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Optimization and Effects of Machining Parameters on Delamination in Drilling of Pure and Al_2O_3 / SiO_2 Added GFRP Composites

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Abstract

The present study concentrates on optimization and the effect of machining parameters on delamination that occurs during drilling operation of pure glass fiber reinforced polymer (GFRP) composites and added GFRP composites which were developed for resistance to erosion wear. Contribution of drilling parameters to delamination was investigated by using Taguchi method and Analysis of Variance (ANOVA). Relationship between machining parameters and delamination was modelled by using response surface methodology. Correlations were established between the machining parameters by quadratic regression using response surface methodology (RSM). Delamination factors in the hole entrance and exit were obtained in drilling of pure glass-fiber epoxy, SiO_2 and Al_2O_3 added GFRP materials using the experimental plan. Delamination factors at the hole exits were found bigger than delamination factors at the hole entrances. The smallest delamination values were obtained in GFRP/Epoxy composite compared to Al_2O_3 / SiO_2 added GFRP composites at the hole exit. In the investigation of machinability of composites, considering the material as a variable, it has been determined that the material has a greater effect on delamination than the cutting parameters. A new machinability index defined and the material having the best machinability of the three materials was Al_2O_3 added GFRP composite at the entrance. Good machinability was obtained in drilling of pure GFRP/epoxy composite at the hole exit. It has been found that the effect of feed rate on delamination is greater than the cutting speed and the cutting speed has a low effect. Optimization of the multi-objective function created for maximizing the material removal rate, minimizing the delamination was performed, and the optimum drilling parameters were obtained. As a result of the experimental study, it was found that the amount of delamination increased although the low mechanical properties added GFRP composites with the high resistance to erosion wear in accordance with pure epoxy GFRP composites due to the lack of a strong bond between the epoxy and the fibers in AL_2O_3 and SiO_2. It was observed that the delamination amounts of pure epoxy GFRP, Al_2O_3 added GFRP, and SiO_2 added GFRP composites increased respectively, while the compressive and tensile strengths of these three materials decreased.

***Keywords*:** Glass fiber reinforced polymer, drilling, delamination factor, Taguchi method, response surface methodology, machinability

1.Introduction

Fiber reinforced polymer composite materials offer superior properties such as high strength-to-weight ratio, stiffness-to-weight ratio, and good corrosion resistance, and therefore, they are preferred for high-performance applications in several industries such as in the aerospace, automotive, defense, and sport goods industries.
Due to this increase in the use of FRPCs(Fiber Reinforced Polymer Composites), studies on the machining of FRPCs have become increasingly important. Matrix material in composite materials holds the fibers together and a layered structure is obtained. Unlike conventional chip removal processes, machining of composites requires a special approach. The layered structure of composites, heat sensitivity and abrasive effects of reinforcements lead to studying machinability of composites in particular [1,2]. The quality of the drilled hole is influenced adversely by matrix grid cratering, thermal damage, spalling, surface delamination, and material debasement or fiber pull-out. Defects such as fiber pull-out, matrix cratering, thermal damage and delamination effecting quality of hole occur by drilling.

Khashaba et al. studied on the machinability of GFRP composites and investigated the effect of cutting parameters on thrust force and delamination. They concluded that an increase of the cutting speed and feed rate lead an increasing of delamination and as feed rate increases, thrust force and delamination increase. It was shown that a high feed rate of drilling cause a crack around the exit edge of the hole. The next phase of this study is the investigation of the effect of tool wear on thrust force. Results were indicated that an increasing of tool wear at high cutting speed and feed rate causes a rising of thrust force [3,4]. Delamination is a critical damage mode under impact loading in fibre-reinforced composites. It may lead directly to through-thickness failure owing to interlaminar stresses caused by out-of-plane loading, or discontinuities owing to cracks, ply drops or free edges. Impact loading causes multiple delaminations, which can propagate in conjunction with sublaminate buckling, greatly reducing the residual compressive strength. Delamination is a major problem associated with drilling of fiber reinforced composite materials that, in addition to reducing the structural integrity of the material, also results in poor assembly tolerance and has the potential for long-term performance deterioration [5]. Direct and interactive effect of process variables influences machining performance in terms of quality of the drilled hole. Therefore, an optimal parameter setting is indeed required. Abhishek et al., aims at evaluating an appropriate drilling parameter setting toward optimization of thrust, torque, entry, and exist delamination factor during drilling of CFRP (epoxy) composites. An integrated multi-response optimization philosophy combining principal component analysis (PCA), fuzzy inference system (FIS), and Taguchi method have been proposed [6]. In a study conducted by Davim et al., a statistical approach was handled to identify the most appropriate cutting parameters to realize drilling operations on carbon fiber reinforced thermoset materials. They put forward an approach through Taguchi's experimental analysis along with the multi-purpose optimization [7]. In another study carried out by Mohan et al., the Taguchi technique and response surface methodology were applied on GFRP composites. The major objective of this study is to find out the factors affecting delamination and optimizing the processing parameters for minimum delamination [8]. M. F. Ameur et al, defined the cutting conditions that allow the drilling of carbon fiber reinforced epoxy (CFRE) composite materials taking into consideration the quality of the drilled holes (the exit delamination factor and the cylindricity error) and the optimum combination of drilling parameters [9]. They used grey relational analysis to improve the quality of the drilled holes. The experiment design was accomplished by application of the statistical analysis of variance (ANOVA). Their results show that the tool materials and the feed rate, which has a strong influence on the exit delamination factor, mainly influence the thrust force. Rajamurugan et al. 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 [10]. They analysed delamination in drilling glass fiber reinforced polyester composites. An attempt was made to develop empirical relationships between the drilling parameters. Sardinas et al. [11] used a micro-genetic algorithm and Krishnamoorthy et al. [12] a fuzzy grey method both with the aim of optimizing the drilling process conditions. Gaitonde et al. analysed the effects of cutting speed, feed rate, and the point angle on the delamination factor by generating response surface methodology (RSM) plots models [13]. S. Prakash et al, presented the systematic experimental investigation, analysis and optimization of delamination factor in drilling of medium density fiberboards (MDF). They were developed an empirical model for predicting the delamination factor at entry and exit of the holes in drilling of MDF boards. Desirability function based approach was employed for the optimization drilling parameters for minimizing the delamination factor at entry and exit in drilling of MDF boards [14]. In a study conducted by Davim et al., a statistical approach was handled to identify the most appropriate cutting parameters to realize drilling operations on carbon fiber reinforced thermoset materials. They put forward an approach through Taguchi's experimental analysis along with the multi-purpose optimization. [15, 16]. Marques et all performed delamination analysis of carbon fibre reinforced laminates and evaluation of a special step drill [17]. Campos Rubio et all investigated delamination in high speed drilling of carbon fiber reinforced plastic (CFRP) [18]. Abrao et al. studied on the effect of cutting tool geometry on thrust force and delamination of drilling of glass fibre reinforced plastic composites[19]. Palanikumar used Taguchi and response surface methodologies for minimizing the surface roughness in machining glass fiber reinforced (GFRP) plastics with a polycrystalline diamond (PCD) tool. The cutting parameters used are cutting speed, feed and depth of cut. The effect of cutting parameters on surface roughness was evaluated and the optimum cutting condition for minimizing the surface roughness is determined [20]. Sait et al. presented a new approach for optimizing the machining parameters on turning glass-fibre-reinforced plastic (GFRP) pipes. Optimisation of machining parameters was done by an analysis called desirability function analysis, which is a useful tool for optimizing multi-response problems [21]. Işık et al. presented a new comprehensive approach to select cutting parameters for damage factor in drilling of glass fiber-reinforced polymer (GFRP) composite material. The influence of drilling on surface quality of woven GFRP plastic composite material was investigated experimentally. Damage factor was investigated based on hole entrance and exit. Analysis of variance (ANOVA) test was applied to the experimental results[22]. Kilickap investigated the influence of the cutting parameters, such as cutting speed and feed rate, and point angle on delamination produced when drilling a GFRP composite.

The damages generated associated with drilling GFRP composites were observed, both at the entrance and at the exit during the drilling. He obtained the optimum cutting parameters minimizing delamination at drilling of GFRP composites [23]. Ghasemi et al. studied the effects of some the cutting parameters, such as feed rate, drilling rotation speed and drill point angle on delamination area produced during drilling of glass-epoxy composites using full factorial technique and ANOVA. The results indicated that the drill thrust force was minimum at feed rate of 25 mm/min, rotational speed of 2000 rpm and drill point angle of 90°[24]. 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[25]. Tian et al. investigated the coupling effect between the clearance angles of outer cutting edges, the spindle speed, and the feed speed when drilling the GFRP materials with candlestick drills. It was found that the reason for the coupling effect of the machining and tool parameters was that the change of these parameters would have different effect on the pushing, cutting, and physical properties of the materials at the same time[26].

In this study, the investigation of the effects of cutting parameters on delaminations at hole entry and exit in the drilling of the Al_2O_3 and SiO_2 reinforced glass fiber composites developed for resistance to erosion wear with the pure GFRP/epoxy and the determination of optimum cutting conditions for these composites was aimed. In order to achieve this objective, empirical models have been developed to estimate the delamination factors at the entrance and exit of the holes when drilling pure and Al_2O_3 / SiO_2 doped GFRP composites. In the drilling of composites, Khun-Tucker conditions are used in optimization drilling parameters to minimize the delamination factors at entry and exit. The major objective of this study is to find out the factors affecting delamination and optimizing the machining parameters for minimum delamination. In order to provide delamination minimization and material removal rate maximization, the cutting parameters are optimized with the multi-purpose optimization method, thus enabling the cutting conditions to be applied in the real environment.

2. Experimental Procedure

2.1. Equipment

The samples used in the experiment consisted of pure glass-fiber pure epoxy, SiO_2/Al_2O_3 added reinforced composite GFRP materials. Sample materials were 4mm thick and had the dimensions of 65x165 mm. The mechanical properties of the samples are provided in Table 1 and experiment set-up is given in Fig. 1. During the experiments, Mazak Variaxis 500-5X machining center was used as milling machine to perform the experiments. In the drilling operations, K10 carbide drill with 118° point angle and 6 mm diameter was used as cutting tool.

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 SiO_2 and Al_2O_3 fillers separately, with an average particle diameter of 150 μm 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.
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 Al_2O_3 and SiO_2 added to the matrix created better erosion resistance compared to the pure GFRP structure, and an improvement in erosion resistance occurred.

Table 1:

Fig. 1.

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

$$Fd = \frac{Dmax}{D} \qquad (1)$$

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

Drilling-induced delamination occurs at the entry and exit planes of the workpiece as illustrated schematically in Fig. 2(a). Peel-up occurs as the drill enters the laminate. After the cutting edge of the drill makes contact with the laminate, the cutting force acting in the peripheral direction is the driving force for delamination. It generates a peeling force in the axial direction through the slope of the drill flute that results in separating the laminas from each other forming a delamination zone at the top surface of the laminate [5]. Push-out delamination occurs before the drill completely drills the sheet and exits from it as shown in Fig. 2(b) [5]. The drill point exerts compressive force on the uncut plies below causing them to bend elastically. As the drill approaches the exit, the number of uncut plies supporting it reduces and the resistance to bending decreases.

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 relations between the response and independent variables are modelled [27]. In mathematical model, the relation between cutting parameters and delamination factor is stated as follows:

$$F_d = C_i\, v^{\rho 1} f^{\rho 2} \qquad (2)$$

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

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

In this equation, while C_i is a constant coefficient, ρ_1 and ρ_2 are the coefficients of the parameters. Equation (2) is stated in first order polynomial model as follows:

$$Y^{\prime} = y - \varepsilon = b_0x_0 + b_1x_1 + b_2x_2 \quad (3)$$

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

$$Y^{\prime} = y - \varepsilon = b_0x_0 + b_1x_1 + b_2x_2 + b_{11}x_1^2 + b_{22}x_2^2 + b_{12}x_1x_2 \quad (4)$$

In this equation, $Y^{\prime}$ is the estimated response depending on first and second order equations, while y is real response. The coded variables of cutting speed and feed are x_1 and x_2, experimental error is 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

Taguchi Method is an experimental technique developed by Dr. Genichi Taguchi to identify the most appropriate processing parameter intervals. The number of experiments will increase depending on the number of processing parameters. In order to solve this problem, Taguchi method reaches the result by combining three methods; orthogonal experimental design, signal-noise (S/N) ratio and variance analysis (ANOVA). Orthogonal experimental design is used to create a special design by scanning all parameter space with minimum number of experiments. The results obtained from the planned experiments according to orthogonal experimental design are analyzed by transporting them into S/N ratio. The S/N ratio is used to measure performance characteristics of required values. The S/N ratio is identified depending on three major performance characteristics such as "$(S/N)_{SB}$, the smaller-the better", "$(S/N)_{LB}$, the larger-the better" and "$(S/N)_{NB}$, nominal-the best". ANOVA is used to find out the statistical significance degree of processing parameters on performance characteristics. Apart from these there significant tools, one final verification test is conducted to check the reliability of the optimum results obtained through Taguchi method. The above-mentioned three major performance characteristics are stated with the equations of (5), (6) and (7) [9]. Here y_i indicates the result measured in experiments, $\bar{y}$ indicates the average of measured results from experiments, ŋ indicates the number of experiments and s^2 indicates the variance of y.

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

$$S/N_{LB} = \eta = -10 \log \left[1/n \Sigma_{i=1} 1/(y_i^2)\right] \quad (6)$$

$$S/N_{NB} = \eta = -10 \log \left[s^2/\bar{y}\right] \quad (7)$$

3. Experimental works and modelling

3.1. Delamination Modelling

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

In this current study, 12 tests based on rotatable centred composite design, three levels for any variable, were conducted. Table 2 shows the levels of variables.
Experimental plan and levels given in Table 3 were used to create second order RSM model for three different composite materials. Specimens were drilled according to the defined plan and delamination factors were recorded. Relationships of Coded variables and real parameters are given as follows
x_1=1+2((ln$v$-ln90)/(ln90-ln50))
x_2=1+2((ln$f$-ln0.2)/(ln0.2-ln0.05))

Table 2

Table 3

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 (8), (9), and (10) respectively. 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 (11), (12), and (13) respectively.

For GFRP/Epoxy at the hole entrance;
Y_{dfen1} = 0,10705 - 0,00018x_1+ 0,09915x_2+ 0,13957x_1^2+ 0,03264x_2^2+ 0,011285x_1x_2 ....(8)
For %15 Al_2O_3Added GFRP/Epoxy at the hole entrance
Y_{dfen2} = 0,15208 - 0,00723x_1 + 0,01596x_2 - 0,01225x_1^2+ 0,02173x_2^2- 0,03428x_1x_2 .... (9)
For %15 SiO_2 Added GFRP/Epoxy at the hole entrance
Y_{dfen3} = 0,276417 - 0,007865x_1+ 0,11997x_2 +0,0168x_1^2 - 0,00075 x_2^2-0,04214 x_1x_2............. (10)
The mathematical models derived from second degree RSM are stated with the equations (8), (9), and (10). When the second order mathematical models obtained for delamination factor are examined, it is seen that the values of delamination factors for pure GFRP/epoxy composites are lower than for 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 three of the materials.
For GFRP/Epoxy at the hole exit
Y_{dfex1} = 0,2684 - 0,0209x_1 + 0,1200x_2 + 0,0258x_1^2- 0,0230x_2^2- 0,0187x_1x_2 .... (11)
For %15 Al_2O_3 added GFRP/Epoxy at the hole exit
Y_{dfex2} = 0,4169 + 0,0802x_1 + 0,1824x_2 + 0,0374x_1^2- 0,0042x_2^2- 0,0040x_1x_2 .... (12)
For %15 SiO_2 Added GFRP/Epoxy at the hole exit
Y_{dfex3} = 0,4156 + 0,00138x_1 + 0,09950x_2 - 0,0170x_1^2- 0,0184x_2^2+ 0,0203x_1x_2 .... (13)
When the mathematical models derived from second degree RSM stated with the equations (11), (12), and (13) for delamination factors at hole exit are examined, 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 three of the materials. But linear effect of cutting speed is very smaller than the quadratic effects of cutting speed for SiO2 added GFRP at the hole exit.

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

3.2. Taguchi Analysis

Taguchi experimental design and selection of parameters

In the Taguchi analysis, the average value of experimental response and its corresponding signal to noise ratio (S/N) of each run can be calculated to 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 experiment plan designed through Taguchi method is shown for at the entrance in Table 4 and for at the exit in Table 5.

Table 4:

Table 5:

3.2.1. Variance analysis for GFRP/Epoxy

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

Table 6:

Table 7:

Fig. 4

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

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 is obtained according to “the smaller-the better” rule for a minimum of 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 %.

Within the scope of Taguchi method, the variance analysis for GFRP/Epoxy at the hole exit is provided in Table 8 and the response table is given in Table 9.

Table 8:

Table 9:

Fig. 5

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

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

3.2.2. Variance Analysis for Al_2O_3 Added Material

Variance analysis for delamination factor at the hole entrance of Al_2O_3 added GFRP/Epoxy composite material is given in Table 10 and the response table is provided in Table 11.

Table 10:

Table 11:

Fig. 6

The peel-up delamination factor obtained for various speed and feed combinations during the drilling of Al_2O_3 added GFRP are presented in Fig. 6.The delamination at lower speeds were much lower than those obtained at higher speed. Al_2O_3 added GFRP composites showed similar properties to pure GFRP composites in terms of the effect of speed and feed on deformation.

In the drilling of 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 is given in Table 12 and response table is provided in Table 13.

Table 12:

Table 13:

Fig. 7

The push-out delamination factor obtained for various speed and feed combinations during the drilling of Al_2O_3 added GFRP are presented in Fig. 7. The push-out delamination factor increases with an increase in feed rate and cutting speed. Delamination factor increases less from low speed to high speeds.
In drilling 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 %.

3.2.3. Variance Analysis for SiO_2 Added Composite Material

Table 14:

Table 15:

Fig. 8

The peel-up delamination factor obtained for various speed and feed combinations during the drilling of SiO_2 added GFRP are presented in Fig. 8. Delamination factor increases with an increase in feed rate and cutting speed.

Variance analysis for delamination factor at the hole entrance of SiO_2 added GFRP/Epoxy composite material is given in Table 14 and response table is provided in Table 15. In drilling SiO_2 added 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 %.

Table 16:

Table 17:

Fig. 9

The push-out delamination factor obtained for various speed and feed combinations during the drilling of SiO_2 added GFRP are presented in Fig. 9. The push-out delamination factor increases with an increase in feed rate and cutting speed. The delamination is not influenced by speed in the selected range. The delamination factors are bigger than those Pure GFRP and Al_2O_3 added GFRP composites for various speed and feed combinations at the hole exit.
Variance analysis for delamination factor at the hole exit of SiO_2 added GFRP/Epoxy composite material is given in Table 16 and the response tables is provided in Table 17. In drilling SiO_2 added materials, feed rate of 0,05 mm/rev and cutting speed of 50 m/min were

obtained as minimum values for delamination factor at the hole exit according to “the smaller-the better” rule. Feed rate displays the biggest effect on delamination factor. The effect of feed is 93,31 % and the effect of cutting speed is 1,05 %.

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

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

Table 18:

Table 19:

Table 20:

Table 21.

To determine the percentage contribution and optimum combination of drilling parameters more accurately ANOVA was used. The results of ANOVA of the raw data or mean of delamination factor and the results of ANOVA of S/N ratios are given in table 19 and table20. The percentage contributions all the drilling parameters and materials are quantified under the last column of both the tables. Both of the tables suggest that the influence of material on delamination factor is very much larger than the influence of feed rate and cutting speed.
It is clear from table 20 that delamination factor is minimum at first level of cutting speed, first level of feed rate and at second level of material. The S/N ratio analysis from table 20 also shows the same results that delamination factor is minimum at first levels of cutting speed, feed rate and second level material. To accordance with that, the minimum delamination factor was obtained for the smallest cutting speed and feed rate in the drilling of AL_2O_3 added GFRP composite.

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

Table 22:

Table 23:

Table 24:

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

effects of material, feed rate and cutting speed on the delamination factor are 23,62%, 57,93% and 7,39%, respectively.
In the investigation of the change of delamination factor for the values of three levels of cutting speed and feed rate of three different composite materials in the drilling, it was found that the effect of the material on the delamination 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 GFRP/epoxy composite material in according to the rule is “the smallest is better”. The minimum value of delamination factor was obtained at 0.05 mm/rev feed and 50 m/min speed values.
Due to the effect of delamination on the quality of the drilled surface, delamination is an indicator of the machinability of the material. For this reason, the material obtained the minimum delamination is a material that has better machinability from the three examined materials. Good machinability was obtained in drilling of pure GFRP/epoxy composite.
Machinability gradually decreases from pure GRFP/epoxy composite toward Al_2O_3 added composite and SiO_2 added composite materials.

3.2.4.1 Machinability index

A machinability index established in function of delamination factor. L9 orthogonal array that has nine rows corresponding to the number of tests (8 degrees of freedom) with two columns at three levels was chosen for determining machinability index.
The plan of experiments is made of nine tests (array rows) in which the first column was assigned to the cutting velocity (v) and the second column to the feed rate (f) .The experimental plan and the chosen cutting parameters is given in Table 2.
In order to analyse the machinability of these materials, delamination factor (Fd) from experimental data have been obtained. These are given in Table 4 and Table5 for delamination factor at hole entrance and exit respectively. A machinability index (MI) is constructed as in Eq. 11.

$$MI = [(1/Fd)] \tag{11}$$

Machinability indexes calculated with the delamination values obtained by using feed rate and cutting speed values according to L9 orthogonal index used in Taguchi analysis are given in Table 25.

It can be evidenced that at the hole entrance the Al2O3 added Epoxy/GFRP composite provides a better MI (average MI = 0,865) in comparison to Epoxy/GFRP (average MI = 0,792) and SiO2 added Epoxy/GFRP (average MI = 0,778). The material having the best machinability of the three materials was AL_2O_3 added GFRP composite at the entrance.
It can be evidenced that at the hole exit the Epoxy/GFRP composite provides a better MI (average MI = 0,767) in comparison to Al_2O_3 added Epoxy/GFRP (average MI = 0,653) and SiO2 added Epoxy/GFRP (average MI = 0,678). Good machinability was obtained in drilling of pure GFRP/epoxy composite at the hole exit.

3.2.5 Optimization in drilling of composite materials

3.2.5.1 Optimization of delamination factor

3.2.5.1.1 Modified objective function and Kuhn- Tucker conditions;

Generalized mathematic model for delamination factor is taken as follows.
$Y=b_0+b_2x_2+b_{11}x_1^2+b_{22}x_2^2+b_{12}x_1x_2$
For only one objective function and constraints, the formulation of optimization problem is as follows.
Minimization of $F=b_0+b_2x_2+b_{11}x_1^2+b_{22}x_2^2+b_{12}x_1x_2+\lambda_1(-1-x_1)+\lambda_2(x_1-1)+\lambda_3(-1-x_2)+\lambda_4(x_2-1)$
Subject to
$g_1=-x_1-1<=0$
$g_2=x_1-1<=0$
$g_3=-x_2-1<=0$
$g_4=x_2-1<=0$
The derivatives of the modified objective function are as follows.
$F_{X1}=b_1+2b_{11}x_1+b_{12}x_2-\lambda_1+\lambda_2$
$F_{X2}=b_2+2b_{22}x_2+b_{12}x_1-\lambda_3+\lambda_4$
The optimum values for delamination factor of Epoxy/ CFRP plate, SiO_2 added GFRP/epoxy and Al_2O_3 added GFRP/epoxy plate are given in table 26 in the constraint region.

Table 26.

The optimum values for delamination factors of Epoxy/ GFRP plate, SiO_2 Added GFRP/epoxy plate and Al_2O_3 added GFRP/epoxy plate are given in table 26. For pure epoxy GFRP composite, the optimum parameters are $x_1=1$(v=90m/min) and $x_2=-1$(f=0.05mm/rev) For both of other materials, the optimum parameters was obtained as $x_1=-1$(v=50m/min) and $x_2=-1$(f=0.05mm/rev). The results of optimization were shown that the smallest value of feed rate decreases delamination factor, but the effect of cutting speed to delamination factor is less.

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

In machining operation, maximizing the material removal rate and minimizing the surface quality are important criteria. The objectives set for the optimization is maximization of material removal rate and minimization of surface quality.
First step in optimization is the formulation of objective function. Multi-objective function consists of the sum of each objective function using different weight coefficients for each criteria. Weighting factor assigns such that their sum was always equal to one. The weighting factor assigns to each parameter based on relative importance.
In the multi-objective optimization problem, two different and mutually conflicting objectives are selected to be optimized. The first objective function is material removal rate. The second objective function is the delamination factor, which describes the hole quality of the produced hole. First objective function must be maximized while the second one must be minimized. In order to homogenize all objectives, the material removal rate must be multiplied by-1. After this change, in the problem there are only minimization objectives in the problem.
Multi-objective function for maximizing the metal removal rate and minimizing delamination and constraints are given as follows respectively:
$MOF=\phi\ Y-\theta\ M$

MOF is multi-objective function; ϕ and θ are weighting factors for material removal rate. Where Y represent objective function for delamination factor. Y is any one of Y_{dfen1}, Y_{dfen2}, Y_{dfen3}. Also for the hole exit the objective function for delamination factor is taken any one of Y_{dfex1}, Y_{dfex2}, Y_{dfex3}.

Constraints:

There are the allowed ranges for the cutting parameters given by the validity range of the experimental models;

$v_{min} < v < v_{max}$

$f_{min} <= f <= f_{max}$

or constraints are given for the coded variables as follows.

$-1 <= x_1 <= 1$

$-1 <= x_2 <= 1$

or

$g_1 = -x_1 - 1 <= 0$

$g_2 = x_1 - 1 <= 0$

$g_3 = -x_2 - 1 <= 0$

$g_4 = x_2 - 1 <= 0$

3.2.5.2.1 Objective function for the material removal rate

The first objective is the material removal rate, M, the material removal rate in drilling which can be computed by the expression:

$$MMR=250dfv \quad (12)$$

Where, d is the diameter of hole, f is the feed rate, v is the cutting speed.

Material removal rate is inversely proportional to the machining time.

$\ln MRR = \ln 250 + \ln d + \ln f + \ln v$

$M = \ln MMR = 7.424 + \ln d + 0.2939x_1 + 0.693x_2$

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

$M = \ln MMR = 9.21576 + 0.2939x_1 + 0.693x_2$

3.2.5.2.2 Multi-objective optimization

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

$MOF = \phi\ Y - \theta\ M$

$v_{min} < v < v_{max}$

$f_{min} <= f <= f_{max}$

or constraints are given for the coded variables as follows.

$-1 <= x_1 <= 1$

$-1 <= x_2 <= 1$

3.2.5.2.3 Modified objective functions and Kuhn- Tucker conditions;

For multi- objective function and constraints, the formulation of problem is as following.
Minimization of F=MOF + $\lambda_1(-1-x_1)+ \lambda_2(x_1-1)+ \lambda_3(-1-x_2)+ \lambda_4(x_2-1)= \phi\ Y-\theta\ M+ \lambda_1(-1-x_1)+ \lambda_2(x_1-1)+ \lambda_3(-1-x_2)+ \lambda_4(x_2-1)$
or optimization model is as following
Minimization of $F=\phi(b_0 + b_1x_1 +b_2x_2+b_{11}x_1^2+b_{22}x_2^2+b_{12}x_1x_2) – \theta(9{,}2157+0{,}2939x_1+0{,}693x_2) + \lambda_1(-1-x_1) + \lambda_2(x_1-1) + \lambda_3(-1-x_2) + \lambda_4(x_2-1)$
Subject to
$g_1= -x_1-1<=0$
$g_2= x_1-1<=0$
$g_3= -x_2-1<=0$
$g_4= x_2-1<=0$
The derivatives of the modified objective function are as following.
$F_{X1}= (b_1+2b_{11}x_1+b_{12}x_2) - 0{,}2939\ \theta - \lambda_1+ \lambda_2$
$F_{X2}= \phi\ (b_2+2b_{22}x_2+b_{12}x_1) - 0{,}693\ \theta - \lambda_3+ \lambda_4$

Table 27.

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

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

When the effects of the cutting parameters of the three materials on the delamination were examined, it was observed that the delamination increased gradually towards pure epoxy, Al_2O_3 doped and SiO_2 added GFRP respectively. This situation can be explained so that the bonding of powder AL_2O_3 and SiO_2 additives added to pure epoxy with glass fiber is weaker than the bonding of pure epoxy to glass fibers. Therefore, it is easier to separate the fibers.The reason of this, is that the mechanical properties of Al_2O_3 and SiO_2 added GFRP composites are lower than Pure Epoxy GFRP.

It was observed that the delamination factor increased as the cutting speed and feed rate increased for the three materials at the hole entrance while the increase of delamination factor was lower with the increase of feed rate at 70 m/min speed for pure and AL_2O_3 added GFRP. The effect on delamination factor of cutting speed is low at high feed rates at pure epoxy GFRP and at AL_2O_3 added GFRP as the effect on delamination is less at low feed rates at 70 m/min speed. Also, it was observed that delamination increased as cutting speeds and feed rates increased at SiO_2 added GFRP. Low cutting speeds and feed rates give low delamination, while high feed and cutting speeds give higher delamination values.

It was observed that the delamination factor increased as the cutting speed and feed rate increased at the hole exit for all three materials.

The delamination factor increased with the increase in cutting speed at low feed rates, the effect of cutting speed on delamination was less with the increase in cutting speed at the high feed at pure epoxy GFRP and the deformation factor increased as the cutting speed increase at AL_2O_3 and SiO_2 added GFRP composites.

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

5. Conclusions

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

The minimum delamination factor obtained at the smallest feed rate for three of the materials and feed rate shown the biggest effect to delamination factor.

The effect of cutting speed to delamination factor is less and the cutting speeds for the minimum delamination were obtained 70 m/min for GFRP/Epoxy and 50 m/min for the other composite materials.

The contribution of feed rate to delamination is biggest and the contribution of cutting speed is the smallest for GFRP/Epoxy according to added GFRP composites.

The minimum delamination factor was obtained for the smallest cutting speed and feed rate in drilling of Al_2O_3 added GFRP composite.

For delamination at the hole exit, the minimum delamination factor was obtained for the smallest cutting speed and feed rate in drilling of pure GFRP/epoxy composite.

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. For delamination at the hole exit, it was found that the effect of material is smaller than feed rate and bigger than cutting speed on delamination factor.

The delamination factors at the hole exit were greater than the delamination factors at the hole entrance.

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

The optimum of delamination factor was obtained for the smallest cutting speed and feed rate for the three composites

To maximize MRR and minimize deformation factor, Multi-optimization function was created , the weighing factors MRR and deformation factor are taken as equal, Optimum machining parameters were found that the cutting speed had the biggest value and feed rate had the smallest value for the three composites.

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.
Compliance with ethical standards
Consent to Participate: All authors participated for the publication.
Consent to Publish: All authors give consent for publication.
Competing interests: The authors have no competing interests or conflicts of interest to declare that are relevant to the contents of this article.
Data availability: The authors confirm that the data and material supporting the findings of this work are available within the article.
Authors' Contributions:
Ali Ünüvar: supervision, methodology, writing (original draft preparation), visualization, validation, investigation, reviewing and editing.
Murat Koyunbakan: methodology, reviewing and editing.
Mehmet Bağcı: methodology, validation, writing (reviewing and editing), visualization.

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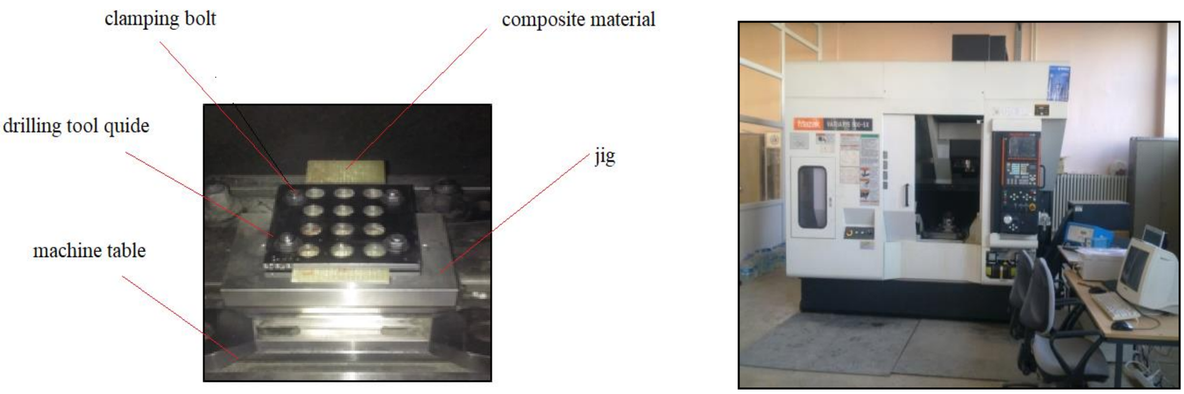
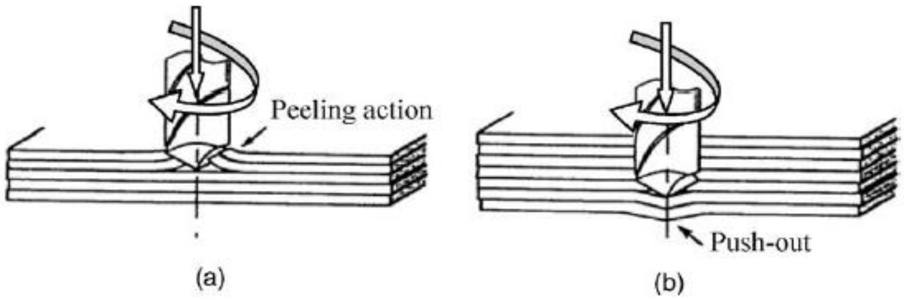
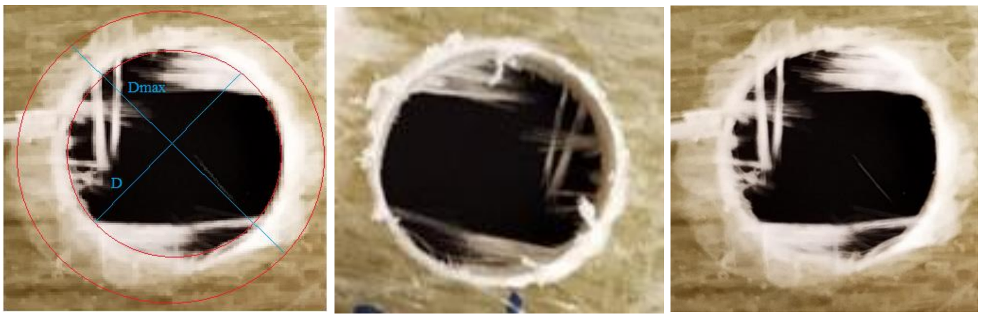


Fig. 1 Experimental setup and CNC machining center.



(peel up) (push out)



(c)delamination factor (d) entrance delamination (e) exit delamination

Fig. 2 Mechanisms of delamination; (a) Peel-up delamination at entrance and (b) Push-out delamination at exit[5] and scheme of delamination factor and the optical image of entrance and exit delamination for pure GFRP,

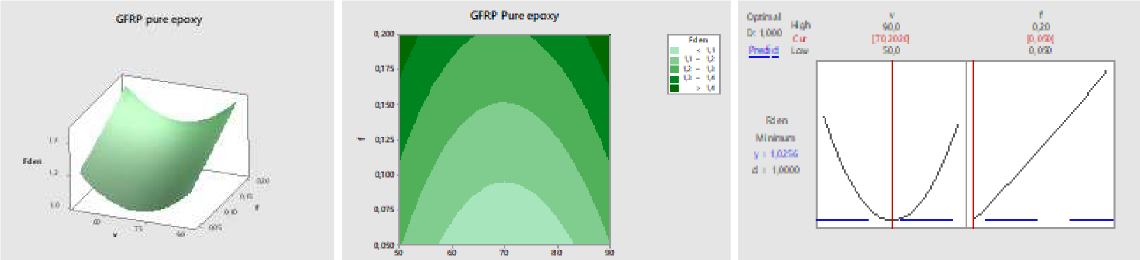


Fig. 3 Surface response, contour plot and optimum cutting parameters for delamination of GFRP/Epoxy at the hole entrance

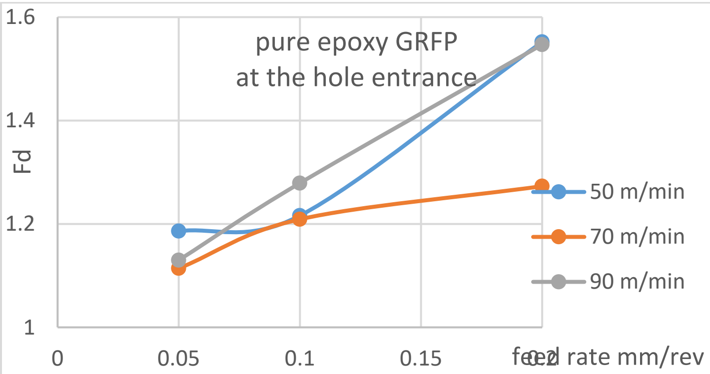


Fig. 4 The effect of cutting speed and feed on peel-up delamination factor

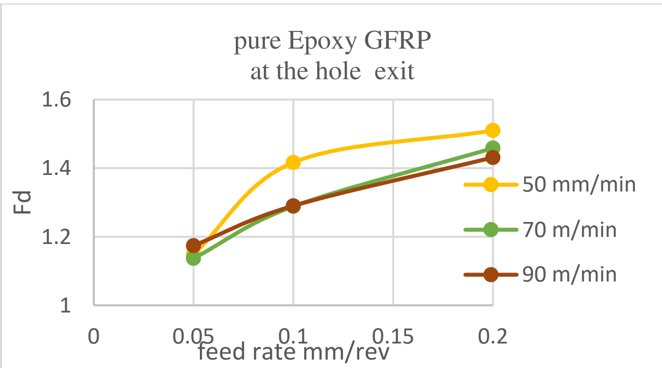


Fig. 5 The effect of cutting speed and feed on push-out delamination factor

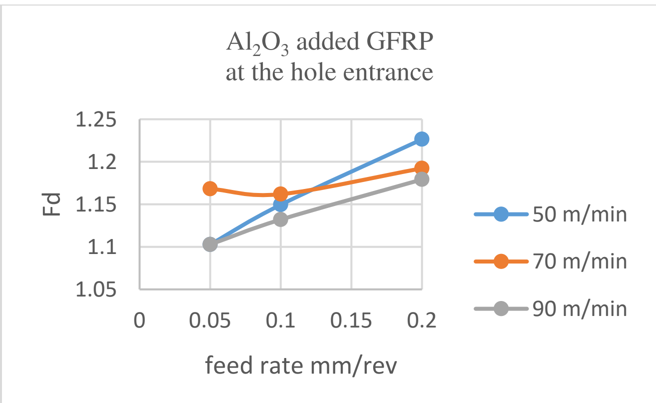


Fig. 6 The effect of cutting speed and feed on peel-up delamination factor

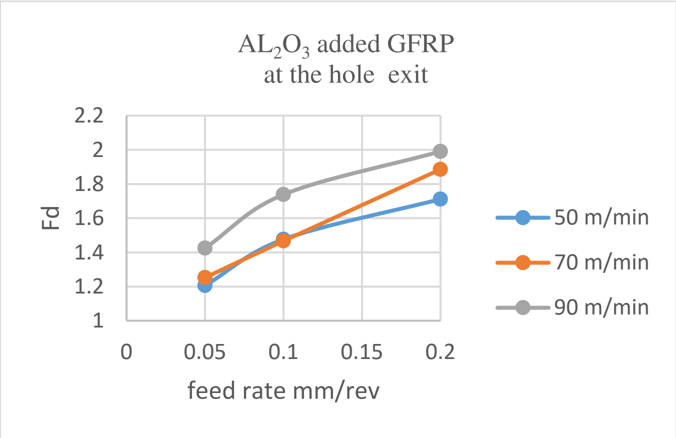


Fig. 7 The effect of cutting speed and feed on push-out delamination factor

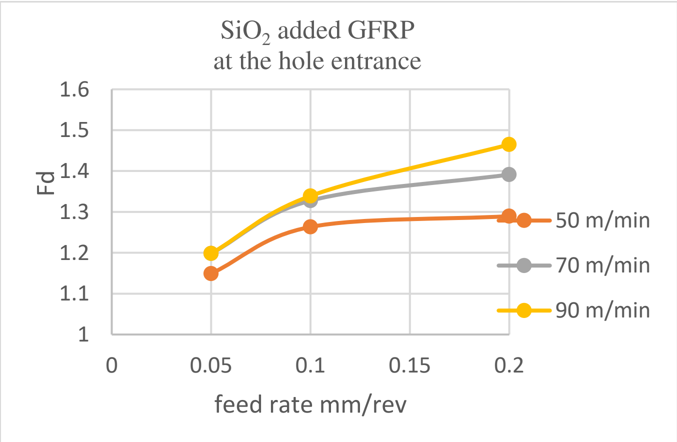


Fig. 8 The effect of cutting speed and feed on peel-up delamination factor

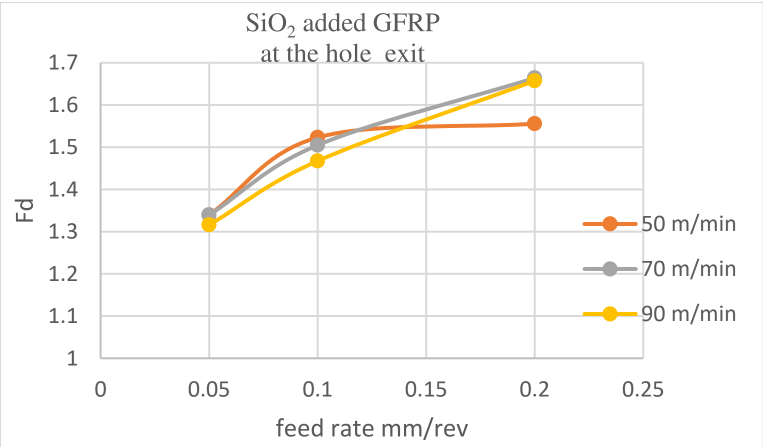


Fig. 9 The effect of cutting speed and feed on push-out delamination factor

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

Mechanical Properties	**GFRP Epoxy**	**SiO_2 added GFRP**	**Al_2O_3 added GFRP**
Tensile Strength (MPa)	533	431	454
Compression Strength (MPa)	607	474	516
Modulus of Elasticity (MPa)	144	138	141
Hardness, Barcol (HB)	78 (87)	66 (55)	71 (67)
Fiber Volume Fraction	0.5	0.5	0.5

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

Parameters	**Levels**		
	-1	**0**	**1**
v (m/min)	50	70	90
f (mm/rev)	0,05	0,1	0,2

Table 3: 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		15% Al_2O_3 Added GFRP/Epoxy		15% 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 4: Mean delamination factors and S/N ratios according to Taguchi method for three composite materials at the hole entrance

Parameter		GFRP/Epoxy			%15 Al_2O_3Added 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	1,186	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 5: Mean delamination factors and S/N ratios according to Taguchi method for three **c**omposite materials at the hole exit.

Parameter		GFRP/Epoxy			%15 Al_2O_3Added 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 6: Variance analysis for GFRP/Epoxy at hole entrance

	Source	DOF	Sum of Squares	Mean Squares	F-Ratio	% Contribution
Delamination factor	Cutting Speed	2	0,028701	0,01435	2,039153	13,46121
	Feed	2	0,156361	0,078181	11,1092	73,33603
	Error	4	0,02815	0,007037		13,20275
	Total	8	0,213212			
	Source	DOF	Sum of Squares	Mean Square	F-Ratio	% Contribution
S/N Ratio	Cutting Speed	2	1,193278	0,596639	2,239703	13,27041
	Feed	2	6,733177	3,366588	12,63772	74,87944
	Error	4	1,065568	0,266392		11,85015
	Total	8	8,992024			

Table 7: Response tables for GFRP/Epoxy at hole entrance.

Response table for mean			Response table for S/N		
Level	Cutting Speed	Feed	Level	Cutting Speed	Feed
1	1,317833	1,14325	1	-2,33231	-1,16034
2	1,198417	1,2345	2	-1,5595	-1,8276
3	1,318583	1,457083	3	-2,33154	-3,23542
Delta	0,120167	0,313833	Delta	0,772813	2,075084
Rank	2	1	Rank	2	1

Table 8: Variance analysis for GFRP/Epoxy at hole exit

	Source	DOF	Sum of Squares	Mean Square	F-Ratio	% Contribution
Delamination factor	Cutting Speed	2	0,007698	0,003849	2,200589	4,733092
	Feed	2	0,147948	0,073974	42,29311	90,96525
	Error	4	0,006996	0,001749		4,301445
	Total	8	0,162643			
	Source	DOF	Sum of Squares	Mean Square	F-Ratio	% Contribution
S/N Ratio	Cutting Speed	2	0,297124	0,148562	1,989083	4,128692
	Feed	2	6,600696	3,300348	44,18799	91,71996
	Error	4	0,298755	0,074689		4,151349
	Total	8	7,196576			

Table 9: Response tables for GFRP/Epoxy at hole exit.

Response table for mean			Response table for S/N		
Level	Cutting Speed	Feed rate	Level	Cutting Speed	Feed rate
1	1,35855	1,153417	1	-2,60412	-1,23927
2	1,294667	1,331883	2	-2,19929	-2,4814
3	1,298533	1,46645	3	-2,24155	-3,3243
Delta	0,063883	0,313033	Delta	0,404827	2,085027
Rank	2	1	Rank	2	1

Table 10: Variance analysis for delamination factor at the hole entrance of Al_2O_3 added composite.

	Source	DOF	Sum of Squares	Mean Square	F-Ratio	% Contribution
Mean delamination factor	Cutting Speed	2	0,001979	0,00099	1,578238	14,93
	Feed	2	0,008769	0,004384	6,992679	66,15017
	Error	4	0,002508	0,000627		18,91973
	Total	8	0,013256			
	Source	DOF	Sum of Squares	Mean Square	F-Ratio	% Contribution
S/N Ratio	Cutting Speed	2	0,113492	0,056746	1,610112	15,21516
	Feed	2	0,491446	0,245723	6,972177	65,88534
	Error	4	0,140974	0,035243		18,89957
	Total	8	0,745911			

Table 11: Response tables for Al_2O_3 added composite at the hole entrance.

Response table for mean			Response table for S/N		
Level	Cutting	Feed	Level	Cutting	Feed
1	1,159567	1,1246	1	-1,27759	-1,01674
2	1,174133	1,147833	2	-1,39381	-1,19708
3	1,138033	1,1993	3	-1,11979	-1,57737
Delta	0,0361	0,0747	Delta	0,27402	0,56063
Rank	2	1	Rank	2	1

Table 12: Variance analysis for delamination factor at the hole exit of Al_2O_3 added composite.

	Source	DOF	Sum of Squares	Mean Square	F-Ratio	% Contribution
Mean delamination	Cutting	2	0,102584	0,051292	18,25157	17,12169
	Feed	2	0,485319	0,24266	86,34752	81,00212
	Error	4	0,011241	0,00281		1,876177
	Total	8	0,599144			
S/N Ratio	Source	DOF	Sum of Squares	Mean Square	F-Ratio	% Contribution
	Cutting	2	3,123684	1,561842	20,01355	16,88919
	Feed	2	15,05933	7,529664	96,48563	81,42304
	Error	4	0,312157	0,078039		1,687776
	Total	8	18,49517			

Table 13: Response tables for Al_2O_3 added composite at the hole exit.

Response table for mean			Response table for S/N		
Level	Cutting Speed	Feed	Level	Cutting Speed	Feed
1	1,464433	1,294133	1	-3,22484	-2,21716
2	1,5349	1,5604	2	-3,59682	-3,83741
3	1,717767	1,862567	3	-4,61833	-5,38541
Delta	-0,18287	0,568433	Delta	-1,02151	3,168251
Rank	1,464433	1,294133	Rank	2	1

Table 14: Variance analysis for delamination factor at the hole entrance of SiO_2 added composite.

	Source	DOF	Sum of Squares	Mean Square	F-Ratio	% Contribution
Mean delamination factor	Cutting	2	0,015985	0,007992	7,123766	19,47697
	Feed	2	0,061597	0,030799	27,45157	75,05486
	Material	4	0,004488	0,001122		5,468166
	Error	8	0,08207			
S/N Ratio	Source	DOF	Sum of Squares	Mean	F-Ratio	% Contribution
	Cutting	2	0,700544	0,350272	8,845103	19,03564
	Feed	2	2,821222	1,410611	35,62091	76,66014
	Material	4	0,158403	0,039601		4,304221
	Error	8	3,680168			

Table 15: Response tables for SiO_2 added composite at the hole entrance

Response tables for mean			Response tables for S/N		
Level	Cutting Speed	Feed	Level	Cutting Speed	Feed
1	1,233933	1,181867	1	-1,81501	-1,44968
2	1,305733	1,309967	2	-2,30036	-2,34235
3	1,334067	1,3819	3	-2,47434	-2,79767
Delta	0,100133	0,200033	Delta	0,659327	1,347983
Rank	2	1	Rank	2	1

Table 16: Variance analysis for delamination factor at the hole exit of SiO_2 added composite.

	Source	DOF	Sum of Squares	Mean Square	F-Ratio	% Contribution
Mean delamination factor	Cutting Speed	2	0,001467	0,000734	0,372786	1,050177
	Feed	2	0,130354	0,065177	33,1247	93,31562
	Material	4	0,00787	0,001968		5,633863
	Error	8	0,139691			
	Source	DOF	Sum of Squares	Mean	F-Ratio	% Contribution
S/N Ratio	Cutting Speed	2	0,044712	0,022356	0,372014	0,927983
	Feed	2	4,533127	2,266564	37,71649	94,08306
	Material	4	0,240379	0,060095		4,988961
	Error	8	4,818218			

Table 17: Response tables for SiO_2 added composite at the hole exit

Response tables for mean			Response tables for S/N		
Level	Cutting Speed	Feed	Level	Cutting Speed	Feed
1	1,4726	1,331533	1	-3,34301	-2,48674
2	1,502633	1,498333	2	-3,50309	-3,51113
3	1,480067	1,625433	3	-3,36705	-4,21529
Delta	0,030033	0,2939	Delta	0,160083	1,728555
Rank	2	1	Rank	2	1

Table 18: 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 19: 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 20: 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 speed	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 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		6,969653
	Total	8	0,18459			

Table 21. 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 22: Mean delamination factor, loss function and S/N rates for three materials (for delamination factor at the hole exit).

	v	f	Mean	Loss F.	S/N
1	50	0.05	1,149	1,320669	-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 23: Analysis of Variance in case of taking as a variable of material (for delamination factor at hole exit).

	Source	DOF	Sum of Squares	Mean Square	F-Ratio	% Contribution
For Mean delamination factor	Cutting speed	2	0,035464	0,017732	0,669102	7,392048
	Feed	2	0,277931	0,138966	5,243826	57,93228
	Material	2	0,113356	0,056678	2,13872	23,62796
	Error	2	0,053002	0,026501		
	Total	8	0,479752			
	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 24: Response table for three materials (for delamination factor at hole exit).

Response Table for mean				Response Table for S/N			
Level	Cutting Speed	Feed	Material	Level	Cutting Speed	Feed	Material
1	1,393633	1,2391	1,299333	1	-2,80942	-1,84864	-2,23381
2	1,4052	1,423767	1,573	2	-2,92762	-3,04895	-3,77211
93	1,5322	1,668167	1,4587	3	-3,5258	-4,36526	-3,25692
Delta	0,138567	0,429067	0,273667	Delta	0,716384	2,51662	1,538299
Rank	3	1	2	Rank	3	1	2

Table 25 Machinability index for GFRP/Epoxy, Al2O3 added GFRP and SiO2 added GFRP

Experimental Plan	GFRP/Epoxy	15% Al2O3 Added GFRP/Epoxy	15% SiO2Added GFRP/Epoxy

No	v	f	F_d ent.	MI ent	F_d ex	MI ex	F_d ent.	MI ent	F_d ex.	MI ex	F_d ent.	MI ent	F_d ex.	MI ex
1	50	0.05	1,186	0,8431	1,1492	0,870	1,1028	0,906	1,2056	0,829	1,1491	0,8702	1,3394	0,746
2	50	0.1	1,216	0,8223	1,4167	0,705	1,1495	0,869	1,4762	0,677	1,2632	0,7916	1,5229	0,656
3	50	0.2	1,552	0,6443	1,5098	0,662	1,2264	0,815	1,7115	0,584	1,2895	0,7754	1,5555	0,642
4	70	0.05	1,114	0,8976	1,1369	0,879	1,1682	0,856	1,2523	0,798	1,1983	0,8345	1,3394	0,746
5	70	0.1	1,209	0,8271	1,2887	0,775	1,1619	0,860	1,4667	0,681	1,3276	0,7532	1,5048	0,664
6	70	0.2	1,273	0,7855	1,4584	0,685	1,1923	0,838	1,8857	0,530	1,3913	0,7187	1,6637	0,601
7	90	0.05	1,13	0,8849	1,1741	0,851	1,1028	0,906	1,4245	0,702	1,1982	0,8345	1,3158	0,759
8	90	0.1	1,279	0,7818	1,2903	0,775	1,1321	0,883	1,7383	0,575	1,3391	0,7467	1,4673	0,681
9	90	0.2	1,547	0,6464	1,4312	0,698	1,1792	0,848	1,9905	0,502	1,4649	0,6826	1,6571	0,603
	MI averange			*0,792*		0,767		0,865		0,653		*0,778*		0,678

Table 26. The optimum values for delamination factor of Epoxy/ GFRP plate epoxy/ GFRP plate, SiO_2 added GFRP/epoxy plate and Al_2O_3 added GFRP/epoxy plate

	Epoxy/ GFRP				SiO_2 added GFRP/epoxy				Al_2O_3 added GFRP/epoxy			
x_1	-1	1	1.177	1	-1	1	0.0867	1	-1	1	2.46	1
x_2	-1	1	2.13	-1	-1	1	21.67	-1	-1	1	4.065	-1
λ_1	-0,054	0	0	0.0494	0.0094	0	0	0	0.015	0	0	0
λ_2	0	-0.012	0	0	0	0.0639	0	0.159	0	-0.015	0	-0.053
λ_3	0.1847	0	0	0.1473	0.1948	0	0	0.187	0.116	0	0	0.156
λ_4	0	-0.055	0	0	0	-0.17	0	0	0	-0.083	0	0
Y	0.1534	0.3516	-	0.149	0.1835	0.7087	-	0,3519	0.24962	0.5014	-	0.26178
Result	saddle	max	Out of region	Global min	Global min	saddle	Out of region	min	global min	max	Out of region	saddle

Table 27. The optimum values for modified objective function of material removal rate and delamination factor of GFRP/Epoxy plate, SiO_2 added GFRP/epoxy plate and Al_2O_3 added GFRP/epoxy plate at the hole exit

	Epoxy/ GFRP				SiO_2 added GFRP/epoxy				Al_2O_3 added GFRP/epoxy			
x_1	-1	1	-0,181	1	-1	1	-0,09	1	-1	1	-0,084	1
x_2	-1	1	0,367	-1	-1	1	0,259	-1	-1	1	0,092	-1
λ_1	-0.632	0	0	0	0.1	0	0	0	-0,1431	0	0	0
λ_2	0	0.374	0	0.18	0	-0,916	0	0,996	0	0,41	0	0,82
λ_3	1.154	0	0	0.78	0.23	0	0	0,153	0,367	0	0	0
λ_4	0	0.14	0	0	0	0,015	0	0	0	-0,23	0	0,773
Y	0,153	0,351	0,305	0,149	0,18	0,7087	0,456	0,3519	0,299	0,501	0,424	0,261
MMR	8,228	10,20	9,523	8,816	8,228	10,202	9,367	8,8166	8,228	10,202	9,254	8,816
MOF	-6,695	-6,686	-6,47	-7,32	-6,394	-3,116	-4,801	-5,298	-5,2327	-5,1889	-5,013	-6,198

Results	saddle	min	saddle	Global min	global min	saddle	saddle	min	saddle	saddle	saddle	Min