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Optimization of CFRP Micro Drilling Parameter using 2-Level Factorial Method Towards Thrust Force

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Abstract*: *Carbon Fiber Reinforced Polymer (CFRP) is extensively used in aircraft and automotive industries due to it exceptional material properties such as high strength to weight ratio and corrosion resistance. Nevertheless, micro drilling process of CFRP material poses various challenge as it has irregular material properties along the structure. High cutting force which lead to poor hole quality is one of the issues that always occur when drilling this material. Hence, the understanding on the relationship between process parameter and material behavior is vital to achieve optimum performance of machining process. The experiment was carried out using 2-level factorial design with variable spindle speed range of 8,000 – 12,000 rpm and feed rate range of 0.01-0.015 mm/rev. Micro drill bit with diameter of 0.9 mm was used and new fresh drill were used for every run to avoid tool wear effect. As a result, lower thrust force of 6.3742 N is obtained from the combination of spindle speed 10k rpm and feed rate 0.0125 N. Therefore, it can be concluded that, optimum parameter falls between the range of 8,000 – 12,000 rpm of spindle speed and 0.01-0.015 mm/rev of feed rate. Validation of the optimum parameter suggested from 2-level factorial which are 8,000 rpm and 0.01 mm/rev is executed. The final result obtained shows 4.5% of error from targeted value and this result is absolutely acceptable and portray the reliability of the experiment.

Keywords* : *CFRP, factorial, micro drilling, thrust force

I. INTRODUCTION

Fiber-reinforced polymer (FRP) composites were explored as the substitution to the metal materials in the mid of 1950s. This is because, metal have high propensity to rust which can easily cause the major defect in part produced. The drilling of hole is necessary to provide the join between different FRP components due to the FRP consists of multi-layer plies to form a composite laminate [1].

In the other hand, most of the high technology industries such as aerospace, electronics, medicine and automobiles are developing rapidly and the design of products become smaller, cheaper and faster as all of these factors are being consumer choice. Therefore, the application of micro drilling has been increase in the industry in order to drill the micro size of the hole diameter [2]. There is no specific definition for the micro drill however, researcher generally define that the drilling process with drills bit diameter in between 1μm and 1mm and the aspect ratio greater than 10 [3].

The condition of the cutting tool gives high impact on the sensitivity of the thrust force during machining process. As the tool wear increase, the thrust force starts to change its behavior [4]. As CFRP has inhomogeneity of material properties along the composite layer lead to fluctuate distribution of machining force among the plies that can cause defects in internal structure such as delamination and uncut fiber [5]. Fig. 1 shows the image of uncut fiber on the drilled hole of CFRP laminates. This defect lead to inaccurate dimension of drilled hole which require major and fine finishing that can cost extra money and time consuming.

Figure 1: Image of uncut fiber under microscope

Hence, the tool life and quality of the drilled hole can be improved by selecting the optimum cutting parameter which can minimize the cutting force during machining [6]. In order to control drilling-induced damage while drilling FRP material, force and temperature are the main factor need to be considered [7].

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The machine feed rate contribute higher impact on thrust force compared to the cutting speed and it exposed a significant variation throughout the rotation of the drill [8].

This research focused on the optimization of thrust force during micro drilling process using 2-level factorial method since the factor involved is only spindle speed and feed rate. The reliability of the experiment design was proof by ANOVA analysis which require P-value has to be less than 0.0500 to achieve significant model. Optimization of parameter can be achieved when all the models are significant otherwise the design of the experiment need to be revisited. Coded equation is described in discussion section for prediction of thrust force when applying other machining parameter in order to avoid higher thrust force produced which can cause rapid tool wear.

II. METHODOLOGY

A. Workpiece and Cutting Tool

The CFRP laminates in Fig. 2 is used as a workpiece with the dimension of 184 mm x 86 mm and maximum thickness of 3.8 mm. It was manufactured by Hexcel© in accordance to AS4 Carbon Fiber and epoxy matrix with 57% nominal fiber volume [9]. The laminates consist of 26 unidirectional pre-impregnated plies. It has stacking sequence of $[45/135/90_2/0/90/0/90/0/135/45_2/135]$s.

High performance two flutes micro-drills in Fig. 3 with 0.9 mm diameter made from solid carbide and coated with titanium aluminum nitride, TiAlN with 130° points angle were used. The maximum drilling depth is 9.2 mm. Minimum spindle speed recommended from supplier is 8,000 rpm to ensure the drill bit will not easily broken during machining. For every run, new fresh drill bit was employed.

Figure 2: Carbon Fiber Reinforced Polymer (CFRP) laminates

Figure 3: Cutting tool D0.9m TiAlN coated solid carbide

B. Experimental Setup

The drilling experiments were carried out on 3-axis router machine MDX-540 with the spindle speed up to 12,000 rpm and ensure low round out value of spindle. The cutting parameter were used during initial experiment is tabulated in Table 2. From the initial experiment, the least significant parameter was removed to narrow down the range of parameter for optimization purposed. Then, the optimum range was deployed to 2-level factorial method to find the most optimum parameter to achieve lower thrust force.

The special designed holding fixture was fabricated in order to install the dynamometer underneath the workpiece during experiment. This fixture was mounted on the dynamometer which provided the safety gap between workpiece and dynamometer to prevent damage on dynamometer. All experiments of drilling were carried out in a dry condition which is without coolant to prevent contamination between composite and coolant fluid. In addition, there was no pre-drilled hole made in this experiment for thrust force measurement. Experimental set up is shown in Fig. 4.

Table 2. Cutting parameter

Run	Spindle Speed (rpm)	Feed Rate (mm/rev)
1	8,000	0.001
2	8,000	0.01
3	8,000	0.015
4	10,000	0.001
5	10,000	0.01
6	10,000	0.015
7	12,000	0.001
8	12,000	0.01
9	12,000	0.015

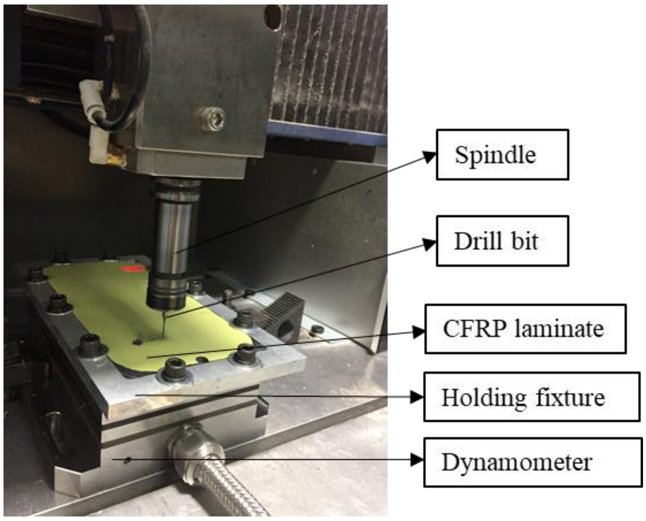


Figure 4: Experimental setup

C. Thrust Force Measurement

Thrust force value was captured by 3-axis Kistler 5233A1 dynamometer during the drilling process. Real time result was displayed by Dyno Ware software along the experiment as per Fig. 5. According to real time data acquisition, any noise or unreliable data can be detected earlier and the machine can be stop immediately. It can prevent excessive material and cutting tool use. The dynamometer detected 3-axis of force which are labelled as FX, Fy and Fz while Fx is the force acting on x-axis, Fy is the force acting on the y-axis and Fz is the force acting on the z-axis or we called it thrust force . For each CFRP composite panel, 20 of holes were drilled then the average of thrust force was measured from 1st to 20th hole.

The actual force exerted during the drilling process was obtained by removing the initial force acting on the dynamometer due to the installation of the holding fixture and workpiece.

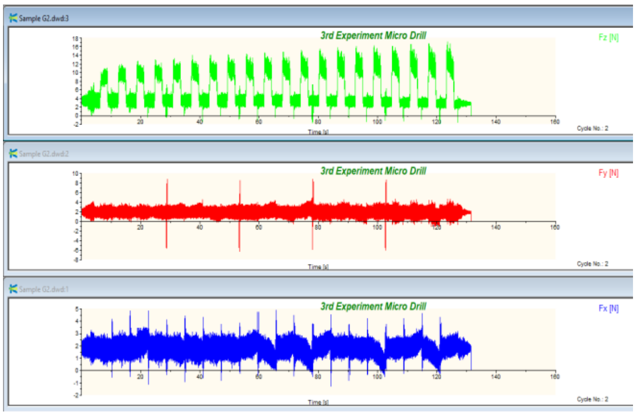


Figure 5: Real time data acquisition from Dyno Ware

D. Optimization and Design

After screening the initial experiment results, feed rate of 0.001 mm/rev was eliminated as it provided higher thrust force for all the combination with the spindle speed of 8k – 12k rpm. Hence, the optimum range for feed rate became narrow down to 0.010 – 0.015 mm/rev. Optimization of parameter was obtained using 2-level factorial method with number of factors of 2^2 designed with one block and 5 center points. There were 9 runs in total for this type of design. The design of experiment for 2-level factorial is shown in Table 2.

Table 2: 2-level Factorial Design

Std	Run	Factor 1: Spindle Speed (rpm)	Factor 2: Feed Rate (mm/rev)
8	1	10000.00	0.0125
3	2	8000.00	0.0150
2	3	12000.00	0.0100
9	4	10000.00	0.0125
6	5	10000.00	0.0125
5	6	10000.00	0.0125
7	7	10000.00	0.0125
4	8	12000.00	0.0150
1	9	8000.00	0.0100

III. RESULTS AND DISCUSSION

The main result of the experiment was thrust force which is Fz. Raw thrust force data from the 2-level factorial experiment were collected by Dyno Ware software then been analyzed using 2-level factorial method. Fig. 6 illustrated the normal plot of residuals from the result obtained. Normal probability plot shows that residues are deviated significantly which is mirroring on the best line.

Compared the actual result with predicted as per Fig. 7, there is no significant deviated of the data observed from the expected value. The data lies between the expected range and no outlier data is found. That is mean, the experiment is carried out with minimal amount of noise which is not affecting the result of the test.

In addition, for preliminary evaluation of result the ANOVA method was used. Table 3 explained the sensitivity of the result analyzed using ANOVA. The Model F-value of 31.50 implies the model is significant. There is only a 0.30% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant.

In this case B, AB are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. Therefore, the thrust force is strongly sensitive to the change of feed rate. The selection of feed rate must be taken as the first priority to ensure the results obtained is accurate. There is low sensitivity of thrust force towards spindle speed. The low sensitivity might be due to the smaller range of spindle speed tested. The variance analysis elaborated the impact of the input parameters on the thrust force value.

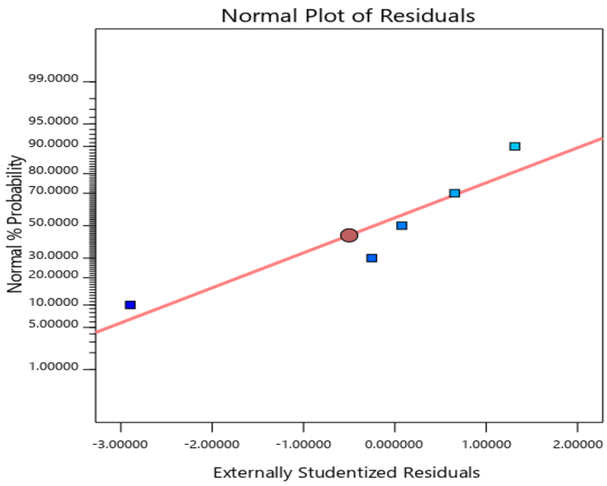


Figure 6: Normal plot of residuals

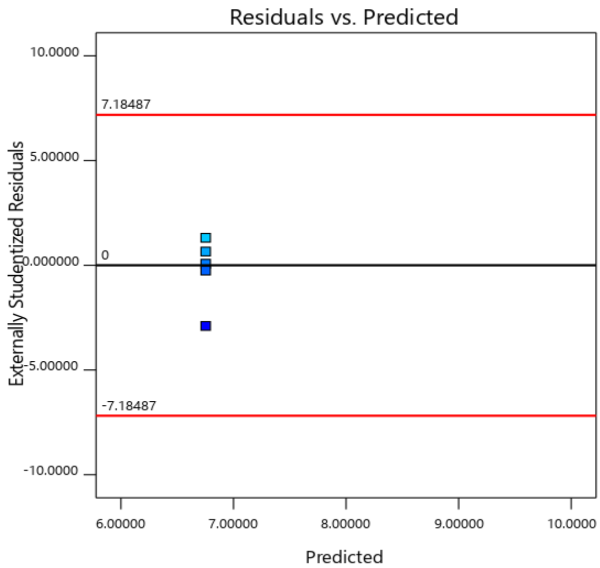
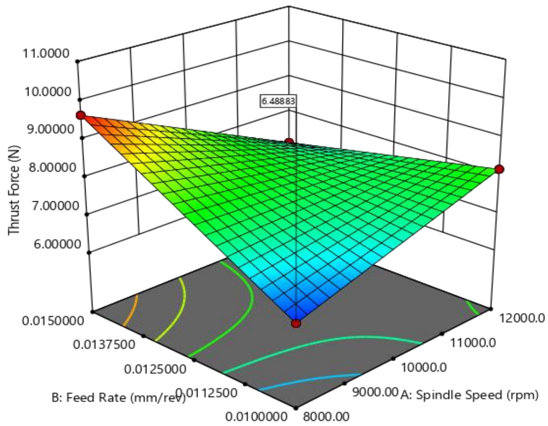


Figure 7: Residual vs. Predicted

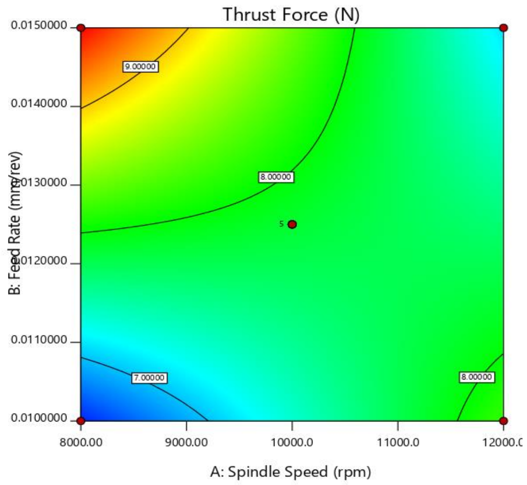
Table 3: Analysis of variance results

Source	Sum of Square	df	Mean Square	F-value	p-value	
Model	5.75615	3	1.91872	31.50149	0.00305	significant
A- Spindle Speed	0.17959	1	0.17959	2.94848	0.16109	
B- Feed Rate	1.08024	1	1.08024	17.73534	0.01357	
AB	4.49632	1	4.49632	73.82064	0.00101	
Curvature	2.70740	1	2.70740	44.45006	0.00263	significant
Pure Error	0.24364	4	0.06091			
Core Total	8.70718	8				

Fig. 8 below illustrated the 3D surface and contour plot of thrust force to comprehend the general trends easily. The lower thrust force of 6.4888 N is captured at the combination of spindle speed of 8,000 rpm and feed rate of 0.010 mm/rev. Therefore, this combination is the optimum parameter for the lower thrust force. Meanwhile, higher thrust force of 9.6486 N is detected at the combination of spindle speed of 8,000 rpm and feed rate of 0.015 mm/rev. Both results show that, the spindle speed provide least impact on the sensitivity of the thrust force compare to the feed rate.



(a)



(b)

Figure 8: a) 3D surface, b) Contour plot of thrust force

Table 4 represented the coefficients in term of coded factors while final equation of the coded factors is as per Eq. 1. This equation can predict the value of thrust force obtained from other combination of input parameters. By default, the high levels of the factors are coded as +1 and the low levels are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

Table 4: Coefficient of Coded Factors

Factor	Coefficient Estimate	df	Standard Error	95% Cl Low	95% Cl High	VIF
Intercept	7.85684	1	0.12340	7.51423	8.19945	
A- Spindle Speed	-0.21189	1	0.12340	-0.55450	0.13072	1
B- Feed Rate	0.51967	1	0.12340	0.17706	0.86228	1
AB	-1.06023	1	0.12340	-1.40284	-0.71762	1
Ctr Pt 1	-1.10378	1	0.16556			

Thrust Force = 7.85684 - 0.211889*A + 0.51967*B -1.060226 *AB (Eq. 1)

The coefficient estimate represents the expected change in response per unit change in factor value when all remaining factors are held constant. The intercept in an orthogonal design is the overall average response of all the runs. The coefficients are adjustments around that average based on the factor settings. When the factors are orthogonal the VIFs are 1; VIFs greater than 1 indicate multi-collinearity, the higher the VIF the more severe the correlation of factors. As a rough rule, VIFs less than 10 are tolerable.

IV. CONCLUSION

The present research demonstrates the efficiency of 2-level factorial method for finding the optimum parameter of CFRP micro drilling process. The experiment was done using 2-level factorial 2^2 method. The input parameter were spindle speed and feed rate. The minimum thrust force produced from the combination of spindle speed 8,000 rpm and feed rate of 10,000 rpm. Hence, this parameter is suggested as the optimum parameter for lower thrust force from 2-level factorial analysis. The optimum parameter is validated and the results show 4.5% of error from the predicted value. The percentage of error below 5% is acceptable.

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