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The Effect of Machining Parameters on Drilling Induced Delamination of Carbon Fiber Reinforced Polymer Composite

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Abstract

Delamination is one of the most common defects occur during drilling of carbon fiber reinforced polymer composites. It is an inter-ply failure phenomenon and it has to be minimized to have better quality of drilled holes for structural applications. The current study is conducted to investigate the effect of machining parameters (spindle speed, drill diameter, feed rate and point angle) on delamination while drilling of 60-40 weight % and 55-45 weight % of bi-directional carbon fiber reinforced polymer (BD CFRP) composites with titanium nitride (TiN) coated solid carbide drills. Taguchi L_{27} orthogonal array is used for determining the experimental results of delamination and the Taguchi methodology is also employed for determining the predicted results of delamination of both BD CFRP composite laminates. The investigation reveals that there is a good concurrence between the experimental and the predicted results of delamination. The main effect plot shows that the drill diameter has a significant effect on delamination as compared to the effect of spindle speed and feed rate. The point angle has an insignificant influence on delamination in drilling of BD CFRP composites. It is evident from the investigation that 45 weight % of resin content of BD CFRP composite gives lesser delamination as compared to the composite containing 40% of resin. Hence, 45-55 weight % of BD CFRP composite laminate can be a better choice for structural applications in industries.

Keywords: carbon fiber reinforced polymer composite; delamination; drilling; orthogonal array; solid carbide drills; Taguchi methodology.

INTRODUCTION

Drilling is one of the key machining operations used in carbon fiber reinforced polymer (CFRP) composites for preparing structural joints [1]. Because of the special characteristics such as non-homogeneity, anisotropy and abrasiveness, machining of CFRP composites differ substantially from the machining of conventional alloys and metals [2, 3]. Some of the most commonly facing problems occur during drilling of CFRP composites are fiber de-bonding, breakage, fiber pull-out, thermal damage, micro cracking and delamination at the entry and the exit layers [4]. Amongst these problems, delamination is considered as a key defect in the structure of the composite which reduces the assembly strength and tolerance of the finished components and thus, degrades its stability and reliability [5]. Therefore, a high quality machining is necessary to reduce the damage due to delamination in drilling of composite laminates.

Since CFRP composites are having exclusionary mechanical properties such as high strength and stiffness, low weight, high damping, excellent fatigue and corrosion resistance and low thermal expansion, they are the perfect materials which can replace most of the metal structures in automobile, aerospace, defence and marine industries [6, 7]. In the last few decades, the results of research and experimentations show that glass fiber reinforced polymer (GFRP) composite and CFRP composite laminates are commonly used in the industries for structural applications [8, 9].

It is well-known that drilling induced delamination in CFRP composites is the most commonly found inter-ply failure phenomenon that not only affects the reliability of the structure but also causes the degradation in the load carrying capacity of the composite structures. The study shows that 60% of the total rejections occurring in the final assembly of an aircraft are mainly due to drilling associated delamination [10, 11]. Performance of the composite is drastically reduced due to delamination, micro-cracking and stress concentration [12]. The main focus of the current research is to identify the optimum machining parameters for minimum delamination in drilling of BD CFRP composites with TiN coated carbide drills and to suggest the best combination of reinforcement and resin content of BD CFRP composite for structural applications. The reason for fabricating the BD CFRP composites is that they have maximum strength and stiffness due to the orientation of fibers in both X and Y direction.

METHODOLOGY

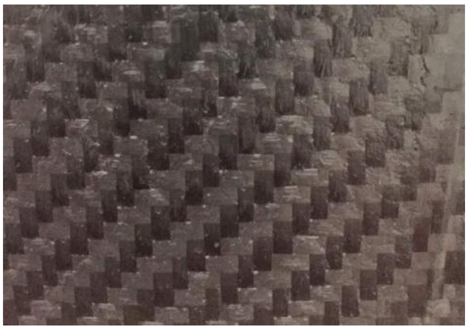
Material preparation

The bi-direction carbon fiber reinforced polymer (BD CFRP) composite laminates (300 mm × 300 mm × 4 mm) are fabricated at room temperature by hand lay-up process (Fig.1) followed by compression moulding technique. The Fig.2 shows the compression moulding machine used in the present study. Bisphenol A based epoxy resin 520 and hardener Amino K-6 is used for the preparation of matrix and the bi-directional plain weave type carbon fiber is used as reinforcement.

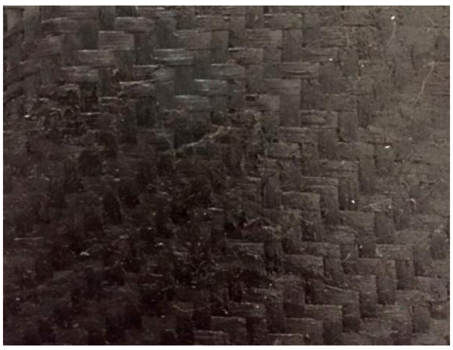
Figure 1: Hand lay-up process

The resin content of the composites is maintained at 40 and 45 weight %. A brush and a roller is used for applying the resin mixture onto the different layers of the carbon fiber which is then pressed in the hydraulic compression moulding machine with a pressure of 0.5 MPa for about 24 hours at room temperature. The post curing of the composite laminates is carried out for about eight hours at 80°C. The Fig. 3 shows the samples of fabricated BD CFRP composites. The mechanical properties of BD CFRP composites are shown in Table 1. From the Table 1, it is observed that 55-45 weight % of BD CFRP composite shows better mechanical properties as compared to that of 60-40 weight % of BD CFRP composite. This may be due to the fact that in 55-45 weight % BD CFRP composite may have less number of voids.

Figure 2: Compression moulding machine



(a)



(b)

Figure 3: BD CFRP composite (a) with 45% resin content (b) with 40% resin content

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Table 1: Mechanical properties of BD CFRP composites

Material	Density (g/cm^3)	Vickers hardness (H_v)	Tensile strength at break (MPa)	Young's modulus Secant (GPa)	Young's modulus Tangent (GPa)	Elongation at break (%)	Flexural strength (MPa)	Flexural modulus (MPa)	Interlaminar shear strength (MPa)
55-45 wt.%	1.295 (1.30)*	23.34	424.25	7.37	8.86	12.29	104.10	801.97	14.42
60-40 wt. %	1.282 (1.30)*	22.34	419.25	6.87	7.60	11.24	102.21	798.32	12.56

*Theoretical density

Taguchi method

Taguchi method is used for analyzing the effect of each machining/cutting parameter on delamination and to predict the drilling induced delamination factors for confirming the accuracy of the experimental results of delamination. The Taguchi analysis is carried out using MINITAB software (version 15) and the L_{27} orthogonal array of Taguchi is employed for conducting the experiments. The signal-to-noise (S/N) ratio (smaller the better) is used for selecting the optimum machining parameters and is shown in the equation given below [13].

$$S/N=-10*\log 1/n\ ((\Sigma Y^2) \qquad (1)$$

where, n is the number of trials and y is the experimental data.

The machining parameters and the levels chosen for performing the experiments are given in Table 2.

Figure 4: Vertical machining center

Table 2: Machining parameters and levels

Levels	Spindle speed (rpm) (A)	Feed rate (mm/min) (B)	Point angle (degree) (C)	Drill diameter (D)
1	1200	10	90	4
2	1500	15	104	6
3	1800	20	118	8

(a) (b) (c)

Figure 5: TiN coated solid carbide tools (a) 4 mm (b) 6 mm and (c) 8 mm

Measurement of delamination

The drilling experiments are carried out using a CNC vertical machining centre (Fig. 4) with TiN coated solid carbide tools of 4, 6 and 8 mm diameters for measuring delamination. The Fig. 5 shows the different sizes of the drill bits used in present study.

A high resolution scanner (Model: HP Scanjet G4010, Hewlett-Packard Company, USA) is used for scanning the drilled holes and the dimension of the drilled holes is measured with the help of Trimos Labconcept Premium Co-ordinate measuring machine (CMM) which is shown in Fig. 6.

The delamination factor (F_d) of BD CFRP composite laminates is calculated using the equation given below:

$$F_d= D_{max}/D_{nom} \qquad (2)$$

where, D_{max} is the maximum delaminated diameter and D_{nom} is the nominal diameter of the drilled hole.

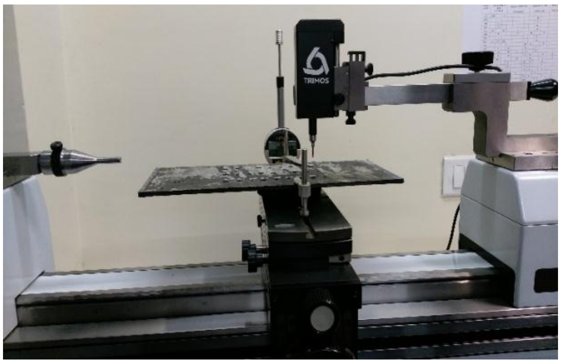


Figure 6: Co-ordinate measuring machine

RESULTS AND DISCUSSION

Analyses of delamination

The delamination during drilling of composite seriously affects the structural integrity of the system [14]. Therefore, it is required to minimize the delamination for maintaining the stability and integrity of the structural assembly. The experimental and the predicted results of delamination for 40 and 45 weight % of resin content of BD CFRP composites are presented in Table 3.

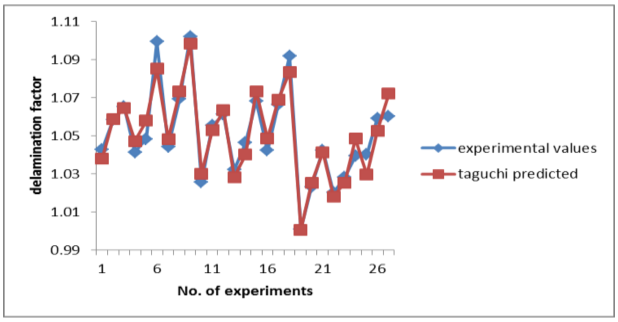
Table 3: Delamination factors of BD CFRP composites

Trial No.	40% resin content			45% resin content		
	F_d(expt)	F_d(predt)	Error %	F_d(expt)	F_d(predt)	Error %
1	1.0428	1.0380	0.4624	1.0101	1.0125	-0.2399
2	1.0583	1.0585	-0.0273	1.0399	1.0417	-0.1670
3	1.0652	1.0644	0.0723	1.0812	1.0807	0.0508
4	1.0413	1.0472	-0.5634	1.0210	1.0195	0.1432
5	1.0482	1.0579	-0.9169	1.0661	1.0646	0.1371
6	1.0992	1.0850	1.3087	1.0893	1.0828	0.5966
7	1.0442	1.0483	-0.3911	1.0210	1.0217	-0.0704
8	1.0693	1.0732	-0.3624	1.0462	1.0547	-0.8068
9	1.1020	1.0981	0.3551	1.1002	1.0967	0.3173
10	1.0256	1.0301	-0.4358	1.0099	1.0109	-0.1028
11	1.0553	1.0528	0.2374	1.0376	1.0448	-0.6853
12	1.0612	1.0633	-0.1984	1.0775	1.0750	0.2269
13	1.0321	1.0283	0.3734	1.0047	1.0074	-0.2729
14	1.0462	1.0401	0.5864	1.0562	1.0566	-0.0378
15	1.0682	1.0733	-0.4770	1.0832	1.0837	-0.0442
16	1.0422	1.0485	-0.5999	1.0193	1.0182	0.1119
17	1.0662	1.0688	-0.2432	1.0452	1.0424	0.2695
18	1.0917	1.0835	0.7558	1.0896	1.0842	0.5008
19	1.0010	1.0007	0.0269	0.9862	0.9827	0.3530
20	1.0231	1.0251	-0.1951	1.0296	1.0207	0.8729
21	1.0425	1.0413	0.1190	1.0569	1.0599	-0.2830
22	1.0201	1.0180	0.2033	0.9891	0.9878	0.1305
23	1.0282	1.0253	0.2818	1.0272	1.0283	-0.1030
24	1.0393	1.0484	-0.8642	1.0491	1.0551	-0.5667
25	1.0400	1.0296	1.0101	1.0001	1.0005	-0.0419
26	1.0591	1.0526	0.6165	1.0351	1.0294	0.5537
27	1.0600	1.0721	-1.1277	1.0536	1.0625	-0.8385

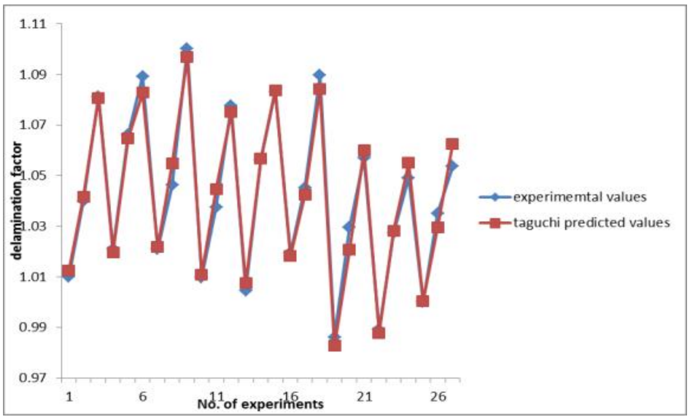
F_d (expt)=Experimental delamination factor and F_d (predt)=Predicted delamination factor

From the Table 3, it is noticed that the percentage error values of delamination factor in the prediction by Taguchi method is between -1.1277 to 1.3087 in 40 weight percentage resin content of BD CFRP composite and -0.8385 to 0.8729 in 45 weight percentage resin content of BD CFRP composite in drilling with TiN coated solid carbide drills. This shows that the percentage range of errors deduced from both BD CFRP composites are very much within the permissible limit of accuracy for any prediction system. It is also noticed from the Table 3 that the minimum values of delamination factor (Trial no. 19) are achieved at spindle speed of 1800 rpm, point angle of 108 degree, drill diameter of 4 mm and feed rate of 10 mm/min both in 60-40 and 55-45 weight % of BD CFRP composites. This indicates that drilling induced delamination decreases with increase in spindle speed and decreases with decrease in drill diameter and feed rate. Generally, the point angle has a negligible impact on delamination. The increase in spindle speed increases the temperature while drilling of composites. This increase in temperature helps for softening of the matrix material and thus, reduces the delamination during the drilling of composites [15-17]. The increase in drill diameter and feed rate accelerates the delamination during drilling of composite due to increase in thrust force and torque [18,19].

It is evident from the Table 3 that the experimental and the predicted values of delamination factor obtained in 60-40 weight % BD CFRP composite is less than 1.1020 and 1.0981 respectively, and in 55-45 weight % of BD CFRP composite, it is less than 1.1002 and 1.0967 respectively. This minimum values of delamination obtained while drilling of BD CFRP composites is may be due to the fact that the TiN coating acts as a lubricant while drilling and thus, induces lesser cutting forces (thrust force and torque). Since the cutting forces have a direct relationship with delamination, reduction in thrust force and torque reduces the delamination and thereby improve the quality of the drilled holes [20, 21]. It is also evident from Table 3 that the majority of the delamination factor values obtained from both experimental and Taguchi predicted are less in 55-45 weight % of BD CFRP composite as compared to 60-40 weight % BD CFRP composite laminate. Therefore, 55-45 weight % of BD CFRP composite can be a good option for structural applications in the manufacturing sectors.



(a)



(b)

Figure 7: Correlation of experimental and predicted results of delamination for (a) 60-40 weight % and (b) 55-45 weight % of BD CFRP composite

The Fig. 9(a, b) illustrates the relationship between the experimental and the Taguchi predicted values of delamination factor. From the Fig.9 (a, b), it is seen that the experimental results of delamination factor and the Taguchi predicted results of delamination factor are in good agreement. Hence, it is clear from the investigation that Taguchi method can be efficiently used for predicting the delamination in drilling of composite materials.

Main effect plot for delamination

The Fig. 10 (a, b) shows the main effect plot of BD CFRP composites for delamination while drilling with TiN coated solid carbide drills. From Fig.10 (a, b), it is clear that drill diameter and spindle speed have a significant influence on delamination compared to the effect of feed rate on delamination as the slope of the drill diameter and spindle speed is more in both 60-40 and 55-45 weight % of the BD CFRP composites. It is also clear from the Fig.10(a, b), that the point angle has a negligible effect on delamination as the slope of the point angle is almost horizontal. The optimum machining parameters required for minimum delamination given by the main effect plot (Fig.10 a) for 60-40 weight % of BD CFRP composite laminate are drill diameter of 4 mm, spindle speed of 1800 rpm, feed rate of 10 mm/min and point angle of 180 degree, whereas, in 55-45 weight % of BD CFRP composite laminate (Fig. 10 b) the optimum process parameters for minimum delamination are drill diameter of 4 mm, spindle speed of 1800 rpm, feed rate of 10 mm/min and point angle of 90 degree.

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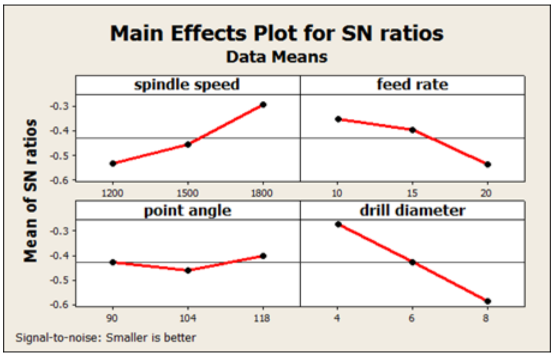
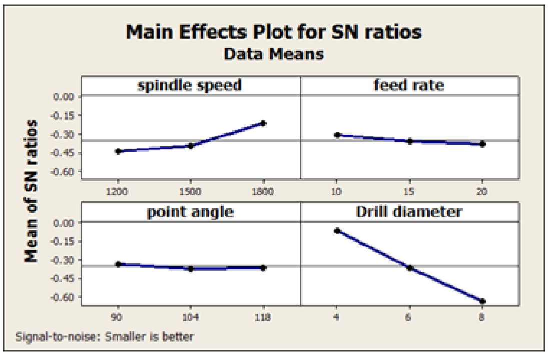


(a)

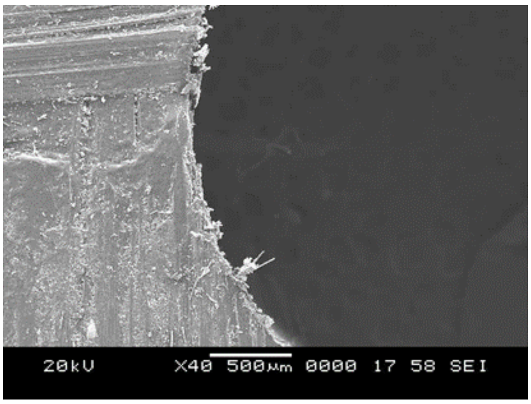


(b)

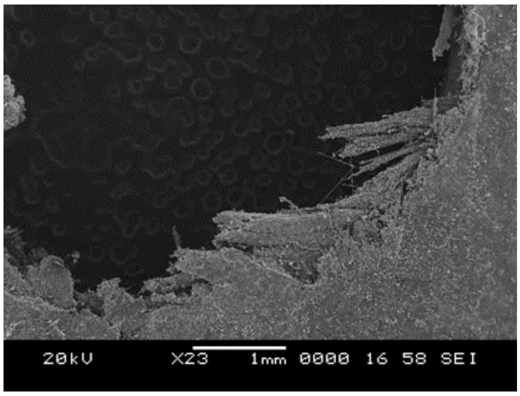
Figure 8: Main effect plot for (a) 60-40 weight % and (b) 55-45 weight % of BD CFRP composite

Morphological study

The microscopic level of investigation of drilled holes helps to identify some of the defects occurred in drilling of composite materials. The Fig.11 (a, b) shows the sample of SEM pictures of the drilled holes of both BD CFRP composite laminates. The minimum delamination and fiber pull-out is seen in 55-45 weight % of BD CFRP composite (Fig. 11a) as compared to that of 60-40 weight % of BD CFRP composite (Fig.11b) while drilling with TiN coated solid carbide drills. It may be due to the fact that cutting action is dominating over the ploughing action while drilling of 55-45 weight % of BD CFRP composite laminate [22].



(a)



(b)

Figure 9: SEM pictures of drilled hole at spindle speed of 1200 rpm, feed rate of 20 mm/min, drill diameter of 8 mm and point angle of 118 degree for (a) 55-45 weight % (b) 60-40 weight % of BD CFRP composite

Confirmation test

The results of the confirmation test carried out for optimal machining parameters for both 60-40 weight % and 55-45 weight % of BD CFRP composites during drilling are presented in Table 4. From the Table 4, it is seen that both the experimental and the predicted results of delamination factor deduced for optimal process parameter are less than the delamination factors obtained from the Taguchi L_{27} orthogonal array and the Taguchi prediction method. It is also seen from the Table 4 that the experimental and the predicted results of delamination factors of both the composite materials are in good agreement. From the confirmation test it is concluded that the better quality of holes can be drilled using the optimum process parameters mention in Table 4 with minimum cost and time by using TiN coated solid carbide drills.

Table 4: Results of delamination obtained for optimal machining parameters

BD CFRP composite (weight%)	Optimal machining parameters	Experimental F_d	Prediction F_d	% of agreement
55-45	$A_3 B_1 C_1 D_1$	0.9652	0.9762	98.87%
60-40	$A_3 B_1 C_3 D_1$	1.00037	1.00064	99.97%

A_3=1800 rpm, B_1=10 mm/min, C_1=90 degree, D_1=4 mm, C_3=118 degree

CONCLUSIONS

The following are the conclusions derived from the study:

1. The investigation shows that the experimental and the Taguchi predicted results of delamination deduced during

drilling of BD CFRP composites using TiN coated drills are closely matches with each other. Hence, the Taguchi method can be effectively used as a tool for predicting drilling induced delamination.

2. The study reveals that the 55-45 weight % of BD CFRP composite laminate gives better mechanical properties than 60-40 weight % of BD CFRP composite laminate.

3. The optimum machining parameters given by the Taguchi main effect plot for SN ratios helps for drilling better quality of holes with minimum delamination.

4. The study demonstrated that drill diameter has a momentous influence on delamination as compared to spindle speed, feed rate and point angle during drilling of BD CFRP composites with TiN coated solid carbide drills.

5. The confirmation test confirms the truth fullness of the experimental results of delamination factor deduced from Taguchi L_{27} orthogonal array and Taguchi method.

6. It is evident from the SEM images that the delamination and the fiber pull-out are more in 60- 40 weight % of BD CFRP composite as compared to that of 55-45 weight % of BD CFRP composite. Hence, 55-45 weight % of BD CFRP composite is a better option for structural applications.

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