EVALUATION OF THRUST FORCE IN DRILLING OF BD-CFRP COMPOSITE USING TAGUCHI ANALYSIS, RESPONSE SURFACE METHODOLOGY AND NEURAL NETWORK

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Abstract

Drilling is the most frequently used machining operation in carbon fiber reinforced polymer (CFRP) composite materials. The quality of the drilled holes is significantly affected by the thrust force generated during drilling of CFRP composite materials. In the present work, an attempt has been made to study the effects of process parameters such as feed rate, spindle speed, drill diameter and point angle on thrust force in drilling of bi-directional carbon fiber reinforced polymer (BD-CFRP) composite laminate using Taguchi design of experiments (DOE), the response surface methodology (RSM) and the genetic algorithm optimized radial basis function neural network (GA-RBFNN). The analysis of variance (ANOVA) is also performed for investigating the influence of process parameters on machining process using high speed steel (HSS) drills. The results reveal that the drill diameter is the most significant design factor influencing the thrust force followed by the spindle speed. It is evident from the investigation that the experimental results of the thrust force in drilling of BD-CFRP composite laminate are in good agreement with the predicted results as per RSM and GA-RBFNN.

Keywords: Bi-directional carbon fiber reinforced polymer composite laminate, Taguchi design of experiments, analysis of variance, response surface methodology and neural network

1. Introduction

The utility of fiber reinforced polymer composite materials has increased significantly in the fabrication of structural elements owing to their higher specific strength, low weight, excellent fatigue and corrosion resistance, and low thermal expansion coefficients. The growth in the use of carbon fiber reinforced polymers (CFRP) is being driven by the need for the lower maintenance through improved environment resistance. The CFRP composites are widely used in aerospace, defense, automobile, shipping, oil and gas industries. Machining of composite materials needs better understanding of the cutting processes regarding accuracy and efficiency. Drilling is the most often encountered machining process in the parts made out of fiber reinforced composites. The drilling induced delamination is a critical aspect as it can lead to the failure of the dynamic structure (Mihai-Bozdan Layar 2011) (Hocheng, H 1992) (Park, K. Y 1995). The delamination was found to occur at tool entry (peel-up) or tool exit (push out). The tool-exit delamination was found to be related to the thrust force generated during drilling (Drahan, C. K. H 1990) (Zitoune, R 2007).

Many researchers have shown that there is a significant correlation between the delamination and the thrust force during drilling of FRP composites, and that monitoring of force can provide a reliable indication of delamination (Kim, D 2005) (Hocheng, H 2006). Most of the experimental investigations on drilling of fiber reinforced composites analyze only the total thrust and torque generated during drilling or separately the forces caused by the chisel edge and cutting lips by drilling with or without pilot hole (Fernandes, M 2006) (Chen, W. C 1997) (Lin, S. C 1996). The later studies have indicated that it is possible to obtain more detailed information about distribution loads in drilling from the analysis of variation of forces during tool entry into the work-piece. This is useful for selecting appropriate drills, accurate modeling of delamination defects, improving cutting forces prediction models, and process planning optimization (Mihai-Bozdan Layar 2011). The quality of the drilled holes is influenced by the thrust force and the torque generated in drilling which in turn is affected by the factors such as tool geometry, speed, feed, etc. The higher thrust force induces more extensive delamination to the work piece (Hocheng, H 2003). Therefore, many researchers have attempted to minimize the generation of the thrust force by designing different types of drilling tools (Wong, T. L 1982).

The objective of this study is to analyze the effects of process parameters such as tool feed rate, spindle speed, drill diameter and point angle on the thrust force using Taguchi DOE, ANOVA, RSM and GA-RBFNN, during drilling of BD-CFRP composite laminate with HSS drills. The advantage of using BD-CFRP composite laminate is that it has maximum stiffness and strength 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 areal density of 200 $g.m^{-2}$ 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 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 hours at room temperature and the post curing of the composite laminate is carried out for about eight hours at 80°C.

2.2. Experimental method

A Matsuzawa micro-hardness testing machine (Model No MMT-X7A, Japan) is used for measuring the Vickers hardness of 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).

Fig. 1. Experimental set up

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. 1.

The thrust force generated during drilling of BD-CFRP composite is measured using the 9257BA KISTLER dynamometer. The mechanical properties of the test specimen are given in Table 1.

Table 1 Mechanical properties of the 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	861.19130	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 (Montgomery, D. C 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, without using ANOVA, and thus, making the analysis simple. The analysis is made using the software specially used for the DOE applications known as MINITAB 15. The S/N ratio characteristics can be divided into three categories:

Nominal is the best characteristic $$\frac{S}{N} = 10\log\frac{\bar{y}}{s_y^2} \quad (1)$$

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

Larger is the better characteristic $$\frac{S}{N} = -\log\frac{1}{n}\left(\sum\frac{1}{y^2}\right) \quad (3)$$

where, $\bar{y}$ the average of the 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 of delamination factor, surface roughness, thrust force, torque and stress (Phadke, M. S 1989). In this work, in order to identify the optimal cutting parameters for minimum thrust force, S/N ratio characteristic and L_{27} orthogonal array have been used. Table 2 indicates drilling test parameters and levels.

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

The response surface methodology (RSM) is a statistical tool that is 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 (Myers, R. H 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 among 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 thrust force can be expressed as

$$\text{Thrust force} = \beta_0 + \beta_1(A) + \beta_2(B) + \beta_3(C) + \beta_4(D) + \beta_5(A^2) + \beta_6(B^2) + \beta_7(C^2) + \beta_8(D^2) + \beta_9(AB) + \beta_{10}(AC) + \beta_{11}(AD) + \beta_{12}(BC) + \beta_{13}(BD) + \beta_{14}(CD) \quad (4)$$

From the observed data for the thrust force, the response function is given as

$$\text{Thrust force} = -9.49406 - 0.153712A - 0.454631B + 3.03693C + 21.1698D + 3.72593\times10^{-5}A^2 + 0.123133B^2 - 0.0170748C^2 - 1.28292D^2 - 0.00157667AB + 0.000191369AC + 0.00144167AD + 0.0155357BC - 0.196125BD + 0.0136607CD \quad (5)$$

3.3. Genetic algorithm optimized radial basis neural network (GA-RBFNN)

The artificial neural network (ANN) is considered a robust modeling tool that can perform a non-linear mapping from a multi-dimensional input space to a multi-dimensional output space. Generally, an ANN consists of three layers of neurons: one input layer, one or more hidden layers, and one output layer, where each neuron is a computational unit. The number of neurons in the input and output layers are equal to the number of inputs and outputs of the system to be modeled. The neurons of the layers are linked through weighted connections. The response of the hidden and the output layers are generally obtained through some transfer functions like sigmoid and tan sigmoid functions (Haykin Simon, 1999) (Anil Jain, K 1996).

The radial basis function neural network (RBFNN) is an ANN which consists of only one hidden layer, made up of special neurons known as the radial basis function (RBF) neurons. The merit of the RBFNN is that it combines the gradient method and the least square estimators. In the present work, the authors have used the RBFNN as a modeling tool for predicting the thrust force for unseen inputs during drilling of BD-CFRP composite laminate. The input layer receives the inputs: spindle speed (SS), feed rate (FR), point angle (PA) and drill diameter (DD). The connections between the input and the hidden layer of the RBFNN are un-scaled (unit weights), whereas the connections from the hidden layer to the output layer are weighted (w_{kj}). The activation functions in the output layer are sigmoid. The output layer consists of only one neuron corresponding to the thrust force. The response V_j^p of the j^{th} neuron in the hidden layer, for the p^{th} input is given as:

$$V_j^p = exp\left(\frac{-\left\| x_i^p - c_j \right\|^2}{2\sigma_j^{\ 2}} \right) \tag{6}$$

where, x_i^p is the p^{th} input vector, c_j and σ_j are the center and width of the j^{th} hidden neuron respectively. Then the RBFNN output O_k^p of the k^{th} output neuron, for the p^{th} input is given as:

$$O_k^p = \frac{1}{\left[1 + exp\left(-\sum_{j=1}^{h} w_{kj} \times V_j^p \right) \right]} \tag{7}$$

The successful implementation of the RBFNN training depends upon the proper selection of the RBFNN training parameters, viz., h (number of hidden neurons), σ (width of the RBF neurons), α (learning rate) and μ (momentum rate). Genetic Algorithm (GA) is a global optimization tool that can be used for optimizing the parameters of a given system (David Goldberg, E 1989) (Wen-Yang Lin, 2003). The GA has been used in the RBFNN for optimizing the training parameters. The fitness function of the GA depends upon the mean relative error (MRE) of the RBFNN on the training data and the test data as given in equation (8). Fig. 2 shows the structure of the GA based RBFNN architecture used for the work in this paper. It consists of four nodes in the input layer (SS, FR, PA and DD), h nodes in the hidden layer and one node (TF) in the output layer.

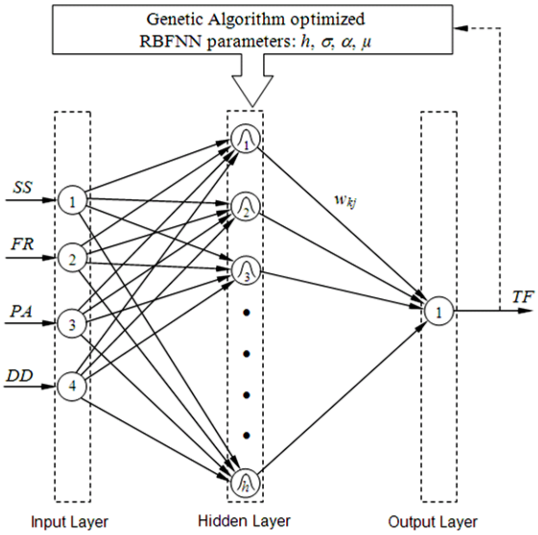

Fig. 2. Structure of the GA-RBFNN used in the study.

$$\text{Fitness} = \frac{\left[(100 - \text{MRE}_{Trg}) + (100 - \text{MRE}_{Tst})\right]}{2} \tag{8}$$

where, MRE_{Trg} and MRE_{Tst} are the MRE on the training and the test data respectively. The expression for computing the MRE is given in equation (9).

$$\text{MRE}(\%) = \frac{1}{n}\sum_{p=1}^{n}\left(\frac{|O_p - y_p|}{O_p} \times 100\right) \tag{9}$$

where, O_p and y_p are the GA-RBFNN predicted and the experimental thrust force values respectively, and n is the number of experiments.

4. Results and discussion

4.1. Analysis of thrust force by Taguchi DOE and ANNOVA

The minimization of thrust force is the key for minimizing the drilling induced delamination in composite materials. In this study, the experiments have been carried out for investigating the effects of process parameters such as spindle speed, feed rate, point angle and drill diameter on thrust force in drilling of BD-CFRP composite using HSS drills. The experimental and predicted results of the thrust force of BD-CFRP composite laminate are given in Table 3.

The main effects plot for S/N ratio of thrust force (smaller is the better) is shown in Fig. 3. From the plot it is evident that the drill diameter and the spindle speed are more significant design parameters that influence the thrust force as the slope gradient is large.

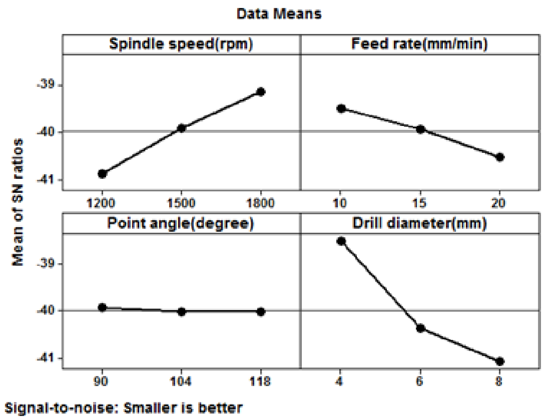

Fig.3. Main effects plot for S/N of thrust force.

It is also evident from the main effects plot that drill diameter of 4 mm, feed rate of 10 mm/min, spindle speed of 1800 rpm, and point angle of 90° are the optimum parametric conditions to obtain the minimum thrust force during drilling of BD-CFRP composite laminate. Since the point angle has less significance, it could be set at any convenient value for getting better surface finish.

Table 3 Experimental and predicted results of the thrust force.

Test No.	Experimental thrust force (N)	Predicted thrust force (N) by RSM	Error (%)	Predicted thrust force (N) by GA-RBFNN	Error (%)
1	84.84	86.36	1.79	84.73	0.12
2	108.07	105.04	2.80	108.21	0.12
3	118.55	113.45	4.30	116.41	1.80
4	90.66	96.47	6.40	91.83	1.29
5	118.16	113.57	3.88	117.67	0.41
6	125.93	120.41	4.38	124.69	0.98
7	103.64	108.22	4.41	103.81	0.16
8	121.21	123.74	2.08	122.94	1.42
9	136.26	129.00	5.32	130.93	3.91
10	80.46	75.69	5.92	80.40	0.07
11	97.81	95.62	2.23	97.14	0.68
12	108.24	105.28	2.73	113.90	5.22
13	84.33	78.64	6.74	84.17	0.18
14	100.97	96.98	3.95	100.18	0.78
15	109.67	105.07	4.19	111.63	1.78
16	92.17	87.47	5.09	88.09	4.42
17	108.04	103.09	4.58	109.90	1.72
18	115.92	108.45	6.44	115.80	0.10
19	67.89	66.65	1.82	67.37	0.76
20	92.28	87.82	4.83	94.70	2.62
21	101.37	98.73	2.60	94.16	7.11
22	75.11	67.53	10.09	75.43	0.42

23	95.07	85.98	9.56	94.94	0.13
24	103.26	94.16	8.81	103.42	0.15
25	84.07	81.76	2.74	85.90	2.17
26	100.58	98.63	1.93	99.92	0.65
27	104.03	105.24	1.16	103.93	0.09
Avg. Error			4.47	Avg. Error	1.46

Table4 Analysis of variance for S/N ratios of thrust force.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	P (%)	Rank
Spindle speed(A)	2	13.7468	13.7468	6.8734	108.04	0.000	27.020	2
Feed rate(B)	2	4.9635	4.9635	2.4818	39.01	0.000	9.750	3
Point angle(C)	2	0.0460	0.0460	0.0230	0.36	0.711	0.090	4
Drill diameter(D)	2	31.5545	31.5545	15.7773	248.00	0.000	62.040	1
A*D	4	0.2913	0.2913	0.0728	1.14	0.419	0.285	
B*D	4	0.7299	0.7299	0.1825	2.87	0.120	0.717	
C*D	4	0.0793	0.0793	0.0198	0.31	0.861	0.077	
Residual Error	6	0.3817	0.3817	0.0636				
Total	26	51.7930					100	

The ANOVA for S/N ratio of thrust force is carried out for a significance level of α = 0.05, i.e., for a confidence level of 95%. The P values in the ANOVA Table 4 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 objective of ANOVA is to determine the factors and the combination of factors that significantly affect the machining process. It can be seen from the ANOVA Table 4 that the drill diameter has the highest contribution (P = 62.04%), followed by spindle speed (P = 27.02%). It can also be seen from the ANOVA table that the interaction effects of the process parameters on thrust force in drilling of BD-CFRP composite laminate have no statistical and physical significance.

4.2. Analysis of thrust force using RSM and GA – RBFNN

It is observed from the Table 3 that the average errors of the thrust force as per RSM and GA-RBFNN are less than 4.5%, indicating that there is a good agreement between the experimental and the predicted results. It is also observed from the table that the GA-RBFNN is better than the RSM model for predicting the drilling induced thrust force.

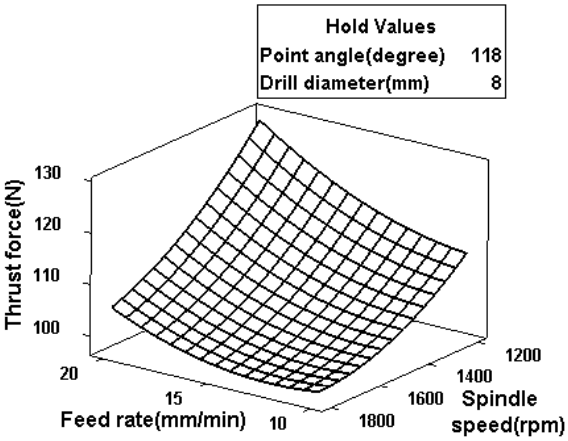

Fig. 4. Interaction effects of feed rate and spindle speed on thrust force.

The thrust force generated during drilling of BD-CFRP composite laminate is analyzed through the RSM prediction model by generating 3D response surface plots. Fig.4 shows the interaction effects of the feed rate and the spindle speed on thrust force, with the drill diameter (8 mm) and the point angle (118°) held constant. It is clear from the figure that the increase of feed rate increases the thrust force in drilling (Palanikumar, K 2008). From the figure it is also clear that with feed rate kept at a low value, minimum thrust force can be achieved with higher spindle speed during drilling of BD-CFRP composite laminate using HSS drills. This is due to the reason that the increase in spindle speed increases the temperature in drilling of composites, which softens and shears the matrix material, in turn reduces the thrust force (Palanikumar, K 2012).

Fig. 5 illustrates the interaction effect of the feed rate and the drill diameter on thrust force, with the spindle speed (1800 rpm) and the point angle (118°) held constant. It is evident from the figure that increase in drill diameter increases the thrust force generated during drilling of composite material. The reason is that the increase of drill diameter increases the contact area of the hole produced which increases the thrust force in drilling of composites. The increase in the thrust force leads to the increase of drilling induced delamination (Palanikumar, K 2011). Fig 6 shows the push-out delamination obtained from HP high resolution scanner. The results reveal that the increase in the feed rate and the drill diameter increases the thrust force and vice-versa.

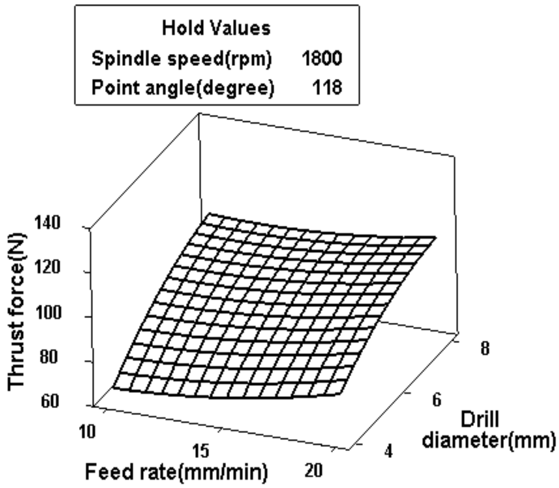

Fig. 5. Interaction effects of feed rate and drill diameter on thrust force.

(b) (c)

Fig. 6. Delamination obtained for (a) 1200rpm, 20mm/min, 118degree (b) 1500rpm, 20mm/min, 90degree (c) 1800rpm, 20mm/min, 104degree.

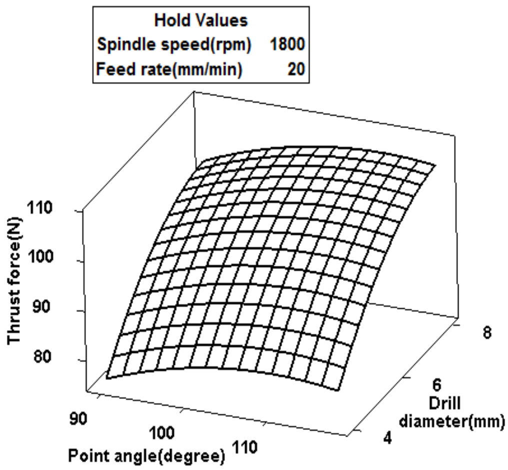

Fig. 7. Interaction effects point angle and drill diameter on thrust force.

The influence of the drill diameter and the point angle on thrust force with the feed rate (20 mm/min) and the spindle speed (1800 rpm) held constant, is illustrated in Fig. 7. It is clear from the figure that the minimum thrust force in drilling of BD-CFRP composite is observed at lower drill diameter and minimum point angle. It is also clear from the Fig. 7 that the thrust force of the BD-CFRP composite is least sensitive to the variation in point angle. From the analyses of the figures, it is concluded that maximum spindle speed, minimum drill diameter, minimum feed rate and minimum point angle are preferred to reduce the thrust force generated during drilling of BD-CFRP composite laminate.

Table 5 ANOVA table for response function for thrust force.

Source	DF	Seq SS	Adj MS	F	P
Regression	14	6311.53	450.82	17.65	0.000
Residual Error	15	357.62	25.54		
Total	29	6669.15			

The adequacy of the RSM model has been tested through the ANOVA at 5% significance level, i.e., for a confidence level of 95%. The result of ANOVA for the response function of thrust force is presented in Table 5. From the table it is apparent that, the calculated value of F-ratio of the developed model (17.65) 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.

Table 6 Results of confirmation experiment of thrust force.

Response	Optimum cutting parameters	Experimental	Prediction	% of agreement
Thrust force(N)	$A_3B_1C_1D_1$	65.98	65.44	99.18

It is observed from the Table 6 that the predicted value of thrust force generated during drilling for the optimum cutting condition (A_3=1800rpm, B_1=10mm/min, C_1=90degree, D_1=4mm) is 65.44. The experimental value of thrust force obtained for the optimum cutting condition is 65.98, confirming within the 99.18% of confidence.

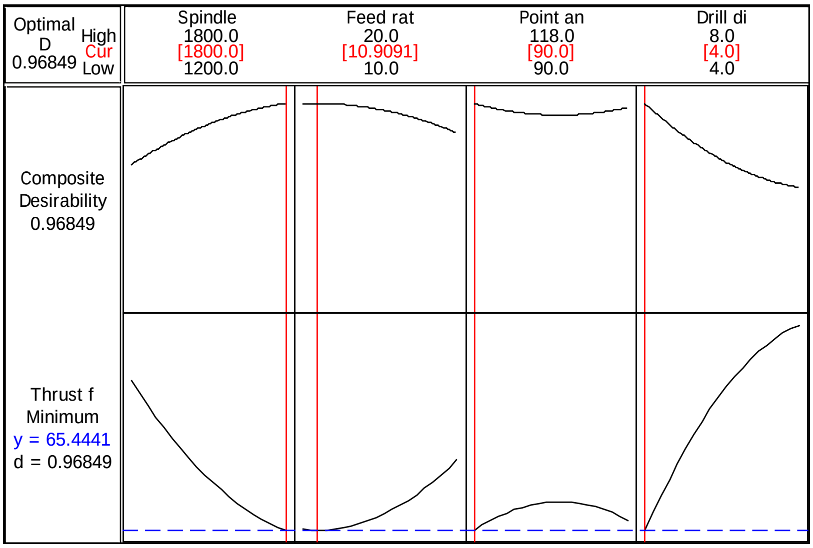

Fig. 8. Optimized response surface plot of thrust force.

The Fig. 8 shows the optimized response surface plot of thrust force generated during drilling of BD-CFRP composite laminate with HSS drills. From the figure it is clear that minimum thrust force obtained for the optimum condition is 65.44. The merit of this optimized response plot is that it is possible to get optimal thrust force by re-defining the values of process parameters within the experimental range.

The data obtained from Taguchi L_{27} orthogonal array is used to train the RBFNN. The entire training set is presented to the neural network repeatedly until the training goal reaches an acceptable value. In the present work, the RBFNN is set to run for a maximum of 1000 epochs and the weights are initialized to small arbitrary values. The training goal considered here is the mean square error (MSE) which is set to 1×10^{-4}. In the GA, a real valued chromosome of length four units corresponding to the four training parameters (h, σ, α and μ) is considered. A population size of ten is used in the GA. The GA is set to run for a maximum of 200 generations. The crossover and mutation rates are 0.6 and 0.2 respectively, wherein the multi-point crossover is adopted. The selection of the parent chromosomes for reproduction is done by the normalized geometrical ranking method. The GA optimized training parameters of the RBFNN obtained in this study are: epoch number1000 , number of hidden neurons 23, width of the RBF units 0.171886, learning rate 0.692878, momentum rate 0.01,mean relative error on training data 1.4579% and training MSE reached 2.872×10^{-4}. Once the prediction mode of thrust force is established, the thrust force for different cutting conditions can be predicted quickly and accurately. The comparison of the experimental and the predicted results of the thrust force are shown in

Figs. 9 and 10. The figures illustrate that there is a good correlation between the experimental and the predicted results of the thrust force obtained from RSM and GA-RBFNN.

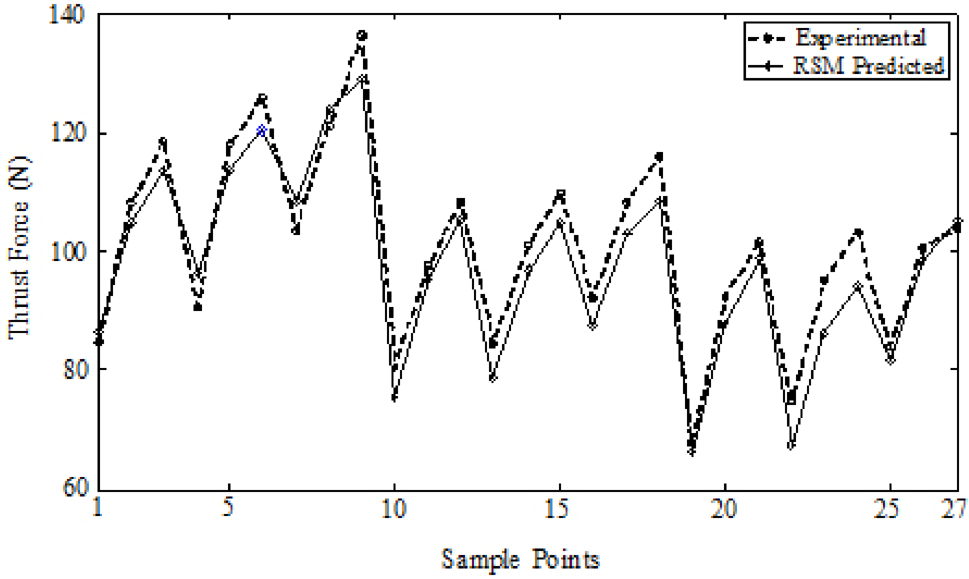

Fig. 9. Comparison of the experimental and the predicted thrust force, as per RSM for the data obtained from the Taguchi L_{27} orthogonal array.

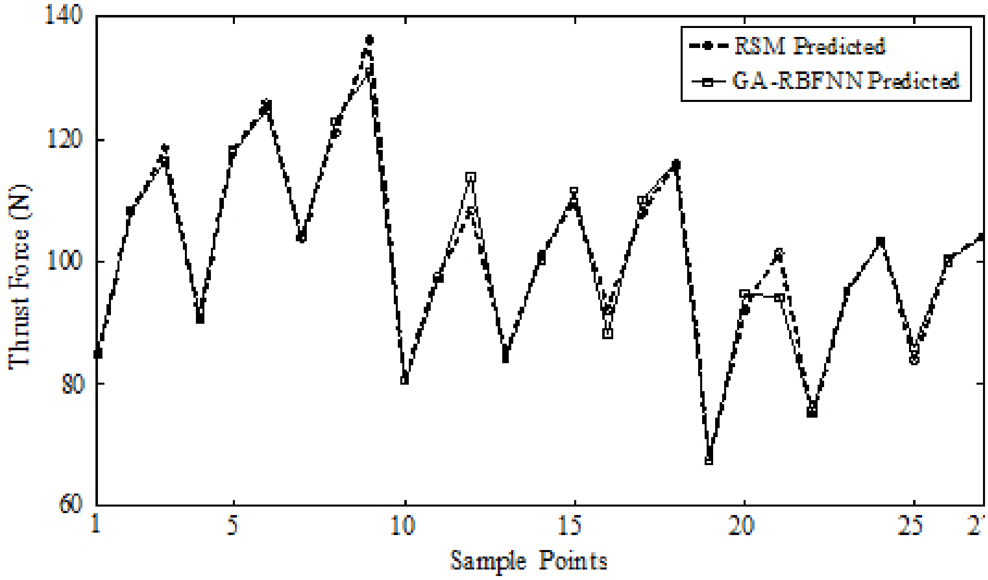

Fig. 10. Comparison of the experimental and the predicted thrust force, as per GA-RBFNN for the data obtained from the Taguchi L_{27} orthogonal array.

4.3. Confirmation test

In order to check the accuracy of the results of the thrust force, the confirmation test is carried out using the cutting conditions given in Table 7. From the Table 8, it is observed that the average errors of the thrust force as per RSM and GA-RBFNN are 3.89% and 2.56% respectively. This indicates that the average errors of the thrust force obtained from the confirmation test are in good approximation with those obtained through the integration of Taguchi DOE, RSM and GA-RBFNN (Table 3). The Fig. 11 depicts that the experimental and the predicted values of the thrust force obtained from RSM and GA-RBFNN fairly match with each other. The results of the confirmation test indicate that GA-RBFNN is a better predicting tool than RSM model.

Table 7 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 8 Results of confirmation test with RSM and GA-RBFNN.

Test No.	Experimental thrust force	Predicted thrust force by RSM	Error (%)	Predicted thrust force by GA-RBFNN	Error (%)
1	86.53	88.66	2.46	84.02	2.90
2	115.24	109.80	4.72	112.72	2.19
3	128.67	130.45	1.38	129.12	0.35
4	78.83	72.10	8.54	75.03	4.82
5	101.38	94.54	6.75	106.92	5.47
6	118.96	113.84	4.30	123.70	3.98
7	69.98	69.44	0.77	70.42	0.62
8	88.05	90.03	2.25	87.89	0.18
Avg. Error			3.89	Avg. Error	2.56

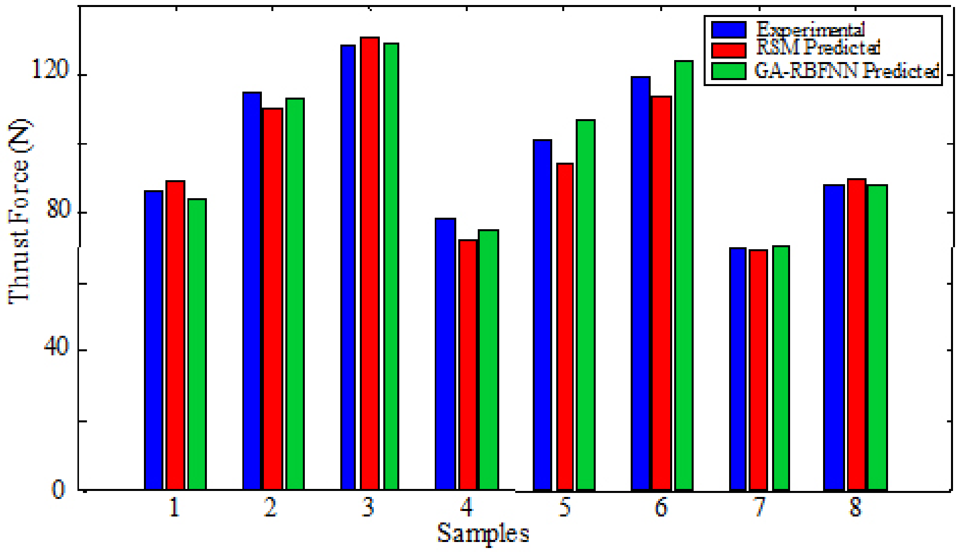

Fig. 11. Comparison of the experimental and the predicted thrust force, as per RSM and GA-RBFNN, for the confirmation test data.

5. Conclusion

Based on the experimental results, the following conclusions can be drawn in drilling of the BD-CFRP composite laminate:

1. The model generated by the design package (MINITAB 15) shows the effects of process parameters on the thrust force for HSS drills.
2. The experimental results show that the drill diameter has the highest physical and statistical influence on the thrust force followed by the spindle speed.
3. The investigation reveals that minimum thrust force is obtained at higher spindle speed, lower drill diameter, lower tool feed rate and minimum point angle.
4. The analyses of the study demonstrate that there is a good agreement between the experimental and the predicted results of the thrust force as per RSM and GA-RBFNN.
5. The study shows that GA-RBFNN is more precise and accurate than the RSM for the evaluation of thrust force using HSS drills.

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