Analysis of the Effect of Tool Geometry and Hole Quality on Drilling Carbon-Fibre Reinforced Polymer Composite Using ANSYS

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ABSTRACT

This study focused on the analysis of the effect of tool geometry and hole quality on drilling carbon-fibre reinforced polymer (CFRP) composite using ANSYS. The experiment was conducted on computer numerical control machine (CNC) using high speed steel (HSS) twist drill bit and HSS-COBALT drill type. Taguchi L9 orthogonal array was used for the optimization analysis. Analysis of variance (ANOVA) was employed to determine the most significant control factors affecting the drilling process. The machining parameters involving tool type, point angle, spindle speed and feed rate were selected as control factors. While the dependable variables on workpiece were cutting force, stress and strain. The main interaction effect of the input variables on the predicted responses was investigated. The ANOVA/F-test results for cutting force with the contribution of each machining parameters revealed that the cutting speed was the dominant factor influencing cutting force developed with a contribution of 57 percent, The second factor affecting cutting force developed was point angle with a contribution of 5.7 percent, while feed rate had the least effect on cutting force developed where its contribution of 1.4 percent. Based on the results observed, the optimal machining parameters that produced minimum stress was observed with HSS-COBALT drill at 118 degrees of point angle, 300 mm/min of feed and 500 rpm of speed. Also from Taguchi results, the optimal combination of process parameters to obtain maximum strain with HSS drill, 135 degrees of point angle, and 300 mm/min of feed and 1500 rpm of speed produced the optimal drilling condition for CFRC polymer within the scope of this research work.

Keywords: *ANOVA, ANSYS, CFRC polymer, Drilling parameters, Tool Geometry.*

1. INTRODUCTION

Composite materials are increasingly used in various fields of endeavors, such as aeronautics, maritime, and automobile industries. The assembly of different aircrafts structures requires machining of different component parts. Drilling of thick component plates have posed some significant challenges during drilling operations because of the fast rise of stress and strain induced in the work piece material by cutting force. This causes defects at the hole entry, exit and on the walls of the drilled hole. The defect reduces the resistance of the structural failures and hence the need to find a solution to minimize and reduce them if possible. The cutting conditions are the main parameters that affect the quality of the drilling operation.

Machining process includes three principal categories: turning, milling, and drilling. Drilling machining process makes 40% of the machining processes used in industrial applications (Tsao & Hocheng, 2007).

Drilling process can be conducted either on conventional lathe machine (manual) or on computer numerically controlled (CNC) lathe machine. (Mathews & Nedheesh ,2014)

In this research work, the experiment was conducted based on Taguchi's L9 orthogonal array. The control parameters are as follows; feed rate, spindle speed, drill bit type and point angle while drilling the holes, the maximum cutting force generation, stresses and total strain were simulated and analyzed using ANSYS and finally the obtained results were optimized by using single objective optimization technique known as Taguchi robust method.

Yingying *et al.* (2016) investigated the effect of drilling parameters and tool geometry on drilling performance in drilling carbon fibre–reinforced plastic/ titanium alloy stacks. An experimental study on drilling of carbon fibre–reinforced plastic/titanium alloy was conducted using three kinds of drills to investigate the cutting process. Their research was mainly focused on the drilling forces, drilling temperatures, chips, and delamination area with respect to the cutting parameters and tool geometries. . The influence of drilling parameters and tool geometries was analysed and the conclusions were drawn that the proper selection of drilling parameters and drill geometries could lead to better hole quality

Pravin *et al.* (2017) performed modeling and simulation of drilling process in Ti-6Al-4V, Al6061 using Deform-3D software. They stated that drilling is an important process for the manufacturing of any products. In their research work the drilling process was carried out by finite element modeling and simulated with the help of DEFORM-3D software. The composite alloy material Ti-6Al-4V and Al6061 was drilled to obtain the desired hole using the diamond drill bit. They stated that the titanium alloy which is widely used in the field of biomedical applications, whereas the Al6061 aluminium alloy is mostly applicable in automotive and aerospace industries. The simulation obtained showed that Ti-6Al-4V had higher stresses and temperature distribution than Al6061 material, which may possibly be an effect of physical properties of Ti-6Al-4V material.

Manoj *et al.* (2019) carried out finite element stress analysis of drill bit in ANSYS. They stated that drilling is a slicing procedure that utilizes a boring device to reduce or amplify a gap of round about move-location in strong substances. Their study aimed at investigating the dull tool essentially with help of Finite factor exam. Right off the bat the dull device was displayed in Catia and the equal was added into the ANSYS for modular and auxiliary exam of present Tungsten carbide device and D2 metallic cloth tool. The result from their examination showed that the explicit condition the D2 metallic material should be taken into consideration for making drill holes.

Madhavan and Balasivanadha (2012) conducted an experimental investigation and analysis of thrust force in drilling of carbon fibre reinforced plastic composites using response surface methodology (RSM). Their study reported the effect of thrust force during drilling of 10mm diameter holes in 20mm thick Carbon Fibre Reinforced Plastic composite laminate using

HSS, Solid Carbide (K20) and Polycrystalline Diamond insert drills .The correlation model for drilling parameters considering thrust force and Response surface Methodology (RSM) revealed that it was good for thrust force prediction. The investigation revealed that the type of drill geometry affects the thrust force significantly followed by the feed rate and the speed.

1.1 Objectives of the Study

The specific objectives of the study were:

i To analyse the effect of drilling parameters on cutting force in CNC drilling of carbon-fibre reinforced composite (CFRC) polymer.

ii To analyse the effect of induced stress and strain on hole quality (delamination) when drilling CFRC polymer.

iii To determine optimal machining parameters (feed, spindle speed and cutting force) for the drilling operation of CFRC polymer.

2.0 MATERIALS AND METHODS

2.1 Materials

The material of the work piece used in carrying out this study is the carbon-fibre reinforced polymer composite (coir-bagasse hybrid polyester) composite. For drilling, the composite specimen was cut in square shape of 150mm by 150mm with thickness of 10mm.The experimental specimen (workpiece) is a soft material which has good mechanical and metallurgical properties.

The machining tool used was the High-Speed Steel tool drill bit (HSS) and HSS Cobalt tool single point cutting tool. Series of experiments were made by HSS and HSS Cobalt type twisted drills and each with three different point angles of 118º, 130º, and 135º respectively

The material properties of carbon-fibre reinforced polymer composite work-piece and the drilling tool specifications are presented in table 1 and 2 respectively.

Table 1 Material Carbon-Fibre Reinforced Polymer Composite Work-Piece.

Properties	Value
Thermal Coefficient of Expansion	$2.1 \times 10^{-6}\ K^{-1}$
Compressive Strength	570 MPa
Density	1.6 g/cm3
Shear Modulus	5 GPa
Shear Strength	90 MPa

Tensile Strength	600 MPa
Fibre Volume	50%
Modulus of Elasticity	70 GPa

(Source: Shim *et al*., 2002)

Table 2 Geometric Variables of the Machining Tool

Parameter	**Value**
Overall Length of tool (mm)	700
Shank diameter (mm)	50
Flute length (mm)	210
Number of flute	2
Flute diameter (mm)	50
Helix angle (degree)	75^o

(Shim *et al*., 2002)

2.2 Methods

I

The Taguchi method L9 orthogonal array was applied to design of experiment in this research work since the control factors are more than two.This method explores the concept of quadratic quality loss function and uses a statistical measure of performance called signal to noise (S/N) ratio (Akhyar *et al*., 2008).

II

The analysis of variance (ANOVA)/F-test was used to test the significance between the simulated and experimental results. The F-test is best used in cases where the hypothesis means of a normally distributed population all have the same standard deviation.

2.3 Drilling process analysis

Optimal drilling performance cannot be actualized without taking the following drilling parameters into consideration; Cutting parameters (spindle speed and axial feed), cutting conditions (dry, with coolant or lubricant), work-piece characteristics (material, geometry, structure etc.), fixturing configuration and the machine tool are to be considered as well in the drilling process analysis.

Ignoring the feed, the cutting speed at the periphery can be expressed as:

$$V = \pi . D . n \qquad (1)$$

Where D is the drill diameter. The axial feed, often simply referred to as "*feed*" is the tool advancement per revolution along its cutting path in mm/rev. The feed rate (or axial speed) $f_r = v_n$ is the speed at which the tool advances into the part in (mm/min), and is related to f through the spindle speed n by:

$$f_r = f . n \qquad (2)$$

The feed per tooth, ft (mm/rev) depends on axial feed (f) and the number of flutes

N [-], and is used to calculate the depth of cut (t_c).

$$f_r = \frac{f}{N} \qquad (3)$$

The feed rate (axial speed) is the input parameter provided to the machine tool.

The cutting force can be estimated using the equation specified by Madhavan & Balasivanadha, (2012).

$$Cutting\ Force = \frac{(Pe\ x\ 60\ \ x\ 10^3\ \ x\ Coeffcient\ of\ Efficiency)}{(Feed\ \ x\ Spindle Cutting\ Speed\ x\ \cos\alpha)} \qquad (4)$$

Where,

Pe = Power Energy of machine (2.238kW)

Coefficient of Efficiency = 0.75

α = Point angle

The analysis of hole quality (delamination) in terms of stresses and strains are shown in equations 5 to 7 (Johnson & Cook's,1983).

$$\sigma = (A + B\varepsilon_p^n[1 + Cln(\dot{\varepsilon}^*)][1 - (T^*)^m]) \qquad (5)$$

$$\bar{\sigma} = A + B\left(\varepsilon^{pl}\right)^n\left[1 + Cln\frac{\dot{\bar{\varepsilon}}}{\dot{\varepsilon}_0}\right]\left[1 - \frac{T - T_r}{T_m - T_r}\right]^m \qquad (6)$$

$$T^* = \begin{cases} 0; T < T_{room} \\ (T - T_{room})/(T_{melt} - T_{room}); T_{room} \le T \le T_{melt} \\ 1; T > T_{melt} \end{cases} \qquad (7)$$

(Johnson & Cook's ,1983).

Properly selection of the parameter levels to maximize optimal performance was achieved from Taguchi techniques and signal to noise ratio (S/N)

Summarized the levels from equations. 8, 9 & 10 respectively.

Nalbant et al. (2007)

(i) The nominal-the-better (NB)

$$\frac{S}{N_T} = 10 * log\left(\frac{\bar{y}^2}{s^2}\right) \qquad (8)$$

(ii) Larger-The-Better (LB)

$$\frac{S}{N_L} = -10\log\left(\frac{1}{y}\sum_{i=1}^{n}\frac{1}{y^{i2}}\right) \qquad (9)$$

(iii) The smaller-the-better (SB)

$$\frac{S}{N} = -10 * log\left(\frac{1}{y}\sum_{i=1}^{n}y^{i2}\right) \qquad (10)$$

But the larger the better was chosen for this research work.

$$Degree\ of\ \ Freedom(DOF) = [(L-1)x\ P]+1 \qquad (11)$$

2.4 Completely Randomized Design (CRD).

Completely randomized design is a basic single factor design, in this design the treatment (response parameters) are assigned completely at random so that each experimental unit has the same chance of receiving any one treatment. But CRD is appropriate only when the experimental material is homogeneous. CRD is utilised to analyse data when the following conditions are needed;

i. To determine whether the difference between the group means are statistically significant.
ii. To examine the group means.
iii. To compare the group means.
iv. To determine how well the model fits a given set of data.
v. To determine if your model fits the assumption of your data

Grand Mean $G = \frac{\mu_1+\mu_2+\mu_3......+\mu_n}{n}$ (12)

$$\text{Sum of Squares (SS)} = \sum_{i=0}^{n}(X_i - \bar{X})^2 \qquad (13)$$

Where: $X_i = i^{th}$ term

$\bar{X}$ = Grand mean

$$SS_{total=\sum x^2-CF} \quad (14)$$

$$Treatment\ \ SS = \sum\frac{T^2}{r} = \frac{T_1^2}{r_1} + \frac{T_2^2}{r_2} + \frac{T_3^2}{r_3} \dots \frac{T_n^{n+1}}{r_{n+1}} - CF \quad (15)$$

Correction factor (C.F) = $\frac{G^2}{n}$ (16)

$$Means\ Square\ error(MSE) = \frac{SS\ \ Error}{Df\ Error} \quad (17)$$

$$F - Calculated = \frac{Means\ Square\ treatment\ \ (MST)}{means\ Square\ error(MSE)} \quad (18)$$

3. RESULTS AND DISCUSSION

The carbon fibre reinforced composite (CFRC) polymer (workpiece Model) was prepared and geometry were after meshing generated, the equivalent cutting force ,stresses and strains was analyzed and simulated using Ansys. The results of these with HSS & HSS-Cobalt drill type at different speed levels, tool point angle, and feed rate engaged at 500rpm (261.6 m/sec) spindle speed. Eighteen holes were examined i.e 18 experimental runs and the results presented in table 3.

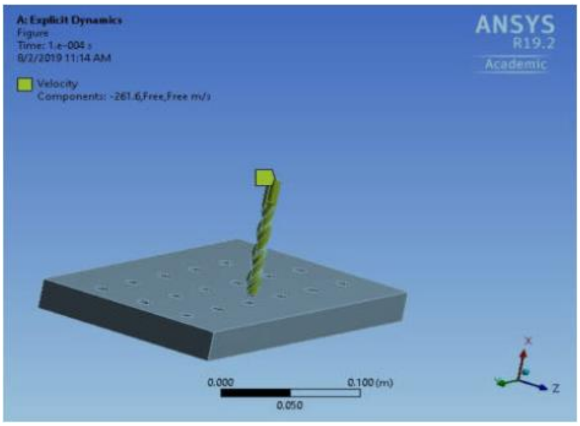

Figure 1 Initial Geometry before Meshing

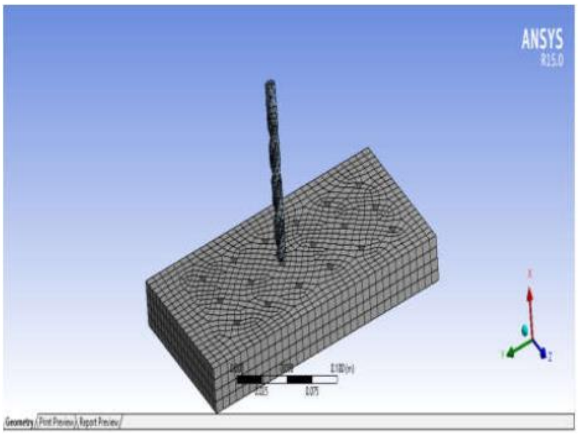

Figure 2 Geometry after Meshing

Table 3: Experimental Design Using L9 Orthogonal Array and Results.

Exp. No	Tool Geometry		Feed rate (mm/min)	Spindle speed (rpm)	Cutting Force (N)	Stress (x10^9) (N/m^2)	Strain
	Drill Type	Point angle (^{o})					
1	HSS	118	100	500	4.290	8.652	0.8627
2	HSS	118	200	1000	1.073	2.227	1.2091
3	HSS	118	300	1500	0.476	2.049	1.4171
4	HSS	130	100	1500	1.045	8.652	1.0091
5	HSS	130	200	500	1.567	5.301	1.2091
6	HSS	130	300	1000	0.226	3.106	1.4171
7	HSS	135	100	1000	1.424	7.713	1.2784
8	HSS	135	200	1500	0.475	4.372	1.2784
9	HSS	135	300	500	0.950	2.667	1.5154
10	HSS-CO	118	100	500	4.576	7.713	1.2784
11	HSS-CO	118	200	1000	1.144	1.667	1.5154
12	HSS-CO	118	300	1500	1.671	1.349	1.2704

13	HSS-CO	130	100	1500	1.114	7.713	1.2784
14	HSS-CO	130	200	500	1.671	1.665	1.5095
15	HSS-CO	130	300	1000	0.557	1.350	1.5154
16	HSS-CO	135	100	1000	1.519	7.521	1.2784
17	HSS-CO	135	200	1500	0.506	4.001	1.3154
18	HSS-CO	135	300	500	1.013	2.227	1.2784

High speed steel (HSS);High Speed Steel Cobalt(HSS-Cobalt)

Table 3. reveals the results of the cutting force of the drill tools on the carbon-fibre reinforced composite polymer work-piece for the nine (9) runs of experiments. The figure showed that the 10^{th} experiment using HSS-COBALT drill tool (experiment with point angle 118 degrees, feed rate at 100mm/min.

Table 4: Experimental results for signal ratio on cutting force

Experiment No.	Cutting Force, x10^9(N) F_{c1}	Cutting Force, x10^9(N) F_{c1}	Average $= \frac{F_{c1}+F_{c2}}{2}$	S/N Ratio
1	4.309	4.320	4.315	3.6938
2	1.071	1.091	1.081	4.2255
3	1.039	1.142	1.091	6.6509
4	1.047	1.056	1.046	4.5097
5	1.574	1.559	1.567	2.6153
6	0.228	0.234	0.231	1.1761
7	1.458	1.446	1.452	9.1196
8	0.485	1.471	0.978	0.6281
9	0.855	0.822	0.839	5.1927

10	4.576	4.497	4.537	1.2784
11	1.148	1.150	1.149	0.4154
12	1.671	0.509	1.090	1.2703
13	1.116	1.120	1.118	1.2784
14	0.584	0.641	0.613	1.5095
15	0.647	0.900	0.774	0.3152
16	1.023	1.041	1.032	1.2784
17	0.259	0.265	0.262	1.3251
18	0.923	0.917	0.920	1.2784

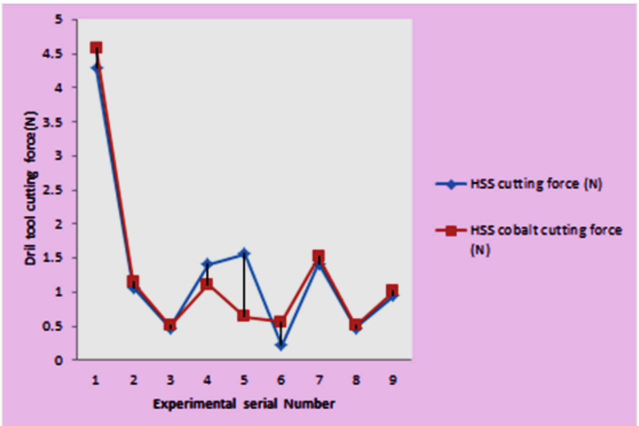

Figure 3: Cutting Force of the Drill Tools

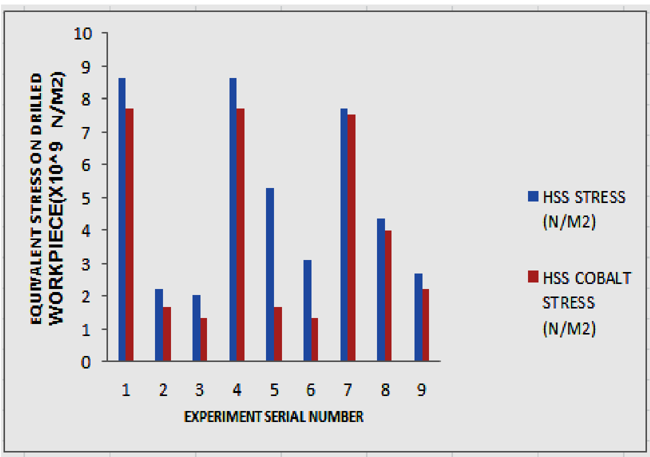

Figure 4: Equivalent Stress Developed on Drilled Polymer Workpiece

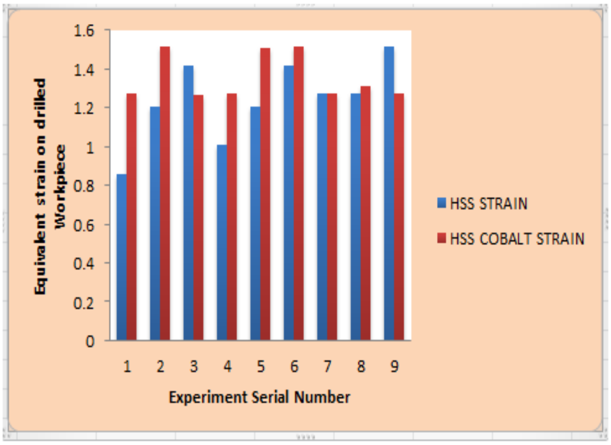

Figure 5: Equivalent Strain Developed on Drilled Polymer Workpiece

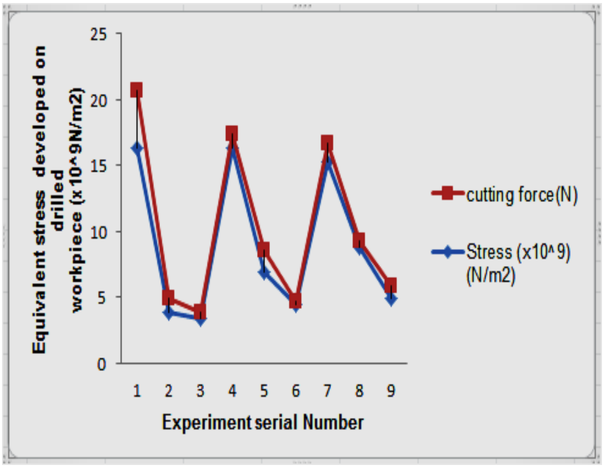

Figure 6: Stress Developed Against Cutting Force of HSS Drill Tool and HSS-Cobalt

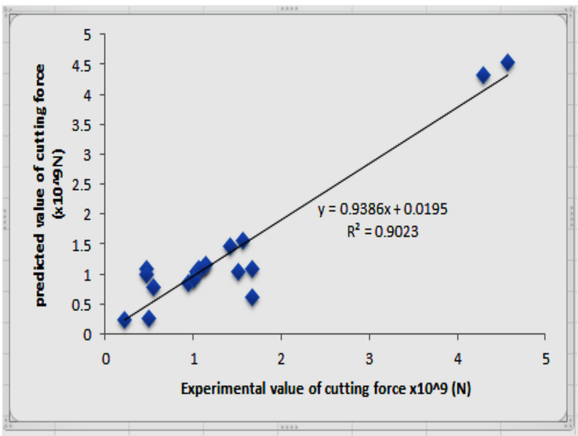

Figure 7: Scatter Plots of the Experimental and Predicted Values of Cutting Force on HSS and HSS-Cobalt Tool

3.1 Optimization of Result

The obtained results of equivalent stresses, strain and cutting force were optimized using single objective optimization tool called Taguchi method while Minitab16 was used for analyzing the experimental data.

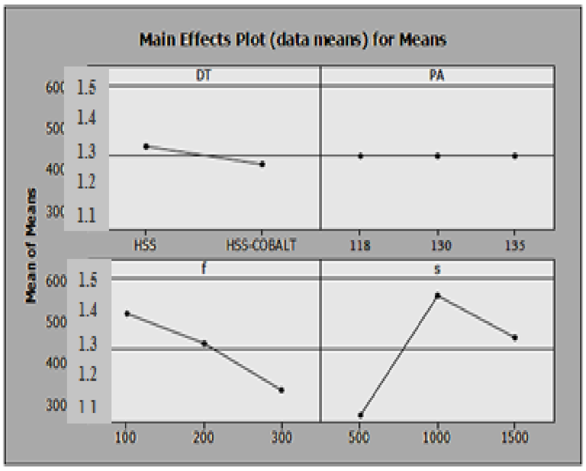

Figure 8: Main Effects Plots of Means for cutting Force Developed

The significant relationship between the experimental and simulated results of the experiment was done using ANOVA analysis (Complete randomized design techniques).

(i) From cutting force, the F-value calculated 3.02 was less than the F-value 4.35 tabulated at 5% confidence level which shows there was insignificant difference between the interactions of the control machining parameters used during experiment.

(ii) From equivalent Stress, the F-value calculated 186.7 was greater than the F-value 4.38 tabulated at 5% confidence level which shows that there was significance difference between the machining parameters used in the drilling process.

(iii) From equivalent Strain, the F-value calculated 1.79 was less than the F-value 4.38 tabulated at 5% confidence level which shows that there was insignificant difference between the machining parameters used in the drilling operation of CFRC polymer.

(iv)

4. CONCLUSION

The first objectives of this study which was to evaluate the effect of drilling parameters and tool geometry on cutting force in CNC drilling of carbon-fibre reinforced polymer composite was achieved from the ANSYS computer simulation as presented in Figure 1 which revealed using HSS-COBALT drill tool (10^{th} experiment with point angle 118 degrees, feed rate at 100mm/min. and spindle speed at 500rpm) produced the greatest cutting force at 4.578N when compared HSS tool (Ist experiment with point angle 118^0, feed rate 100mm/min, and spindle speed 500rpm) at 4.290N.

The second objective which was to determine an optimal machining parameter for the drilling operation of carbon-fibre reinforced polymer composite that enhances its quality and productivity. The ANOVA analysis results for signal to Noise ratio on cutting force with the contribution of each machining parameters in decreasing order are cutting speed with contribution of 57.8%, point angle with contribution of 5.7%, feed rate with contribution of 1.4%.

i. The tool geometry and cutting parameter that produces optimal results of the equivalent cutting force, stress and equivalent elastic strain exerted by the drilling tool on the work piece during a machining have been identified and should be adopted to control the tool deflection and improves hole quality integrity and productivity.
ii. This research can be extended by investigating the use of different diameter of drills and helix angles to improve productivity and performance when drilling CFRC Polymer.

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