Machinability analysis of delamination and thrust force in drilling of pure and added GFRP composites

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Abstract
The effects of cutting parameters on the thrust force and delamination factor in the drilling of pure, Al₂O₃, and SiO₂ added GFRP/epoxy composites were investigated. Experimental studies were performed to investigate thrust force and delamination factor. Taguchi experimental design and response surface methodology were employed to establish parametric relationships between the experimental parameters and the machinability outputs consisting of delamination and thrust force. When examining the effect of cutting speed and feed on thrust forces and delamination factors for the three materials, the smallest values of the cutting parameters for all three materials gave the minimum thrust forces and delamination factors. Machinability Index is also proposed. According to the machinability index, under the effect of delamination and thrust force parameters, it was seen that pure epoxy composite material has better machinability than the other composite materials. 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.

Keywords
GFRP, delamination, machining, thrust force

Introduction
The glass-fiber-reinforced plastic (GFRP) composites have been widely used in various industries for their excellent properties, such as lightweight, high modulus, high specific strength, and good corrosive resistance. Drilling is frequently used in assembling these composite components due to the fastener mechanical connection. The drilling of GFRP composites is quite different from that of ordinary metals and their alloys. It is often accompanied by multiple damages such as tool wear, rough surface finish, burr, tearing, fiber pull-out, thermal damage, matrix crack, and delamination. The most serious damage is delamination that can happen both at the entrance and exit of the laminate and generally refers to the peel-up delamination at the entrance surface and push-down delamination at the exit surface.¹⁻⁴ Many researchers have conducted corresponding studies on drilling composites using traditional twist drills.

Khashaba et al. studied the machinability of GFRP composites and investigated the effect of cutting parameters on thrust force and delamination. They concluded that an increase in the cutting speed and the feed rate leads to an increase in delamination, and also, as the feed rate increases, the 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 indicated that increasing tool wear at high cutting speed and feed rate causes a rising thrust force.³⁻⁴ Heisel et al. investigated the influence of the point angle of a drill tool and increased cutting speeds on machining forces and drill hole quality. They determined that elevated point angles result in increased feed force while the drilling torque stays almost constant.⁵ Rajamurugan et al. modeled the effect of drilling parameters on delamination of GFRP composites using response surface methodology. Thus, delamination became predictable according to selected cutting parameters.⁶ The drilling parameters are important for minimizing delamination damage, and the thrust force plays a critical role in influencing the size of the delamination zone. Tan et al.
attempted an analytical study of drilling characteristics for composite material. Results of the analytical research indicate that the delamination damage can be lightened if the applied thrust force is lower than the critical thrust force value. The applied thrust force and delamination damage from experimental results were used to validate the proposed model. Mohan et al. applied the Taguchi technique and response surface methodology on GFRP composites. The major objective of this study is to find out the factors affecting delamination and optimize the process parameters for minimum delamination.

The first analytical model to determine the critical thrust force was developed by Hocheng and Dharan. Hocheng and Tsao also developed a series of comprehensive analytical models of critical thrust force leading to the onset of push-out delamination for various drill bits and compared with the conventional twist drill bit. Khashaba et al. found that the effect of cutting speed on thrust force in drilling woven-ply GFRP composite laminates varied with tool wear. They illustrated the effect of drill bit pre-wear on the thrust force at different cutting speeds. They observed that the cutting speed has an insignificant effect on thrust force in drilling GFRP composite laminates with fresh drill bits. In contrast, thrust force increased noticeably with increasing cutting speed when using pre-wear drill bits. Khashaba et al. investigated the effect of machining parameters (feed, cutting speed, and drill diameter) on the thrust force and machinability of woven glass fiber-reinforced epoxy (GFRE) composites.

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 carbonfiber-reinforced thermoset materials. They put forward an approach through Taguchi’s experimental analysis and the multi-purpose optimization. Palanikumar et al. performed drilling experiments in GFRC composites to study the influence of the drilling parameters on push-down delamination. They disclosed that feed rate was the main factor that had the most significant influence on push-down delamination, followed by rotational speed. Latha and Senthilkumar revealed that feed rate and drill diameter were the main factors that impacted the push-down delamination in the drilling of GFRP composites. The cutting speed only showed a limited effect on push-down delamination in drilling GFRP composites. Killickap et al. revealed that the peel-up delamination and the push-down delamination increased with the feed rate and cutting speed in the drilling of composites. Palanikumar et al. analyzed the influences of machining parameters on thrust force and delamination in drilling GFRP using candlestick drills. Experimental results showed that the drilling performance in composites could be improved by optimizing the drilling parameters. Candlestick drills have been recognized as advantageous tools for reducing thrust force and delamination damage in drilling composites. Liu et al. carried out Drilling experiments on glass fiber-reinforced plastic (GFRP) composites and finite element simulations. Three candlestick drills with different drill tip geometries and one twist drill were compared in terms of thrust force, peel-up delamination, and push-down delamination. Ozturk et al. investigated the effect of drilling parameters on the thrust force, and machinability of added glass-fiber-reinforced epoxy (GFRE) composites. There are also several recent studies on the drilling performance of GFRP composites. Khassaba et al. investigated the effect of drill angle, laminate thickness, and process parameters on the machinability of GFRP composite. It was found that laminate thickness made the most significant contribution and drill angle made the lowest contribution to the machinability. Khassaba et al. improved the investigation of GFRP composites’ machinability by considering the material’s heat-affected areas. The main conclusion of this study is the dependency of delamination on the thrust force and the temperature. It was found that delamination is proportional to thrust force and inversely proportional to temperature. Yazman investigated the effect of back-up use on the drilling performance of GFRP pipes. It was found that using back-up when drilling GFRP composite pipes prevents severe delamination and material damage while it causes higher thrust forces during drilling. Juvvala investigated the effect of machining parameters and reinforcement of nano MMT on the drilling machinability of GFRP composites. It was found that delamination can be reduced by optimizing machining parameters and using nano MMT additives.

Despite the importance of the literature review about the machinability of GFRP given above, there are also several studies on the significance of particle reinforcement on GFRP. Singh et al. developed and investigated the mechanical properties of Al2O3 reinforced glass fiber polymer composite with epoxy matrix. As a result, It was found that the reinforcement of certain particle sizes of Al2O3 improved the mechanical properties of glass fiber composite. However, larger and heavier particles of Al2O3 negatively influence the composite material’s mechanical properties. Pardeep et al. investigated on characterization and machinability of Al-4032/SiC metal matrix composite. Mechanical (tensile strength, micro-hardness, impact strength) characterization of the fabricated AMC has been attempted. The MMC has been machined with various combinations of machining parameters using a carbide cutter. Response surface methodology (RSM) has been applied to optimize the surface finish. Deepak et al. have carried out the morphological (microstructure, SEM, XRD) and mechanical (tensile strength, micro-hardness, impact strength) characterization of the aluminum alloy (Al-4032) matrix-based composites (AMCs). The mechanical properties of
the AMCs have been observed to be better than the unreinforced alloy. Pardeep et al. performed optimization of process parameters in end milling of Al-4032-based metal matrix composite using Taguchi’s gray relational analysis (TGRA). Experiments were carried out following Taguchi’s L9 orthogonal array. Optimum cutting speed, feed rate, and depth of cut values were maximized MRR and minimized surface roughness. Vikrant et al. presented a prediction of depth of cut values. Pradeep et al. presented experimental trials. The optimum of the process parameters has been obtained using TGRA. Pardeep et al. realized optimization of end milling parameters for rough and finish machining of Al-4032/3% SiC metal matrix composite using TGRA. Pardeep et al. presented the study on end milling of Al-4032/3% SiC composite, considering the cutting speed, feed rate, and depth of cut as the process parameters. Surface finish and material removal rate (MRR) are chosen as the response parameters. Taguchi’s L27 orthogonal array (OA) has been used for experimental trials. The optimum of the process parameters has been obtained using TGRA. Pradeep et al. presented an assessment of the effect of the machining parameters in drilling of EN-31 alloy steel on surface roughness and hole diameter accuracy using TGRA based analysis. L27 Orthogonal array has been used to develop relationships for predicting surface roughness and hole diametrical error. Spindle speed, feed rate, and point angle of the drill as process parameters have been taken to optimize the response parameters.

In this study, the effects of cutting speed and feed rate on thrust force and delamination in drilling the materials, including pure glass-fiber epoxy and SiO2/Al2O3 added reinforced epoxy, were studied through an experimental design. A mathematical model was created by applying the response surface methodology to achieve this goal. The significance levels and contributions of machining parameters to the thrust forces and delamination factors were determined using the response surface methodology and Taguchi method. The machinability of three composite materials was investigated. To determine the effects of drilling parameters on machinability parameters such as thrust force and delamination, the machinability index has been created and compared with pure and added GFRP composites. The minimum values of thrust forces and delamination factors for all three materials are focused on finding the values of the cutting parameters. It is aimed to investigate the machinability effect of the abrasive effects of additives such as SiO2 and Al2O3 of the doped composites compared to the machining performance of pure GFRP. At the hole entrance and the hole exit, the effects of the material and the cutting parameters on the machinability have been investigated by determining minimum delamination factors and thrust forces for all three composite materials according to RSM and Taguchi analysis.

### Materials and methods

The samples used in the experiment consisted of pure glass-fiber pure epoxy, SiO2 and Al2O3 reinforced composite GFRP composites. The dimensions of the sample materials are 4 × 65 × 165 mm. The mechanical properties of the samples are provided in Table 1. Bagci et al. employed that 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 mm–3 and 15% of the resin, into this pure structure. In this new formation it is aimed to reduce the resin cost and increase the erosion resistance with mechanical property change. Bagci et al., in their experimental studies, determined that the abrasives encountered with the resistance of the additives as a result of the abrasive particles hitting the test samples in the Silicon Oxide and Aluminium Oxide doped GFRP samples created for the purpose of resistance to erosion wear, caused 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 Al2O3 and SiO2 added to the matrix created better erosion resistance than the pure GFRP structure, and erosion resistance was improved. It is possible to encounter the erosive type of wear in the space craft industry, energy conversion systems, engines, helicopter rotor blades, and coal mine plants. The importance of this type of wear is progressively increasing.

The experimental setup is given in Figure 1. Mazak Variaxis 500–5X machining center was used to perform the experiments, and the thrust force was measured by Kistler 9257B type dynamometer. In the drilling operation, K10 carbide solid drill with 118° point angle and 6 mm diameter was used as a cutting tool. The thrust forces for different cutting parameters were recorded according to the experimental design using Dynware software.

To calculate the delamination factor at the entrance and exit of holes on the workpiece, the relation is given as

$$ F_d = \frac{D_{\text{max}}}{D} \quad (1) $$

Where $D_{\text{max}}$ is the maximum diameter of the delamination zone and $D$ is the hole diameter. The scheme of delamination is indicated in Figure 2.

Drilling-induced delamination occurs at the entry and exit planes of the workpiece, as illustrated schematically in Fig. 2(d). 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 separates the laminas from each other, forming a delamination zone at the top surface of the laminate. Push-out delamination occurs before the drill completely drills the sheet and exits from it, as shown in Figure 2(e). The drill point exerts compressive force on the uncut plies below, causing them to bend elastically. As the drill approaches the exit, the number of uncut plies supporting it reduces, and the resistance to bending decreases.

Response surface methodology

To model the process, the implementation of experimental tests is required to find the relationship between responses and independent variables. An important step in response surface modeling 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 the response variable to several independent variables. After the machining parameters and the response function are identified, the relationship between the response and independent variables is modeled. In the mathematical model, the relation between cutting parameters and the delamination factor is stated as follows:

\[ F_d = C_i v^{\rho_1} f^{\rho_2} \]  

In the above equation, \( F_d \) indicates delamination factor; \( v \) indicates cutting speed; \( f \) indicates feed rate. The model coefficients are estimated by taking the equation’s natural logarithm of both sides.

\[ \ln F_d = \ln C_i + \rho_1 \ln v + \rho_2 \ln f \]

In this equation, \( \rho_1 \) and \( \rho_2 \) are the coefficients of the parameters, while \( C_i \) is a constant coefficient. Equations (3) and (4) are first and second-order polynomial models, respectively.

\[ Y^1 = y - e = b_0 x_0 + b_1 x_1 + b_2 x_2 \]  

\[ Y^4 = y - e = b_{00} x_0 + b_{11} x_1 + b_{22} x_2 + b_{12} x_1 x_2 + b_{11} x_1^2 + b_{22} x_2^2 + b_{12} x_1 x_2 \]   

In this equation, \( Y^1 \) is the estimated response depending on the first and second-order equations, while \( y \) is the real response. The coded cutting speed and feed rate variables are \( x_1 \) and \( x_2 \), the experimental error is \( e \), and the estimated values of related parameters are \( b_0, b_1, b_2, b_{11}, b_{22}, \) and \( b_{12}. \)
The number of experiments increases depending on the number of processing parameters. The Taguchi method is used to analyze the results and to reduce the number of experiments. This method combines orthogonal experimental design, signal-noise (S/N) ratio, and variance analysis (ANOVA). Orthogonal experimental design is used to create a specific design of parameters for different levels by scanning all parameter space with the minimum number of experiments. The results obtained from the planned experiments according to orthogonal experimental design are analyzed by transporting them into the S/N ratio. The S/N ratio is used to measure the 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”. “(S/N)$_{SB}$, the smaller-the better” are stated with the equation of (5). Here $y_i$ indicates the result measured in experiments, and $n$ indicates the number of experiments.

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

**Taguchi method**

The number of experiments increases depending on the number of processing parameters. The Taguchi method is used to analyze the results and to reduce the number of experiments. This method combines orthogonal experimental design, signal-noise (S/N) ratio, and variance analysis (ANOVA). Orthogonal experimental design is used to create a specific design of parameters for different levels by scanning all parameter space with the minimum number of experiments. The results obtained from the planned experiments according to orthogonal experimental design are analyzed by transporting them into the S/N ratio. The S/N ratio is used to measure the 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”. “(S/N)$_{SB}$, the smaller-the better” are stated with the equation of (5). Here $y_i$ indicates the result measured in experiments, and $n$ indicates the number of experiments.

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

**Figure 2.** Schematic representation of delamination factor and the optical image of (a) entrance and (b) exit delamination for pure GFRP. (c) Schematic view of the diameter of delamination zone ($D_{max}$) and drilled hole (D) Mechanisms of delamination; (d) Peel-up delamination at the entrance, and (e) Push-out delamination at exit.
**Experimental results and discussion**

The modeling was accomplished through mathematical and statistical methods to search for the thrust force as the dependent variable. The parameters of cutting values were identified at five different levels, which are provided in Table 2. In the current study, 12 experiments were performed based on a rotatable centered composite design. Five level for each variable was determined, which is given in Table 2. Relationships between the coded variables and the real variables are given below.

\[
x_1 = 2 \frac{(ln v - ln 90)}{(ln 90 - ln 50)} + 1 \quad x_2 = 2 \frac{(ln f - ln 0.2)}{(ln 0.2 - ln 0.05)} + 1
\]

**RSM modelling for thrust force**

The experimental plan in Table 3 was used to create the second-order RSM model for three different composite materials. Specimens were drilled according to the experimental plan, and the thrust forces were recorded.

Second-order mathematical models were obtained for three different materials through RSM modeling by using the experiment plan. Coded variables are used in equations. Second-order mathematical models for Pure GFRP/epoxy, Al2O3 added GFRP/epoxy, and SiO2 added GFRP/epoxy are given by equations (8), (9), and (10), respectively.

\[
y_{pure} = 5.885 + 0.136x_1 + 0.15x_2 - 0.04x_1^2 - 0.1x_2^2 - 0.195x_1x_2
\]

\[
y_v = 6.867 + 0.0414x_1 + 0.34615x_2 - 0.0915x_1^2 - 0.1133x_2^2 - 0.0984x_1x_2
\]

\[
y_s = 6.833 + 0.0578x_1 + 0.4364x_2 - 0.003x_1^2 - 0.052x_2^2 - 0.0913x_1x_2
\]

The surface graphs of the second-order mathematical models are given in Figure 3.

The F-ratios calculated for each of the three materials are bigger than the F-table values; the models with 95% reliability are adequate. As the “calculated F-ratio” is larger than the F-table value for pure GFRP/epoxy, SiO2 added GFRP/epoxy and Al2O3 added GFRP/epoxy materials, cutting speed \(x_1\) and feed rate \(x_2\) were found to be significant in a drilling operation.

When the second-order mathematical models created for the three materials are examined, it is seen that the thrust force for pure epoxy composites is lower, and the thrust values for Al2O3 and SiO2 are closer to each other. The linear effects of cutting speed and feed increase from pure epoxy composite towards Al2O3 and SiO2 reinforced composite materials. It was found that the quadratic effects cause a decrease in the thrust forces for three of the materials, and the biggest quadratic effect was observed on SiO2 reinforced composite.

Second-order mathematical models were created by splitting the fractional factorial experimental design into two blocks, thus reducing the number of experiments in the experiment plan.

**Optimization of thrust forces**

The objective function and constraints of the problem are given below. The objective function is aimed to be minimized.

\[
F_i = Y = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_{11} x_1^2 + b_{22} x_2^2 + b_{12} x_1 x_2
\]

Subject to \(g_1 = -x_1 - 2 \leq 0\)

\[
g_2 = x_1 - 2 \leq 0
\]

\[
g_3 = x_2 - 2 \leq 0
\]

Where \(Y\) represents the objective function for delamination factors and thrust forces. \(Y\) is any one of \(Y_{pure}, Y_{al}, Y_{si}\).

Constraint nonlinear minimization method was applied, the optimum value of drilling parameters are obtained as \(x_i = -2, x_j = -2\) for pure GFRP/epoxy, \(x_i = -2, x_j = -2\) for Al2O3 added GFRP/epoxy and \(x_i = -2, x_j = -2\) for SiO2 added GFRP/epoxy. The minimum thrust forces were obtained for all three composite materials with the smallest feed rate and cutting speeds.

**RSM modelling for delamination**

The modeling was 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, provided in Table 2.

In the current study, 12 tests based on rotatable centered composite design, three levels for each variable, were conducted. The experimental plan and levels in Table 4 were used to create a second-order RSM model for three different
Table 3. Thrust forces obtained in the drilling of pure glass-fiber pure epoxy, SiO₂, and Al₂O₃ reinforced composite GFRP materials.

| Experimental plan | GFRP/Epoxy Fᵢ (N) | SiO₂ added GFRP/Epoxy Fᵢ (N) | Al₂O₃ added GFRP/Epoxy Fᵢ (N) |
|-------------------|-------------------|-----------------------------|-----------------------------|
| No.               | v f               |                             |                             |
| 1                 | –1 –1             | 196.570                     | 621.4                       | 618.27                       |
| 2                 | 1 –1              | 265.000                     | 725.2                       | 749.79                       |
| 3                 | –1 1              | 291.010                     | 1126.3                      | 1084.86                      |
| 4                 | 1 1               | 269.950                     | 1150.5                      | 1160.91                      |
| 5                 | –2 0              | 241.750                     | 596.48                      | 850.14                       |
| 6                 | 2 0               | 399.360                     | 632.34                      | 936.18                       |
| 7                 | 0 –2              | 160.230                     | 246.52                      | 238.77                       |
| 8                 | 0 2               | 394.760                     | 1284.77                     | 2240.25                      |
| 9                 | 0 0               | 358.480                     | 844.7                       | 833.18                       |
| 10                | 0 0               | 374.760                     | 925.3                       | 900.3                        |
| 11                | 0 0               | 382.100                     | 885.3                       | 930.5                        |
| 12                | 0 0               | 397.750                     | 889.5                       | 953.29                       |

Figure 3. Graphical representation of the second order mathematical models for pure GFRP/epoxy, Al₂O₃ added GFRP/epoxy, SiO₂ added GFRP/epoxy.
Table 4. Delamination factors were obtained in drilling pure glass-fiber epoxy, SiO₂, and Al₂O₃ reinforced composite GFRP materials in hole entrance and exit.

| Experimental plan | GFRP/Epoxy | Al₂O₃ added GFRP/Epoxy | SiO₂ Added GFRP/Epoxy |
|-------------------|------------|------------------------|-----------------------|
| No. v f F_d(N)ent F_d(N)ex | F_d(N)ent | F_d(N)ex | F_d(N)ent | F_d(N)ex |
| 1 -l -l | 1.186 | 1.1492 | 1.1028 | 1.2056 |
| 2 l -l | 1.130 | 1.1741 | 1.2162 | 1.4245 |
| 3 -l l | 1.552 | 1.5098 | 1.2264 | 1.7115 |
| 4 l l | 1.547 | 1.4312 | 1.1792 | 1.9905 |
| 5 -l 0 | 1.216 | 1.4167 | 1.1495 | 1.4762 |
| 6 l 0 | 1.279 | 1.2903 | 1.1321 | 1.7383 |
| 7 0 -l | 1.114 | 1.1369 | 1.1682 | 1.568255 |
| 8 0 l | 1.1273 | 1.4584 | 1.1923 | 1.8857 |
| 9 0 0 | 1.1258 | 1.3197 | 1.16197 | 1.4667 |
| 10 0 0 | 1.1237 | 1.2681 | 1.1876 | 1.4754 |
| 11 0 0 | 1.1291 | 1.2679 | 1.1527 | 1.435 |
| 12 0 0 | 1.1312 | 1.2989 | 1.174 | 1.424 |

Composite materials. Specimens were drilled according to the defined plan, and delamination factors were recorded.

Second-order mathematical models were obtained for three different materials by means of RSM modeling 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, Al₂O₃ added GFRP/epoxy, SiO₂ added GFRP/epoxy were given with equations (11), (12), and (13), respectively.

\[
Y_{d_{ef1}} = 0.107050 - 0.0018x_1 + 0.09915x_2 + 0.13957x_1^2 + 0.03264x_2^2 + 0.011285x_1x_2 \tag{11}
\]

\[
Y_{d_{ef2}} = 0.15208 - 0.00723x_1 + 0.01596x_2 - 0.1225x_1^2 + 0.2173x_2^2 - 0.04328x_1x_2 \tag{12}
\]

\[
Y_{d_{ef3}} = 0.276417 + 0.007865x_1 + 0.11997x_2 - 0.0168x_1^2 - 0.00075x_2^2 + 0.04214x_1x_2 \tag{13}
\]

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. Still, 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 all three materials.

**Optimization of delamination factors**

The objective function and constraints of the problem are given below. The objective function is aimed to be minimized.

\[
F_d = Y = b_0x_0 + b_1x_1 + b_2x_2 + b_{11}x_1^2 + b_{22}x_2^2 + b_{12}x_1x_2
\]

Subject to \(g_i = -x_i - I \leq 0\)

\[
\begin{align*}
g_2 &= x_1 - 1 < 0 \\
g_3 &= -x_2 - 1 < 0 \\
g_4 &= x_2 - 1 < 0
\end{align*}
\]

Where \(Y\) represents the objective function for delamination factors or thrust forces. \(Y\) is any one of \(Y_{t1}, Y_{t2}, Y_{d_{en1}}\).
The constraint nonlinear minimization method was applied. The optimum value of drilling parameters were obtained at hole entrances as \(x_1=0.065, x_2=C_0\) for pure GFRP/epoxy, \(x_1=1, x_2=C_0\) for Al\(_2\)O\(_3\) added GFRP/epoxy and \(x_1=1, x_2=C_0\) for Si\(_2\)O added GFRP/epoxy. The optimum value of drilling parameters were obtained at hole exits \(x_1=0.043, x_2=C_0\) for pure GFRP/epoxy, \(x_1=C_0, x_2=C_0\) for Al\(_2\)O\(_3\) added GFRP/epoxy, \(x_1=C_0, x_2=C_0\) for Si\(_2\)O added GFRP/epoxy.

While for all three composite materials, the minimum delamination factors at hole entrances and hole exits were obtained with the smallest feed rate, the values of cutting speeds indicate the change from minimum to maximum.

**Taguchi analysis for thrust force**

In the present analysis, the L9 orthogonal array was used. The data obtained from the experimental plan designed with the Taguchi method are shown in Table 5.

**Variance analysis for thrust force of GFRP/epoxy**

Within the scope of the Taguchi method, the variance analysis for GFRP/Epox and response tables was performed. In drilling GFRP/Epoy materials, minimum drilling parameters are a feed rate of 0.05 mm/rev and a cutting speed of 50 m/min obtained according to “the smaller the better” rule for thrust force. Feed rate displays the highest effect on thrust forces. The effect of feed is 91.3%, and the effect of cutting speed is 2.8%. The average value for minimum thrust force is 256.2 N.

**Variance analysis for thrust force of Si\(_2\)O added material**

Variance analysis for Si\(_2\)O added GFRP/Epoy composite material was performed. In drilling Si\(_2\)O added materials, feed of 0.05 mm/rev and cutting speed of 50 m/min are obtained as minimum values for thrust force according to “the smaller the better” rule. Feed rate displays the highest effect on thrust forces. The effect of feed is 89.9%, and the cutting speed is 5.32%. The average value for minimum thrust force is 621.41 N.

**Application of Taguchi approach for thrust forces of three Composite materials**

If we take the material as the third parameter, the orthogonal array in the Taguchi method turns into the state in Table 6. Table 7, on the other hand, displays the average force-loss function and S/N ratios.

ANOVA was used to determine the percentage contribution and optimum combination of drilling parameters. The results of ANOVA of the raw data or mean of thrust force and the results of ANOVA of S/N ratios are given in Table 8. The percentage contributions of all the drilling parameters and materials were quantified in the last columns.

**Table 5. Mean Forces and S/N ratios according to the Taguchi method for three composite materials.**

| Experimental design | GFRP/Epoxy | Al\(_2\)O\(_3\) added GFRP/Epoxy | Si\(_2\)O added GFRP/Epoxy |
|---------------------|-----------|--------------------------------|---------------------------|
| No | \(v\) | \(f\) | \(F_{i(\text{mean})}\) | \(\text{Loss func}\) | \(\text{S/N ratio}\) | \(F_{i(\text{mean})}\) | \(\text{Loss func}\) | \(\text{S/N ratio}\) | \(F_{i(\text{mean})}\) | \(\text{Loss func}\) | \(\text{S/N ratio}\) |
| 1 | 50 | 0.05 | 256.2 | 66335.5 | -48.2 | 618.27 | 383979.2 | -55.84 | 621.4 | 387971.5 | -55.88 |
| 2 | 50 | 0.1 | 339.9 | 115464.5 | -50.62 | 765.86 | 587478.8 | -57.69 | 817.6 | 665681.8 | -58.23 |
| 3 | 50 | 0.2 | 714.5 | 511931.4 | -57.09 | 1084.86 | 1162251 | -60.65 | 1126.3 | 1281261 | -61.08 |
| 4 | 70 | 0.05 | 363.1 | 133122.2 | -51.24 | 710.34 | 509243.3 | -57.07 | 731.8 | 528639.4 | -57.23 |
| 5 | 70 | 0.1 | 399.5 | 158719.7 | -52.00 | 900.93 | 813178.4 | -59.10 | 844.7 | 701634.6 | -58.46 |
| 6 | 70 | 0.2 | 683.8 | 465319.9 | -56.67 | 1327.03 | 1758257 | -62.45 | 1418.4 | 2062767 | -63.14 |
| 7 | 90 | 0.05 | 261.8 | 69016.06 | -48.39 | 749.79 | 546900.8 | -57.37 | 725.2 | 528393.4 | -57.23 |
| 8 | 90 | 0.1 | 443.9 | 198630.9 | -52.98 | 1079.75 | 1159537 | -60.64 | 1048.1 | 834401.2 | -59.21 |
| 9 | 90 | 0.2 | 783.6 | 615123.7 | -57.89 | 1160.91 | 1364632 | -61.35 | 1150.5 | 1330154 | -61.24 |
of the results in Table 9. Both results suggest that the influence of feed rate on thrust force is much larger than that of cutting speed.

Response Table for mean and Response Table for the S/N ratio in Table 10 show that thrust force is minimum at the first levels of cutting speed, feed rate, and material. It means that minimum values of cutting speed and feed rate and the use of pure epoxy GFRP composite material give the minimum value of thrust force. In this analysis, composite material shows the greatest effect on the thrust force. While thrust force has a minimum value for pure epoxy/GFRP, thrust force has a maximum value for SiO2 added GFRP. It means that pure epoxy/GFRP has the best machinability. The second significant effect on the thrust force was obtained for feed rate, while the minimum effect was identified for cutting speed. According to the “the smaller the better” rule, the minimum thrust force was determined for epoxy. Middle and high values of thrust force for Al2O3 and SiO2 were obtained, respectively. It was observed that the thrust force for Al2O3 and SiO2 are close. The feed rate displays less effect than the material on the thrust force. The minimum value of thrust force was obtained at 0.05 mm/rev feed and 50 m/min cutting speed values. It was seen that the influence of material on thrust force is 59%, while the influences of feed rate and cutting speed are 34% and 4%, respectively.

**Taguchi analysis for delamination**

In the Taguchi analysis, the average value of the experimental response and its corresponding signal-to-noise ratio

### Table 6. L9 Orthogonal array for three 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)        |

### Table 7. Mean thrust force, loss function, and S/N rates for three materials.

| Ex. No | v  | f  | l  | 2  | 3  | 4  | Mean | Loss F | S/N  |
|--------|----|----|----|----|----|----|------|--------|------|
| 1      | 50 | 0.05 | 250 | 261 | 264 | 255 | 257.5 | 66558.1 | -48.2384 |
| 2      | 50 | 0.1  | 755.33 | 767.32 | 779.45 | 763.59 | 766.4225 | 588562.3 | -57.6979 |
| 3      | 50 | 0.2  | 1125.41 | 1147.49 | 1151.45 | 1102.69 | 1131.76 | 1297500 | -61.1311 |
| 4      | 70 | 0.05 | 700.34 | 722.18 | 735.43 | 695.77 | 713.43 | 515464.9 | -57.122  |
| 5      | 70 | 0.1  | 885.38 | 798.11 | 823.24 | 841.39 | 837.03 | 699805.2 | -58.4498 |
| 6      | 70 | 0.2  | 685.45 | 668.56 | 693.78 | 680.54 | 682.0825 | 465845.4 | -56.6824 |
| 7      | 90 | 0.05 | 695.37 | 740.39 | 750.34 | 720.31 | 726.6025 | 530669.5 | -57.2482 |
| 8      | 90 | 0.1  | 440.34 | 44.89 | 460.65 | 435.44 | 445.58 | 200864.3 | -53.029 |
| 9      | 90 | 0.2  | 1135.99 | 1210.49 | 1145.3 | 67.76 | 889.885 | 1214842 | -60.8452 |

### Table 8. Analysis of Variance in case of taking as a variable of material.

| Source        | DOF | SS     | MS     | F-ratio | % Contribution |
|---------------|-----|--------|--------|---------|----------------|
| For mean thrust force |     |        |        |         |                |
| Cutting speed | 2   | 4859.217 | 2429.609 | 0.304558 | 0.962417       |
| Feed         | 2   | 173845.1 | 86922.57 | 10.89598 | 34.43178       |
| Material     | 2   | 310.238  | 155.119 | 19.44458 | 61.44576       |
| Error        | 2   | 15954.98 | 7977.491 | 3.160045 |                |
| Total        | 8   | 504897.3 |        |         |                |
| For S/N Ratio |     |        |        |         |                |
| Cutting speed | 2   | 4.958605 | 2.479303 | 1.442197 | 3.922131       |
| Feed         | 2   | 43.40584 | 21.70292 | 12.62447 | 34.33292       |
| Material     | 2   | 74.62363 | 37.31182 | 21.70408 | 59.0254        |
| Error        | 2   | 3.438231 | 1.719115 | 2.719553 |                |
| Total        | 8   | 126.4263 |        |         |                |
(S/N) of each run can be calculated to analyze the effects of the machining parameters. However, the S/N ratio was chosen for the Taguchi analysis because the S/N ratio represents both the average and variation of the experimental results. In the current analysis, the L9 orthogonal array was used. The data obtained from the experimental plan, designed through the Taguchi method, is given for the entrance region in Table 10 and the exit region in Table 10.41

Variance analysis for delamination of GFRP/Epoxy

Variance analysis for pure GFRP/Epoxy composite material was performed. In drilling GFRP/Epoxy materials at the hole entrance, the drilling parameters are a feed rate of 0.05 mm/rev and a cutting speed of 70 m/min that was obtained according to “the smaller the better” rule for the minimum delamination. Feed rate displays the highest effect on delamination factors. The contribution of feed rate is 74.87%, and the effect of cutting speed is 13.27%. Variance analysis was performed for pure GFRP/Epoxy composite material for delamination at the exit. In the drilling of GFRP/Epoxy materials, at the hole exit, 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%.41

Variance analysis for delamination of SiO2 added Composite material

Variance analysis was performed for delamination factor at the hole entrance of SiO2 added GFRP/Epoxy composite material. In drilling, SiO2 added GFRP/Epoxy 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 the delamination factor. The effect of feed is 81.42%, and the cutting speed is 16.89%.

Variance analysis for delamination of Al2O3 added Composite material

Variance analysis was performed for delamination factor at the hole exit of Al2O3 added GFRP/Epoxy composite material. In drilling, Al2O3 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 the delamination factor. The effect of feed is 76.66%, and the cutting speed is 19.03%.

Application of Taguchi approach by taking Composite material as a variable

If we take the material as the third parameter, the orthogonal array in the Taguchi method turns into the state in Table 6. Table 12, on the other hand, displays average loss function and S/N ratios. In applying the Taguchi method, where the material is taken as a variable, for the delamination factor at the hole entrance, variance analysis for the three composite materials is given in Table 13; and the response table is shown in Table 14.

ANOVA was used to accurately determine the percentage contribution and optimum combination of drilling parameters. The results of ANOVA of the raw data or mean of

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### Table 9. Response Table in case of taking as a variable of material.

| Response table for mean | Response table for S/N |
|-------------------------|------------------------|
| Level | Cutting speed | Feed | Material | Level | Cutting speed | Feed | Material |
| 1 | 718.5608 | 565.8442 | 461.7208 | 1 | –55.6891* | –54.2029* |
| 2 | 744.1808 | 683.0108 | 789.9125 | 2 | –57.4181 | –56.3922 |
| 3 | 687.3558 | 901.2425 | 898.4642 | 3 | –57.0408 | –59.5529 |
| Delta | 56.825 | 335.3983 | 436.7433 | Delta | 1.728934 | 5.350025 | 6.293087 |
| Rank | 3 | 2 | 1 | Rank | 3 | 2 | 1 |

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### Table 10. Response Table in case of taking as a variable of material.

| Level | Cutting speed | Feed | Material |
|-------|---------------|------|----------|
| 1 | 718.5608 | 565.8442 | 461.7208 |
| 2 | 744.1808 | 683.0108 | 789.9125 |
| 3 | 687.3558 | 901.2425 | 898.4642 |
| Delta | 56.825 | 335.3983 | 436.7433 |
| Rank | 3 | 2 | 1 |
Table 10. Mean delamination factors and S/N ratios according to the Taguchi method for three composite materials at the hole entrance.

| Parameter | GFRP/Epoxy | Al₂O₃Added GFRP/Epoxy | SiO₂ added GFRP/Epoxy |
|-----------|-------------|------------------------|------------------------|
|           | F_d(mean)   | Loss func              | S/N ratio              | F_d(mean)   | Loss func  | S/N ratio  | F_d(mean)   | Loss func  | S/N ratio  |
| ν         | f           |                        |                        |            |            |            |            |            |            |
| 50        | 0.05        | 1186                   | 1.40607                | −1.48007   | 1.1028     | 1.2162     | −0.84994   | 1.1491     | 1.3204     | −1.20716   |
| 50        | 0.1         | 1216                   | 1.478487               | −1.69817   | 1.1495     | 1.3214     | −1.21018   | 1.2632     | 1.5957     | −2.02944   |
| 50        | 0.2         | 1552                   | 2.409185               | −3.8187    | 1.2264     | 1.5041     | −1.77264   | 1.2895     | 1.6628     | −2.20843   |
| 70        | 0.05        | 1114                   | 1.241145               | −0.93822   | 1.1682     | 1.3647     | −1.35034   | 1.1983     | 1.4359     | −1.57131   |
| 70        | 0.1         | 1209                   | 1.460507               | −1.64503   | 1.1619     | 1.3500     | −1.30338   | 1.3276     | 1.7625     | −2.46134   |
| 70        | 0.2         | 1273                   | 1.620036               | −2.09525   | 1.1923     | 1.4216     | −1.52771   | 1.3913     | 1.9357     | −2.86842   |
| 90        | 0.05        | 1130                   | 1.277238               | −1.06272   | 1.1028     | 1.2162     | −0.84994   | 1.1982     | 1.4357     | −1.57059   |
| 90        | 0.1         | 1279                   | 1.636657               | −2.13958   | 1.1321     | 1.2817     | −1.0777    | 1.3391     | 1.7932     | −2.53626   |
| 90        | 0.2         | 1547                   | 2.394592               | −3.79231   | 1.1792     | 1.3905     | −1.43175   | 1.4649     | 2.1459     | −3.31616   |
delamination factor and the results of ANOVA of S/N ratios are given in Table 12 and Table 13. The percentage contributions of all the drilling parameters and materials are quantified under the tables’ last column. Both tables suggest that the influence of material on the delamination factor is much more significant than the influence of feed rate and cutting speed. It is clear from Table 14 that the delamination factor is minimum at the first level of cutting speed, the first level of feed rate, and the second level of material. The S/N ratio analysis from Table 16 shows similar results: the delamination factor is minimum at the first levels of cutting speed and feed rate in the drilling of Al2O3 added GFRP/epoxy composite. The material having the best machinability of the three materials was Al2O3 added GFRP composite.

In the application of the Taguchi method, when the material is taken as a variable for delamination factor at hole exit, Table 15 displays average loss function and S/N ratios for delamination factor at hole exit, variance analysis for the three materials is given in Table 16, and the response table is shown in Table 17.

It is clear from Table 17 that the delamination factor is minimum at the first level of cutting speed, the first level of feed rate, and the first level of material. The S/N ratio analysis from Table 18 also shows similar results. In accordance with that, the minimum delamination factor was obtained for the smallest cutting speed and feed rate in the drilling of Al2O3 added GFRP/epoxy composite. When the contribution percentage is examined in Table 16, 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 factor at the hole exit is larger than the effect of cutting speed and less than feed rate.

According to the rule, the best result of minimum delamination was obtained at pure GFRP/epoxy composite material in “the smallest is better.” The minimum value of the delamination factor was determined 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 which obtains minimum delamination is the material that has better machinability than the three examined materials. Good machinability was obtained in the drilling of pure GFRP/epoxy composite. Machinability gradually decreases from pure GFRP/epoxy composite toward Al2O3 added composite and SiO2 added composite materials.

Machinability analysis

Response surface methodology and Taguchi method were used to investigate the effect and contribution of cutting parameters on thrust force and delamination factor in drilling pure epoxy, Al2O3, and SiO2 added GFRP/epoxy
composites. The results of this study were summarized in Table 18 and Table 19 and explained as follows:

According to the results of the Taguchi analysis, a feed of 0.05 mm/rev gave the minimum delamination factor for three of the materials, and the feed rate showed the biggest effect on the delamination factor. Feed rate is an important parameter, and its contributions for GFRP/Epoxy, Al₂O₃ added GFRP, and SiO₂ added GFRP were obtained at 74.87%, 65.88%, and 76.66% at the hole entrance and 92.22%, 81.42%, and 93.31% at the hole exit respectively.

The effect of cutting speed on delamination is less. The cutting speeds for the minimum delamination were obtained at 70 m/min for GFRP/Epoxy and 50 m/min for the other composite materials. The contributions of cutting speed for GFRP/Epoxy, Al₂O₃ added GFRP, and SiO₂ added GFRP were found at 13.27%, 15.21%, and 19.03% at the entrance, 4.13%, 16.89%, and 1.05% at the exit, respectively.

When the material was considered as a variable for delamination at the hole entrance, it was found that the effect of the material was higher than feed rate and cutting speed on the delamination factor. Secondly, the parameter with the maximum effect is feed rate, and cutting speed is the parameter with minimum effect. The minimum delamination factor was obtained for the smallest cutting speed and feed rate in Al₂O₃ added GFRP composite drilling.

For delamination at the hole exit, it was found that the effect of the material is smaller than the feed rate and less than the cutting speed on the delamination factor. The minimum delamination factor was obtained by the smallest cutting speed and feed rate in pure GFRP/epoxy composite drilling. It was observed that the delamination factors at the hole exit were greater than those at the hole entrance. Due to

Table 13. Analysis of variance in taking as a variable of composite material for delamination factor at hole entrance.

| Source                      | DOF | Sum of squares | Mean square | F-ratio | %Contribution |
|-----------------------------|-----|----------------|-------------|---------|---------------|
| For the mean delamination factor |     |                |             |         |               |
| Cutting speed               | 2   | 0.003811       | 0.001905    | 1.666464| 11.51338      |
| Feed                        | 2   | 0.008615       | 0.004308    | 3.767222| 26.02751      |
| Material                    | 2   | 0.018387       | 0.009194    | 8.040332| 55.55017      |
| Error                       | 2   | 0.002287       | 0.001143    | 3.971264| 26.02751      |
| Total                       | 8   | 0.0331         |             |         |               |
| For S/N Ratio               |     |                |             |         |               |
| Cutting speed               | 2   | 0.18459        | 0.092295    | 1.614614| 11.2533       |
| Feed                        | 2   | 0.419446       | 0.209723    | 3.668906| 25.571        |
| Material                    | 2   | 0.921958       | 0.460979    | 8.064397| 56.20605      |
| Error                       | 2   | 0.114324       | 0.057162    | 3.971264| 26.02751      |
| Total                       | 8   | 0.18459        |             |         |               |

Table 14. Response table for three materials for delamination factor at the hole entrance.

| Level | Cutting speed | Feed rate | Material |
|-------|---------------|-----------|----------|
| 1     | 1.208333      | 1.184133  | 1246     |
| 2     | 1.256267      | 1.252033  | 1.165633 |
| 3     | 1.2188        | 1.247233  | 1.271767 |
| Delta | 0.047933      | 0.0679    | 0.106133 |
| Rank  | 3             | 2         | 1        |

Table 15. 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  | 1.320669 | -1.20794 |
| 2    | 50  | 0.1  | 1.1495 | 1.32135  | -1.21018 |
| 3    | 50  | 0.2  | 1.5555 | 2.41958  | -3.8374  |
| 4    | 70  | 0.05 | 1.1682 | 1.364691 | -1.35034 |
| 5    | 70  | 0.1  | 1.5048 | 2.264423 | -3.54958 |
| 6    | 70  | 0.2  | 1.459  | 2.127709 | -3.27912 |
| 7    | 90  | 0.05 | 1.3158 | 1.73133  | -2.3838  |
| 8    | 90  | 0.1  | 1.2903 | 1.665082 | -2.21436 |
| 9    | 90  | 0.2  | 1.1792 | 1.3905   | -1.43175 |

| v    | f   | Mean | Loss F | S/N  |
|------|-----|------|--------|------|
|      | 1.307889 | -2.27383 |
the effect of delamination on the quality of the drilled surface, the material with the minimum delamination was defined as the material with better machinability. The pure GFRP composite was the material with good quality machinability at the hole exit.

According to the other results of the Taguchi analysis, a cutting speed of 50 m/min and feed of 0.05 mm/rev gave the minimum thrust force for all three materials. The minimum thrust force for GFRP/pure epoxy is 256 N; SiO₂ and Al₂O₃ added reinforced composites is approximately 620 N, almost 2.4 times bigger than the thrust force for GFRP/pure epoxy. Feed is an important parameter for GFRP/pure epoxy and SiO₂ reinforced composites, and its contribution is 90%. The effect of feed for Al₂O₃ reinforced composite is 80%. Good machinability is obtained with pure epoxy composite material. Machinability gradually decreases from pure epoxy composite material toward Al₂O₃ and SiO₂ added composite materials.

In this study, it was seen that when the material is taken as a variable, the effect of the material on the thrust force is higher than the feed and cutting speed. The second parameter with the maximum effect is the feed, and the cutting speed is the parameter with the minimum effect.

In optimizing second-order mathematical models of delamination and thrust forces created by RSM, the lowest thrust force value for pure epoxy GFRP composite material compared to doped GFRP materials was obtained at low values of drilling parameters. The thrust force values obtained in optimizing doped GFRP composites are close. The RSM model obtained minimum thrust force values at low drilling parameters for all three composite materials. Pure epoxy GFRP composite material has a lower thrust value than GFRP composites. Therefore, pure epoxy GFRP composite materials have better machinability.

### Machinability index

Table 16. Analysis of Variance in case of taking the material as a variable (for delamination factor at hole exit).

| Source                      | DOF | Sum of squares | Mean square | F-ratio | Contribution% |
|-----------------------------|-----|----------------|-------------|---------|---------------|
| For the 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    |         |              |
| Total                       | 8   | 15.33679       |             |         |              |

Table 17. Response table for three materials (for delamination factor at hole exit).

| Level | Cutting speed | Feed | Material |
|-------|---------------|------|----------|
| 1     | 1.393633      | 1.2391 | 1.299333 |
| 2     | 1.4052        | 1.423767 | 1.573    |
| 3     | 1.5322        | 1.668167 | 1.4587   |
| Delta | 0.138567      | 0.429067 | 0.273667 |
| Rank  | 3             | 2     | 1        |

| Level | Cutting speed | Feed | Material |
|-------|---------------|------|----------|
| 1     | -2.80942      | -1.84864 | -2.23381 |
| 2     | -2.92762      | -3.04895 | -3.77211 |
| 3     | -3.5258       | -4.36526  | -3.25692 |
| Delta | 0.716384      | 2.51662   | 1.538299 |
| Rank  | 3             | 2     | 1        |
velocity ($v$) and the second column to the feed rate ($f$). The experimental plan and the chosen cutting parameters are given in Table 2.

To analyze the machinability of these materials, delamination factor ($F_d$) and thrust force ($F_t$) from experimental data have been obtained. These are given in Table 3 for thrust force and Table 4 for delamination factor, respectively. A new machinability index (MI) is constructed as in Eq. 17.

\[
MI = \frac{1}{(F_t)^*\alpha} \frac{1}{(F_d)^*\beta}
\]  

(17)

Where $F_t$ is the thrust force in N, $F_d$ is the delamination factor in mm, and $\alpha$ and $\beta$ are the weight of the parameters. The values of $\alpha$ and $\beta$ have been obtained to contribute to $F_t$ and $F_d$ in MI. The relation between the thrust force ($F_t$) and the delamination factor ($F_d$) allows calculating $\alpha = 100$ and $\beta = 1$ by considering the results of this study.

Machinability indexes calculated with the delamination and the thrust force values obtained by using feed rate and cutting speed values according to the L9 orthogonal index used in Taguchi analysis are given in Table 20.

MI increases with the feed rate decrease for several cutting velocities and presents a maximum of 0.05 mm/rev. A graphical representation of the variation of MI according to the material is given in Figure 4.

It can be evidenced that the Epoxy/GFRP composite provides a better MI (average MI = 0.203) in comparison to Al$_2$O$_3$ doped Epoxy/GFRP (average MI = 0.076) and SiO$_2$ added Epoxy/GFRP (average MI = 0.078). This behavior is due to the smaller values of $F_d$ and $F_t$ for pure Epoxy/GF.

### Table 18. Summary of results of Taguchi analysis of delamination and thrust forces.

#### Delamination at the hole entrance

|         | Pure epoxy | Added Al$_2$O$_3$ | Added SiO$_2$ |
|---------|------------|-------------------|--------------|
| $f$, mm/rev | $v$, m/min | $f$, mm/rev | $v$, m/min | $f$, mm/rev | $v$, m/min |
| 0.05    | 70         | 0.05             | 50           | 0.05         | 50          |
| The values of drilling parameters for minimum delamination | The minimum delamination values | Contributions to delamination of the drilling parameters |
| 0.05    | 70         | 0.05             | 50           | 0.05         | 50          |
| The minimum delamination values | Contributions to delamination of the drilling parameters |
| 1.11418 | 1.028      | 1.1491           |
| 74.87%  | 13.27%     | 65.88%           | 15.21%       | 76.66%       | 19.03%      |

The effect of the material on the machinability is 55.55%, the effect of the feed rate on the machinability is 26%, and the effect of the cutting speed on the machinability is 11.5%. The smallest value of the delamination factors for three materials at the low feed rate values and cutting speed was achieved when machining Al$_2$O$_3$ doped GFRP.

#### Delamination at the hole exit

| Pure epoxy | Added Al$_2$O$_3$ | Added SiO$_2$ |
|------------|-------------------|--------------|
| $f$, mm/rev | $v$, m/min | $f$, mm/rev | $v$, m/min | $f$, mm/rev | $v$, m/min |
| 0.05    | 70         | 0.05             | 50           | 0.05         | 50          |
| The values of drilling parameters for minimum delamination | The minimum delamination values | Contributions to delamination of the drilling parameters |
| 0.05    | 70         | 0.05             | 50           | 0.05         | 50          |
| The minimum delamination values | Contributions to delamination of the drilling parameters |
| 1.1492  | 4.13%      | 81.42%           | 16.89%       | 93.31%       | 1.05%       |

The effect of the material on the machinability is 23.6%, the effect of the feed rate on the machinability is 57.9%, and the effect of the cutting speed on the machinability is 7.39%. The smallest value of the delamination factors for three materials at the low feed rate values and cutting speed was achieved when machining pure epoxy GFRP.

#### Optimization of thrust force

| Pure epoxy | Added Al$_2$O$_3$ | Added SiO$_2$ |
|------------|-------------------|--------------|
| $f$, mm/rev | $v$, m/min | $f$, mm/rev | $v$, m/min | $f$, mm/rev | $v$, m/min |
| 0.05    | 70         | 0.05             | 50           | 0.05         | 50          |
| Drilling parameters for minimum delamination | Contributions to thrust force of the drilling parameters |
| 0.05    | 70         | 0.05             | 50           | 0.05         | 50          |
| Minimum values of thrust force | Contributions to thrust force of the drilling parameters |
| 256.2 N | 618.24 N | 621.41 N |

The effect of the material on the thrust force is 61.44%, the effect of the feed rate on the thrust force is 34.43%, and the effect of the cutting speed on the thrust force is 0.94%. The smallest value of the thrust force for three materials at the low feed rate values and cutting speed was achieved when machining pure epoxy GFRP.

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Table 19. Summary of results of RSM Optimization of delamination and thrust forces.

Optimization of thrust force

| Pure epoxy | Added Al₂O₃ | Added SiO₂ |
|------------|-------------|------------|
| Drilling parameters | f, mm/rev | v, m/min | f, mm/rev | v, m/min | f, mm/rev | v, m/min |
| Parameter values for minimum delamination | 0.005 | 37 | 0.005 | 37 | 0.005 | 37 |
| Thrust Force, N | 53.09 | 131.88 | 105.65 |

Optimization of delamination at the hole entrance

| Pure epoxy | Added Al₂O₃ | Added SiO₂ |
|------------|-------------|------------|
| Drilling parameters | F, mm/rev | v, m/min | F, mm/rev | v, m/min | F, mm/rev | v, m/min |
| Parameter values for minimum delamination | 0.05 | 50 | 0.05 | 50 | 0.05 | 50 |
| Delamination factor | 1.113 | 1.1028 | 1.1491 |

Optimization of delamination at the hole exit

| Pure epoxy | Added Al₂O₃ | Added SiO₂ |
|------------|-------------|------------|
| Drilling parameters | F, mm/rev | v, m/min | F, mm/rev | v, m/min | F, mm/rev | v, m/min |
| Parameter values for minimum delamination | 0.05 | 50 | 0.05 | 50 |
| Delamination factor | 1.1369 | 1.2056 | 1.3158 |

Table 20. Machinability index for GFRP/Epoxy, Al₂O₃ added GFRP and SiO₂ added GFRP.

| Experimental design | GFRP/Epoxy | SiO₂ added GFRP/Epoxy | Al₂O₃ added GFRP/Epoxy |
|---------------------|-------------|------------------------|------------------------|
| No | v | f | Fₜ | F_den | F_dex | Mₑpoxy | Fₜ | F_dent | F_dex | Mₑpoxy | Fₜ | F_den | F_dex | Mₑpoxy |
| 1 | 50 | 0.05 | 256.2 | 1.186 | 1.1492 | 0.34 | 621.4 | 1.1028 | 1.2056 | 0.133 | 618.27 | 1.1491 | 1.3394 | 0.1207 |
| 2 | 50 | 0.1 | 339.9 | 1.216 | 1.4167 | 0.207 | 817.6 | 1.1495 | 1.4762 | 0.083 | 765.86 | 1.2632 | 1.5229 | 0.0857 |
| 3 | 50 | 0.2 | 714.5 | 1.552 | 1.5098 | 0.092 | 1126.3 | 1.2264 | 1.7115 | 0.0518 | 1084.86 | 1.2895 | 1.5555 | 0.059 |
| 4 | 75 | 0.05 | 363.1 | 1.114 | 1.1369 | 0.3065 | 731.8 | 1.1682 | 1.2523 | 0.109 | 710.34 | 1.1983 | 1.3394 | 0.105 |
| 5 | 75 | 0.1 | 399.5 | 1.209 | 1.2887 | 0.194 | 844.7 | 1.1619 | 1.4667 | 0.0807 | 900.93 | 1.3276 | 1.5048 | 0.074 |
| 6 | 75 | 0.2 | 683.8 | 1.273 | 1.4584 | 0.100 | 1418.4 | 1.1923 | 1.8857 | 0.037 | 1327.03 | 1.4649 | 1.6571 | 0.052 |
| 7 | 90 | 0.05 | 261.8 | 1.130 | 1.1741 | 0.325 | 725.2 | 1.1028 | 1.4245 | 0.097 | 749.79 | 1.1982 | 1.3158 | 0.103 |
| 8 | 90 | 0.1 | 443.9 | 1.279 | 1.2903 | 0.175 | 1048.1 | 1.1321 | 1.7383 | 0.05 | 1079.75 | 1.3391 | 1.4673 | 0.063 |
| 9 | 90 | 0.2 | 783.6 | 1.547 | 1.4312 | 0.089 | 1150.5 | 1.1792 | 1.9905 | 0.044 | 1160.91 | 1.4649 | 1.6571 | 0.052 |

Figure 4. A graphical representation of the variation of MI for all three materials.
According to the machinability index, the pure epoxy composite material has better machinability than the other composite materials. Epoxy composites reinforced with Al₂O₃ and SiO₂ additives had equivalent machinability. The reason for this deterioration of machining performance may be the effect of abrasive effects of additives such as SiO₂ and Al₂O₃.

Conclusions

- Pure epoxy GFRP composite has minimum thrust force values at low feed rates and medium cutting speeds. The added GFRP Composites have minimum thrust force values at low drilling parameters and are higher than the thrust force of pure epoxy GFRP composite.
- The delamination factors at the hole exit are larger than those at the hole entrance. In terms of hole quality, the delamination factor at the hole exit should be considered in the delamination analysis. -Minimum delamination factors and thrust forces are obtained for the same drilling parameters. When drilling parameters show change, if the delamination increases, the thrust forces increase, or if the delamination decreases, the thrust forces decrease. Therefore, the change in delamination can be followed by the change in thrust forces.
- The smallest values of the cutting parameters for all three materials gave the minimum thrust forces and delamination factors.
- According to the machinability index, the pure epoxy composite material has better machinability than the SiO₂/Al₂O₃ Added GFRP composite materials. That is, it was seen that Epoxy composites reinforced with Al₂O₃ and SiO₂ additives had the worse machining performance. Another reason for this deterioration is the effect of the SiO₂ and Al₂O₃ fillers on the bonding between epoxy and glass fibers. It is thought that the additives both improve the wear resistance in service and deteriorate the bonding between main structural materials. Therefore the machinability of glass fiber composites decreases when additives such as SiO₂ and Al₂O₃ are used.

Authors’ contributions

Ali Ünüvar: supervision, methodology, writing (original draft preparation), visualization, validation, investigation, reviewing, and editing. Osman Öztürk: methodology, reviewing and editing, experimental work.

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References

1. El-Sonbaty I, Khashaba UA and Machaly T. Factors affecting the machinability of GFR/epoxy composites. Compos Structures 2004; 63: 329–338.
2. Davim JP and Reis P. Study of delamination in drilling carbon fiber reinforced plastics (CFRP) using design experiments. Compos Structures 2003; 59: 481–487.
3. Khashaba UA, El-Sonbaty IA, Selmy AI, et al. Machinability analysis in drilling woven GFR/epoxy composites: part II - Effect of drill wear. Composites A 2010; 41: 1130–1137.
4. Khashaba UA, El-Sonbaty IA, Selmy AI, et al. Machinability analysis in drilling woven GFR/epoxy composites: part I - effect of machining parameters. Composites Part A 2009; 41: 391–400.
5. Heisela U and Tobias P. Influence of point angle on drill hole quality and machining forces when drilling CFRP. 5th CIRP Conf High Perform Cutting Procedia CIRP 2012; 1: 471–476.
6. Abrão AM, Campos Rubio JC, Faria PE, et al. The effect of cutting tool geometry on thrust force and delamination when drilling glass fibre reinforced plastic composite. Mater Des 2008; 29: 508–513.
7. Lih TC and Azwan IA. Analytical study of critical thrust force for on-set delamination damage of drilling hybrid carbon/glass composite. Int J Adv Manuf Technol 2017; 92: 929–941. DOI: 10.1007/s00170-017-0152-1.
8. Mohan NS, Kulkarni SN and Ramachandra A. Delamination analysis in drilling process of glass fiber reinforced plastic (GFRP) composite materials. J Mater Process Technology 2006; 186: 265–271.
9. Hocheng H and Dharan CKH. Delamination during drilling in composite laminates. ASME J Eng Indus 1990; 112: 236–239.
10. Hocheng H and Tsao CC. The path towards delamination-free drilling of composite materials. J Mater Process Technol 2005; 167: 251–264.
11. Hocheng H and Tsao CC. Comprehensive analysis of delamination in drilling of composite materials with various drill bits. J Mater Process Technol 2003; 140: 335–339.
12. Hocheng H and Tsao CC. Effect of special drill bits on drilling-induced delamination of composite materials. J Mach Tools Manuf 2006; 46: 1403–1416.
13. Khashaba UA, El-Sobaty IA, Selmy AI, et al. Machinability analysis in drilling woven GFR/epoxy composites: part II – effect of drill wear. Composites: A 2010; 41: 1130–1137.
14. Khashaba UA, El-Sonbaty IA, Selmy AI, et al. Megahed machinability analysis in drilling woven GFR/epoxy composites: part I—effect of machining parameters. Composites: Part A 2010; 41: 391–400.
15. Davim JP and Reis P. Drilling carbon fiber reinforced plastics manufactured by autoclave experimental and statistical study. *Mater Des* 2003; 24: 315–324.

16. Davim JP and Pedro R. Study of delamination in drilling carbon fiber reinforced plastic (CFRP) using design experiments. *Compos Struct* 2003; 59: 481–487.

17. Palanikumar K, Rubio JC, Abrao A, et al. Statistical analysis of delamination in drilling glass fiber-reinforced plastics (GFRP). *J Reinf Plast Comp* 2008; 27(15): 1615–1623.

18. Latha B and Senthilkumar VS. Fuzzy rule based modeling of drilling parameters for delamination in drilling GFRP composites. *J Reinf Plast Comp* 2009; 28(8): 951–964.

19. Kilickap E. Investigation into the effect of drilling parameters on delamination in drilling GFRP. *J Reinf Plast Comp* 2010; 29(23): 3498–3503.

20. Palanikumar K. Modeling and analysis of delamination factor and surface roughness in drilling GFRP composites. *Mater Manuf Process* 2010; 25(10): 1059–1067.

21. Palanikumar K, Latha B, Senthilkumar VS, et al. Analysis on drilling of glass fiber–reinforced polymer (GFRP) composites using grey relational analysis. *Mater Manuf Process* 2012; 27(3): 297–305, DOI: 10.1080/10426914.2011.577865.

22. Palanikumar K, Srinivasan T, Rajagopal K, et al. Thrust force analysis in drilling glass fiber reinforced/polypropylene (GFR/PP) composites. *Mater Manuf Process* 2016; 31(5): 581–586.

23. Srinivasan T, Palanikumar K, Rajagopal K, et al. Optimization of delamination factor in drilling GFR–polypropylene composites. *Mater Manuf Process* 2017; 32(2): 226–233.

24. Liu L, Qi C, Wu F, et al. Analysis of thrust force and delamination in drilling GFRP composites with candle stick drills. *The Int J Adv Manufacturing Technology* 2018; 95: 2585–2600.

25. Osman O, Ali U, Murat K, et al. Kesme parametrelerinin ve SiO2-Al2O3 katkısının cеп/epoksi kompozit malzemelerin ıslenebilirligine etkisini Taguchi yöntemi ile analiz et. Bursa: Ulusal Talaslı İmalat Sempozyumu, 2014, pp. 23–24.

26. Khashaba UA, Abd-Elwahed MS, Eltaher MA, et al. Thermo-mechanical and delamination properties in drilling GFRP composites by various drill angles. *Polymers* 2021; 13(11): 1884.

27. Khashaba UA, Abd-Elwahed MS, Najjar I, et al. Heat affected zone and mechanical analysis of GFRP composites with different thicknesses in drilling processes. *Polymers* 2021; 13(14): 2246.

28. Yazman Ş. The effects of back-up on drilling machinability of filament wound GFRP composite pipes: mechanical characterization and drilling tests. *J Manufacturing Process* 2021; 68: 1535–1552.

29. Juwala SR, Chebattina KR, Venkata Ramana VSN, et al. Machinability aspects of nano MMT deposited GFRP composites to minimize the drilling induced delaminations. *Journal of The Institution of Engineers (India)* Series C, 2022, pp. 1–7.

30. Singh PK, Modanwal RP and Deepak K. Fabrication and mechanical characterization of glass fiber/Al2O3 hybrid-epoxy composite. *Sadhana* 2021; 46(1): 1–10, DOI: 10.1007/s12046-020-01539-3.

31. Saini P and Pradeep K. Singh investigation on characterization and machinability of Al-4032/SiC metal matrix composite. *Surf Topography: Metrology Properties* 2022; 10(2): 25007.

32. Kumar D and Singh PK. Pardeep saini morphological and mechanical characterization of the Al-4032/granite powder composites. *J Compos Mater* 2022; 56(15): 2433–2442, DOI: 10.1177/00219983221092837.

33. Saini P, Singh PK, Deepak K, et al. Optimization of process parameters in end milling of Al-4032 based metal matrix composite using TGRA. *Adv Mater Process Tech* 2021; 3: 1–13, DOI: 10.1080/2374068X.2021.1946750.

34. Guleria V, Kumar V, Pradeep K, et al. A novel approach for prediction of surface roughness in turning of EN353 steel by RVR-PSO using selected features of VMD along with cutting parameters. *J Mech Sci Technology* 2022; 36: 1–11, DOI: 10.1007/s12206-022-0510-2.

35. Saini P and Singh PK. Optimization of end milling parameters for rough and finish machining of Al-4032/35% SiC metal matrix composite. *Eng Res Express* 2021; 3(4): 45009, DOI: 10.1088/2631-8695/ac1e11.

36. Saini P, Pradeep KS and Deepak K. Effect of machining parameters for surface finish and material removal rate of Al-4032/SiC composite during end milling using TGRA and ANN. *J Adv Manufacturing Syst* 2022; 21: no01, DOI: 10.1142/S021968721500438.

37. Pradeep K, Singh KK and Pardeep S. Optimization of surface roughness and hole diameter accuracy in drilling of EN-31 alloy steel–ATGRA based analysis. *Mater Today: Proc* 2020; 26: 2961–2971, DOI: 10.1016/j.matpr.2020.02.611.

38. Bagci M and Imrek H. Solid particle erosion wear of GF/EP composites with added Al2O3. In: Chinesta F, Chastel El and Mansori M (eds). *International Conference on Advances in Materr/ s and Processing Technologies (AMP7)* 2010, 978. American Institute of Physics, 2010. DOI: 10.7354-0871-5/10/$30.00.

39. Bagci M, Imrek H and Khalfian OM. Effects of Silicon Oxide Filler Material and Fibre Orientation on Erosive Wear of GF/ EP Composites. *World Academy of Science, Eng Technology* 2011; 5: 78.

40. Khuri AI and Mukhopodhgay S. Response surface methodology. *Wiley Interdisciplinary Reviews: Computational Statistics*, 2010; 2: 128–144.

41. Ünüvar A, Koyunbakan M and Bagci M. Optimization and effects of machining parameters on delamination in drilling of pure and Al2O3/SiO2-added GFRP composites. *Int J Adv Manuf Technol* 2021; 119: 657–675, DOI: 10.1007/s00170-021-08258-x.