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Research Article

Optimization of the Process Parameters to Minimize the Surface Roughness in Drilling of CFRP Composites using Taguchi Method and RSM

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Abstract

Carbon Fiber Reinforced Polymer (CFRP) composites are finding wide application in all fields as they offer an excellent combination of strength, low weight and high modulus. The tensile strength of carbon fiber is equal to glass fiber while its modulus is about three to four times higher than glass fiber. Drilling is the most common machining operation performed on composites for the fabrication and the quality of hole has an important influence on its applications. In the present work, experiments were conducted to check the effect of drill point angle, spindle speed, feed rate and drill diameter on the surface roughness of the drilled hole. The Carbon Fiber Reinforced Polymer (CFRP) test specimen is prepared by hand-layup method. Design of Experiments (DOE) technique is used to design the drilling experiment procedure. The results have indicated that among the variables of study spindle speed has maximum influence on the surface finish of the drilled hole followed by the drill point angle. Feed rate has minimum influence on the quality of drilled hole. The research has also resulted in the listing of the optimum combination of process parameters using Response Surface Methodology (RSM) and Taguchi Method.

Keywords: *CFRP composite drilling, Surface roughness, DOE, RSM, Taguchi method.*

1. Introduction

Carbon fiber reinforced plastics (CFRP) exhibit properties such as high strength, high specific stiffness, high damping and low thermal expansion wear resistant (Guu *et al*., 2001). Hence, they find wide applications in aerospace industries, defense, ships, automobiles, machine tools, sports equipment's, transportation structures, power generations, oil and gas industries (Guu *et al*., 2001; Arul *et al*., 2006). Composite materials are synergistic combination of two or more micro-constituents that differ in physical form and chemical composition. The objective of having two or more constituents is to take benefit of superior properties of all the constituents without compromising on weakness of either (Mohan *et al*., 2005). However, CFRP composites pose different kinds of machining problems due to the presence of two or more dissimilar phases. Thus, the mechanism of machining composites has been recognized as a process different from that of homogeneous metal removal of conventional materials (Koenig *et al*., 1985). The composite materials are characterized by marked anisotropic, structural non-homogeneity and lack of plastic deformation (Devim *et al*., 2003). It was observed that the damage during machining on carbon/epoxy laminates reduces the strength and fatigue life of the part (Persson *et al*., 1997).

Although CFRP composites are produced to near-net shape, additional operation such as drilling is required in final stage during assembly of structures. The drilling operation on FRP composites has several undesirable effects such as fiber breakage, de-bonding, pull out, stress concentration, thermal damage, spalling, micro cracking, delamination, etc. Among the problems caused by drilling, delamination is the defect in composite structure, occurs mainly due to localized bending in the zone situated at the point of attack of the drill. The delamination drastically reduces assembly tolerance and strength against fatigue, thus degrading the long-term performance of composites (Chen *et al*., 1997, Won *et al*., 2002). Delamination is one of the most critical defects because it is responsible for the rejection of approximately 60% of the components produced in the aircraft industry (Wong *et al*., 1992). So many case studies have been made to minimize the delamination free hole by adopting different types of drill bit (Piquet *et al*., 2000; Hocheng *et al*., 2003) and selection of process parameters (Miller, 1987, UgoEnemuoh *et al*., 2001). Surface finish of the drilled hole has formulated as an important design feature in many situations such as parts subject to fatigue loads, precision fits, fastener holes and aesthetic requirements. Therefore measuring and characterizing surface properties represent one of the most important aspects in manufacturing process. Tsao and Hocheng (2008) have evaluated the surface roughness in drilling of composite

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materials. They indicated that the feed rate and spindle speed contribute the most to the surface roughness. The surface finish in drilling composite materials have been found to be influenced by a number of factors such as feed rate, cutting speed, drill geometry, tool wear and tool material (Hocheng *et al*., 1992; Chen. *et al*., 1997, Koplev *et al*., 1983).

From the literature review, it is observed that there is adequate scope for the investigative work on the prediction of process parameter's influence on the Surface Roughness during drilling of CFRP composites with Solid Carbide drills. Hence, an attempt has been made in this work for optimization of process parameters such as spindle speed, feed rate, drill diameter and drill point angle on Surface Roughness in the drilling of CFRP composite material using DOE and RSM.

2. Experimentation

2.1 The Test Specimen

The composites were made by hand layup moulding method. The reinforcement consists of carbon fiber mat which are manufactured by transforming the polyacrylonitrile fiber under the high heat and pressure resulting into strong carbon fiber fabrics. General purpose polyester resin (GP) with a room temperature curing accelerator catalyst methyl ethyl ketone peroxide (MEKP) hardener was used as the matrix system. The weight fraction of the composite is 50% and the post curing of the composite laminate is carried out for about 10 hours. The properties of the reinforced carbon fiber are presented in table 1.

Table 1: Properties of carbon fibers

Fibre type	Woven mat 0˚/90˚
Density g/cc	1.80
Tensile Strength, Gpa [ksi]	500
Strain to Failure [%]	2.4
Tensile Modulus, Gpa	138
Coefficient of Thermal Expansion : $10^{-6}/^{0}c$	0.54
Mat Thickness (mm)	0.2

2.2 Experimental methods

The experiment has been conducted on the TRIAC CNC vertical machining centre which enables high precision machining. The laminate composite specimen was rigidly held by the fixture which is attached to the dynamometer mounted on the machine table. The thrust force and the torque were measured with the help of KISTELER dynamometer and the charge amplifier. The data collected was transferred to a computer for further analysis. Solid carbide drills have been used in the present study because of their better heat and wear resistance characteristics. The experimental set-up is shown in figure 1.Technical specifications of TRIAC CNC are as follows: Tool Type (ATC)-BT30, Tool holding capacity, (ATC)-8 tools, spindle speed (programmable) 100 – 4000 rpm. Maximum feed rate on X and Y axis -2500 mm/min. Maximum feed rate on Z axis -1000 mm/min.

Figure 1: Experimental setup.

2.3 Taguchi Method

Taguchi defines the quality of a product in terms of the loss imparted by the product to the society from the time products are shipped to the customer. Some of these losses occur due to the deviation of the product's functional characteristics from its desired value and these are called losses due to functional variation. Uncontrollable factors, which cause the functional characteristics of a product to deviate from their target values, are known as noise factors. Taguchi recommends analyzing the means and S/N ratio using conceptual approach which involves graphing the effects and identifying the factors visually that appear to be significant without using ANOVA, which makes the analysis simple. The characteristics of the S/N ratio are given by the following equations.
Larger the better characteristic:

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

Nominal is the better characteristic:

$$\frac{S}{N}=10\log\frac{\bar{y}}{s^2\,y} \qquad (2)$$

Smaller is the better characteristic:

$$\frac{S}{N}=-10\log\frac{1}{n}\left(\sum y^2\right) \qquad (3)$$

Where, $\bar{y}$ the average of observed data, S_y^2 is the variation of y, n is the number of observations, and y is the observed data. For each type of the characteristics, with the above S/N ratio transformation, the smaller the S/N ratio the better is the result when we consider delamination factor, surface roughness, thrust force, torque and stress. In this work, in order to identify the best cutting parameters and to obtain minimum surface roughness, S/N ratio characteristic and L_{18} orthogonal array are used. Table 2 indicates drilling test parameters and levels.

Table 2: Factors and levels

Levels	(DA) Drill point angle (deg)	(DD) Drill diameter (mm)	(S) Spindle speed (rpm)	(F) Feed rate (mm/min)
1	90	8	750	50
2	103	10	1000	75
3	118	---	1250	100

2.4 Response surface methodology (RSM)

RSM is a collection of statistical and mathematical techniques that are useful for the modeling and analyzing problems in which a response of interest is influenced by several variables. RSM also quantifies the relationship between the controllable input parameters and obtained response surfaces. The main goal of RSM is to optimize the response that is influenced by various process parameters.

2.5 Measurement of Surface roughness

The surface roughness of the drilled hole is measured with the help of MITUTOYO Surface Roughness Tester SJ-301. Three readings were taken at different positions in the direction of drilling and the average is taken as the roughness value. The set-up of the instrument is shown in figure 2.

Figure 2: Surface Roughness measurement setup.

3. Results and Discussion

The quality of hole plays a vital role in drilling. Obtaining desired hole dimensions, roundness and surface finish along the length of the hole are of vital importance to the industry. To have a better surface finish of the drilled holes, it is necessary to control the influence of process parameters such as spindle speed, tool feed rate, drill diameter and the point angle on the surface roughness during drilling. In this study, the drilling experiments are conducted on the CFRP composite laminate at different cutting conditions and the results are shown in Table 3.

The main effect plots for Signal to Noise ratio (S/N) of surface roughness factor (smaller is the better) is shown in the figure 3. It is evident from the plot that the spindle speed and the drill angle are the most significant design parameters those influence the Surface Roughness. As the slope gradient of these parameters are large, variation of S/N ratio is also large. The drill diameter and tool feed rate are the least contributing process parameters for Surface Roughness as their slope gradient is smaller.

Table 3: Experimental and predicted values for Ra

DA	DD	S	F	Ra (Exp)	Ra (Predicted)	Error (%)
90	8	750	50	1.001	0.924	7.7
90	8	1000	75	1.342	1.393	3.7
90	8	1250	100	1.731	1.862	7
103	8	750	50	1.18	1.123	4.83
103	8	1000	75	1.74	1.592	8.5
103	8	1250	100	2.122	2.061	2.87
118	8	750	75	1.38	1.421	4.1
118	8	1000	100	1.843	1.89	2.49
118	8	1250	50	2.134	2.153	0.88
90	10	750	100	1.18	1.249	6.90
90	10	1000	50	1.54	1.512	1.82
90	10	1250	75	2.121	1.98	6.64
103	10	750	75	1.21	1.375	12
103	10	1000	100	1.97	1.848	6.19
103	10	1250	50	2.038	2.108	7.00
118	10	750	100	1.751	1.677	7.4
118	10	1000	50	1.941	1.94	0.05
118	10	1250	75	2.4301	2.409	0.87

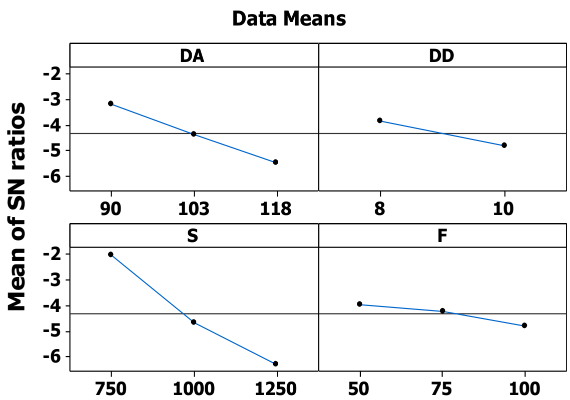


Figure 3: Main effect plot for SN ratio (smaller is better)

It is evident from the main effect plots of Surface Roughness that the optimum parametric conditions for minimum Surface Roughness in drilling of CFRP composite are obtained for drill angle 90 degree, drill diameter 8mm, spindle speed 750rpm and feed rate 50mm/min. For the present set of parameters considered, feed rate is having least significant, hence it can be set to any convenient value to get better surface finish. The response table 4 for S/N ratio of surface roughness also indicates that spindle speed is the dominant factor which influences the surface roughness in the drilling of CFRP composites. Drill point angle follows the spindle speed.

Table 4: SN Response table for Ra (Smaller is better)

Level	DA	DD	S	F
1	-3.17	-3.851	-2.001	-3.972
2	-4.353	-4.816	-4.679	-4.235
3	-5.477	----	-6.319	-4.793
Delta	2.306	0.965	4.318	0.82
Rank	2	3	1	4

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%. 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. It can be seen from table that spindle speed has the highest contribution (P=66.84%), followed by drill angle (P=18.7%). The interaction effects of process parameters on surface roughness during drilling of CFRP composites have no statistical and physical significance as shown in table. The investigation reveals that ANOVA results of surface roughness are in good agreement with the conceptual S/N ratio approach used for data analysis.

Table 5: SN ANOVA for Ra (Smaller is the better).

Source	DF	SS	MS	F	P	P%
DA	2	15.958	7.979	6.95	0.126	18.7
DD	1	4.189	4.189	3.65	0.196	4.91
S	2	57.018	28.509	24.82	0.039	66.84
F	2	2.105	0.416	0.36	0.734	2.4
DA*DD	2	1.546	0.773	0.67	0.598	1.8
DA*S	4	2.045	0.5	0.44	0.783	2.41
DD*S	2	0.15	0.075	0.07	0.939	0.17
Error	2	2.297	1.148			2.7
Total	17	85.309				

The regression equation shows the correlation between the input variables and the response parameter. The regression equation obtained for the surface roughness at the present experimentation conditions is presented in equation 4.

$$Ra = - 2.54 + 0.0153\ DA + 0.0937\ DD + 0.00160\ S + 0.00275\ F \quad (4)$$

In the regression equation, since all the process parameters are assigned with the positive sign, the surface roughness increases for any increment in the level of these input variables.

The surface roughness of the composite laminate is analyzed by generating contour plots and the corresponding 3D response surface plots. Figure 4 shows the interaction effects of drill diameter and drill point angle on the surface roughness of the drilled hole.

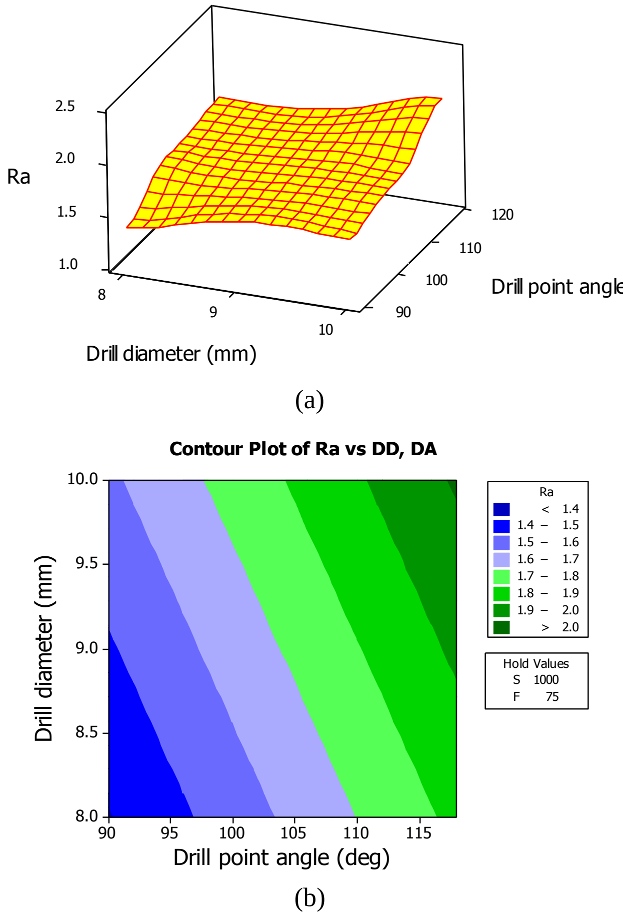
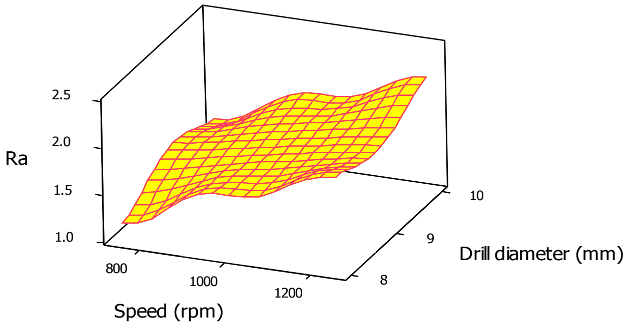


Figure 4: Interaction effects of drill diameter and drill point angle on Ra.

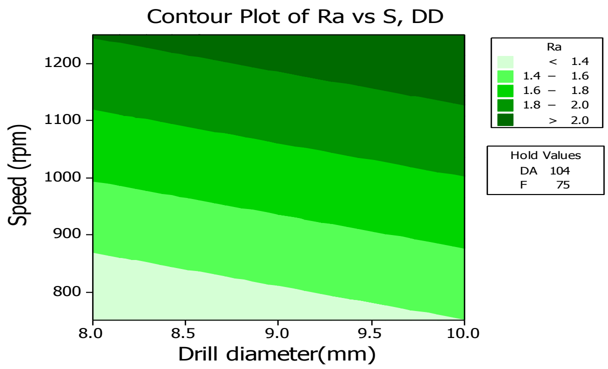
It is observed from the figure surface plot that of figure 4 (a) that the increase of drill point angle and the drill diameter increases the surface roughness. From the contour plot of figure 4 (b), it is clear that with both drill point angle and drill diameter kept at low value, minimum surface roughness can be achieved during the drilling of CFRP composites.

Figure 5 (a & b) express the interaction effect of spindle speed and drill diameter on the surface roughness with drill point angle (104^0) and feed rate (75mm/min) are hold values. It is clear from the figures that increase in drill diameter increases the surface roughness during drilling of composite materials. The reason may be that the increase of drill diameter increases the thrust force because of the increment in the contact area of the hole produced. It is evident from the figures that to achieve minimum surface roughness, it is necessary to keep the drill diameter and spindle speed at lesser level.

The influence of spindle speed and feed rate on the surface roughness is presented in figure 6 (a & b). It is evident from the figures that the minimum surface roughness in drilling of CFRP composite is observed when spindle speed and feed rate are at lowers level. From the analysis of the figures, it is concluded that the minimum drill point angle, lower drill diameter, lesser spindle speed and minimum feed rate are preferred to reduce the surface roughness of CFRP composite drilling. Hence the optimum combination is DA1 DD1 S1 F1 which is similar to the combination obtained by the response table.



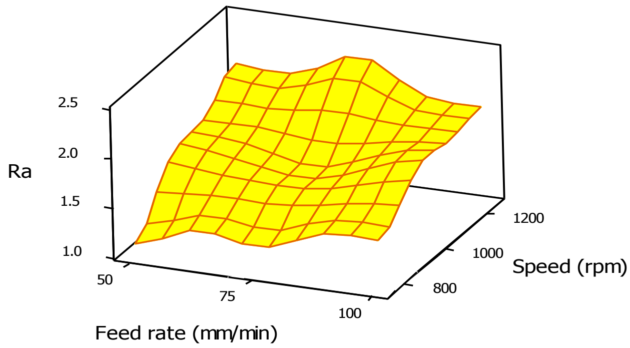
(a)



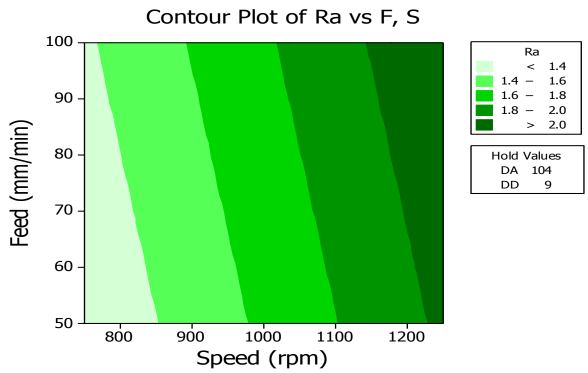
(b)

Figure 5: Interaction effects of speed and drill diameter on Ra.

Figure 7 is the RSM optimization plot for surface roughness. In the plot the influence level of a particular variable over the surface roughness is represented by its slope gradient. In the slope gradient of a particular parameter is more, the influence level of that parameter over surface roughness is also more. The plot shows the maximum slope gradient for the parameter spindle speed. Hence the influence level of this parameter is more on surface roughness. The plot is showing the optimum combination of process parameters in order to achieve the minimum surface roughness in the drilling of CFRP composite material is. According to the plot, the optimum combination of parameters is: drill point is 90^0 , drill diameter is 8mm, spindle speed is 750 rpm and feed rate is 50 mm/min (DA1 DD1 S1 F1). The advantage of the RSM optimization plot is that in addition to the optimum combination of process parameters it will show the value of the response parameter obtained for that particular combination. For the present experimentation the minimum possible surface roughness is 0.9264 (y value in the plot). From the observations of the present work, it can be concluded that the optimum combination of process parameters obtained by DOE and RSM methods are similar.



(a)



(b)

Figure 6: Interaction effects of speed and feed rates on Ra.

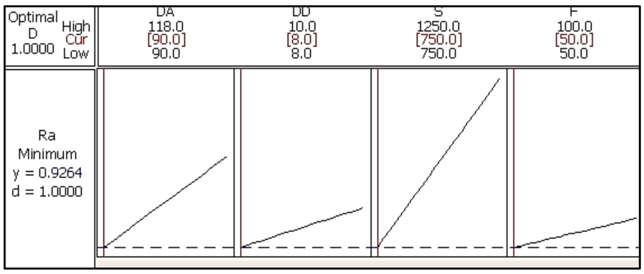


Figure 7: RSM optimization plot for Ra.

Conclusions

Based on the experimental results, the following inferences can be drawn in the drilling of CFRP composite materials using solid carbide drill bits.

1. The model generated by means of the commercial software (MINITAB 16) package shows the influence of the process parameters on the surface roughness.
2. The results reveal that spindle speed is the most influencing design parameter on the surface roughness followed by drill point angle.
3. The interaction plot reveals that the minimum surface roughness is obtained at smaller drill point angle, smaller drill diameter, lower spindle speed and lesser feed rate.
4. For the present experimentation condition, the feed rate is the design parameter which shows the minimum influence.

5. The results of ANOVA for S/N ratio for surface roughness are in good agreement with the responses obtained from S/N ratio of Taguchi analysis.
6. The investigation reveals that the optimum combination of parameters obtained by Taguchi method and RSM is same.

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