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Research article

Study of drilling of multi-material (CFRP/Al) using Taguchi and statistical techniques

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Abstract

The thrust force and surface roughness of plain carbide drill (K20) with drill parameters (drill diameter, spindle speed and feed rate) in drilling carbon fibre reinforced plastic (CFRP) laminate/aluminum (Grade 2024) stack was experimentally investigated in this study. A L27 orthogonal array and signal-to-noise (S/N) were employed to analyze the effect of drill parameters. Using Taguchi method for design of a robust experiment, the interactions among factors are also investigated. The analysis of variance (ANOVA) shows that the feed rate and drill diameter are the most significant parameters to the overall performance while drilling CFRP/al stack. These results are in good agreement with Signal/Noise (S/N) ratio of Taguchi analysis. Hole diameter of CFRP is found to be less (10μm) than the nominal diameter of drill. Circularity is found to be around 6μm at low feed rates in CFRP. When the feed is increased, the circularity increases to 25 μm.

Keywords: Drilling, composite/aluminum, ANOVA, experimental design, quality of hole

1. Introduction

Composite materials are becoming more important to aerospace, naval, space, and automotive industries [1-2]. Some aircraft structures use stacks of fibre composites and aluminum or titanium, and these present unique machining challenges. Abrasive water jet machining can be a good solution for trimming the edges of composites and other materials, but through holes in stacks typically require hard cutting tools and multistep drilling methods [3]. Drilling of such materials is a challenging task to manufacturing engineers because of differential machining properties [1-5].

Due to laminated constructions of composites several types of damages like matrix cracking and thermal alterations, fiber pullout and fuzzing, are introduced during drilling in addition to geometrical defects similar to those found in metal drilling [1,2]. About 60% of the rejections are due to the defects in the holes. These defects would create reduction in structural stiffness, leading to variation in the dynamic performance of the

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whole structure. Many of these problems are due to the use of non-optimal cutting tool designs, rapid tool wear, and machining conditions [3,4]. Cutting forces while machining, and surface finish of composites are dependent on the fibre angle, the depth of cut as well as the direction of cutting [5,6]. Investigators have studied analytically and experimentally where delamination in drilling has been correlated to the thrust force during exit of the drill [7]. Zitoune et al. [8-9] showed that deformation due to shear stress has an influence on the critical thrust force which is responsible for delamination at the hole exit. Furthermore, the manufacturing processes have an influence on the delamination at the entry and exit of the hole. The influence of various drill bits in drilling of CFRP [10,11], and the influence of process parameters on thrust force and torque during drilling of GFRP [12,13] were analyzed statistically.

The most important wear mechanisms in machining of aluminum alloy are: built-up edge, adherent layer and diffusion. At low cutting conditions (cutting speed), the built-up edges are formed on the tool rake face and take over the function of the cutting edge. Many of the chipping and surface finish difficulties encountered in machining aluminum alloys can be eliminated by increasing cutting speed. At very high cutting speed, temperature is higher; mechanisms of tool wear involve chemical action and diffusion [14,15]. Rivero et al. [16] reports that the smallest burrs occur when feed increases; however, high feed rate is not good during machining of composites materials. Numerous sets of designed experiments were conducted on cast aluminum alloys, studying the effects of the cutting conditions on the drilling process in order to optimize the chip-formation mechanics and hole surface quality effects [17]. It was shown that the important parameters affecting the hole quality are the feed, material and drill type and to a lesser extent, cutting-fluid presence and drilling speed.

During drilling of multi-material, due to different material properties, holes with small diameter tolerances are difficult to drill. The modulus of elasticity (E) of the materials causes different elastic deformations and therefore varying tolerances along the entire hole. Additionally, the chips shape and length of the chip passing through the hole as well as built up edges of aluminum at the primary cutting edges combined with increased tool wear affect the hole quality [18]. For machining multi-material, sharp and high hot hardness tool materials are required. Ramulu et al. [19] and Kim et al. [20] reported that tool wear occur rapidly when drilling Gr/Bi-Ti stacks. Multi material theoretically calls for different tools, one that fits the attributes of a composite and a different one that fits the attributes of aluminum, or Titanium. Multilayer materials drilled with adapted step drills improved diameter tolerances, surface quality, and reduced tool wear [18].

Kim et al. [21,22] have studied drilling of Gr/Bi-Ti in the context of process conditions and cost optimization. From these studies the authors proposed the process parameters of 660 rpm and 0.08 mm/rev for Ti-Gr stacks. Roudge et al. [23] established a quantification method particularly for delamination on drilling of multilayer materials. Denkena et al. [24] showed that the quality of the holes could be increased by helical milling of CFRP-Ti stacks.

Aircraft orders are expected to grow gradually over the next few years, but machining applications for composite parts may double by 2010 [25]. Drilling of multi material stack has problems like chip disposal, change in dynamic cutting forces, tool temperature and tool wear. Polymer composite chips are continuous at low feeds [21] and became dust-like chips as feed increased. Aluminum chips will be continuous when the spindle speed is high and feed is less. When aluminum is stacked at the bottom of CFRP, continuous and high temperature chips passing through the CFRP deteriorate the quality of the hole. The choice of cutting tool, process parameters should be a compromise, in drilling ductile aluminum as well as drilling highly abrasive carbon fibre.

According to our survey, the literature related to multi material stacks is limited. Various sources confirm that the composite in aircraft assembly is generally carbon-fibre reinforced plastic, and whenever the stack is formed with aluminum, normally composite is placed on top most of the time. So it is necessary to analyze the drilling effect of CFRP/Al stack on drilling parameters. In this paper, experimental study on drilling of CFRP/Aluminum stack has been carried out using carbide drills (K20) to study the influence of diameter, spindle speed and feed rate on thrust force and surface finish of the CFRP/Al stack.

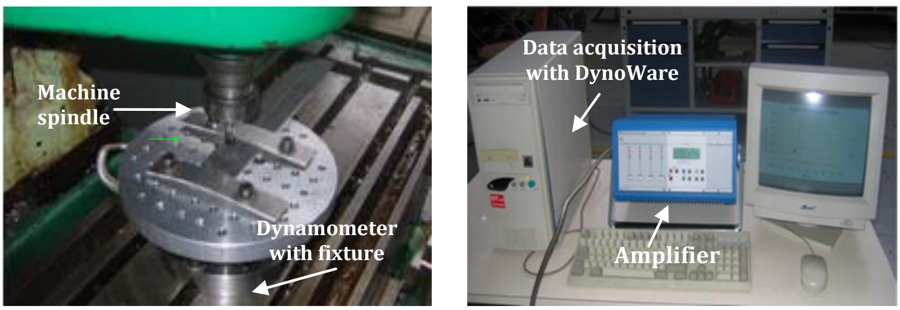
2. Experimentation

2.1. Workpiece Details

Carbon fibre reinforced plastic (CFRP) composite of 4.2 mm thickness (16 layers) was used for conducting the drilling studies. The CFRP composite was made using unidirectional prepregs supplied by Hexcel Composite Company referenced as Hexply T700-M21. The lay-up sequence of the CFRP was $[90/-45/0/45/90/-45/0/45]_S$ so as to get a quasi-isotropic laminate, and the laminate was cured in an autoclave. The nominal fibre volume fraction is 0.58. Aluminum sheet (Grade 2024) of 3 mm thickness was used to form the stack.

2.2. Experimental Details

The experimental set up in Fig.1 shows the workpiece is mounted on the dynamometer on the table of a precision milling machine, and the drill is fed to the workpiece.



(a) (b)

Fig. 1 Experimental set-up, (a) machine and experimental device, (b) system of acquisition

Drilling trials have been carried out on Al/CFRP stack using 4 mm, 6 mm and 8 mm diameter tungsten carbide (K20) drills. These three diameters are chosen based on the requirements of the aircraft industry. Table 1 gives the summary of experimental conditions. Three spindle speeds and three feeds were selected in such a way that it suits the requirements of both CFRP and aluminum. In order to reproduce the industrial conditions, all tests were conducted without coolant.

Table 1
Summary of experimental conditions

Drilling composite-aluminum stacks	
Machine tool	Milling machine. Spindle power 3 Kw
Workpiece material	CFRP (58% Vf. 4.2 mm thick) and Al 2024 (3 mm thick)
Tools	Plain carbide (K20) drill Φ 4, 6 and 8 mm. Point angle 118°
Drilling conditions	Spindle speed (rpm) 1050, 2020 and 2750, Feed rate (mm/rev) 0.05, 0.10 and 0.15

The thrust force and torque during machining was measured using piezo-electric (Kistler 9366AB) dynamometer. The charge amplifier converts the resulting charge signals, which are proportional to the force, to voltage and managed through the data acquisition system. Each experimental condition was repeated 5 times so as to get consistent values. Each test condition was performed with a new drill in order to remove the influence tool wear. The surface roughness (Ra) of the hole was measured by surface roughness tester (Mitutoya SJ 500) with a sampling length of 0.8 mm.

2.3. Taguchi Method

Taguchi methods which combine the experiment design theory and the quality loss function concept have been applied to the robust design of products and process and have solved some confusing problems in manufacturing. In order to observe the influence degree of control factors (spindle speed, feed, and drill diameter) in drilling, three factors, each at three levels, are considered. Namely, a L27 (3^{13}) orthogonal array was employed. Table 2 gives the experimental conditions and thrust force, torque and surface finish measured during the experiments.

Taguchi has used signal-noise [S/N] ratio as the quality characteristic of choice. S/N ratio is used as measurable value instead of standard deviation due to the fact that as the mean decreases, the standard deviation also decreases and vice versa. In other words, the standard deviation cannot be minimized first and the mean brought to the target. In practice, the target mean value may change during the process development. Two of the applications in which the concept of S/N ratio is useful are the improvement of quality through variability reduction and the improvement of measurement. The S/N ratio characteristics can be divided into three categories given by Eqs. 1–3, when the characteristic is continuous.

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

Smaller the better characteristic: $$\frac{S}{N} = \log\frac{1}{n}\left(\sum_{i=1}^{i=n} {y_i}^2\right) \qquad (2)$$

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

where; $\overline{y}$ is the average of observed data, S^2y the variation of y, n the number of observations, and y the observed data. For each type of characteristics, with the above S/N ratio transformation, the higher the S/N ratio the better is the result. In the present experimental study, in order to identify the best process parameters, to obtain the minimum thrust force, torque as well as surface roughness, Taguchi S/N ratio (smaller the best) characteristic is used.

Table 2
Experimental results of force and surface roughness

Trial	Speed (rpm)	Feed mm/rev	Dia (mm)	TF (N)		TQ (N.cm)		Ra (μm)	
				CFRP	Al	CFRP	Al	CFRP	Al
1	1050	0.05	4	49.00	98.4	7.60	17.4	2.726	1.093
2	1050	0.10	4	74.60	204.0	9.40	25.2	3.870	2.346
3	1050	0.15	4	100.25	304.7	10.00	32.7	6.806	2.465
4	2020	0.05	4	52.00	102.0	8.00	17.2	2.462	1.699
5	2020	0.10	4	71.80	213.2	9.80	24.8	4.193	2.683
6	2020	0.15	4	89.60	278.4	11.40	27.4	4.736	2.242
7	2750	0.05	4	44.40	98.6	9.20	22.2	2.299	1.610
8	2750	0.10	4	70.80	222.6	9.00	22.6	5.268	1.964
9	2750	0.15	4	89.00	285.2	12.40	26.0	4.513	1.894
10	1050	0.05	6	61.80	120.0	13.00	21.1	4.161	0.663
11	1050	0.10	6	79.60	222.6	13.78	40.6	5.760	1.461
12	1050	0.15	6	102.20	342.2	17.86	54.0	7.190	0.975
13	2020	0.05	6	56.00	134.8	11.77	29.1	3.633	0.612
14	2020	0.10	6	85.17	236.0	17.17	39.5	5.615	0.840
15	2020	0.15	6	97.80	335.2	16.40	55.4	6.256	1.458
16	2750	0.05	6	53.60	142.6	12.84	34.7	3.296	0.434
17	2750	0.10	6	71.20	242.8	16.20	37.6	4.997	1.042
18	2750	0.15	6	90.20	329.2	17.13	61.8	6.937	0.908
19	1050	0.05	8	88.00	116.4	23.00	40.0	2.086	1.925
20	1050	0.10	8	103.20	243.2	24.60	69.2	5.349	1.585
21	1050	0.15	8	129.40	394.4	29.40	91.4	6.434	2.214
22	2020	0.05	8	89.00	133.4	21.80	41.4	2.016	0.805
23	2020	0.10	8	111.20	279.0	21.40	62.6	4.600	1.949
24	2020	0.15	8	124.25	404.2	28.25	87.5	6.620	1.778
25	2750	0.05	8	73.20	129.0	17.60	34.6	2.104	1.384
26	2750	0.10	8	100.25	301.0	22.25	59.0	4.530	1.448
27	2750	0.15	8	137.33	424.0	30.67	97.7	6.640	2.015

TF (N) CFRP: Thrust force (N) in CFRP, TF (N) Al: Thrust force (N) in aluminum
TQ (N.cm) CFRP: Torque (N.cm) in CFRP, TQ (N.cm) Al: Torque (N.cm) in aluminum
Ra (μm) CFRP: Surface roughness (μm) in CFRP, Ra (μm) Al: Surface roughness (μm) in aluminum.

3. Results and Discussion

3.1. The Effect of Thrust Force and Torque

During drilling with twist drill instead of cutting, the chisel edge of the drill point pushes aside the material at the center as it penetrates into the hole. Thrust force and torque raise steeply while drill enters aluminum when compared to CFRP. The sudden change in cutting forces during drilling shall affect the performance of the drill and quality of the hole in CFRP. The purpose of the statistical analysis of variance (ANOVA) is to investigate which drilling parameters significantly affect the drilling performance. Based on ANOVA the optimal combinations of the process parameters are predicted. This analysis is carried out for level of significance of 5% (i.e., the level of confidence 95%). From the study of analysis of variance of thrust force for CFRP (Table 3), it is found that the feed rate (55%) has the highest contribution followed by drill diameter (40%). The effect of spindle speed on thrust force on drilling of CFRP seems to be absent; these results are similar to the results given by Davim et al. [13] during GFRP drilling. The effect of feed rate on thrust force of aluminum is 87.5%, and effect of thrust force on diameter of the drill is 8.08%. The interaction between the above parameters does not have significant influence on thrust force of CFRP/Al stack. The higher contribution of the drill diameter on CFRP when compared to aluminum may be due to the behavior of materials under machining conditions at the chisel edge. During machining the higher contribution of the drill diameter derives from the temperature and pressure the tool displacement near the chisel edge aluminum flows. During the drilling of CFRP this phenomenon of material flow is not present. The change of thrust force during drilling of CFRP/Al is presented in Fig. 2.

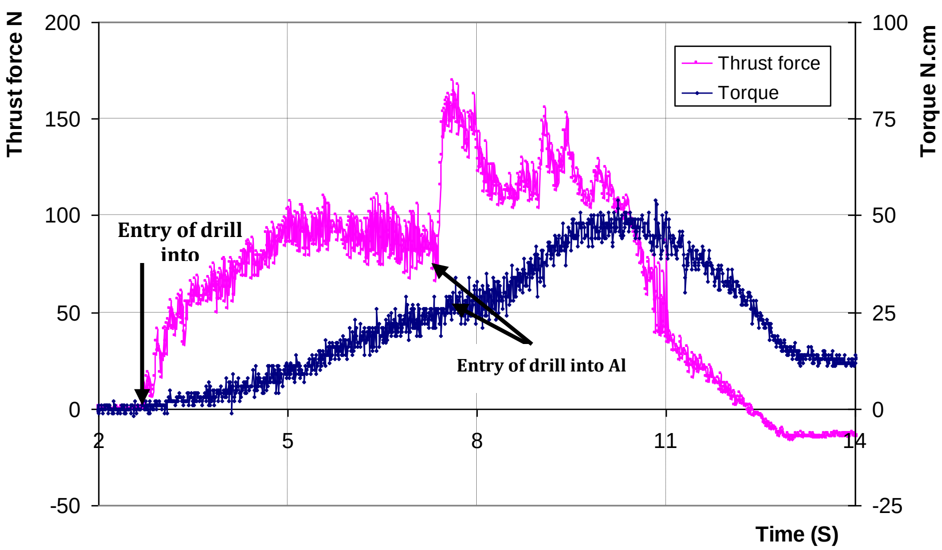


Fig. 2 Thrust force and torque profiles while drilling CFRP/Al stacks, drill diameter 8 mm, spindle speed 1050 rpm, feed rate 0.05 mm/rev

Fig. 3 presents the main effects plot for data means for the thrust force during CFRP drilling. From these results it is seen that the optimum combination for obtaining minimum thrust in drilling CFRP is 4 mm of diameter, 0.05 mm/rev of feed rate and 2750 of spindle speed. We note that the factor of spindle speed has less influence (shown in Fig. 3c). This is in agreement with ANOVA results (Table 3).

Fig. 4 presents the main effects plot for data means for the thrust force during aluminum drilling. These results show that the optimum combination of drilling of aluminum is drill diameter of 4 mm, feed of 0.05 mm/rev and spindle speed of 1050 rpm. From the experimental results it is found that increasing spindle speed reduces the thrust force while drilling CFRP whereas it is not the case during aluminum drilling [26]. However, the influence of spindle speed on the thrust force during drilling of aluminum is less. This observation is in good agreement with ANOVA results (shown in Table 3). In order to remove the effect of build-up edge, it's preferable to use high spindle speed.

Table 3
ANOVA for thrust force of CFRP and Al

Source of variance	Sum of squares	Df	Variance	Test F	$F_{(\alpha=5\%)}$	P*
			Thrust force- CFRP			
Spindle speed (N)			**Pooled**			
Feed (mm/rev)	8615.86	2	4307.93	767.902	3.07	55
Drill dia (mm)	6201.83	2	3100.92	552.749	3.07	40
P. Error	729.39	130	5.61	--		4
Total	15546.08	134	--	--	--	100
			Thrust force - Al			
Spindle speed (N)			**Pooled**			
Feed (mm/rev)	227679	2	113839	1330.67	3.07	87.50
Drill dia (mm)	21192	2	10596	123.85	3.07	8.08
P. Error	11122	130	85.55	--	--	4.42
Total	259993	134	--	--	--	100.00

P*=Percentage of contribution

From the analysis of variance of torque (Table 4) for CFRP, it is found that the drill diameter (82.65%) has the highest contribution followed by feed (11.13%). The effect of spindle speed on torque of CFRP and aluminum is absent. The effect of drill diameter on torque of aluminum is 56.2%, followed by feed which is 30.15%. The higher contribution of drill diameter on torque over feed is due to the increase in chip load in the radial direction of the drill with increase in diameter. The feed rate has high contribution (30.15%) on torque of aluminum whereas feed contribution of torque over CFRP (11.13%) is less, this could be because of nature of chip.

While drilling CFRP the chip was in the form of powder whereas while drilling aluminum it was continuous at low feed and segmented at high feed. The Feed*Diameter interaction has influence of 2.92% on torque over drilling of CFRP and 10.57% on torque over drilling of aluminum. This can be explained that when the feed and diameter increases the cross section of the chip increases as well. It is better to reduce the feed when diameter of the drill is high. From the main effects plots of torque of CFRP and aluminum

(Fig. 5,6) it is found that drill diameter of 4mm, 0.05mm/rev feed is optimum for drilling CFRP and aluminum with less torque, and the effect of spindle speed on torque is very small. From the study of analysis of variance (Table 5) of surface finish for CFRP it is found that the feed has a contribution of 78.15% followed by drill diameter 9.68%.

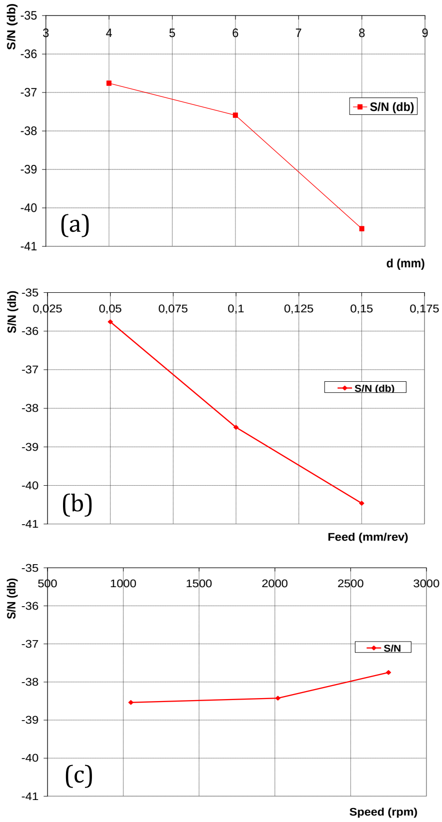


Fig. 3 Main effects plot for data means (Thrust force of CFRP), (a) S/N ratio vs. diameter, (b) S/N ratio vs. feed, (c) S/N ratio vs. speed

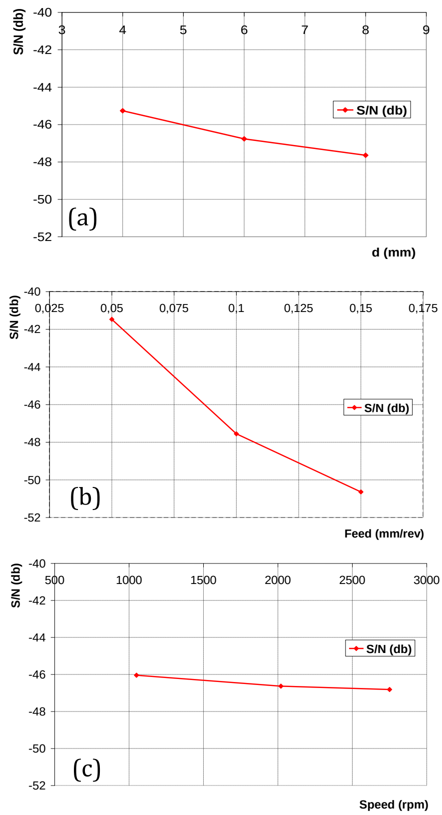


Fig. 4 Main effects plot for data means (Thrust force of Al), (a) S/N ratio vs. diameter, (b) S/N ratio vs. feed, (c) S/N ratio vs. speed

The effect of drill diameter on surface finish of aluminum is 54.86%, followed by feed which is 22.14%. The effect of spindle speed on surface finish of CFRP and aluminum is less. The higher contribution of feed on surface finish of CFRP (78.15%) and feed (23.76%) on surface finish of aluminum could be related to the nature of material. The interactions between the parameters have statistical significance but do not have any physical significance (error>percentage contribution of interactions). The pooled error is 8.98% for CFRP and 15.19% for aluminum.

From the main effects plots of surface finish of CFRP and aluminum (Fig. 7,8) it is found that drill diameter of 4mm, spindle speed of 2750 rpm and feed of 0.05 mm/rev are optimum for drilling CFRP and drill diameter of 6 mm, spindle speed of 2750 rpm, and feed of 0.05 mm/rev is optimum for aluminum to get better surface finish. In general to get better surface finish high spindle speed and low feed is required, since the effect of spindle speed seems to be less, it is better to control the feed rate in order to get better finish. To get better surface finish in CFRP sharpness of the tool and process parameters are significant. During drilling of aluminum apart from these built up edge effect has to be removed. From the literature it is found that high cutting speed is required to remove the built up edge [17].

Table 4
ANOVA for torque of CFRP and Al

Source of variance	Sum of squares	Df	Variance	Test F	$F_{(\alpha=5\%)}$	P
			Torque – CFRP			
Spindle speed (N)			**Pooled**			
Feed (mm/rev)	134.05	2	67.03	223.43	3.07	11.13
Drill dia (mm)	991.24	2	495.62	1652.06	3.07	82.65
Feed*Dia	36.13	4	9.03	30.10	2.45	2.92
P. Error	37.18	126	0.30			3.30
Total	1198.60	134	--	--		100.00
			Torque – Al			
Spindle speed (N)			**Pooled**			
Feed (mm/rev)	3993.30	2	1996.65	93.16	3.07	30.15
Drill dia (mm)	7438.60	2	3719.33	173.55	3.07	56.20
Feed*Dia	1410.02	4	352.51	16.45	2.45	10.57
P. Error	384.24	126	3.05	--		3.08
Total	13226.21	134	--	--		100.00

Table 5
ANOVA for surface finish of CFRP and Al

Source of variance	Sum of squares	Df	Variance	Test F	$F_{(\alpha=5\%)}$	P
			Surface finish – CFRP			
Spindle speed (N)			**Pooled error**			
Feed (mm/rev)	55.648	2	27.824	57.51	3.07	78.15
Drill dia (mm)	6.976	2	3.488	7.21	3.07	9.68
Feed*Dia	2.480	4	0.620	1.28	2.45	3.22
P. Error	5.977	126	0.047	--	--	8.98
Total	71.086	134	--	--	--	100.00
			Surface finish – Al			
Spindle speed (N)	0.2372	2	0.1186	10.69	3.07	2.20
Feed (mm/rev)	2.1888	2	1.0944	98.68	3.07	22.14
Drill dia (mm)	5.3907	2	2.6954	243.05	3.07	54.86
Dia*Speed	0.3357	4	0.0839	7.57	2.45	2.98
Dia*Feed	0.3020	4	0.0755	6.81	2.45	2.63
P. Error	1.3319	120	0.0110	--	--	15.19
Total	9.5877	134	--	--	--	100.00

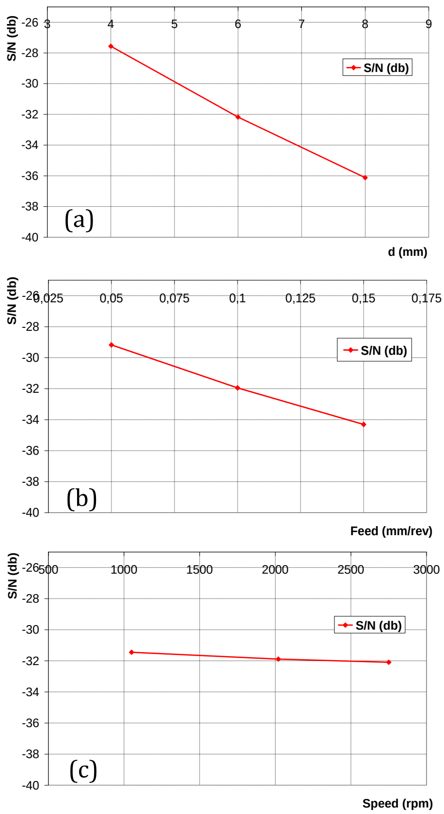


Fig. 5 Main effects plot for data means (Torque of CFRP), (a) S/N ratio vs. diameter, (b) S/N ratio vs. feed, (c) S/N ratio vs. speed

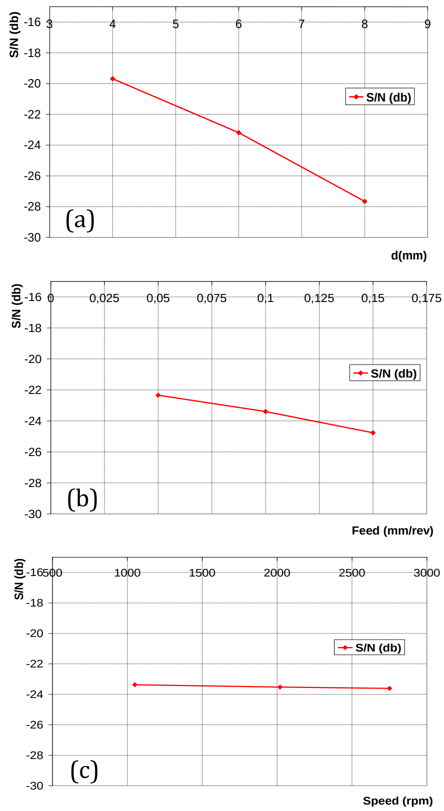


Fig. 6 Main effects plot for data means (Torque of Al), (a) S/N ratio vs. diameter, (b) S/N ratio vs. feed, (c) S/N ratio vs. speed

3.2. The Effect of Spindle Speed, Feed and Diameter of Drill on Quality of Hole

While drilling the CFRP diameter tolerances of 30 µm or less than that are required [18]. Aluminum chips flowing through CFRP shall have influence on quality of hole. Fig. 9 shows the setup used to measure diameter and circularity of CFRP and aluminum. Hole diameters and circularity were measured at the middle of the thickness of the laminates and aluminum using co-ordinate measuring machine (CMM). The values presented in Fig. 10 are the average values of three holes. It is seen from Fig. 10, circularity is found to be around 6 µm at low feed rates. When the feed is increased the circularity increases to 25 µm, while the effect of spindle speeds on circularity seems to be absent. From the measurements of hole diameter on CFRP, it is found that the nominal hole diameter is 10 µm less than the nominal diameter of the drill. This could be because of the relaxation of elastic stresses during machining.

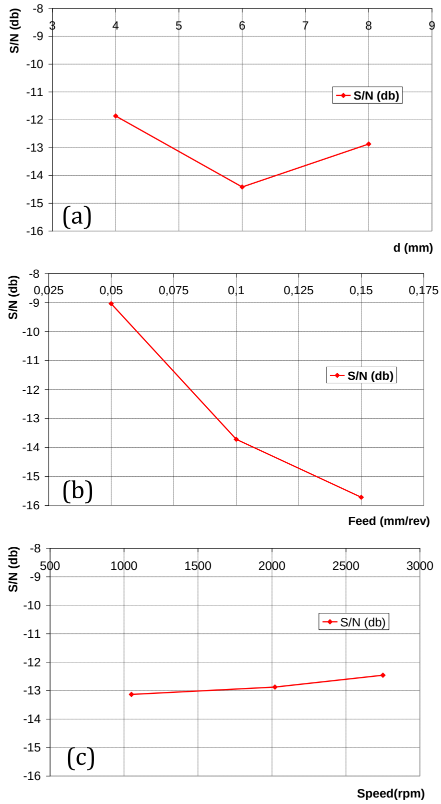


Fig. 7 Main effects plot for data means (Ra of CFRP), (a) S/N ratio vs. diameter, (b) S/N ratio vs. feed, (c) S/N ratio vs. speed

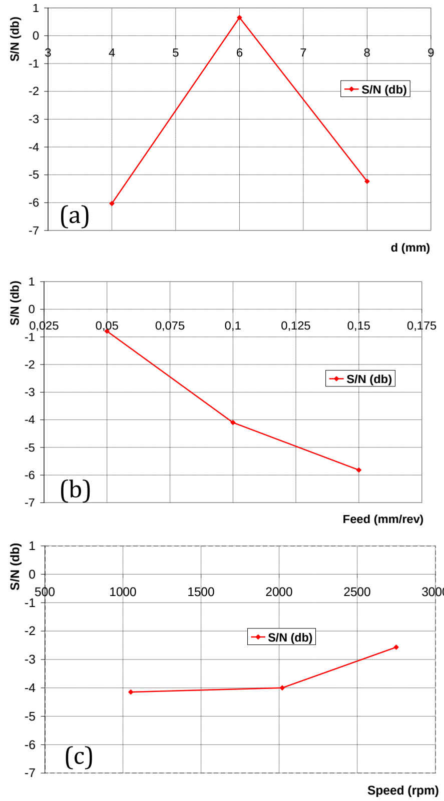


Fig. 8 Main effects plot for data means (Ra of Al), (a) S/N ratio vs. diameter, (b) S/N ratio vs. feed, (c) S/N ratio vs. speed

The tendency of reduction in the hole diameter tries to increase the friction between the drill and the surface of the hole while drilling aluminum. The nominal hole diameter of aluminum was observed to be on the positive (5 μm) side with less circularity error.

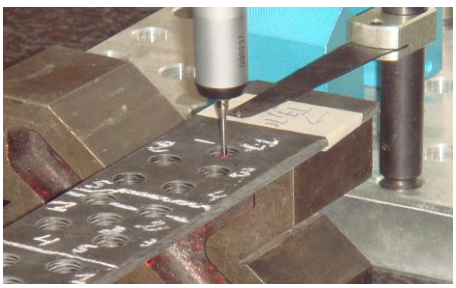


Fig. 9 Experimental setup to measure diameter and circularity of CFRP and Aluminum

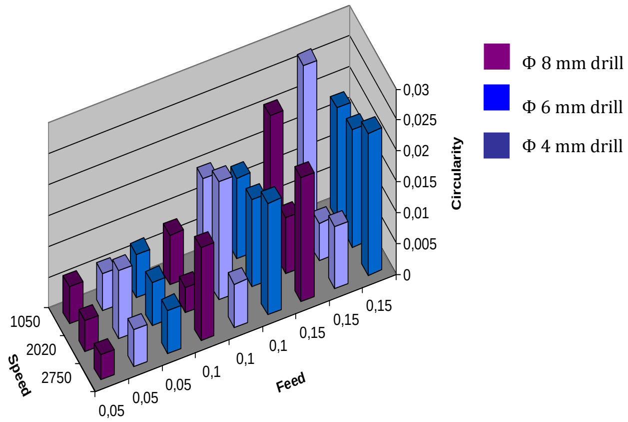
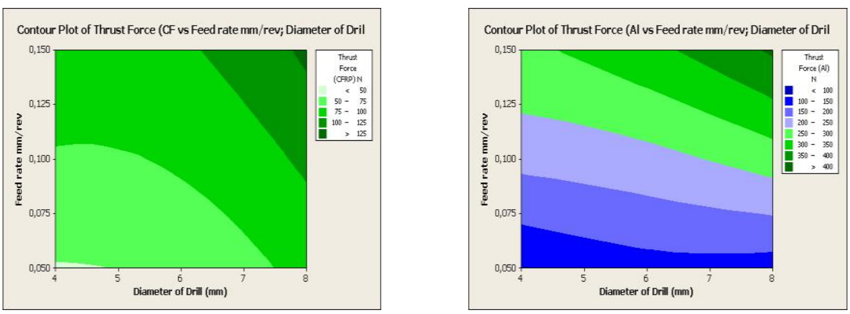


Fig. 10 Circularity of CFRP at various spindle speeds vs. feed

4. Conclusion

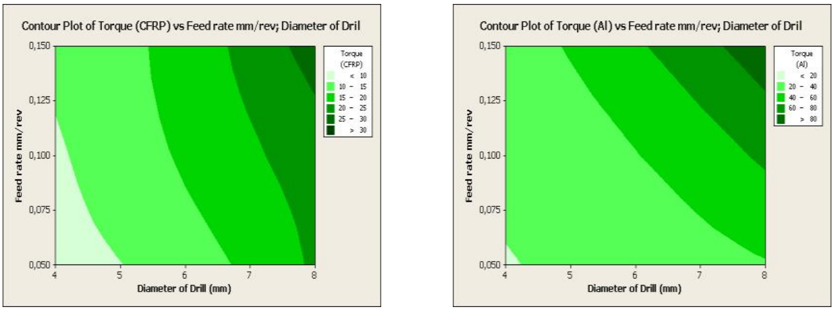
The statistical approach to the evaluation of optimum drilling parameters for drilling CFRP/Al stack, using design of experiments, has been proposed in this study. The results are summarized as follows:

i. From the statistical analysis it is found that the feed (55%) and the diameter of drill (40%) contribute to the thrust force of the drilling of CFRP. And the feed (87.5%) and the diameter of drill (8.08%) contribute to aluminum drilling. Moreover, it is also found that feed (11.13%) and diameter of drill (82.65%) have contribution of torque while drilling CFRP and feed (30.15%) and diameter (56.2%) contribute to torque when aluminum drilling. It is found that the effect of spindle speed is small; so, it is suggested to select spindle speed of 2750 rpm (with in the range chosen for study) which is advantageous in terms of production rate and the elimination of built-up edge in aluminum. From the surface response plot of CFRP and aluminum (Fig. 11,12), drill diameter of 4 mm and feed of 0.05 mm/rev is the optimum combination for drilling of CFRP/aluminum stack with less thrust force and torque.



(a) CFRP (b) Aluminum

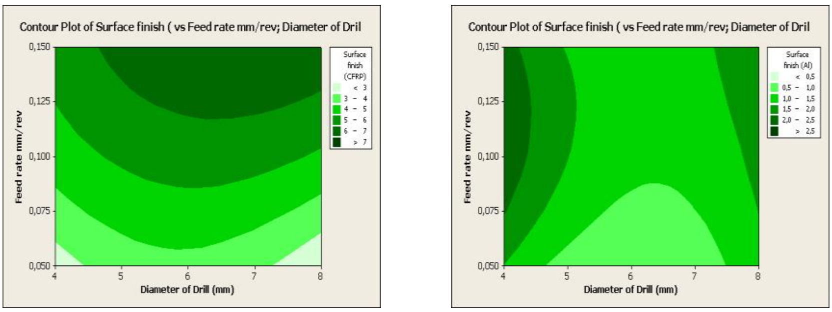
Fig. 11 Surface response plots for thrust force of CFRP and Aluminum



(a) CFRP (b) Aluminum

Fig. 12 Surface response plots for torque of CFRP and Aluminum

ii. Feed (78.15%) and diameter of drill (9.68%) have contribution of surface roughness of CFRP, and feed (22.14%) and diameter of drill (54.86%) have contribution of surface roughness of aluminium. From Fig. 13, it is seen that all diameters tested (4 mm to 8 mm) present an acceptable surface roughness in CFRP (less than 5 μm), and the surface roughness (Ra) of aluminium is less than 1.5 μm.



(a) CFRP (b) Aluminum

Fig. 13 Surface response plots for surface roughness of CFRP and Aluminum

iii. Circularity is found to be around 6 μm at low feed rates. While the feed is increased the circularity increases to 25 μm, while the effect of spindle speeds on circularity seems to be meager.

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