International Journal of Current Engineering and Technology
ISSN 2277 - 4106
© 2013 INPRESSCO. All Rights Reserved.
Available at http://inpressco.com/category/ijcet

Research Article

Investigation into the Effects of Process Parameters on Surface Roughness in Drilling of BD-CFRP Composite Using HSS Twist Drills

Nagaraja[*a], Mervin A Herbert [a] , Divakara Shetty[b] , Vijay G S[b] and Raviraj Shetty[b]

[a]Department of Mechanical Engineering, National Institute of Technology Karnataka, Srinivasa Nagar, Surathkal, Mangalore-575025, India
[b]Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal University, Manipal-576 104, Karnataka, India

Accepted 12 September 2013, Available online 01 October 2013, **Vol.3, No.4 (October 2013)**

Abstract

In the present work, an attempt has been made to investigate the effects of process parameters such as spindle speed, feed rate, drill diameter and point angle on surface roughness in drilling of the bi-directional carbon fiber reinforced polymer (BD-CFRP) composite using high speed steel (HSS) drills. Taguchi L_{27} orthogonal array, the analysis of variance (ANOVA) and the response surface of methodology (RSM) are employed to analyze the effects of drilling parameters on surface roughness(Ra). The study shows that the increase in drill diameter and the spindle speed increases the surface roughness and no clear effect is noticed for point angle in drilling of BD-CFRP composite. It is evident from the study that the tool feed rate has very little influence on the surface roughness. The investigation reveals that the experimental and the predicted values of surface roughness are in good agreement.

Keywords: *Bi-directional carbon fiber polymer composite, high speed steel, analysis of variance, Taguchi orthogonal array, response surface methodology.*

1. Introduction

The carbon fiber reinforced polymer composite (CFRP) materials are finding wide applications in aeronautical, automobile, sporting goods and medical device sectors due to their high strength to weight ratio, low thermal conductivity, high specific strength and stiffness, light weight, excellent resistance to corrosion and good impact properties [Chawla, 2001]. The machining of composite materials is different from the conventional machining of metals due to their anisotropic and non-homogeneous nature [Ram Kumar et al., 2004]. Amongst traditional machining process, the drilling is one of the most important machining operations in composite materials.

The drilling operation is evaluated based on the performance characteristics such as surface roughness, material removal rate, tool wear, tool life, cutting force, hole diameter error, power consumption etc., and are strongly correlated with the cutting parameters such as cutting speed, depth of cut, tool geometry [Chua et al., 1993 and Yang et al., 1998]. Surface roughness has received serious attentions for many years. It has formulated an important design feature in many situations such as parts subjected to fatigue loads, precision fits, fastener holes, and aesthetic requirements. In addition to tolerances, surface roughness imposes one of the most critical constraints for selection of machines and cutting parameters in process planning. For these reasons, research developments have been carried out with the purpose of optimizing the cutting conditions to reach a specific surface roughness [Jack Feng et al., 2002, Ramulu et al., 1993 and Erisken et al., 1999].

There have been many studies in the machining of FRPs. Wang and Zhang [2003] investigated the machinability of epoxy composites reinforced by unidirectional carbon fiber materials when subjected to orthogonal cutting and found that the subsurface damage and its mechanisms of a machined component are greatly influenced by fiber orientation. Krishnamurthy et.al [2011] used the artificial neural network (ANN) for the prediction of delamination factor at the exit plane of the CFRP material in drilling operation and found that ANN model predicts the delamination for any given set of machining parameters with maximum error of 0.81% and minimum error of 0.03%. Islam et al [2010] have studied the effect of laminate configuration and feed rate on thrust force, torque, wear, and delamination in drilling of 3 mm thick CFRP laminates (unidirectional and woven} using tungsten carbide twist drill of 1.5 mm diameter It is found that best results were obtained with woven MTM44 - 1/HTS oven cured material.

Palanikumar et. al [2008] have conducted experiment by using high- speed steel-made twist drill and 4-flute cutter and have used regression and analysis of variance(ANOVA) for analysis. Mustafa et.al [2009] performed an experimental investigation in the

*Corresponding author: **Nagaraja**

optimization of cutting parameters for surface roughness in dry drilling process using Taguchi method. Sonbaty et.al [2004] studied the effective factors on machining of GFR/epoxy composites. Their results revealed that increase in cutting speed, torque and force are decreased, and finally surface roughness is improved. Mital and Mehta [1988] conducted a survey surface roughness models and found that most of the surface roughness predictions were developed for steels.

It is evident from the literature that very few studies have been carried out on optimization of surface roughness through the integration of Taguchi design of experiments (DOE), ANOVA and RSM during drilling of BD-CFRP composite laminate. Therefore, there exists a need to study and analyze the effects of process parameters such as feed rate, spindle speed, drill diameter and point angle on surface roughness in drilling of BD-CFRP composite through Taguchi DOE, ANOVA, and RSM, with HSS drills. The BD-CFRP composite is selected for this study for the reason that it has maximum strength and stiffness in all directions.

2. Materials and Methods

2.1 Preparation of Test Specimen

The BD-CFRP composite specimen of 200 mm × 200 mm × 4 mm is fabricated by hand lay-up followed by the compression moulding technique at room temperature. The bi-directional plain weave type carbon fiber of arial density of 200 gm^{-2} is used as reinforcement.

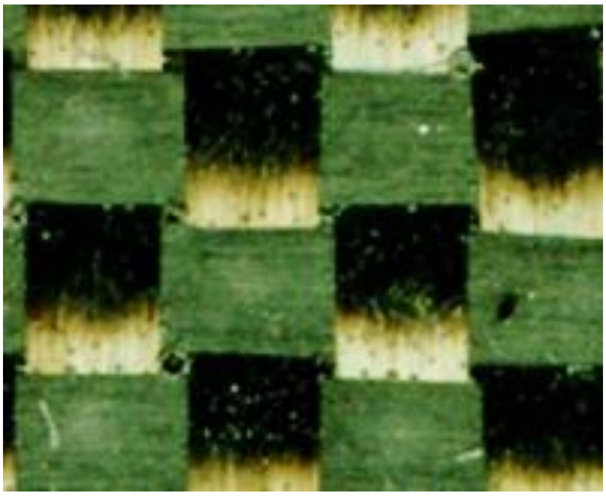


Fig.1 BD-CFRP composite specimen.

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 of the carbon fabric by using a brush and a roller. The matrix resin impregnated fabric stock is pressed in the hydraulic press under a pressure of 0.5 MPa for about 24 hrs at room temperature and the post curing of the composite laminate is carried out for about eight hours at 80°C. The scanned image of the test specimen is shown in Fig. 1.

2.2. Experimental method

A Matsuzawa micro-hardness testing machine (Model No MMT-X7A, Japan) is used for measuring the Vickers hardness of the BD-CFRP composite specimen. The tensile strength of the specimen is measured as per the ASTM: D 638, using Universal Testing Machine (Lloyd LR100 K, UK). The three point bending technique is adopted for measuring the flexural properties of the test specimen as per the ASTM: D 790-10. The inter-laminar shear strength is recorded according to the ASTM: D 2344 (short beam shear test method), using the Universal Testing Machine (Instron 3366). The displacement method is used for measuring the density of the composite specimen as per the ASTM: D 792-08, using an electronic balance (Mettler Toledo USA). The drilling experiments on the BD-CFRP composite specimen have been carried out with the help of the CNC vertical (TRIAC VMC) machining centre as shown in Fig.2. The mechanical properties of the test specimen are given in Table 1.

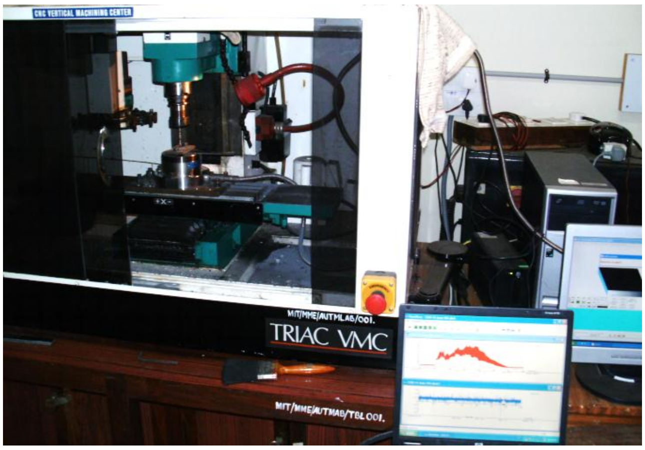


Fig.2 Experimental set up

Table 1 Mechanical properties of BD-CFRP composite specimen.

Density(g.cm-3)	Vickers hardness	Tensile strength(MPa)	Young's modulus(GPa)	Elongation(%)	Flexural strength(MPa)	Flexural modulus(MPa)	Interlaminar Shear strength(MPa)
1.302	18.2	427.46	5.9	13.32	109.35	861.19	20

3. Design of Experiments

3.1. Taguchi Method

Taguchi's robust DOE has been used to formulate the experimental layout, analyze the effect of each cutting parameters and optimize the process parameters which are least sensitive to the causes of the variation. Taguchi's approach to DOE is easy to adopt and apply for users with limited knowledge of statistics, and it requires minimum number of experiments to be conducted. Hence, it has gained a wide popularity in the engineering and scientific community. Taguchi recommends the analysis of the means and signal to noise (S/N) ratio using conceptual approach that involves graphing the effects and visually identifying the factors that appear to be significant, without using ANOVA, and thus, making the analysis simple as shown in Montgomery [2005]. The analysis is made using the software specially used for the DOE applications known as MINITAB15. The S/N ratio characteristic (Smaller is the better) is given in equation 1.

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

Where 'n' is the number of observations, and y is the observed data. Drilling test parameters and levels are given in Table 2.

Table 2 Level and factors

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

3.2. Response Surface Methodology

Response surface methodology (RSM) is a collection of mathematical and statistical techniques that are useful for modeling and analyzing problems in which a response of interest is influenced by several variables. The main goal of RSM is to optimize the response that is influenced by various process parameters as observed in Myers et.al.[1995]. The central composite design (CCD) is one of the important design methods used in RSM. In this study, CCD is used for establishing empirical relationships between the process parameters. The number of experiments used in this case is 30 and the number of drilling parameter considered is four.

The RSM model chosen for predicting the surface roughness can be expressed as

$$\text{Surface roughness (Ra)} = \beta_0 + \beta_1(A) + \beta_2(B) + \beta_3(C) + \beta_4(D) + \beta_5(A^2) + \beta_6(B^2) + \beta_7(C^2) + \beta_8(D^2) + \beta_9(AB) + \beta_{10}(AC) + \beta_{11}(AD) + \beta_{12}(BC) + \beta_{13}(BD) + \beta_{14}(CD) \quad (2)$$

From the observed data for surface roughness, the response function is given as

$$Ra = 2.74827 - 1.63451E^{-04}A + 0.00836346B + 0.00535363C + 0.0831914D - 1.49158E^{-07}A^2 - 3.36970E^{-04}B^2 - 3.53278E^{-05}C^2 + 0.00176894D^2 + 3.04167E^{-06}AB + 3.64583E^{-06}AC + 1.14583E^{-06}AD + 7.58929E^{-05}BC - 6.81250E^{-04}BD - 5.37946E^{-04}CD \quad (3)$$

4. Results and Discussion

4.1 Analysis of surface roughness using Taguchi DOE and ANOVA

Surface roughness has received serious attentions for many years. It has formulated an important design feature in many situations such as parts subject to fatigue loads, precision fits, fastener holes and aesthetic requirements. In addition to tolerances, surface roughness imposes one of the most critical constraints for selection of machines and cutting parameters in process planning. To have a better surface finish of the drilled holes, it is necessary to control the influence of process parameters during drilling. In the present work, the experiments have been carried out for investigating the effects of cutting parameters such as spindle speed, tool feed rate, point angle and drill diameter on surface roughness in drilling of the BD-CFRP composite using HSS drills. The experimental and the predicted results of surface roughness of the BD-CFRP composite laminate are given in Table 3.

Table 3 Experimental and predicted results of surface roughness.

Test No.	Experimental Surface roughness (microns).	Predicted Surface roughness as per RSM (microns).	Error (%)
1	3.224	3.227	0.093
2	3.353	3.321	0.954
3	3.409	3.429	0.587
4	3.301	3.291	0.303
5	3.386	3.363	0.679
6	3.423	3.45	0.789
7	3.312	3.336	0.725
8	3.413	3.386	0.791
9	3.452	3.45	0.058
10	3.207	3.202	0.156
11	3.275	3.281	0.183
12	3.406	3.375	0.91
13	3.281	3.278	0.091
14	3.328	3.335	0.21
15	3.407	3.407	0
16	3.269	3.235	1.04
17	3.35	3.316	1.015
18	3.409	3.411	0.059
19	3.17	3.167	0.095
20	3.223	3.232	0.279
21	3.301	3.312	0.333
22	3.182	3.126	1.76
23	3.238	3.214	0.741
24	3.294	3.317	0.698
25	3.24	3.218	0.679
26	3.312	3.285	0.815
27	3.363	3.366	0.089
Avg.error			0.52

Fig. 3 shows the comparative plot of surface roughness obtained from Taguchi DOE and RSM. From the figure, it is clear that there is a good agreement between the experimental and predicted results of surface roughness of BD-CFRP composite. The main effects plot for signal to noise ratio (S/N) of surface roughness (smaller is the better) is shown in Fig. 4. It is observed from the plot that the drill diameter and the spindle speed are the most significant design parameters affecting surface roughness as the slope gradient is large. The tool feed rate and point angle are the least contributing cutting parameters for surface roughness as the slope gradient is very small.

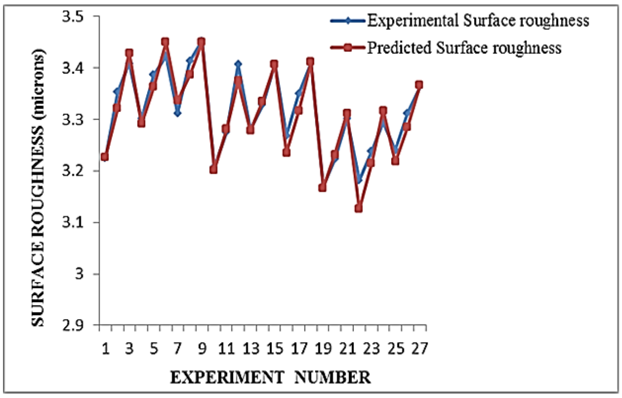


Fig. 3 Comparison plot of surface roughness obtained from the Taguchi DOE and RSM.

It is also observed from the main effects plot of surface roughness that the optimum parametric condition for minimum surface roughness in drilling of the BD-CFRP composite is obtained for drill diameter of 4 mm, feed rate of 10 mm/min, spindle speed of 1800 rpm, and point angle of 90°. Since the point angle is less significant, it could be set at the convenient value for drilling quality holes. Table 4 shows the responses for S/N ratio (smaller is the better) of surface roughness. It is evident from the table that drill diameter is the most dominant factor which influences the surface roughness in drilling of BD-CFRP composite laminate followed by spindle speed. The analysis of variance (ANOVA) for S/N ratio of surface roughness is carried out for a significance level of $\alpha = 0.05$, i.e. for a confidence level of 95%.

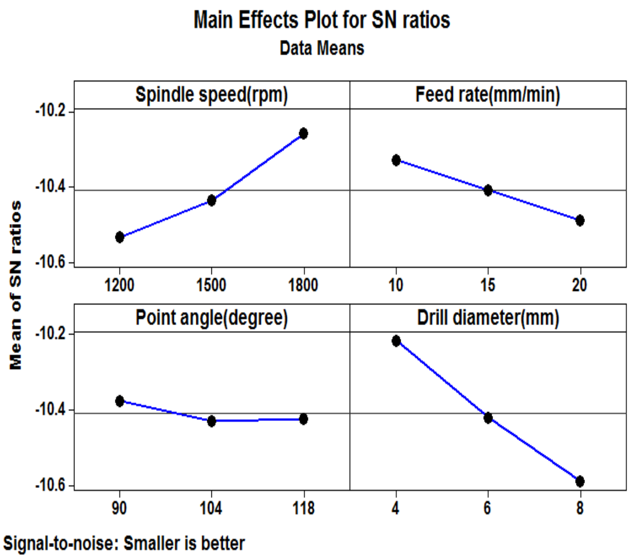


Fig. 4 Main effect plots for SN ratios of surface roughness.

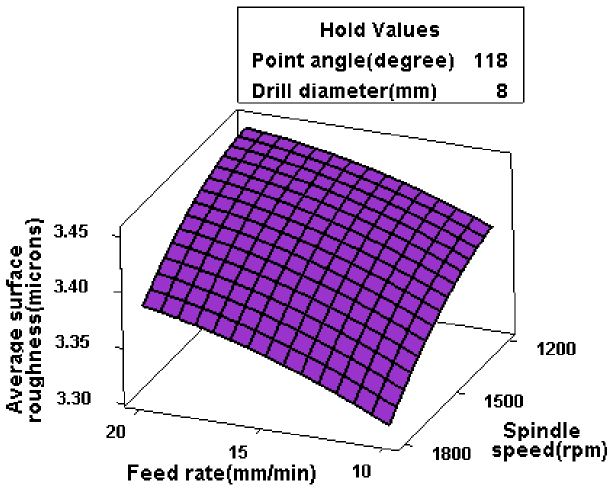
Table 4 Responses for S/N ratio (smaller is the better) of surface roughness.

Level	Spindle Speed (rpm)	Feed rate (mm/min)	Point angle (degree)	Drill diameter (mm)
1	-10.53	-10.33	-10.38	-10.22
2	-10.44	-10.41	-10.43	-10.42
3	-10.26	-10.49	-10.42	-10.59
Delta	0.28	0.16	0.05	0.37
Rank	2	3	4	1

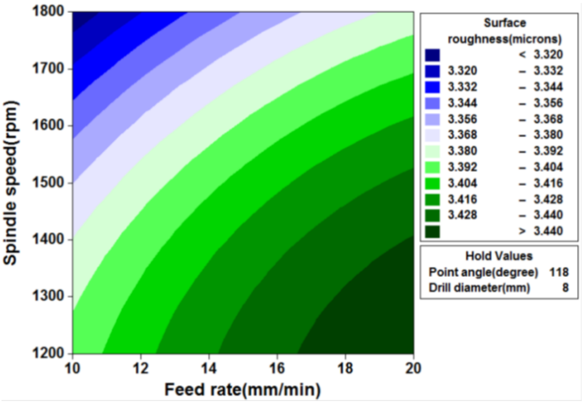
The ANOVA technique is used to find the significant main and interaction factors. The results of second order response surface model fitted in the form of Analysis of Variance are given in the table 5. The P values in the ANOVA table are the realized significance levels, associated with Fischer's F test 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. The ANOVA table illustrates that the drill diameter has the highest contribution (55.21%) on surface roughness followed by the spindle speed (31.25%) and the tool feed rate (10.39%). The interaction effects of process parameters on surface roughness in drilling of the BD-CFRP composite have no statistical and physical significance as shown in the Table 5. It is observed that there is a good correlation between the results of surface roughness obtained from the S/N ratio and the ANOVA tables.

4.2. Analysis of Surface Roughness using RSM

The surface roughness of BD-CFRP composite laminate is analyzed by generating 3D response surface plots and contour plots. Fig. 5 (a & b) shows the interaction effects of feed rate and the spindle speed on surface roughness with drill diameter (8 mm) and point angle (118°) are held constant. Figure illustrates that the surface roughness is minimum at minimum feed rate. The reason being, at low feed rate fracture is less violent and more controllable.

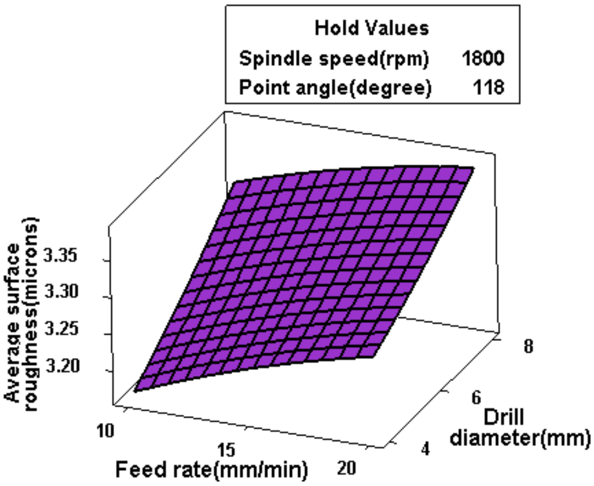


(a)

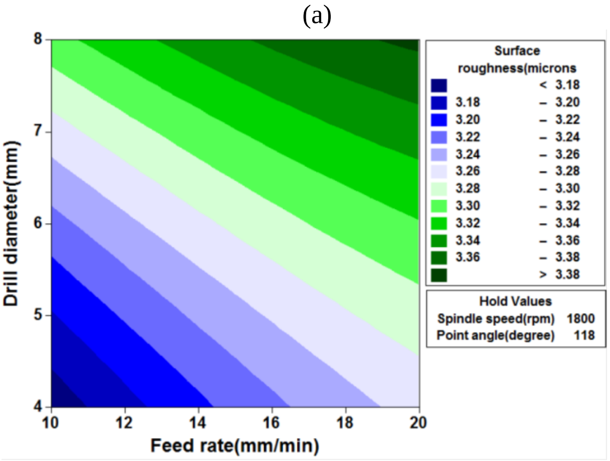


(b)

Fig. 5 Interaction effects of feed rate and spindle speed on surface roughness



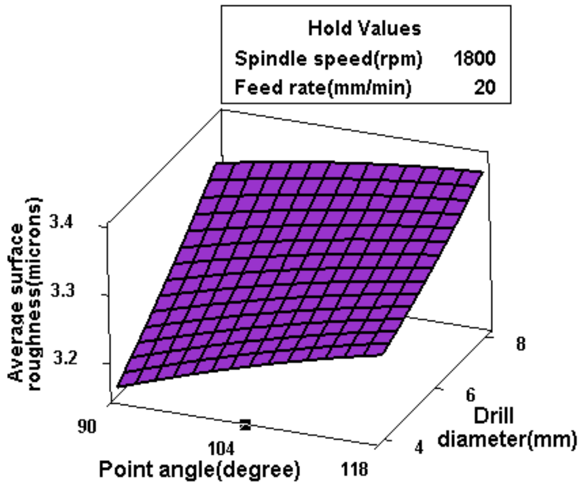
(a)



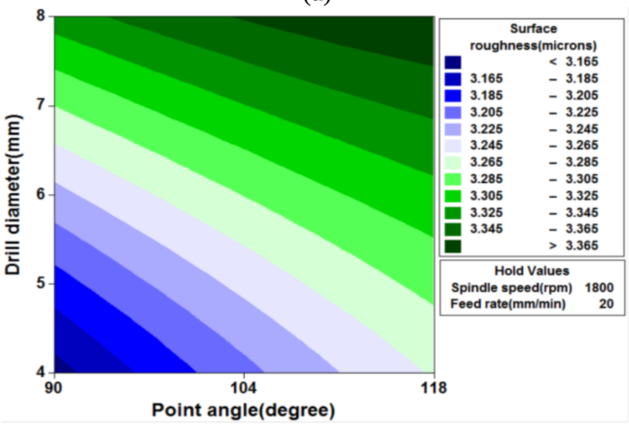
(b)

Fig.6 Interaction effects of feed rate and drill diameter on surface roughness

It is due to the fact that at low feed rate, the strain rate is low as observed in Palani Kumar et. al.[2007]. From the figure it is clear that with feed rate kept at low value, minimum surface roughness can be achieved with higher spindle speed during drilling of BD-CFRP composite laminate using HSS drills.



(a)



(b)

Fig.7 Interaction effects of point angle and drill diameter on surface roughness

At low speeds, the built up edge (BUE) may be formed and the chip fracture readily producing the rough surface. As the speed increase, the BUE vanishes, chip fracture decreases, and hence the roughness decreases. This indicates that higher cutting speed is suitable for machining CFRP composites for getting a good surface finish.

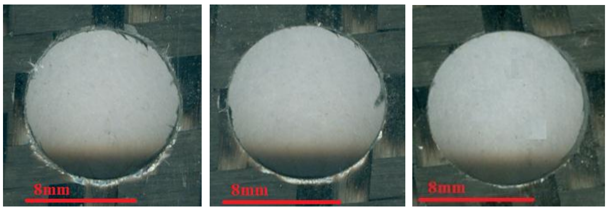
Fig.6 (a & b) depicts the interaction effect of feed rate and drill diameter on surface roughness with spindle speed (1800 rpm) and point angle (118°) are held constant. From the figure it can be seen that increase in drill increases the surface roughness during drilling of composite materials. The increase in drill diameter may results in high normal pressure and seizure on the rake face and promotes the BUE formation. Hence, the surface roughness increases along with increase in drill diameter. The results reveal that the increase in feed rate and drill diameter increases the surface roughness and vice-versa.

The influence of drill diameter and point angle on surface roughness with feed rate (20 mm/min) and spindle speed (1800 rpm) are held constant as illustrated in

Fig. 7(a &b). It is noticed from the figure that the minimum surface roughness in drilling of the BD-CFRP composite is observed at lower drill diameter and minimum point angle.

The results shown prove that the surface roughness of BD-CFRP composite laminate is highly influenced by the drill diameter followed by the spindle speed. The feed rate also plays an important role on machining of composite in deciding the surface roughness.

Fig. 8 shows the scanned images of the drilled holes used for measuring the surface roughness of the BD-CFRP composite specimen with the help of Taylor/Hobson Surtronic 3+. The result of the surface roughness for optimum process parameters as per RSM is presented in the Table 6. From the table it is observed that the predicted value of surface roughness generated during drilling for the optimum cutting condition (A_3=1800 rpm, B_1=10 mm/min, C_1=90 degree, D_1=4 mm) as per RSM is 3.078 and the experimental value of surface roughness obtained for that optimum cutting condition is 3.057, confirming within the 99.31% of confidence level.



(a) (b) (c)

Fig.8 Delamination obtained for (a) 1200rpm, 20mm/min, 118degree (b) 1500rpm, 20mm/min, 90degree (c) 1800rpm, 20mm/min, 104degree

Table 6 Result of surface roughness obtained for optimum cutting parameters using RSM.

Response	Optimum cutting parameters	Experimental	Prediction	% of agreement
Surface roughness	$A_3B_1C_1D_1$	3.057	3.078	99.31

Fig. 9 shows the optimized response surface plot of surface roughness as per RSM during drilling of BD-CFRP composite laminate with HSS drills. From the figure it is clear that minimum surface roughness obtained for the optimum condition is 3.078. The merit of this plot is that, it is possible to get an optimal surface roughness value by re-defining the values of process parameters within the experimental range. The adequacy of the model has been tested through ANOVA method at 95% confidence level. The ANOVA has been performed to justify the goodness of fit of the developed model. The ANOVA for surface roughness is presented in Table 7. The sum of squares is usually performed into contributions from regression model and residual error.

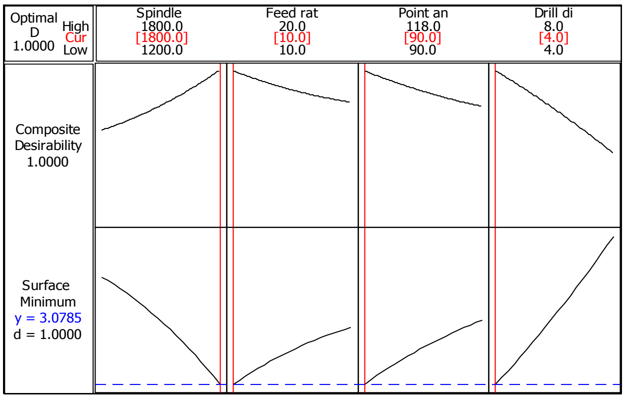


Fig. 9 Optimized response surface plot of surface roughness.

Table 7 ANOVA for response function of the surface roughness

Source	DF	Seq SS	Adj MS	F	P
Regression	14	0.204531	0.014609	26.34	0
Residual Error	15	0.007764	0.000555		
Total	29	0.20738			

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. From the analysis of Table 6, it is apparent that, the calculated value of F-ratio of the developed model (26.34) is 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 at 95% confidence limit.

4.3 Confirmation test

In order to check the accuracy of results of surface roughness obtained from Taguchi L_{27} orthogonal array, the confirmation test is carried out. Drilling conditions in confirmation test and its results are given in Table 8 and Table 9 respectively.

Table 8 Drilling conditions in confirmation test

Test No.	Spindle speed (rpm)	Feed rate (mm/min)	Point angle (degree)	Drill diameter (mm)
1	1200	10	104	4
2	1200	15	90	6
3	1200	20	104	8
4	1500	10	118	4
5	1500	15	90	6
6	1500	20	118	8
7	1800	10	104	4
8	1800	15	118	6

Table 9 Results of confirmation test with RSM

Test No.	Experimental surface roughness	Predicted surface roughness by RSM	Error (%)
1	3.238	3.247	0.28
2	3.346	3.352	0.18
3	3.454	3.463	0.26
4	3.236	3.224	0.37
5	3.289	3.297	0.24
6	3.424	3.431	0.20
7	3.118	3.129	0.35
8	3.292	3.284	0.24
Avg.Error			0.27

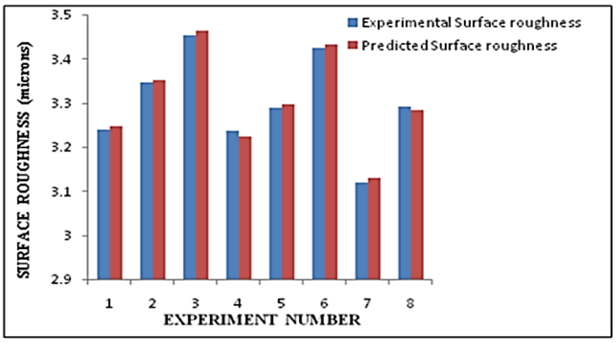


Fig.10 Comparison of the experimental and the predicted values of surface roughness

From the Table 9 it is observed that the average error of surface roughness is less than 0.3 indicating that the surface roughness derived from the confirmation test is in good approximation with those obtained through the integration of Taguchi DOE and RSM .The comparison of the experimental and the predicted values of surface roughness are shown in the Fig. 10. It can be seen from the figure that the experimental and predicted values of surface roughness obtained from the confirmation test in drilling of BD-CFRP composite laminate are fairly match with each other.

Conclusions

The following conclusions can be drawn during drilling of BD-CFRP composite laminate using HSS drills:

1. The model generated by the design software (MINITAB 15) package shows the influence of process parameters on surface roughness.
2. Surface roughness increase with increase in drill diameter and tool feed rate.
3. The results reveals that the drill diameter is the most influencing design parameter on surface roughness followed by the spindle speed and feed rate.
4. The experimental results of surface roughness are in perfect correlation with the predicted results as per response surface methodology.
5. The interactions between the process parameters have no influence on surface roughness.
6. The study reveals that the RSM model developed is quite adequate at 95% confidence level.
7. The investigation reveals that minimum surface roughness obtained at higher spindle speed, lower drill diameter, lower tool feed rate and minimum point angle.

Acknowledgements

The authors are very grateful to the department of Mechanical Engineering, Manipal Institute of Technology, Manipal University, Manipal for the support rendered for carrying out the drilling experiments.

References

Chawla Krishnan K, (1993), Composite materials science and Engineering, New York, Springer.

Chua M S, Rahman M, Wong Y S, Loh HT. Determination of optimal cutting conditions using design of experiments and optimization techniques, *International Journal of Machine Tools Manufacturing*, 33 (2), 297-305.

Erisken E, (1999), Influence from production parameters on the surface roughness of a machine. Short fibre reinforced thermoplastic, *International Journal of Machine Tools Manufacturing*, 39, 1611-1618.

Islam S, Sein L S, Devid A, Sam B.,(2010), Effect of laminate configuration and feed rate on cutting performance when drilling holes in carbon fiber reinforced plastic composites. *Journal of Material Process Technology*, 210, 1023-1034.

Jack Feng CX, Wang X, (2002), Development of empirical models for surface roughness prediction in finish turning, *International Journal of Advances in Manufacturing Technology*, 20, 348-56.

Krishnamoorthy A, Rajendra B, Palanikumar K.,(2011), Delamination prediction in drilling of CFRP composites using artificial neural network, *Journal of Engineering Science and Technology*, 6(2), 191-203.

Mital A, Mehta M, (1988), Surface roughness prediction models for fine turning, *International Journal of Production Research, 26, 1861*-1876.

Montgomery D C., (2005), Design and Analysis of Experiments. New York: John Wiley and Sons.

Mustafa Kurt, Eyup Bagei,Yusuf Kaynak, (2009), Application of taguchi methods in the optimization of cutting parameters for surface finish and hole diameter accuracy in dry drilling process, *International Journal of Advances in Manufacturing Technology*, 40, 458-469.

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

Palanikumar K, (2007), Modeling and analysis for surface roughness in machining glass fiber reinforced plastics using response surface methodology, *Materials and Design*, 28, 2611-2618.

Palanikumar K, PrakashS,Shanmugan K.,(2008), Evaluation of delamination in drilling GFRP Composites, *Materials and Manufacturing Process*, 8, 858-64.

Ram Kumar J, Aravindan S, Malhotra S K, Krishnamurthy R., (2004), An enhancement of the machining performance of GFRP by oscillatory assisted drilling, *International Journal of Advances in Manufacturing Technology*, 23,240-244.

Ramulu M Wern CW, Garbini J L., (1993), Effect of the direction on surface roughness measurements of machined graphite/exposy composite, *Composites Manufacturing,* 4(1), 39-51.

Sonbaty Mulgrew B, Khashaba U, Machaly T, (2004), Factors affecting the machinabilityof GFR/epoxy composites, *Composites Structures*, 63,329-338.

Wang X M, Zang L C., (2003), An experimental investigation into the orthogonal cutting of unidirectional fiber reinforced plastics. *International Journal of Machine Tools Manufacturing*, 43, 1015-1022.

Yang H, Tarng Y S., (1998), Design optimization of cutting parameters for turning operations based on the Taguchi method, *Journal Material Process and Technology*, 84, 122-129.