



RESPONSE SURFACE METHODOLOGY INTEGRATED MODELING OF GLASS FIBER REINFORCED POLYMER DELAMINATION IN HIGH SPEED DRILLING

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ABSTRACT

Extensive research efforts has been made in the conventional drilling of glass fiber reinforced polymer, where most researches focused in the studies of drilling parameters and thrust force relationship to delamination and tool wear. The effect of drilling generated heat was suggested frequently in these studies, but not many in-depth researches was done in this area. In this paper, an experiment was performed to study the effects of thrust force and drilling generated temperature generated from drilling parameters on delamination factor. A response surface method (RSM) integrated model consist of two phases was developed. The first phase of RSM modelling explained the relationship of drilling parameters with thrust force and drilling generated heat as mediator. The relationship between the mediator and the delamination factor were developed in the second phase of RSM modeling. The final RSM integrated models were validated and it resulted in a low percentage error delamination factor estimation equation from drilling parameters, while understanding and controlling the thrust force and drilling generated temperature.

Keywords: glass fiber reinforced polymer, high speed drilling, response surface methodology modeling.

INTRODUCTION

The application of polymer composite materials became a highly sought exposition, especially in 1950s. Due to the superior properties and high cost of metals and metal processing, polymer composite materials become more popular during the last decade. The applications of composite materials are increasing in aircraft, spacecraft and maritime industries due to their high strength to weight ratio [1]. Approximately 30% of external body of Boeing 767 is made of carbon or glass fiber composites, while the 777 comprises more than 50% [2]. The use of glass fiber reinforced polymer (GFRP) is becoming increasingly vital especially in electronic industry where it is used in wiring printing board [3].

Delamination is the most critical defect reoccurring during the drilling of GFRP. Several studies using different approaches have been conducted to understand the mechanism of delamination in GFRP. Mohan *et al* [6] studied the effects of drilling parameters on the delamination using S/N ratio method. V. Sonkar *et al*. [7] also used S/N ratio method to analyze multiple responses such as entrance, exiting delamination and thrust force in optimizing the drilling parameters. Murthy *et al*. [8, 9] studied the effect of drilling parameters on the thrust force generated during conventional drilling. Most published research is focused on the thrust force generated during the conventional drilling. While researchers agreed that thrust force is the main factor that causes delamination, they also pointed that drilling generated temperature may be another critical factor that affects the delamination in GFRP during the drilling process [1, 3, 6, 9-12].

In conventional drilling of metal, the drilling generated temperature is always related to the tool wear.

Higher drilling generated temperature affects the cutting tool under continuous drilling operation and tends to accumulate higher thermal effects thus causing tool wear; whereas the metal work piece having higher thermal properties has little effect on its finishing quality. Unlike metal, polymeric composites are more liable to the effects of drilling generated temperature. Khashaba *et al*. [13-15] reported that increasing cutting speed in drilling of GFRP raises temperature at the cutting zone. J. Campos Rubio *et al*. [5] studied the effect of high speed in drilling of GFRP on its delamination factor and they concluded that high speed machining is more efficient in drilling of GFRP by controlling the drilling parameters. Although their study focused on the thrust force related delamination, drilling generated heat was also suggested to be the cause of delamination. It was also agreed in these studies that drilling generated temperature plays a key role in the quality of the drilled work piece, but not many researchers have ventured into the studies of drilling generated temperature in high speed drilling. The development of higher efficiency machine also changes the manufacturing and machining industry. With lower cost, less machining time and better yield become highly sought opposition; high speed machining becomes a staple requirement where the study of drilling generated temperature becomes more vital.

In order to understand the effects of drilling parameter on the thrust force, drilling generated temperature and delamination factor, a large number of experiments have to be performed in order to develop a mathematical model which is complex and expensive [6]. Therefore, empirical model became a more viable modeling solution and widely adapted due to its higher application accuracy and lower experimental cost. In this



study, a relationship of drilling parameters with thrust force and temperature generated during the high speed drilling of GFRP was examined with the development of first phase RSM model. The relationship of thrust force and drilling generated temperature with delamination factor were then examined, with the development of second phase RSM model. Finally, the integration of first and second phase empirical model was developed where independent variables were the drilling parameters; drill entrance and drill exit delamination factor as dependent variable or output, while thrust force and drilling generated temperature were the mediators.

MATERIALS AND EXPERIMENT TECHNIQUES

The GFRP test samples fabricated for this study and the drilling experiment is discussed in this section.

Drill bit and work piece materials

In this study, GFRP of thickness 3mm, 5mm and 7mm were fabricated into dimensions of 350mmx 350mm with EWR600 0°/90° woven glass fiber and epoxy (Epicote 2820) using vacuum infusion molding with -90kPa pressure which were then cured in the furnace at 90 °C for 2 hours. The thickness was controlled by numbers of woven glass fiber plies used in the fabrication process. The cured GFRP were tested for their physical and mechanical properties adhering to ASTM standards. The test samples were cut into 125mm x 15mm for the drilling experiment. Five holes were drilled on each GFRP test samples.

The drilling test was conducted on Mazak Variaxis 630 CNC machine without coolant. High speed steel twist drill bit with 118° point angle was selected for this study.

Drilling experiment set up

In this study thrust force was measured using dynamometer 9265B with 9441B holder during the drilling of GFRP test samples. Some modifications were made on the 9441B turning tool holder where a special jig that holds the GFRP test sample for drilling purpose was designed. Two aluminum plates with 8 studs were fabricated so that they could be connected to the dynamometer. Both aluminum plates were pre-drilled with five 10 mm diameter as the drill guiding hole for the GFRP test samples. Before drilling process, the dynamometer was calibrated and tested for its accuracy in the thrust force measurement to avoid any errors. The signal from the dynamometer was amplified by the multichannel charge amplifier 9017b before it is recorded by a connected computer with Dynoware software.

The drilling generated temperature at the entrance and exit of the drill bit were measured using infrared thermometers placed 30cm from the entry point and exiting point of drill bit at the work piece. Delamination was measured using Mitutoyo Quick Vision Pro 3D non-contact measuring system. Experiment was carried out without any coolant.

The machine parameters considered in this study were spindle speed and feed rate. Three levels for each parameter were selected with three different thicknesses of GFRP test samples as shown in Table-1.

Table-1. Parameters used in this study and their levels.

Drilling Parameters	symbol	unit	levels		
			1	2	3
Spindle Speed	v	rpm	12000	15000	18000
Feed Rate	f	mm/min	300	500	700
Thickness of GFRP	t	mm	3	5	7

These parameters were selected based on published researches which strongly agreed that these are the predominant factors that influenced the drilled holes delamination as well as temperature generated and thrust force during the drilling operation.

Delamination factor evaluation

Among all the drilling induced damages, delamination is the most critical often occurring in the drilling operation. It is one of the main factors that limit the use of composite laminates in more structural applications [16, 17]. It results in poor assembly tolerance, thus lowering the load bearing strength of the joint which impacts the long term performance of the material [1, 12, 14, 18, 19]. It accounts for almost 60% of the rejection of component due to machining defects in aircraft industry [20, 21]. Delamination often occurs both on the entrance (peel up) and exit (push out) side of the work piece where the exit delamination is commonly more severe [2, 6, 14, 20, 22, 23]. Figure-1 illustrates the peel up and push out delamination occurring during the drilling of GFRP. Push out delamination occurs when the drill bit first makes contact with the work piece.

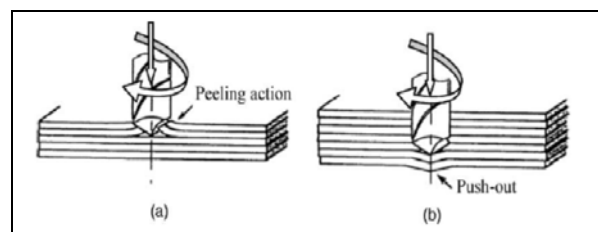


Figure-1. Mechanism of delamination a) peel up delamination at entrance b) Push out delamination at exit [18].

The orthogonal cutting geometry of the tool bit creates an upward pulling force whose the main function is to draw cutting chips away from the drilling point while the cutting lips remove the material [19]. When the pulling force exceeded the laminar force of the composites, the upper layer of the laminate may not be enough to withstand the upwards pulling force thus separates from



the rest of the composite causing pull up delamination. When the tool approaches the exit plane of the drill hole, the stiffness and laminar force of the remaining uncut composite may not be able to withstand the thrust force, causing the separation of lamina which is observed as a push out delamination [24].

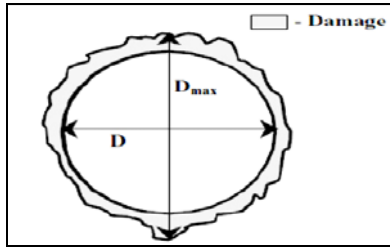


Figure-2. Delamination factor assessment [25].

J. Campos Rubio *et al.* [5], suggested that a quantitative evaluation is needed for assessing the drilling induced damage. Although there is still no standard procedure in drilling induced damage evaluation in composite, most authors agreed that a ratio based delamination factor is to be used as the damage evaluation which allows comparisons among the result from different researches. Figure-2 illustrates the measurement of maximum delamination, and drilled diameter. Therefore, a delamination factor was introduced and has been widely practiced in recent years. The delamination factor was a dimensionless factor devised based on the total extend of delamination diameter along the peripheral over the drilled diameter [5, 11, 12, 18, 25–27]; where the calculation is given in Equation. (1).

$$F_d = \frac{D_{max}}{D_0} \quad (1)$$

Where;

- F_d = Delamination factor
- D_{max} = maximum delamination diameter
- D_o = drilled diameter

Response surface methodology

Response Surface Methodology (RSM) is a statistical approach that is based on actual data from experiment or computer simulation to develop an approximation model [28]. An accurate overview of the various parameters and its relationship to the responses for a system were analyzed. This method is useful when multiple responses are analyzed with various parameters in a complex and high cost study [29]. The application of RSM is aimed at reducing the cost of expensive analyses methods (e.g. finite element method or CFD analysis); to obtain optimized responses and to avoid the theoretical associated numerical noise [8]. The convergence of the optimization process can be improved with smooth approximated functions because they reduce the effects of noise by analysis and they allow for the use of derivative-based algorithms. A second order model given in Equation. (2) is utilized in the response surface method

analysis due to the non-linear response obtained from the ANOVA analysis.

$$Y = b_0 + b_1x_1 + b_2x_2 + \dots + x_i x_j \quad (2)$$

In this study, two phases of RSM modeling were generated, and integrated. The main objective of this approach is to study the effect of thrust force and drilling generated heat on the delamination by controlling the drilling parameter. By using thrust force and drilling generated temperature as mediator, it enables the analyses that bridge the relationship between drilling parameters and delamination. With the understanding of thrust force and drilling generated temperature behavior, it provides an alternative method in predicting delamination while the results can be used in the design of composite cutting tools. Figure-3 illustrates the concept of two phase RSM integration model.

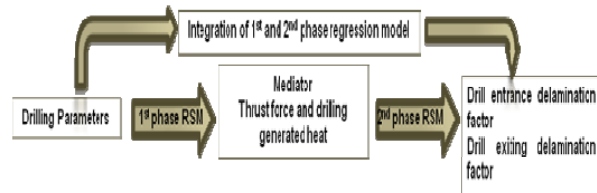


Figure-3. Two phase RSM model integration flow chart.

The first phase second order RSM modeling of three drilling parameters on mediator (thrust force and drilling generated temperature) is expressed as Equation. (3) and (4) below.

$$F = b_0 + b_1v + b_2f + b_3t + b_{12}vf + b_{13}vt + b_{23}ft + b_{11}v^2 + b_{22}f^2 + b_{33}t^2 \quad (3)$$

$$T = b_0 + b_1v + b_2f + b_3t + b_{12}vf + b_{13}vt + b_{23}ft + b_{11}v^2 + b_{22}f^2 + b_{33}t^2 \quad (4)$$

The analysis was repeated for the second phase second order RSM modeling of mediator (thrust force and drilling generated temperature) on the drill entrance and exiting delamination factor. It is expressed as Equation. (5) and (6) below.

$$DF_{in} = b_0 + b_1F + b_2T + b_{12}FT + b_{11}F^2 + b_{22}T^2 \quad (5)$$

$$DF_{out} = b_0 + b_1F + b_2T + b_{12}FT + b_{11}F^2 + b_{22}T^2 \quad (6)$$

Where;

- DF_{in} = Drill entrance delamination factor
- DF_{out} = Drill exiting delamination factor
- F = Thrust Force
- T = Drilling generated temperature
- v = Spindle speed
- f = Feed rate
- t = GFRP thickness
- b_{ij} = Coefficient of main and interaction effect



The first phase RSM models were integrated into the second phase RSM models to link the drilling parameters to the delamination factor, while retaining mediators as gauging elements in these integrated models. The models were examined for their good of fits with a new random set of experiments to evaluate their prediction accuracy.

RESULTS AND DISCUSSIONS

The results from the mechanical and physical evaluation of the GFRP test sample and the experimental results are discussed in this section.

Mechanical and physical properties of GFRP

The GFRP samples were tested for their mechanical and physical properties. The testing procedures were done adhering to ASTM. Table-2 shows the results of the mechanical and physical testing.

Table-2. Physical and mechanical properties of the GFRP.

GFRP Thickness (mm)	Fiber Volume (%)	ILSS (MPa)	Tensile Strength (MPa)
3	57.76	56	148
5	57.83	59	164
7	58.87	64	178
Glass transition temperature			76°C
Degradation temperature			350°C

The drilling experiment was performed according to the Design of Experiment (DOE) where run orders were randomized to avoid noise factors. The experiment consists of 15 runs with 5 replicates for each grade of twist drill bit.

ANOVA analysis

Table-3 shows the mean results for 15 runs in 5 replicates and their results in high speed drilling GFRP using high speed steel (HSS) twist drill bit. 5 replicates with 75 runs were performed to determine the mean value for each set of drilling parameters performed.

Table-3. Design of experiment and their mean results.

Run Order	Drilling Parameters			Thrust force (N)	Drilling Generated Temperature (°C)	Drilling entrance damage factor	Drilling exiting damage factor
	Spindle Speed (rpm)	Feed rate (mm/min)	GFRP thickness (mm)				
1	18000	700	5	24.879	42.5	1.359	1.531
2	18000	500	3	17.152	30.5	1.319	1.507
3	15000	700	3	19.866	28.3	1.340	1.460
4	12000	700	5	19.038	29.6	1.362	1.571
5	15000	500	5	19.034	41.3	1.341	1.413
6	15000	300	3	8.474	28.3	1.287	1.414
7	15000	700	7	24.509	55.8	1.389	1.436
8	15000	300	7	15.968	76.7	1.293	1.457
9	18000	500	7	23.296	62.5	1.329	1.460
10	18000	300	5	11.916	69.6	1.370	1.454
11	15000	500	5	19.034	41.3	1.341	1.413
12	15000	500	5	19.352	42.1	1.365	1.411
13	12000	500	3	14.019	26.9	1.321	1.563
14	12000	500	7	16.344	46.4	1.292	1.455
15	12000	300	5	12.923	50.4	1.311	1.520

ANOVA tests were performed on the experiment data which evaluate the main and interaction effects of each parameter. It is observed in Table-4, feed rate has the highest effect on the thrust force and drilling generated temperature. When higher feed rate was used, the temperature and thrust force increased significantly. Although feed rate contributed to the increasing thrust force and drilling generated temperature, it was observed that the interaction between spindle speed and feed rate might also affect the thrust force and temperature generated. When higher spindle speed was used, it relatively lowered the thrust force and drilling generated heat. This occurred when higher spindle speed with higher material removal rate, dampened the thrust force generated by removing materials before the drill bit was able to push

through the work piece when high feed rate was used. Thrust force was also increased when GFRP thickness increased. This was due to longer time needed for removal of higher volume of materials, hence progressively elevating the concentrated thrust force at the cutting zone.

First phase RSM modeling

RSM analysis was performed to generate the coefficient for each main and interactive effect in order to develop an empirical model that relates the drilling parameters to thrust force and temperature generated during GFRP high speed drilling using HSS twist drill bit. The coefficient calculated using RSM approach is shown in Table-5.

**Table-4.** ANOVA results for thrust force and drilling generated temperature.

Source	Thrust force				Drilling Generated Temperature			
	F _{value}	F _{0.05}	P	Contribution %	F _{value}	F _{0.05}	P	Contribution %
Linear								
Feed Rate (mm/min)	170.22	3.8774	0	31.48	112.59	2.6393	0	54.22
Spindle Speed (RPM)	22.96	3.8774	0	4.25	27.42	3.8774	0	4.40
Thickness (mm)	62.22	3.8774	0	11.51	23.54	3.8774	0	3.78
Square								
Feed Rate *Feed Rate	0.08	3.8774	0.771	0.02	3.5	2.6393	0.016	1.69
Spindle Speed*Spindle Speed	0.12	3.8774	0.727	0.02	9	3.8774	0.003	1.44
Thickness*Thickness	0.15	3.8774	0.703	0.03	1.49	3.8774	0.224	0.24
Interaction								
Feed Rate*Spindle Speed	22.51	3.8774	0	4.16	4.91	2.6393	0.002	2.37
Feed Rate*Thickness	0.7	3.8774	0.402	0.13	1.17	3.8774	0.28	0.19
Spindle Speed*Thickness	1.74	3.8774	0.188	0.32	7.41	3.8774	0.007	1.19

Table-5. RSM analyzed coefficient of drilling parameter on thrust force and drilling generated temperature.

Term	Coefficient for thrust force	Coefficient for drilling generated temperature
Constant	34.9312	100.805
Feed Rate (mm/min)	-0.0411	-0.135
Spindle Speed (RPM)	-0.0026	-0.008
Thickness (mm)	-1.1822	4.08
Feed Rate * Feed Rate	0	0
Spindle Speed * Spindle Speed	0	0
Thickness *Thickness	0.0644	0.054
Feed Rate * Spindle Speed	0	0
Feed Rate *Thickness	0.001	-0.008
Spindle Speed *Thickness	0.0001	0

From the RSM analysis, the first phase RSM models between drilling parameters with thrust force and temperature generated during GFRP high speed drilling using HSS twist drill bit can be expressed as Equation. (7) and (8) below.

$$F = 0.0411f - 0.0026v - 1.1822t + 0.0644t^2 + 0.001ft + 0.0001vt + 34.9312 \quad (7)$$

$$T = -0.135f - 0.008v + 4.08t + 0.054t^2 - 0.008ft + 100.805 \quad (8)$$

The empirical model in Equation. (7) shows the relationship between drilling parameters and thrust force generated during the high speed drilling using HSS. While Equation. (8) shows the relationship between drilling parameters and temperature generated during the high speed drilling using HSS.

Second phase RSM modeling

In the second phase of RSM modeling, thrust force and drilling generated temperature were analyzed as mediators. It is agreed in published researches that thrust force and drilling generated temperature significantly affect the delamination factor during the GFRP drilling

operation. By analyzing the thrust force and temperature as mediator between drilling parameters and delamination factor, an in-depth understanding of thrust force and drilling generated temperature can be obtained. The understanding of thrust force and drilling generated temperature were particularly important, where it provides an overview for future tool bit design and drilling operation.

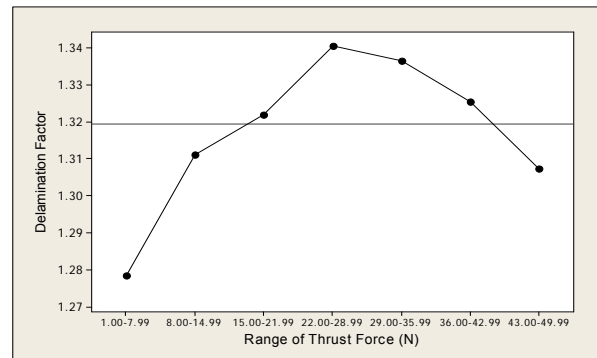
**Figure-4.** Effect of thrust force on drill entrance delamination factor.

Figure-4 shows the effect of thrust force on the drill entrance delamination factor using HSS twist drill bit. The graph exhibits a quadratic relationship where the drill entrance delamination factor increased from 1N to 22N of thrust force while the drill entrance delamination factor decreased when thrust force increased from 22N to 50N. This is in contrary to the published researches that concluded increasing thrust force increased the delamination factor. The reason may due to the spindle speed used in the study. Most published researches focused on conventional drilling, which utilized a set of lower spindle speed. The higher spindle speed in high speed drilling generates higher material removal rate, which successively lowers the thrust force generated. The mean thrust force generated in this study of high speed drilling was also 80-150% lower as to compare to conventional drilling.

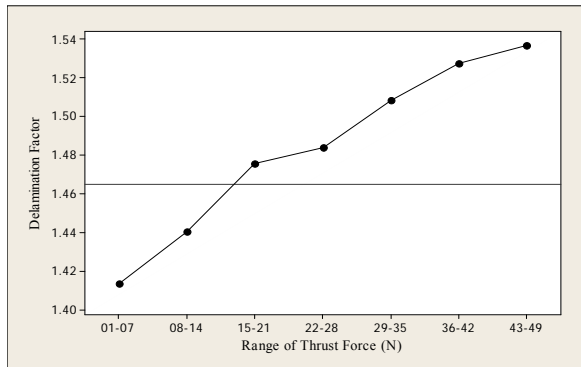


Figure-5. Effect of thrust force on drill exiting delamination factor.

Drill exiting delamination factor (Figure-5) shows a linear increment when thrust force increased. This may be due to high thrust force generated during the high speed drilling, penetrated the work piece before any material removal process was completely executed. This forced the tool bit to push through the work piece instead of shearing through.

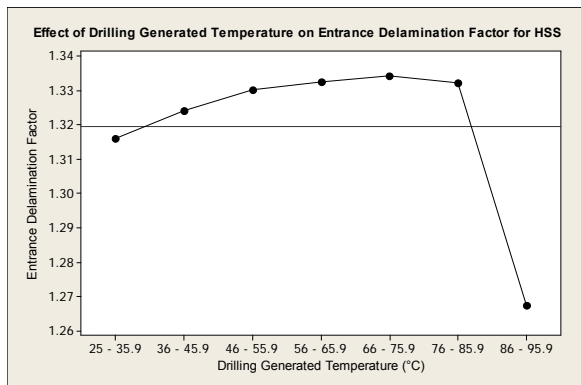


Figure-6. Effect of drilling generated temperature on drill entrance delamination factor.

The effect of drilling generated temperature on the drill entrance delamination factor is illustrated in Figure-6. It is observed that the drill entrance delamination factor increased slightly with increasing temperature from 25 °C to 70 °C. A drastic decrement in drill entrance delamination factor is seen when drilling generated temperature exceeded 75 °C to 96 °C. The decrease in drill entrance delamination factor may be due to the drilling generated temperature reaching the glass transition temperature. At 76 °C (epoxy glass transition temperature), the epoxy matrix in the GFRP softened into a rubbery state which gradually lowers the stiffness of the matrix. This assisted the tool flank to shear through the GFRP work piece without chipping the surface with pull up force generated by the tool bit flute.

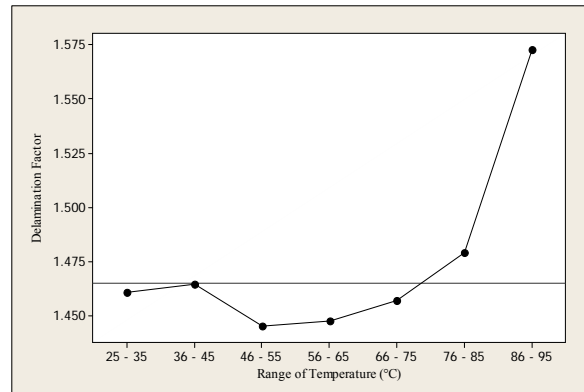


Figure-7. Effect of drilling generated temperature on drill exiting delamination factor.

The drill exiting delamination factor responded differently to drilling generated heat as illustrated in Figure-7. It is observed that the drill exiting delamination factor decreased at the range of 36 °C – 55 °C. The thermal conductivity of high speed steel is relatively lower compared to other drill bit such as solid carbide coated and non-coated twist drill bit. Due to the low thermal conductivity, the tool bit dissipated heat slower, this phenomenon was seen to escalate when higher feed rate and lower spindle speed was used. With low heat dissipation rate, the temperature at the cutting zone increased drastically when heat at the cutting zone throughout the drilling process accumulated. Drill exiting delamination factor increased when drilling generated temperature exceeded 65 °C. The stiffness of the lower surface of the work piece decreased with the softening of epoxy at high temperature. This causes the lower surface of work piece unable to withstand the push down force generated by the drill bit, thus increased the drill exiting delamination factor by chipping prematurely before the shearing motion is completed.

The above results were analyzed using RSM approach, the coefficients of drilling generated heat and thrust force is shown in Table-6.

Table-6. RSM analyzed coefficient of thrust force and drilling generated temperature on delamination factor.

Term	Coef for DF _{in}	Coef for DF _{out}
Constant	1.21117	1.51294
Drilling Generated Temperature (°C)	0.00272	-0.00741
Thrust Force (N)	0.00425	0.00974
Drilling Generated Temperature * Drilling Generated Temperature	-0.00003	0.00008
Thrust Force*Thrust Force	-0.00004	-0.00011
Drilling Generated Temperature*Thrust Force	-0.00001	-0.00003

From Table-6, the second phase RSM models can be expressed as Equation. (9) and (10);



$$DF_{in} = 0.00272 T + 0.00425 F - 0.00003 T^2 - 0.00004 F^2 - 0.00001 TF + 1.21117 \quad (9)$$

$$DF_{out} = -0.00741T + 0.00974F + 0.00008T^2 - 0.00011F^2 - 0.00003TF + 1.51294 \quad (10)$$

Equation. (9) relates the effect of thrust force and drilling generated temperature to the drill entrance delamination factor; whereas Equation. (10) explains the relationship between thrust force and drilling generated temperature to the drill exiting delamination factor.

Contour and surface plot were generated using Equation. (9) and (10). The contour plot and surface plot enabled the understanding of how both the thrust force and drilling generated heat affected the delamination.

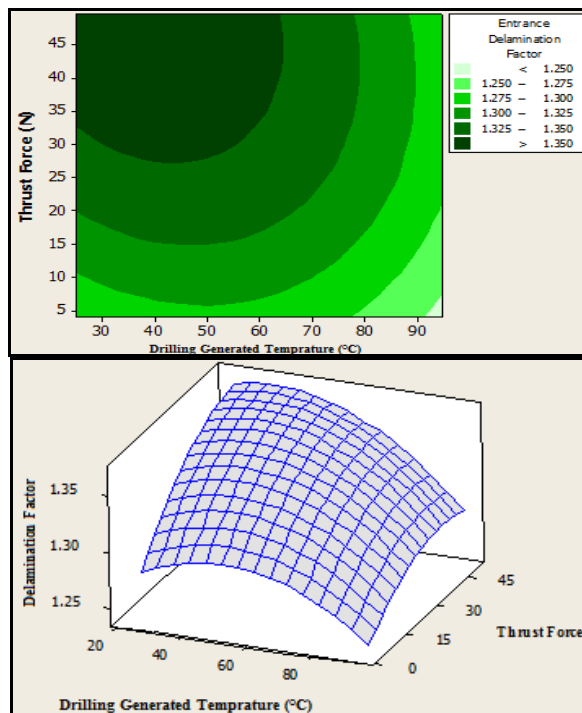


Figure-8. Contour and surface plot for drill entrance delamination factor.

From Figure-8, the lowest drilling entrance delamination factor of less than 1.25 was observed at the region where drilling generated temperature was at 90 °C and thrust force at 5N. The drill entrance delamination factor is higher when the thrust force exceeded 30N with drilling generated heat at 60 °C and lower. This aligned with the results from published researches stating that higher thrust force increases delamination factor while further reinforced that higher drilling temperature decreased the drill entrance delamination.

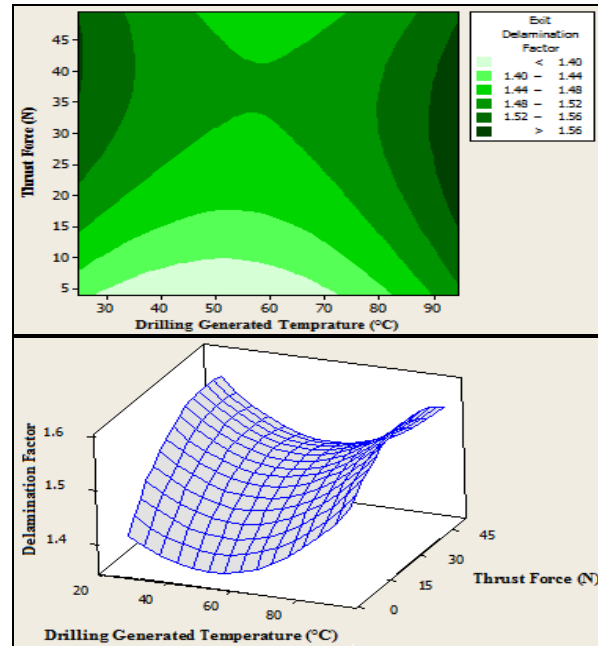


Figure-9. Contour and surface plot for drill exiting delamination factor.

The contour and surface plot of drill exiting delamination factor is illustrated in Figure-9, showing a saddle form surface plot. This indicates that the drilling generated temperature that fell between 30 °C to 70 °C were the most optimum drilling generated temperature range for minimal drill exiting delamination. It is observed that the thrust force below 10N generated from the high speed drilling also contributed to lower drill exiting delamination factor which is below 1.40.

Integrated model of high speed drilling of GFRP using HSS

The first phase RSM modeling explained the relationship of drilling parameters to mediators which were thrust force and drilling generated temperature; whereas the second phase of RSM modeling explained the relationship of mediators which were thrust force and drilling generated heat with the drill entrance and exiting delamination factor. The integration of both phases of RSM modeling will explained the relationship of drilling parameters and delamination factor.

The first phase RSM models of drilling parameter on thrust force and drilling generated temperature [Equation. (7) and (8)] are substituted into the second phase of RSM model of drill entrance and exiting delamination factor [Equation. (9) and (10)]. The integrated models were simply and expressed as Equation. (11) and (12) below.

$$DF_{in} = -0.000002 ft^2 - 0.000009 t^3 - 0.000001 f^2 + 0.000064 ft - 0.000677 t^2 - 0.000002 tv + 0.000515 f - 0.015534 t + 0.000028 v + 1.244948 \quad (11)$$



$$\begin{aligned}
 DF_{out} = & -0.000007 ft^2 + 0.000046 t^3 + 0.000001 f^2 \\
 & - 0.00015 ft + 0.001674 t^2 - 0.000006 tv \quad (12) \\
 & - 0.001075 f + 0.032443 t - 0.000059 v \\
 & + 1.79279
 \end{aligned}$$

Equation. (11) expressed the relationship between drilling parameters with drill entrance delamination factor; while Equation. (12) expressed the relationship between drilling parameters with drill exiting delamination factor. The models were then tested with a random set of drilling experiment to validate its fit.

Models validation

Before proceeding to validate the models in Equation. (11) and (12), it is necessary to perform a random set of validation experiments. 10 sets of parameters were selected randomly with 3 sets of parameters selected beyond the experiment range which is spindle speed 12000-18000RPM and feed rate 300-700mm/min to test its range of prediction. The validation experiment was performed with 3 replicates to obtain the mean delamination factor. The results from the validation experiment were compared to the results calculated from the models.

Table-7. Percentage of error results.

Drilling Parameters			Drilling entrance delamination factor			Drilling exiting delamination factor		
Spindle Speed (rpm)	Feed rate (mm/min)	GFRP thickness (mm)	Validation experiment	Model calculation	% error	Validation experiment	Model calculation	% error
20000	200	5	1.352	1.622	20.0	1.131	1.348	19.2
17000	600	3	1.709	1.612	5.7	1.421	1.388	2.32
15000	700	3	1.464	1.506	2.9	1.415	1.387	2.0
10000	300	5	1.633	1.469	10.0	1.676	1.800	7.4
13000	500	5	1.447	1.516	4.8	1.422	1.383	2.7
15000	300	3	1.523	1.635	7.4	1.697	1.741	2.6
16000	300	7	1.433	1.485	3.6	1.289	1.212	5.8
15000	600	7	1.512	1.452	4.0	1.290	1.183	8.3
9000	800	7	1.597	1.256	21.4	1.793	1.063	40.7
18000	400	5	1.533	1.619	5.6	1.145	1.214	6.0
Average percentage of error			8.54			9.70		

Table-7 shows the results from the validation experiment and the values calculated from model Equation. (11) and (12). The percentage of error was calculated using Equation. (13) below.

$$\text{Percentage error} = \frac{DF_v - DF_m}{DF_v} \times 100\% \quad (13)$$

The average percentage of error obtain from the validation test was 8.54% for drill entrance delamination factor and 9.7% for drill exiting delamination. It is observed that the out of range error was still within acceptable range with percentage error below 20%. When 9000RPM spindle speed was used, the percentage of error was 40.7% which indicates that the model prediction limit for spindle speed is 10000RPM – 20000RPM, feed rate range from 200-700mm/min and GFRP thickness of 3-7mm with below 20% error.

CONCLUSIONS

- Experiment was conducted on woven glass fiber reinforce epoxy fabricated using vacuum infusion molding with fiber volume fraction of ~60%.
- From first phase of RSM analysis and model development, it was observed that :
 - Feed rate and GFRP thickness contributes significantly to the increase of thrust force, while feed rate significantly affects the drilling generated heat followed by thickness and spindle speed.
 - Spindle speed plays a vital role in dampening the thrust force and drilling generated heat caused by high feed rate used in high speed drilling of GFRP in this study
- From second phase of RSM analysis and model development, it was observed that :
 - Low thrust force with higher drilling generated temperature lowered the drill entrance delamination factor.



- Drilling generated heat in the range of 30-70°C couple with low thrust force generated low drill exiting delamination factor.
- Controlling of drilling generated temperature was as crucial as controlling the thrust force generated during high speed drilling in lowering the delamination factor.
- The approach of integrated models with percentage error less than 10% was suitable for predicting the delamination factor in high speed drilling of GFRP using HSS.
- The integrated model was still fit to predict drilling parameters $\pm 20\%$ of beyond its developed range.

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