represents the weight. The \( s, t \) and \( r \) terms in Eqs (1)-(3) indicate the weights and they are defined according to the requirement of the user. If the corresponding response is expected to be closer to the target, the weight can be set to the larger value; otherwise, the weight can be set to the smaller value.

**Step 2**: Compute the composite desirability \( (d_C) \): The individual desirability index of all the responses can be combined to form a single value called composite desirability \( (d_C) \) by the following equation Eq. (4)

\[
d_C = \sqrt[\sum w_i]{d_1^w_1 \times d_2^w_2 \times \cdots \times d_i^w_i}
\]

where, \( d_i \) is the individual desirability of the property \( Y_i \), \( w_i \) is the weight of the property \( "Y_i" \) in the composite desirability and \( w \) is the sum of the individual weights.

**Step 3**: Determine the optimal parameter and its level combination: The higher the composite desirability value implies better product quality. Therefore on the basis of the composite desirability \( (d_C) \), the parameter effect and the optimum level for each controllable parameter are estimated.

**Step 4**: Perform ANOVA for identifying the significant parameters. ANOVA establishes the relative significance of parameters in terms of their percentage contribution. The calculated total sum of square values is used to measure the relative influence of the parameters.

**Step 5**: Calculate the predicted optimum condition: Once the optimal level of the design parameters has been selected, the final step is to predict and verify the quality characteristics using the optimal level of the design parameters.

**Experimental Set-up**

The machining experiments were carried out using CNC VMC that is equipped with microtool holder namely ER32 collet chuck shown in Fig. 2 by using the experimental conditions shown in Table 1. The micro carbide drill mounted in the collect and the collect fixed on the main spindle drive. The CFRP composite is mounted on the worktable fixture. Experiments were conducted as per design of experiments by considering feed rate, spindle speed and air pressure as input parameters. The range of input parameters was chosen from trial experiments and previous studies. Thus, 9 holes were machined and microscopic images of the microholes are captured using VMS-2010F video measuring system. Circularity \( (C) \) and Feret’s diameter \( (F) \) (ratio of major axis diameter to the minor axis diameter) of the microholes were measured and compared using an image-processing tool (image J), in which the value of circularity \( (C) \) is calculated using \( C = \frac{4 \pi A}{P^2} \), where \( A \) is the area of the circle, and \( P \) is the perimeter of the circle. If the value of circularity is closer to 1, then it is perfect circle and vice versa.

<table>
<thead>
<tr>
<th>Process parameters</th>
<th>Notation</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed rate (mm/min)</td>
<td>( F )</td>
<td>0.01 0.03 0.05</td>
</tr>
<tr>
<td>Spindle speed (rpm)</td>
<td>( S )</td>
<td>2000 2500 3000</td>
</tr>
<tr>
<td>Air pressure (bars)</td>
<td>( P )</td>
<td>1 3 5</td>
</tr>
</tbody>
</table>

![Fig. 2 — Collet chuck set](image-url)
Results and Discussion

Drilling experiments have been carried out based on L₉ orthogonal array to investigate the influence of the predominant process parameters on the responses circularity and feret’s diameter. The results of the experiments are given Table 2. From the experimental results the regression modelings are formed.

Regression modeling

The model between the input factors (feed rate, spindle speed and air pressure) and the circularity and feret’s diameter in CFRP composite were obtained by multiple linear regressions. The regression equations obtained were as follow:

Circularity = 1.05 + 0.717 * F -0.000032 * S -0.00325* P  … (5)
R-Sq = 96.1% R-Sq (adj) = 93.8%
Feret’s diameter = 0.949 - 0.767 * F + 0.000034 * S + 0.00358 * P
R-Sq = 95.9% R-Sq (adj) = 93.4% … (6)

F is feed rate in mm/min, S is spindle speed in rpm and P is air pressure in bar. In this multiple linear regression analysis, R-Sq is the regression coefficient (R-Sq>0.90) for the developed models, which specify that the experimental data are fit with the model satisfactory. Mean effects plot for circularity and feret’s diameter were drawn from the experimental results. An optimal combination of process parameters for effective and efficient VMC is identified. Single objective optimization of process parameters for circularity and feret’s diameter was carried out using Taguchi’s approach. In the VMC, lower circularity and lower feret’s diameter are the indicators of better performance.Circularity is taken as lower the better criterion and feret’s diameter is taken as lower the better criterion for data pre-processing in the desirability functional analysis.

The S/N ratio of responses is computed by using statistical software. From the main effects plot for circularity is shown in Fig. 3. It can be noted that circularity increases with increase in the feed rate by 39.21%. This may be due to the higher dynamic stability offered by low feed rates compounded with the ploughing effect and frictional heating. Better circularity is observed at high spindle speed of 3000 rpm when compared to low spindle speeds. This is because of the good rotational stability achieved at higher spindle speeds.

From Fig. 3, it is seen that circularity decreases by 49.32% with increase in spindle speed. It is also observed that a rise in the air pressure improves circularity as it may ease the movement of drill bit inside the work-piece without the disturbance of chip movement. From Table 3, the optimum machine settings are low feed rate (0.01 mm/min), high spindle speed (3000 rpm) and high air pressure (5 bars). From ANOVA Table 4, it is learnt that the spindle speed strongly influences the quality of the hole in terms of circularity, having a contribution of 49.32% which is more than the other two parameters. Throughout the
experiments, Feret’s diameter showed values greater than one (Table 2). That is, the major axis diameter was larger than the minor axis diameter, which caused by small force accompanied by air flushing done in the direction of major axis. From the main effects plot feret’s diameter is shown in Fig. 4. It can be noted that feret’s diameter decreases with increase in the feed rate by 39.57%. It can be inferred that the diameter of the drilled hole lies near the expected value (0.5 mm) at higher feed rate. Since the feed rates are lesser than the depth of cut, the self induced vibration decreases with an increase in feed resulting in holes with diameter closer to nominal diameter. At high spindle speed and low feed rate (order number 3), because of frictional heating the cutting temperature goes up which result in higher feret’s diameter. The specific cutting resistance increases at lower feeds due to smaller uncut chip thickness resulting in higher shear forces which in turn increase the vibration. It also results in larger hole diameter at lower feeds and decreases at higher feeds. From Table 5, S/N ratio of the spindle speed and feed for the feret’s diameter determined show that a feed rate of 0.05 mm/min, a spindle speed of 2000 rpm and air pressure of 1 bar is optimum. From the ANOVA calculations (Table 6), it can be inferred that the feret’s diameter is primarily influenced by speed. The contribution speed (48.11%) is greater than that of feed rate (39.57%). If high spindle speed is desired for increase in production rate, it is preferable to go for a feed rate of 0.01 mm/min.

Multi response optimization

The evaluated desirability functional grade responses were obtained by converting the multi response optimization model into single response desirability functional grade. The distinguishing coefficient has been taken as 0.5. The rank of each trial has been tabulated based on the desirability functional grade and evaluated desirability functional grade for the responses for machining of CFRP as shown in Table 7. The desirability functional grades for all the experiments are as shown in Fig. 5. From Fig. 5, it is proved that experiment 6 has the optimal set of parameters for best multi response characteristics such as circularity and feret’s diameter. The average composite desirability functional grade value for every level of the input parameters have been computed by taking average for each level group in all the levels of process parameters and the values are given in Table 8.

![Table 4 — ANOVA for circularity](image)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
<th>Contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed rate</td>
<td>2</td>
<td>0.001233</td>
<td>0.001233</td>
<td>0.000616</td>
<td>13.56</td>
<td>0.069</td>
<td>39.21</td>
</tr>
<tr>
<td>Spindle speed</td>
<td>2</td>
<td>0.00155</td>
<td>0.00155</td>
<td>0.000775</td>
<td>17.06</td>
<td>0.055</td>
<td>49.32</td>
</tr>
<tr>
<td>Air pressure</td>
<td>2</td>
<td>0.00027</td>
<td>0.00027</td>
<td>0.000135</td>
<td>2.97</td>
<td>0.252</td>
<td>8.58</td>
</tr>
<tr>
<td>Error</td>
<td>2</td>
<td>9.09E-05</td>
<td>9.09E-05</td>
<td>4.54E-05</td>
<td>2.89</td>
<td></td>
<td>2.89</td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>0.003144</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100.00</td>
</tr>
</tbody>
</table>

![Table 5 — Taguchi analysis response table for feret’s diameter by S/N ratio](image)

<table>
<thead>
<tr>
<th>Level</th>
<th>Feed rate</th>
<th>Spindle speed</th>
<th>Air pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.31079</td>
<td>-0.02886</td>
<td>-0.12855</td>
</tr>
<tr>
<td>2</td>
<td>-0.1769</td>
<td>-0.19654</td>
<td>-0.16245</td>
</tr>
<tr>
<td>3</td>
<td>-0.05178</td>
<td>-0.31407</td>
<td>-0.24848</td>
</tr>
<tr>
<td>Delta</td>
<td>0.25901</td>
<td>0.28522</td>
<td>0.11993</td>
</tr>
<tr>
<td>Rank</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

![Fig. 4 — Main effects plot for feret’s diameter (F)](image)
and air pressure 3 bar. From the ANOVA Table 9 of composite desirability, the percentage of contribution spindle speed, air pressure and experimental error are 28.99%, 29.46% and 23.23%, respectively. The experimental error is equal contribution to other two factors. Therefore, experimental error may be the logic of increase of percentage of contribution of air pressure of multi response optimization.

### Confirmation test

The experimental confirmation test is the final step in verifying the results drawn based on Taguchi’s design approach. The optimal conditions are set for the significant factors and a selected number of experiments are run under specified cutting conditions. The average of the results from the confirmation experiment is compared with the predicted average based on the parameters and levels tested.

The confirmation experiment is a crucial step and is highly recommended by Taguchi to verify the experimental results. In this study, a confirmation experiment was conducted by utilizing the levels of the optimal process parameters (F2S2P2) for circularity and feret’s diameter in the drilling of CFRP and results are shown in Table 10 and illustrate the results of initial and optimal machining performance. The
optimized parameter shows significant improvement in performance. Figure 6 exhibits the SEM images of confirmation test.

Conclusions

The CFRP is increasingly used in several industries including the printed circuit board and automobile components manufacturers. Estimation on the influence of the process parameters for drilling of CFRP composites is important. The drilling of CFRP with solid carbide drill is investigated using Taguchi based desirability analysis. The influence of input parameters feed rate, spindle speed and air pressure on output values of circularity and feret’s diameter are analyzed and reported. Statistical analysis shows that the feed rate, spindle speed and air pressure affects the circularity by 39.21%, 49.32% and 8.58% in the drilling of CFRP composites, respectively. The feed rate, spindle speed and air pressure affects the feret’s diameter by 39.57%, 48.11% and 9.20% in the drilling of CFRP composites, respectively. The multi-objective optimization is done using desirability analysis. From the ANOVA, it is clear that the air pressure is significantly contributing towards drilling performance and it is followed by spindle feed, feed rate, respectively.

References