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Influence on Thrust Force and Delamination for One Shot Drilling of Carbon Fibre Reinforced Plastic (CFRP)

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Abstract-- **The requirement of drilling process of Carbon Fibre Reinforced Plastic (CFRP) is vital in order to fulfil final assembly specifications. Despite the excellent mechanical properties of composites, they are hard to be machined due to its toughness. The damages such as peel-up and push-out delamination usually occur during its machining. To provide drilling induced delamination is a priority to reduce parts rejection and lead to waste in time and money. In this work, a comparative study of three geometries under different cutting conditions is presented. Application Taguchi's design of experiments for this experimental works increase the analysis reliability. Various penetration angle drilling also studied to determine the effect of thrust force and delamination. Thrust force was monitored during drilling tests, and delamination extension was quantified using image processing software. Results are processed using analysis of variance (ANOVA) then further presented by response surface graph showed that the best drill geometry, spindle speed and feed rate selection is fundamental to reduce delamination. The result obtained from the analysis shown delamination both for peel-up and push-out spread worse with increasing of drilling angle. Delamination factors are directly proportional with thrust force generated during drilling and increasing of thrust force will worsening the delamination damages. Straight flute drill is the best drill that generates lower thrust force thus reducing delamination effect compared with twist and dagger drill which on optimum feed rate and spindle speed parameter is 0.05 mm/rev and 4000 rpm, respectively.**

Index Term-- **cfrp; one-shot drilling; delamination; thrust force.**

1 INTRODUCTION

Drilling is the secondary machining those required for aircraft assembly processes[1]. One of the advantages of manufacturing carbon fibre reinforced plastics (CFRP) composite components is near to the final net shape, but drilling in dimensional tolerances specifications is still required[2]. CFRP is used widely in aircraft manufacturing especially for large aircraft structures by aircraft manufacturer attributed to its high strength to weight ratio, excellent mechanical properties, high and superior fracture toughness and ability to resist corrosion[3].

Drilling of composite materials inevitably to be associated with an abrasive characteristic and operational temperature generated during the process that leads to quality issues on drilling CFRP such as delamination, surface finish and hole error. The characteristic most related to machining parameters and drill bit geometry used explicitly for a particular drilling process [4]. Delamination is one of the defects that need to be avoided because drilled holes are used to attach components to other components using rivets that can lead to severe mechanical failure.

There are many approaches to evaluate the delamination on composites, and till now there was no resolution on delamination assessment standard. There was numerous evaluation of delamination factor by time. Conventional delamination factor (F_d) is firstly introduced by the ratio of the maximum diameter of the delamination area to nominal drilled diameter[5]. This calculation of delamination factor is widely used and most popular within researchers[6]–[13]. Delamination size is different from the radius of the delamination area and nominal hole[14]. Others delamination evaluation in the research are two-dimensional delamination (F_a) [15], damage ratio (D_{RAT}), adjusted delamination factor (F_{da}) [8], equivalent delamination factor (F_{ed}) [16], refined delamination factor (F_{DR}) [17], shape circularity (f) [10] and minimum delamination factor ($F_{d,min}$) [18]. For delamination evaluation in this research work, the delamination factor will use delamination factor equation will as in the next section [19].

A few of research has been conducted in order to compare the effects of various geometrical types or nominal diameter of drill bits for its optimum working machining parameters. As the primary influence factor to composites drilling damage, the studies on the geometry of drill bits for drilling CFRP application conducted by researchers. The comparison is mainly to compare the drill type geometrical factor that affects with drilled hole quality using on particular machining parameters. In addition to standard twist drill study, much particular design drill also compared to evaluate the competitiveness the drill design to the quality of drilled holes. Davim et al. [20] had studied helical and Brad & Spur drills. Grilo et al.[21] established the study of Spur, helical and four flute drill. Others unique design of drill bits are saw, stick, core and step-core drills by Hocheng [22], step and non-step drills by Tsao [23], and tapered, eight facet and two facet twist drills by Lazar et al.[24].

In this research work, the new study using a unique design for one shot drilling process of CFRP is presented. Twist drill, dagger drill and straight flute drill which commercially used by the aircraft manufacturer had been tested. Thrust force, peel-up delamination and push-out delamination were measured and analysed in different penetration angle drilling. The proper drill bit selection is an essential factor to achieve best-drilled hole quality demanded. Therefore, the interaction of thrust force generated and delamination damages occurred will be investigated in order to select the best drill types to reduce delamination during the drilling process.

2 METHODOLOGY

2.1 Material and Methods

The specimen of CFRP composite laminates used for experiment consist of 26 unidirectional plies. Each ply thickness is 0.125 mm making the total thickness of laminates is 3.25 mm. These laminates have stacking sequence of [45/135/90$_2$/0/90/0/90/0/135/45$_2$/135]s and at top and bottom of CFRP laminates have a thin layer of glass/epoxy fabrics of 0.08 mm to minimise peel-up and push-down delamination during the drilling process. The total thickness of the experimental specimen is 3.587 mm including base paint application. Throughout the curing process, the CFRP were compacted using a vacuum pump at controlled atmosphere condition. A mould for the laminate was prepared and placed inside the autoclave. The cure cycle consisted of raising the temperature to 180°C at the rate of 3°C/min and maintained for 120 minutes. Then the temperature was brought down to room temperature at the rate of 3°C/min. The whole cycle was carried out at the pressure of 700 kPa in an autoclave and evacuated in a vacuum bagging to 70 kPa. The nominal fibre volume fraction for specimen become 60 %. Three different drill bit geometry types with 6.35 mm and made from tungsten carbide (WC 90% & Co 10%) were used in this experiment as presented in Figure 1. The drilling trials were carried out using 6.35 mm diameter drill bits of three different types: twist drill, dagger drill and straight flute drill manufactured by Gandtrack Asia Sdn. Bhd. Summary of the drills for this experiment as in Table 1. The experiment was conducted on a 15kW DMU40 monoBLOCK® CNC machine. A backing plate was used to support the laminate and clamp together with a set of clamping plate specially designated for this experiment which was firmly held in between the workpiece and dynamometer to avoid any vibration effect and can influence thrust force measurement [25]. All drilling process was carried out in a dry condition without any coolant to prevent contamination between composite and coolant fluid. There also no pre-drilled hole was made in this experiment for thrust force measurement. Experimental setup for the experiment as shown as Figure 2. All trial for experiment uses new drill bits for all cases.

Table I
Drill bit geometrical features for a designed experiment

Features	**Twist**	**Dagger**	**Straight flute**
Point angle (º)	120	30	90
Helix angle (º)	11	0	0
Web thickness (%)	30	-	30
No. of flutes	4	2	4
No. of cutting edges	2	2	4

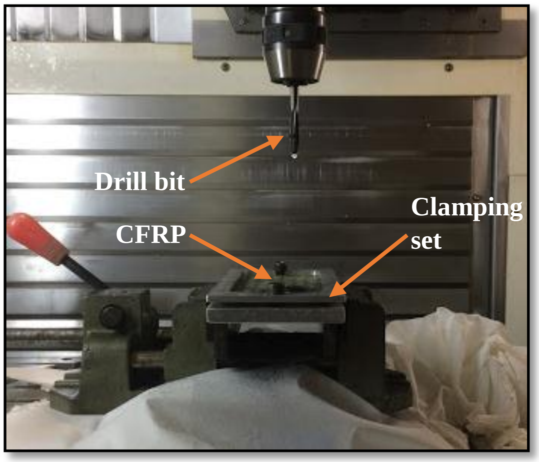


Fig. 2. Clamping set upper and beneath CFRP laminates panel to prevent vibration.

2.2 Taguchi Orthogonal Array (Design of Experiment)

Nowadays, the design of experiments already used widely in engineering analysis environment [26]. This method in many ways could reduce numbers of trial with better results depending on the selected technique chosen. Taguchi orthogonal array design technique is one of the designs of experiment techniques available. Taguchi design techniques could plan the experiments in a controlled way to execute the experiments with dedicated objectives. This experiment was conducted by Taguchi's method for four factors at three levels in consideration for the degree of the control factors observation as shown in Table 2. Three different types of experiments which is for three types of drill bits conducted using Taguchi orthogonal array L_9 (3^4). This method of Taguchi design more reliable and robust with dedicated to the number of trials with four columns at three levels which is related to four factors: drill types, drilling penetration angle (°), spindle rotation speed (rpm) and feed rate (f) for machining. Table 3 shows the Taguchi Orthogonal Array design scheme for the experiment. For each drilling process, three holes are drilled at 6.35 mm in diameter for each hole. Vertical axial penetration angle drilling executed to mimic manual drilling in the industry using a pneumatic/electrical-powered hand drill [27] to study an effect in term of thrust force, and delamination occurred during drilling. Operational of penetration angle drilling as shown in Figure 3.

Table II
Levels to the drill test factors assigned

Level		**1**	**2**	**3**
Drills type		1	2	3
Penetration angle	(°)	0	3	5
Feed rate	(mm/rev)	0.05	0.10	0.15
Spindle speed	(rpm)	1000	2500	4000

Drill types 1: Twist drill 2: Dagger drill 3: Straight flute drill

Table III
Plan of Taguchi's design of experiments orthogonal array

L_9 (3^4) Test	**Drill Types**	**Penetration Angle (º)**	**Feed Rate (mm/rev)**	**Spindle Speed (rpm)**
1	1	0	0.05	1000
2	1	3	0.1	2500
3	1	5	0.15	4000
4	2	0	0.1	4000
5	2	3	0.15	1000
6	2	5	0.05	2500
7	3	0	0.15	2500
8	3	3	0.05	4000
9	3	5	0.1	1000

Drill types 1: Twist drill 2: Dagger drill 3: Straight flute drill

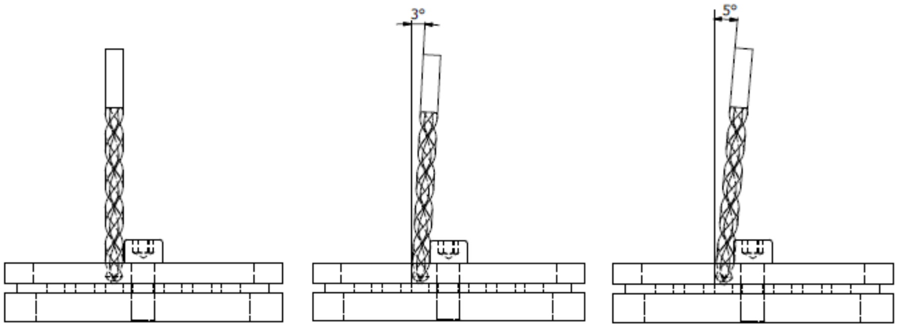


Fig. 3. Various penetration angle drilling

2.3 Experiment's Responses

2.3.1 Maximum thrust force

The results of thrust force values recorded using Kistler dynamometer type 5223A. The main concern of this experiment is to record the fluctuates of thrust force for same drilling condition with various drilling penetration angle. The output from dynamometer was processed by DynoWare software and visualised in the form of a graph for Z-axis of force. Figure 4 shows the region of interest in this experiment for maximum thrust force.

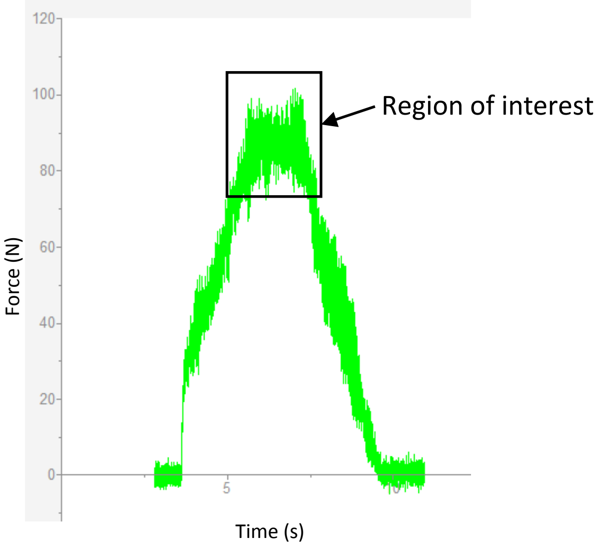


Fig. 4. Region of interest for maximum thrust force (i.e. twist drill)

2.3.2 Peel-up delamination and push-out delamination

Each drilled hole evaluated using Optical Microscope EMZ-Meiji equipped with a digital camera. Each drilled hole further processed using ImageJ software by JAVA with proper selection of brightness, contrast and noise to observe and measure delamination area. Figure 5 shows the delamination area for investigation. In this research work, the delamination factor equation is used to obtain the delamination factor (F_d) as in Eq.1[19]. The equation of delamination factor calculates the ratio of damage (delamination) area, A_d to the nominal drilled area, A [28] rather than the commonly used delamination factor (F_d), the ratio of the diameter of damage (delamination) area to a nominal diameter of the drilled hole. The observation will consist of peel-up delamination and push-out delamination.

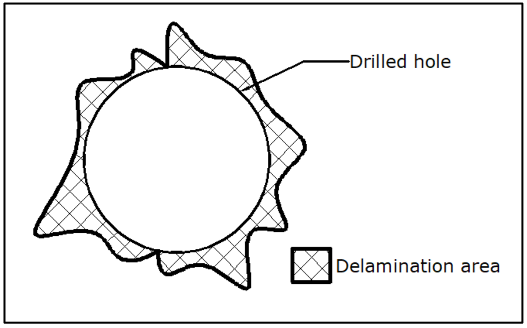


Fig. 5. Schematic diagram of geometric delamination parameters.

$$F_d = \frac{A_d}{A} \qquad (1)$$

Next, the results of the experiment were analysed with the analysis of variance (ANOVA) using Design Expert 10 software to find the contribution percentage of machining parameters influence to dedicated factors set. A set of experiments designed by Taguchi method using Design Expert 10 software. Taguchi design method was designed in order to investigate the relation between the factors parameters and responses. The software also was used for graphical analysis for the middle of factors level. The experiment data have also been analysed using Minitab 16 Statistical Software to obtain main effect plot for Signal to Noise (S/N) ratio in order to gain the effect of parameters to responses. S/N ratio on ANOVA is to identify the significant parameters based on the difference between mean and variation in order to evaluate the significance of the main factors. The evaluation is obtained by comparing mean square to the experiment errors estimation at specific confidence levels [29]. Based on Taguchi recommendation, mean response for each run analyse in the inner array. However, analysing variation using S/N ratio also suggested by Taguchi. In this study, S/N ratios with lower are the best was selected. The standard equation for S/N ratios was derived from quadratic loss function as Eq. 2;

-

Lower is the best : $\frac{S}{N} = -10\log(\frac{1}{N}\sum_{i=1}^{n}\frac{1}{y^2})$ (2)

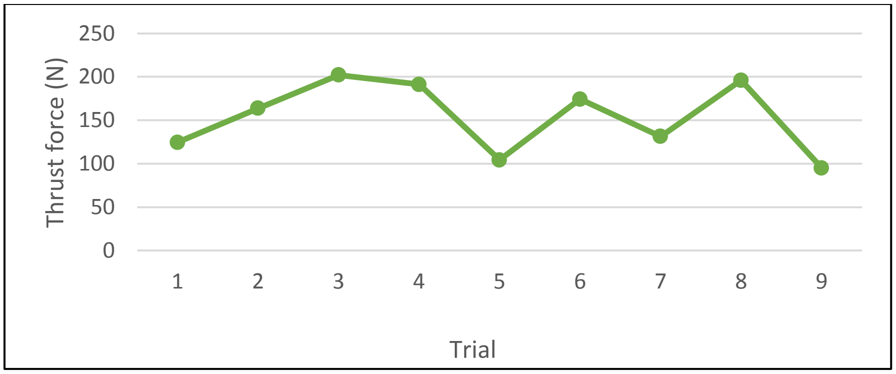
where $\tilde{y}$ is the average of observed data, s^2 is the variation of y, n is the number of observations, and y is the observed data[19].

3 RESULTS AND DISCUSSION

3.1 Measurement results and analysis of variance (ANOVA) for maximum thrust force (FT_{max}) and delamination.

Drilling thrust force values obtained using Kistler dynamometer type 5233A and processed by DynoWare software. The experiment test conducted with cutting parameters such as drill types, drilling penetration angle, feed rate and spindle speed influenced thrust force of drilling CFRP in various vertical axial penetration angle. Figure 6 shows results for the experimental test using Taguchi's design method. The results of the experiment on drilling CFRP have been further analysed by analysis of variance (ANOVA) as summarised in Table 4a, 4b and 4c for maximum thrust force, peel-up delamination and push-out delamination, respectively.

The ANOVA also signify the model posses the p-value is less than 0.05 which means the polynomial equation that generated able to represent the actual experimental condition between cutting parameters and the thrust force, peel-up delamination and push-out delamination. The model F-value of 51.96, 7.93 and 13.53 implies the model is significant for maximum thrust force, peel-up delamination and push-out delamination, respectively. There only 0.01% chance that a "Model F-Value" this large could occur due to noise. According to Table 5a, 5b and 5c, the developed model found to be the most suitable model with adjusted R^2 and predicted R^2 as much as 0.9225 and 0.9084 for thrust force, 0.7450 and 0.6510 for peel-up delamination and 0.7111 and 0.6585 for push-out delamination respectively. The predicted R^2 is in reasonable agreement with the adjusted R^2 for studied responses. The agreement specifies that the model obtained will be able to give a good estimate of the response of the system in the experimental range studied. The adequate precision was also found to be 19.508 for thrust force, 6.867 for peel-up delamination and 11.162 for push-out delamination. "Adeq Precision" measures the signal to noise ratio. A ratio higher than four is considered to be desirable.



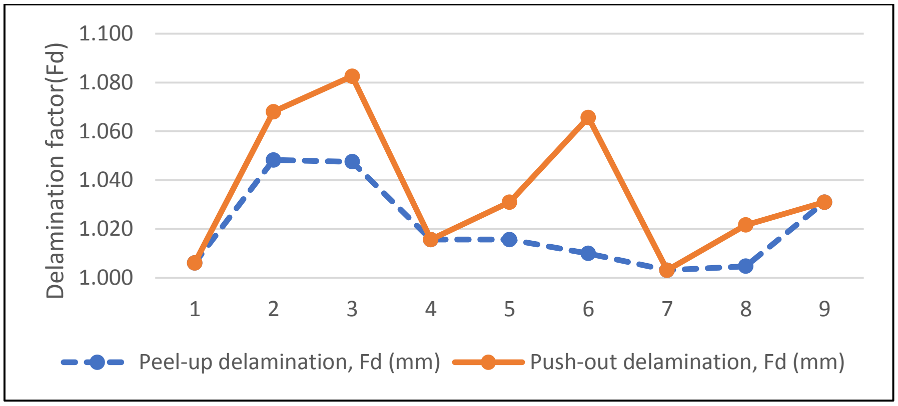


Fig. 6. Experiment results of thrust force and delamination factor.

Table IVa
ANOVA for the response surface reduced quadratic model for thrust force

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	39647.83	5	7929.57	51.96	< 0.0001	significant
A-Drill type	*2319.26*	*1*	*2319.26*	*15.20*	*0.0008*	
B-Angle	*309.77*	*1*	*309.77*	*2.03*	*0.1689*	
C-Spindle Speed	*1635.92*	*1*	*1635.92*	*10.72*	*0.0036*	
D-Feed rate	*35264.60*	*1*	*35264.60*	*231.10*	*< 0.0001*	
A^2	*118.28*	*1*	*118.28*	*0.78*	*0.3886*	
Residual	3204.50	21	152.60			
Lack of Fit	*286.65*	*3*	*95.55*	*0.59*	*0.6298*	*not significant*
Pure Error	*2917.86*	*18*	*162.10*			
Cor Total	42852.33	26				

Table IVb
ANOVA for the response surface reduced quadratic model for peel-up delamination

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	8.107E-003	7	1.158E-003	7.93	0.0002	significant
A-Drill type	*2.240E-003*	*1*	*2.240E-003*	*15.33*	*0.0009*	
B-Angle	*2.493E-003*	*1*	*2.493E-003*	*17.07*	*0.0006*	
C-Spindle Speed	*1.802E-003*	*1*	*1.802E-003*	*12.34*	*0.0023*	
D-Feed rate	*8.134E-004*	*1*	*8.134E-004*	*5.57*	*0.0291*	
AB	*9.687E-004*	*1*	*9.687E-004*	*6.63*	*0.0185*	
BC	*9.918E-004*	*1*	*9.918E-004*	*6.79*	*0.0174*	
A^2	*2.616E-003*	*1*	*2.616E-003*	*17.90*	*0.0005*	
Residual	2.775E-003	19	1.461E-004			
Lack of Fit	*3.132E-005*	*1*	*3.132E-005*	*0.21*	*0.6558*	*not significant*
Pure Error	*2.744E-003*	*18*	*1.525E-004*			
Cor Total	0.011	26				

Table IVc
ANOVA for the response surface linear model for push-out delamination

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	6.392E-003	4	1.598E-003	13.53	< 0.0001	significant
A-Drill type	*1.754E-003*	*1*	*1.754E-003*	*14.86*	*0.0009*	
B-Angle	*3.672E-003*	*1*	*3.672E-003*	*31.10*	*< 0.0001*	
C-Spindle Speed	*6.676E-004*	*1*	*6.676E-004*	*5.65*	*0.0265*	
D-Feed rate	*2.980E-004*	*1*	*2.980E-004*	*2.52*	*0.1264*	
Residual	2.597E-003	22	1.181E-004			
Lack of Fit	*7.590E-004*	*4*	*1.898E-004*	*1.86*	*0.1618*	*not significant*
Pure Error	*1.838E-003*	*18*	*1.021E-004*			
Cor Total	8.989E-003	26				

Table Va
R-squared analysis for response surface in thrust force

Std. Dev.	12.35	R-Squared	0.9252
Mean	153.62	Adj R-Squared	0.9074
C.V. %	8.04	Pred R-Squared	0.8706

Table Vb
R-squared analysis for response surface in peel-up delamination

Std. Dev.	0.012	R-Squared	0.7450
Mean	1.02	Adj R-Squared	0.6510
C.V. %	1.19	Pred R-Squared	0.4853

Table Vc
R-squared analysis for response surface in push-out delamination

Std. Dev.	0.011	R-Squared	0.7111
Mean	1.06	Adj R-Squared	0.6585
C.V. %	1.02	Pred R-Squared	0.5672

Referred to ANOVA results in Table 4a, 4b and 4c, the statistical significance of terms on thrust force are A, C and D, on peel-up delamination are A, B, C, D, AB, BC and A^2, and on push-out delamination are A, B, and C which the confidence level is less than 0.05. From Figure 6, the normal probability plot indicates the residuals follow a normal distribution for experiment response data.

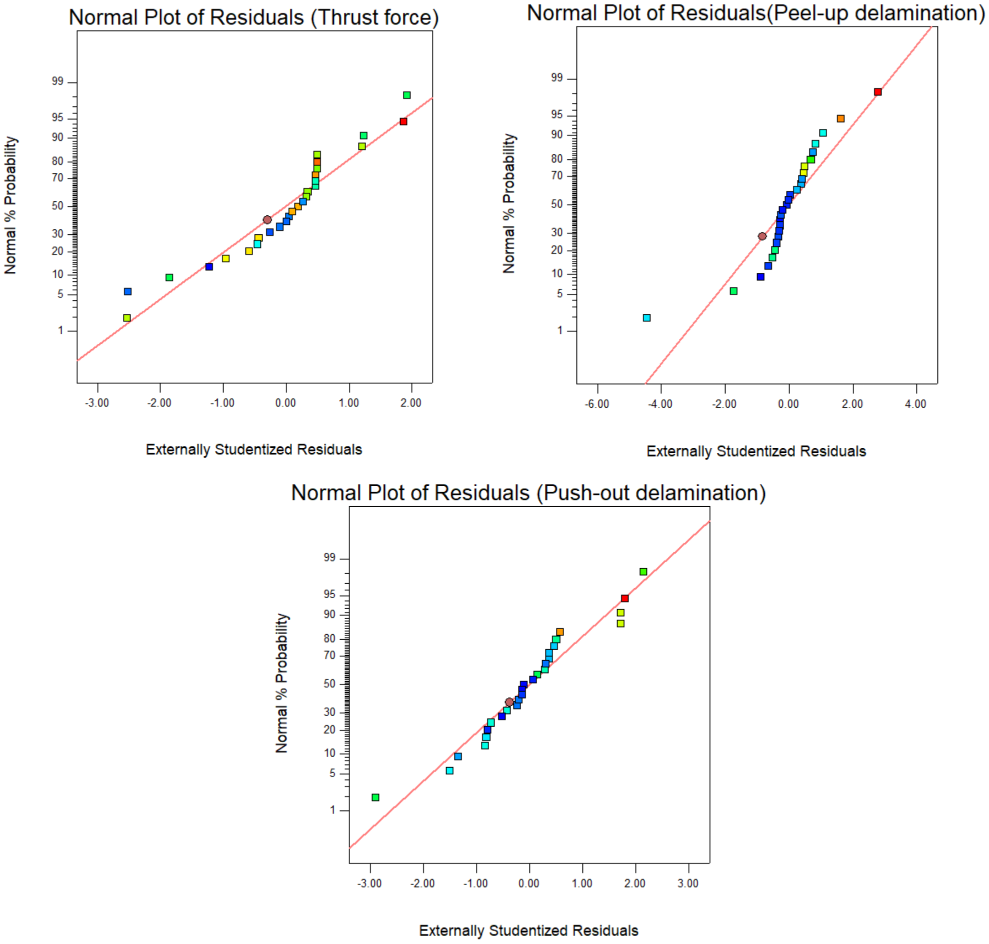


Fig. 6. Experiment data normal plot of residual graph

3.2 Thrust force analysis

The thrust force is an essential role in drilling CFRP composites. Thrust force factor is effect drilled hole quality, i.e., delamination and drilled hole wall surface roughness[30]. Figure 7 shows the maximum thrust force main effects plot for S/N ratios. Straight flute drill bit contributes the lowest thrust force compared with twist drill and dagger drill. In Table 1 above, the straight flute has four cutting edges compared with others that have two cutting edges which may cut the composites laminates easily. Numbers of cutting edges also influence thrust force generated, due to this reason lower thrust force observed for straight flute drill[31].

From Figure 7 and Table 8, the most influential factor on thrust force is feed rate. From F-value in ANOVA statistical result, feed rate contributing 89% of parameters influence. Drill types, spindle speed and drilling penetration angle contributing 6%, 4% and less than 1% respectively. From the observation on response surface graph in Figure 8, that as a feed rate increase, thrust force also increases, however, thrust force will decrease with increasing spindle speed. Dhiraj and K.K Sigh found the same observation in thrust force response [31]. The feed rate was a dominating factor that influences thrust force measurement. Spindle speed is contributing a slight decrease in thrust force when spindle speed is increasing. Drilling penetration angle contributes to increasing thrust force when the angle is not perpendicular with the workpiece. Straight flute generates the lowest thrust force due to four cutting edges were in contact with CFRP during cutting process compared only two of cutting edges of twist drill and dagger drill. A higher number of cutting edges with contact with the workpiece led to higher material cutting and decreased thrust force generated.

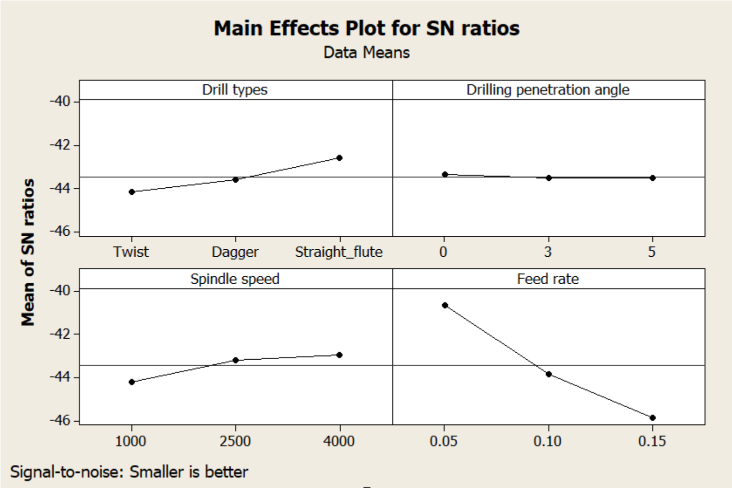


Fig. 7. Main effect for S/N ratio for FT_{max}

Table VI
Response for Signal to Noise Ratios (Smaller is better) for FT_{max}

Level	Drill types	Drilling penetration angle	Spindle speed	Feed rate
1	-44.15	-43.34	-44.22	-40.64
2	-43.61	-43.51	-43.18	-43.8
3	-42.60	-43.52	-42.96	-45.88
Delta	1.55	0.18	1.26	5.23

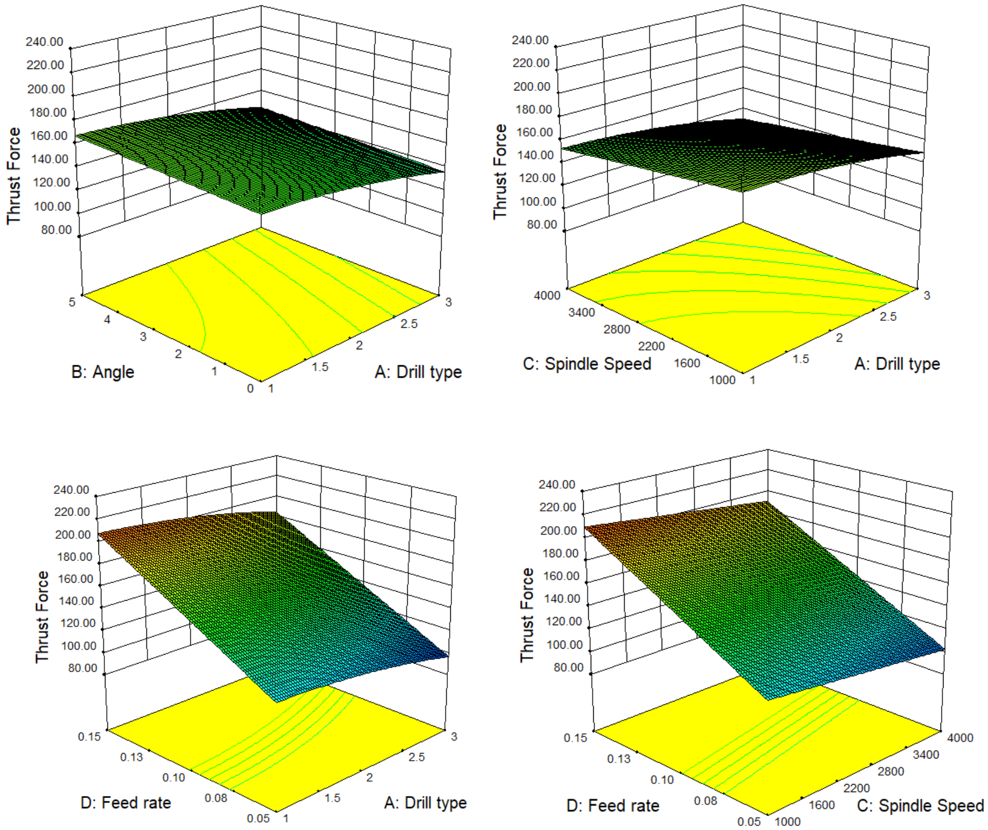


Fig. 8. Effect of parameters on maximum thrust force (FT_{max})

3.3 Peel-up delamination analysis

Delamination is the severe damage occurred during the drilling process of composites and can lead to parts rejection. The inlet drilled holes were observed using an optical microscope, and the delaminated area is measured by ImageJ processing software. The delamination factor is calculated using Eq. 1. Figure 9 shows the processed delaminated area for peel-up delamination. Figure 10 and Table 7 show the peel-up delamination main effects plot for S/N ratios. Straight flute drill bit contributes the lowest peel-up delamination factor (F_d) compared with twist drill and dagger drill.

Based on ANOVA results, F-value assigns the contribution influence for each main effect factor to peel-up delamination response. Penetration angle contributes the most significant influence percentage in peel-up delamination, with 34% of parameters influence. Then drills type also play the leading role of influence which contributing 30% of parameters influence. Spindle speed contributes 25%, and the feed rate contributes 11% of the influence of peel-up delamination. Figure 11 shows the response surface for peel-up delamination damage. Straight flute drill to record the lowest peel-up delamination occurrence in any parameters. In various penetration angle drilling, twist drill exhibits decreasing of thrust force when the penetration angle is increasing. However, dagger drill and straight flute drill act opposed. Also observed from the experiment analysis, peel-up delamination increase with increasing spindle speed and increasing feed rate. This finding coincides with studies carried out by Rajakumar et al. [32]. Drilling penetration angle contributing a nominating factor of thrust force due to the force will concentrate at below the drill slanting area thus maximise the damage to a specific area rather than distribute equally to the workpiece.

Composite materials, cutting parameters and tools are significant contributors to peel-up delamination. Peel-up delamination occurred at the time the drill bit tip strike the first ply of composite materials [33]. Chisel edge of the drill bit pushes the top of the composite ply and the delamination increase with orthogonal rake angle to take place towards plies cutting. The chips produced is turned backwards of the tool flank surface. The thrust force and torque generated from load pushed towards drilling increase delamination damages, however bonding strength of reinforcement and matrix materials resist the delamination phenomena[34]. In this experiment, the CFRP with thin woven composites laminate at the top and the bottom surface of CFRP reduce the delamination due to localised peel force is higher than allowable for ply delamination.

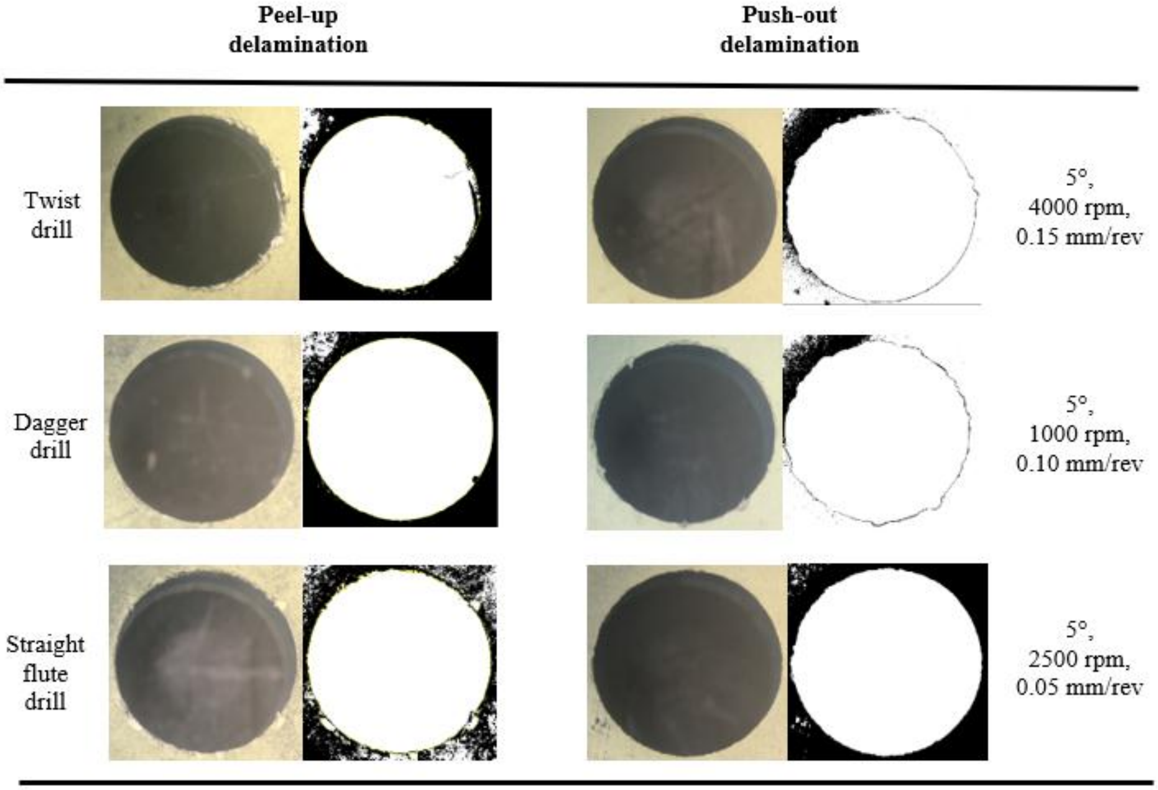


Fig. 9. Image processing for peel-up and push-out delamination.

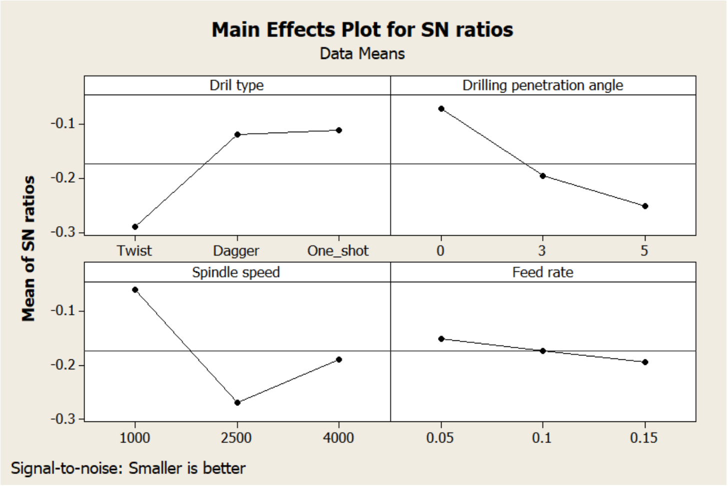


Fig. 10. Main effect for S/N ratio for peel-up, F_d

Table VII
Response for Signal to Noise Ratios (Smaller is better) for peel-up F_d

Level	Drill types	Drilling penetration angle	Spindle speed	Feed rate
1	-0.28941	-0.07152	-0.06019	-0.15101
2	-0.11876	-0.19547	-0.27014	-0.17437
3	-0.11121	-0.25240	-0.18905	-0.19401
Delta	0.17820	0.18088	0.20995	0.04300

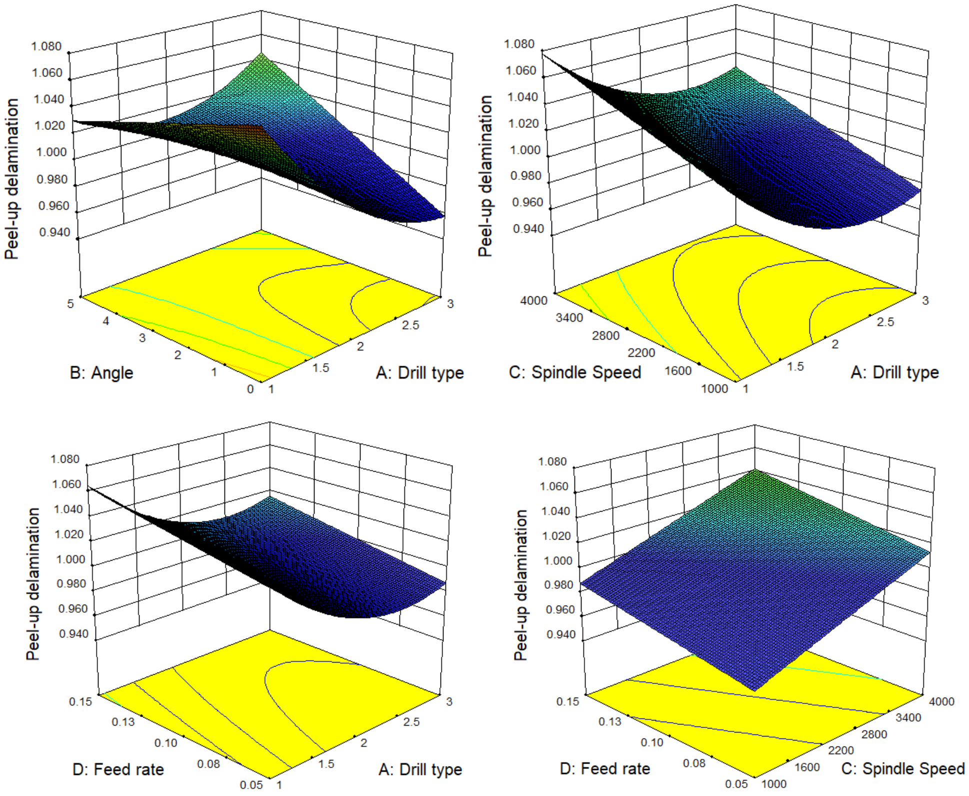


Fig. 11. Effect of parameters on peel-up delamination (F_d)

3.4 Push-out delamination analysis

A processing method for the exit drilled holes are the same method as peel-up delamination at upper hole section. Figure 9 shows the delaminated area for push-out delamination after been processed by Image-J software program. Figure 12 and Table 8 show the push-out delamination main effects plot for S/N ratios. Straight flute drill bit contributes the lowest delamination factor (F_d) for push-out delamination compared with twist drill and dagger drill.

Based on ANOVA results, F-value assigns the contribution influence for each main effect factor to push-out delamination response. Penetration angle, drill types, spindle speed, and feed rate contributes to push-out delamination with 57%, 27% 10% and 5% respectively. Hence, the drilling penetration angle contributes the highest influence to delamination factor. From Figure 13 that show response surface of parameters effects to push-out delamination also indicate similar best drill type is straight flute drill to record the lowest push-out delamination occurrence in any parameters yet shown by peel-up delamination. Increasing spindle speed and feed rate will increase push-out delamination. Some of the previous research also found that feed rate is the nominating factor which influences delamination[28][35]36]. The push-out delamination also observed increase with increasing the penetration angle and has severe delamination than peel-up. This is because of the drill approaches to the end of laminates, which have a resistance of deforming on the smaller undrilled thickness of the composite. Push-out delamination arises before the tool completely penetrate the composite when the loads apply beyond the interlaminar load's strength[37].

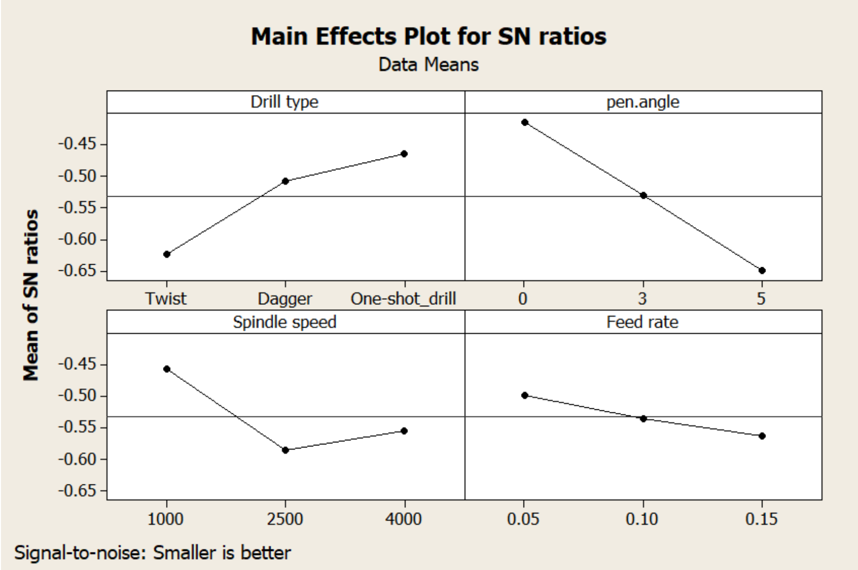


Fig. 12. Main effect for S/N ratio for push-out, F_d

Table VIII
Response for Signal to Noise Ratios (Smaller is better) for push-out F_d

Level	Drill types	Drilling penetration angle	Spindle speed	Feed rate
1	-0.6244	-0.4150	-0.4558	-0.4978
2	-0.5079	-0.5311	-0.5859	-0.5349
3	-0.4638	-0.6500	-0.5544	-0.5634
Delta	0.1606	0.2351	0.1301	0.0655

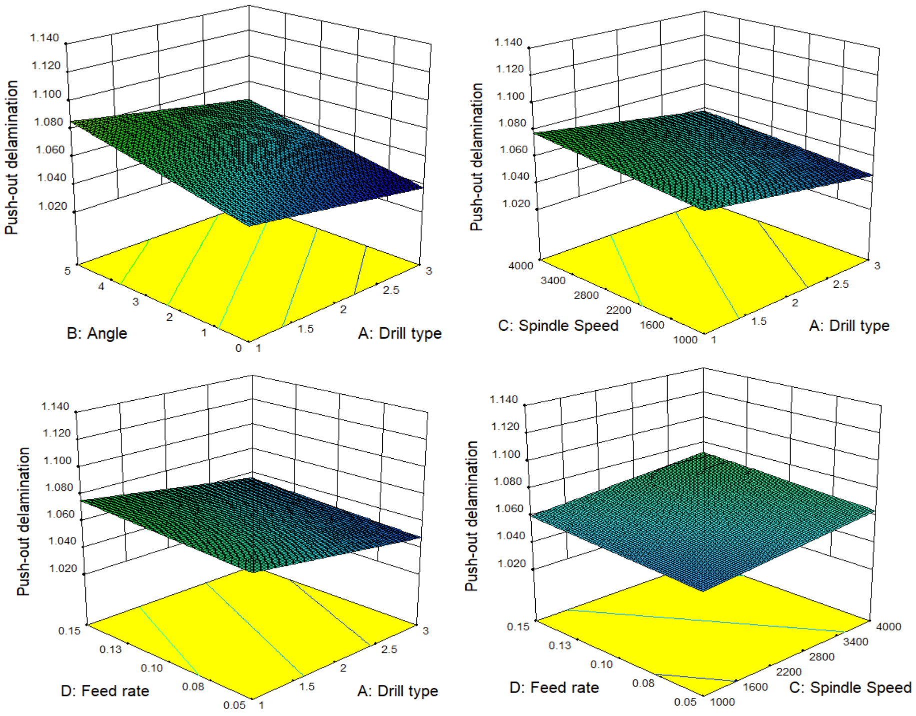


Fig. 13. Effect of parameters on push-out delamination (F_d)

4 CONCLUSION

This paper discussed the effect of various drill bits, drilling penetration angle and cutting parameters using application of the Taguchi design method on thrust force and delamination of CFRP materials. From the present study conducted, the following conclusions can be derived:

- i. The experimental results analysis is carried out using Taguchi's orthogonal array design method and analysis of variance (ANOVA) to verify the factors contribution of the selected response. Response surface graph generated is used to obtain the best parameters on thrust force and delamination.
- ii. Thrust force increases at a high feed rate and lowering spindle speed. Drilling penetration angle does not significantly contribute to thrust force. A slight increment of thrust force is observed when slant drilling of CFRP surface.
- iii. Push-out delamination at exit drilled hole showed a severe condition than peel-up delamination at entry drilled hole.
- iv. Both peel-up and push-out delamination are increasing at a higher feed rate and spindle speed. Slant drilling on CFRP surface caused higher delamination damage.
- v. Increasing feed rate caused higher thrust force generated and contributes to more severe delamination damage.
- vi. Based on ANOVA results, straight flute drill is the best drill type as compared with dagger drill and twist drill on thrust force and delamination damage (optimum parameters: penetration angle = 0º, feed rate = 0.05 mm/rev, and spindle speed = 4000 rpm).
- vii. This research has also proved that the straight flute drill can be further optimised in term of the drill geometrical design to achieve the best performance in drilling.

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