Indian Journal of Science and Technology, *Vol 9(16), DOI: 10.17485/ijst/2016/v9i16/87981, April 2016*
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Modeling and Analysis of Drilling Induced Damages on Hybrid Composites

R. Vinayagamoorthy*, Kanakadandi Guru Subramanyam, Tuduru Nikhil Kumar and Yerasi Harshavardhan Reddy

Department of Mechanical Engineering, SCSVMV University, Kancheepuram - 631561, Tamil Nadu, India; vmmailbox@rediffmail.com, kgsmanyam777@gmail.com, tudurumikhil@gmail.com, yerasihvr1995@gmail.com

Abstract

Background/Objectives: To investigate the damages that occurs during drilling on newly prepared hybrid composites. **Methods/Analysis:** Composites have been prepared by using randomly oriented steel wool and woven jute as reinforcements and polyester as the matrix resin. Drilling experiments have been carried out on the developed composite by adopting Box-Behnken methodology. Speed, feed rate, point angle and tool diameter are taken as the input factors and the damage at entrance and exit surfaces have been measured as output responses. **Findings:** The output factors have been analyzed and optimized to yield a set of optimum conditions on the basis of desirability approach. The results showed that speed, feed rate and tool angle have significant influence on the entrance and exit damages but tool diameter does not have any influence. A speed of 500 rpm-970 rpm, a constant feed of 0.1 mm/rev, a tool angle of 90^0-120^0, and selection of 8 mm and 10 mm as tool diameter are found to be the optimum input conditions for drilling. Confirmatory experiments have been conducted for the set of optimum conditions and the responses have been measured. The developed model is validated by an error analysis between the model and confirmatory runs. The observed errors between the model and confirmatory runs are meagre and hence the optimization using Box-Behnken design is satisfactory. **Novelty/Improvement:** Machining associated failures must be resolved in order to improve the productivity. This research made an attempt to optimize drilling associated damages on new composites made by using metal and natural fibers as reinforcement.

Keywords: Box-Behnken Design, Damage Factor, Drilling, Hybrid Composites, Optimization

1. Introduction

Fiber reinforced plastics is one among the several classification of composite materials. They are otherwise known as polymer matrix composites as they possess polymers as their matrix material. Fiber reinforced plastics are used as alternatives for conventional materials due to its improved properties at a reasonable cost. Due to this reason, the use of fiber reinforced plastics have been increasing in automobile, aircraft, marine and construction industries[1]. A composite material after its manufacturing would be subjected to several machining operations like drilling for producing holes, milling for finishing the edges and to remove the excess material and grinding for surface finishing[2]. Hence, machining of composites is an important task for manufacturing sectors. During drilling, the drilled hole is subjected to two type of damages. One is the profile damage which occurs on the circular profile of the holes made and the other is the damage of inner surface. The profile damage could be measured in terms of damage or delamination factor and the inner surface damage could be measured by its surface roughness. In a study, carbon reinforced composites have been subjected to drilling and reported that, the damage of profile and damage of inner surface are found to be minimum at low feed rates[3].

In another research, glass reinforced composites have been subjected to drilling and reported that, delamination is highly affected by thrust force and torque. The study also concluded that the residual strength of composites decreases due to delamination during drilling[4].

**Author for correspondence*

During drilling, the work piece is subjected to thrust force which acts normal to the surface of the work. The drill tool develops torque as a result of the rotation during its traverse in to the work piece. These thrust force and torque must be minimized during drilling. In an investigation, drilling has been carried out onglass reinforced composites and it has been concluded that, the surface roughness increases with increase in spindle speed and tool diameter[5]. In another study, an empirical model has been developed for predicting the thrust force during drilling of glass reinforced plastics and reported that the fiber orientation plays an important role in deciding the thrust force[6]. Holes could be made on the composites by two different methods namely drilling and milling. Drilling uses a drill tool whereas milling uses an end mill tool for hole making. A comparative study of drilling and milling on glass reinforced composites reported that milling process is suitable for hole making at high speed and at low feed rate[7].

In recent days, machining studies have been carried out in composites with natural fiber. A study on drilling of coir reinforced composites reported that, feed rate is majorly affecting the thrust force and torque. It has been concluded that, the optimum conditions for drilling are medium level feed rate, high level spindle speed and medium level drill size[8]. In another study, delamination has been investigated during drilling on wood composite panels and reported that, feed rate and drill diameter are majorly affecting the delamination[9]. Nowadays composites are developed with more than one reinforcement and hence they are called as hybrid composites. Mechanical properties of such hybrid composites are good as compared to that of an ordinary composites[10]. These composites when subjected to machining are also subjected to damages. In a study, drilling is performed on sisal and glass reinforced hybrid composites and reported that, feed rate has the major influence on delamination[11].

Always there a need to develop new composites aiming to improve the mechanical properties and this may be achieved by introducing new type of reinforcements. Although several research works have investigated the machining associated studies on synthetic, natural and hybrid fiber reinforced composites, very few attempts have been made to use metals as reinforcements in polymeric composites and no attempts have been made to use metallic fibers in hybrid form. The author in an earlier research made four new compositesby using jute, glass, bronze and steel as reinforcements and investigated the mechanical properties[12]. It has been concluded that, the composite sample with jute and steel reinforcements produced high compression and impact strength as compared to that of the other samples. This sample is taken for the present machining study and subjected to a series of drilling experiments based on Box-Behnken design. Damage factors at entrance and exit of the drilled holes have been measured and optimized. The optimum machining conditions are validated by conducting a set of confirmatory runs.

2. Material and Machining

2.1 Composites Preparation and Characterization

The composite sample is prepared by using two types of reinforcements namely steel wool and woven jute. Before the preparation of samples, steel fiber is thoroughly washed in soap water in order to remove the impurities present in it and then dried to remove the moisture. The steel fiber has been used in random form and jute fiber has been woven in the form of $0^0/90^0$. The composite sample of 12 mm thickness are prepared by using hand layup method. The jute fiber proportion is maintained as 20% by weight, steel fiber proportion is maintained as 10% by weight and the polyester matrix proportion is maintained as 70% by weight. During this process, Methyl Ethyl Ketone Peroxide (MEKP) is taken as a catalyst and octate is taken as an accelerator[10]. Mechanical properties of the developed sample have been tested according to ASTM standards and are presented in Table 1.

The microstructure of developed sample is presented in Figure 1. The bonding between the jute fiber and resin seems to be good as compared to that of the bonding between steel and resin. The reason being that, the jute fiber have more capacity of absorbing the resin than the steel fiber. This leads to proper adhesion and hence during

Table 1. Properties of composite sample

Property	Value
Tensile strength	5 MPa
Compressive strength	106 MPa
Flexural strength	123 MPa
Impact Energy	33 J
Elongation at break	6 %

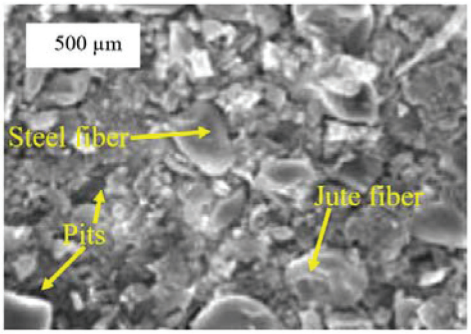

Figure 1. Microstructure of developed sample.

machining, the resistance offered by the area around jute fiber would be more than that of the area around the steel fiber. There are few pits visible in the microstructure and this happens due to improper coverage of resin around the fiber during the hand layup process. The presence of these pits will increase the damage of matrix whereas the area where there is a proper coverage of resin will offer more resistance to the cutting force during drilling.

2.2 Machining and Measurement

Drilling experiments have been carried out in a Bharat Fritz Werner make CNC machining center with an upper limit speed of 6000 rpm. Three set of drill tools in 8 mm diameter, 10 mm diameter and 12 mm diameter have been purchased from a local supplier. The point angles of these tools have been modified to 90^0, 120^0 and 150^0 in 8 mm, 10 mm and 12 mm drills thus forming nine drill tools in total. Four input factors namely spindle speed, spindle feed rate, tool point angle and tool diameter are considered for this study and damage factor is measured as the output factor. The input factors and their levels used for drilling are presented in Table 2. The maximum diameter of the hole on the top and bottom surface of the work piece as presented in Figure 2 have been measured by using tool makers microscope. Damage factor has been calculated using the formula[9] as presented in Equation (1).

$$Damage\ factor = \frac{Dmax}{D} \quad (1)$$

3. Box-Behnken Design

Statistical modeling helps the researchers to analyze the importance of input factors in an experiment and in recent days, statistical techniques are used in manufacturing sectors to study the machinability[13]. Response surface method is one among the different statistical techniques which helps to analyze the output responses under the influence of several input factors. Response surface is a three dimensional surface in which the variation of output response with respect to two input variables could be analyzed[14,15]. Response surface method develops quadratic equations using which, output responses could be predicted from known input factors. A general second order response equation takes the form as presented in Equation (2).

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \beta_{11} X_1^2 + \beta_{23} X_2^2 + \beta_{33} X_3^2 \quad (2)$$

Where Y is the output variable, X_1, X_2 etc are the input variables, β_0, β_1 etc are the constants.

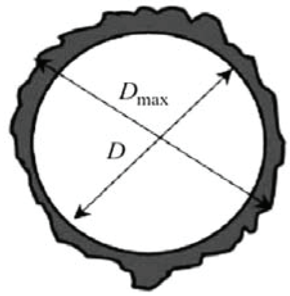

Figure 2. Measurement of damage factor.

Table 2. Input factors and levels

Sl. No.	Input factor	Levels		
		Level 1	Level 2	Level 3
1.	Speed (N) rpm	500	1250	2000
2.	Feed (F) mm/rev	0.1	0.2	0.3
3.	Tool angle (θ) degree	90	120	150
4.	Tool diameter (D) mm	8	10	12

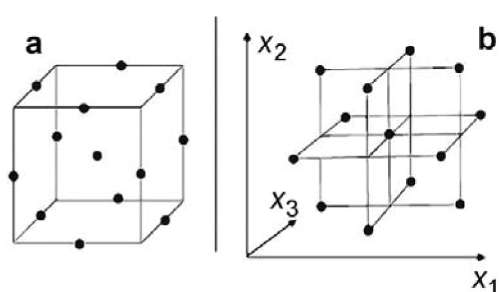

Figure 3. Graphical representation of Box-Behnken design.

This method is generally used along with any one of the factorial design methods like central composite design or Box-Behnken design and these methods will certainly reduce the number of experiments without reducing the accuracy[16]. Box-Behnken model is based on second order rotatable or nearly rotatable design with three level factors. It generally uses three levels in its factors for fitting the response surface. It is graphically represented in two forms. The first form is a cube consisting of central point and points at the middle of each edges. The second form is the scheme consisting of three intersecting 2^2 factorial design with a central point as presented in Figure 3. The main advantage of using this method is that, it does not have combination of input factors at extreme low and high levels simultaneously. So this method avoids conducting experiments in extreme conditions during which there might be a possibility for unsatisfactory results[17]. It involves less treatment combination as compared to that of central composite design. The number of experiments in a Box-Behnken design could be obtained by using the formula as presented in Equation (2).

$$N = 2k\ (k\text{-}1)+C_0 \qquad (3)$$

Where k represents the number of input factors and C_0 represents the number of central points. The present research uses a four factor Box-Behnken design for statistical analysis and optimization by using Design Expert 8 software. The actual design table consisting 29 trial runs and observed responses for the present study are presented in Table 3.

4. Result and Discussions

4.1 Analysis of Variance Study

The ANOVA study gives a detailed analysis like the significance and contribution of input factors on output responses. It also presents the effects of one factor, two factor and square of one factor, residual and pure error on the output responses. Often the model and lack of fit are compared by using the F-value. From ANOVA analysis as presented in Table 4, the model value is significant and lack of fit is insignificant with respect to pure error. Adequacy of the model is analyzed by comparing the correlation co-efficient (R^2) and adjusted correlation coefficient (adj R^2) values. They are a measure of how close the model fits the data. When these values are closer to each other and close to unity, then the model is statistically significant[18]. Further, one more important term in this analysis is the Adequate Precision (AP). It is a measure of signal to noise ratio and it compares the predicted value with the predicted error. An AP value more than 4 indicates that the model is adequate for model prediction[19,20]. In the present analysis, R^2 and adj R^2 are very close to each other and AP value is also well above 4. This shows that the model is adequate for response prediction. Validation of the model is carried out by analyzing the normal probability plots. A close resemblance of straight line indicates that the error distribution is normal and the model is significant. The normal plots for output responses as presented in Figure 4 closely resembles like a straight line. This clearly shows that the model is highly significant.

4.2 Damage Investigations

As far as entrance damage is concerned, the input factors namely speed, feed and tool angle have major influence on the entrance damage with contributions of 40%, 9.43% and 6.86% respectively. Tool diameter does not have significant influence on the entrance damage. Considering the interaction effects, feed-tool angle combinations have an influence of about 1.8%. All other interactions have very less influence on the entrance damage. Among the squares of input factors, it has been observed that all the factors namely speed, feed, tool angle and tool diameter have influences on the entrance damage with contributions of 27.57%, 1.8%, 4.8% and 7.3% respectively. Speed has predominant influence on the entrance damage. As far as exit damage is concerned, the input factors namely speed, feed and tool angle have major influence on the exit damage with contributions of 39.29%, 8.6% and 8.57% respectively. Tool diameter does not have significant influence on the entrance damage. This behavior is quite similar to that of the entrance damage. Considering the interaction effects, feed-tool angle and feed-tool diameter combinations have an influence of about 3.21% and 1.43% respectively. All other interactions have very less influence on the exit damage. Among the squares of input factors, it has been observed that all the factors namely speed, feed, tool angle and tool diameter have influences on the exit damage with contributions of 27.18%, 2.55%, 3.89% and 11% respectively. Speed has predominant influence on the exit damage andthese behaviors are quite similar to that of the entrance damage.

Table 3. Box-Behnken design table

Run No.	Speed (rpm)	Feed (mm/rev)	Tool angle (degree)	Tool diameter (mm)	D Entrance	D Exit
1	500	0.1	120	10	1.02	1.04
2	2000	0.1	120	10	1.10	1.11
3	500	0.3	120	10	1.05	1.07
4	2000	0.3	120	10	1.10	1.11
5	1250	0.2	90	8	1.07	1.08
6	1250	0.2	150	8	1.09	1.10
7	1250	0.2	90	12	1.07	1.08
8	1250	0.2	150	12	1.09	1.11
9	500	0.2	120	8	1.04	1.05
10	2000	0.2	120	8	1.11	1.12
11	500	0.2	120	12	1.05	1.06
12	2000	0.2	120	12	1.12	1.12
13	1250	0.1	90	10	1.06	1.07
14	1250	0.3	90	10	1.12	1.13
15	1250	0.1	150	10	1.13	1.14
16	1250	0.3	150	10	1.14	1.14
17	500	0.2	90	10	1.03	1.05
18	2000	0.2	90	10	1.10	1.11
19	500	0.2	150	10	1.05	1.07
20	2000	0.2	150	10	1.12	1.13
21	1250	0.1	120	8	1.07	1.08
22	1250	0.3	120	8	1.13	1.13
23	1250	0.1	120	12	1.08	1.09
24	1250	0.3	120	12	1.12	1.12
25	1250	0.2	120	10	1.14	1.14
26	1250	0.2	120	10	1.12	1.13
27	1250	0.2	120	10	1.13	1.14
28	1250	0.2	120	10	1.13	1.14
29	1250	0.2	120	10	1.12	1.13

The response surface plots for entrance damage and exit damage are presented in Figure. 5. The entrance damage and exit damage plots seems to be more or less same with meagre variations. As speed increases, both the entrance and exit damages also increases rapidly until a speed of around 1600 rpm and thereafter there is a slight decrease in damage until 2000 rpm. The reason being that, during high speed drilling the matrix would be subjected to high stresses and vibration due to rotation of the drill tool, as a result the top and bottom surface area surrounding the drill would be damaged. This affects the damage of the profile and hence the damage increases[21]. As feed increases, the entrance damage also increases gradually between 0.1 mm/rev and 0.3 mm/rev. The increase in exit damage with respect to feed rate happens until a feed of 0.25 mm/rev and thereafter the damage remains constant. Hence, increase in feed rate increases both the entrance and exit damages. The reason being that, at feed rate the thrust force impressed by the tool on the work piece would be more and this causes more damage on the entrance surface and exit surface of the hole. As tool angle increases, the entrance

Table 4. Combined ANOVA table for responses

Source	Sum of squares	Degrees of freedom	Mean square	F value	p value	% Contribution / Significance
Damage at Entrance						
Model	0.032000	14	0.002260	9.19	<0.0001	Significant
N-Speed	0.014000	1	0.014000	56.76	<0.0001	**40%**
F-Feed	0.003330	1	0.003330	13.51	0.0025	**9.43%**
θ -Tool angle	0.002400	1	0.002400	9.76	0.0075	**6.86%**
D-Tool diameter	0.000033	1	0.000033	0.14	0.7187	0.1%
N*F	0.000225	1	0.000225	0.91	0.356	0.64%
N* θ	0.000000	1	0.000000	0.00	1.000	0%
N*D	0.000000	1	0.000000	0.00	1.000	0%
F* θ	0.000625	1	0.000625	2.53	0.1338	**1.8%**
F*D	0.000100	1	0.000100	0.41	0.5347	0.3%
D* θ	0.000000	1	0.000000	0.00	1.000	0%
N^2	0.009650	1	0.009650	39.13	<0.0001	**27.57%**
F^2	0.000627	1	0.000627	2.54	0.1332	**1.8%**
θ^2	0.001680	1	0.001680	6.80	0.0207	**4.8%**
D^2	0.002550	1	0.002550	10.34	0.0062	**7.3%**
Residual	0.003450	14	0.000247	-	-	-
Lack of fit	0.003180	10	0.000320	4.54	0.0791	Not significant
Pure error	0.000280	4	0.000070	-	-	-
Total	0.035000	28	-	-	-	-
$R^2 = 0.902$, Adj $R^2 = 0.804$, AP = 9.45						
Damage at Exit						
Model	0.026000	14	0.001870	14.61	<0.0001	Significant
N-Speed	0.011000	1	0.011000	84.32	<0.0001	**39.29%**
F-Feed	0.002400	1	0.002400	18.78	0.0007	**8.6%**
θ -Tool angle	0.002400	1	0.002400	18.78	0.0007	**8.57%**
D-Tool diameter	0.000033	1	0.000033	0.26	0.6181	0.12%
N*F	0.000225	1	0.000225	1.75	0.2065	0.8%
N* θ	0.000000	1	0.000000	0.00	1.000	0%
N*D	0.000025	1	0.000025	0.19	0.6655	0.09%
F* θ	0.000900	1	0.000900	7.02	0.0191	**3.21%**
F*D	0.000400	1	0.000400	0.78	0.3921	**1.43%**
D* θ	0.000025	1	0.000025	0.19	0.6655	0.09%
N^2	0.007610	1	0.007610	59.35	<0.0001	**27.18%**
F^2	0.000715	1	0.000715	5.58	0.0332	**2.55%**
θ^2	0.001090	1	0.001090	8.55	0.0111	**3.89%**
D^2	0.003070	1	0.003070	23.93	0.0002	**11%**
Residual	0.001795	14	0.000128	-	-	-
Lack of fit	0.001675	10	0.016750	5.58	0.056	Not significant
Pure error	0.000120	4	0.000030	-	-	-
Total	0.028000	28	-	-	-	-
$R^2 = 0.936$, Adj $R^2 = 0.872$, AP = 11.84						

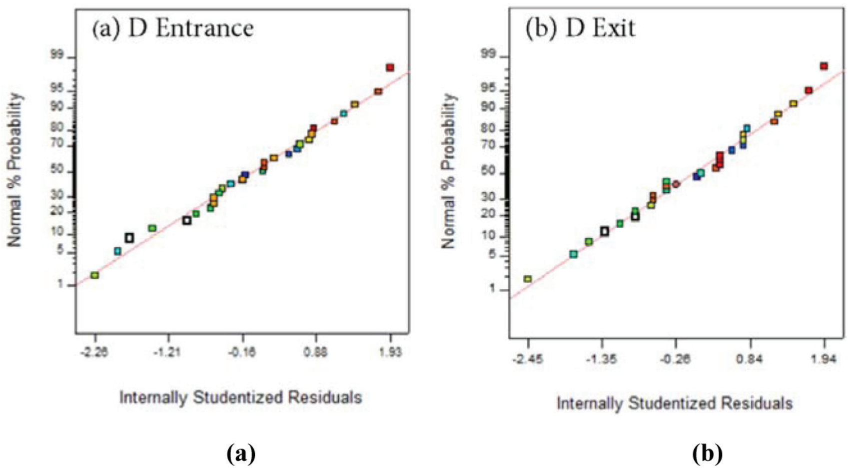

Figure 4. Normal plots for. (a) Entrance damage. **(b)** Exit damage.

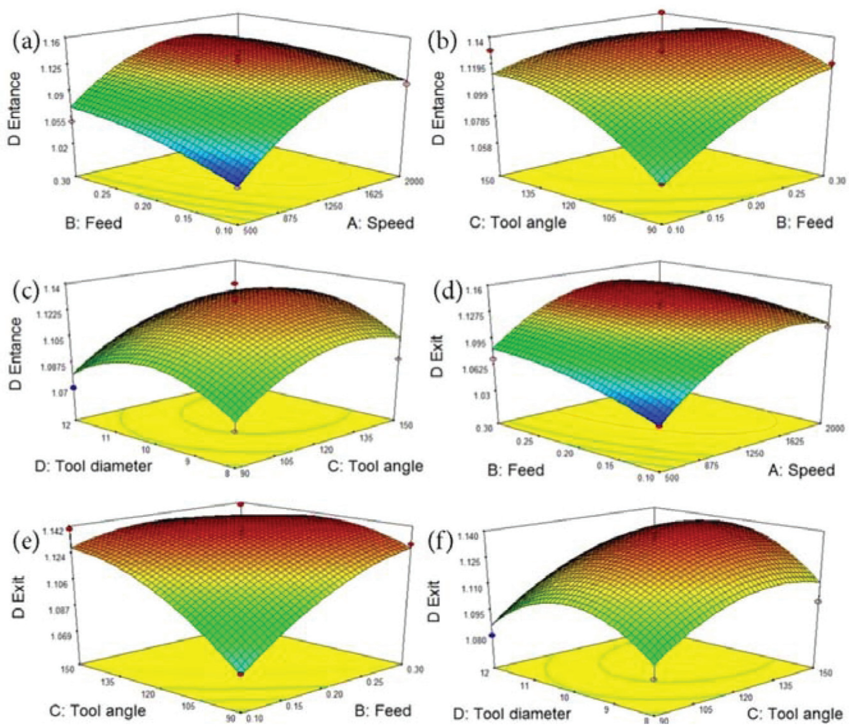

Figure 5. Response plot for. **(a)** Speed-feed vs D entrance. **(b)** Feed-tool angle vs D entrance. **(c)** Tool angle-tool diameter vs D entrance. **(d)** Speed-feed vs D exit. **(e)** Feed-tool vs D exit. **(f)** Tool angle-tool diameter vs D exit.

and exit damages also increases slightly until an angle of 120^0 and thereafter, the damage remains constant until the high value of 150^0. This happens because, as tool angle increases, the contact area of the tool cutting edge on the work surface increases[22]. This increases the thrust force on the work sample and hence causes more damage at entrance and at exit. There is no clear trend observed for damages against the tool diameter. As tool diameter increases, the entrance and exit damages also increases until the middle tool diameter of 10 mm and thereafter the damage starts decreasing until the high tool diameter of 12 mm.

Table 5. Regression table

Sl. No.	Response	Regression equation
1	D Entrance	
3	D Exit	

Second order regressions equations have developed for the output responses. These equations provide a mathematical model of the response in terms of input factors and helps to predict the response for any value of input factors. The terms with a positive sign indicates that, an increase in that term would increase the response. In the same way, the terms with negative sign indicates that, an increase in that term would decrease the response. The regression equations for responses are presented in Table 5.

4.3 4.3 Optimization and Confirmation

Optimizing the machining parameters is a big task for manufacturing sectors and there is a great deal in reducing the experimentation during machining. This reduces the manufacturing cost, labor cost and idle time during machining. Hence, there is always a need to select appropriate machining conditions for manufacturing sectors. This could be achieved by optimizing the input factors and arriving a set of optimum machining conditions. Damages in any form during machining must be minimized in order to improve the accuracy of the job. The present study aims to minimize the responses namely entrance damage and exit damage during drilling. Model optimization is carried out by setting the objectives and a desirability based approach is used to select the optimum conditions. A desirability value close to unity is always acceptable and a value closer to zero is not acceptable. The prediction plots for output responses have been presented in Figure 6. It has been observed that an entrance damage value of 1.018 and an exit damage value of 1.03 are found to be the optimum conditions for drilling.

A set of ten optimum conditions are selected based on the desirability values as shown in Table 6. A speed between 500 rpm to 970 rpm, a constant feed of 0.1 mm/rev, a tool angle between 90^0 and 120^0, and selection of 8mm and 10 mm as tool diameter are found to be the optimum input conditions for drilling. Based on these conditions the CNC machine is re-programmed to work under the optimum input conditions as mentioned in the table. Two new drill tools are purchased and their point angles were modified to 100^0 and 110^0 respectively. Confirmatory runs are conducted for the 10 set of optimum conditions and the output responses are recorded. An average error between the Box-Behnken model and the confirmatory runs has been calculated.The observed errors are 0.95 %, and -0.038 % respectively for entrance and exit damages. These error values are less than unity which shows that the Box-Behnken model data closely follows the confirmatory runs and hence, the optimization is satisfactory.

5. Conclusion

Machining of composites is being an important task for industries and hence the study of optimization of machinability parameters would be helpful for industries to select the appropriate input conditions. Productivity could be improved by the selection of correct machin-

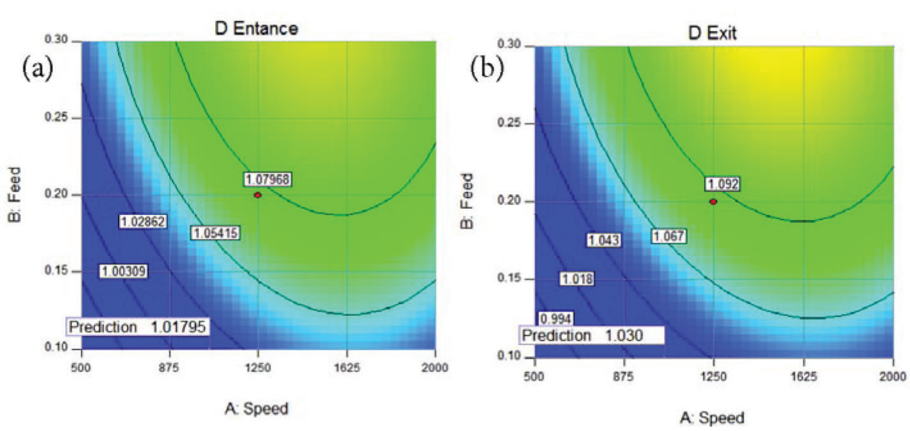

Figure 6. Optimization plots for. **(a)** D entrance. **(b)** D exit.

Table 6. Optimum conditions and comparison

Sl. No.	Speed (rpm)	Feed (mm/rev)	Tool angle (degree)	Tool Diameter (mm)	Box-Behnken		Desirability	Confirmatory	
					D Entrance	D Exit		D Entrance	D Exit
1	550	0.1	120	8	1.01	1.02	0.981	1.02	1.03
2	500	0.1	110	10	1.02	1.03	0.975	1.01	1.03
3	500	0.1	90	10	1.01	1.03	0.966	1.02	1.03
4	520	0.1	90	10	1.01	1.03	0.942	1.01	1.02
5	700	0.1	90	8	1.01	1.02	0.931	1.02	1.03
6	500	0.1	120	10	1.02	1.04	0.921	1.01	1.04
7	530	0.1	100	10	1.02	1.04	0.900	1.01	1.03
8	970	0.1	90	8	1.02	1.03	0.889	1.02	1.03
9	550	0.1	100	8	1.01	1.03	0.885	1.01	1.04
10	500	0.1	100	10	1.02	1.04	0.873	1.01	1.03
Error between Box-Behnken and Confirmatory: D Entrance = 0.95 %, D Exit = -0.03 %									

ing conditions and by effectively utilizing the available resources. This research has focused on the drilling associated machinability analysis on newly made metallic and natural fiber reinforced hybrid composites and the conclusions are as follows:

- Speed, feed rate and tool angle have significant influence on the entrance and exit damages but tool diameter does not have any influence. Similarly the squares of all input factors have a dominant influence on the damages.
- Optimization has been done by setting the objective as minimizing the output responses. Desirability analysis has been made for optimization anda speed between 500 rpm to 970 rpm, a constant feed of 0.1 mm/rev, a tool angle between 90^0 and 120^0, and selection of 8mm and 10 mm as tool diameter are found to be the optimum input conditions for drilling.
- Confirmatory runs have been conducted and the average error between the Box-Behnken model and confirmatory runs is calculated. The average error for the responses are meagre and hence, the optimization by using Box-Behnken design is highly satisfactory.

6. References

1. Nayak D, Bhatnagar N, Mahajan P. Machining studies of Unidirectional Glass Fiber Reinforced Plastic (UD-FRP) composites Part 1: Effect of geometrical and process parameters. Machining Science and Technology. 2005; 9(5):481–501.
2. Vinayagamoorthy R, Rajeswari N, Karthikeyan S. Investigations of damages during drilling of natural sandwich composites. Applied Mechanics and Materials. 2014; 766-767:812–7.
3. Arraiza L, Amenabar I, Agirregomezkorta A, Sarrionandia M, Aurrekoetxea J. Experimental analysis of drilling damage in carbon-fiber reinforced thermoplastic laminates manufactured by resin transfer molding. Journal of Composite Materials. 2012; 46:717–25.
4. Singh I, Bhatnagar N. Drilling induced damage in Unidirectional Glass Fiber Reinforced Plastic (UD-FRP) composite laminates. International Journal of Advanced Manufacturing Technology. 2006; 27(9):877–82.
5. Rao S, Rodrigues L. Controlling process factors to optimize surface quality in drilling of GFRP composites by integrating DoE, ANOVA and RSM Techniques. Indian Journal of Science and Technology. 2015; 8(29):1–9.
6. Rajamurugan TV, Shanmugam K, Palanikumar K. Mathematical model for predicting thrust force in drilling of GFRP composites by multifaceted drill. Indian Journal of Science and Technology. 2013; 10(6):5316–24.
7. Ali HM, Iqbal A, Liang L. A comparative study on the use of drilling and milling processes in hole making of GFRP composites. Sadhana- Academy Proceedings in Engineering Sciences. 2013; 38(4):743–60.
8. Jayabal S, Natarajan U, Sekar U. Regression modeling and optimization of machinability behavior of

glass-coir-polyester hybrid composite using factorial design methodology. International Journal of Advanced Manufacturing Technology. 2011; 55(1):263–73.

9. Valarmathi TN, Palanikumar K, Sekar S. Parametric analysis on delamination in drilling of wood composite panels. Indian Journal of Science and Technology. 2013; 6(4): 4347–56.
10. Vinayagamoorthy R, Rajeswari N. Mechanical performance studies on Vetiveria zizanioides/jute/glass fiber-reinforced hybrid polymeric composites. Journal of Reinforced Plastics and Composites. 2014; 33:81–92.
11. Velumani S, Navaneethakrishnan P, Jayabal S, Ramprasath R. Regression modelling and optimization of cutting parameters through Nelder-Mead simplex search and CCFD during drilling of sisl-glass/vimyl ester composites. International Journal of Machining and Machinability of Materials. 2013; 14:1–23.
12. Vinayagamoorthy R, Karthikeyan S, Bhargav RSP, Rajivalochan TV. Properties investigations on metallic fiber reinforced sandwich composites. Applied Mechanics and Materials. 2015; 814:101–5.
13. Khajavi A, Kolahan F, Esmaeelzadeh A. A Taguchi approach for optimization of process parameters in water jet cleaning process. Iranian Journal of Science and Technology –Transactions of Mechanical Engineering. 2014; 38(M1): 97–104.
14. Vinayagamoorthy R, Rajeswari N, Balasubramanian K. Optimization studies on thrust force and torque during drilling of natural fiber reinforced sandwich composites. Jordan Journal of Mechanical and Industrial Engineering. 2014; 8(6):385–92.
15. Shihab SK, Khan ZA, Mohammad AAS, Siddiquee AN. Optimization of surface integrity in dry hard turning using RSM. Sadhana- Academy Proceedings in Engineering Sciences. 2014; 39(5):1035–53.
16. Qiu P, Cui M, Kang K, Park B, Son Y, Khim E, Jang M, Khim J. Application of Box-Behnken design with response surface methodology for modeling and optimizing ultrasonic oxidation of arsentite with H_2O_2. Central European Journal of Chemistry. 2014; 12(2):164–72.
17. Ferreira SLC, Bruns RE, Ferreira HS, Matos GD, David JM, Brandao GC, da Silva EGP, Portugal LA, dos Reis PS, Souza AS, dos Santos WNL. Box-Behnken design: An alternative for the optimization of analytical methods. Analitica Chimica Acta. 2007; 597(2):179–86.
18. Latha B, Senthilkumar VS, Palanikumar K. Modeling and optimization of process parameters for delamination in drilling Glass Fiber Reinforced Plastic (GFRP) composites. Machining Science and Technology. 2011; 15(2):172–91.
19. Grcic I, Vujevic D, Koprivanac N. The use of D-optimal design to model the effects of process parameters on mine realization and discoloration kinetics of Fenton-type oxidation. Chemical Engineering Journal. 2010; 157:408–19.
20. Rajmohan T, Palanikumar K. Modeling and analysis of performances in drilling hybrid metal matrix composites using D-optimal design. International Journal of Advanced Manufacturing Technology. 2013; 64(9):1249–61.
21. Davim JP, Reis P. Study of delamination in drilling Carbon Fiber Reinforced Plastics (CFRP) using design experiments. Composite Structures. 2003; 59(4):481–7.
22. Kaleemulla MM, Siddeswarappa B. Effect of fibre content and laminate thickness on the drilling behavior of GSFRP composites under varied drill geometries. International Journal of Machining and Machinability of Materials. 2011; 10(3):222–34.