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Optimization of drilling parameters of untreated JFRP PU foam sandwich by Taguchi method

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Many researchers have studied the fabrication of composite materials and their mechanical and thermomechanical properties and applications. In contrast, limited work in the field of machining of composite materials has been reported in the literature. The aim of this work is to optimize the drilling parameters such as speed, feed rate and drill diameter using a high-speed steel (HSS) twist drill and a titanium aluminum nitrate (TAN)-coated carbide twist with a drill angle of 118°. The present experimental work has been carried out using Taguchi design analysis of L_{27} orthogonal array on jute-fiber-reinforced plastic polyurethane (JFRP PU) foam sandwich composites. A coordinate measuring machine was used to measure the drilled hole diameter to optimize the quality of the drilled hole with the combination of drilling parameters. Minitab 16 was used to investigate the variance (analysis of variance) of the test, which led to determining the significance of each parameter on drilling. The results clearly show that the HSS-twist-drilled hole exhibited a minimum thrust force of 90 N at a 3 mm dia. hole with a feed of 80 mm/min, a speed of 1500 revolutions per minute (rpm) and a torque of 0·14 N m. In contrast, the TAN-coated-carbide-drilled hole exhibited a thrust force of 88 N at a 3 mm dia. hole with a feed rate of 80 mm/min, a speed of 1500 rpm and a torque of 0·13 N m. Regression analysis evidently showed that drill diameter has the most significant effect, feed rate has a marginally significant effect and speed does not have any significant effect on minimizing the thrust force for both HSS- and TAN-drilled holes. However, the influence of torque has a marginally smaller variation for TAN compared to that for HSS. Speed and drill diameter have the most significant effect on delamination of both entrance and exit holes using the HSS tool, whereas, for delamination of both the TAN-twist-drilled entrance and exit holes, drill diameter is a more significant factor compared to speed and feed.

Notation

D	nominal hole diameter
$D_{\max}$	delaminated diameter
F_d	factor
n	number of replications
S/N	signal to noise ratio
s_i^2	standard deviation of the responses for all noise factors for the given factor level combination
Y	observed response value

1. Introduction

In the Asian continent, natural fibers such as jute, sisal, hemp and banana fibers are abundantly available. In particular, jute fiber and its varieties have a major role and find diverse applications. Because of their unique properties such as corrosion resistance, high stiffness, light weight and low thermal conduction with weight ratio, the composite materials are used in many applications such as railway floors, marine shipyards and aircraft.[1] Jute fiber and its woven mats are economical, have a high specific modulus and are biodegradable.[2,3] Matrix-to-fiber ratios of 50:50 and 60:40 give better mechanical and thermal properties. Many researchers worked on studying the drilling parameters of composites, the drilling hole quality based on the workpiece and tool geometry and feed rate of the material.[4,5] This twist drill point geometry is the most significant factor of the thrust force.[6] Many researchers have studied and observed that no damage occurs below the critical thrust force during the drilling of the hole.[7,8] Drilling is commonly employed for making holes in assembling the structural components. The influence of speed, feed rate, drill diameter, point angle and material thickness on thrust force and torque during drilling of composite materials has been studied.[9] In many studies, it was found that feed rate and drill geometry are correlated with production of delamination, which indicates a reduction in the load-carrying capacity of the composite. Work on mechanisms of the drilled hole has been carried out, and peeling up of the top layer and pushing out of the bottom layer were observed.[10] These mechanisms lead to the delamination of the composites.[11] The drilling geometry also has a significant impact on drilling quality and delamination. The twist drill geometry has a major influence on thrust force and causes the separation of plies. Further, the critical thrust force was formulated analytically to understand the effect of input variables and compare the same experimentally.[12] Overall, from the aforementioned literature, the common defects in drilling holes are delamination, pulled-out fibers, debonding, fiber breakage and interlaminar cracking.[13,14] In the drilling of glass fiber reinforced plastic material, speed and drill size are the more significant factors on thrust force. Similarly, feed rate and speed are highly influential factors on delamination. However, drilling process development with the optimum parameters is evidently necessary for better quality of drills and economic hole production. Chen[15] proposed a relating factor that allows the evaluation and analysis of delamination degree in laminated composites. Sathishkumar *et al.*[16] studied the effect of chemical treatment of jute-laminated sandwich structures and observed that, with chemical treatment, mechanical properties were improved. The authors determined that feed rate is a significant factor in delamination, as higher feeds result in a higher thrust force, thus increasing the risk of damage occurrence around the hole. The delamination factor (F_d) defined has the maximum delaminated diameter (D_{max}) and the nominal hole diameter

1. $$F_d = \frac{D_{max}}{D}$$

2. Material and methods

2.1 Material

The material used to prepare composite are plain-woven jute and vinyl ester. The vinyl ester was procured from Naphtha Resins & Chemicals, Bangalore, and the plain jute fiber was procured from Vijay Trading Corporation, Bangalore. The woven jute fiber reinforced with vinyl ester resin at 60:40 ratio and 0°/90° stacking sequence was made through the vacuum-bagging method from a 5 mm sheet. A pressure of 10^{-2} torr was used during the vacuum-bagging process using vacuum systems and a product-pumping system. The mold was kept for 3 h and postcured at 80°C for a 1 h duration to avoid residual stresses during fabrication. The polyurethane sandwich was purchased from Polynate Foams Pvt, Bangalore. The sandwich structures were prepared with a jute fiber mat vinyl ester composite sheet that was embedded on either side of the rigid polyurethane foam with a thickness of 20 mm in a mold of dimensions 200 × 200 × 30 mm.

2.2 Methods

The sandwich composites were used to analyze the drilling parameters using a high-speed steel (HSS) twist drill and a titanium aluminum nitrate (TAN)-coated carbide twist drill with a tip angle of 118° using a Fanuc computer numerically controlled drilling machine. An Ieicos drill tool dynamometer (600 series model) was used to measure the thrust force and torque. This dynamometer has the capacity to measure a thrust force of 500 kilogram-force (kgf) and a torque of 20 kg m with a digital force indicator model number 652. A Hexagon Metrology Global Performance coordinate measuring machine (CMM) (Brown & Sharpe) was used to analyze the delamination at both entrance and exit holes. This CMM has a measuring range from 700 to 1000 mm and an accuracy of $1{\cdot}6 + L/300\,\mu\text{m}$ in the X–Y direction.

Table 1. Factors and levels for the Taguchi approach

Type	Levels	Main factor	Factor	Values
Fixed	3	*A*	Speed: rpm	500, 1000, 1500
Fixed	3	*B*	Feed rate: mm/min	80, 120, 150
Fixed	3	*C*	Drill diameter: mm	3, 4, 5

2.3 Factors and levels

The factors used to analyze the drilling effects and its levels are shown in Table 1. In order to see the effect of response on thrust force, torque was conducted using L_{27} orthogonal array given in Table 2. The reduced response clarified by signal-to-noise (S/N) ratio characteristics is given in Equations 2–4 (nominal, smaller and better). The deviation of the drilling hole was further transformed into the S/N ratio to analyze the optimal design for achieving a more stable quality.

- The nominal is the best characteristic formula is

2. $$S/N = -10 \log \frac{Y}{s_i^2}$$

- The smaller is better characteristic formula is

3. $$S/N = -10 \log \frac{1}{n} \sum Y^2$$

- The larger the better characteristic formula is

4. $$S/N = -10 \log \frac{1}{n} \sum \frac{1}{Y^2}$$

where Y is the observed values' average; s_i^2 is the Y variance; and n is the number of observations.

3. Results and discussion

The drilling was performed according to L_{27} array on jute-fiber-reinforced plastic polyurethane (JFRP PU) foam sandwich composites. To understand the influence of input variables such as speed, feed and drill diameter on the output response such as thrust force, torque and delamination factor at both the entrance

Table 2. Experimental design using L_{27} orthogonal array to analyze drilling parameters using HSS and TAN-coated carbide twist drill tools

Trial number	*A* Speed: rpm	*B* Feed rate: mm/min	*C* Drill diameter: mm	HSS-drilled hole				TAN-drilled hole			
				HSS thrust force: N	HSS torque: N m	$F_{\mathrm{del}}\mathrm{HSS} = D_{\max}/D$	$F_{\mathrm{del}}\mathrm{HSS} = D_{\max}/D$	TAN thrust force: N	TAN torque $T = f \times r$: N m	$F_{\mathrm{del}}\mathrm{TAN} = D_{\max}/D$	$F_{\mathrm{del}}\mathrm{TAN} = D_{\max}/D$
1	500	80	3	98	0·15	1·0517	1·0551	96	0·14	1·0484	1·0517
2	500	80	4	107	0·21	1·0621	1·0646	105	0·21	1·0596	1·0621
3	500	80	5	115	0·29	1·0698	1·0718	113	0·28	1·0678	1·0698
4	500	120	3	99	0·15	1·0515	1·0549	97	0·15	1·0482	1·0515
5	500	120	4	112	0·22	1·0581	1·0606	110	0·22	1·0556	1·0581
6	500	120	5	120	0·30	1·0686	1·0706	118	0·30	1·0666	1·0686
7	500	150	3	103	0·15	1·0475	1·0509	101	0·15	1·0442	1·0475
8	500	150	4	123	0·25	1·0572	1·0597	121	0·24	1·0547	1·0572
9	500	150	5	145	0·36	1·0645	1·0665	143	0·36	1·0625	1·0645
10	1000	80	3	92	0·14	1·0527	1·0561	90	0·14	1·0494	1·0527
11	1000	80	4	108	0·22	1·0547	1·0572	106	0·21	1·0522	1·0547
12	1000	80	5	113	0·28	1·0615	1·0635	111	0·28	1·0595	1·0615
13	1000	120	3	94	0·14	1·0478	1·0511	92	0·14	1·0445	1·0478
14	1000	120	4	114	0·23	1·0516	1·0541	112	0·22	1·0491	1·0516
15	1000	120	5	121	0·30	1·0597	1·0617	119	0·30	1·0577	1·0597
16	1000	150	3	96	0·14	1·0461	1·0494	94	0·14	1·0427	1·0461
17	1000	150	4	117	0·23	1·0512	1·0537	115	0·23	1·0487	1·0512
18	1000	150	5	137	0·34	1·0513	1·0533	135	0·34	1·0493	1·0513
19	1500	80	3	90	0·14	1·0556	1·0589	88	0·13	1·0522	1·0556
20	1500	80	4	92	0·18	1·0508	1·0533	90	0·18	1·0483	1·0508
21	1500	80	5	113	0·28	1·0512	1·0532	111	0·28	1·0492	1·0512
22	1500	120	3	91	0·14	1·0544	1·0577	89	0·13	1·0511	1·0544
23	1500	120	4	116	0·23	1·0504	1·0529	114	0·23	1·0479	1·0504
24	1500	120	5	126	0·32	1·0484	1·0504	124	0·31	1·0464	1·0484
25	1500	150	3	103	0·15	1·0537	1·0571	101	0·15	1·0504	1·0537
26	1500	150	4	109	0·22	1·0492	1·0517	107	0·21	1·0467	1·0492
27	1500	150	5	129	0·32	1·0466	1·0486	127	0·32	1·0446	1·0466

and exit holes, the regression method was used. The results of analysis of variance (Anova) were analyzed using F-test, P-value $\leq 0{\cdot}05$ and percentage contribution of speed, feed rate and drill diameter for both HSS-twist-drilled and TAN-coated-carbide-twist-drilled hole of sandwich structures.

Table 3. Effect on thrust force (N) of the drilled hole for the HSS-twist-drilled hole

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	$P \leq 0{\cdot}05$	%C
A	2	156·96	156·96	78·48	3·32	0·089	2·94
B	2	997·85	997·85	498·93	21·12	0·001	18·68
C	2	3558·30	3558·30	1779·15	75·32	0·000	66·63
$A \times B$	4	114·59	114·59	28·65	1·21	0·377	2·15
$A \times C$	4	58·15	58·15	14·54	0·62	0·664	1·09
$B \times C$	4	265·93	265·93	66·48	2·81	0·099	4·98
Error	8	188·96	188·96	23·62	—	—	3·54
Total	26	5340·74	—	—	—	—	—

Adj. MS, adjusted mean squares; Adj. SS, adjusted sum of squares; DF, degrees of freedom; Seq. SS, sequential sum of squares
$R^2 = 96{\cdot}46\%$; $R^2_{\text{adj}} = 88{\cdot}5\%$; $S = 4{\cdot}86008$

Table 4. Unusual observations for HSS thrust force

Obs	HSS thrust force	Fit	SE fit	Residual	St. resid.
22	91	96·593	4·077	−5·593	−2·11R
25	101	97·593	4·077	5·407	2·04R

Obs, observation; SE fit, standard error of the fit; St. resid., standardized residual
R denotes an observation with a large standardized residual

3.1 HSS-twist-drilled hole

- Anova for thrust force (N) (Tables 3 and 4)
- Anova for torque (N m) (Table 5)

The drilling process parameters shown in Table 1 are used as input variables, and their effects on response output such as thrust force, torque and delamination were analyzed separately. The P-values $\leq 0{\cdot}05$ in Tables 3 and 5 show the significance of input parameters. Drill diameter ($0{\cdot}000 \leq 0{\cdot}05$) and feed rate ($0{\cdot}001 \leq 0{\cdot}05$) show the highest significance. Speed ($0{\cdot}089 > 0{\cdot}05$) is not significant, so it is ignored. The F-test value shows that drill diameter has the largest value (75·32), and next is feed rate (21·12), both of which have a significant effect in minimizing the thrust force. The percentage contributions of drill diameter (66·63%) and feed rate (18·68%) show them to be more significant factors in reducing thrust force. The thrust force reduction confidence level shows $R^2 = 96{\cdot}46\%$, higher than 95%. Further, Table 4 shows unusual observations at trial number 22 and 25.

The influence on torque (N m) is revealed in Table 5; the F-test values show that drill diameter (513·26) is more important than feed rate (16·83) and speed (2·34). The P-values show drill diameter ($0{\cdot}000 < 0{\cdot}05$) and feed rate ($0{\cdot}001 < 0{\cdot}05$) to be more significant factors for reducing torque. The percentage contribution of drill diameter is 93·13% for reducing torque. $R^2 = 99{\cdot}27\%$ is higher than the 95% confidence level.

- Anova for the entrance hole (Table 6)
- Anova for the exit hole (Table 7)

Table 5. Effect on torque (N m) for the HSS-twist-drilled hole

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	$P \leq 0{\cdot}05$	%C
A	2	0·0005630	0·0005630	0·0002815	2·34	0·159	0·42
B	2	0·0040519	0·0040519	0·0020259	16·83	0·001	3·05
C	2	0·1235630	0·1235630	0·0617815	513·26	0·000	93·13
$A \times B$	4	0·0008593	0·0008593	0·0002148	1·78	0·225	0·65
$A \times C$	4	0·0003481	0·0003481	0·0000870	0·72	0·600	0·26
$B \times C$	4	0·0023259	0·0023259	0·0005815	4·83	0·028	1·75
Error	8	0·0009630	0·0009630	0·0001204	—	—	0·73
Total	26	0·1326741	—	—	—	—	—

$R^2 = 99{\cdot}27\%$; $R^2_{\text{adj}} = 97{\cdot}64\%$; $S = 0{\cdot}0109713$
Adj. MS, adjusted mean squares; Adj. SS, adjusted sums of squares; DF, degrees of freedom; Seq. SS, sequential sums of squares

Table 6. Effect on delamination of the entrance drilled hole for the HSS twist drill

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	$P \leq 0{\cdot}05$	%C
A	2	0·0003038	0·0003038	0·0001519	80·75	0·000	28·5
B	2	0·0001020	0·0001020	0·0000510	27·10	0·000	9·6
C	2	0·0002067	0·0002067	0·0001033	54·94	0·000	19·4
$A \times B$	4	0·0000129	0·0000129	0·0000032	1·71	0·239	1·2
$A \times C$	4	0·0004129	0·0004129	0·0001032	54·87	0·003	38·7
$B \times C$	4	0·0000142	0·0000142	0·0000036	1·89	0·206	1·3
Error	8	0·0000150	0·0000150	0·0000019	—	—	1·4
Total	26	0·0010675	—	—	—	—	—

$R^2 = 98{\cdot}59\%$; $R^2_{\text{adj}} = 95{\cdot}42\%$; $S = 0{\cdot}00137155$
Adj. MS, adjusted mean squares; Adj. SS, adjusted sums of squares; DF, degrees of freedom; Seq. SS, sequential sums of squares

Table 7. Effect on delamination of the exit drilled hole for the HSS twist drill

Source	DF	Seq. SS	Adj. SS	Adj. MS	*F*	$P \leq 0{\cdot}05$	%*C*
A	2	0·0003038	0·0003038	0·0001519	80·75	0·000	30·49
B	2	0·0001020	0·0001020	0·0000510	27·10	0·000	10·24
C	2	0·0001355	0·0001355	0·0000678	36·02	0·000	13·60
A × *B*	4	0·0000129	0·0000129	0·0000032	1·71	0·239	1·29
A × *C*	4	0·0004129	0·0004129	0·0001032	54·87	0·003	41·44
B × *C*	4	0·0000142	0·0000142	0·0000036	1·89	0·206	1·43
Error	8	0·0000150	0·0000150	0·0000019	—	—	1·51
Total	26	0·0009963	—	—	—	—	—

R^2 = 98·49%; R^2_{adj} = 95·09%; S = 0·00137155
Adj. MS, adjusted mean squares; Adj. SS, adjusted sums of squares; DF, degrees of freedom; Seq. SS, sequential sums of squares

Tables 6 and 7 show the effect of drilling process parameters ondelamination of the entrance and exit holes. The drilling process parameters are shown in the form of *P*-value ≤ 0·05. Drill diameter (0·000 ≤ 0·05) and feed rate (0·001 ≤ 0·05) are significant. However, speed (0·089 > 0·05) is negligible. The *F*-test value is the largest for speed (80·75), and next are those for drill diameter (54·94) and feed rate (27·10), indicating significant evidence of their effect in minimizing the thrust force. The percentage contributions of speed (28·5%) and the drill diameter (19·4%) show them to be more significant factors in reducing thrust force, and that of feed rate (9·6%) is negligible. The thrust force exhibiting confidence level of 96·46% which is more than the 95%, so model shows higher confidence level.

For reducing the exit hole wall delamination, the larger *F*-test value for speed (80·75) shows that it is a more significant factor than drill diameter (36·02) and feed rate (24·10). The contribution of speed (30·49%) is followed by those of drill diameter (13·60%) and feed rate (10·24%). This shows that speed is a more significant factor in the delamination of the exit hole. R^2 = 98·40%, higher than 95%. This means that the model is acceptable and can reliably predict the delamination of the exit hole.

3.2 TAN-coated-carbide-twist-drilled hole

- Anova for thrust force (Tables 8 and 9)
- Anova for torque (Table 10)

Tables 8 and 10 show the effect on thrust force and torque considering the TAN tool and Table 9 shows the unusual observations. The regression analysis of thrust force shows a response similar to that for the HSS tool, but the significant level of torque is marginally better compared to that for the HSS tool.

- Anova for the entrance hole (Tables 11 and 12)

Table 11 shows the influence of input parameters on the response of drilling using the TAN-coated carbide twist drill. The *P*-values show that drill diameter (0·000 < 0·05), speed (0·000 < 0·05) and feed rate (0·000 < 0·05) are significant factors. Table 12 shows the unusual observations for untreated TAN drilled hole at entrance. The *F*-test shows that drill diameter (58·04) has a greater influence than speed (50·75) and feed rate (25·98). The contributions of drill diameter (26·89%) and

Table 8. Effect on thrust force (N) of the drilled hole for the TAN-twist-drilled hole

Source	DF	Seq. SS	Adj. SS	Adj. MS	*F*	$P \leq 0{\cdot}05$	%*C*
A	2	156·96	156·96	78·48	3·32	0·089	2·94
B	2	997·85	997·85	498·93	21·12	0·001	18·68
C	2	3558·30	3558·30	1779·15	75·32	0·000	66·63
A × *B*	4	114·59	114·59	28·65	1·21	0·377	2·15
A × *C*	4	58·15	58·15	14·54	0·62	0·664	1·09
B × *C*	4	265·93	265·93	66·48	2·81	0·099	4·98
Error	8	188·96	188·96	23·62	—	—	3·54
Total	26	5340·74	—	205·413	—	—	—

R^2 = 96·46%; R^2_{adj} = 88·5%; S = 4·86008
Adj. MS, adjusted mean squares; Adj. SS, adjusted sums of squares; DF, degrees of freedom; Seq. SS, sequential sums of squares

Table 9. Unusual observations for TAN thrust force

Obs	TAN thrust force	Fit	SE fit	Residual	St. resid.
22	91	96·593	4·077	–5·593	–2·11*R*
25	101	97·593	4·077	5·407	2·04*R*

R denotes an observation with a large standardized residual
Obs, observation; SE fit, standard error of the fit; St. resid., standardized residual

Table 10. Effect on torque (N m) for the TAN-twist-drilled hole

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	$P \leq 0{\cdot}05$	%C
A	2	0·0006741	0·0006741	0·0003370	2·62	0·133	0·500790
B	2	0·0046741	0·0046741	0·0023370	18·16	0·001	3·472395
C	2	0·1253630	0·1253630	0·0626815	487·02	0·000	93·132320
$A \times B$	4	0·0005259	0·0005259	0·0001315	1·02	0·452	0·390692
$A \times C$	4	0·0001037	0·0001037	0·0000259	0·20	0·931	0·077039
$B \times C$	4	0·0022370	0·0022370	0·0005593	4·35	0·037	1·661870
Error	8	0·0010296	0·0010296	0·0001287	—	—	0·764891
Total	26	0·1346074	—	—	—	—	—

R^2 = 99·24%; R^2_{adj} = 97·51%; S = 0·0113448
Adj. MS, adjusted mean squares; Adj. SS, adjusted sums of squares; DF, degrees of freedom; Seq. SS, sequential sums of squares

Table 11. TAN-coated-carbide-twist-drilled hole wall delamination of the entrance hole

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	$P \leq 0{\cdot}05$	%C
A	2	0·0002508	0·0002508	0·0001254	50·75	0·000	23·5
B	2	0·0001285	0·0001285	0·0000643	25·98	0·000	12·0
C	2	0·0002871	0·0002871	0·0001436	58·04	0·000	26·9
$A \times B$	4	0·0000151	0·0000151	0·0000038	1·53	0·282	1·4
$A \times C$	4	0·0004088	0·0004088	0·0001022	41·32	0·000	38·3
$B \times C$	4	0·0000144	0·0000144	0·0000036	1·45	0·302	1·3
Error	8	0·0000198	0·0000198	0·0000025	—	—	1·9
Total	26	0·0010675	0·0011245	—	—	—	—

R^2 = 98·24%; R^2_{adj} = 94·28%; S = 0·00157277
Adj. MS, adjusted mean squares; Adj. SS, adjusted sums of squares; DF, degrees of freedom; Seq. SS, sequential sums of squares

Table 12. Unusual observations for untreated TAN entrance hole F_d

Obs	Untreated TAN entrance hole F_d	Fit	SE fit	Residual	St. resid.
17	1·0506	1·04883	0·00132	0·00177	2·06R

R denotes an observation with a large standardized residual
Obs, observation; SE fit, standard error of the fit; St. resid., standardized residual

Table 13. TAN-coated-carbide-twist-drilled hole wall delamination of the exit hole

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	$P \leq 0{\cdot}05$	%C
A	2	0·0002508	0·0002508	0·0001254	50·69	0·000	24·20
B	2	0·0001285	0·0001285	0·0000643	25·98	0·000	12·40
C	2	0·0001989	0·0001989	0·0000995	40·21	0·000	19·19
$A \times B$	4	0·0000151	0·0000151	0·0000038	1·53	0·282	1·46
$A \times C$	4	0·0004088	0·0004088	0·0001022	41·32	0·000	39·45
$B \times C$	4	0·0000144	0·0000144	0·0000036	1·45	0·302	1·39
Error	8	0·0000198	0·0000198	0·0000025	—	—	1·91
Total	26	0·0010363	—	—	—	—	—

R^2 = 98·09%; R^2_{adj} = 93·79%; S = 0·00157277
Adj. MS, adjusted mean squares; Adj. SS, adjusted sums of squares; DF, degrees of freedom; Seq. SS, sequential sums of squares

Table 14. Unusual observations for untreated TAN exit hole F_d

Obs	Untreated TAN exit hole F_d	Fit	SE fit	Residual	St. resid.
17	1·0531	1·05133	0·00132	0·00177	2·06R

R denotes an observation with a large standardized residual
Obs, observation; SE fit, standard error of the fit; St. resid., standardized residual

speed (23·49%) show that they are almost nearly significant factors for entrance hole wall delamination. R^2 = 98·24% is higher than the confidence level of value 95%, the model indicates that the quality of hole wall at entry is better result then the exit.

- Anova for the exit hole (Tables 13 and 14)

Table 13 shows the effect of input parameters on exit hole wall delamination. The *F*-test shows that speed (50·69) has a greater influence than drill diameter (40·21), followed by feed rate (25·98) and Table 14 shows unusual observations for untreated TAN drill at exit. The contribution of speed (24·20%) is higher than those of drill diameter (19·19%) and feed rate (12·40%). Thus, this model indicates that the delamination of the exit hole is greater than the delamination at the entrance hole. The confidence level R^2 = 98·09% is higher than 95%.

3.3 Main-effects plots for thrust force (N) and torque (N m)

- HSS-twist-drilled hole (Figure 1)
- TAN-coated-carbide-twist-drilled hole (Figure 2)

Generally, the pattern shows that when the line is horizontal (parallel to the *x*-axis), there is no significant effect. When the line is not horizontal, there is a significant effect on various levels of the factors affect the response in a different way.

Tables 3–5 and 8–10 and Figures 1 and 2 respectively show that the thrust force and torque lines are nearer the mean line; thus, speed has no effect. However, thrust force is reduced at higher speeds from 1000 to 1500 revolutions per minute (rpm) and lower feed rates from 80 to 120 mm/min at diameters of 3 and 4 mm for both HSS-twist-drilled and TAN-coated-carbide-twist-drilled holes on untreated JFRP PU foam sandwich structures.

3.4 Main-effects plot for hole wall delamination (mm)

- HSS-twist-drilled hole wall delamination of entrance and exit holes (Figure 3)
- TAN-twist-drilled hole wall delamination of entrance and exit holes (Figure 4)

The Anova in Tables 6 and 7 and Figure 3 show that HSS-twist-drilled hole wall delamination at the entrance side is reduced with increasing speed (28·5%) and feed rate (9·6%), whereas

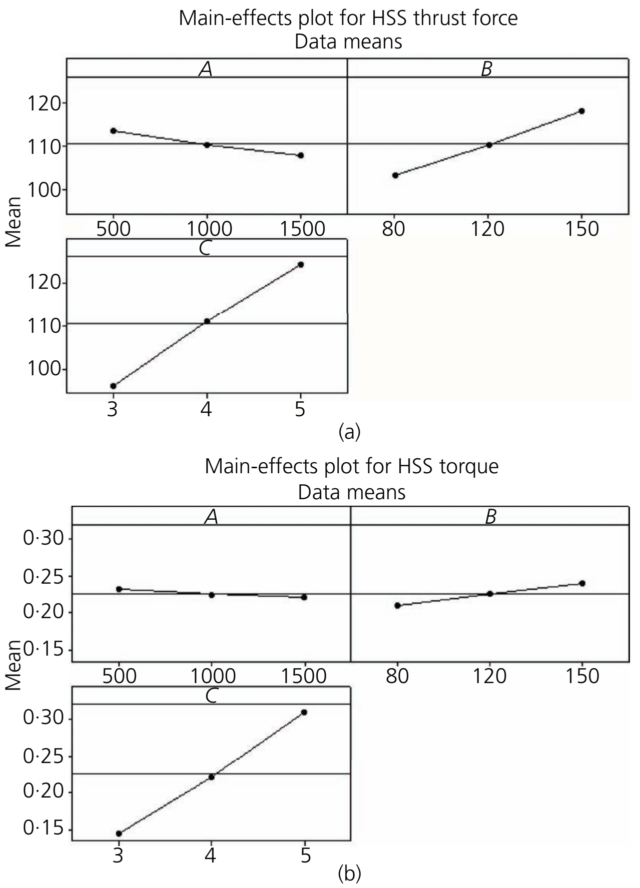

Figure 1. *S/N* ratios of (a) thrust force and (b) torque

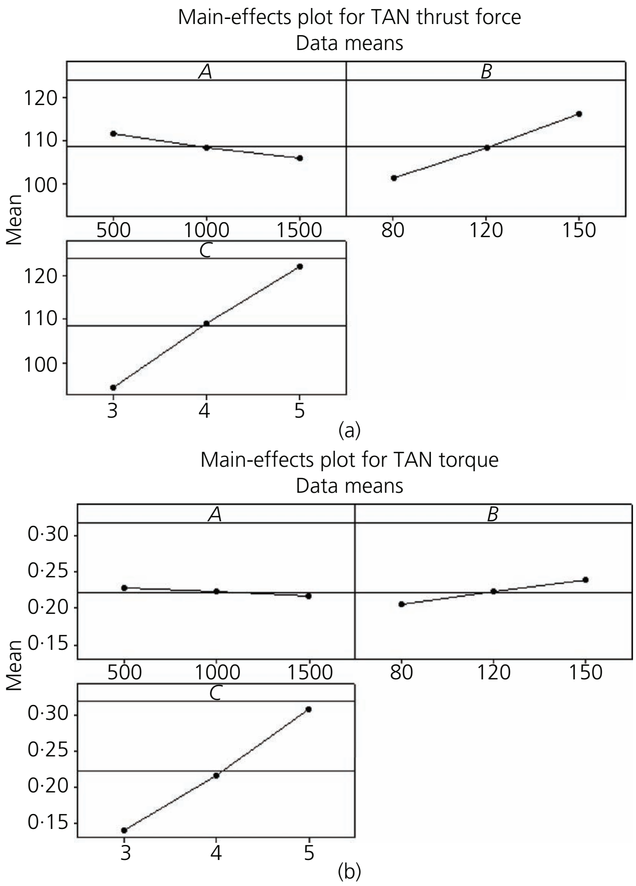

Figure 2. *S/N* ratios of (a) thrust force and (b) torque

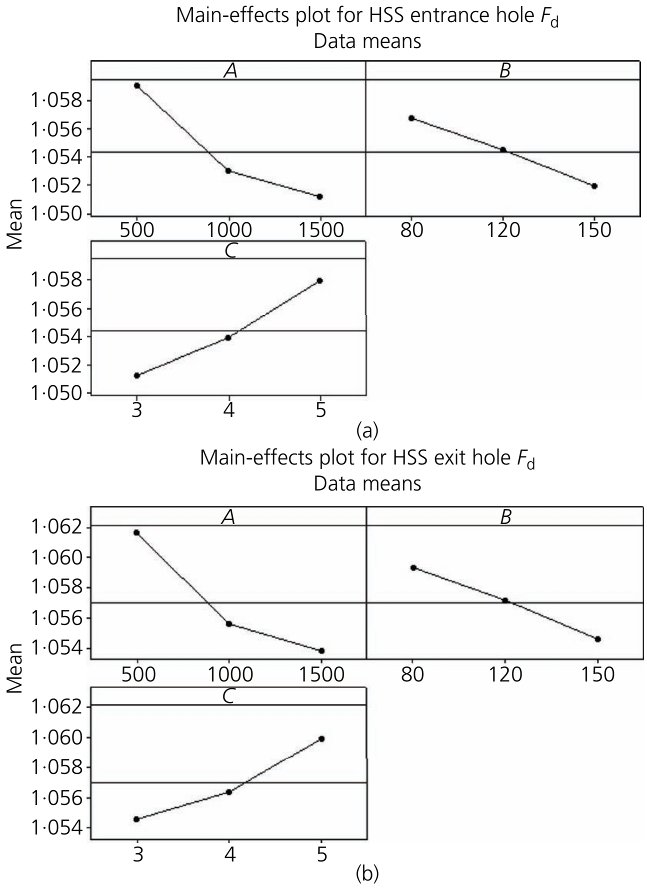

Figure 3. *S/N* ratios of delamination: (a) entrance and (b) exit holes

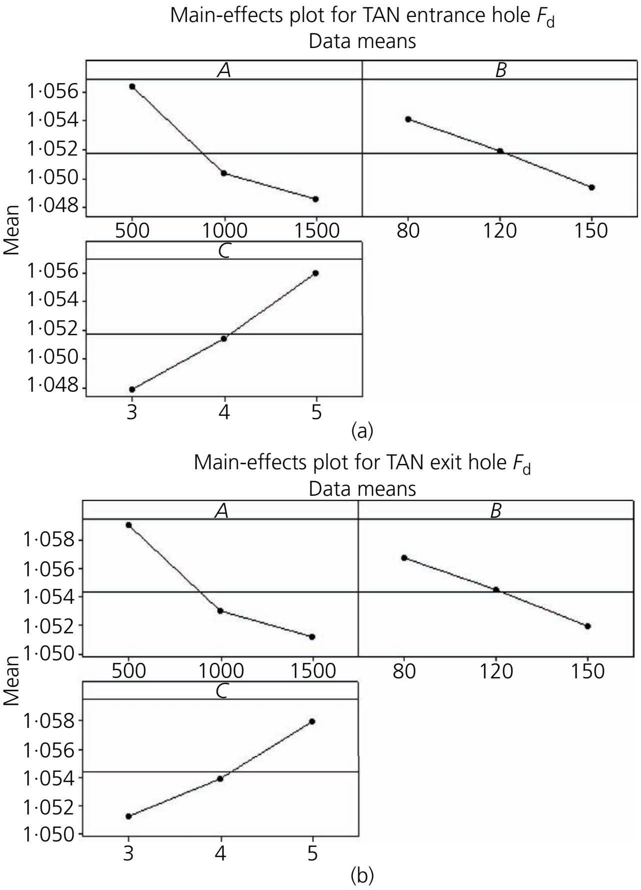

Figure 4. Main-effects plot for *S/N* ratio of delamination: (a) entrance and (b) exit holes

that at the exit side slightly increases with speed (30·49%) and feed rate (10·24%). Similarly, Tables 11 and 13 and Figure 4 show that for TAN-coated-carbide-twist-drilled hole wall delamination, speed (23·5%) and feed rate (12%) contribute to optimum outputs at the entrance side and speed (24·20%) and feed rate (12·40%) contribute to those at the exit side. Based on comparison, it is concluded that, for HSS-twist-drilled and TAN-twist-drilled entrance and exit holes, the speed contribution of TAN-coated-drilled is less than the HSS-twist-drilled hole and feed contributions is more.

3.5 Surface hole wall quality

- HSS-twist-drilled hole (Figure 5)
- TAN-coated-carbide-twist-drilled hole (Figure 6)

HSS-twist-drilled holes on an untreated JFRP PU foam are shown in Figure 5. Defects were observed such as nail heads, uncut fibers and resin, splintering, burrs, matrix cracks and wedge voids, as seen in the entire drilled hole. The burrs defects were observed around the holes. The irregularity of the circle at the entrance and exit holes was attributed to moisture and uncured resin between the fibers and matrix. Figure 6 shows that TAN-coated-carbide-twist-drilled hole sandwich structures have better hole walls with less gouging and also found that tear out of inner surface of hole wall for all speed levels and also increase in feed. This can also concluded that curing of resin was good and resistance to moisture in dry conditions.

3.6 Gray regression analysis

Table 15 shows the gray regression analysis of drilled holes considering thrust force, torque and delamination at entrance and exit holes. The gray regression grades (GRGs) were calculated to minimize all four output responses and were ranked based on the gray regression values.[17–20] Trial run number 16 shows that it has minimized the outputs with optimum input variables for both HSS- and TAN-drilled holes. This clearly gives evidence that all responses have a minimum effect when considering 1000 rpm speed, 150 mm/min feed and 3 mm diameter. The same observation was evidently found during analysis of delamination at both entrance and exit holes using the two- and three-dimensional images in Figures 5 and 6.

4. Conclusion

This study carried out optimization and analysis of drilling process parameters on minimization of thrust force, torque and

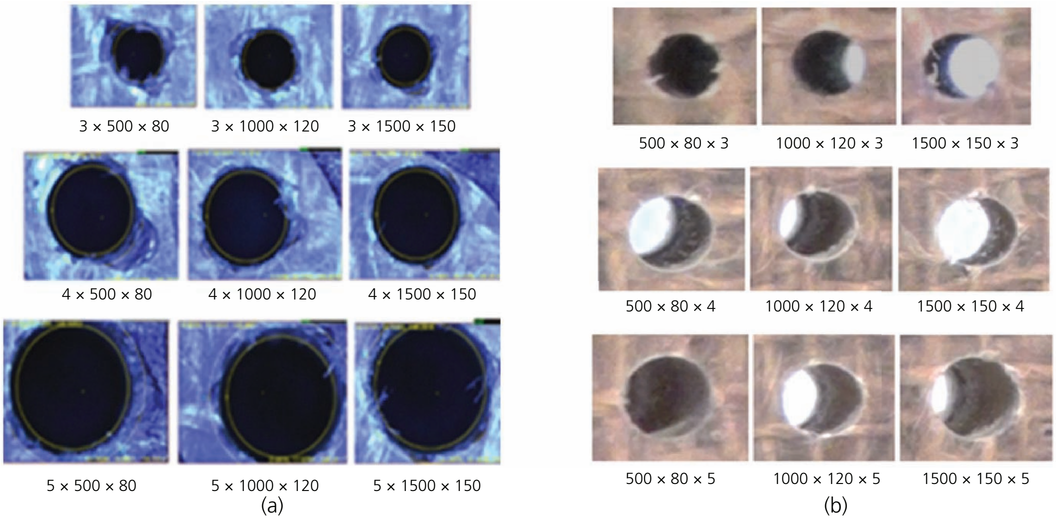

Figure 5. HSS-twist-drilled hole: (a) two- and (b) three-dimensional views (all dimensions in mm)

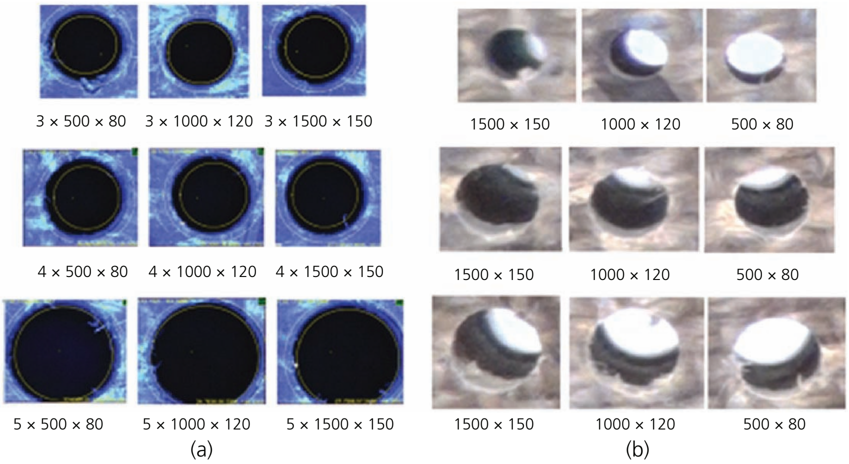

Figure 6. TAN-coated-carbide-twist-drilled hole: (a) two- and (b) three-dimensional views (all dimensions in mm)

Table 15. Gray regression analysis and its ranking

Run number		1	2	3	4	5	6	7	8	9
HSS	GRG	0·75282	0·518718	0·403388	0·751273	0·530721	0·393971	0·831138	0·495475	0·362906
	Rank	8	21	25	9	20	26	3	22	27
TAN	GRG	0·765351	0·51484	0·40611	0·746881	0·526628	0·392764	0·829611	0·4983	0·361587
	Rank	7	21	25	9	19	26	3	22	27
Run number		10	11	12	13	14	15	**16**	17	18
HSS	GRG	0·795452	0·584266	0·464288	0·892562	0·611335	0·453187	**0·939095**	0·612078	0·532659
	Rank	4	18	23	2	16	24	**1**	15	19
TAN	GRG	0·786607	0·585691	0·460244	0·88553	0·610056	0·448687	**0·935224**	0·603784	0·518335
	Rank	5	17	23	2	14	24	**1**	16	20
Run number		19	20	21	22	23	24	25	26	27
HSS	GRG	0·771179	0·773301	0·59993	0·778347	0·631831	0·628877	0·695512	0·688026	0·68809
	Rank	7	6	17	5	13	14	10	12	11
TAN	GRG	0·781049	0·759161	0·584106	0·788012	0·622423	0·608166	0·689968	0·683023	0·654652
	Rank	6	8	18	4	13	15	10	11	12

Bold numbers ranked 1 based on output (minimizing toque, toque, delamination at entrance and exit) result delamination of a hole in untreated JFRP PU foam sandwich structures. The HSS-twist-drilled hole has a minimized thrust force of 90 N and a torque of 0·14 N m at a speed of 1500 rpm with a feed rate of 80 mm/min for a 3 mm hole. Similarly, for a 4 mm hole, a thrust force of 92 N and a torque 0·18 of N m were found. The high percentage contributions of drill diameter and feed rate (66·63 and 18·68%, respectively) show that they are significant factors affecting thrust force, with speed (2·94%) having no major effect. Drill diameter (93·13%) has a significant effect on torque, while speed (3·05%) and feed rate (0·42%) do not have a significant effect.

Whereas in TAN-drilled hole minimized thrust force (88 N) and torque (0·13 N m) were found at a speed of 1500 rpm with a feed rate of 80 mm/min at 3 mm drill diameter. For the same input variable (speed and feed) thrust force and torque were found to be 90 N and 0·18 N m at 4 mm drill diameter. For hole wall delamination, the results show that the TAN-twist-drilled hole is influenced by the effect of speed at the entrance and exit holes (23·5 and 24·20%, respectively), while speed has a smaller contribution for HSS-twist-drilled entrance and exit holes (28·5 and 30·49%, respectively). The other influencing factor, feed rate, has a smaller contribution for TAN-drilled hole at the entrance and exit sides (9·6 and 10·24%, respectively) compared to that for the HSS-twist-drilled entrance and exit holes (12·0 and 12·4%, respectively). The Taguchi technique optimized the drill parameters using HSS and TAN drill tools found that drilled hole from experimental results in a medium-level speed of 1000 rpm and feed rate of 120 mm/min at 4 mm. According to gray regression analysis, the optimum drilling parameters were found to be 1000 rpm speed, 150 mm/min feed and 3 mm diameter.

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