ANALYSIS OF PARAMETRIC INFLUENCE ON MACHINING IN DRY DRILLING CARBON FIBER REINFORCED EPOXY COMPOSITES

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Abstract

The present work defines the cutting conditions that allow to dry drilling of carbon fiber reinforced epoxy composites material, which takes into consideration the drilled holes quality, the optimum combination of drilling parameters, using grey relational analysis to obtain high surface quality results. The experiments were performed under different cutting conditions of speed and feed rate. The spindle speed was varied from 3000 to 9000 rev/min and the feed rate from 60 to 180 mm/min. Drilling tests were carried out by using carbide (WC), high speed steel (HSS) and TiN coated carbide drills (WC-Ti).

A statistical analysis of variance (ANOVA) was applied to complete the experiment model. The results show that the thrust force is mainly influenced by spindle speed and feed rate. On the other hand, both feed rate and tool materials have statistical significance on the exit delamination factor and cylindricity error of the holes. In addition, the objective of the correlation between spindle speed and feed rate with the evolution of machining parameters was reached. These correlations were obtained by quadratic regression with using the response surface methodology (RSM).

1. Introduction

In industrial fields such as aerospace and aircraft, carbon fiber reinforced epoxy (CFRE) composites are used owing to their excellent mechanical properties. However, the machinability of the relevant composites is not easy to yield good-quality products. Drilling of composites materials is a very common process in the assembly of aeronautic composites structures.

Regarding the quality characteristics of drilled holes in CFRE, some problems have been encountered including surface delamination and fiber pull out. With the increasing demand for advanced composite materials, different cutting conditions are required. Delamination is the most common defect when drilling. This is because of the heterogeneity between fibers and matrix [1].

Tsao C.C. [2] experimented the drilling-induced thrust force of composite polymer (CFRP) material, with step-core drill, by taking into consideration: diameter ratio, feed rate and spindle speed parameters. For the same material Zitoune et al [3] improved drilling by using various dimensions of double cone drill with analysis including cutting force, tool lifetime, chip form and hole quality. Besides, Liet al [4] detailed the effect of variable feed rate and lay-up configuration on surface roughness and integrity, that following the drilling of CFRP composites under chilled air conditions. In addition, S. Rawat et al. [5], utillises the carbon fiber and different matrix epoxy. With the same carbon/epoxy composite plates, Piquet et al [6] investigated the effect of drilling with two types of drills, a conventional twist drill and a specific cutting tool. Bhatnagar et al [7] studied the orthogonal

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cutting of unidirectional carbon fiber reinforced epoxy composite with different fiber orientations. Khashaba et al. [8] treated the effect of drill pre-wear on the machinability parameters when drilling glass fiber reinforced epoxy composites (GFRE) at different cutting conditions. Linear regression models were developed to correlate the machinability parameters with drill wear and cutting conditions. Although, a lot of research work has been carried out on effects of cutting parameters on delamination during drilling of CFRP composites, notice that a little work was reported on the effect of hole geometric quality [9]. The prevouis related work explains the cutting composite materials, but no assumptions were made about geometric cylindricity defects.
The present study investigates the dry drilling of a Carbon/Epoxy Composites (CFRE) plates. The twisted tools used are from HSS, carbide, and TiN coated carbide with the same dimensions (6 mm diameter, 118° point angle and 30° helical angle). Cutting parameters (spindle speed and feed rate) effect on generated cutting forces and holes quality are studied. Analysis of variance (ANOVA) was used to examine the significance and the relevance of the models which are used to draw the response surface RSM, in order to estimate the influence and the simultaneous interaction of the cutting parameters (rotation speed (*N*) and feed rate (*f*)) with the studied phenomena (thrust force (*Fz*), torque (*Mz*), exit delamination factor and the cylidricity error).

2. Experimental procedure

Dry drilling experiments were realized on a vertical mill CNC machine. Three different tool materials were used, high speed steel (HSS), coated carbide, and carbide drill, with different spindle speeds and feed rates. Experimental results were collected and recorded by an acquisition data system. as shown in Figure. 1.

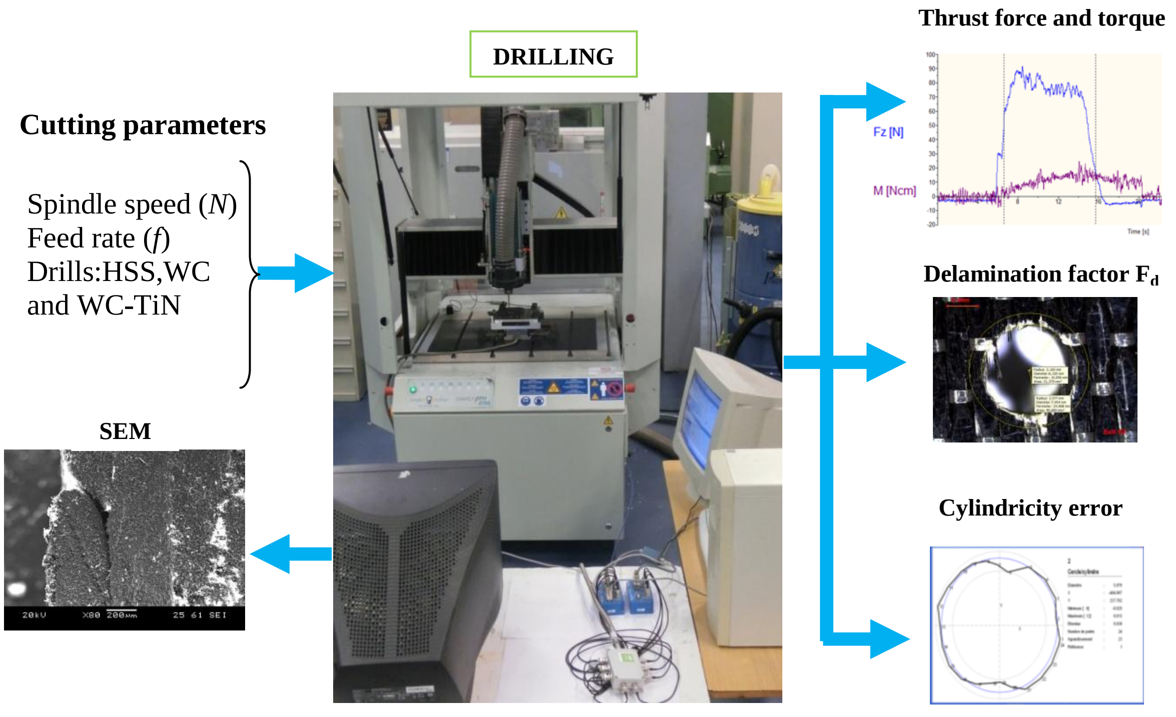

Figure 1. Schematic of experimental processes.

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3. Results and discussion

The results of the machining parameters are measured according to 3^3 full factorial designs (27 experiments with actual independent process variables). The measured responses (output) are shown in Table 1. They are analyzed by the Design-Expert software which indicates that the quadratic models are statistically recommended.

Table 1. Experimental results for *Fz*, *Mz*, F_d-Exit and *Cylindricity error*.

N°	Machining parameters			Response factors			
	N (rev/min)	*f* (mm/s)	Drill type	*Fz* (N)	*Mz* (N×cm)	F_d-*Exit* factor	*Cylindricity error* (mm)
1	3000	60	HSS	72.39	11.28	1.223	0.052
2	3000	60	WC	50.62	16.50	1.108	0.055
3	3000	60	WC -TiN	59.29	8.91	1.140	0.036
4	3000	120	HSS	96.69	12.90	1.355	0.042
5	3000	120	WC	62.61	23.66	1.121	0.032
6	3000	120	WC -TiN	73.15	10.17	1.142	0.025
7	3000	180	HSS	121.60	14.71	1.368	0.046
8	3000	180	WC	65.31	25.16	1.146	0.037
9	3000	180	WC-TiN	81.11	13.34	1.215	0.026
10	6000	60	HSS	50.79	16.33	1.276	0.054
11	6000	60	WC	34.42	16.51	1.118	0.070
12	6000	60	WC -TiN	39.19	12.52	1.081	0.064
13	6000	120	HSS	77.02	18.17	1.281	0.049
14	6000	120	WC	47.27	25.34	1.144	0.064
15	6000	120	WC -TiN	55.09	14.32	1.132	0.045
16	6000	180	HSS	96.68	20.71	1.347	0.050
17	6000	180	WC	53.49	27.45	1.199	0.060
18	6000	180	WC -TiN	67.03	14.67	1.183	0.039
19	9000	60	HSS	40.83	11.42	1.219	0.091
20	9000	60	WC	28.34	12.03	1.108	0.084
21	9000	60	WC -TiN	30.79	10.44	1.183	0.070
22	9000	120	HSS	30.33	11.64	1.282	0.079
23	9000	120	WC	38.78	13.02	1.134	0.064
24	9000	120	WC -TiN	44.74	10.80	1.136	0.050
25	9000	180	HSS	69.15	10.82	1.340	0.071
26	9000	180	WC	43.03	13.77	1.159	0.068
27	9000	180	WC -TiN	55.50	8.23	1.161	0.052

3.1. Statistical analysis

The analysis of variance (ANOVA) method consists of fractioning the total variation in an experiment into ascribable components to control factors and errors.
The variant analysis results of the thrust force (*Fz*), torque (*Mz*), factor delamination exit (F_{d-Exit}) and cylidricity error, respectively of composites (CFRE) drilling. This analysis was carried out for a significance level of 5%, i.e. for a confidence level of 95%.
The ANOVA analysis of the thrust force model , shows that the R^2 : 91.27 %, Adj-R^2 : 86.64 % and Pred-R^2 : 78.11 % in this case, there is a good agreement between Adj-R^2 and Pred-R^2 values. Thus, the thrust force model can be used to navigate the response space.

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The model of Torque (*Mz*) analysis gives R^2 equal to 83.48%, which indicates a more preponderant fit of the model. The Adj-R^2 of 74.73% is in reasonable agreement with the "Pred-R^2" of 59.66 %.
The model for factor delamination exit ($F_{d\text{-}Exit}$) provide values of R^2, Adj-R^2 and Pred-R^2 of 92.33%, 88.26% and 78.16 %, respectively. It is worth to mention that the Adj-R^2 and Pred-R^2 do not ensure a good prediction model. These values should be used as indication of fit goodness.
Finally, the results of cylindricity error indicate that the model is still significant. The spindle speed is the most significant factor related to cylindricity error. This is expected because it is well known that with the increase of the spindle speed, vibration of tool increase. This induces an increase of cylindricity error [11]. The value of R^2 is 90.10% of the total variability, Adj-R^2 is 84.87% and the Pred-R^2 is 76.26 %. The latter is in good agreement with the Adj-R^2. Adequate precision of 14.83 is an adequate value for the model to perform well in prediction.

3.2. Pareto graph

Best results of the Pareto graph from the analysis of variance are built in Fig. 2. This figure ranks the cutting parameters and their interactions of their growing influence on the thrust force (*Fz*), torque (*Mz*), exit delamination factor ($F_{d\text{-}Exit}$) and cylindricity error. Standardized values in this figure are obtained by dividing the effect of each factor by the error on the estimated value of the corresponding factor. If the F-values are greater than 4.45; the effects are significant. Conversely, if the value of F-value is less than 4.45; the effects are not significant. The confidence interval chosen is 95 %.

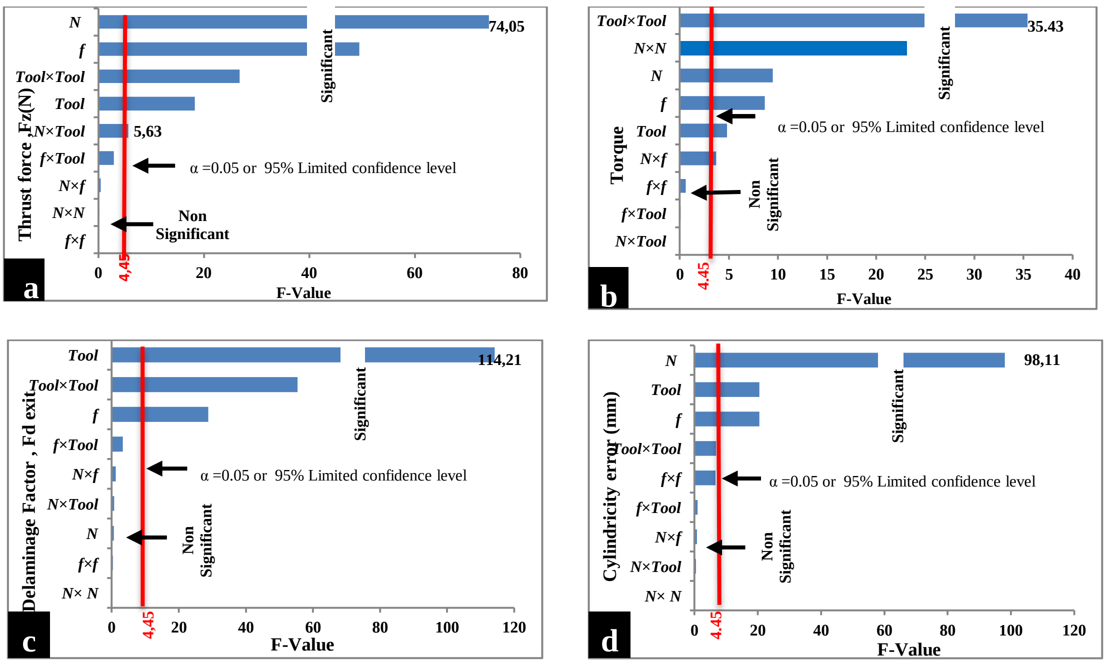

Figure 2. Pareto graph, (a) Thrust force, (b) Torque, (c) Exit delaminage factor, (d) Cylindricity error

4. Response surface analysis

3D generating response surface model exhibits the interaction effects, due to spindle speed *N* and feed rate *f* on thrust force *Fz*, torque *Mz*, delamination factor at the exit ($F_{d\text{-}Exit}$) and the cylidricity error during drilling of CFRE composites were analyzed for three different drill materials: high speed steel, carbide, and coated carbide through response surface plots (Figs. 3-6).

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4.1. Effect of drilling parameters on cutting forces (thrust forces and torque)

The thrust force during drilling of CFRE composites depend on input variables, such as cutting speed or spindle speed, feed rate and drill materials. This effect is summarized in Fig. 3. The thrust force highly increases with feed rate. However, the thrust force changes slightly when the spindle speed varies. It can also be observed in this figure that drilling with HSS drill leads to higher thrust force compared to WC and WC-TiN drills. Also it can be noticed that for a spindle speed of 3000 rev/min with a feed rate varying from 60 mm/min to 180 mm/min, the drilling thrust force of CFRE composites using WC ,WC-TiN and HSS tools is subjected to an increase of 22.64%, 26.64% and 40.47% respectively.

Drilling torque obtained from the regression model and the optimum torque for the three drills (HSS, WC and WC-TiN) is exhibited by the three-dimensional response surface on Fig.4. It can be observed that the torque increases noticeably with the feed rate for the three drilling tools. Drill materials have a significant effect on the torque during the drilling of the CFRE composites. In addition, maximal torque values are obtained when drilling composite laminates with a speed spindle of 6000 rev/min, for the three tool materials. For the same spindle speed of 6000 rev/min, WC drill was subjected to the highest torque value when the feed rate is 180 mm/min.

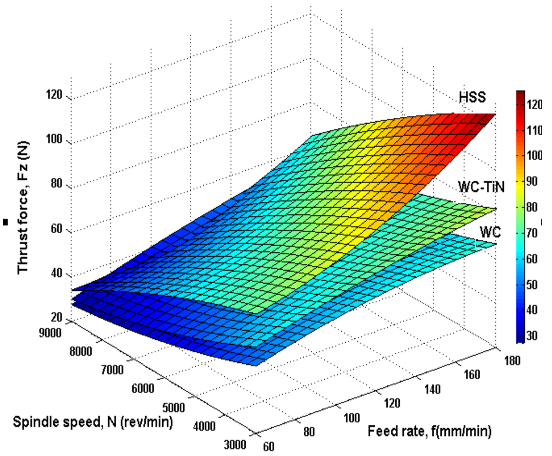

Figure 3. Effect of spindle speed and feed rate on thrust force; Tools: a) HSS, b) Carbide and c) TiN coated carbide.

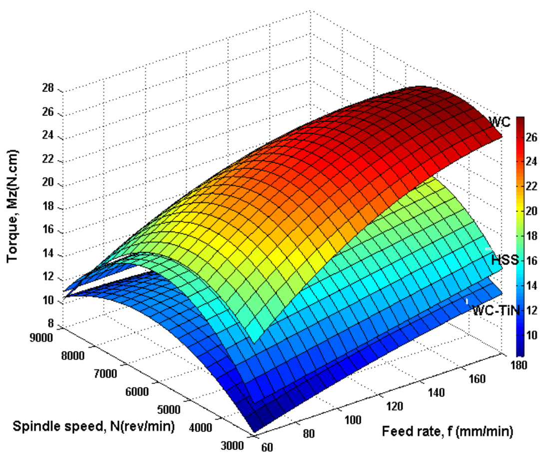

Figure4. Effect of spindle speed and feed rate on torque;Tools: a) HSS, b) Carbide and c) TiN coated carbide.

4.2. Effect of drilling parameters on the exit delamination factor and cylindricity error

From the response surface analysis in Fig.5, noticed that the exit delamination factor is highly sensitive to the feed rate variation. It can also be observed from Fig. 5, that the delamination has a tendency to increase with the feed rate during drilling of CFRE composites for the different drills (HSS, WC and WC-TiN). In addition, the HSS drill has the greatest effect on delamination compared with the other tools.

The influence of feed rate and spindle speed on cylindricity error using the HSS, WC and WC-TiN drills is illustrated in Fig. 6. It can be observed that cylindricity error is related linearly to spindle speed and feed rate. The high spindle speed increases the cylindricity error in drilling of composite materials for the different drills (HSS, WC and WC-TiN). It is the most influencing parameter on the holes quality, in particular the cylindricity error. On the other hand, the effect of feed rate on the cylindricity error is insignificant for the lowest spindle speed 3000 rpm and slight for high spindle speed 9000 rpm. It is concluded that the combination between the maximum spindle speed and the minimum feed rate for the three tools gives a maximum cylindricity error.

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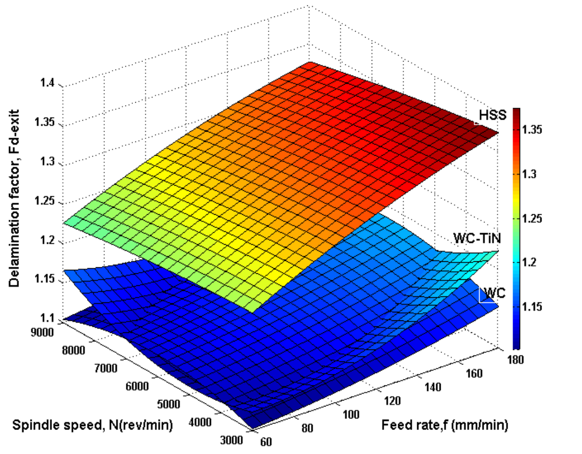

Figure 5. Effect of spindle speed and feed rate on exit delamination factor (Fd-exit); Tools: a) HSS, b) Carbide and c) TiN coated carbide

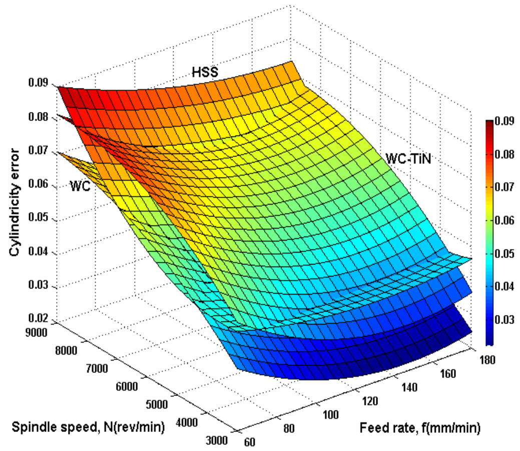

Figure 6. Effect of spindle speed and feed rate on cylidricity error; Tools: a) HSS, b) Carbide and c) TiN coated carbide

5. Surface quality at hole machining

Several damaged areas can be noticed in the SEM observation, when the holes are machined with twist drill WC as shown in Fig.7. These damaged areas were mainly observed at -45°and 90° fiber orientations. However, in WC-Ti machining, the damage areas and depths were less compared to WC. Also, it was found that damages are uniformly distributed as shows in Fig. 7 and the SEM observation of last nine cutting composite layer (90°, 45°, 0°, -45°, 90°, 45°, 0°, -45°) for the holes in drilling of CFRE composites.

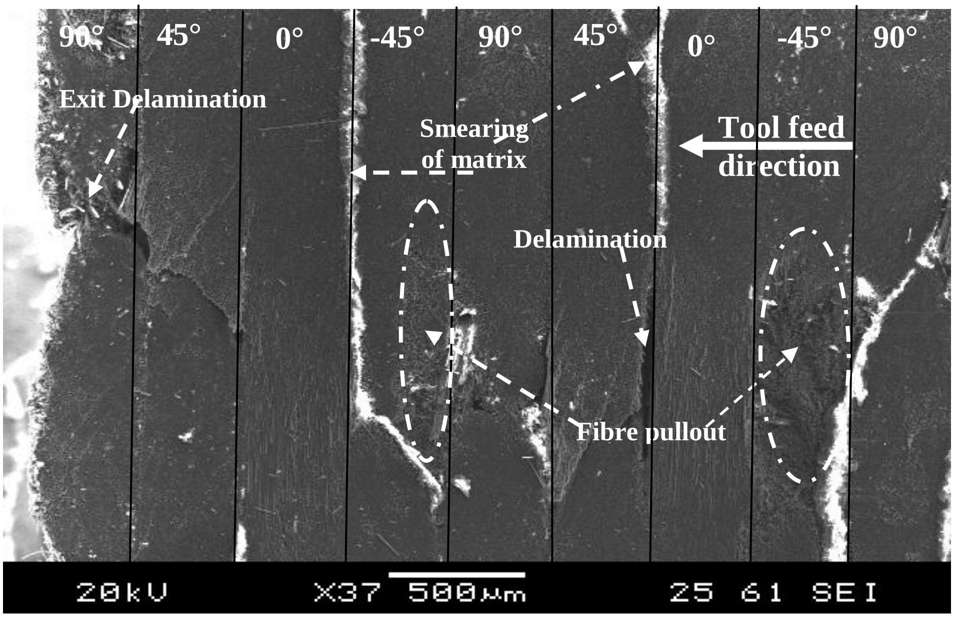

Figure7. SEM photographs of the damages observed of hole drilled.

Close-up view of the distribution of fibers at angles 90° is illustrated in Fig. 8a. The material removal is initiated by an opening, which the material penetrates below the cutting direction according to the interface fiber/matrix extended by a secondary rupture[12], that rises to the shear fibers, as shown in Fig. 8a.

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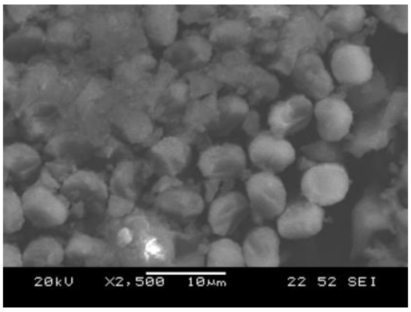
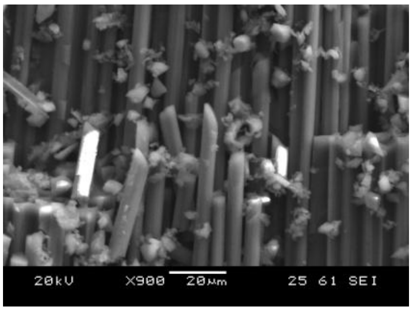
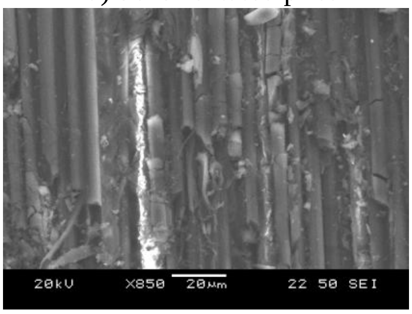
The SEM analysis can also illustrate at plies with -45º orientation, that the selected cross section hole surfaces cavities due to fiber pullouts were primarily concentrated, but causing a considerable damage on the surfaces (Fig. 7). At -45° fibers oriented cutting, as illustrated in Fig. 8b, the fibers are bend. Significant defects propagate inside the material and eventually pullout and tear the fibers, as mentioned in ref. [13].
Chips separation occurs after fibers rupture in a perpendicular direction to their axis. During the cutting of plies at 0° direction, the tool delaminates fibers easily which gives little defects as shown in Fig. 7. Machining of fibers at 0° can produce large fragmented debris. The fibers are stressed and induced buckling which causes cracking as shown in fig 8c.
For plies in the 45º orientations, the chip formation mechanisms begin with a shear of fibers and then a shear matrix, along the fiber/matrix interface to the free surface, as illustrated in Fig. 8d. During the cutting of the fibers oriented at 45°, the cutting tool reaches the layer directly and very small composite debris are formed shown in Fib.9.



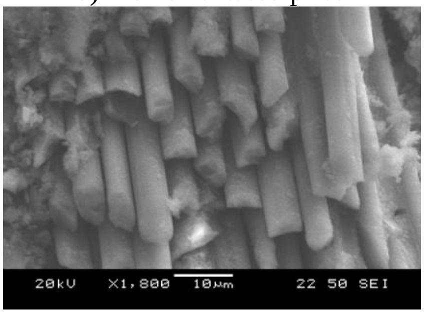
a) 90°orientated plies



b) -45° orientated plies

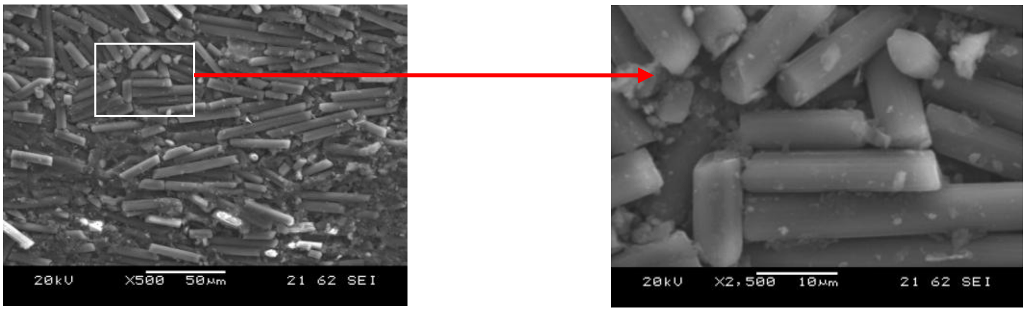


c) 0° orientated plies



d) 45° orientated plies

Figure 8. SEM photographs of fracture of the hole drilled at different orientated of fiber.



a) b)

Figure 9. SEM photographs of the chip CFRE.

6. Conclusions

Present work explain the application of RSM models to study the influence of machining parameters on thrust force, torque, exit delaminage factor and cylindricity error.
The relationship between the machining factors and the provide measured were modeled by quadratic regression. Three process factors: spindle speed, feed rate and tool materials were used for the

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development of the models. The RSM models were developed then tested using ANOVA. The actual models are found to be satisfied at 95% confidence interval to optimize the machining parameters. Through this analysis a conclusion about machining force, exit delamination factor and cylindricity error are deduced:

- Drilling forces were significantly influenced by tool materials. Since the degree of drilling force induced in the drilling process is associated with the power requirements, which is in turn correlated to production cost, low thrust force and torque are preferred.
- Coated carbide (WC-Ti) drills induced the lowest drilling forces, while HSS drills produced the highest drilling forces. Therefore, coated carbide drills present more advantages for CFRE composites drilling.
- The 3D response surface plots clearly indicate the existence of non-linear relationships between the process parameters, the machinability characteristics and thus justifying by using a quadratic model.
- Hence, it is clear that reduction of cylindricity error for drilling composite is at low spindle speed and high feed rate.

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