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EXPERIMENTAL INVESTIGATION ON INFLUENCE OF PROCESS PARAMETERS AND DRILLING PERFORMANCE OPTIMIZATION

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Abstract:

The utility of composites in unconventional industries, especially the aerospace industry, has expanded dramatically due to their unique mechanical properties. Drilling CFRP composite elements is one of the most common operations in assembly and therefore, choosing the right process parameters and geometry is an essential key to controlling damage caused by drilling (i.e. layer separation means delamination). This observation provides a unique mathematical version of predicting the required thrust force at which separation (delamination) begins. The model considers thermos-mechanics loads of a mixed failure mode located in the separation region for unidirectional composites. This incorporated technique consists of 3 stages; (i) Experimental research on drilling thrust force and (ii) Effects of feed rate scheduling on minimizing delamination. It turned perceived that the simplest scheduling the feed rate is not enough for minimizing the delamination. Present work attempts to investigate aspects of machining performance optimization during drilling of CFRP composites. In case of drilling, the following process performance features viz. load (thrust), torque, roughness average (of the drilled hole) and delamination factor (entry and exit both) have been considered. Attempt has been made to determine the optimal machining parameters setting that can simultaneously satisfy aforesaid response features up to the desired extent.

Keywords: Carbon Fibre Reinforced Polymer (CFRP); thrust force, torque, delamination.

Introduction:

Composite materials have grown recently and are increasingly being used in new applications. Because of its high stiffness-to-weight ratio, it is considered competitive with other materials in many applications such as aircraft and automobiles.[1]. Composites can be mainly divided into polymer matrix composites, metal matrix composites and ceramic matrix composites. The addition of fibres improves the tensile properties of the composite material. This improvement is due to the higher strength and stiffness of the fibre compared to the matrix material [2]. Composite materials can be tailored to individual needs to desired specifications in corrosive environments where they offer high strength, lightweight, reduced product life costs, reduced life product life, and a good combination of mechanical and thermal properties. Furthermore,

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it provides the ability to monitor the performance of these materials through an integrated part of the composite sensors and make them superior to other materials [3].

The properties of composite materials are different even though the same material is used, and the same manufacturing process is used to manufacture the material. Epoxy nanocomposites are characterized by excellent mechanical properties, dielectric properties, thermal stability, corrosion resistance and adhesion to wet substrates, good hardness and good tribological properties. Several potential applications have generated widespread interest in this type of material [3, 4]. Using inorganic fillers to reinforce epoxy resins is a popular method, as the nanoparticles fill the weak micro-regions of the resin to improve the interaction between the epoxy surface and the filler. Adding nanoparticles to the epoxy matrix increases the contact surface between them and improves its properties reinforcement efficiency is strongly influenced by the particle size, the dispersion of the nanoparticles and the volume fraction of the nanoparticles in the epoxy matrix. In recent years, carbon fibre composites have become very popular in the manufacturing industry, especially in the aerospace and automotive industries, due to their excellent mechanical and thermal properties, including high mechanical strength and low weight, good fatigue strength, good corrosion resistance and weather resistance. resistance, very low coefficient of thermal expansion and high strength-to-weight ratio. As the demand for CFRP composites increases in the above industries, manufacturers are paying more attention to studying the machinability aspects of these composites. In general, CFRP products are manufactured with an almost mesh shape; however, machining is often performed to remove excess material to meet dimensional accuracy and tolerances. But machining these composites is slightly different from machining conventional metals, rather difficult because of their material discontinuity, anisotropy and homogeneous nature. Carbon fibre reinforced plastic (CFRP) has a higher density than metal and has excellent wear resistance, heat resistance and rust resistance [2,3]. In addition, the need to reduce environmental regulations and improve energy efficiency worldwide is so great that the technological development of processing enterprises is necessary. For this reason, CFRP is used rapidly, and this outlook will continue, as shown in the figure. 1 as a functional component material in the transportation industry. The use of CFRP has increased. rapidly and this outlook will continue, as shown in the fig:1 as a functional component material in the transportation industry.

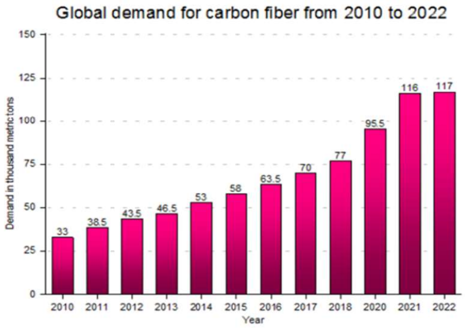


Fig 1: Global demand for carbon fibre from 2010 to 2022 [30]

Literature Review:

The literature review, conducted to improve the quality of machined surface by proper selection of a drilling process. It was investigated that the surface quality of the composites drilled with conventional machining is strongly dependent on the machining parameters such as tool geometry, cutting forces (thrust and torque), the spindle rotation and feed rate of the tool. Thus, in the present work, effect of machining parameters on the drilled surface of the composite material is presented.

R. Teti, V. Lopresto, A. Caggiano [5] and Meng, Q., Zhang, K., Cheng, H., Liu, S., & Jiang, S [6] and Qi, Z., Zhang, K., Cheng, H., Wang, D., & Meng, Q [7] et al were explained Research of the machining process for fibre reinforced plastics (FRP) has been going on for several years. Researchers attempt to formulate new models for FRP composite machining based on existing tools and models, primarily of metal alloy processing. To develop a model for FRP composite materials machining process, it is necessary to understand the metal cutting mechanism and next, it is necessary to discuss the mechanism for the FRP composite material machining. Carbon fibre reinforced plastic (CFRP) has many advantages such as high strength based on density, abrasion resistance, heat resistance, and rust-free so today, CFRP is used in a variety of industries. However, CFRP is difficult to cut, unlike metals due to its brittleness in nature and non-homogeneity. It is difficult to predict cutting forces and surface conditions. The chip formation mechanism is defined by shearing in metallic alloys however, the chip formation is controlled by the bending in the fibre-matrix interface in the machining process of CFRP composite materials. The quality of machining surface is affected by its the fibre orientation. For these reasons, M.P. Groover [8], Lopresto, V., Caggiano, A., & Teti [9] and D. Arola, M. Ramulu, D.H. Wang et al [10] it is complicated to the machining of CFRP composite materials. Therefore, the process of CFRP composite an appropriate mechanism considering fibre orientation and chip formation is required, and optimum processing conditions are required. There have been many studies on FRP composites. According to the Koplev et al [11], the machining of CFRP is examined by experiments with chip preparation technique. Both two processing directions parallel and perpendicular to the fibre orientation of the Unidirectional composite was performed in a cutting operation. During unidirectional CFRP processing, parallel to the fibres, the horizontal cutting force is determined by the rake angle and the cutting depth. And the vertical cutting force is determined by the wear of the tool and the relief angle. Caggiano et al [12] The FRP has machinability depending on the mechanical properties of the composite and fibre orientation. The carbon fibres tend to break into brittle form by the cutting edge, but the fibres tend to break off the fibre shear by bending at the cutting edge. Therefore, the surface quality depends on the fibre strength, orientation and it’s cutting conditions are dependent on the fibre matrix strength. The chip formation is important for understanding the cutting mechanism of the FRP [13-14]. The polymer matrix in the FRPs is an important affectation in the chip formation and its types, since its strength and stiffness are low-grade than those of reinforcement fibres, and they have at least resistance as the cutting. H. Takeyama et al. [21] proposed the chip formation theory in the orthogonal cutting model of FRP. The chip formation of FRP is strongly influenced by the fibre orientation in relation to the cutting direction.

Pramanik et al. [26] developed a mechanic for predicting the forces of cutting metal matrix composite. The cutting force mechanisms are based on the chip formation, matrix ploughing, and particle fracture and displacement. In this article, to define the mechanism of the thrust force generated by drilling, the force generated by the region of the tool in the orthogonal cutting was obtained and the mechanism for the drilling process was obtained through the coordinate transformation.

Delamination at the entry and exit of hole has been analyzed by various researchers. A number of research work illustrated by Davim JP, Reis et al P[45], Dharan CKH, Won MS et al[46] and Zhang H, Chen W, Chen D, Zhang L et al [47] that delamination is influenced by the selection of suitable machining parameters , the geometry of the cutting tool tip explained by Campos Rubio J, Abrao AM, Faria PE et al [48], Singh I, Bhatnagar N, Viswanath P et al [49] and Piquet R, Ferret B, Lachaud F, Swider P. et al [50], and the nature of its material by Davim JP et al [51] and Kilickap E et al [53]. Moreover, these research works found that the thrust force is the main factor for delamination at the hole exit. The Taguchi technique were used Davim JP, Reis et al P[45] , Kilickap E et al [53] and A. Di Ilio, A. Paoletti et al [54] to study the influence of drilling parameters on the delamination. It was found that delamination at the hole entry and exit increases with the cutting speed and the feed rate of the tool. For a higher cutting speed and federate, the delamination is larger in composite materials. Federates of 0.04, 0.08 and 0.15 mm/rev and spindle speed of 1000, 1500 and 2000 rpm were used by Kilickap E et al [53].

Based on a comprehensive analysis of the literature, it was determined to include the aspect of cutting tool geometry in this paper, and therefore, in addition to speed, feed, and approach angle of the cutting tool would be one of the input parameters. We will use thrust, torque, peel-up delamination (F_{in}) and push down delamination (F_{out}) as output parameters to examine economical machining, which is directly related to the quality of the product produced after machining. The aim of this work is to optimise the cutting parameters in order to investigate their impact on the output variables by using various statistical tools like Taguchi analysis and ANOVA analysis and Regression modelling:

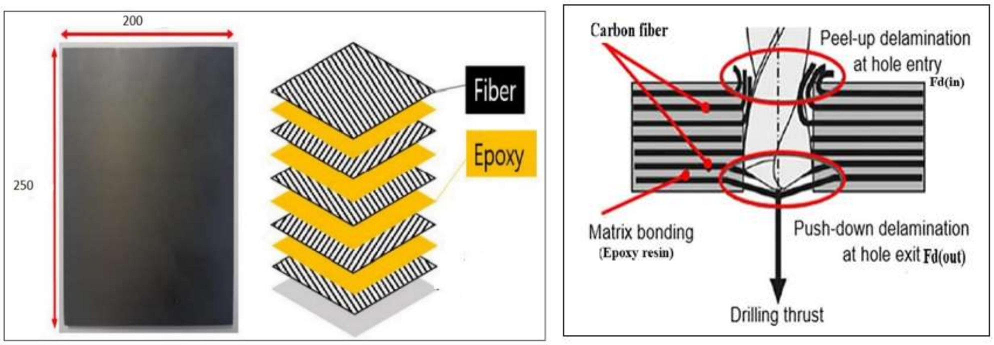
1) To investigate the impact of various cutting parameters such as speed, feed, fibre orientation, thrust, torque, peel-up delamination (F_{in}) and push down delamination (F_{out}). 2) To develop relation among the various chosen influencing parameters in order to evaluate the percentage of contribution among them in case of the speed, feed, thrust, torque, peel-up delamination (F_{in}) and push down delamination (F_{out}), fibre orientation obtained after performing the drilling operation.

Experimental Setup:

Experiments were conducted on a CFRP laminate panel measuring 200 mm × 250 mm × 3 mm. The CFRP panel was constructed using the hand lay-up winding method and oriented at 30°, 45° and 60°. The CFRP panel consists of eight alternating layers of carbon fibre that had gone through an autoclaving process. The cutting parameters used in the experiment are shown in

Table 1. A computer numerical control machine with a 7.5 kW spindle power and maximum spindle speed of 12000 rpm was used in the experiment. Table 1 shows the experimental conditions for CFRP cutting.

Methods used for optimizing machining parameters: i) Design of experiments, ii) Anova iii)Taguchi iv) Regression Analysis using software MINITAB.



(a) (b)

Fig 1 : a. A schematic diagram for peel-up and push down delamination b. The CFRP specimen

Fig 2 : Experimental set up

Fig 3: Drill bit of 5 mm used during experimentation

Table:1 Specification of CFRP plates

Specification/description	Value(s)
Density	02 gm/cm^3
Fibre orientations	Φ1, Φ2, Φ3
Fibre and matrix % ratio	fibre :resin = 70:30
Method of preparation	hand lay-up

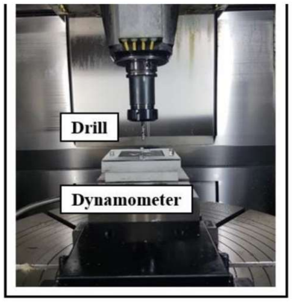
(i) ***Design of Experiments (DOE):*** In this paper, drilling operations have been performed on CNC drilling machine. In order to perform experimentation, it is quite necessary to develop a set of experiments for determining the response measurements. For this, Taguchi method has been applied for selecting design of experiment as it examines the effects of entire machining process parameters with less (i.e., limited) number of experiments in comparison to full factorial design of experiments. The present study focuses on the effects of drilling parameters such as composite type, drill speed, feed rate and fibre orientation, thrust, torque and fibre orientation; each has been varied at three different levels. Attempt has also been made to understand the relationship (influence) between input-output(s); where, inputs i.e., process parameters have been considered like composite type, drill speed, feed rate, and outputs have been and drilling responses like thrust force, torque, delamination at entry and exit and average surface roughness of the drilled hole.

In order to achieve the specific aim of the research analysis, three different criteria are available for that purpose as stated below in the following table 2.
Smaller the better Minimize the response Non negative with a target value of zero S/N = −10 *log(Σ(Y2)/n)).

(ii) Contour Analysis

Contour plots are generally used to show the relation among the two input variables on an individual output parameter. Contour plots can be used to investigate desired output parameters and operating variables. A contour plot consists of following elements:

- On the x- and y-axes, there are predictors.
- Contour lines are drawn between places with the same response value.
- Ranges of response values are shown by coloured contour bands



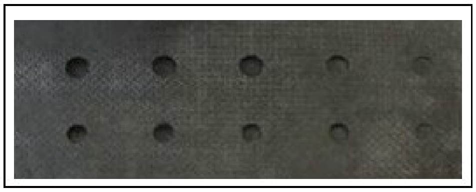


Fig 4: Experimental set for CFRP specimen   Fig 5: Specimens after performing drilling

(iii) Taguchi method Optimation

The ranges of each of the input parameters which are selected on the basis of the manufacturer's catalogue are shown in the table 2 given below:

Table 2: Domain of experiments

Parameters (Notation)	**Unit**	**Level 1**	**Level 2**	**Level 3**
Drill Speed (N)	Rpm	1000	1200	1400
Feed rate (f)	mm/min	100	150	200
Fibre Orientation	angle	30	45	60

Due to limited size of the work specimen CFRP, we opted for L9 orthogonal array design as it is more compact and will help us to perform the requisite engineering experimental design in order to achieve our goal with minimum number of experiments to be performed. The required Taguchi L9 array obtained as per above stated levels are provided below in the table 3.

Table 3: Design of experiment (L9 Orthogonal Array)

Speed Rpm	Feed mm/min	Fiber Orientation (angle)	Thrust kN	Torque Mpa kN-mm	F_d(in)	F_d(out)
1000	100	30	0.054	0.37	1.068	1.072
1000	150	45	0.065	0.4	1.315	1.17
1000	200	60	0.093	0.355	1.558	1.319
1200	100	45	0.0635	0.46	1.328	1.192
1200	150	60	0.109	0.55775	1.562	1.2905
1200	200	30	0.053	0.44	1.078	1.077
1400	100	60	0.068	0.2875	1.557	1.301
1400	150	30	0.129	0.33	1.055	1.08
1400	200	45	0.135	0.295	1.305	1.195

Results and Discussions:

Table: Taguchi and Analysis of Variance for thrust, delamination in and out

SNRA1	MEAN1	SNRA2	MEAN2	SNRA3	MEAN3	FITS1	RESI1	FITS2	RESI2	FITS3	RESI3	PSNRA1	PMEAN1	PSNRA2	PMEAN2
25.35212	0.054	-0.57143	1.068	-0.6039	1.072	0.043917	0.010083	1.074	-0.006	1.068083	0.003917	-0.62163	1.074667	-0.6258	1.074167
23.74173	0.065	-2.37852	1.315	-1.36372	1.17	0.0655	-0.0005	1.318	-0.003	1.186	-0.016				
20.63034	0.093	-3.85135	1.558	-2.4049	1.319	0.087083	0.005917	1.562	-0.004	1.303917	0.015083				
23.94453	0.0635	-2.46396	1.328	-1.52553	1.192	0.069583	-0.00608	1.316	0.012	1.184167	0.007833				
19.25147	0.109	-3.87362	1.562	-2.21516	1.2905	0.091167	0.017833	1.56	0.002	1.302083	-0.01158				

25.51448	0.053	-0.65238	1.078	-0.64431	1.077	0.09575	-0.04275	1.066	0.012	1.07925	-0.00225				
23.34982	0.068	-3.84577	1.557	-2.28555	1.301	0.09525	-0.02725	1.558	-0.001	1.30025	0.00075				
17.78821	0.129	-0.46505	1.055	-0.66848	1.08	0.099833	0.029167	1.064	-0.009	1.077417	0.002583				
17.39332	0.135	-2.31221	1.305	-1.54736	1.195	0.121417	0.013583	1.308	-0.003	1.195333	-0.00033				

$SNRA_1$, $MEAN_1$, $FITS_1$, $RESI_1$, $PSNRA_1$ - Thrust,
$SNRA_2$, $MEAN_2$, $FITS_2$, $RESI_2$, $PSNRA_2$- Peel up Delamination (F_{in})
$SNRA_3$, $MEAN_3$, $FITS_3$, $RESI_3$, $PSNRA_3$- Push down delamination (F_{out})

Table 3: Analysis of Variance for Thrust versus Speed, Feed, Fiber orientation

Analysis of Variance for Thrust versus Speed, Feed, Fiber orientation							
Source	**DF**	**SeqSS**	**AdjSS**	**AdjMS**	**F**	**P**	**% of Contribution**
Speed	2	25.547	25.547	12.773	1.06	0.486	31.76
Feed	2	25.705	25.705	12.852	1.06	0.485	31.93
Fiber oriantation	2	5.068	5.068	2.534	0.21	0.827	6.29
Residual Error	2	24.178	24.178	12.089			
Total	8	80.497					

Table 4: Analysis of Variance for Fd(in) versus Speed, Feed, Fiber orientation

Analysis of Variance for Fd(in) versus Speed, Feed, Fiber orientation							
Source	**DF**	**Seq SS**	**AdjSS**	**AdjMS**	**F**	**P**	**% of Contribution**
Speed	2	0.0224	0.0224	0.01122	8.39	0.106	0.136
Feed	2	0.0045	0.0045	0.00227	1.7	0.37	0.027
Fiber oriantation	2	16.3365	16.3365	8.16826	6109.41	0	99.78

Residual Error	2	0.0027	0.0027	0.00134			
Total	8	16.3662					

Table 5: Analysis of Variance for Fd(out) versus Speed, Feed, Fiber orientation

Analysis of Variance for Fd(out) versus Speed, Feed, Fiber orientation							
Source	**DF**	**Seq SS**	**AdjSS**	**AdjMS**	**F**	**P**	**% of Contribution**
Speed	2	0.00337	0.00337	0.00168	0.2	0.834	0.0804
Feed	2	0.02034	0.02034	0.01017	1.2	0.455	0.477
Fiber oriantation	2	4.14836	4.14836	2.07418	244.7	0.004	99.23
Residual Error	2	0.01695	0.01695	0.00848			
Total	8	4.18902					

With a P-value of 0.486, we may conclude that Fiber orientation has the greatest influence on machining parameters, followed by cutting speed as the second most affecting component with a P-value 0.485. The next important table which we obtain as a part of the regression analysis is model summary table. The table 6 & 7 listed below represents the model summary.

Regression Analysis

Table 6: Regression Analysis: Thrust versus Feed, Fiber orientation, c

Model Summary	**S**	**R-sq**	**R-sq(adj)**	**R-sq(pred)**
	0.02863	50.09%	20.15%	0.00%

Table 7: Regression Analysis: Fd(in) versus Speed, Feed, Fiber orientation

Model Summary	**S**	**R-sq**	**R-sq(adj)**	**R-sq(pred)**
	0.01189	99.10%	98.56%	96.79%

Table 8: Regression Analysis: Fd(out) versus Speed, Feed, Fiber orientation

Model Summary	**S**	**R-sq**	**R-sq(adj)**	**R-sq(pred)**
	0.0118894	99.10%	98.56%	96.79%

This response table for S/N ratios has been appropriately supported by main effects plot for S/N ratio and main effects plot for means. This plots along with the response table helps in determining the required levels for input parameters for optimal values. The main effects plots for S/N ratios and means are shown in figures below fig 6.

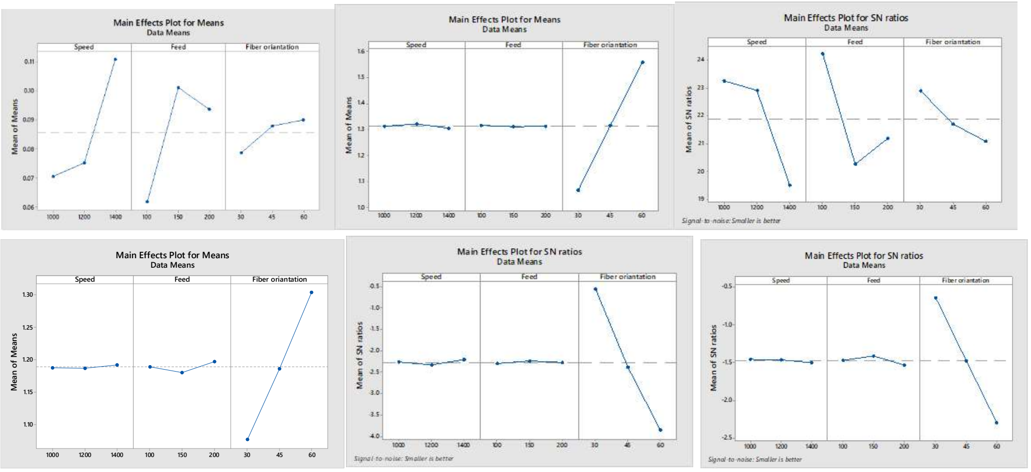


Fig 6: Main Effects Plot For S/N Ratios

From the main effects plot it can be observed that the plot for cutting speed is following an increasing trend with SN value increases when speed increases from level-1 to level-3. The plot for feed also follows the same increasing trend for SN value when feed changes from level-1 to level-3. The plot of approach angle is different as compared to others as the SN value decreases when angle changes from level-1to level-2 and again rises to attain the value at level-3. The plot is steeper for depth of cut compared to others suggesting it has the maximum influence on machining parameters.

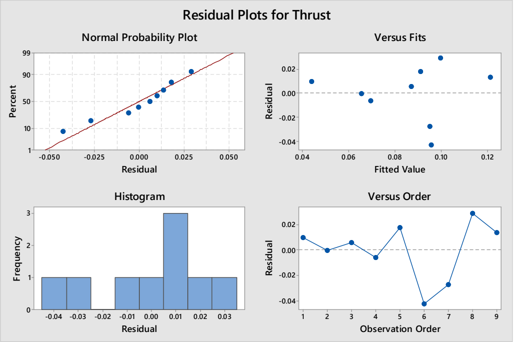


Fig 7: Residual Plots for Thrust

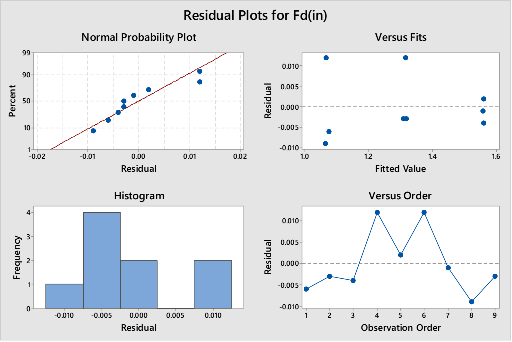


Fig 8: Residual Plots for Fd(in)

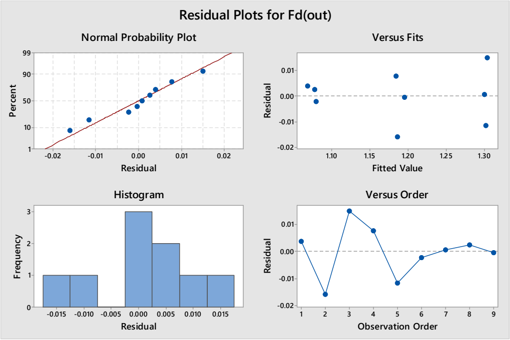


Fig 9: Residual Plots for Fd(out)

We may infer from the above data that the fibre orientation has the greatest influence on machining followed by cutting speed. The feed contributes percent. A pareto chart for standardised effect with machining parameters as the response can also be used to describe the above results. The required pareto chart is shown in the diagram below

Thrust force

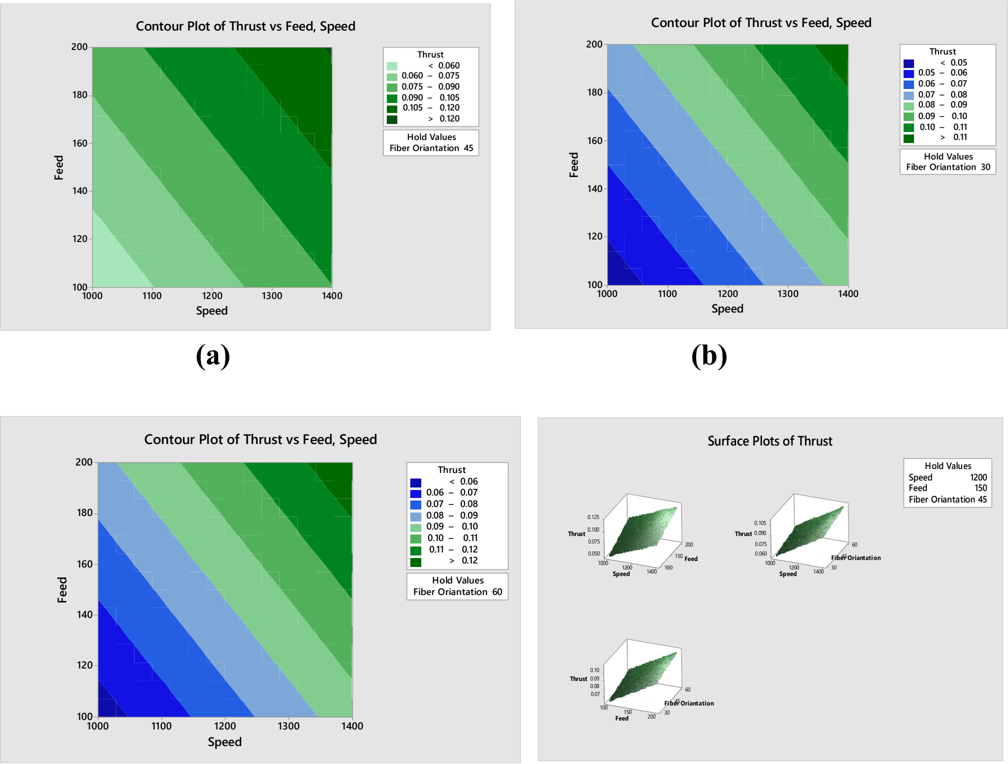
Thrust force obtained from the experiment was analysed. The material used in the drilling process is a stack of CFRP of 30°, 45° and 60°. The carbon fibre used was MRC TR50 and SKR-K51 was used for the resin. The drilling conditions were 3 kinds of rpm (1000rpm, 1200rpm, 1400rpm) and 3 kinds of feeds (100mm/rev, 150 mm/rev, 200 mm/rev). The thrust forces according to the same feed are compared. The results of the thrust force according to each experimental condition were examined (Fig.).

Delamination

Whether delamination occurs in the CFRP stack drilling process is very important. The biggest problem of the CFRP stack drilling process is delamination of CFRP. As the quality of the machining is determined by the occurrence of delamination. The experiment was performed to measure delamination. As a result of the experiment, the surface delamination was measured according to each condition. The degree of surface delamination was visually distinguishable, and delamination was determined through the delamination extent. The following figure shows the result of measuring the delamination extent according to each condition.

Contour plots:

At first, we will draw contour plots with thrust, peel up delamination and push down delamination being the response variable and there will be combinations of two input predictors chosen from cutting speed, feed and fibre orientation of the cutting tool. The contour plots for response variables as shown by the figure given below

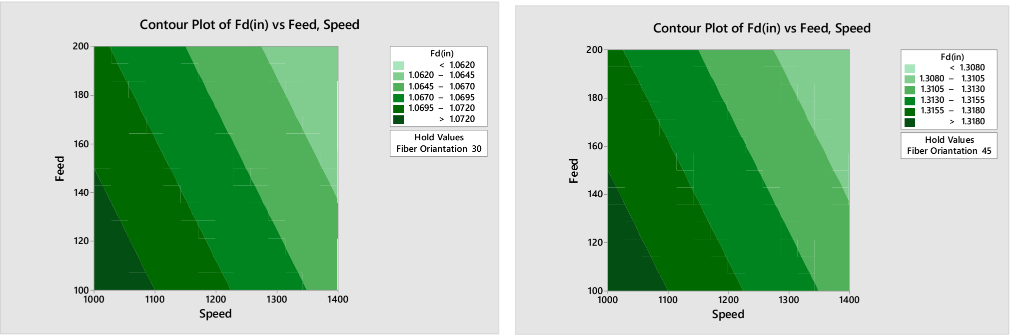


(a) **(b)**

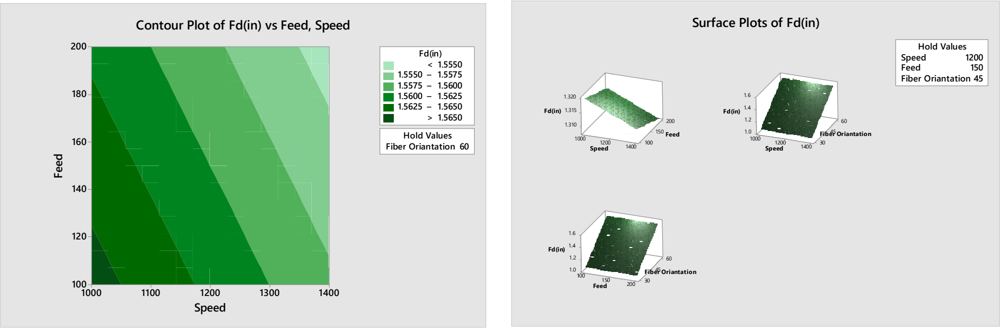
(c) **(d)**

Fig 10: (a, b, c) Contour plots at various fiber orientations and (d) Surface plots of Thrust

We can see from the preceding figure (a) that for lower surface roughness, mid-range cutting speeds and low-range feed are appropriate. We can deduce from (b) that mid-range cutting speeds and depths of cut are preferable for reducing surface roughness. The conclusion reached from (c) is that in order to achieve lesser surface roughness, a higher cutting speed and approach angle must be selected. It can be seen from (d) that for decreased surface roughness, low feed values and mid depths of cut are desirable. Low feed and high approach angle values must be chosen from (e) for a lower value of surface roughness. It comes from (f) that a lower value of surface roughness corresponds to a mid-depth of cut and a larger approach angle.



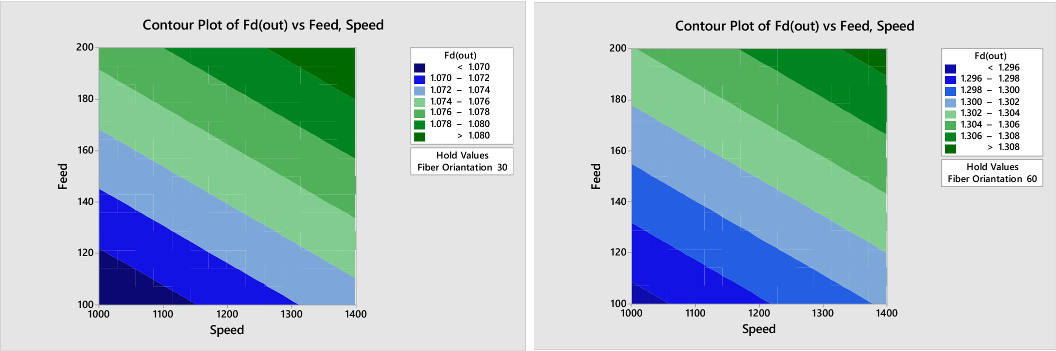
(a) (b)



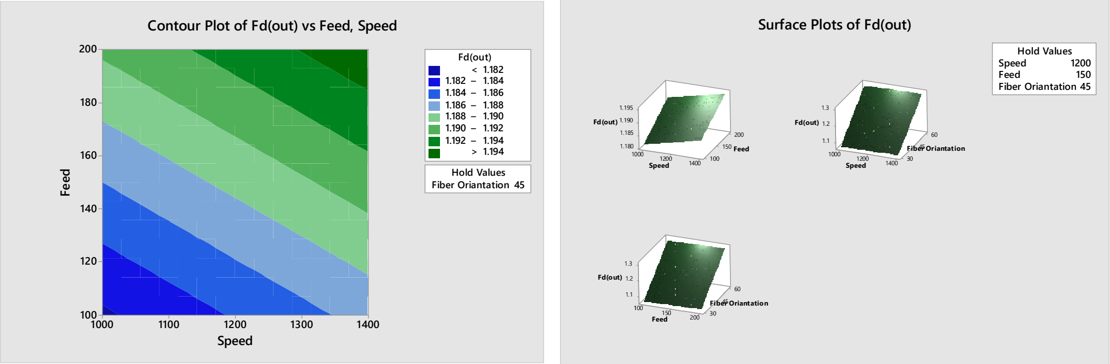
(c) (d)

Fig 11: (a, b, c) Contour plots at various fiber orientations and (d) Surface plots of Fd (in)

We can see from the above figure (a) that greater cutting speed and feed values are appropriate for reducing machining time. We can deduce from (b) that high cutting speeds and intermediate depths of cut are preferable for reducing machining time. The conclusion obtained from (c) is that in order to save machining time, a greater cutting speed and a lower approach angle must be employed. It can be seen from (d) that high feed rates and mid depths of cut are desired for shorter machining times. To achieve a decreased machining time, high feed rates and low approach angles must be selected from (e). From (f) it was found that lower value of machining time corresponds to mid values of depth of cut and lower values of approach angle



(a) (b)



(c) **(d)**

Fig 12: (a, b, c) Contour plots at various fiber orientations and (d) Surface plots of Fd (out)

Table 8: Predicted values at speed, feed and Fiber Orientation

Variable	Setting
Speed	1000
Feed	100
Fiber Orientation	30

Table 9: Prediction for Thrust

Fit	SE Fit	95% CI	95% PI
0.0439167	0.0223781	(-0.0136081, 0.101441)	(-0.0494856, 0.137319)

Table 10: Prediction for Fd(in)

Fit	SE Fit	95% CI	95% PI
1.074	0.0073666	(1.05506, 1.09294)	(1.04325, 1.10475)

Table 11: Prediction for Fd(out)

Fit	SE Fit	95% CI	95% PI
1.06808	0.0092944	(1.04419, 1.09198)	(1.02929, 1.10688)

Regression Results:

Regression technique is also an optimization technique in which an equation obtained to correlates the parameters which are taken in the experiment. The regression equations are as follows Regression equation for Aluminium alloy

Regression Analysis for Thrust versus Feed, Fiber orientation, c

Regression Equation is:

Thrust = -0.0993 + 0.000318 * Feed + 0.000378 * Fiber orientation + 0.000100

Regression Analysis for F_d(in) versus Feed, Fiber orientation, c

Regression Equation is:

F_d(in) = 0.6060 - 0.000040 * Feed + 0.016400 * Fiber orientation - 0.000020 speed

Regression Analysis for F_d(out) versus Feed, Fiber orientation, c

Regression Equation is:

F_d(out) = 0.8197 + 0.000087 * Feed + 0.007572 * Fiber orientation + 0.000013 speed

The approximate predicted values from Taguchi whereas RSM, which shows exact predicted values as shown in below graph

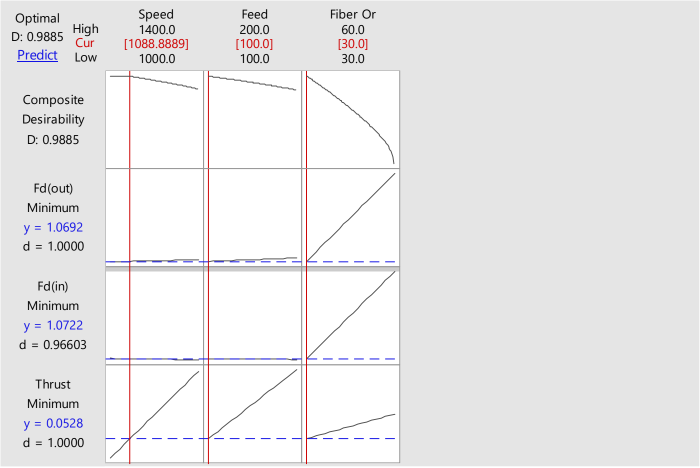


Fig 13: Graph showing predicted values of Taguchi and RSM

Conclusions

Due to the excellent properties of CFRP, it is preferred for many applications, and also drilling is essential for almost in any manufacturing process. It is found that drilling in CFRP is depend on cutting speed, feed rate, fibre orientation thrust and torque the following points are concluded.

1) By using taguchi method of optimization thrust is the main response parameter for speed and fibre orientation.

2) Regression analysis has been performed in order to evaluate mathematical relation between the output parameters like surface machining time and the input parameters like cutting speed, feed and fibre orientation.

3) The model summary concluded that regression model for thrust has a R-sq value of 50.09 %, The R-sq value of regression model for peel-up delamination and push down delamination was 99.88 % and 99.10 % respectively.

4) In order to investigate about interactions between the input parameters and its impact on the output parameter contour plots has been drawn for each of the output parameters like thrust, peel up delamination and push down delamination against the three input parameters combination out of the available input parameters.

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