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Milling damage on Carbon Fibre Reinforced Polymer using TiAlN coated End mills

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Milling damage on Carbon Fibre Reinforced Polymer using TiAlN coated End mills

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Abstract. This paper reports on the damage caused by milling Carbon Fibre Reinforced Composite (CFRP) with 2-flute 4 mm-diameter solid carbide end mills, coated with titanium aluminium nitride. The machining parameters considered in work are, rotation speed, feed rate and depth of cut. Experiments were designed based on Box-Behnken design and the experiments conducted on a Mikrotool DT-110 CNC micro machine. A laser tachometer was used to ascertain a rotational speed for conducting any machining trial. Optical microscopy examination reveals minimum delamination value of 4.05 mm at the spindle speed of 25,000 rpm, depth of cut of 50µm and feed rate of 3 mm/min and the maximum delamination value of 5.04 mm at the spindle speed of 35000 rpm, depth of cut of 150µm and feed rate of 9 mm/min A mathematical model relating the milling parameters and delamination has been established.

1. Introduction

The desire to fabricate materials for light-weight applications has gained renewed interest in composite materials research. Research in the processing of reinforced composites in the recent years seems a gateway to producing light-weight materials. Global applications of fibre reinforced plastic (FRP) for example, include but not limited to marine transportation components, architectural cladding components, aerospace transportation and weapons components, automotive components, energy sector components (wind turbines) and static structural components (buildings/bridges). It well documented in literature that fiberglass, a type of fibre reinforced plastic, is the first modern composite materials. Nevertheless, although glass is a very strong material, it is however brittle and will break easily if bend sharply. Because of this disadvantage, advanced composites made of made carbon fibers are now used instead of glass. Carolin, A. [1] has referred to Fibre Reinforced Polymers (FRP) as composites, materials being formed from two or more separated parts with a distinguished phase between them. It has been reported [2, 3] that Fibre Reinforced Polymers (FRP) composites are lighter and stronger than fiberglass but it costs more to produce them. However, their light weights and high strength characteristics offer them possibilities to be used for making lighter cars and aircraft for less fuel consumption when compared with the heavier vehicles that are currently in use and for sports equipment such as golf clubs. It has also been reported [4] that Boeing 787 Dreamliner was the first world major commercial airliner that used composite materials for the construction of most of its parts.

Although Carbon Fibre Reinforced Plastics (CFRP) are lighter, yet stronger than those typically used, they pose challenges when it comes to machining such as milling and drilling. The materials are difficult to cut because they are very abrasive and tough, these characteristics obviously will affect both the work-piece and cutting tools. The damage on the machined CFRP referred here as delamination, is the separation of individual carbon fiber plies and it is difficult to prevent from occurring while machining. However these challenges have been met with some success with the use of hard, sharp solid-carbide milling cutters that employ special surface coatings. The work of Konneh et al [5] has demonstrated that CFRP can hardly be machined without inducing delamination.

This experimental investigation was done to study how machining parameters influence the production of delamination on milled CFRP using TiAlN coated end mills on a CNC micro machine with maximum rotational speed limited to 2500 rpm. Box-Behnken design of experiments was employed for the designing and analysis of the experiments. A mathematical model relating the milling parameters and delamination response has been established.

2. Experimental details

This section describes the work-piece and cutting tool materials, the experimental conditions, setup and procedure.

2.1 Work and Tool Materials, and experimental conditions

Locally prepared Carbon Fiber Reinforced Polymer (CFRP) by hand lay-up process, with dimensions of 50 mm x 50 mm x 3 mm, was used as the work-piece, Figure 1

The tools chosen for this experimental work are 2-flute 4 mm-diameter solid carbide end mills, coated with titanium aluminium nitride (TiAlN), Figure 2. The cutting tool was selected based on the recommendation from HPMT Cutting Tool Catalogue.

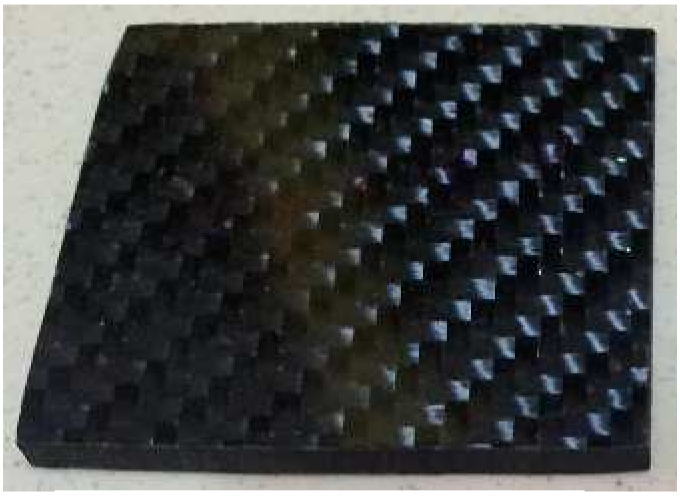

Figure 1. CFRP work-piece material

Figure 2. TiAlN used as cutting tools

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2.2 Experimental conditions

The machining variable for conducting the experiments are summarised in Table 1.

Table 1. Factors and levels in the design of experiments

Factors	Levels		
	Low	Medium	High
Spindle Speed (rpm)	15 000	25 000	35 000
Feed (mm/min)	3.00	9.00	15.00
Depth of Cut (μm)	50.00	100.00	150.00

2.3 Experimental Setup and Procedure

The Figure 3 depicts the setup for the experiments on a CNC Micro-machines having maximum rotational speed of 2500 rpm. To facilitate a high speeding machining, an air turbine was attached to the spindle of the machine to augment the speed of the Mikrotool machine. This could enable rotational speeds up to 50,000 RPM to be obtained. The locally prepared CFRP composite work-piece, consisted of 10 layers of carbon fiber, epoxy and hardener. The layers were compressed by a Universal Testing Machine with a compression force of 55 kPa and left to dry for 6 hours. Seventeen experiments were conducted based on the Box-Behnken experiment design. Straight cuts analogous to end milling were taken along the length of the work-piece. A laser tachometer (A DT 2336B) was used to ascertain a rotational speed for conducting any machining trial. 4 mm-diameter 2-fluted carbides coated with titanium aluminium nitride (TiAlN) were used to cut the work-piece based on the predetermined machining conditions. Delamination of the milled CFRP was determined in terms of the profile path of the surface integrity. Measurements of delamination were done on a Nikon Epiphot 200 Optical Microscope and the average value of the widths of the traversed path by the tool for each trial run noted. Some three points noted during a measurement are shown in the Figure 4.

Figure 3. Micro-machine (DT-110) that was used for experiments

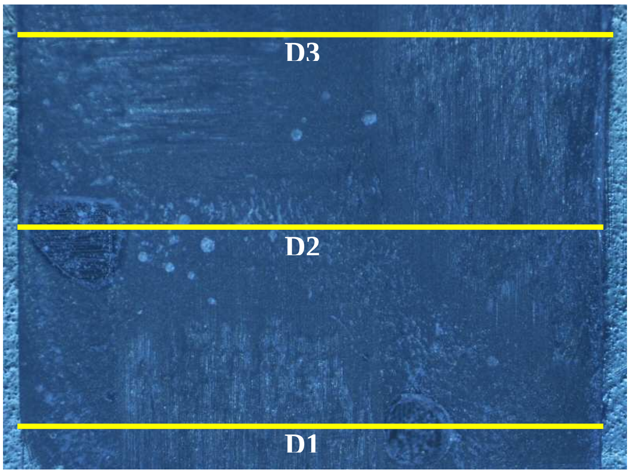

Figure 4. Delamination measurement method along the traversed path on the work-piece; D1, D2 and D3 denote the path widths after milling.

3. Results and discussion

The milling experiments that were conducted to study the effect of machining parameters on delamination are listed in Table 2. It is clearly seen in Table 3 depicting the analysis of variance (ANOVA) that, for the Model F-value of 12.86, the model is significant, thus there is only a 0.14% chance that such a "Model F-Value" could occur due to noise. Statistically, "Prob > F" values less than 0.0500 indicate model terms are significant. This being the case, it is clear that A, C, C^2, BC are the significant model terms. This means that there are some insignificant model terms, not considering those required to support hierarchy.In the light of this, a model reduction became a necessity for improvement, the improved (reduced model) shown in Table 4

In the reduced model (Table 4), the Model F-value of 16.69 implies that the model is significant and there is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. This F-value is better than that obtained (12.86) in the original ANOVA Table 3. In the reduced ANOVA (Table 4), it is evdent that A, C, C^2, BC are the significant model terms the fact that values of "Prob > F" less than 0.0500 statistically imply model terms are significant and values greater than 0.1000 indicating the model terms are not significant. The 1.42 "Lack of Fit F-value" implies the is not significant relative to the pure error. With this Lack of Fit value, is a 38.53% chance that it occur due to noise. A non-significant lack of fit is obviously preferred since it desirable for a model to fit. This is (38.53%) preferrable compared with the 49.78% in Table 3.

Based on statistics, the 0.6836 "Pred R-Squared" seems to be in a reasonable agreement with the 0.8306 "Adj R-Squared" in the Table 4. Also since the "Adeq Precision" measures the signal to noise ratio and a ratio greater than 4 is desirable, it can be concluded that the ratio of 13.640 here indicates an adequate signal. The fact that these statistical indicators in (Table 4) have proven better than the corresponding indicators in Table 3, was necessary to explore the design space for further analysis.

Normality of residuals is evident in the normal probability plot of the studentized residuals, Figure 4. It is also obvious in the Outlier t versus run order (Figure 5) that there are no outliers i.e., influential values. The model statistics and diagnostic plots being adequate, the Model Graphs, Figures 6 and 7 were examined.

Table 2. Box-Behnken designs showing 17 trial runs and response delamination.

Std	Run	Block	Factor 1 A:Rotational sp RPM	Factor 2 B:Feed rate mm/min	Factor 3 C:Depth of cut Microns	Response 1 Delamination mm
7	1	Block 1	15000.00	9.00	150.00	4.209
14	2	Block 1	25000.00	9.00	100.00	4.792
12	3	Block 1	25000.00	15.00	150.00	4.159
13	4	Block 1	25000.00	9.00	100.00	4.526
1	5	Block 1	15000.00	3.00	100.00	4.171
10	6	Block 1	25000.00	15.00	50.00	4.341
11	7	Block 1	25000.00	3.00	150.00	4.753
15	8	Block 1	25000.00	9.00	100.00	4.558
2	9	Block 1	35000.00	3.00	100.00	5.02
4	10	Block 1	35000.00	15.00	100.00	5.024
6	11	Block 1	35000.00	9.00	50.00	4.505
3	12	Block 1	15000.00	15.00	100.00	4.146
17	13	Block 1	25000.00	9.00	100.00	4.792
9	14	Block 1	25000.00	3.00	50.00	4.051
5	15	Block 1	15000.00	9.00	50.00	4.137
8	16	Block 1	35000.00	9.00	150.00	5.049
16	17	Block 1	25000.00	9.00	100.00	4.654

Table 3. Experimental results diagnosed by Analysis of Variance (ANOVA)

ANOVA for Response Surface Quadratic Model Response: Delamination

Analysis of variance table [Partial sum of squares]

Source		Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model		1.79	9	0.20	12.86	0.0014	significant
	A	1.08	1	1.08	69.80	< 0.0001	
	B	0.013	1	0.013	0.86	0.3857	
	C	0.16	1	0.16	10.46	0.0144	
	A^2	5.897E-003	1	5.897E-003	0.38	0.5559	
	B^2	0.052	1	0.052	3.40	0.1078	
	C^2	0.22	1	0.22	14.04	0.0072	
	AB	2.103E-004	1	2.103E-004	0.014	0.9103	
	AC	0.056	1	0.056	3.61	0.0992	
	BC	0.20	1	0.20	12.66	0.0092	
Residual		0.11	7	0.015			
Lack of Fit		0.045	3	0.015	0.95	0.4978	not significant
Pure Error		0.063	4	0.016			
Cor Total		1.89	16				

Std. Dev.	0.12	R-Squared	0.9430
Mean	4.52	Adj R-Squared	0.8696
C.V.	2.75	Pred R-Squared	0.5690
PRESS	0.82	Adeq Precision	11.529

Verification of the adequacy of the model is shown in the ANOVA Table 4 where the Model F-value of 16.69 implies the model is significant.

It can be observed in from the model graph in the Figure 6 showing the individual effects of the process machining parameters that the depth of cut and the rotational speed a considerable effect on delamination under investigation, while the feed rate virtually showing little effect on the same

Table 4. Reduced ANOVA for delamination

Response: Delamination — ANOVA for Response Surface Reduced Quadratic Model
Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	1.67	5	0.33	16.69	< 0.0001	significant
A	*1.08*	*1*	*1.08*	*53.72*	*< 0.0001*	
B	*0.013*	*1*	*0.013*	*0.66*	*0.4343*	
C	*0.16*	*1*	*0.16*	*8.05*	*0.0162*	
C²	*0.23*	*1*	*0.23*	*11.27*	*0.0064*	
BC	*0.20*	*1*	*0.20*	*9.75*	*0.0097*	
Residual	0.22	11	0.020			
Lack of Fit	*0.16*	*7*	*0.022*	*1.42*	*0.3853*	*not significant*
Pure Error	*0.063*	*4*	*0.016*			
Cor Total	1.89	16				

Std. Dev.	0.14	R-Squared	0.8835
Mean	4.52	Adj R-Squared	0.8306
C.V.	3.13	Pred R-Squared	0.6836
PRESS	0.60	Adeq Precision	13.640

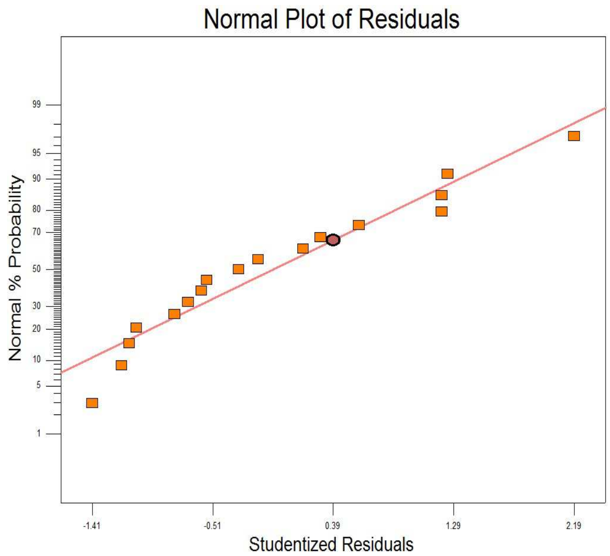

Figure 5. The normal plot of residuals

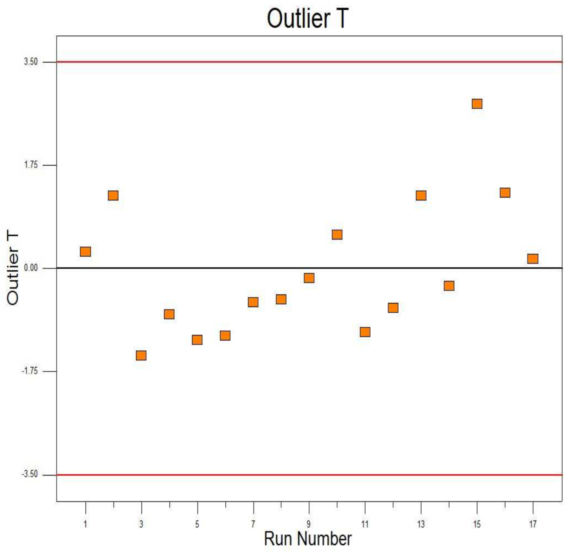

Figure 6. The outlier plot indicating the trial runs are within range.

response variable. Also, taking the cutting tool diameter into consideration, it is evident from the graph that high rotational speed is not a necessary condition for minimising delamination defects at a machined work-piece surface, while taking the tool diameter into consideration. The ANOVA (Table 4) clearly reveals interaction effect between depth of cut (C) and feed rate (B) parameters, the effect which is depicted in both 2D and 3D in the Figures 7 and 8 respectively. Such interaction effect seemed to have caused the feed rate to almost has negligible effect on the machining process.

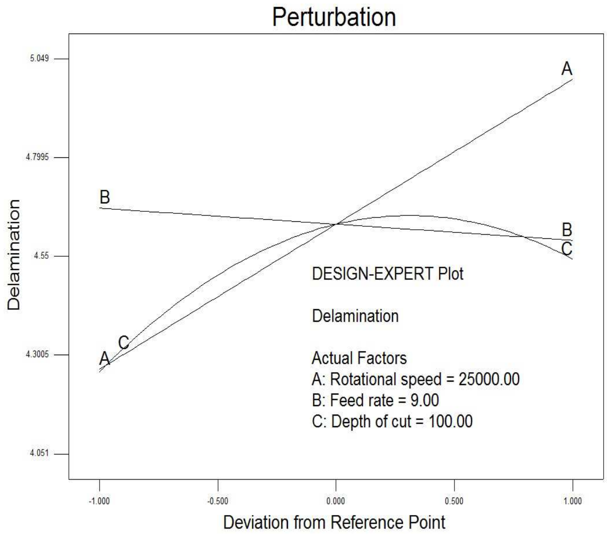

Figure 7. A plot of individual effects of the machining parameters

It seems that the level of depth of cut has an effect of feed rate, when the depth of cut is high, delamination becomes smaller. When the depth of cut is low delamination becomes relatively higher. Such a behaviour has likely hindered a meaningful contribution of the feed rate to the response variable during the machining process. Figure 8 is the 3D plot exemplifying the factor reaction.

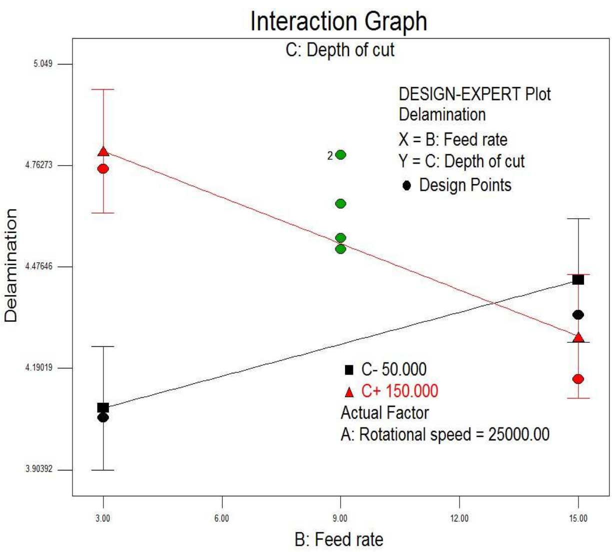

Figure 8. A plot of individual effects of feed rate and depth of cut.

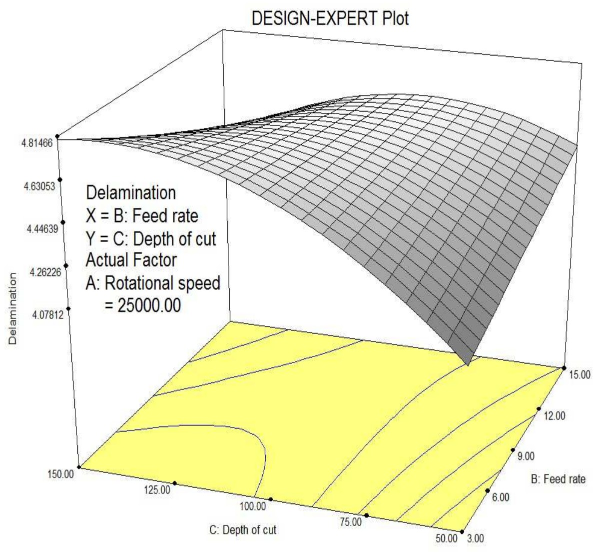

Figure 9. The 3D plot of the interaction effect of feed rate and grit size

A mathematical model is used to relate the response variable (D) and the milling parameters represented by:

$$D = f\,(A, B, C) \qquad (1)$$

where *D* is Delamination; *f* function of, *A* rotational speed; *B* feed rate and *C* depth of cut. It is observed that a second order model suitable to relate delamination and the milling parameters tested under study. In the light well established procedure [6] for predicting first and second order models the model equation (2) is predicted based on the experimental results obtained in this study.

$$\text{Delamination (D)} = +\,4.63+0.37A - 0.041B +0.14C - 0.23C^2 -0.22BC. \qquad (2)$$

where the variables A, B and C are defined above.

4. Conclusion

The following conclusions can be drawn from the experiments that were conducted when CFRP was milled using2-flute 4 mm diameter carbide end mills coated with TiAlN:

- It has been observed that rotational speed and depth of cut have marked effect on delamination, when the feed rate has little effect on the response variable.
- Optical microscopy examination reveals minimum delamination value of 4.05 mm at moderate spindle speed of 25000 rpm, low depth of cut (50µm) and low feed rate (3 mm/min); the maximum delamination value of 5.04 mm at the spindle speed (35000 rpm), depth of cut (150µm) and feed rate (9 mm/min).
- A mathematical model predicted for delamination for the range of machining parameters used in the study is presented by:

  $\text{Delamination (D)} = +\,4.63+0.37A - 0.041B +0.14C - 0.23C^2 -0.22BC$

  where D is Delamination, A rotational speed; B feed rate and C depth of cut
- High rotational speed and moderate depth of cut combination is likely to yield a favourable delamination when a Carbon Fibre Reinforced Plastic is milled with a TiAlN coated tool.

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