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International Review of Mechanical Engineering (I.RE.M.E.), Vol. 8, N. 5
ISSN 1970 - 8734 *September 2014*

Drilling Performance Investigations on Hybrid Composites by Using D-Optimal Design

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Abstract – *The present study is carried out to study the damage observed at entrance and exit of the hole during drilling and surface quality of drilled hole on newly developed natural hybrid composites. Hybrid composite samples are prepared by using vinyl ester resin and three types of reinforcements namely, randomly oriented vetiveria zizanioides, woven jute and woven glass. The natural fibers are pre-treated with alkali and furnace heating in order to improve its surface properties. Three samples are developed by varying the composition of fibers in each one. Machinability study is done by drilling a series of 28 holes based on D-optimal design. Three output responses namely, damage factor at entrance and at exit and surface roughness are measured and optimized with an objective of minimizing the damages. Confirmatory runs are conducted and the responses are measured. The results are validated by calculating the average percentage of error between the model and confirmatory runs. The error was found to be minimal and hence the optimization is highly satisfactory.* ***Copyright © 2014 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Damage Factor, Surface Roughness, Machinability, Natural Fiber, Optimization*

Nomenclature

F	Feed
A	Tool angle
D	Worksample
S	Speed

I. Introduction

Fiber reinforced plastics replaces conventional materials in all applications due to its tailor made properties. Now a days, composite products are made in the form of final finished product in order to minimize the machining operations. But, these manufactured components further requires some finishing operations like removing the excess material from the edges and surfaces, surface finishing operations in holes and slots etc. During drilling, the top and bottom surface of hole gets damaged due to several reasons.

This damage of hole is measured in terms of delamination factor or damage factor. A study of drilling on woven glass reinforced plastic concluded that at higher feed rates the exit surface delamination is constant irrespective of impressed thrust force. Also during drilling of polymeric composites, heat is generated due to its poor thermal properties. This increases tool wear as a result, the machined surface roughness increases [1].

Composites are prepared in different shapes like flat plates, circular rods, spheres etc., according to the needs of customer.

Rajasekaran et al [2] developed carbon fiber reinforced composites in the form of cylindrical rods.

These rods are subjected to turning by using two different tools namely, cubic boron nitride and polycrystalline diamond. The outcomes revealed that surface roughness is more at high feed rate and low at Latha et al [4] investigated thrust force during drilling of glass fibre reinforced composites by using different drill angles and showed that feed rate has the major influence on thrust force. Also increase in spindle speed reduces the thrust force and increase in feed rate increases the thrust force. It was concluded that a high speed, low feed and low or moderate drill diameter are suitable for reduced thrust force.

Morandeau et al [5] studied the influence of tool lead angle on various machinability issues during surface milling and observed that, a tool with 19^0 lead angle showed reduced cutting force, tool wear and delamination than the tool with 60^0 lead angle. Coir is used as a fiber since long time during composite manufacturing due to its comparable properties with synthetic fibers. Jayabal et al [6] investigated the machinability during drilling of coir fiber reinforced composites and noticed that feed rate has more statistical influence on machinability. It concluded that a medium feed, high speed and medium drill diameter provides improved machinability.

Vinayagamoorthy et al [7] studied the cutting forces during milling of jute fibres reinforced polyester composite. The outcomes revealed that speed, feed rate and depth of cut are majorly affecting the thrust force and torque during milling. Velumani et al [8] developed hybrid composites by using sisal and glass fibres and studied the delamination during drilling.

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It was concluded that factors like drill diameter, speed of the spindle and feed rate have major influence in reducing damage of hole. Machinability of any machining operation could be improved by reducing the parameters like delamination, surface roughness, cutting forces, torque, tool wear etc. These parameters are affected by machining factors like speed, feed, depth of cut, tool angle, tool diameter etc. Hence, by appropriate selection of levels for these factors machinability could be comparatively improved [9], [10].

So far, research investigations in the field of machining of polymeric composites dealt with influence of various factors on machinability and selection of optimized level for these factors. The fibers present in composite plays a vital role not only in deciding the mechanical properties also have a major contribution in deciding machinability. In the present study, new hybrid composites are developed by using three types of reinforcements namely natural vetiveria zizanioides, natural jute and synthetic glass. The samples are subjected to 28 holes by drilling based on D-optimal design method. After drilling, the entrance damage factor (*Di*), exit damage factor (*Do*) and machined surface roughness (*Sr*) are measured and optimized.

II. Experimental

II.1. Preparation of Composites

Vetiveria zizanioides is a natural grass and its roots are commonly called as vetiver. They have good properties in comparison with other natural fibers like jute, flax, sisal etc. Vetiver fiber was purchased from a local supplier and pre-treated by soaking in distilled water and sodium hydroxide solution in order to remove the unwanted celluloses. This was followed by heating the fibers in furnace in order to improve its surface properties [11]. Jute and E-glass fibers are commercially available in various forms like strands, mats etc.

In the present study, composite samples are prepared by using vetiver, jute and glass as reinforcements and vinyl ester as matrix resin. The samples were prepared in the form of slabs with 12 mm thickness by using hand layup method. The composition of fiber in each sample was varied whereas the composition of matrix was fixed as a constant as presented in Table I. Mechanical properties like tensile, compressive, flexural and impact strengths of developed samples are presented in Table II.

II.2. Machining and Measurement

Drilling operations were done by using a computer numerical controlled vertical machining center.

TABLE I
SAMPLE COMPOSITIONS

Sample	Vetiver (%)	Jute (%)	Glass (%)	Resin (%)
V17J17	17	17	-	66
V13J13G8	13	13	8	66
V10J10G14	10	10	14	66

TABLE II
SAMPLE PROPERTIES

Sample	Tensile strength (MPa)	Flexural strength (MPa)	Compressive strength (MPa)	Impact energy (J)
V17J17	71.73	133.11	122.21	11
V13J13G8	74.14	131.9	121.81	15.33
V10J10G14	70.96	137.6	128.23	18.33

High speed steel drill tools of 10 mm diameter were purchased from a local supplier and their point angles are ground to 60^0, 90^0, 120^0 and 150^0. Samples are of 100 mm square and 12 mm thick are subjected to a set of 28 holes by drilling at various combination of machining factors namely speed, feed, tool angle and work sample.

Speed, feed and tool angles are varied within four numerical levels whereas work sample is varied within three categorical levels. The assignment of numeric levels to each factors is based on survey of previous research [12], [13] and the data are presented in Table III.

TABLE III
FACTORS AND LEVELS

Factors	Level 1	Level 2	Level 3	Level 4
Speed (S) rpm (Numeric)	500	1000	1500	2000
Feed (F) mm/rev (Numeric)	0.1	0.2	0.3	0.4
Tool angle (A) degree (Numeric)	60	90	120	150
Work sample (D) (Category)	V17J17	V13J13G8	V10J10G14	V13J13G8

Three output responses namely damage factor at entrance, damage factor at exit and surface roughness were noted for the present machinability study. Damage factor at entrance (*Di*) and damage factor at exit (*Do*) were measured by calculating the ratio of maximum diameter to the nominal diameter of hole [14] as presented in Eq. (1):

$$Di \text{ or } Do = \frac{Dmax}{D} \tag{1}$$

The maximum diameter of damaged holes at entrance and exit surfaces were measured by using profile projector and surface roughness (*Sr*) of each hole was measured by using a Mitutoyo make roughness tester.

The roughness tester was mounted horizontally on a vernier height gauge and work sample was held vertically in a machine vice. The entire setup was placed over a surface plate as presented in Fig. 1. During this test, three readings are taken at different points along the hole and average of three readings was taken.

III. Design of Experiment

Response surface method is one of the important tools in experimental design. It helps to develop a new design and optimize it.

It has the capability to quantify the relation between the input and output factors [15].

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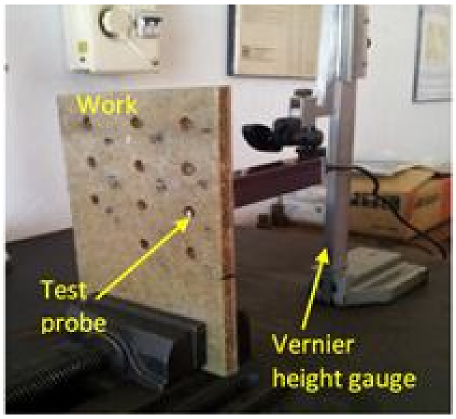

Fig. 1. Surface roughness measurement

D-optimal design is one of the optimality technique in which the variance of regression coefficients in model equation is minimized. There are two main advantages of using this technique. Firstly, it effectively optimizes the responses under the influence of factors with unequal levels. Secondly, it can optimize multiple responses which are influenced by both numerical and categorical factors [16], [17].

Numerical factors are one which always have a numerical value whereas a categorical factor does not have numerical value.

They are of any particular category like tool material, work material, type of lubricant etc. ANOVA analysis was done to evaluate the influence and contribution of factors on each responses. The present work make use of a 4-factor-mixed level D-optimal design method for design, analysis and optimization using Design Expert 8 software.

The factor levels during each experiment and measured responses were presented in Table IV.

Response surface method predicts the output responses for each run and the values are also presented in Table IV. An average error between experimentally measured responses and D-optimal predicted responses was calculated [8] by using the formula as presented in Eq. (2):

$$Error\ \% = 100 \sum_{n=1}^{8} \left(\frac{Experimental\ value + \\ -model\ value}{Experimental\ value} \right) \quad (2)$$

TABLE IV
EXPERIMENTAL RUNS AND RESPONSES

Run	Speed (S) rpm	Feed (F) mm/rev	Tool angle (A) degree	Work sample (D)	Experimental			D-optimal		
					Di (no unit)	Do (no unit)	Sr (μm)	Di (no unit)	Do (no unit)	Sr (μm)
1	500	0.2	60	V10J10G14	1.131	1.121	6.61	1.141	1.12	6.62
2	500	0.1	60	V13J13G8	1.082	1.083	5.07	1.081	1.085	5.1
3	1000	0.4	150	V17J17	1.082	1.082	3.25	1.08	1.08	3.22
4	1000	0.1	120	V13J13G8	1.091	1.107	4.67	1.09	1.108	4.69
5	2000	0.1	90	V10J10G14	1.111	1.121	5.63	1.121	1.123	5.31
6	2000	0.3	90	V17J17	1.052	1.064	4.94	1.05	1.065	5.04
7	500	0.4	150	V10J10G14	1.150	1.150	6.49	1.142	1.151	6.52
8	1500	0.1	60	V17J17	1.015	1.024	3.41	1.018	1.025	3.76
9	500	0.3	150	V13J13G8	1.107	1.111	4.1	1.1	1.11	3.98
10	2000	0.1	150	V17J17	1.042	1.042	2.91	1.041	1.043	3.03
11	2000	0.4	60	V10J10G14	1.141	1.140	6.13	1.15	1.143	6.07
12	2000	0.4	150	V13J13G8	1.111	1.123	4.42	1.11	1.125	4.36
13	2000	0.1	60	V13J13G8	1.063	1.072	3.99	1.062	1.071	4.02
14	500	0.1	120	V17J17	1.034	1.035	3.37	1.031	1.037	3.4
15	2000	0.2	150	V10J10G14	1.131	1.131	6.2	1.13	1.13	6.17
16	500	0.1	150	V10J10G14	1.121	1.124	6.56	1.12	1.125	6.31
17	500	0.4	60	V13J13G8	1.094	1.110	5.22	1.091	1.1	5.18
18	500	0.4	60	V17J17	1.060	1.075	4.23	1.061	1.078	4.1
19	1500	0.3	60	V13J13G8	1.092	1.093	4.41	1.09	1.09	4.21
20	1000	0.4	90	V10J10G14	1.140	1.150	6.26	1.134	1.152	6.28
21	2000	0.3	150	V17J17	1.061	1.077	2.13	1.06	1.08	2.15
22	2000	0.2	120	V13J13G8	1.093	1.103	4.1	1.103	1.1	3.97
23	2000	0.4	120	V10J10G14	1.150	1.141	6.43	1.142	1.14	6.54
24	500	0.1	120	V17J17	1.035	1.043	3.36	1.033	1.045	3.37
25	2000	0.4	150	V13J13G8	1.111	1.110	4.44	1.11	1.11	4.48
26	500	0.4	60	V17J17	1.077	1.074	3.9	1.078	1.072	4.07
27	500	0.1	150	V10J10G14	1.122	1.130	5.18	1.12	1.12	5.2
28	2000	0.4	60	V10J10G14	1.140	1.142	6.13	1.14	1.141	6.04

Error between Experimental and D-optimal: Di = 0.9 %, Do = 0.76 % & Sr = 0.6 %

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IV. Discussions

IV.1. Damage Factor at Entry (Di)

Table V presents the combined ANOVA analysis for responses. The model F-value of 134.27 for Di indicates that the model is significant and lack of fit is insignificant relative to pure error. R^2 and Adj R^2 values of 0.993 and 0.986 are very closer to each other. This indicates the symbol of good adequacy of model.

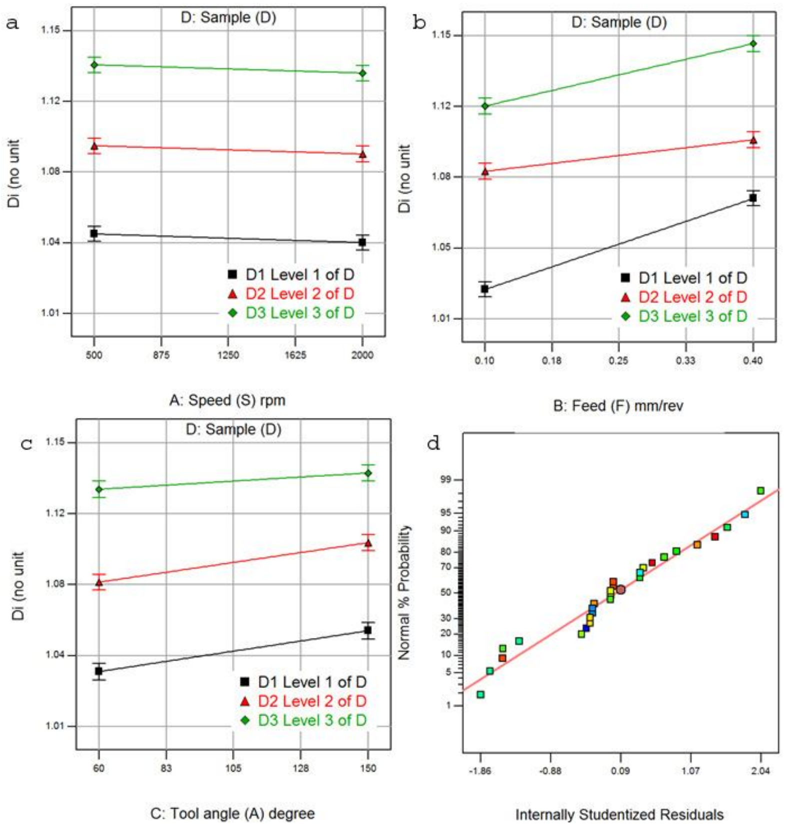
Adequate precision (AP) is a measure of signal to noise ratio. A ratio more than 4 indicates an adequate signal. The AP value of 39.84 for present analysis shows good signal for the model to navigate the design space [17]. A p-value less than 0.05 indicates the factors having more statistical influence and a vale less than 0.1 indicates the factors having less significance. It was observed that feed, tool angle and work sample have significant contribution of 10.7%, 2.15% and 69.05% respectively on Di and speed has very less importance in determining entrance damage of hole.

Interaction plots for Di were presented in Figs. 2. It was observed that as speed increases, there is a meager decrease in Di whereas Di increases considerably when feed and tool angle were increased. This could be due to the fact that during high feed rate, the tool penetrates the work surface faster than at low feed rate. This develops high degree of thrust force on work surfaces causing matrix damage and hence increases Di. As tool angle increases, the surface area of contact of tool on the work increases. This applies more thrust force on the work surface causing more damage.

It was observed that the sample V17J17 shows minimum damage at entrance for varying speed, feed and tool angles. This is followed by sample level 2 refering V13J13G8 and sample level 3 refering V10J10G14. This clearly depicts that the presence of glass fiber and increase of glass fiber content increases the damage at entrance. The reason being that, the chemical treatment given to natural fibers improved the bonding strength between matrix and fiber.

This holds the fiber and matrix together rigidly when force is applied by the tool during drilling thereby, reducing the damage during drilling. In samples V13J13G8 and V10J10G14, the glass fibers present below the top resin layer does not holds the matrix due to less bonding ability of glass fiber. This makes the top layer of work to damage quickly during drilling when compared to the sample V17J17. Also, increase in glass fiber content increases the thrust force during machining [18].

This increased thrust force produces more damage on surface of samples V13J13G8 and V10J10G14. Hence sample V17J17 containing only natural fibers provides good resistance to damage than other samples. The developed model was validated with the help of normal plot as presented in Fig. 2(d). The plot almost follows a straight line which depicts that points are normally distributed and the model is significant. A multivariate regression equations for Di are presented in Table VI.



Figs. 2. Interaction plots for (a) Di Vs S (b) Di Vs F (c) Di Vs A and (d) Normal plot

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TABLE V
COMBINED ANOVA ANALYSIS

Source	Sum of squares	Degrees of freedom	Mean square	F-value	p-value	Contribution	R^2	Adj-R^2	Adequate precision (AP)
Damage factor at entry (Di)									
Model	0.042	14	2.97E-3	134.27	<0.0001	Significant			
Speed (S)	7.16E-5	1	7.16E-5	3.24	0.0953	0.17 %			
Feed (F)	4.49E-3	1	4.49E-3	203.01	<0.0001	10.7%			
Tool angle (A)	9.02E-4	1	9.02E-4	40.77	<0.0001	2.15%	0.993	0.986	39.84
Work (D)	0.029	2	0.014	648.88	<0.0001	69.05%			
Residual	2.88E-4	13	2.21E-5	-	-	-			
Lack of fit	2.38E-4	8	2.97E-5	2.97	0.123	Not significant			
Pure error	5E-5	5	1E-5	-	-	-			
Total	0.042	27		-	-	-			
Damage factor at exit (Do)									
Model	0.037	14	2.67E-3	110.99	<0.0001	Significant			
Speed (S)	2.36E-5	1	2.36E-5	0.98	0.34	0.06%			
Feed (F)	4.04E-3	1	4.04E-3	168.01	<0.0001	10.63%			
Tool angle (A)	9.54E-4	1	9.54E-4	39.69	<0.0001	2.51%	0.992	0.983	35.49
Work (D)	0.026	2	0.013	531.63	<0.0001	68.42%			
Residual	3.14E-4	13	2.4E-5	-	-	-			
Lack of fit	1.62E-4	8	2.03E-5	0.68	0.704	Not significant			
Pure error	1.5E-4	5	3E-5	-	-	-			
Total	0.038	27	-	-	-	-			
Surface roughness (Sr)									
Model	48.72	14	3.48	23.33	<0.0001	Significant			
Speed (S)	1.94	1	1.94	13.01	0.0032	3.83%			
Feed (F)	0.19	1	0.19	1.25	0.283	0.36%			
Tool angle (A)	0.18	1	0.18	1.23	0.289	0.36%	0.962	0.92	15.15
Work (D)	41.42	2	20.71	138.87	<0.0001	81.76%			
Residual	1.94	13	0.15	-	-	-			
Lack of fit	0.93	8	0.12	0.58	0.77	Not significant			
Pure error	1.01	5	0.2	-	-	-			
Total	50.66	27		-	-	-			

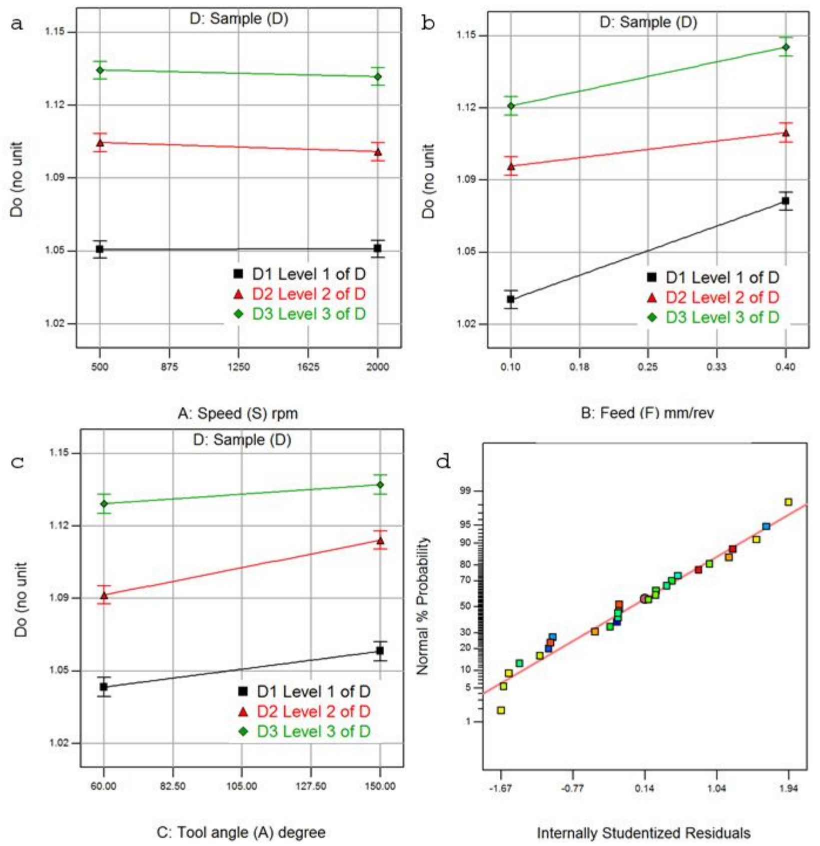

Fig. 3. Interaction plots for (a) Do Vs S (b) Do Vs F (c) Do Vs A and (d) Normal plot

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TABLE VI
TABLE OF REGRESSION EQUATIONS

Response	Equation
Di	$Di_1 = 1.002 - 9.66 \times 10^{-6}S + 0.17F + 5.81 \times 10^{-5}A + 1.55 \times 10^{-5}SF + 10^{-4} SA - 1.96 \times 10^{-4}FA – 3.27 \times 10^{-9}S^2 - 0.047F^2 + 4.32 \times 10^{-7}A^2$
	$Di_2 = 1.07 – 8.79 \times 10^{-6}S + 0.076F + 5.39 \times 10^{-5}A + 1.55 \times 10^{-5}S F + 10^{-4} SA - 1.96 \times 10^{-4}FA - 3.27 \times 10^{-9}S^2 - 0.047F^2 + 4.32 \times 10^{-7}A^2$
	$Di_3 = 1.11 – 8.61 \times 10^{-6}S + 0.13F – 7.37 \times 10^{-5}A + 1.55 \times 10^{-5}S F + 10^{-4} SA - 1.96 \times 10^{-4}FA – 3.27 \times 10^{-9}S^2 - 0.047F^2 + 4.32 \times 10^{-7}A^2$
Do	$Do_1 = 0.97 + 7.54 \times 10^{-6}S + 0.16F + 6.32 \times 10^{-4}A – 2.86 \times 10^{-6}SF + 2.34 \times 10^{-8}SA – 3.66 \times 10^{-4}FA - 3.17 \times 10^{-9}S^2 - 0.072F^2 – 1.87 \times 10^{-6}A^2$
	$Do_2 = 1.035 + 3.29 \times 10^{-6}S + 0.064F + 7.16 \times 10^{-4}A – 2.86 \times 10^{-6}SF + 2.34 \times 10^{-8}SA - 3.66 \times 10^{-4}FA - 3.17 \times 10^{-9}S^2 - 0.072F^2 – 1.87 \times 10^{-6}A^2$
	$Do_3 = 1.08 + 3.71 \times 10^{-6}S + 0.091F + 5.45 \times 10^{-4}A – 2.86 \times 10^{-6}SF + 2.34 \times 10^{-8}SA - 3.66 \times 10^{-4}FA - 3.17 \times 10^{-9}S^2 - 0.072F^2 – 1.87 \times 10^{-6}A^2$
Sr	$Sr_1 = 6.97 – 7.15 \times 10^{-4}S – 5.67F – 0.041A – 4.56 \times 10^{-4}SF + 8.38 \times 10^{-6} SA – 2.39 \times 10^{-3}FA - 3.22 \times 10^{-7}S^2 + 10.2F^2 + 1.2 \times 10^{-4}A^2$
	$Sr_1 = 7.32 – 2.89 \times 10^{-4}S – 4.91F – 0.0381A – 4.56 \times 10^{-4}SF + 8.38 \times 10^{-6}SA – 2.39 \times 10^{-3} FA - 3.22 \times 10^{-7}S^2 + 10.2F^2 + 1.2 \times 10^{-4}A^2$
	$Sr_1 = 8.24 – 1.63 \times 10^{-4}S – 2.91F – 0.035A – 4.56 \times 10^{-4}SF + 8.38 \times 10^{-6}SA – 2.39 \times 10^{-3}FA - 3.22 \times 10^{-7}S^2 + 10.2F^2 + 1.2 \times 10^{-4}A^2$

The suffix 1, 2 and 3 with *Di* corresponds to sample level 1(V17J17), 2 (V13J13G8) and 3 (V10J10G8) respectively. The average error between experimental and D-optimal values for Di is only 0.9 %. This shows that the developed model very closely follows the experimental values.

IV.2. Damage Factor at Exit (D_o)

As presented in Table V, the model F-value of 110.99 for *Do* indicates that the model is significant and the lack of fit F-value of 0.68 indicates that lack of fit is not significant relative to the pure error. R^2 and Adj R^2 values of 0.992and 0.983 are very closer to each other.

This indicates the symbol of good adequacy of model. Adequate precision (AP) value of 35.49 also shows good signal for the model to navigate the design space. It was observed that feed, tool angle and work sample have significant contribution of 10.63%, 2.51% and 68.42% respectively on *Do* and speed has very less influence on damage at exit and these results are quite similar to that of damage at entrance (*Di*). Interaction plots for *Do* are presented in Figs. 3.

It was noted that the trend obtained for *Do* against various input factors are quite similar to that of *Di* but, it was observed that damage of hole at exit was slightly higher than *Di* during majority of runs. This is due to the fact that, as tool reaches near bottom surface of work, thrust force causes the skin matrix layer to bend downward allowing more damage on bottom surface.

Sample V17J17 show a minimum damage in comparison with othar samples. Hence sample V17J17 containing only natural fibers is suitable for reducing the damage at exit.

The normal plot as presented in Fig. 3(d) follows a straight line which gives clear indication of high level significance of the model and normal distribution of points. The average error between experimental and D-optimal values for *Do* is only 0.76 %.

This shows that the developed model very closely follows the experimental values. The regression for *Do* are presented in Table VI.

IV.3. Surface Roughness (Sr)

From Table V, the model F-value of 23.33 for Sr indicates that the model is significant and the lack of fit F-value of 0.58 indicates that lack of fit is not significant relative to the pure error. R^2 and Adj R^2 values of 0.962 and 0.92 are very closer to each other.

This indicates a symbol of good adequacy of the model. Adequate precision (AP) value of 15.15 also shows good signal for the model to navigate the design space. It was observed that work sample and speed have significant contribution of 81.76% and 3.83% respectively on Sr. A contribution of 0.36% for feed rate and tool angle indicates that they does not affect the surface roughness within the selected range. Interaction for Sr are presented in Figs. 4. It was observed that surface roughness decreases when speed is increased. Hence, a high speed drilling is suitable for reducing the surface roughness [19], [20].

This is due to the fact that, at high speed the frictional force between drill cutting edge and work decreases due to which the cutting edge provides a rubbing and smoothening action on drilled surface resulting in reduced surface roughness. Surface roughness remains constant for change in tool angle and feed rate.

The normal plot as presented in Fig. 4(d) follows a straight line. This gives clear indication of significance of the model and normal distribution of points. All the work samples show a steady decrease in surface roughness as the speed is increased. Between the samples, sample V17J17 show a least surface rougness within the speed range. This is followed by sample V13J13G8 and sample V0J10G14. This shows that inclusion of glass fibers increases the machined surface roughness during drilling. Machined surface roughness directly depends on the damage of surface. Damage of the surface is comparatively lesser in sample containing only natural fibers than sample containing glass fibers. Hence, the surface roughness is also low for sample V17J17 than other two samples. As feed increases, surface roughness slightly decreases for sample V17J17 but increases for other two samples. As tool angle increases, surface roughness slightly decreases for sample V17J17 and V13J13G8 but remains constant for sample V10J10G8.

There is no clear trend observed for feed rate and tool angle. Within the feed and tool angle ranges, sample V17J17 show a least surface roughness in comparison with other two samples. Hence, considering the optimum conditions, a high spindle speed and selection of sample V17J17 provides holes with good surface finish.

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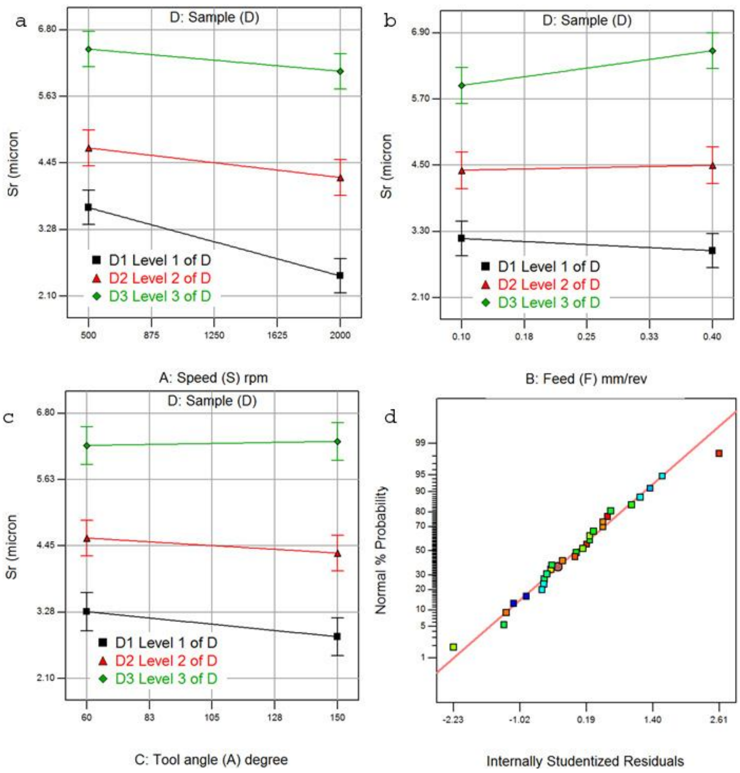

Figs. 4. Interaction plots for (a) Sr Vs S (b) Sr Vs F (c) Sr Vs A and (d) Normal plot

The average error between experimental and D-optimal values for Sr is only 0.6 %. This shows that the developed model very closely follows the experimental values. The regression for Sr are presented in Table VI.

V. Model Optimization

Increase of responses namely, damage factor at entry, damage factor at exit and surface roughness during drilling reduces the machinability of drilling process.

This leads to rejection of job as far as manufacturing industry is concerned. Hence, the optimization is aimed to minimize the responses. Accuracy of the optimization is measured by means of desirability approach. This approach uses a scale value between ‘0’ and ‘1’ for desirability. A scale value closer to ‘1’ is highly acceptable whereas a scale value closer to ‘0’ is unacceptable [21]. A multi-response optimization was done and the optimized values for responses are studied from contour plots as presented in Figs. 5. It was observed that predicted optimal values for responses are 1.01, 1.02 and 2.63 microns for *Di*, *Do* and *Sr* respectively with an overall desirability of 0.962 as presented in Fig. 5(d). The overall desirability is closer to ‘1’ and hence the model is highly accurate for predicting the responses.

A set of 8 optimum conditions were drawn for the present study and are presented in Table VII. It was observed that, a speed ranging from 1965 rpm to 2000 rpm, feed rate of 0.1 mm/rev, tool angle of 60^0 and selection of work sample V17J17 were found to be best conditions for machining. Based on these conditions, confirmatory test runs were conducted and the responses are measured. An average error between the model and confirmatory runs is calculated. A consolidated error analysis plot for responses is presented in Figs. 6. It was found that the average error between D-optimal model and confirmatory runs are 0.3%, 0.5% and 0.95% respectively for *Di*, *Do* and *Sr*. This analyis clearly shows that there is only meager difference between D-optimal and confirmatory runs. It was concluded that optimization by using D-optimal model is highly satisfactory. Hence, the developed models could be used accurately for predicting the responses.

TABLE VII
OPTIMUM CONDITIONS

S. no	Speed (rpm)	Feed (mm/rev)	Tool angle (degree)	Work sample	Di (no unit)	Do (no unit)	Sr (micron)	Desirability
1	2000	0.1	60	V17J17	1.013	1.021	2.63	0.962
2	1990	0.15	70	V17J17	1.014	1.022	2.64	0.961
3	1980	0.1	60	V17J17	1.019	1.024	2.65	0.960
4	1960	0.1	60	V17J17	1.018	1.025	2.66	0.958
5	2000	0.1	70	V17J17	1.012	1.021	2.63	0.953
6	2000	0.15	60	V17J17	1.012	1.031	2.58	0.945
7	1870	0.1	60	V17J17	1.019	1.033	3.30	0.851
8	1800	0.15	70	V17J17	1.021	1.034	3.32	0.802

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VI. Conclusion

The present research focused to develop three hybrid composite specimens containing various proportions of vetiveria zizanioides, jutes and glass fibers and study the machining associated damages. The damage of hole at top and bottom surfaces of composite and roughness of the drilled surface are measured as responses. Optimization was done and confirmatory runs are conducted. The conclusions drawn are as under:

1. Damages at entry (Di) and at exit (Do) are majorly influenced by feed rate, tool angle and work sample. A contribution of 10.7 %, 2.15 % and 69.05 % were observed for feed, tool angle and work sample respectively on Di and a contribution of 10.63 %, 2.51 % and 68.42 % were observed for feed, tool angle and work sample respectively on Do. Speed has very less influence on both damage at entry and at exit.
2. Surface roughness (Sr) is majorly influenced by speed and work sample with a contribution of 3.83 % and 81.76 % respectively. Feed and tool angle does not have much influence on Sr. Inclusion of glass fibers and increase in its proportion increases damage at entry, damage at exit and machined surface roughness.
3. Sample V17J17 shows least damages and surface roughness under all ranges of input factors.This shows that inclusion of natural fibers in composite gives very good performance during drilling.
4. Optimum solutions drawn through D-optimal model in comparison with the confirmatory runs are very closer and it was concluded that optimization is highly satisfactory.
5. Hence, machinability of a machining operation not only depends on the machining factors. The selection and composition of fibers present in the composite plays a vital role in deciding the machinability. Inclusion of natural fibers in composite not only improves the mechanical performance, it also enhances the machinability behaviour by reducing the damages.

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