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Optimization Studies on Thrust Force and Torque during Drilling of Natural Fiber Reinforced Sandwich Composites

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Abstract

This research is carried out to investigate thrust force and torque during drilling on the developed bio-degradable sandwich composites. Two natural fibers, namely vetiveria zizaniodes (vetiver) and jute, and one synthetic fiber, namely E-glass, are used as reinforcements with vinyl ester resin to form three composite specimens. The fiber compositions in each specimen are varied while the resin composition is kept as a constant. The vetiver fibers are pre-treated with alkali and followed by furnace heating in order to improve its surface properties. The specimens are subjected to a set of 28 drilling operations during which the machining parameters, like speed, feed rate, tool point angle and work sample, are varied between four levels to form a four-factor mixed level D-optimal factorial design. During each drilling operation, the thrust force and torque are measured as responses by using a kistler make drill dynamometer with an accuracy level of 0.01N. The responses are analyzed by using response surface method, and non-linear regression equations are developed. Optimization on the experimental data resulted in selection of a high level of speed of 2000 rpm, low level feed of 0.1 mm/rev, tool angle between 600 to 900 and selection of sample level I as optimized values with a thrust force of 82.47 N and torque of 4.4 Nm. Confirmatory runs are conducted and the responses are again measured. The average error between the developed model and the confirmatory runs is found to be minimal and hence the optimization is highly satisfactory.

Keywords: *Vetiver, Jute, Glass, Thrust, Torque, Optimization*.

1. Introduction

In recent days, composites have been developing in the shape of a final component during their manufacturing stage in order to reduce the machining operations. They still need machining operations for producing holes and slots, finishing the holes, slots, edges and exterior surfaces. The damage of the hole is measured by using delamination factor. During the drilling of carbon fiber reinforced composites, it was observed that the delamination decreases with the increase in speed. Also, it was concluded that a low feed rate and a low point angle are found to be the optimum conditions for drilling [1]. During turning of carbon reinforced cylindrical rods, using cubic boron nitride and polycrystalline diamond tools, surface roughness increases with the increase in feed rate, but decreases as the cutting speed is increased [2, 3]. Drilling induced thrust force and torque on work sample. Drilling of unidirectional glass fiber reinforced plastics revealed that both thrust force and torque have a major influence on delamination on the material and the residual strength decreases with the increase in delamination [4]. Optimization studies on surface roughness during end milling of aluminium metal matrix composites concluded that the feed rate has a predominant influence on surface roughness [5, 6].

Machinability is also influenced by the selection of resin, fiber, additives and their proportions used in composites. An investigation drilling of glass fiber reinforced composite reported that the type of chip formed, thrust force and surface roughness depend upon the type of resin used. It was concluded that the thrust force and surface roughness are found to be larger for a composite made of polyester resin when compared to that of composites made of the polypropylene composite [7]. Extensive research has been done in machinability associated issues by using different synthetic fibers as

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reinforcements in composites. In the few recent years, many natural fibers like jute, vetiver, bamboo, sisal, licuri etc. have been introduced in composites. Studies on their mechanical properties showed that, by careful selection of fiber proportions in composites, they could serve as a possible alternative for synthetic fibers [8-11].

Studies on drilling of natural coir reinforced plastics reported that the feed rate has a major influence on thrust force and torque. It was concluded that a medium feed rate of 0.2 mm/rev, a high speed of 1503 rpm and a medium drill diameter of 8 mm are found to be optimum conditions for machinability [12]. Investigations during the drilling of Medium Density Fiberboards (MDF) reported that the delamination factor increases when the feed rate is increased and decreases when the cutting speed is increased [13]; such results are similar to the results obtained during the machining of synthetic fiber reinforced composites. In another study, commercially woven jute fibers are reinforced with polyester in the form of plates and the developed composites are subjected to end milling operations. Analysis of thrust force and torque showed that three factors, namely speed, feed rate and depth of cut, predominantly affect the responses [14]. Extensive studies have been done to analyze the behavior of natural fiber reinforced plastics and only few research works have evolved during the recent years to perform machining and machinability associated investigations.

In an earlier research, Vinayagamoorthy *et al.* [8] developed the nine new composites and made an extensive analysis on properties like tensile, flexural, compressive and impact strengths. It was concluded that, by a proper selection of reinforcement and resin proportions and by giving a suitable chemical treatment to natural fibers, natural fibers served as an alternative to synthetic fibers. As an extension of this work, three composites samples, showing best mechanical properties, were taken for the present machining studies. The samples are subjected to a 28 drilling operations according to mixed level D-optimal design methodology. The responses, namely thrust force and torque, are measured and the data are analyzed and optimized using response surface methodology. This resulted in the selection of the best levels for the factors. Confirmatory runs are conducted and the responses are compared with the model.

2. Material and Methods

Vetiveria zizanioides is a perennial grass whose roots can grow up to a maximum length of 12 meters. It is used as an aromatic agent in perfumes and as an agent for treatment of rheumatism in Indian traditional medicines. These roots have a tensile strength of 723 MPa and modulus of 49.8 GPa with strain at break of 2.4%. In the present study, the composite samples are prepared by using the hand layup method in the form of slabs, each of the size 300 mm x 300 mm x 12 mm. The hand layup method uses a table over which the resin is spread and a fiber layer is placed over it. Again, a layer of resin is applied over the fiber layer and this procedure is repeated until the proportions of fiber and resin are satisfied. Finally, a load is applied over it for about 24 hours for the uniform bonding of resin with fibers. The composition of vetiver fibers and E-glass fibers are varied in each sample to form 34 wt% in total and vinyl ester resin is maintained as 66 wt% in all samples. The composition of fiber and resin in the samples are presented in Table 1. The samples preparation method and the chemical treatment of the fibers were extensively discussed in the earlier study by the authors [8], and the mechanical properties of the developed samples are presented in Table 2.

Table 1. Composition of samples

Sample	Fiber Proportions (wt %)			Resin proportions (wt %)
	Vetiver	Jute	Glass	Vinyl ester
I	17	17	-	66
II	13	13	8	66
III	10	10	14	66

A Computer Numerical Controlled (CNC) vertical machining center, made by Bharat Fritz Werner, is used for drilling operations. This CNC system is controlled by Siemens 802D and has a maximum spindle speed of 6000 rpm and a tool traverse of 510 x 410 x 460 mm. High Speed Steel (HSS) drill tools of 10 mm diameter and M42 grade are used for drilling. As drill tools are available in the market, with only a standard angle of 90°, four drill tools were purchased and three of them were ground to 60°, 120° and 150° by using a tool and cutter grinder. The point angles are measured and ensured by using a tool maker microscope during this process. Work samples, of thickness 12 mm, are cut as a 100 mm square plate for drilling. A kistler make drill dynamometer of model 9257B is used to measure the thrust force and torque during drilling. This setup has a measuring range of -5 KN to 10 KN. The dynamometer is placed over the machine table and the work sample is fixed above it by using a machine vice. Four factors, namely speed, feed, tool angle and work sample, are selected as the input factors for the present study. Speed, feed and tool angle are assigned with four numeric levels and the work sample is assigned with three categorical levels. This type of design is known as a four-factor mixed level D-optimal design. The selection and assignment of the levels to all factors was done on the basis of a survey of the various research works [15-17], and the data are presented in Table 3.

Table 2. Mechanical properties of samples

Sample	Tensile strength (MPa)	Tensile modulus (MPa)	Tensile strain at break (%)	Flexural strength (MPa)	Flexural modulus (MPa)	Flexural strain at break (%)	Compressive strength (MPa)	Impact energy (J)
I	71.73	1736	9.5	133.11	2894	7	122.21	11
II	74.14	2105	7.5	131.9	3358	6.67	121.81	15.33
III	70.96	2318	7.5	137.6	2950	7	128.23	18.33

Table 3. Factors and levels

Factors	Type	Level	Level	Level	Level
Speed (*n*) rpm	Numeric	500	1000	1500	2000
Feed (*f*) mm/rev	Numeric	0.1	0.2	0.3	0.4
Tool angle (*α*) degree	Numeric	60	90	120	150
Work sample	Categorical	I	II	III	-

3. Statistical Design

Response surface method is one of the important statistical tools during designing an experiment. It helps in analyzing and optimizing the statistical data having responses that are affected by multiple factors. It provides three dimensional plots and contour plots for responses against the input factors through which the influence of various factors on the responses could be analyzed. D-optimal design is another important tool for analyzing responses under the influence of factors with different levels. In this design method, the variance of regression coefficients in the model equation is minimized. In general, factors are classified as numeric factors and categorical factors. Numeric factors are varied between any numerical value as per the system requirement or of the interest of researcher. Categorical factors cannot be varied between any ranges but they are of particular importance. D-optimal design is a technique for analyzing the influence of either or both the numeric and the categorical factors on the responses [18]. The significance and contribution of each factor on the response are analyzed using analysis of variance (ANOVA). The runs and responses are presented in Table 4.

Table 4. Experimental runs and responses

Run	Input Parameters				Output Parameters	
	Speed (*n*) rpm	Feed (*f*) mm/rev	Point angle of Tool (*α*) degree	Work sample (*D*)	Thrust force (*F*) N	Torque (*T*) Nm
1	500	0.1	60	II	90.3	5.21
2	500	0.1	120	I	87.2	4.01
3	500	0.1	120	I	88.7	4.02
4	500	0.1	150	III	108.3	5.5
5	500	0.1	150	III	107.6	5.48
6	500	0.2	60	III	102.1	6.27
7	500	0.3	150	II	99.3	4.11
8	500	0.4	60	I	90.9	5.1
9	500	0.4	60	I	91.5	4.18
10	500	0.4	60	II	102.5	5.89
11	500	0.4	150	III	120.4	6.49
12	1000	0.1	120	II	94.1	4.9
13	1000	0.4	90	III	114.5	6.7
14	1000	0.4	150	I	94.8	4.72
15	1500	0.1	60	I	82.7	4.32
16	1500	0.3	60	II	96.3	5.48
17	2000	0.1	60	II	91.6	5.19
18	2000	0.1	90	III	99.3	5.73
19	2000	0.1	150	I	89.5	4.81
20	2000	0.2	120	II	91.5	5.39
21	2000	0.2	150	III	109	6.02
22	2000	0.3	90	I	86.3	4.94
23	2000	0.3	150	I	90.4	4.56
24	2000	0.4	60	III	111.4	7.08
25	2000	0.4	60	III	110.3	7.1
26	2000	0.4	120	III	115.3	6.54
27	2000	0.4	150	II	105.5	5.6
28	2000	0.4	150	II	106.4	5.5

4. Discussion

4.1. Thrust Force (F)

Drilling operation involves the penetration of a tool through the work piece during its rotation; as a result, thrust force is impressed on the working zone. The magnitude of thrust force depends upon various machining parameters. ANOVA analysis for thrust force is presented in Table. 5. The model F-value of 115.68 and lack of fit F-value of 4.57 indicate that the model is significant and the lack of fit is non-significant relative to pure error. A P-value less than 0.05 indicates that the terms are significant. R^2 and adj R^2 values of 0.995 and 0.986, respectively, are closer to each other, which gives the indication of a maximum model adequacy. It was observed that work sample, feed and tool angle predominantly affect the thrust force with a contribution of 55.24% for work sample, 14.5% for feed and 4.64% for tool angle. Also, it was noticed that speed has no influence on the thrust force. A 55.24% contribution of work sample indicates that the selection of natural and synthetic fibers and their composition in the composite plays an important role in reducing the thrust force.

Interaction plots between the thrust force and input factors and the normal probability plot are presented from Figures 1a to 1d. It was observed that variation of speed from 500 rpm to 2000 rpm does not have much influence on the thrust force, whereas thrust force increases when feed and tool angle are increased. This is because the tool, at higher feed rates, penetrates the work piece more quickly than during the low feed rates. Faster penetration leads to an increase in the thrust force [12]. Also, as the tool angle increases the contact area between the cutting edge and the work surface increases leading to an increase in thrust force. These behaviors are commonly seen in all the samples but sample I shows a least thrust force followed by samples II and III. This indicates that the inclusion of glass fibers increases the thrust force and the increase in glass fiber composition also increases the thrust force [19]. This behavior is seen because hardness of glass fibers are greater than that of vetiver fibers. Hence, sample I is suitable for machining under reduced thrust force. The normal probability plot is a graphical representation for checking the adequacy of the model. If the distribution of points follows a straight line, then the model is adequate and can be effectively used for predicting the responses [20]. Figure 1d clearly follows a straight line which is a symbol of good model adequacy.

Table 5. ANOVA table for Thrust force

Source	Sum of Squares	Degrees of freedom	Mean square	F value	P value	% Contribution
Model	2803.5	17	164.91	115.68	<0.0001 **Significant**	-
Speed (*n*)	6.12	1	6.12	4.29	0.0651	0.22
Feed (*f*)	408.03	1	408.03	286.22	<0.0001	**14.5**
Tool angle (*α*)	130.82	1	130.82	91.77	<0.0001	**4.64**
Work sample (*D*)	1556.5	2	778.22	545.89	<0.0001	**55.24**
$n*f$	0.035	1	0.035	0.035	0.025	0.0012
$n*\alpha$	0.74	1	0.74	0.52	0.4876	0.026
$n*D$	2.95	2	1.48	1.04	0.3902	0.104
$f*\alpha$	1.79	1	1.79	1.26	0.2883	0.0635
$f*D$	39.6	2	19.8	13.89	0.0013	1.4
$\alpha*D$	14.26	2	7.13	5	0.0312	0.5
n^2	0.16	1	0.16	0.11	0.748	0.0056
f^2	26.77	1	26.77	18.78	0.0015	0.95
α^2	3.67	1	3.67	2.57	0.1398	0.13
Residual	14.26	10	1.43	-	-	-
Lack of fit	11.7	5	2.34	4.57	0.0605 **Not significant**	-
Pure error	2.56	5	0.51	-	-	-
Total	2817.7	27	-	-	-	-
R^2 = 0.995; Adj R^2 = 0.986						

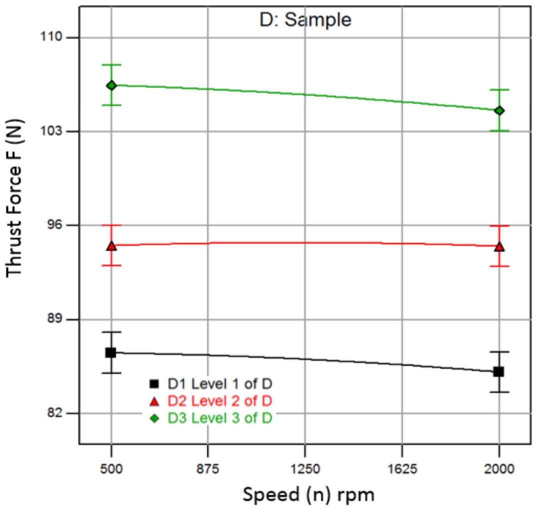

Figure 1a. Speed versus Thrust force

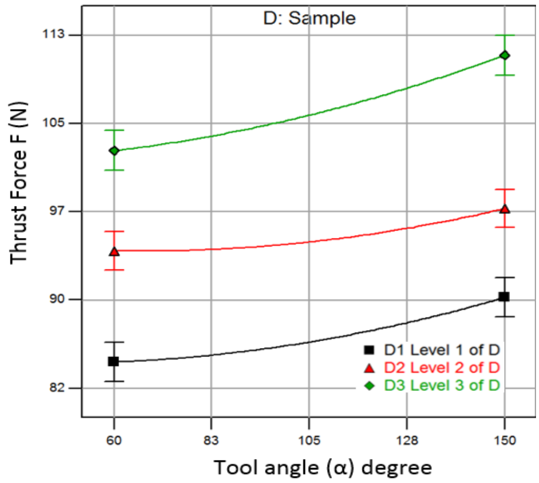

Figure 1c. Tool angle versus Thrust force

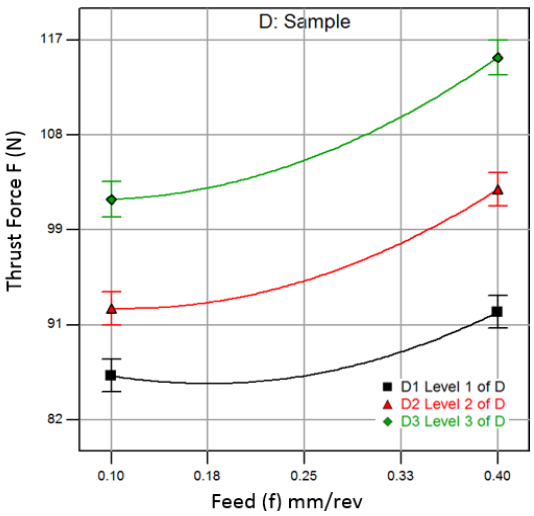

Figure 1b. Feed versus Thrust force

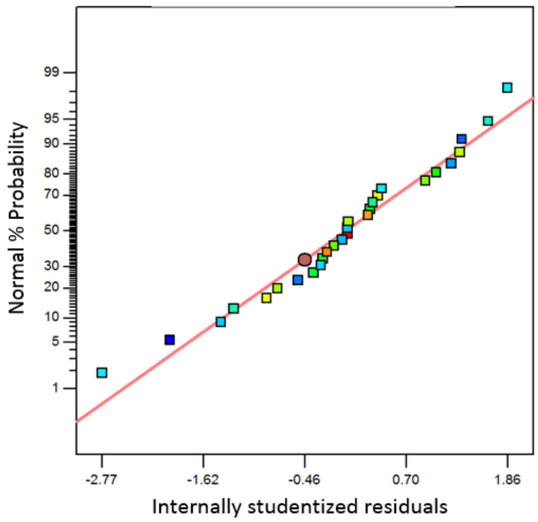

Figure 1d. Normal plot for thrust force

4.2. Torque (T)

During drilling, the drill tool is subjected to rotation at various speeds set by the operator. Hence, torque is developed and its magnitude depends on various machining parameters. The ANOVA table for torque is presented in Table 6. The model and lack of fit F-values of 13.16 and 1.17, respectively, indicates that the model is significant and the lack of fit is non-significant relative to pure error. R^2 and adj R^2 values of 0.95 and 0.88, respectively, are closer to each other, which gives the indication of a maximum model adequacy. It was observed that all the factors, namely speed, feed, tool angle and work sample, predominantly affect the torque with a contribution of 3.35% for speed, 9.29% for feed 3.77% for tool angle and 55.35% for work sample. A 55.35% contribution of work sample indicates that the selection of natural and synthetic fibers and their composition in the composite play an important role in reducing the thrust force. This contribution is almost equal to that of the contriburion of work sample with thrust force. Hence, work sample has a major influence on thrust force and torque.

The influence of each factor on the response is analyzed by using interaction plots. These plots present the behavior of the response under the influence for a combination of two input factors, namely speed-work sample, feed-work sample and tool angle-work sample. Interaction plots between the torque and input factors and the normal probability plot are presented in Figures 2a to 2d. It was observed that the increase in speed and feed increases the torque, whereas the increase in tool angle decreases the torque. The torque is found to be low for sample I between the ranges of speed, feed and tool angle. This is followed by sample II and sample III. This clearly indicates that the presence of glass fibers increases the torque and the increase in glass composition also increases the torque. Hence, sample I may be selected for machining under minimum torque conditions. This behavior is similar to the observations during thrust force and, hence, the overall performance of sample I was found to be satisfactory when compared to that of other samples. The normal probability plot as shown in Figure 2d which clearly follows a straight line, which is a symbol of a good model adequacy.

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Table 6. ANOVA table for Torque

Source	Sum of Squares	Degrees of freedom	Mean square	F value	P value	% Contribution
Model	20.82	17	1.22	13.16	<0.0001 **Significant**	-
Speed (*n*)	0.73	1	0.73	7.88	0.0185	**3.35**
Feed (*f*)	2.02	1	2.02	21.7	0.0009	**9.29**
Tool angle (*α*)	0.82	1	0.82	8.84	0.014	**3.77**
Work sample (*D*)	12.04	2	6.02	64.64	<0.0001	**55.35**
$n*f$	0.011	1	0.011	0.12	0.7339	0.05
$n*\alpha$	0.25	1	0.25	2.7	0.1316	1.15
$n*D$	0.35	2	0.18	1.9	0.1998	1.6
$f*\alpha$	0.1	1	0.1	1.12	0.3143	0.46
$f*D$	0.22	2	0.11	1.18	0.3465	1.01
$\alpha*D$	0.28	2	0.14	1.49	0.2715	1.29
n^2	$3.43x10^{-6}$	1	$3.43x10^{-6}$	$3.68x10^{-5}$	0.9953	0.000015
f^2	0.17	1	0.17	1.82	0.2074	0.78
α^2	$3.7x10^{-4}$	1	$3.7x10^{-4}$	$3.97x10^{-3}$	0.951	0.0017
Residual	0.93	10	0.093	-	-	-
Lack of fit	0.5	5	0.1	1.17	0.433 **Not significant**	-
Pure error	0.43	5	0.086	-	-	-
Total	21.75	27	-	-	-	-

R^2 = 0.95; Adj R^2 = 0.88

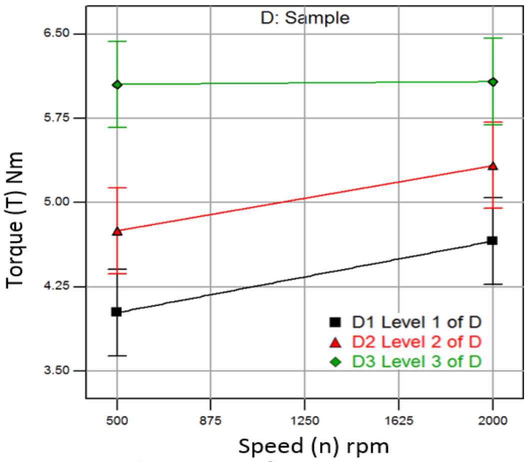

Figure 2a. Speed versus Torque

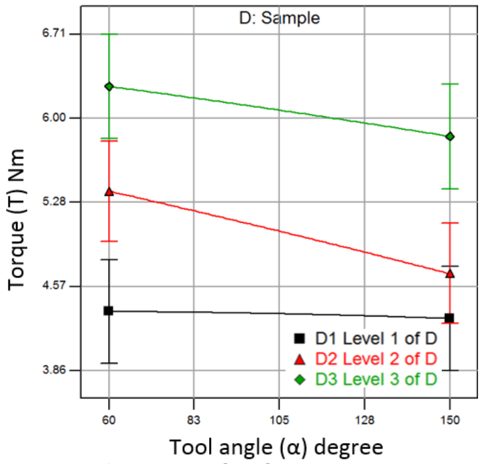

Figure 2c. Tool angle versus Torque

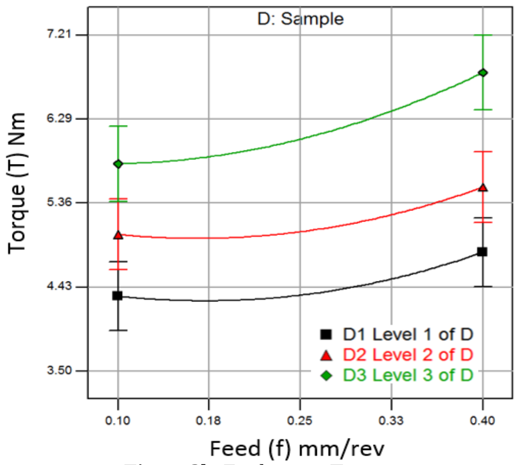

Figure 2b. Feed versus Torque

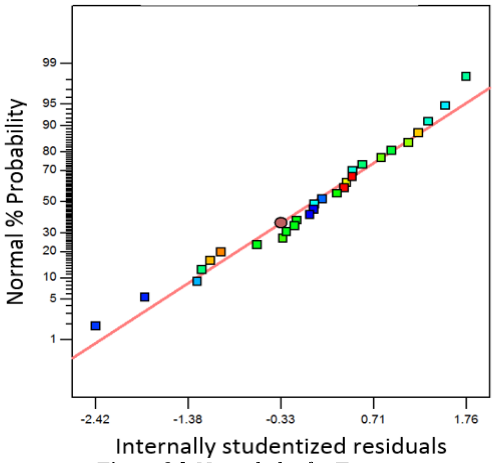

Figure 2d. Normal plot for Torque

4.3. Optimization

Design Expert 7 software is used in this study for statistical analysis and optimization. Multi-response optimization is carried out aiming to minimize the thrust force and torque. The optimized values of factors and responses are presented in Table 7. Seven runs are selected based on the desirability factor closer to unity. The first five runs show that a high level speed, a low level feed rate, sample I and a tool angle from 60° to 90° would be suitable for reducing the thrust force and torque with a desirability of 0.95. The sixth and the seventh runs show that a low level speed, a low level feed rate, sample I and a tool angle from 90° to 100° would be the optimum conditions with desirability of 0.85. Tools are ground to new tool angle values of 70°, 80° 90° and 100° and confirmatory runs are conducted. The average percentage of error between the model and confirmatory runs are 0.74% for thrust and 1.07% for torque. As the error percentages are minimal, the optimization is satisfactory and the model could be used to accurately predict the responses.

5. Conclusions

The present study focused on designing and optimizing thrust force and torque during the drilling of three new hybrid polymeric composites. The influence of various fibers in each composite on thrust and torque are investigated and optimization is carried out aiming to reduce the responses. The conclusions are as follows:

- The influence of work sample, feed and tool angle are predominant on thrust force and it was noticed that speed has no influence on the thrust force as presented in Table 5.
- All the factors, namely speed, feed, tool angle and work sample, affect the torque.
- A 55% contribution of work sample with both thrust force and torque indicates that the selection of natural and synthetic fibers and their composition in the composite plays an important role in reducing the thrust force.
- Presence of glass fibers and the increase in their content increase the thrust force and torque. Hence, a composite sample without the presence of glass fibers would be suitable for improving the machinability.
- Optimization of the model seems good with an overall desirabilty factor of 0.95, and the results of confirmatory runs are closer to the developed model with average errors of 0.74% for thrust force and 1.07% for torque.

Improving machinability is a primary objective of all manufacturers irrespective of the nature of the material. This exhaustive research helps end users to appropriately select the best machining conditions in order to improve the machinability.

Table 7. Optimization and confirmation

S. No	Speed n (rpm)	Feed f (mm/rev)	Tool angle α (degree)	Sample (D)	Desirability factor	D-Optimal Model		Confirmatory runs	
						Thrust F (N)	Torque T (Nm)	Thrust F (N)	Torque T (Nm)
1	2000	0.1	60	I	0.95	82.47	4.4	81.22	4.78
2	1975	0.1	60	I	0.95	82.74	4.41	83.17	4.5
3	2000	0.1	90	I	0.95	84.08	4.56	82.1	4.31
4	2000	0.1	70	I	0.95	83	4.46	82.16	3.9
5	2000	0.1	80	I	0.95	83.61	4.52	82.41	4.18
6	570	0.1	90	I	0.85	85.86	4.05	84.92	4.21
7	500	0.1	100	I	0.85	86.03	4.05	87.52	4.19

Error between model and confirmatory for Thrust force = 0.74%

Error between model and confirmatory for Torque = 1.07%

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