EVALUATION OF DRILLING INDUCED DELAMINATION OF CARBON FIBER REINFORCED POLYMER COMPOSITE USING SOLID CARBIDE DRILLS

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Abstract

Delamination in drilling is an inter-ply failure phenomenon and has been recognized as the most common defect in drilling of carbon fiber reinforced polymer composites. This problem can affect not only the load carrying capacity of the produced-parts but also the reliability. In the present work, an attempt has been made to study the influence of process parameters (spindle speed, drill diameter, feed rate and point angle) on delamination in drilling of bi-directional carbon fabric reinforced polymer (BD CFRP) composite using uncoated and TiN coated solid carbide drills. Taguchi design of experiments (DOE), response surface methodology (RSM) and analysis of variance (ANOVA) techniques are employed for investigating the effects of process parameters on delamination. The results indicate that drill diameter has a significant influence on delamination, followed by spindle speed and feed rate. It is evident from the study that the experimental results of delamination factor are in good approximation with the predicted results as per RSM. The study reveals that the TiN coated solid carbide drills are preferred to uncoated solid carbide drills in reducing the drilling induced delamination. Furthermore, the study also reveals that the optimum parametric conditions required for minimum delamination in drilling of BD CFRP composite are drill diameter of 4 mm, feed rate of 10 mm/min, spindle speed of 1800 rpm and point angle of 90°.

Keywords: Solid carbide, Taguchi design of experiments, Response surface methodology, delamination, polymer composite, Analysis of variance.

1. Introduction

Carbon fiber reinforced polymer (CFRP) composites are widely used in industries such as spacecraft, aircraft, automotive, railway, naval, sports and many others, due to their unique properties like low weight, high strength and stiffness, excellent fatigue and corrosion resistance and low thermal expansion (Guu 2011) (Arul 2006). The merit of using CFRP composite laminate in dynamic structures is that there is a considerable reduction in weight and consequently, an improvement in their characteristics and performance. Machining operations in CFRP composites can be performed using conventional machinery with adaptations. Among machining operations, drilling is one of the frequently used operations to make quality holes for structural joints. Since composites are neither homogeneous nor isotropic, drilling causes specific problems in the region around the hole. The most commonly occurring defects in drilling are delamination, fibre pull-out, inter-laminar cracking, de-bonding, fiber breakage, etc., (Koplar 1983).

Among the problems caused by drilling, the delamination is considered to be a major defect in composite structure. It was reported that, in aircraft industries, the rejection of components due to drilling induced delamination was as high as 60% (Stone 1996). Therefore, the delamination tendency needs greater attention during drilling of composites. The thrust force generated in drilling was one of the key indexes to describe machinability of composite laminates owing to the fact that it directly affects the quality of drilled holes, especially drilling induced delamination (Zitoune 2007). The delamination was found to occur at tool entry or tool exit. The tool exit delamination was found to be related to the thrust force generated during drilling and there was a positive linear correlation between drilling - induced delamination and thrust force for various drill bits (Hockeng 2006). Higher thrust force induces more extensive delamintion to the workpiece (Hockeng 2003). The influence of machining parameters on specific cutting pressure, delamination and cutting power in carbon fibre reinforced plastics was investigated and concluded that the feed rate had a significant influence on thrust force, so the damage increased with feed rate (Devim 2003).

The objective of the present study is to analyze the influence of process parameters such as drill diameter, spindle speed, tool feed rate and point angle on delamination through the integration of Taguchi DOE, ANOVA, and RSM in drilling of BD CFRP composite laminate with uncoated and TiN coated solid carbide drills. The reason for selecting BD CFRP composite is that in BD CFRP composite lamina, the orientation of fibers is in both X and Y direction, whereas in UD CFRP composite lamina, fibers are arranged in only one direction. Due to this, a better interface between the lamina can be observed in BD CFRP composite and also has less number of voids as compared to multi-layer UD CFRP composite. Lesser void content in BD CFRP composite is a significant factor for its higher strength due to lower stress concentration at voids. This results in higher tensile and flexural properties in BD CFRP composite as compared to UD CFRP composite.

2. Experimental

2.1 Preparation of test specimen

The BD CFRP composite specimen of 200 mm × 200 mm × 4 mm is fabricated by the hand lay-up process followed by compression moulding technique at room temperature. The bi-directional plain weave type carbon fabric of areal density of 200g.m^{-2} is used as reinforcement. The resin used for the preparation of matrix is Bisphenol A based epoxy resin L-12 and the hardener used is Amino K-6. The resin content of the composite laminate is maintained around 50 wt %. The resin mixture is applied onto each layer by using a brush and a roller. The matrix resin impregnated fabric stock is pressed in a hydraulic press under a pressure of 0.5 MPa for about 24 hours at room temperature. The hand lay-up process and the compression moulding machine are shown in Fig.1.

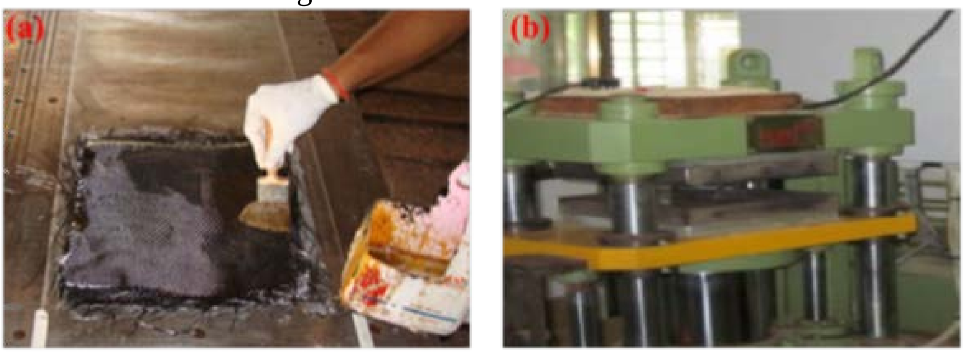

Fig. 1. (a) Hand lay-up process and (b) Compression moulding machine

The post curing of the composite laminate is carried out for about eight hours at 80°C. The drilling experiments are carried out using CNC vertical machining centre as shown in Fig.2.

Fig. 2. Experimental setup

The uncoated and TiN coated solid carbide drill bits with different diameters used in the present study are shown in Fig. 3. A high resolution scanner (HP make, 4800 dpi) is used for measuring the delamination factor of the drilled hole. The dimensions of the scanned images of the drilled hole are measured with the help of CATIA software (Fig.4). The delamination factor (F_d) is estimated using the Eqn.1.

$$F_d = D_{max}/D_{nom} \quad (1)$$

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

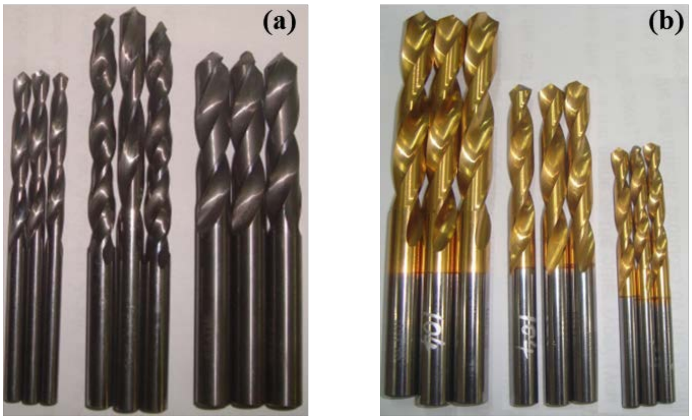

Fig. 3. Photograph of (a) Uncoated solid carbide drills and (b) TiN coated solid carbide drills

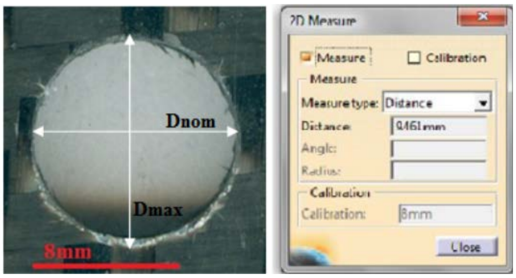

Fig. 4. Delamination measurement using CATIA

2.2 Taguchi method

The Taguchi DOE method is used to formulate the experimental layout, analyse the effect of each cutting parameters, and to minimize the number experiments in order to reach optimum conditions. Hence, it has gained a wide popularity in engineering and scientific community (Montgomery 2005). Taguchi recommends the analysis of the means and signal-to-noise (S/N) ratio using the conceptual approach that involves graphing the effects and visually identifying the factors that appear to be significant (Montgomery 2005). Taguchi analysis is made by using software known as MINITAB 15.

In the present study, L_{27} orthogonal array and the S/N ratio characteristic (smaller is the better) are employed to identify the optimum cutting parameters for minimum delamination. S/N ratio characteristic (smaller is the better) is given in the Eqn. 2.

$$\frac{S}{N} = -10\log\frac{1}{n}\left(\sum y^2\right) \tag{2}$$

where, n is the number of observations and y is the observed data. The factors and levels chosen for conducting the drilling experiments are presented in Table 1.

Table 1 Level and factors of process parameters.

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

2.3 Response surface methodology

The response surface methodology (RSM) is a statistical tool used for modelling and analysing problems in which a response of interest is influenced by several variables. In the present work, the central composite design (CCD) of RSM is used for establishing empirical relationships among the process parameters (Myers 1995). The RSM model chosen for predicting the delamination factor (F_d) can be expressed as follows:

F_d with solid carbide = 0.142669+ 0.000550418A + 0.0128512B + 0.00453397C + 0.0745416D – 2.02862$E^{-07}A^2$ – 1.50303$E^{-04}B^2$ – 2.42733$E^{-05}C^2$ – 0.00368939D^2 – 9.16667E^{-07}AB + 5.35714E^{-07}AC – 8.75000E^{-06}AD – 2.32143E^{-05}BC – 4.62500E^{-04}BD + 5.35714E^{-05}CD (3)

F_d with TiN coated solid carbide = 0.694763 + 9.67773E^{-05}A + 0.00485382B + 0.00370825C + 0.0231316D – 3.92256$E^{-08}A^2$ – 1.21212$E^{-06}B^2$ – 1.80118$E^{-05}C^2$ + 0.000242424D^2 – 6.25000E^{-07}AB + 1.48810E^{-08}AC – 8.85417E^{-06}AD – 9.82143E^{-06}BC – 1.18750E^{-04}BD + 1.11607E^{-05}CD (4)

3. Results and discussion

3.1. Analysis of delamination using Taguchi and RSM

The delamination is a measure of the quality of the drilled holes, which in turn is primarily dependent on the thrust force. In general, delamination can be reduced by minimizing the axial thrust force exerted by the drill chisel edge. The present work focuses on the performance evaluation of uncoated and TiN coated solid carbide drills during drilling of BD CFRP composite. The reason for selecting the solid carbide drills in this study is that they produce smaller thrust force compared to both HSS and polycrystalline diamond tools during drilling operation. The minimum thrust force generated during drilling of composite results in minimum delamination.

The experimental and the predicted results of delamination factor of BD CFRP composite with uncoated and TiN coated solid carbide drills are presented in Table 2 and Fig. 5. It is observed from the table and the figure that there is a close approximation between the experimental results and the predicted results of delamination factor as per RSM with a deviation of less than 5%. Therefore, it is concluded that RSM can be effectively used for predicting the numerical results of delamination factor in drilling of BD CFRP composite using both uncoated and TiN coated solid carbide drills. The Fig. 6 illustrates the comparison of experimental results of delamination factor for uncoated and TiN coated solid carbide drills in drilling of BD CFRP composite. From the figure it is clear that the values of delamination factor obtained for TiN coated solid carbide drills are comparatively lesser than that obtained for uncoated solid carbide drills. This is due to the fact that TiN coating may acts as lubricant that reduces the stick-slip friction at the interface of the tool and the workpeice. It is also clear from the scanned images (Fig.7) that the delamination caused by uncoated solid carbide drill is more as compared to that caused by TiN coated solid carbide drill during drilling of BD CFRP composite.

Table 2 Experimental and predicted results of delamination factor

	Solid carbide		TiN coated solid carbide	
Trial No.	Experimental	RSM Predicted	Experimental	RSM Predicted
1	1.065	1.059	1.050	1.046
2	1.113	1.114	1.072	1.076
3	1.130	1.139	1.105	1.107
4	1.102	1.084	1.077	1.075
5	1.130	1.136	1.105	1.103
6	1.146	1.158	1.121	1.134
7	1.123	1.089	1.108	1.097
8	1.148	1.137	1.121	1.125
9	1.164	1.156	1.138	1.155
10	1.061	1.070	1.037	1.037
11	1.105	1.121	1.070	1.061
12	1.123	1.142	1.101	1.088
13	1.082	1.085	1.075	1.058
14	1.128	1.132	1.097	1.081
15	1.146	1.151	1.121	1.107
16	1.094	1.092	1.069	1.074
17	1.126	1.132	1.101	1.096
18	1.141	1.143	1.126	1.120
19	1.047	1.039	1.024	1.013
20	1.070	1.086	1.045	1.033
21	1.097	1.104	1.072	1.054
22	1.058	1.044	1.033	1.030
23	1.082	1.084	1.058	1.048
24	1.112	1.094	1.082	1.067
25	1.075	1.062	1.050	1.057
26	1.104	1.098	1.087	1.074
27	1.121	1.105	1.107	1.093

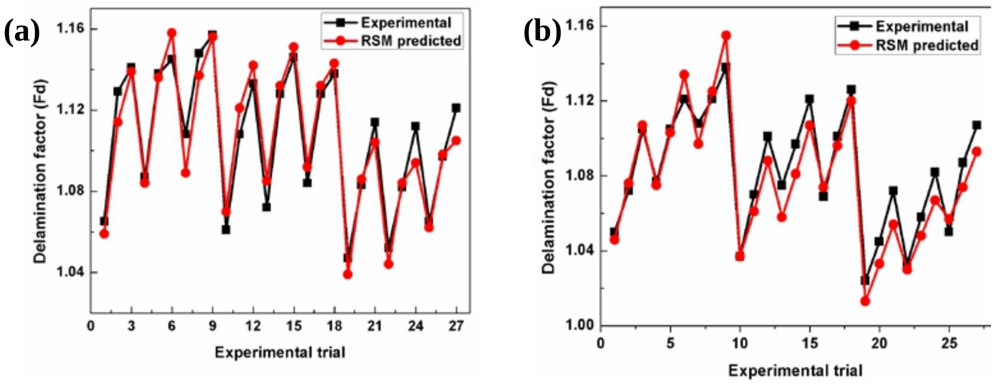

Fig. 5. Comparison of experimental and predicted results of delamination factor for (a) solid carbide (b) TiN coated solid carbide

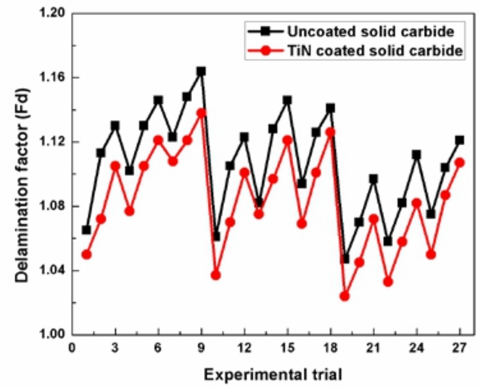

Fig. 6. Comparison of experimental results of delamination factor in BD CFRP composite using uncoated and TiN coated solid carbide drills

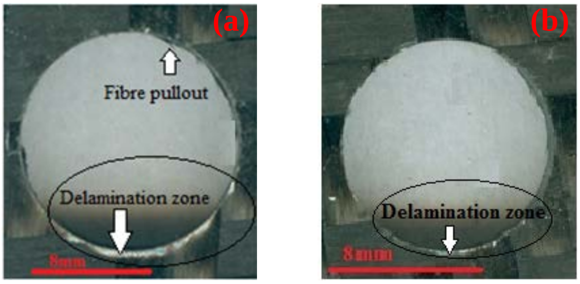

Fig. 7. Scanned images of the hole drilled at spindle speed 1200 rpm, 20 mm/min, 118° and 8 mm for (a) solid carbide and (b) TiN coated solid carbide drill in BD CFRP composite

The main effect plot of Taguchi DOE is one of the tools used for analysing the influence of process parameters on delamination during drilling of composites. The Fig. 8 shows the main effect plots for delamination factor of BD CFRP composite in drilling with both uncoated and TiN coated solid carbide drills. It is clear from the figure that the drill diameter, the spindle speed and the feed rate are the most significant design parameters influence the delamination factor as the slope of these plots are more. The point angle is the least contributing process parameter for delamination factor as the slope of this plot is almost horizontal. It is also clear from the Fig.8 that the optimum parametric conditions required for obtaining minimum delamination in drilling of BD CFRP composite are drill diameter of 4 mm, feed rate of 10 mm/min, spindle speed of 1800 rpm, and point angle of 90°.

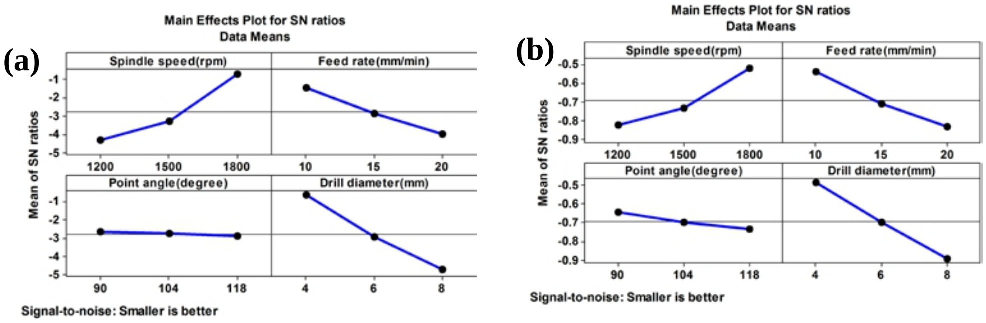

Fig. 7. Main effect plots for delamination factor for (a) solid carbide (b) TiN coated solid carbide

3.2. Evaluation of delamination using ANOVA

The analysis of variance (ANOVA) is a technique used to draw the conclusion, concerning which parameters affect the response of the inquired process through the series of experimental results. This analysis is carried out for a significance level of $\alpha = 0.05$, i.e., for a confidence level of 95%. The P values in the ANOVA Table 3 are the realized significance levels, associated with Fischer's F test for each source of variation. The sources with P values less than 0.05 are considered to have statistically significant contribution to the performance measures. From the ANOVA it is observed that the drill diameter has the highest contribution (50.63%), followed by the spindle speed (28.82%) in uncoated solid carbide drills. However, in TiN coated solid carbide drills, the drill diameter (45.08%) has the highest contribution followed by the spindle speed (27.02%) and the feed rate (24.53%). It is also observed from the ANOVA results that the point angle and the interaction effects of process parameters on delamination factor have no statistical and physical significance.

Table 3 ANOVA for delamination factor of BD CFRP composite

	Solid carbide			TiN coated solid carbide		
Source	F	P	P (%)	F	P	P (%)
A	110.03	0.000	28.82	330.76	0.000	27.02
B	69.63	0.000	18.24	300.34	0.000	24.53
C	5.59	0.043	1.46	28.91	0.001	2.36
D	193.31	0.000	50.63	551.86	0.000	45.08
A*D	1.49	0.314	0.39	3.52	0.083	0.29
B*D	1.54	0.303	0.40	3.19	0.099	0.26
C*D	0.22	0.917	0.06	5.73	0.030	0.47
R-Sq = 99.2% R-Sq(adj) = 96.7%				R-Sq = 99.8% R-Sq(adj) = 99.0%		

3.3. Analysis of delamination using 3D response surface plots of RSM

The delamination tendency can also be analysed through RSM model by generating 3D response surface plots. The Fig.8 exhibits the interaction effects of spindle speed and drill diameter on delamination with point angle (118°) and feed rate (20 mm/min) are held at constant.

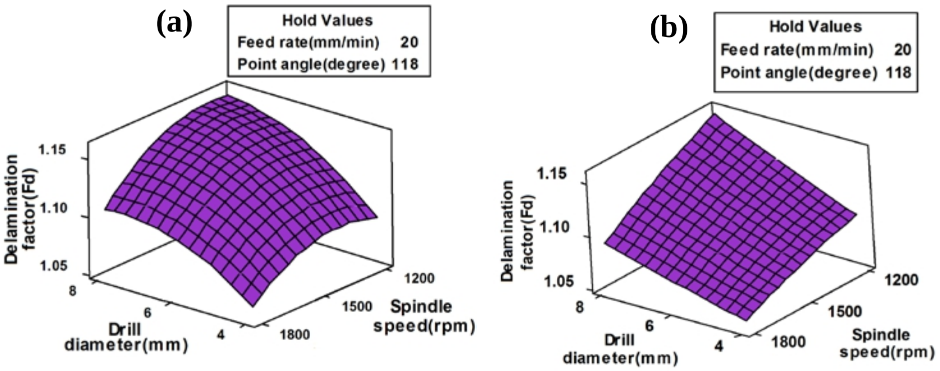

Fig. 8. Interaction effects of spindle speed and drill diameter on delamination factor for (a) solid carbide (b) TiN coated solid carbide

From the figure, it is observed that the delamination factor of BD CFRP composite increases with increase in drill diameter and decreases with increase in spindle speed. Increase in drill diameter increases the contact area of the drilled hole which increases the thrust force. Increase in thrust force leads to increase in drilling induced delamination (Palanikumar 2012), whereas, increase in spindle speed raises the temperature while drilling of composites, thus softening the matrix material, thereby reducing the delamination (Palanikumar 2011).

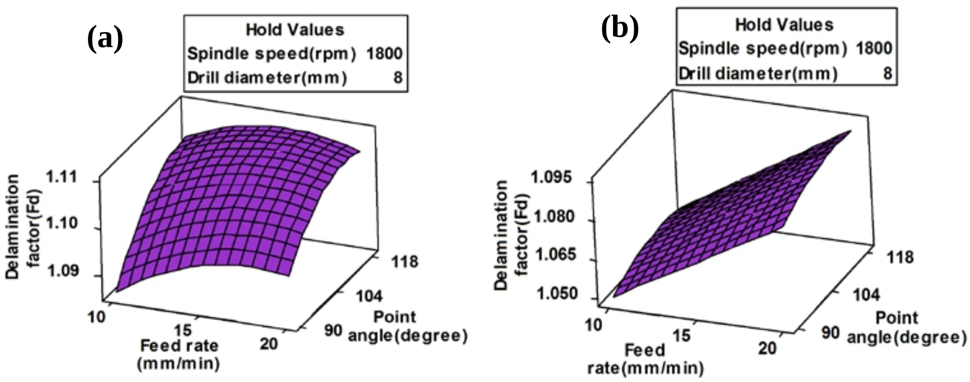

Fig. 9. Interaction effects of feed rate and point angle on delamination factor for (a) solid carbide (b) TiN coated solid carbide

The Fig. 9 depicts the influence of feed rate and point angle on drilling induced-delamination with spindle speed (1800 rpm) and drill diameter (8 mm) are held at constant. It is seen from the figure that the increase in tool feed rate increases the delamination due to increase of thrust force (Palanikumar 2008). The point angle has very little effect on delamination during drilling of BD CFRP composite laminate using both uncoated and TiN coated drills.

The adequacy of RSM model has been tested through ANOVA method for a confidence level of 95%. The ANOVA result for delamination factor for justifying the goodness of fit of the developed model is presented in Table 4. The sum of squares is usually performed into contributions from regression model and residual error. Mean square is the ratio of sum of squares to the degrees of freedom and F-ratio is the ratio of mean square of regression model to the mean square of residual error.

Table 4 ANOVA results for justifying goodness of fit of the RSM model.

		Solid carbide			TiN coated solid carbide		
Source	DF	SS	MS	F	SS	MS	F
Regression	14	0.034	0.002444	25.18	0.030152	0.002154	14.49
Residual Error	15	0.001	0.000097		0.002081	0.000149	
Total	29	0.042			0.033		

From the Table 4, it is apparent that, the calculated values of F-ratio of the developed model (25.18 and 14.49) are greater than the F-table value (F 0.05, 14, 15 =2.46) and hence the second degree response function model developed is quite adequate.

3.4. Morphological study

The delamination, fiber pull-out, micro-cracking, de-bonding, fiber breakage, and thermal degradation etc., are the most common problems encountered during drilling of CFRP composites. The drilling-induced delamination is a major defect which reduces the structural integrity and in-service life of the material under fatigue loads. Therefore, it is necessary to investigate at microscopic level to understand the damage mechanism during drilling of CFRP composites. The SEM images of the drilled hole of BD CFRP composite using uncoated and TiN coated solid carbide drills are shown in Fig. 10. It is observed from the SEM images that the push-down delamination and the fiber pull-out are more in uncoated solid carbide drills as compared to TiN solid carbide drills. This is due to the fact that the ploughing action is dominating over the cutting action which degrades the matrix and pulled out fibres considerably. The ploughing action is mainly due to the heating effect which creates friction between the cutting edge of the tool and the work piece.

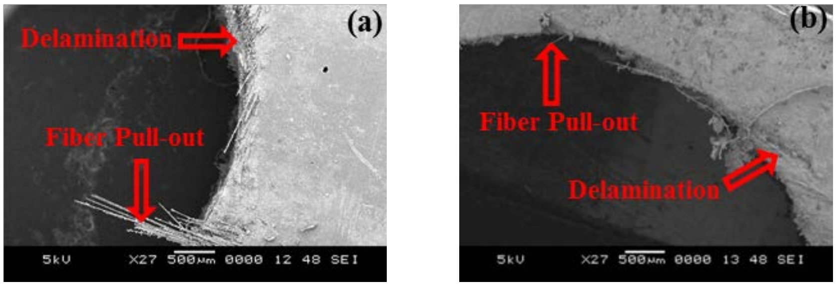

Fig. 10. SEM images of the drilled hole (bottom surface) at spindle speed 1200 rpm, 20 mm/min, 118°, and 8 mm for (a) solid carbide and (b) TiN coated solid carbide drill in drilling of BD CFRP composite

3.5. Confirmation test for optimum process parameters

The confirmation test results obtained for optimum process parameters during drilling of BD-CFRP composite with uncoated and TiN coated solid carbide drills are shown in Table 5. It is observed from the results that the experimental and the predicted values of delamination factor are in good agreement with more than 99 % confidence level. The confirmation test proves that the value of delamination factor obtained for optimum parametric conditions is less than the minimum value of the delamination factor obtained from the Taguchi L_{27} orthogonal array.

Table 5 Results of confirmation test for optimal cutting condition

Tool	Response	Optimum cutting parameters	Experi-mental	Prediction	% of agreement
Solid carbide	Delamination factor	$A_3B_1C_1D_1$	1.025	1.028	99.70
TiN coated Solid carbide			1.016	1.010	99.40

A_3=1800 rpm, B_1=10 mm/min, C_1 =90°, D_1 =4 mm

4. Conclusion

The following conclusions can be drawn in drilling of BD CFRP composite with uncoated and TiN coated solid carbide drills:

1. The model generated by means of design software (MINITAB 15) package shows the influence of process parameters on delamination.
2. The investigation reveals that there is a perfect correlation between the experimental and the predicted results of delamination factor. This indicates that RSM model can be effectively used to predict the delamination factor.
3. The ANOVA shows that the point angle and the interaction of the process parameters have negligible influence on drilling induced delamination.

4. The study reveals that delamination factor increases with increase in drill diameter and feed rate, and decreases with increase in spindle speed.
5. The experimental results demonstrate that TiN coated solid carbide drills are preferable to uncoated solid carbide drills, in achieving minimum drilling delamination.
6. The study demonstrates that the minimum delamination is obtained for the optimum process parameters (spindle speed of 1800 rpm, feed rate of 10 mm/min, point angle of 90˚and drill diameter of 4 mm).
7. The SEM micrographs show that the damage caused by uncoated solid carbide drills is more compared to that caused by TiN coated solid carbide drills.

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References:

Guu, Y. H., Hocheng, H., Tai, N., and Liu, S.Y., "Effect of electrical discharge machining on the characteristics of carbon fiber reinforced carbon composites", Journal of Material Science., 36, 2037- 2043, 2011.

Arul, S., Vijayarahavan, L., Malhotra, S. K., and Krishnamurthy, R., "The effect of vibratory drilling on hole quality in polymeric composites", Int. Journal of Mech. Tools Manuf, 46, 252-259, 2006.

Kopler, A., Lystrup, A., and Vorm, P., "The cutting process, chips, and cutting forces in machining CFRP", Composites., 14(4), 371-376, 1983.

Stone, R., Krishnamurthy, K,."A neural network thrust force controller to minimize delamination during drilling of graphite-epoxy laminates". Int. Journal of Mach. Tools and Manuf., 36, 985-1003, 1996.

Zitoune, R., and Collombet, F., "Numerical prediction of the thrust force responsible of delamination during the drilling of the long-fibre composite structures", Journal of Composites part- A., 38, 858-866, 2007.

Hockeng, H., and Tsao, C. C., "Effects of special drill bits on drilling-induced delamination of composite materials", Journal of Machine Tools Manuf., 46, 1403-1416, 2006.

Hockeng, H., and Tsao, C. C., "Compresensive analysis of delamination in drilling of composite materials with various drill bits", Journal of Materials Processing Technology., 140, 335-339, 2003.

Devim, J. P., and Reis, P., “Drilling carbon fiber reinforced plastics manufactured by autoclave-experimental and statistical study”, Materials and Design., 24, 315-324, 2003.

Montgomery, D.C., “Design and Analysis of Experiments”, New York: John Wiley and Sons Inc., 2005.

Myers, R. H., and Montgomery, D.C., “Response surface methodology: process and product optimization using designed experiments” (2^{nd}ed.), New York: John Wiley and Sons Inc., 1995.

Palanikumar, K., Latha, B., Senthilkumar, V., and Paulo Davim., “Analyses of drilling of GFRP composites using grey relational analyses”, Mater. Manuf. Process., 27, 297-305, 2012.

Palanikumar, K., “Experimental investigation and optimization in drilling of GFRP composites”, Measurement., 44, 2138-2148, 2011.

Palanikumar, K., Prakash, S., and Shanmugan, K., “Evaluation of delamination in drilling GFRP composites”, Mater. Manuf. Process., 8, 858-64, 2008.