Machinability Analysis of Delamination and Thrust Force in Drilling of Pure and Added GFRP Composites

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Research Article

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Machinability Analysis of Delamination and Thrust Force in Drilling of Pure and Added GFRP Composites

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Abstract
The aim of this work is to define the cutting conditions that allow the drilling of added glass fiber reinforced epoxy composite materials by taking into consideration the exit delamination factor, thrust force and the optimum combination of drilling parameters. The experiments were carried out under two cutting parameters such as cutting speed and feed rate for three levels each. Taguchi experimental design is used to reduce the excessive number of experiments. The experiment design was accomplished by application of the statistical analysis of variance (ANOVA). Correlations between cutting speed/feed rate and the various machining parameters were established to optimize cutting conditions. These correlations were found by quadratic regression using response surface methodology (RSM). Multiple regression analysis (MRA) was also employed to establish parametric relationships between the experimental parameters and the machinability outputs consisting of delamination and thrust force. The machinability refers to the relative ease or difficulty under certain cutting conditions. Therefore, it is very important to understand the factors affect the machinability and to evaluate their effects. Machinability of GFRP composites was enquired. It is aimed to evaluate the machinability of these materials. A machinability index has been developed in current study.

Keywords: Glass fiber reinforced polymer, drilling, delamination factor, Taguchi method, Response surface methodology

1. Introduction

The glass fiber-reinforced plastic (GFRP) composites have been widely used in various industries in recent years due to their excellent properties, such as light weight, high modulus, high specific strength, and good corrosive resistance. Drilling is frequently used in assembling this type of composite components due to the need of the fastener mechanical connection. The drilling of GFRP composites is quite different from that of ordinary metals and their alloys and is often accompanied with 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 surely 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]. A large number of researches have carried out corresponding studies on drilling composites using traditional twist drill.

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 the feed rate leads an increasing of 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 an increasing of tool wear at high cutting speed and feed rate causes a rising of thrust force [3,4]. Uwe 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 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 [6]. The drilling parameters are important for minimization of delamination damage and the thrust force plays a critical role in influencing the size of the delamination zone. Chye Lih Tan et al. attempted an analytical study of drilling characteristics for composite material. Results of the analytical study 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 [7]. 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 optimizing the process parameters for minimum delamination [8]. The first analytical model to determine the critical thrust force was developed by Hocheng and Dharan [9]. 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 model of conventional twist drill bit [10,11,12]. Khashaba et al. [13] found that the effect of cutting speed on thrust force in drilling woven-ply GFRP composite laminates varied with tool wear. It was illustrated the effect of drill bit pre-wear on the thrust force at different cutting speed. They observed that the cutting speed has insignificant effect on thrust force in drilling GFRP composite laminates with fresh drill bits, while 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[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]. Palanikumar et al. [17] performed drilling experiments in GFRP composites to study the influence of the drilling parameters on push down delamination. They disclosed that feed rate was the main factor which had the greatest influence on push down delamination, followed by rotational speed. Latha and Senthilkumar [18] revealed that feed rate and drill diameter were the main factors which impacted the push down delamination in drilling of GFRP composites. The cutting speed showed only limited effect on push down delamination in drilling of GFRP composites. Kilickap et al. [19] revealed that the peel up delamination and the push down delamination increased with the increase of feed rate and cutting speed in drilling of

composites. Palanikumar et al. [20–23] analyzed in detail the influences of machining parameters on thrust force and delamination in drilling GFRP using candle stick drills. Experimental results showed that the drilling performance in composites could be improved by optimizing the drilling parameters. Candle stick drills have been recognized as advantageous tools for the reduction of thrust force and delamination damage in drilling composites. Liping Liu et al. carried out Drilling experiments of glass fiber-reinforced plastic (GFRP) composites and finite element simulations. Three candle stick drills with different drill tip geometries and one twist drill were compared in terms of thrust force, peel up delamination, and push down delamination[24]. Ozturk et al. investigated the effect of drlling parameters on the thrust force and machinability of added glass fiber-reinforced epoxy (GFRE) composites[25].
In this study, the effects of cutting speed and feed rate on thrust force and delamination in drilling of the materials including pure glass-fiber epoxy, SiO_2 /Al_2O_3 added reinforced epoxy were studied by means of an experimental design. To achieve this goal, a mathematical model was created by applying the response surface methodology. Using the response surface methodology and Taguchi method together, the significance levels and contributions of machining parameters to the thrust force were determined. Machinability of three composite materials was investigated. To determine the effects of drilling parameters on machinability parameters such as thrust force and delamination, machinability index has been created and compared machinability of pure and added GFRP composites.

2. Experimental Method

The samples used in the experiment consisted of pure glass-fiber pure epoxy, SiO_2 and Al_2O_3 reinforced composite GFRP composites. The dimensions of the sample materials are 4x65x165 mm. The mechanical properties of the samples are provided on Table 1 and experimental set-up 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 118^0 point angle and 6 mm diameter was used as cutting tool. The thrust forces for different cutting parameters were recorded according to experimental design by using Dynoware software.

Table 1

Figure 1:

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

$$Fd = \frac{Dmax}{D} \tag{1}$$

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

Fig.2

2.2. Response Surface Methodology

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 behaviour of response variable to several independent variables. After the machining parameters and the response function are identified, the relationship between the response and independent variables are modelled [26]. In the mathematical model, the relation between cutting parameters and delamination factor is stated as follows:

$$F_d = C_i\, v^{\rho 1}\, f^{\rho 2} \tag{2}$$

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

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

In this equation; ρ_1 and ρ_2 are the coefficients of the parameters while C_i is a constant coefficient. Equation (3) and (4) are the first order and the second order polynomial models respectively.

$$Y^{I} = y - \varepsilon = b_0x_0 + b_1x_1 + b_2x_2 \tag{3}$$

$$Y^{I} = y - \varepsilon = b_0x_0 + b_1x_1 + b_2x_2 + b_{11}x_1^2 + b_{22}x_2^2 + b_{12}x_1x_2 \tag{4}$$

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

2.3. Taguchi Method

The number of experiments increase depending on the number of processing parameters. In order to reduce the number of experiments, Taguchi method is used to analyze the results. This method combines three methods; orthogonal experimental design, signal-noise (S/N) ratio and variance analysis (ANOVA). Orthogonal experimental design is used to create a speicific design of parameters for different levels 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". "$(S/N)_{SB}$, the smaller-the better " are stated with the equation of (5). Here y_i indicates the result measured in experiments, n indicates the number of experiments.

$$S/N_{SB} = \eta = -10 \log \left[1/n\ \Sigma_{\,i=1}\ y_i^2\right] \tag{5}$$

3. Experimental Results

3.1.RSM Modeling for Thrust Force

The modelling 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 and these are provided on Table 2. In current study, 12 experiments were performed based on rotatable centred composite design. Five level for each variable was determined which is given in Table 2. 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 are recorded. Relationships between the coded variables and the real variables were given below.

$$x_1 = 2\frac{(lnv - ln90)}{(ln90 - ln50)} + 1 \qquad x_2 = 2\frac{(lnf - ln0.2)}{(ln0.2 - ln0.05)} + 1$$

Table 2:

Table 3:

Second order mathematical models were obtained for three different materials by means of RSM modelling by using the experiment plan. Coded variables are used in equations. Second order mathematical models for Pure GFRP/epoxy, Al_2O_3 added GFRP/epoxy, SiO_2 added GFRP/epoxy are given by equations (8), (9), and (10) respectively.

$$y_{pure} = 5.885+0.136x_1+0.15x_2–0.04x_1^2– 0.1x_2^2–0.195x_1x_2 \tag{8}$$

$$y_{al}=6.867+0.0414x_1+0.34615x_2-0.0915x_1^2-0.1133x_2^2-0.0984x_1x_2 \tag{9}$$

$$y_{si}=6.833+0.0578x_1+0.4364x_2-0.003x_1^{2-}0.052x_2^2-0.0913x_1x_2 \tag{10}$$

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

Fig.3

The F-ratios calculated for each of the three materials are bigger than F-table values; the models with 95% reliability are adequate. Table 4 contains the obtained significant parameters. As “calculated F-ratio” is larger than F-table value for pure GFRP/epoxy, cutting speed (x_1) and feed rate (x_2) were found to be significant in drilling operation. As “calculated F-ratio” is larger than F-table value for both SiO_2 added GFRP/epoxy and Al_2O_3 added GFRP/epoxy materials, feed rate (x_2) is observed to be significant.

3.1.1 Optimization of Thrust Forces

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

$$F=Y=b_0\,x_0+b_1\,x_1+b_2\,x_2+b_{11}\,x_1^2+b_{22}\,x_2^2+b_{12}\,x_1\,x_2$$

Subject to $g_1=-x_1-2<=0$

$g_2=x_1-2<=0$

$g_3=-x_2-2<=0$

$g_4=x_2-2<=0$

Where Y represents the objective function for delamination factors and thrust forces. Y is any one of *Ypure, Yal, Ysi.* Constraint nonlinear minimization method was applied, the optimum value of drilling parameters are obtained as x_1=-2, x_2=-2 for pure GFRP/epoxy, x_1=-2, x_2=-2 for Al_2O_3 added GFRP/epoxy and x_1=-2, x_2=-2 for SiO_2 added GFRP/epoxy. For all three composite materials the minimum thrust forces were obtained with the smallest feed rate and cutting speeds.

3.2 RSM Modelling for Delamination

The modelling 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 and these are provided in Table 2.

In current study, 12 tests based on rotatable centred composite design, three levels for each variable, were conducted. The experimental plan and levels given in Table 4 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.

Table 4:

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, Al_2O_3 added GFRP/epoxy, SiO_2 added GFRP/epoxy were given with equations (11), (12), and (13) respectively.

$$Y_{dfen1}=0{,}1214-0{,}0002x_1+0{,}1194x_2+0{,}0887x_1^2+0{,}0425x_2^2+0{,}0113x_1x_2 \quad (11)$$

$$Y_{dfen2}=0{,}1528-0{,}00908x_1+0{,}03227x_2-0{,}0225x_1^2+0{,}0115x_2^2-0{,}0098x_1x_2 \quad (12)$$

$$Y_{dfen3}=0{,}28162+0{,}03795x_1+0{,}07760x_2-0{,}01792\;2x_1^2-0{,}02518\,x_2^2+0{,}02142\,x_1x_2 \quad (13)$$

It is seen that the values of delamination factors for pure GFRP/epoxy composites are lower than for Al_2O_3 and SiO_2 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 all three materials.

Also, second order mathematical models of delamination factors at hole exit for pure GFRP/epoxy, Al_2O_3 added GFRP/epoxy and SiO_2 added GFRP/epoxy were given with equations (14), (15) and (16) respectively.

$$Y_{dfex1} = 0{,}2684 - 0{,}0209x_1 + 0{,}1200x_2 + 0{,}0258x_1^2 - 0{,}0230x_2^2 - 0{,}0187x_1x_2 \quad (14)$$

$$Y_{dfex2} = 0{,}4169 + 0{,}0802x_1 + 0{,}1824x_2 + 0{,}0374x_1^2 - 0{,}0042x_2^2 - 0{,}0040x_1x_2 \quad (15)$$

$$Y_{dfex3} = 0{,}4156 + 0{,}00138x_1 + 0{,}09950x_2 - 0{,}0170x_1^2 - 0{,}0184x_2^2 + 0{,}0203x_1x_2 \quad (16)$$

It is seen that the values of delamination factors for pure GFRP/epoxy composites is lower than for Al_2O_3 and SiO_2 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 all three materials.

3.2.1 Optimization of delamination factors

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

$$F=Y=b_0\,x_0+b_1\,x_1+b_2\,x_2+b_{11}\,x_1^2+b_{22}\,x_2^2+b_{12}\,x_1\,x_2$$

Subject to
$$g_1=-x_1-1<=0$$
$$g_2=x_1-1<=0$$
$$g_3=-x_2-1<=0$$
$$g_4=x_2-1<=0$$

Where Y represents objective function for delamination factors or thrust forces. Y is any one of *Ytf1, Ytf2, Yden1, Ydex1, Yden2, Ydex2*. Constraint nonlinear minimization method was applied. The optimum value of drilling parameters were obtained at hole entrances as x_1=0.065, x_2=-1 for pure GFRP/epoxy, x_1=1, x_2=-0.977 for Al_2O_3 added GFRP/epoxy and x_1=-1, x_2=-1 for SiO_2 added GFRP/epoxy. The optimum value of drilling parameters were obtained at hole exits x_1=0.043, x_2=-1 for pure GFRP/epoxy, x_1=-1, x_2=-1 for Al_2O_3 added GFRP/epoxy, x_1=1, x_2=-1 for SiO_2 added GFRP/epoxy.

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

3.3. Taguchi Analysis for Thrust Force

In the present analysis, the L9 orthogonal array was used. The data obtained from the experimental plan designed with Taguchi method are shown in Table 6.

Table 5:

Table 6:

3.3.1. Variance analysis for Thrust Force of GFRP/Epoxy

Within the scope of Taguchi method, the variance analysis for GFRP/Epoxy and response tables was performed. In drilling GFRP/Epoxy materials, minimum drilling parameters are feed rate of 0.05 mm/rev and cutting speed of 50 m/min that are obtained according to "the smaller-the better" rule for thrust force. Feed rate displays the highest effect on thrust forces. The contribution of feed rate is 91.3% and the effect of cutting speed is 2.8%. The average value for minimum thrust force is 256.2 [19].

3.3.2. Variance Analysis for Thrust Force of SiO_2 Added Material

Variance analysis for SiO_2 added GFRP/Epoxy composite material and response tables was performed. In drilling SiO_2 added composite materials, feed of 0.05 mm/rev and cutting speed 50 m/min are obtained as minimum drilling parameters 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 effect of cutting speed is 5.32%. The average value for minimum thrust force is 621.41 N [19].

3.3.3. Variance Analysis for Thrust Force of Al_2O_3 Added Material

Variance analysis for Al_2O_3 added GFRP/Epoxy composite material was performed. In drilling Al_2O_3 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 biggest effect on thrust forces. The effect of feed is 82.03% and the effect of cutting speed is 12.85%. The average value for minimum thrust force is 618.27 N [19].

3.3.4. Application of Taguchi approach for Thrust Forces of Three Composite Materials

If we take material as the third parameter, orthogonal array in Taguchi method turns into the state in Table 7. Table 8, on the other hand, displays average force-loss function and S/N ratios.

Table 7:

Table 8:

Table 9:

Table 10:

In the application of Taguchi method, when the material is taken as variable, the analysis of variance for the three materials is given in Table 9 and the response table in Table 10.

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 trust force and the results of ANOVA of S/N ratios is given Table 9. The percentage contributions all the drilling parameters and materials were quantified at the last columns of both of the results in the Table 9. Both of the results suggest that the influence of feed rate on trust force is very much larger than that of the influence of cutting speed.

From Response Table for mean and Response Table for the S/N ratio in Table 10 show that trust force is minimum at 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 maximum value for SiO_2 added GFRP. It means that pure epoxy/GFRP has the best machinability. The second great effect on the trust force was obtained for feed rate while the minimum effect was identified for cutting speed. The minimum thrust force was determined for epoxy according to the rule “the smaller-the better”. Middle and high values of thrust force for Al_2O_3 and SiO_2 were obtained respectively. It was observed that the thrust force for Al_2O_3 and SiO_2 are close to each other. Feed rate displays less effect than 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.

3.4. Taguchi Analysis for Delamination

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 analyse 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 obtained from experimental plan, which is designed through Taguchi method, is given for the entrance region in Table 11 and for the exit region in Table 12.

Table 11:

Table 12:

3.4.1. 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 feed rate of 0.05 mm/rev and cutting speed of 70 m/min that were 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 for pure GFRP/Epoxy composite material for delamination at the exit was performed. 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%.

3.4.2. Variance Analysis for delamination of Al_2O_3 Added Material

Variance analysis for delamination factor at the hole entrance of Al_2O_3 added GFRP/Epoxy composite material was performed.
In the drilling of Al_2O_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 Al_2O_3 added GFRP/Epoxy composite material was performed. In drilling Al_2O_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 %.

3.4.3. Variance Analysis for delamination of SiO2 Added Composite Material

Variance analysis for delamination factor at the hole entrance of SiO_2 added GFRP/Epoxy composite material was performed. In drilling SiO_2 added GFRP/Epoxy composite materials, feed of 0.05 mm/rev and cutting speed of 50 m/min are obtained as minimum values for delamination factor according to "the smaller-the better" rule. Feed rate displays the biggest effect on delamination factor. The effect of feed is 76.66 % and the effect of cutting speed is 19.03 %.

Variance analysis for delamination factor at the hole exit of SiO_2 added GFRP/Epoxy composite material was realized. In drilling SiO_2 added GFRP/Epoxy composite 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 76.66 % and the effect of cutting speed is 19.035 %.

3.4.4. 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 13. Table 14, on the other hand, displays average loss function and S/N ratios. In application of Taguchi method, where material is taken as a variable, for delamination factor at hole entrance, variance analysis for the three composite materials is given in Table 15 and the response table is given in Table 16.

Table 13:

Table 14:

Table 15:

Table 16.

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 table 14 and table15. 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 15 that delamination factor is minimum at first level of cutting speed, first level of feed rate and at second level of material. The S/N ratio analysis from Table 16 also shows the same results that delamination factor is minimum at first levels of cutting speed, feed rate and second level of material. In accordance with that, the minimum delamination factor was obtained for the smallest cutting speed and feed rate in the drilling of Al_2O_3 added GFRP composite. The material having the best machinability of the three materials was Al_2O_3 added GFRP composite.

In the application of Taguchi method, when material is taken as a variable, for delamination factor at hole exit, Table 17, displays average loss function and S/N ratios for delamination factor at hole exit, variance analysis for the three materials is given in Table 18 and the response table is given in Table 19.

Table 17:

Table 18:

Table 19:

It is clear from table 19 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 31 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 are examined in Table 18, 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 effect of cutting speed and less than feed rate.

The best result of minimum delamination was obtained at pure GFRT/epox composite material in according to the rule is “the smallest is better”. The minimum value of 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 from the three examined materials. Good machinability was obtained in drilling of pure GFRP/epoxy composite. Machinability gradually decreases from pure GRFP/epoxy composite toward Al_2O_3 added composite and SiO_2 added composite materials.

3.5 Machinability

The applications of GFRP require high quality drilling surfaces, including dimensional accuracy and surface integrity, using an appropriate tool and drilling parameters. Machinability of Epoxy/GF, SiO_2 added-Epoxy/GF and Al_2O_3 added-Epoxy/GF was investigated. A machinability index established in function of delamination factor and thrust force. 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 is given in Table 2.
In order 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 in Table 7 for delamination factor respectively. A new machinability index (MI) is constructed as in Eq. 17.

$$MI = [(1/Ft)*\alpha]\ [(1/Fd)*\beta] \qquad (17)$$

Where, F_t is the thrust force in N, F_d is the delamination factor in mm, α and β are the weight of the parameters. The values of α and β have been obtained to provide a similar contribution for F_t and F_d in MI. The relation between the thrust force (F_t) and the delamination factor (F_d) allows to calculate α =100 and β =1, by taking into consideration of 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 L9 orthogonal index used in Taguchi analysis are given in Table 32.
MI increase with the decrease of feed rate for several cutting velocities and present a maximum for 0.05 mm/ rev. A graphical representation of variation of MI according to material is given in Fig. 4.

Figure 4:

It can be evidenced that the Epoxy/GFRP composite provides a better MI (average MI = 0,239) in comparison to Al_2O_3 added Epoxy/GFRP (average MI = 0,181) and SiO_2added Epoxy/GFRP (average MI = 0,181). This behavior is due to the smaller values of F_d and F_t for Epoxy/GFRP. It can be evidenced that the Epoxy/GFRP composite provides a better MI (average MI = 0,203) in comparison to Al_2O_3 added Epoxy/GFRP (average MI = 0,076) and

SiO_2 added Epoxy/GFRP (average MI = 0,078). This behaviour is due to the smaller values of F_d and F_t for pure Epoxy/GF.

Table 20.

4. Conclusions

In this study, the effects of cutting parameters on the thrust force and delamination factor in drilling of pure, Al_2O_3 and SiO_2 added GFRP/epoxy composites was investigated. For this purpose, a series of experimental study were performed according to experimental plan to investigate thrust force and delamination factor. A single indicator of the machinability of composites is also proposed and it was called MI (Machinability Index).

Taguchi method and ANOVA were used to investigate effect and contribution of cutting parameters on thrust force and delamination factor in drilling pure epoxy, Al_2O_3 and SiO_2 added GFRP / epoxy composites. The results of this study were summarized as follows:

According to the results of Taguchi analysis, feed of 0.05 mm/rev gave the minimum delamination factor for three of the materials and feed rate shown the biggest effect to delamination factor.

The effect of cutting speed to delamination 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.

Feed rate is an important parameter and its contributions for GFRP/Epoxy, Al_2O_3 added GFRP, and SiO_2 added GFRP were obtained 91.72%, 80% and 76.66 % respectively.

The contributions of cutting speed for GFRP/Epoxy, Al_2O_3 added GFRP and SiO_2 added GFRP were found 4.13 %, 16. 89 % and 19.035 % respectively.

When material was considered as a variable, for delamination at the hole entrance, it was found that the effect of material is higher than feed rate and cutting speed on 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 the drilling of Al_2O_3 added GFRP composite. Feed rate displays less effect than material on the delamination factor.

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

It was observed that the delamination factors at the hole exit were greater than the delamination factors at the hole entrance. Due to 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 and the pure GFRP composite was found to be the material with good machinability at the hole exit.

According to the results of Taguchi analysis, cutting speed of 50 m/min and feed of 0.05 mm/rev gave the minimum thrust force for all three materials. The minimum obtained thrust

force for epoxy is 256 N, for SiO_2 and Al_2O_3 added reinforced composites is approximately 620 N, which is almost three times bigger.
For epoxy and SiO_2 reinforced composites, feed is an important parameter and its contribution is 90%. The effect of feed for Al_2O_3 reinforced composite is 80%. Good machinability is obtained with pure epoxy composite material. Machinability gradually decreases from pure epoxy composite material toward Al_2O_3 and SiO_2 added composite materials.
In this study, it was seen that when the material is taken as 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 this analysis, the thrust forces were higher in GFRP / epoxy composites with Al_2O_3 and SiO_2 added compared to pure GFRP / epoxy.

In general, 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. This will increase the cutting time and processing cost in terms of labour. Optimum cutting parameters should be determined by taking an acceptable delamination factor as a constraint. By this way, it will reduce the cutting time and processing cost.

When the second order mathematical models created for three materials are examined, it is seen that the thrust force for pure epoxy composites is lower and the thrust values for Al_2O3 and SiO_2 are closer to each other. The *linear* effects of cutting speed and feed increase from pure epoxy composite towards Al_2O_3 and SiO_2 reinforced composite material. 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 SiO_2 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.

A new machinability index was established in function of delamination factor and thrust force. 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. In addition, it was determined that epoxy composites reinforced with Al_2O_3 and SiO_2 additives have been equivalent machinability. The reason of this deterioration of machining performance may be the effect of abrasive effects of additives such as SiO_2 and Al_2O_3

Declarations:

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Ethical approval: The article follows the guidelines of the Committee on Publication Ethics (COPE) and involves no studies on human or animal subjects. Not applicable The authors state that this paper is an original work, it has not been published in any journals, and this research does not involve any ethical issues of humans or animals.
Compliance with ethical standards

Consent to Participate: Not applicable. The authors declare that this research involves no human participants and/or animals.
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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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Figure 1: Experimental setup and CNC machining center.

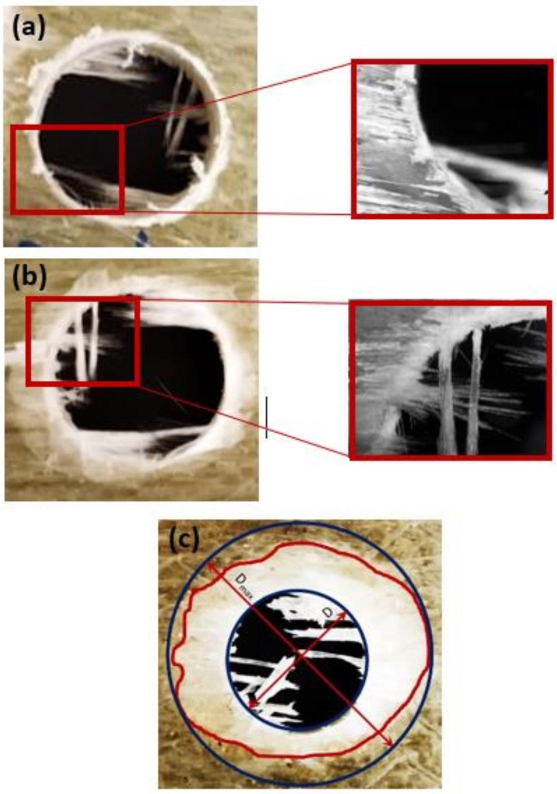

Fig.2. Scheme of delamination factor and the optical image of (a) entrance and (b) exit delamination for pure GFRP. (c) Schematic view of diameter of delamination zone (D_{max}) and drilled hole (D).

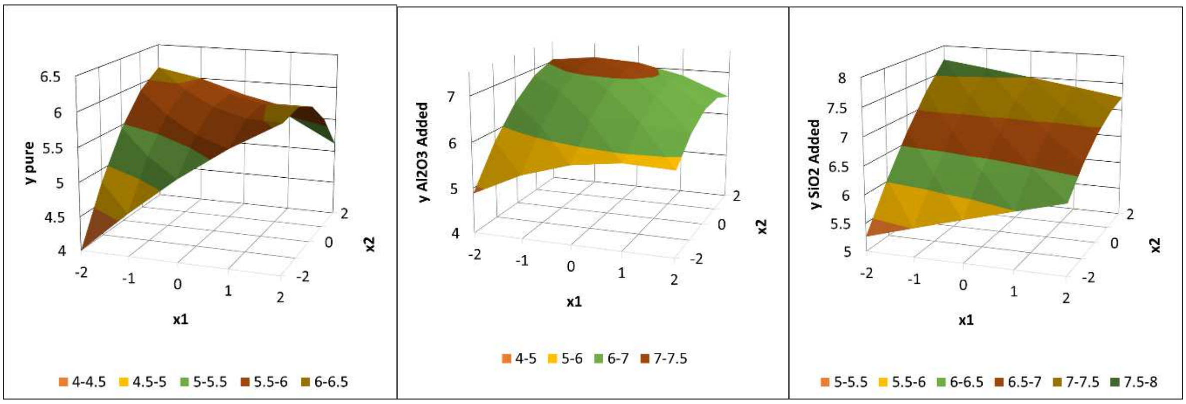

Fig.3. Graphical represantation of the second order mathematical models for pure GFRP/epoxy, Al_2O_3 added GFRP/epoxy, SiO_2 added GFRP/epoxy.

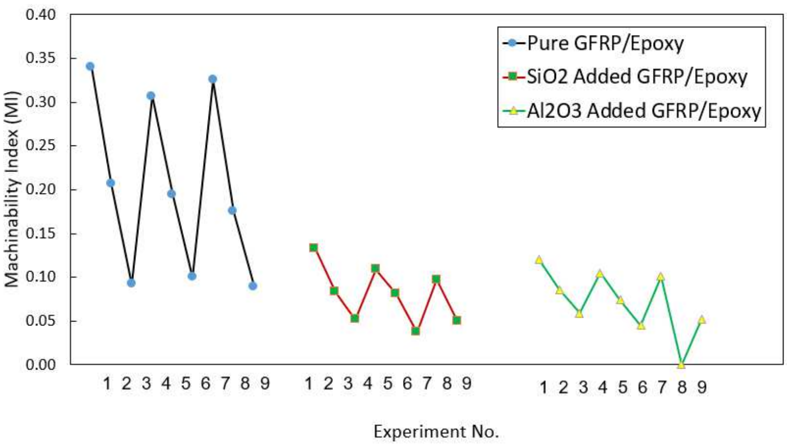

Figure 4: A graphical representation of variaton of MI for all three materials.

List of Tables

Table 1: The mechanical properties and fibre volume fraction of the samples.

Mechanical Properties	Epoxy GFRP	%15 SiO_2	%15 Al_2O_3
Tensile Strength (MPa)	533	431	454
Compression Strength (MPa)	607	474	516
Modulus of Elasticity (MPa)	144	138	141
Hardness, (HB)	78	66	71
Fiber Volume Fraction	0.5	0.5	0.5

Table 2: Parameters and levels that are used in experimental plan.

Parameters	Levels				
	-2	**-1**	**0**	**1**	**2**
v (m/min)	37	50	67	90	121
f (mm/rev)	0,005	0,05	0,1	0,2	0,4

Table 3: Thrust forces obtained in drilling of pure glass-fiber pure epoxy, SiO_2 and Al_2O_3 reinforced composite GFRP materials

Experimental Plan			GFRP/Epoxy	SiO_2 Added GFRP/Epoxy	Al_2O_3 Added GFRP/Epoxy
No.	*v*	*f*	F_i (N)	F_i (N)	F_i (N)
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

Table 4: Delamination factors obtained in drilling of pure glass-fiber epoxy, SiO_2 and Al_2O_3 added reinforced composite GFRP materials in hole entrance and exit.

Experimental Plan			GFRP/Epoxy		Al_2O_3 Added GFRP/Epoxy		SiO_2Added 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	-1	-1	1,186	1,1492	1,1028	1,2056	1,1491	1,3158
2	1	-1	1,130	1,1741	1,2162	1,4245	1,1982	1,5555
3	-1	1	1,552	1,5098	1,2264	1,7115	1,6628	1,6571
4	1	1	1,547	1,4312	1,1792	1,9905	1,4649	1,5229

5	-1	0	1,216	1,4167	1,1495	1,4762	1,2895	1,4673
6	1	0	1,279	1,2903	1,1321	1,7383	1,3391	1,3394
7	0	-1	1,114	1,1369	1,1682	1,568255	1,1983	1,6637
8	0	1	1,1273	1,4584	1,1923	1,8857	1,3913	1,5048
9	0	0	1,1258	1,3197	1,16197	1,4667	1,3276	1,485
10	0	0	1.1237	1,2681	1,1876	1,4754	1,318	1,518
11	0	0	1,1291	1,2679	1,1527	1,435	1,3614	1.495
12	0	0	1,1312	1,2989	1.174	1,424	1,3203	1,394

Table 5: Experimental plan of first order model of Thrust forces obtained in drilling of pure glass-fiber pure epoxy, (SiO_2) and (Al_2O_3) reinforced composite GFRP materials

Experimental Plan			**GFRP/Epoxy**	**SiO_2 Added GFRP/Epoxy**	**Al_2O_3 Added GFRP/Epoxy**
No.	*v*	*f*	F_i (N)	F_i (N)	F_i (N)
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	0	0	358,480	844,7	833,18
6	0	0	374,760	925,3	900,3
7	0	0	382,100	885,3	930,5
8	0	0	397,750	889,5	953,29

Table 6: Mean Forces and S/N ratios according to Taguchi method for three composite materials.

Experimental			GFRP/Epoxy			SiO_2 Added GFRP/Epoxy			Al_2O_3 Added GFRP/Epoxy		
No	*v*	*f*	$F_{i(mean)}$	Loss Func.	S/N	$F_{i(mean)}$	Loss Func.	S/N ratio	$F_{i(mean)}$	Loss Func.	S/N ratio
1	50	0.05	256,2	66335,5	-48,21	621,4	387971,5	-55,88	618,27	383979,2	-55,84
2	50	0.1	339,9	115464,5	-50,62	817,6	665681,8	-58,23	765,86	587478,8	-57,69
3	50	0.2	714,5	511931,4	-57,09	1126,3	1281261	-61,08	1084,86	1162251	-60,65
4	75	0.05	363,1	133122,2	-51,24	731,8	528639,4	-57,23	710,34	509243,3	-57,07
5	75	0.1	399,5	158719,7	-52,00	844,7	701634,6	-58,46	900,93	813178,4	-59,10
6	75	0.2	683,8	465319,9	-56,67	1418,4	2062767	-63,14	1327,03	1758257	-62,45
7	90	0.05	261,8	69016,06	-48,39	725,2	528393,4	-57,23	749,79	546900,8	-57,37
8	90	0.1	443,9	198630,9	-52,98	1048,1	834401,2	-59,21	1079,75	1159537	-60,64
9	90	0.2	783,6	615123,7	-57,89	1150,5	1330154	-61,24	1160,91	1364632	-61,35

Table 7: L9 Orthogonal array for three materials.

No.	*v*	*f*		Material
1	1	1	1	(Epoxy)
2	1	2	2	(Al_2O_3)

3	1	3	3	(SiO_2)
4	2	1	2	(Al_2O_3)
5	2	2	3	(SiO_2)
6	2	3	1	(Epoxy)
7	3	1	3	(SiO_2)
8	3	2	1	(Epoxy)
9	3	3	2	(Al_2O_3)

Table 8: Mean thrust force, loss function and S/N rates for three materials.

Ex. No	*v*	*f*	1	2	3	4	Mean	Loss F.	S/N
1	50	0.05	250	261	264	255	257,5	66655,81	-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	445,89	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
							716,6992		-56,716

Table 9: 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	310238	155119	19,44458	61,44576
	Error	2	15954,98	7977,491		3,160045
	Total	8	504897,3			
	Source	DOF	SS	MS	F-Ratio	% Contribution
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			

Table 10: 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*	-	-52,6499*
2	744,1808	683,0108	789,9125	2	-57,4181	-56,3922	-58,555
3	687,3558	901,2425	898,4642	3	-57,0408	-59,5529	-58,943
Delta	56,825	335,3983	436,7433	Delta	1,728934	5,350025	6,293087
Rank	3	2	1	Rank	3	2	1

Table 11: Mean delamination factors and S/N ratios according to Taguchi method for three composite materials at the hole entrance.

Parameter		GFRP/Epoxy			Al_2O_3 Added GFRP/Epoxy			SiO_2 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	1,1028	1,2162	-0,84994	1,1491	1,3204	-1,20716
50	0.1	1,216	1,478487	-1,69817	1,1495	1,3214	-1,21018	1,2632	1,5957	-2,02944
50	0.2	1,552	2,409185	-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

Table 12: Mean delamination factors and S/N ratios according to Taguchi method for three composite materials at the hole exit.

Parameter		GFRP/Epoxy			%15 Al_2O_3 Added GFRP/Epoxy			%15 SiO_2 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	1,1492	1,320669	-1,20794	1,2056	1,453471	-1,62406	1,3394	1,793992	-2,53821
50	0.1	1,4167	2,007185	-3,02587	1,4762	2,179166	-3,3829	1,5229	2,319224	-3,65343
50	0.2	1,5098	2,279576	-3,57854	1,7115	2,929232	-4,66754	1,5555	2,41958	-3,8374
70	0.05	1,1369	1,292646	-1,1148	1,2523	1,568255	-1,95417	1,3394	1,793992	-2,53821
70	0.1	1,2887	1,661099	-2,20396	1,4667	2,151209	-3,32683	1,5048	2,264423	-3,54958
70	0.2	1,4584	2,127709	-3,27912	1,8857	3,555864	-5,50945	1,6637	2,767898	-4,4215
90	0.05	1,1741	1,37882	-1,39507	1,4245	2,0292	-3,07325	1,3158	1,73133	-2,3838
90	0.1	1,2903	1,665082	-2,21436	1,7383	3,021687	-4,80249	1,4673	2,152969	-3,33038
90	0.2	1,4312	2,04891	-3,11523	1,9905	3,96209	-5,97924	1,6571	2,74598	-4,38697

Table 13: L9 Orthogonal array for three composites materials.

No.	*v*	*f*	Material	
1	1	1	1	(Epoxy)
2	1	2	2	(Al_2O_3)
3	1	3	3	(SiO_2)
4	2	1	2	(Al_2O_3)
5	2	2	3	(SiO_2)
6	2	3	1	(Epoxy)
7	3	1	3	(SiO_2)
8	3	2	1	(Epoxy)
9	3	3	2	(Al_2O_3)

Table 14: Mean delamination factor, loss function and S/N rates for three materials for delamination factor at the hole entrance.

v	*f*	Mean	Loss F.	S/N

1	50	0.05	1,186	1,40607	-1,48007
2	50	0.1	1,1495	1,3214	-1,21018
3	50	0.2	1,2895	1,6628	-2,20843
4	70	0.05	1,1682	1,3647	-1,35034
5	70	0.1	1,3276	1,7625	-2,46134
6	70	0.2	1,273	1,620067	-2,09533
7	90	0.05	1,1982	1,4357	-1,57059
8	90	0.1	1,279	1,636657	-2,13958
9	90	0.2	1,186	1,40607	-1,48007
			1,2278		-1,77196

Table 15: Analysis of Variance in case of taking as a variable of composite material for delamination factor at hole entrance.

	Source	DOF	Sum of Squares	Mean Square	F-Ratio	%Contribution
For Mean delamination factor	Cutting	2	0,003811	0,001905	1,666446	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		6,90894
	Total	8	0,0331			
	Source	DOF	Sum of Squares	Mean Square	F-Ratio	%Contribution
For S/N Ratio	Cutting	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		6,969653
	Total	8	0,18459			

Table 16. Response table for three materials for delamination factor at hole entrance.

Response Table for mean				Response Table for S/N			
Level	Cutting Speed	Feed rate	Material	Level	Cutting Speed	Feed rate	Material
1	1,208333	1,184133	1,246	1	-1,63289	-1,467	-1,90499
2	1,256267	1,252033	1,165633	2	-1,96901	-1,93703	-1,33076
3	1,2188	1,247233	1,271767	3	-1,71397	-1,91184	-2,08012
Delta	0,047933	0,0679	0,106133	Delta	0,336114	0,470034	0,749362
Rank	3	2	1	Rank	3	2	1

Table 17: 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
			1,307889		-2,27383

Table 18: 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			
	Source	DOF	Sum of Squares	Mean Square	F-Ratio	Contribution%
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 19: 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	2	1	Rank	3	2	1

Table 20. Machinability index for GFRP/Epoxy, Al_2O_3 added GFRP and SiO_2 added GFRP

Experimental			GFRP/Epoxy				SiO_2 Added GFRP/Epoxy				Al_2O_3 Added GFRP/Epoxy			
No	*v*	*f*	F_t	F_{den}	F_{dex}	MI_{epoyx}	F_t	$F_{d\ ent}$	F_{dex}	MI_{sio}	F_t	F_{den}	F_{dex}	MI_{alo}
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	1,3913	1,6637	0.045
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	0.1013
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

Figures

Figure 1

Experimental setup and CNC machining center.

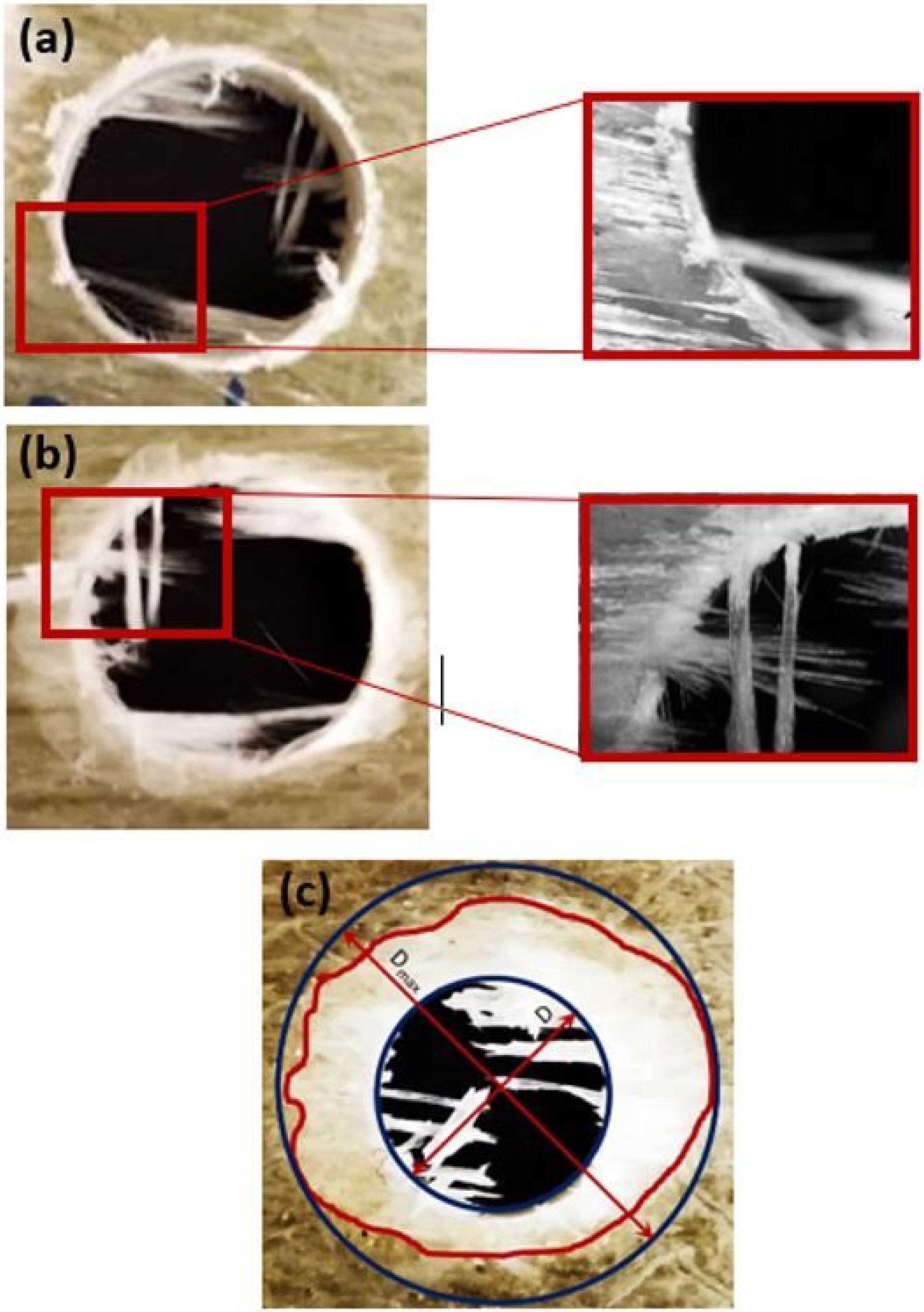

Figure 2

Scheme of delamination factor and the optical image of (a) entrance and (b) exit delamination for pure GFRP. (c) Schematic view of diameter of delamination zone (Dmax) and drilled hole (D).

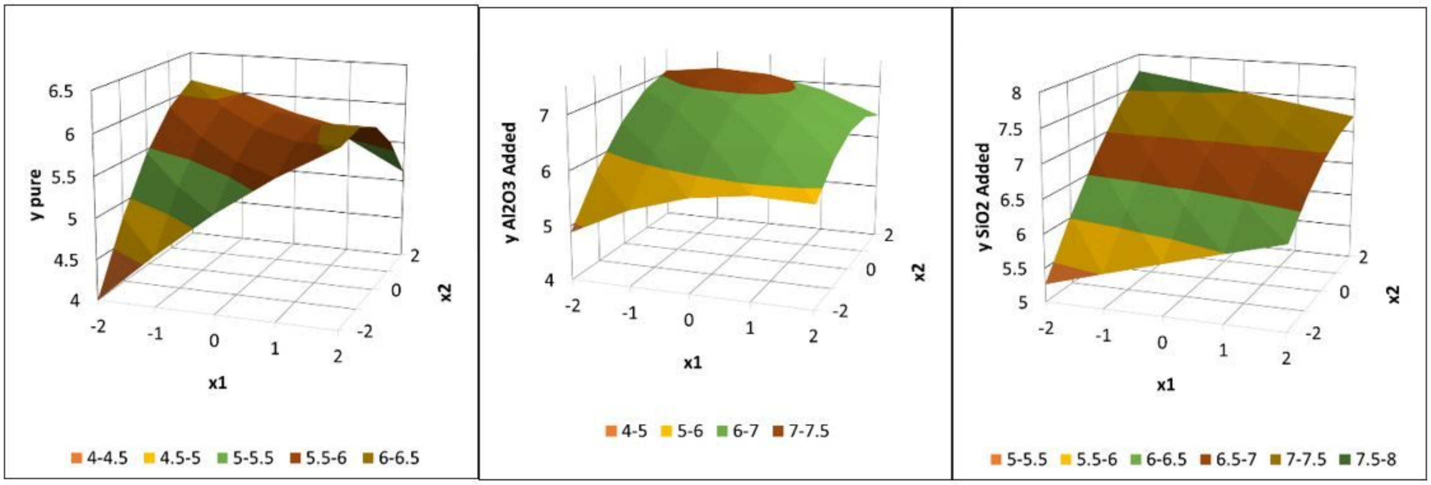

Figure 3

Graphical represantation of the second order mathematical models for pure GFRP/epoxy, Al2O3 added GFRP/epoxy, SiO2 added GFRP/epoxy.

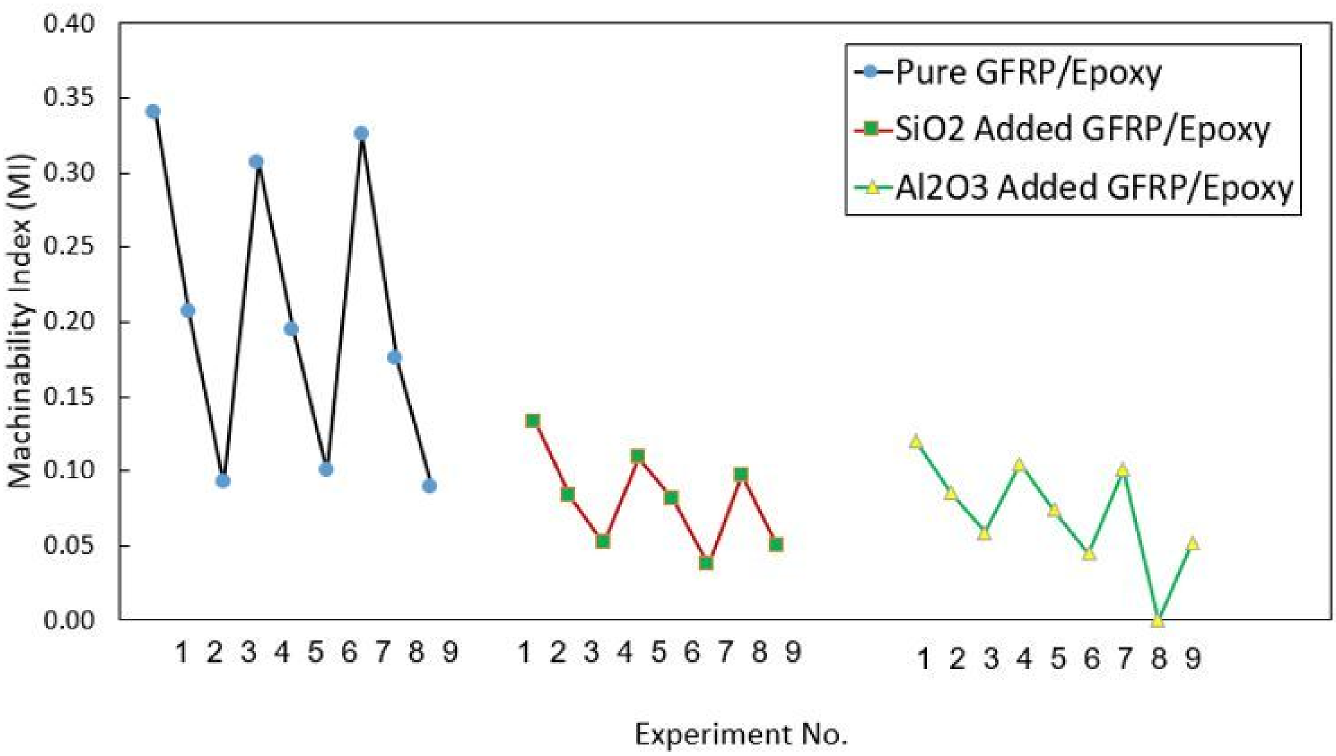

Figure 4

A graphical representation of variaton of MI for all three materials.