Optimization and effects of machining parameters on delamination in drilling of pure and Al$_2$O$_3$/SiO$_2$-added GFRP composites

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Abstract
The present study concentrates on optimization and the effect of machining parameters on delamination that occurs during drilling operation of pure glass fiber-reinforced polymer (GFRP) composites and added GFRP composites which were developed for resistance to erosion wear. Contribution of drilling parameters to delamination was investigated by using Taguchi method and analysis of variance (ANOVA). Relationship between machining parameters and delamination was modelled by using response surface methodology. Correlations were established between the machining parameters by quadratic regression using response surface methodology (RSM). Delamination factors in the hole entrance and exit were obtained in drilling of pure glass fiber epoxy, and SiO$_2$- and Al$_2$O$_3$-added GFRP materials using the experimental plan. Delamination factors at the hole exits were found bigger than delamination factors at the hole entrances. The smallest delamination values were obtained in GFRP/epoxy composite compared to Al$_2$O$_3$/SiO$_2$-added GFRP composites at the hole exit. In the investigation of machinability of composites, considering the material as a variable, it has been determined that the material has a greater effect on delamination than the cutting parameters. A new machinability index defined and the material having the best machinability of the three materials was Al$_2$O$_3$-added GFRP composite at the entrance. Good machinability was obtained in drilling of pure GFRP/epoxy composite at the hole exit. It has been found that the effect of feed rate on delamination is greater than the cutting speed and the cutting speed has a low effect. Optimization of the multi-objective function created for maximizing the material removal rate, minimizing the delamination, was performed, and the optimum drilling parameters were obtained. As a result of the experimental study, it was found that the amount of delamination increased although the low mechanical property-added GFRP composites with the high resistance to erosion wear in accordance with pure epoxy GFRP composites due to the lack of a strong bond between the epoxy and the fibers in Al$_2$O$_3$ and SiO$_2$. It was observed that the delamination amounts of pure epoxy GFRP, Al$_2$O$_3$-added GFRP, and SiO$_2$-added GFRP composites increased respectively, while the compressive and tensile strengths of these three materials decreased.

Keywords Glass fiber-reinforced polymer · Drilling · Delamination factor · Taguchi method · Response surface methodology · Machinability

1 Introduction
Fiber-reinforced polymer composite materials offer superior properties such as high strength-to-weight ratio, stiffness-to-weight ratio, and good corrosion resistance, and therefore, they are preferred for high-performance applications in several industries such as in the aerospace, automotive, defense, and sport goods industries.

Due to this increase in the use of FRPCs (fiber-reinforced polymer composites), studies on the machining of FRPCs have become increasingly important. Matrix material in composite materials holds the fibers together and a layered structure is obtained. Unlike conventional chip removal
processes, machining of composites requires a special approach. The layered structure of composites, heat sensitivity, and abrasive effects of reinforcements lead to studying machinability of composites in particular [1, 2]. The quality of the drilled hole is influenced adversely by matrix grid cratering, thermal damage, spalling, surface delamination, and material debasement or fiber pull-out. Defects such as fiber pull-out, matrix cratering, thermal damage, and delamination effecting quality of hole occur by drilling.

Khashaba et al. studied on the machinability of GFRP composites and investigated the effect of cutting parameters on thrust force and delamination. They concluded that an increase of the cutting speed and feed rate lead an increasing of delamination and as feed rate increases, thrust force and delamination increase. It was shown that a high feed rate of drilling causes a crack around the exit edge of the hole. The next phase of this study is the investigation of the effect of tool wear on thrust force. Results were indicated that an increasing of tool wear at high cutting speed and feed rate causes a rising of thrust force [3, 4]. Delamination is a critical damage mode under impact loading in fiber-reinforced composites. It may lead directly to through-thickness failure owing to interlaminar stresses caused by out-of-plane loading, or discontinuities owing to cracks, ply drops, or free edges. Impact loading causes multiple delamination, which can propagate in conjunction with sublaminate buckling, greatly reducing the residual compressive strength. Delamination is a major problem associated with drilling of fiber-reinforced composite materials that, in addition to reducing the structural integrity of the material, also results in poor assembly tolerance and has the potential for long-term performance deterioration [5]. Direct and interactive effect of process variables influences machining performance in terms of quality of the drilled hole. Therefore, an optimal parameter setting is indeed required. Abhishek et al. aims at evaluating an appropriate drilling parameter setting toward optimization of thrust, torque, entry, and exist delamination factor during drilling of CFRP (epoxy) composites. An integrated multi-response optimization philosophy combining principal component analysis (PCA), fuzzy inference system (FIS), and Taguchi method have been proposed [6].

In a study conducted by Davim et al., a statistical approach was handled to identify the most appropriate cutting parameters to realize drilling operations on carbon fiber-reinforced thermoset materials. They put forward an approach through Taguchi’s experimental analysis along with the multi-purpose optimization [7]. In another study carried out by Mohan et al., the Taguchi technique and response surface methodology were applied on GFRP composites. The major objective of this study is to find out the factors affecting delamination and optimizing the processing parameters for minimum delamination [8]. M. F. Ameur et al. defined the cutting conditions that allow the drilling of carbon fiber-reinforced epoxy (CFRE) composite materials taking into consideration the quality of the drilled holes (the exit delamination factor and the cylindricity error) and the optimum combination of drilling parameters [9]. They used grey relational analysis to improve the quality of the drilled holes. The experiment design was accomplished by application of the statistical analysis of variance (ANOVA). Their results show that the tool materials and the feed rate, which has a strong influence on the exit delamination factor, mainly influence the thrust force. Rajamurugan et al. modelled that the effect of drilling parameters on delamination of GFRP composites by using response surface methodology. Thus, delamination became predictable according to selected cutting parameters [10]. They analyzed delamination in drilling glass fiber-reinforced polyester composites. An attempt was made to develop empirical relationships between the drilling parameters. Sardinas et al. [11] used a micro-genetic algorithm and Krishnamoorthy et al. [12] a fuzzy grey method both with the aim of optimizing the drilling process conditions. Gaïtonde et al. analyzed the effects of cutting speed, feed rate, and the point angle on the delamination factor by generating response surface methodology (RSM) plots models [13]. S. Prakash et al. presented the systematic experimental investigation, analysis, and optimization of delamination factor in drilling of medium-density fiberboards (MDF). They developed an empirical model for predicting the delamination factor at entry and exit of the holes in drilling of MDF boards. Desirability function-based approach was employed for the optimization drilling parameters for minimizing the delamination factor at entry and exit in drilling of MDF boards [14]. In a study conducted by Davim et al., a statistical approach was handled to identify the most appropriate cutting parameters to realize drilling operations on carbon fiber-reinforced thermoset materials. They put forward an approach through Taguchi’s experimental analysis along with the multi-purpose optimization [15, 16]. Marques et al. performed delamination analysis of carbon fiber-reinforced laminates and evaluation of a special step drill [17]. Campos Rubio et al. investigated delamination in high-speed drilling of carbon fiber-reinforced plastic (CFRP) [18]. Abrao et al. studied on the effect of cutting tool geometry on thrust force and delamination of drilling of glass fiber-reinforced plastic composites [19]. Palanikumar used Taguchi and response surface methodologies for minimizing the surface roughness in machining glass fiber-reinforced (GFRP) plastics with a polycrystalline diamond (PCD) tool. The cutting parameters used are cutting speed, feed, and depth of cut. The effect of cutting parameters on surface roughness was evaluated and the optimum cutting condition for minimizing the surface roughness is determined [20]. Sait et al. presented a new approach for optimizing the machining parameters on turning glass fiber-reinforced plastic (GFRP) pipes. Optimization of machining parameters was done by an analysis called...
determining conditions for these composites was aimed. In order to achieve this objective, empirical models have been developed to estimate the delamination factors at the entrance and exit of the holes when drilling pure and doped GFRP composites. In the drilling of composites, drilling-induced delamination occurs at the entry and exit of holes on workpiece, the relation is indicated in Fig. 2. 

\[ D_{\text{max}} = D + \frac{F_d}{D} \]

where \( D_{\text{max}} \) is maximum diameter of the delamination zone and \( D \) is the diameter of hole. The scheme of delamination is indicated in Fig. 2.

Drilling-induced delamination occurs at the entry and exit planes of the workpiece as illustrated schematically in Fig. 2 a. Peel-up occurs as the drill enters the laminate. After the cutting edge of the drill makes contact with the laminate, the cutting force acting in the peripheral direction is the driving force for delamination. It generates a peeling force in the axial direction through the slope of the drill flute that results in separating the laminas from each other forming

| Table 1 The mechanical properties and fiber volume fraction of the samples |
|-------------------------------------------------|
| **Mechanical properties** | GFRP epoxy | SiO₂-added GFRP | Al₂O₃-added GFRP |
|--------------------------|------------|-----------------|-----------------|
| Tensile strength (MPa)   | 533        | 431             | 454             |
| Compression strength (MPa) | 607      | 474             | 516             |
| Modulus of elasticity (MPa) | 144     | 138             | 141             |
| Hardness, Barcol (HB)    | 78 (87)   | 66 (55)         | 71 (67)         |
| Fiber volume fraction    | 0.5        | 0.5             | 0.5             |
a delamination zone at the top surface of the laminate [5]. Push-out delamination occurs before the drill completely drills the sheet and exits from it as shown in Fig. 2 b [5]. The drill point exerts compressive force on the uncut plies below causing them to bend elastically. As the drill approaches the exit, the resistance to bending is decreased due to the reduction in the number of uncut layers.

2.2 Material properties

Glass fiber-reinforced epoxy composite materials in pure form were selected as the main test sample, and new composite test samples were created by adding SiO₂ and Al₂O₃ fillers separately, with an average particle diameter of 150 μm and 15% of the resin, into this pure structure. In the new formation, it is aimed to reduce the resin cost and increase the erosion resistance with mechanical property change.

Bagci et al. determined the solid particle erosive wear rates of the %15 Al₂O₃-added GFRP test specimens that are at lower level than those of pure GFRP/EP test specimens. Al₂O₃ filler has helped in improving the wear resistance of the test specimens. Materials with addition of Al₂O₃ filler material at various amounts exhibited lower wear as compared to neat materials with no added filler material. That means the filler material has increased the erosive wear resistance [27].

Bagci et al. investigated that 15%SiO₂-added GFRP has had a reducing effects on erosion wear. It increased the GF/EP composite material ‘s wear resistance. The added
Silicon dioxide ($\text{SiO}_2$) has formed a powerful bond with epoxy resin. The bond between epoxy and the filler material has been effective over a wide zone. $\text{SiO}_2$ filler materials were used in order to lower expenses and increase material strength. It was also found that by adding $\text{SiO}_2$ into the matrix, the resulting new composite shows a decrease in erosion rate at about 10–15% lower than material and thereby being the best effect to the erosive wear. $\text{SiO}_2$-added specimens have exhibited resistance against the abrasive particles and hence only slight deformation was encountered on the specimen surfaces [28].

As a result, abrasives encountered with the resistance of the additives as a result of the abrasive particles hitting the test samples in the silicon oxide- and aluminum oxide-doped GFRP samples created for the purpose of resistance to erosion wear, causing a crushing effect on the surfaces. Crushes on this surface prevented further breakage of the fibers by preventing matrix separation and caused some improvement in the wear properties of the test specimens. Composites with $\text{Al}_2\text{O}_3$ and $\text{SiO}_2$-added to the matrix created better erosion resistance compared to the pure GFRP structure, and an improvement in erosion resistance occurred.

3 Experimental works and modelling

3.1 Delamination modelling

To model the process, implementation of experimental tests is required to find the relationship between responses and independent variables. An important step in response surface modelling is to define an appropriate approximation for the actual relationship between the response and the set of independent variables. A response surface is an analytical function such as a polynomial that relates the behavior of response variable to several independent variables. After the machining parameters and the response function are identified, the relations between the response and independent variables are modelled [29]. In mathematical model, the relation between cutting parameters and delamination factor is stated as follows:

$$ F_d = C_1 v^{\rho_1} f^{\rho_2} $$  \hspace{1cm} (2)

In the above equation, $F_d$ indicates delamination factor, $v$ indicates cutting speed, and $f$ indicates feed rate. In order to estimate the model coefficients, it is taken logarithms of both sides of the equation.

$$ \ln F_d = \ln C_1 + \rho_1 \ln v + \rho_2 \ln f $$

In this equation, while $C_1$ is a constant coefficient, $\rho_1$ and $\rho_2$ are the coefficients of the parameters. Equation (2) is stated in first order polynomial model as follows:

$$ Y^i = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 $$ \hspace{1cm} (3)

When the same mathematical model is stated into second order, it is as follows:

$$ Y^i = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_{11} x_1^2 + b_{22} x_2^2 + b_{12} x_1 x_2 $$ \hspace{1cm} (4)

In this equation, $Y^i$ is the estimated response depending on first- and second-order equations, while $y$ is real response. The coded variables of cutting speed and feed are $x_1$ and $x_2$, experimental error is $\varepsilon$, and the estimated values of related parameters are $b_0$, $b_1$, $b_2$, $b_{11}$, $b_{22}$, and $b_{12}$.

The modelling is accomplished through mathematical and statistical methods to search for the delamination factor as the dependent variable. The cutting parameters were identified at three different levels and these are provided in Table 2.

In this current study, 12 tests based on rotatable centered composite design, three levels for any variable, were conducted. Table 2 shows the levels of variables. Experimental plan and levels given in Table 3 were used to create second-order RSM model for three different composite materials. Specimens were drilled according to the defined plan and delamination factors were recorded. Relationships of coded variables and real parameters are given as follows:

$$ x_1 = 1 + 2((\ln v - \ln 90)/(\ln 90 - \ln 50)) $$

$$ x_2 = 1 + 2((\ln f - \ln 0.2)/(\ln 0.2 - \ln 0.05)) $$

Second-order mathematical models were obtained for three different materials by means of RSM modelling using the experiment plan data given in Table 2. Coded variables were used in equations. Second-order mathematical models of delamination factors at hole entrance for pure GFRP/epoxy, $\text{Al}_2\text{O}_3$-added GFRP/epoxy, and $\text{SiO}_2$-added GFRP/epoxy were given with Eqs. (5), (6), and (7) respectively. Also, second-order mathematical models of delamination factors at hole exit for pure GFRP/epoxy, $\text{Al}_2\text{O}_3$-added GFRP/epoxy, and $\text{SiO}_2$-added GFRP/epoxy were given with Eqs. (8), (9), and (10) respectively.

For GFRP/epoxy at the hole entrance:

Table 2 Parameters and levels that are used in experimental plan

| Parameters | Levels |
|------------|--------|
| $v$ (m/min) | 50 70 90 |
| $f$ (mm/rev) | 0.05 0.1 0.2 |
For %15 Al₂O₃-added GFRP/epoxy at the hole entrance:

\[
Y_{\text{dfen1}} = 0.10705 - 0.00018x_1 + 0.09915x_2 \\
+ 0.13957x_2^2 + 0.03264x_2^3 + 0.011285x_1x_2
\]  \hspace{1cm} (5)

For %15 SiO₂-added GFRP/epoxy at the hole entrance:

\[
Y_{\text{dfen2}} = 0.15208 - 0.00723x_1 + 0.01596x_2 \\
- 0.01225x_1^2 + 0.02173x_2^2 - 0.03428x_1x_2
\]  \hspace{1cm} (6)

The mathematical models derived from second-degree RSM are stated with Eqs. (5), (6), and (7). When the second-order mathematical models obtained for delamination factor are examined, it is seen that the values of delamination factors for pure GFRP/epoxy composites are lower than for Al₂O₃- and SiO₂-added GFRP composites. The linear effects of feed rate are bigger than cutting speed for three composite materials. The quadratic effects of cutting speed and feed rate are important for three of the materials. But linear effect of cutting speed is very smaller than the quadratic effects of cutting speed for SiO₂-added GFRP at the hole exit.

For GFRP/epoxy at the hole exit:

\[
Y_{\text{dfex1}} = 0.2684 - 0.0209x_1 + 0.1200x_2 + 0.0258x_1^2 - 0.0230x_2^2 - 0.0187x_1x_2
\]  \hspace{1cm} (8)

For %15 Al₂O₃-added GFRP/epoxy at the hole exit:

\[
Y_{\text{dfex2}} = 0.4169 + 0.0802x_1 + 0.1824x_2 + 0.0374x_1^2 - 0.0042x_2^2 - 0.0040x_1x_2
\]  \hspace{1cm} (9)

For %15 SiO₂-added GFRP/epoxy at the hole exit:

\[
Y_{\text{dfex3}} = 0.4156 + 0.00138x_1 \\
+ 0.09950x_2 - 0.0170x_1^2 - 0.0184x_2^2 \\
+ 0.0203x_1x_2
\]  \hspace{1cm} (10)

When the mathematical models derived from second-degree RSM stated with the Eqs. (8), (9), and (10) for delamination factors at hole exit are examined, it is seen that the values of delamination factors for pure GFRP/epoxy composites are lower than for Al₂O₃ and SiO₂ GFRP/epoxy composites. The linear effect of the cutting speed is smaller than the linear effect of the feed rate, but the linear effect of the cutting speed on the delamination factor at the hole exit is greater than the effect on the delamination factor at the hole entrance. The quadratic effects of cutting speed and feed rate are important for three of the materials. But linear effect of cutting speed is very smaller than the quadratic effects of cutting speed for SiO₂-added GFRP at the hole exit.

As an example, it is seen the surface response, projection of contour plot, and optimum cutting speed and feed rate real values acquired from the delamination equation for GFRP/epoxy at the hole entrance obtained with RSM modelling in Fig. 3. It is obtained the minimum
delamination value of 1.0411, optimum cutting speed of 70.2 m/min, and feed rate 0.05 mm/rev.

3.2 Taguchi analysis

Taguchi method is an experimental technique developed by Dr. Genichi Taguchi to identify the most appropriate processing parameter intervals. The number of experiments will increase depending on the number of processing parameters. In order to solve this problem, Taguchi method reaches the result by combining three methods: orthogonal experimental design, signal–noise (S/N) ratio, and variance analysis (ANOVA). Orthogonal experimental design is used to create a special design by scanning all parameter space with minimum number of experiments. The results obtained from the planned experiments according to orthogonal experimental design are analyzed by transporting them into S/N ratio. The S/N ratio is used to measure performance characteristics of required values. The S/N ratio is identified depending on three major performance characteristics such as “(S/N)SB, the smaller-the better;” “(S/N)LB, the larger-the better;” and “(S/N)NB, nominal-the best.” ANOVA is used to find out the statistical significance degree of processing parameters on performance characteristics. Apart from these there significant tools, one final verification test is conducted to check the reliability of the optimum results obtained through Taguchi method. The above-mentioned three major performance characteristics are stated with Eqs. (11), (12), and (13) [9]. Here, \( y_i \) indicates the result measured in experiments, \( \bar{y} \) indicates the average of measured results from experiments, \( n \) indicates the number of experiments, and \( s^2 \) indicates the variance of \( y \).

\[
S/N_{SB} = \eta = -10 \log \left[ \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right] \quad \text{(11)}
\]

\[
S/N_{LB} = \eta = -10 \log \left[ \frac{1}{n} \sum_{i=1}^{n} \frac{1}{(y_i^2)} \right] \quad \text{(12)}
\]

\[
S/N_{NB} = \eta = -10 \log \left[ \frac{s^2}{\bar{y}} \right] \quad \text{(13)}
\]

Taguchi experimental design and selection of parameters In the Taguchi analysis, the average value of experimental response and its corresponding signal to noise ratio (S/N) of each run can be calculated to analyze the effects of the machining parameters. However, S/N ratio was chosen for the Taguchi analysis because S/N ratio represents both the average and variation of the experimental results. In the current analysis, L9 orthogonal array was used. The data

### Table 4 Mean delamination factors and S/N ratios according to Taguchi method for three composite materials at the hole entrance

| Parameter | GFRP/epoxy | %15 Al2O3-added GFRP/Epoxy | %15 SiO2-added GFRP/epoxy |
|-----------|------------|-----------------------------|---------------------------|
| \( v \)  | \( f \) | \( F_{d_{(mean)}} \) | Loss func | S/N ratio | \( F_{d_{(mean)}} \) | Loss func | S/N ratio | \( F_{d_{(mean)}} \) | Loss func | S/N ratio |
|-----------|------------|-----------------------------|---------------------------|
| 50        | 0.05       | 1.186                       | 1.40607                   | −1.48007                  | 1.102                        | 1.2162                   | −0.84994                  | 1.1491                       | 1.3204                   | −1.20716                  |
| 50        | 0.1        | 1.216                       | 1.47848                   | −1.69817                  | 1.1495                       | 1.3214                   | −1.21018                  | 1.2632                       | 1.5957                   | −2.02944                  |
| 50        | 0.2        | 1.552                       | 2.40918                   | −3.8187                   | 1.2264                       | 1.5041                   | −1.77264                  | 1.2895                       | 1.6628                   | −2.20843                  |
| 70        | 0.05       | 1.114                       | 1.241145                  | −0.93822                  | 1.1682                       | 1.3647                   | −1.35034                  | 1.1983                       | 1.4359                   | −1.57131                  |
| 70        | 0.1        | 1.209                       | 1.460507                  | −1.64503                  | 1.1619                       | 1.3500                   | −1.30338                  | 1.3276                       | 1.7625                   | −2.46134                  |
| 70        | 0.2        | 1.273                       | 1.620036                  | −2.09525                  | 1.1923                       | 1.4216                   | −1.52771                  | 1.3913                       | 1.9357                   | −2.86842                  |
| 90        | 0.05       | 1.130                       | 1.277238                  | −1.06272                  | 1.1028                       | 1.2162                   | −0.84994                  | 1.1982                       | 1.4357                   | −1.57059                  |
| 90        | 0.1        | 1.279                       | 1.636657                  | −2.13958                  | 1.1321                       | 1.2817                   | −1.0777                   | 1.3391                       | 1.7932                   | −2.53626                  |
| 90        | 0.2        | 1.547                       | 2.394592                  | −3.79231                  | 1.1792                       | 1.3905                   | −1.43175                  | 1.4649                       | 2.1459                   | −3.31616                  |
obtained from experiment plan designed through Taguchi method is shown for at the entrance in Table 4 and for at the exit in Table 5.

### 3.2.1 Variance analysis for GFRP/epoxy

Within the scope of Taguchi method, the variance analysis for GFRP/epoxy at hole entrance is given in Table 6 and also the response table is given in Table 7.

The peel-up delamination factor obtained for various speed and feed combinations during the drilling of pure GFRP are presented in Fig. 4. The delamination at lower speeds were much lower than those obtained at higher speed. From the ANOVA calculations, it can be inferred that the peel-up delamination is influenced by cutting speed or feed in the selected range (Table 6).

![Fig. 4](image-url)
Within the scope of Taguchi method, the variance analysis for GFRP/epoxy at the hole exit is provided in Table 8 and the response table is given in Table 9.

The push-out delamination factor obtained for various speed and feed combinations during the drilling of GFRP are presented in Fig. 5. It can be observed that the push-out delamination factor increases with an increase in feed rate and cutting speed. This could be because of smaller thickness of the GFRP laminates. In the experiments, the delamination factor increased with an increase in cutting speed and feed rate. As feed rate is increased, the thrust force also increases. At high speed, the delamination may be initiated at lower forces because the heating of matrix resulting in lesser stiffness. Therefore, delamination factor increases less from low speed to high speeds.

In the drilling of GFRP/epoxy materials, according to the “smaller-better” rule, optimum drilling parameters were obtained as the feed rate of 0.05 mm/rev and cutting speed of 70 m/min for minimum delamination at the hole exit. Feed rate shows the highest influence on delamination factors. The contribution of feed rate is 91.72% and the effect of cutting speed is 4.13%.

### 3.2.2 Variance analysis for Al₂O₃-added material

Variance analysis for delamination factor at the hole entrance of Al₂O₃-added GFRP/epoxy composite material is given in Table 10 and the response table is provided in Table 11.
The peel-up delamination factor obtained for various speed and feed combinations during the drilling of \( \text{Al}_2\text{O}_3 \)-added GFRP are presented in Fig. 6. The delamination at lower speeds were much lower than those obtained at higher speed. \( \text{Al}_2\text{O}_3 \)-added GFRP composites showed similar properties to pure GFRP composites in terms of the effect of speed and feed on deformation.

In the drilling of \( \text{Al}_2\text{O}_3 \)-added composite materials, feed of 0.05 mm/rev and cutting speed of 90 m/min were obtained as minimum drilling parameters for delamination according to “the smaller-the better” rule. Feed rate displays the highest effect on delamination. The effect of feed is 65.878% and the effect of cutting speed is 15.21%.

Variance analysis for delamination factor at the hole exit of \( \text{Al}_2\text{O}_3 \)-added GFRP/epoxy composite material is given in Table 12 and response table is provided in Table 13.

The push-out delamination factor obtained for various speed and feed combinations during the drilling of \( \text{Al}_2\text{O}_3 \)-added GFRP are presented in Fig. 7. The push-out delamination factor increases with an increase in feed rate and cutting speed. Delamination factor increases less from low speed to high speeds.

In drilling \( \text{Al}_2\text{O}_3 \)-added composite materials, feed of 0.05 mm/rev and cutting speed of 50 m/min are obtained as minimum drilling parameters for delamination factor according to “the smaller-the better” rule. Feed rate displays the highest effect on delamination factor. The effect of feed is 81.423% and the effect of cutting speed is 16.889%.

### 3.2.3 Variance analysis for \( \text{SiO}_2 \)-added composite material

The peel-up delamination factor obtained for various speed and feed combinations during the drilling of \( \text{SiO}_2 \)-added GFRP are presented in Fig. 8. Delamination factor increases with an increase in feed rate and cutting speed.

Variance analysis for delamination factor at the hole entrance of \( \text{SiO}_2 \)-added GFRP/epoxy composite material is
The push-out delamination factor obtained for various speed and feed combinations during the drilling of SiO$_2$-added GFRP are presented in Fig. 9. The push-out delamination factor increases with an increase in feed rate and cutting speed. The delamination is not influenced by speed in the selected range. The delamination factors are bigger than those Pure GFRP and Al$_2$O$_3$-added GFRP composites for various speed and feed combinations at the hole exit.

Variance analysis for delamination factor at the hole exit of SiO$_2$-added GFRP/epoxy composite material is given in Table 16 and the response tables is provided in Table 17. In drilling SiO$_2$-added materials, feed rate of 0.05 mm/rev and cutting speed of 50 m/min were obtained as minimum values for delamination factor at the hole exit according to “the smaller-the better” rule. Feed rate displays the biggest effect on delamination factor. The effect of feed is 93.31% and the effect of cutting speed is 1.05%.

### 3.2.4 Application of Taguchi approach by taking composite material as a variable

If we take material as the third parameter, orthogonal array in Taguchi method turns into the state in Table 18. Table 19, on the other hand, displays average loss function and S/N ratios. In the application of Taguchi method, for material is taken as a variable, for delamination factor at hole entrance, variance analysis for the three composite materials is given in Table 20 and the response table is in Table 21.

To determine the percentage contribution and optimum combination of drilling parameters more accurately, ANOVA was used. The results of ANOVA of the raw data or mean of delamination factor and the results of ANOVA of S/N ratios are given in Tables 19 and 20. The percentage contributions all the drilling parameters and materials are quantified under the last column of both the tables. Both of the tables suggest that the influence of material on delamination factor is very much larger than the influence of feed rate and cutting speed.

It is clear from Table 20 that delamination factor is minimum at first level of cutting speed, first level of feed rate, and first level of material, which are the best combination of drilling parameters and material in terms of delamination factor.

### Table 14 Variance analysis for delamination factor at the hole entrance of SiO$_2$-added composite

| Source                      | DOF | Sum of squares | Mean square | $F$-ratio | % contribution |
|-----------------------------|-----|----------------|-------------|-----------|----------------|
| Mean delamination factor    |     |                |             |           |                |
| Cutting speed               | 2   | 0.015985       | 0.007992    | 7.123766  | 19.47697       |
| Feed                        | 2   | 0.061597       | 0.030799    | 27.45157  | 75.05486       |
| Material                    | 4   | 0.004488       | 0.001122    | 5.468166  |                |
| Error                       | 8   | 0.08207        |             |           |                |
| S/N ratio                   |     |                |             |           |                |
| Cutting speed               | 2   | 0.700544       | 0.350272    | 8.845103  | 19.0364       |
| Feed                        | 2   | 2.821222       | 1.410611    | 35.62091  | 76.66014       |
| Material                    | 4   | 0.158403       | 0.039601    | 4.304221  |                |
| Error                       | 8   | 3.680168       |             |           |                |
and at second level of material. The S/N ratio analysis from Table 20 also shows the same results that delamination factor is minimum at first levels of cutting speed, feed rate, and second level material. To accordance with that, the minimum delamination factor was obtained for the smallest cutting speed and feed rate in the drilling of Al₂O₃-added GFRP composite.

In the application of Taguchi method for delamination factor at hole exit, when material is taken as a variable, orthogonal array in Taguchi method turns into the state in Table 18. Table 22 displays average loss function and S/N ratios, variance analysis for the three materials is given in Table 23, and the response table is in Table 24.

It is clear from Table 24 that delamination factor is minimum at first level of cutting speed, first level of feed rate, and at first level of material. The S/N ratio analysis from Table 24 also shows the similar results. To accordance with that, the minimum delamination factor was obtained for the smallest cutting speed and feed rate in drilling of pure GFRP/epoxy composite. When the percentage of contribution is examined in Table 23, it is seen that the effects of material, feed rate, and cutting speed on the delamination factor are 23.62%, 57.93% and 7.39%, respectively.

In the investigation of the change of delamination factor for the values of three levels of cutting speed and feed rate of three different composite materials in the drilling, it was found that the effect of the material on the delamination

### Table 15 Response tables for SiO₂-added composite at the hole entrance

| Level | Cutting speed | Feed | Level | Cutting speed | Feed |
|-------|---------------|------|-------|---------------|------|
| 1     | 1.233933      | 1.181867 | 1     | −1.81501      | −1.44968 |
| 2     | 1.305733      | 1.309967 | 2     | −2.30036      | −2.34235 |
| 3     | 1.334067      | 1.3819  | 3     | −2.47434      | −2.79767 |

### Table 16 Variance analysis for delamination factor at the hole exit of SiO₂-added composite

| Source               | DOF | Sum of squares | Mean square | F-ratio | % contribution |
|----------------------|-----|----------------|-------------|---------|----------------|
| Mean delamination factor | 2   | 0.001467       | 0.000734    | 0.372047 | 1.050177       |
| Feed                 | 2   | 0.130354       | 0.065177    | 33.1247  | 93.31562       |
| Material             | 4   | 0.00787        | 0.001968    | 5.633863 | 5.633863       |
| Error                | 8   | 0.139691       | 0.019691    | 49.08306 | 49.08306       |

### Table 17 Response tables for SiO₂-added composite at the hole exit

| Level | Cutting speed | Feed | Level | Cutting speed | Feed |
|-------|---------------|------|-------|---------------|------|
| 1     | 1.4726        | 1.331533 | 1     | −3.34301      | −2.48674 |
| 2     | 1.502633      | 1.498333 | 2     | −3.50309      | −3.51113 |
| 3     | 1.480067      | 1.625433 | 3     | −3.36705      | −4.21529 |

### Table 18 L₉ Orthogonal array for three composites materials

| No | v | f | Material |
|----|---|---|----------|
| 1  | 1 | 1 | (Epoxy)  |
| 2  | 1 | 2 | (Al₂O₃)  |
| 3  | 1 | 3 | (SiO₂)   |
| 4  | 2 | 1 | (Al₂O₃)  |
| 5  | 2 | 2 | (SiO₂)   |
| 6  | 2 | 3 | (Epoxy)  |
| 7  | 3 | 1 | (SiO₂)   |
| 8  | 3 | 2 | (Epoxy)  |
| 9  | 3 | 3 | (Al₂O₃)  |
The factor at the hole exit is larger than the effect of cutting speed and less than the feed rate. The best result of minimum delamination was obtained at pure GFRP/epoxy composite material in accordance with the rule is “the smallest is better.” The minimum value of delamination factor was obtained at 0.05 mm/rev feed and 50 m/min speed values.

Due to the effect of delamination on the quality of the drilled surface, delamination is an indicator of the machinability of the material. For this reason, the material obtained the minimum delamination is a material that has better machinability from the three examined materials. Good machinability was obtained in drilling of pure GFRP/epoxy composite. Machinability gradually decreases from pure GFRP/epoxy composite toward Al₂O₃-added composite and SiO₂-added composite materials.

### 3.3 Machinability index

A machinability index established in function of delamination factor. L₉ orthogonal array that has nine rows corresponding to the number of tests (8 degrees of freedom) with two columns at three levels was chosen for determining machinability index.

The plan of experiments is made of nine tests (array rows) in which the first column was assigned to the cutting velocity \( (v) \) and the second column to the feed rate \( (f) \). The experimental plan and the chosen cutting parameters are given in Table 2.

In order to analyze the machinability of these materials, delamination factor \( (F_d) \) from experimental data have been obtained. These are given in Tables 4 and 5 for delamination factor at hole entrance and exit respectively. A machinability index \( (MI) \) is constructed as in Eq. (14).

\[
MI = \left[\frac{1}{F_d}\right] \tag{14}
\]

Machinability indexes calculated with the delamination values obtained by using feed rate and cutting speed values according to L₉ orthogonal index used in Taguchi analysis are given in Table 25.
It can be evidenced that at the hole entrance, the Al₂O₃-added Epoxy/GFRP composite provides a better MI (average MI = 0.865) in comparison to Epoxy/GFRP (average MI = 0.792) and SiO₂-added Epoxy/GFRP (average MI = 0.778). The material having the best machinability of the three materials was Al₂O₃-added GFRP composite at the entrance.

It can be evidenced that at the hole exit the Epoxy/GFRP composite provides a better MI (average MI = 0.767) in comparison to Al₂O₃-added Epoxy/GFRP (average MI = 0.653) and SiO₂-added Epoxy/GFRP (average MI = 0.678). Good machinability was obtained in drilling of pure GFRP/epoxy composite at the hole exit.

### Table 22
Mean delamination factor, loss function, and S/N rates for three materials (for delamination factor at the hole exit)

| v  | f   | Mean     | Loss f | S/N   |
|----|-----|----------|--------|-------|
| 1  | 50  | 0.05     | 1.149  | -1.20794 |
| 2  | 50  | 0.1      | 1.1495 | -1.20108 |
| 3  | 50  | 0.2      | 1.5555 | -3.874 |
| 4  | 70  | 0.05     | 1.1682 | -3.5034 |
| 5  | 70  | 0.1      | 1.5048 | -3.5958 |
| 6  | 70  | 0.2      | 1.459  | -3.27912 |
| 7  | 90  | 0.05     | 1.3158 | -2.383 |
| 8  | 90  | 0.1      | 1.2903 | -2.1436 |
| 9  | 90  | 0.2      | 1.1792 | -1.43175 |
|    |    |          | 1.307889 | -2.27383 |

### Table 23
Analysis of variance in case of taking as a variable of material (for delamination factor at hole exit)

| Source         | DOF | Sum of squares | Mean square | F-ratio | % contribution |
|----------------|-----|----------------|-------------|---------|----------------|
| For mean delamination factor |       |                 |             |         |                |
| Cutting speed  | 2   | 0.035464       | 0.017732    | 0.669102 | 7.392048       |
| Feed           | 2   | 0.277931       | 0.138966    | 5.243826 | 57.93228       |
| Material       | 2   | 0.113356       | 0.056678    | 2.13872 | 23.62796       |
| Error          | 2   | 0.053002       | 0.026501    |         |                |
| Total          | 8   | 0.479752       |             |         |                |
| For S/N ratio  |       |                 |             |         |                |
| Cutting speed  | 2   | 0.884995       | 0.442498    | 0.698795 | 5.770406       |
| Feed           | 2   | 9.506792       | 4.753396    | 7.506598 | 61.98685       |
| Material       | 2   | 3.678544       | 1.839272    | 2.904592 | 23.9851        |
| Error          | 2   | 1.266458       | 0.633229    | 8.257648 |                |
| Total          | 8   | 15.33679       |             |         |                |

### Table 24
Response table for three materials (for delamination factor at hole exit)

| Response table for mean | Response table for S/N |
|-------------------------|------------------------|
| Level       | Cutting speed | Feed | Material | Level | Cutting speed | Feed | Material |
| 1          | 1.393633      | 1.2391 | 1.299333 | 1     | -2.80942     | -1.84864 | -2.23381 |
| 2          | 1.4052        | 1.423767 | 1.573 | 2     | -2.92762     | -3.04895 | -3.77211 |
| 93         | 1.5322        | 1.668167 | 1.4587 | 3     | -3.5258      | -4.36526 | -3.25692 |
| Delta      | 0.138567      | 0.429067 | 0.273667 | Delta | 0.716384     | 2.51662 | 1.538299 |
| Rank       | 3             | 1       | 2       | Rank  | 3             | 1       | 2       |
The derivatives of the modified objective function are as follows:

\[ F_{X1} = b_1 + 2b_{11}x_1 + b_{12}x_2 - \lambda_1 + \lambda_2 \]

\[ F_{X2} = b_2 + 2b_{22}x_2 + b_{12}x_1 - \lambda_3 + \lambda_4 \]

The optimum values for delamination factor of Epoxy/CFRP plate, SiO2-added GFRP/epoxy, and Al2O3-added GFRP/epoxy plate are given in Table 26 in the constraint region.

The optimum values for delamination factors of Epoxy/GFRP plate, SiO2-added GFRP/epoxy plate and Al2O3-added GFRP/epoxy plate are given in Table 26. For pure epoxy GFRP composite, the optimum parameters are \( x_1 = 1(v = 90 \text{ m/min}) \) and \( x_2 = -1(f = 0.05 \text{ mm/rev}) \). For both of other materials, the optimum parameter was obtained as \( x_1 = -1(v = 50 \text{ m/min}) \) and \( x_2 = -1(f = 0.05 \text{ mm/rev}) \). The results of optimization were shown that the smallest value of feed rate decreases delamination factor, but the effect of cutting speed to delamination factor is less.

### 3.4.2 Multi-optimization for maximizing the material removal rate and minimizing delamination factor

In machining operation, maximizing the material removal rate and minimizing the surface quality are important criteria. The objectives set for the optimization is maximization of material removal rate and minimization of surface quality.

First step in optimization is the formulation of objective function. Multi-objective function consists of the sum of each objective function using different weight coefficients for each criteria. Weighting factor assigns such that their sum was always equal to one. The weighting factor assigns to each parameter based on relative importance.

In the multi-objective optimization problem, two different and mutually conflicting objectives are selected to be optimized. The first objective function is material removal rate. The second objective function is the delamination factor, which describes the hole quality of the produced hole. First objective function must be maximized while the second one must be minimized. In order to homogenize all objectives, the material removal rate must be multiplied by \(-1\). After this change, in the problem there are only minimization objectives in the problem.

Multi-objective function for maximizing the metal removal rate and minimizing delamination and constraints are given as follows respectively:

\[ \text{MOF} = \phi Y - \theta M \]

MOF is multi-objective function; \( \phi \) and \( \theta \) are weighting factors for material removal rate, where \( Y \) represents objective function for delamination factor. \( Y \) is any one of \( Y_{dfen1}, Y_{dfen2}, Y_{dfen3} \). Also for the hole exit, the objective function for delamination factor is taken any one of \( Y_{dfex1}, Y_{dfex2}, Y_{dfex3} \).

**Constraints** There are the allowed ranges for the cutting parameters given by the validity range of the experimental models:

\[ v_{\text{min}} < v < v_{\text{max}} \]

\[ f_{\text{min}} \leq f \leq f_{\text{max}} \]

or constraints are given for the coded variables as follows:

\[ -1 \leq x_1 \leq 1 \]

\[ -1 \leq x_2 \leq 1 \]

or

\[ g_1 = -x_1 - 1 \leq 0 \]

\[ g_2 = x_1 - 1 \leq 0 \]

\[ g_3 = -x_2 - 1 \leq 0 \]
Objective function for the material removal rate  The first objective is the material removal rate, \( M \), the material removal rate in drilling which can be computed by the expression:

\[
\text{MMR} = 250dfv
\]  

(15)

where \( d \) is the diameter of hole, \( f \) is the feed rate, and \( v \) is the cutting speed.

Material removal rate is inversely proportional to the machining time.

\[
\ln \text{MRR} = \ln 250 + \ln d + \ln f + \ln v
\]

\[
M = \ln \text{MMR} = 7.424 + \ln d + 0.2939x_1 + 0.693x_2
\]

where \( d \) is drill diameter, and in this work it was taken as 6 mm. So the statement of material removal is as following. The material removal rate with the coded variables are given as follows:

\[
M = \ln \text{MMR} = 9.21576 + 0.2939x_1 + 0.693x_2
\]

Multi-objective optimization Multi-objective function for maximizing the metal removal rate and minimizing thrust force and constraints are given as follows respectively:

\[
\text{MOF} = \phi Y - \theta M
\]

\[
v_{\text{min}} < v < v_{\text{max}}, f_{\text{min}} \leq f \leq f_{\text{max}}
\]

or constraints are given for the coded variables as follows:

\[-1 \leq x_1 \leq 1 - 1 \leq x_2 \leq 1\]

Modified objective functions and Kuhn-Tucker conditions For multi-objective function and constraints, the formulation of problem is as following:

Minimization of \( F = \text{MOF} + \lambda_1(-1 - x_1) \)

\[
+ \lambda_2(x_1 - 1) + \lambda_3(-1 - x_2)
\]

\[
+ \lambda_4(x_2 - 1) = \phi Y - \theta M + \lambda_1(-1 - x_1)
\]

\[
+ \lambda_2(x_1 - 1) + \lambda_3(-1 - x_2) + \lambda_4(x_2 - 1)
\]

or optimization model is as following:

Minimization of \( F = \phi b_0 + b_1x_1 + b_2x_2 + b_{11}x_1^2 \)

\[
+ b_{22}x_2^2 + b_{12}x_1x_2) - \theta (9.21576 + 0.2939x_1 + 0.693x_2)
\]

\[
+ \lambda_1(-1 - x_1) + \lambda_2(x_1 - 1)
\]

\[
+ \lambda_3(-1 - x_2) + \lambda_4(x_2 - 1)
\]

Subject to:

\[
g_1 = -x_1 - 1 \leq 0
\]
\[ g_2 = x_1 - 1 \leq 0 \]
\[ g_3 = -x_2 - 1 \leq 0 \]
\[ g_4 = x_2 - 1 \leq 0 \]

The derivatives of the modified objective function are as following:

\[ F_{X1} = (b_1 + 2b_{11}x_1 + b_{12}x_2) - 0.2939\theta - \lambda_1 + \lambda_2 \]
\[ F_{X2} = (b_2 + 2b_{22}x_2 + b_{12}x_1) - 0.693\theta - \lambda_3 + \lambda_4 \]

The optimum values for multi-objective functions created from material removal rate and delamination factor for GFRP/epoxy plate, SiO_2-added GFRP/epoxy plate and Al_2O_3-added GFRP/epoxy plate are given in Table 27. It can be seen that \( x_1 \) has the biggest value for three materials and \( x_3 \) have the smallest values for three composite materials. While weighting factor for material removal factor increases, \( x_1 \) and \( x_2 \) have the biggest values for \( y_{dfex1} + M \).

### 4 Data analysis on delamination at the entrance hole and exit hole for three composite materials

When the effects of the cutting parameters of the three materials on the delamination were examined, it was observed that the delamination increased gradually towards pure epoxy, Al_2O_3-doped, and SiO_2-added GFRP respectively. This situation can be explained so that the bonding of powder Al_2O_3 and SiO_2 additives added to pure epoxy with glass fiber is weaker than the bonding of pure epoxy to glass fibers. Therefore, it is easier to separate the fibers. The reason of this is that the mechanical properties of Al_2O_3- and SiO_2-added GFRP composites are lower than Pure Epoxy GFRP.

It was observed that the delamination factor increased as the cutting speed and feed rate increased for the three materials at the hole entrance while the increase of delamination factor was lower with the increase of feed rate at 70 m/min speed for pure and Al_2O_3-added GFRP. The effect on delamination factor of cutting speed is low at high feed rates at pure epoxy GFRP and at Al_2O_3-added GFRP as the effect on delamination is less at low feed rates at 70 m/min speed. Also, it was observed that delamination increased as cutting speeds and feed rates increased at SiO_2-added GFRP. Low cutting speeds and feed rates give low delamination, while high feed and cutting speeds give higher delamination values.

The delamination factor increased with the increase in cutting speed at low feed rates, the effect of cutting speed on delamination was less with the increase in cutting speed at the high feed at pure epoxy GFRP, and the deformation factor increased as the cutting speed increase at Al_2O_3- and SiO_2-added GFRP composites.

In our experimental study, the hole quality obtained as a result of delamination in drilling Al_2O_3- and SiO_2-added glass fiber reinforced epoxy composites with a twist drill bit determined worse than pure epoxy composites. Although Al_2O_3- and SiO_2-added GFRP composites have high resistance to erosion wear, their mechanical properties are lower than pure epoxy composites as seen in Table 1. This shows that the bond of doped material, fiber, and epoxy is not strong and therefore the amount of delamination is high.

### 5 Conclusions

In the drilling of the pure GFRP/epoxy, Al_2O_3- and SiO_2-added GFRP composites which were developed for resistance to erosion wear, the optimization and the effects of the cutting parameters on delamination, and machinability
of the three composites were investigated. The following results were the following.

The minimum delamination factor obtained at the smallest feed rate for three of the materials and feed rate showed the biggest effect to delamination factor. The effect of cutting speed to delamination factor is less and the cutting speeds for the minimum delamination were obtained 70 m/min for GFRP/epoxy and 50 m/min for the other composite materials.

The contribution of feed rate is the biggest and the contribution of cutting speed is the smallest for the delamination formation of pure GFRP/epoxy according to added GFRP composites. The minimum delamination factor was obtained for the smallest cutting speed and feed rate in drilling of Al2O3-added GFRP composite.

The minimum delamination factor was obtained for the smallest cutting speed and feed rate for delamination at the hole exit in the drilling of pure GFRP/epoxy composite. It was found that the effect of the material is higher than feed rate and cutting speed on the delamination factor for delamination at the hole entrance. For delamination at the hole exit, it was found that the effect of the material is smaller than the feed rate and bigger than the cutting speed on the delamination factor. It was observed that the delamination factors at the hole exit were greater than the delamination factors at the hole entrance. It was seen that the delamination factor increased as the cutting speed and feed rate increased at the hole exit for all three materials.

The doped GFRP epoxy composite materials with high resistance to erosion wear have lower mechanical properties, lower machinability, and with higher delamination than pure epoxy GFRP materials since the bond between filler, fibers, and epoxy in doped composite materials is not strong.

According to the machinability index, it was seen that pure epoxy composite material has worse machinability than the other composite materials at the exit. Al2O3- and SiO2-added GFRPs have been equivalent machinability. The reason for this deterioration of machining performance may be the abrasive effects of additives such as SiO2 and Al2O3.

The optimum of delamination factor was obtained for the smallest cutting speed and feed rate for the three composites. To maximize MRR and minimize deformation factor, a multi-optimization function was created; the weighing factors MRR and deformation factor are taken as equal, optimum machining parameters were found that the cutting speed had the biggest value, and feed rate had the smallest value for the three composites.

Author contribution Ali Ünüvar: supervision, methodology, writing (original draft preparation), visualization, validation, investigation, reviewing, and editing. Murat Koyunbakan: methodology, reviewing, and editing. Mehmet Bağcı: methodology, validation, writing (reviewing and editing), and visualization.

Data availability The authors confirm that the data and material supporting the findings of this work are available within the article.

Declarations

Ethics approval The article follows the guidelines of the Committee on Publication Ethics (COPE) and involves no studies on human or animal subjects.

Consent to participate All authors participated for the publication.

Consent to publish All authors give consent for publication.

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References

1. El-Sonbaty I, Khashaba UA, Machaly T (2004) Factors affecting the machinability of GFR/epoxy composites. Compos Struct 63:329–338
2. Davim JP, Reis P (2003) Study of delamination in drilling carbon fiber reinforced plastics (CFRP) using design experiments. Compos Struct 59:481–487
3. Khashaba UA, El-Sonbaty IA, Selmy AI, Megahed AA (2010) Machinability analysis in drilling woven GFR/epoxy composites. Part II - Effect of drill wear "C. Compos A 41:1130–1137
4. Khashaba UA, El-Sonbaty IA, Selmy AI, Megahed AA (2009) Machinability analysis in drilling woven GFR/epoxy composites. Part I - Effect of machining parameters. Compos A 41:391–400
5. Khashaba UA (2004) Delamination in drilling GFR-thermoset composites. Compos Struct 63:313–327
6. Abhishek K, Datta S, Mahapatra SS (2015) Optimization of thrust, torque, entry, and exit delamination factor during drilling of CFRP composites. Int J Adv Manuf Technol 76:401–416
7. Enemuoh EU, El-Gizawy AS, Okafor AC (2001) An approach for development of damage-free drilling of carbon fiber reinforced thermosets. Int J Mach Tools Manuf 41:1795–1814
8. Mohan NS, Kulkarni SN, Ramachandra A (2006) Delamination analysis in drilling process of glass fiber reinforced plastic (GFRP) composite materials. J Mater Process Technol 186:265–271
9. Ameur MF, Habak M, Kenane M, Aouici H, Cheikh M (2017) Machinability analysis of dry drilling of carbon/epoxy composites: cases of exit delamination and cylindricity error. Int J Adv Manuf Technol 88:2557–2571
10. Rajamurugan TV, Shanmugam K, Palanikumar K (2013) Analysis of delamination in drilling glass fiber reinforced polyester composites. Mater Des 45:80–87
11. Sardinas RQ, Reis P, Davim JP (2006) Multi-objective optimization of cutting parameters for drilling laminate composite materials by using genetic algorithms. Compos Sci Technol 66:3083–3088
12. Krishnamoorthy A, RajendraBoopathy S, Palanikumar K, Paulo DJ (2012) Application of grey fuzzy logic for the optimization of drilling parameters for CFRP composites with multiple performance characteristics. Measurement 45:1286–1296
13. Gaitonde VN, Karkin SR, Rubio Campos J, CorreiaEsteves A, Abrão AM, Paulo Davim J (2008) Analysis of parametric influence on delamination in high-speed drilling of carbon
fiber reinforced plastic composites. J Mater Process Technol 203:431–438
14. Prakash S, Palanikumar K, Manoharan N (2009) Optimization of delamination factor in drilling medium-density fiberboards (MDF) using desirability-based approach. Int J Adv Manuf Technol 45:370–381
15. Davim JP, Reis P (2003) Drilling carbon fiber reinforced plastics manufactured by autoclave – experimental and statistical study. Mater Des 24:315–324
16. Davim JP, Pedro R (2003) Study of delamination in drilling carbon fiber reinforced plastic (CFRP) using design experiments. Compos Struct 59:481–487
17. Marques AT, Durão LM, Magalhães AG, Silva JF, Tavares IMRS (2009) Delamination analysis of carbon fibre reinforced laminates: evaluation of a special step drill. Compos Sci Technol 69:2376–2382
18. Campos Rubio J, Abrao AM, Faria PE, Correia AE, Davim JP (2008) Delamination in high speed drilling of carbon fiber reinforced plastic (CFRP). J Compos Mater 42:1523–1532
19. Abrao AM, Campos Rubio JC, Faria PE, Davim JP (2008) The effect of cutting tool geometry on thrust force and delamination when drilling glass fibre reinforced plastic composite. Mater Des 29:508–513
20. Palanikumar K (2008) Application of Taguchi and response surface methodologies for surface roughness in machining glass fiber reinforced plastics by PCD tooling. Int J Adv Manuf Technol 36:19–27
21. Naveen Sait A, Aravindan S, NoorulHaq A (2009) Optimisation of machining parameters of glass-fibre-reinforced plastic (GFRP) pipes by desirability function analysis using Taguchi technique. Int J Adv Manuf Technol 43:article number 581
22. İşik B, Ekici E (2010) Experimental investigations of damage analysis in drilling of woven glass fiber-reinforced plastic composites. Int J Adv Manuf Technol 49:861–869
23. Klickap E (2010) Optimization of cutting parameters on delamination based on Taguchi method during drilling of GFRP composite. Expert Syst Appl 37:6116–6122
24. Ghasemi FA, Hyvadi A, Payganeh G, Arab NBM (2011) Effects of drilling parameters on delamination of glass-epoxy composites. Aust J Basic Appl Sci 5(12):1433–1440
25. Liu L, Qi C, Feng Wu, Zhang X, Zhu X (2018) Analysis of thrust force and delamination in drilling GFRP composites with candle stick drills. Int J Adv Manuf Technol 95:2585–2600
26. Tian J, Feng Wu, Zhang P, Lin B, Liu T, Liu L (2019) The coupling effect and damage analysis when drilling GFRP laminates using candlestick drills. Int J Adv Manuf Technol 102:519–531
27. Bagci M, Imrek H (2010) Solid particle erosion wear of GF/EP composites with added Al₂O₃. AIP Conf Proc 1315:1389–1394
28. Bagci M, Imrek H, Khalfan OM (2011) Effects of silicon oxide filler material and fibre orientation on erosive wear of GF/EP composites. World Acad Sci Eng Technol 78:765–769
29. Khuri AI, Mukhopodhgay S (2010) Response Surface methodology. Wiley Interdiscip Rev Comput Stat 2:128–149

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