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Analysis of thrust force in drilling cotton with bamboo blended fibre-reinforced composites using Box-Behnken methodology

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In this study, cotton/bamboo woven fabric reinforced composite has been subjected to drilling operation and thrust force is analysed for different combination of feed rate, cutting speed and drill geomentry. Box-Behnken experimental design is used to optimize the cutting parameters along with the input parameters, such as drill- bit geomentry, spindle speed and rate of feed. Further, a drill with standard twist is used for drilling operation. The results show that with the increase in thrust force, feed rate increases and cutting speed experiences decrease when drill diameter is increased. The SEM analysis is also done to reveal about various damages, like fibre pullout, peel off, uncut fibres and voids.

Keywords : Box-Behnken, Cotton, Drilling, Fibre reinforced composite, Natural fibre, Thrust force

1 Introduction

The demand for composites increases in many fields like automotive, railways, aviation industries, etc. Natural fibre reinforced (NFR) composites are the emerging potential substitutes for synthetic fibre reinforced composites because of their unique qualities. NFR composites are recommended, as they are eco-friendly in nature combined with easy disposability and wide availability in the world[1]. A composite structure made of a single part is not practically possible in all the applications. In many applications, composite structures are assembled by means of joining many parts using rivets or temporary fasteners. The strength of the assembly depends more on the strength of joints. Therefore, the design of joints is the primary field in this research. Conventional drilling has become the most common hole making process. Composites are difficult to drill as they have heterogeneity, low thermal conductivity, anisotropy and heat sensitivity of the specimen[2]. Mechanical properties are affected based on the measure of damage to the hole. The quality of the holes is affected by some of the geometrical properties of the cross section of the hole, namely roughness, waviness, straightness, roundness etc. Such condition may cause internal stress within the joints, and this results in premature failure of the structure[3]. Delaminating, micro cracking and stress concentration are the chief damages associated with the drilled holes which lower the performance of the joint[4]. Vijayaragavan *et al*.[5] reported that as the drilling thrust force increases, the damages for the holes also increase.

There are several factors which affect the magnitude of thrust force, namely drill-bit materials, process parameters and drill-bit geometry. Khashaba[3] studied the consequence of cutting criterion and diameter of drill-bit on the thrust force. Many studies are available on the discontinuous and random oriented fibre reinforced laminates[6]. The random orientation and the discontinuous nature exhibit lower strength and other mechanical properties[7], and make them unfit for high load application. Since discontinuous fibre laminates exhibit lower mechanical properties, continuous fibre laminates exhibit better mechanical properties. Woven fabrics are more continuous and provide better mechanical properties as compared to nonwoven fabric laminates[8]. The cutting criterion and the thickness of the work specimen in drilling of composites laminates were optimized using Taguchi method. Various drilling experiments were performed using HSS drill bits which generate less thrust force and damage, as compared to other drill- bit namely brad and spur as well as multi twist drill-bit[1,9]. Antonio *et al*.[10] have reported appropriate selection of cutting parameter, drill geometry, rate of feed and spindle speed in order to minimize the thrust force and delamination. Seenivasan *et al*.[11] have indicated that the increase in

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drill diameter and rate of feed increase the thrust force. The influence of thrust force was analyzed using BBD and ANOVA, and thus the minimum thrust force is achieved from low feed rate, high spindle speed and low drill diameter. In present study, cotton/ bamboo woven fabric reinforced composite is subjected to drilling operation. Thrust force has been analyzed for different combinations of feed rate, cutting speed and drill geometries and finally, optimum cutting parameters are identified in order to get minimum thrust force and the machining criterion to be associated with response surface methodology (RSM). BBD is used to control the experiment. 3D Graphs and effect graphs are used to analyse the results. After drilling, the surface is analysed with the help of scanning electron microscope.

2 Materials and Methods

2.1 Preparation of Cotton/ Bamboo Woven Fabric

In this study, cotton / bamboo fabric (164 g/m^2 fabric weight, 69 ends/in and 54 picks/in) was produced with cotton yarn packed in warp direction and bamboo yarn in weft direction. Epoxy resin was used as matrix material (Araldite LY556) and HY 951 hardener. The weight ratio of epoxy and hardener was 10:1 as recommended.

2.2 Composite Fabrication

The composite was fabricated using compression moulding method. The mould release agent (wax) was first applied on the inner surface of a three piece chromium plated tool steel mould having dimensions 270 mm × 270 mm × 3 mm. The mould was later closed and the setup was allowed to cure for a time period of 1 hour at 80°C under a load of 1500 PSI pressure in a compression moulding machine. The composite laminates were fabricated with a constant 45 % weight fraction.

2.3 Drilling Scheme

The experimental details of drilling process parameters were : spindle speed (N) 1000-3000 rpm, diameter of drill bit (D) 6,9,12 mm, and rate of feed (F) 20,40,60 mm/min**.** The drilling operation was conducted using computer control vertical machining center (Karunya University, Coimbatore). The cutting force was calculated with the help of Kistler-9257B four component piezoelectric dynamometer and mounted tool holder type 9403 was used to clamp the composite laminate. The piezoelectric drill dynamometer is coupled in a charge amplifier 5070-Kristler connected to a computer for data processing. In this type of dynamometer , maximum range was maintained at 10kN. The experimental setup is shown in Fig. 1

2.4 Observation on Drilling Force Signals

In this investigation, thrust force signals were observed by drill dynamometer with the help of data acquisition system. Figure 2 has thrust force signals for solid twist drill geometry. It has been noticed from the obtained signals that there are three major different phases in drilling process. When tool touched the composite laminate a sharp increase of thrust force was noted, as shown in Fig. 2 [phase 1 (a)]. Phase 2 (b) in Fig. 2 shows that cutting force is constant. The actual machining action can be observed when drill bit is completely engaged with composite laminate. In phase 3 (c) of Fig. 2 the drill-bit exits the composite laminate and drilling signals start decreasing and eventually reached zero because the drill-bit fully exits after complete drilling operation[12].

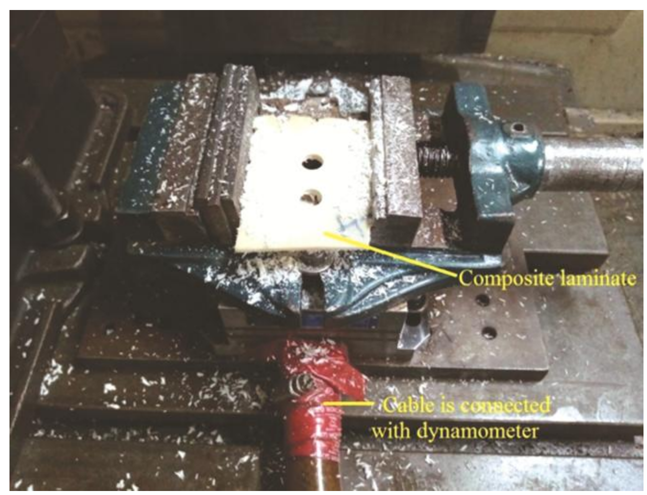

Fig. 1 — Drilling of composite laminate

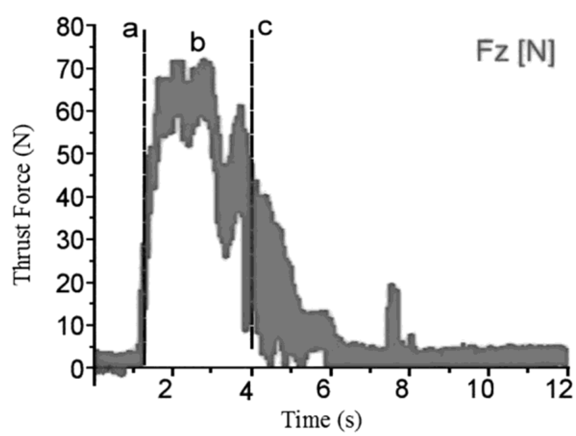

Fig. 2 — Typical thrust force signal with twist drill (1800 rpm and 60 mm/min)

Solid twist drills have the similar material replacement system. The entire drill bit completely engages with the laminate at the middle of the drilling operation such that an indenation was formed. The long/short chips are produced because of the material removal from the laminate. The size and the geometry of the chips mainly depend upon the drilling parameters.

2.5 RS Model for Cotton / Bamboo Woven Fabric Composite

Response surface methodology consists of statistical modeling of experiment to establish approximate relationship that exists between the input and the output variables and also optimization of technique to find the level of experiment. They also quantity the relationship between measured responses and input parameters. In RSM, first the limit of the experimental domain needs to be explored. The rate of feed, the spindle speed and the drill diameter remained as the process parameter variables selected for this investigation, and further more BBD was used for planning to accomplish the experiments. The most significant statistical analysis used in the design of experiments is BBD, which is an alternative method to central composite design. Experiments containing factors at three levels are analysed using this method. The BBD is rotatable and it is reported that this has no fractional factorial design and it is easier to interpret with the result[13]. Following equation suggests relationship between the response and the variables[14]:

$$F_{th} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots + \beta_i x_i + \ldots\ldots. + \in \quad \ldots (1)$$

where

F_{th} = Thrust force,

$\beta_0\, \beta_1, \beta_2 \ldots\ldots \beta_i$ = Coefficients,

$x_1, x_2, \ldots\ldots x_i$ = Predictor variables,

$\in$ = Error of the model

Using response surface methodology, quardratic response activities can be calculated from equation :

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_1 + \sum_{i=1}^{k} \beta_{ii}\, x_i^2 + \sum_{i<j}^{k} \beta_{ij} x_i x_j + \in \quad \ldots (2)$$

The equation model contains square, interaction and linear effects. The quadratic relation is newly developed for thrust force to obtain accurate process parameter for drilling operation by considering the input variables. The thrust force model is

$$\text{Thrust force} = +47.98875+1.80142d-0.770088 f-0.012145\, N +0.103500d * f+0.000210d* N -0.000078f * N -0.195333d^2 + 0.013543f^2 + 3.62361E\text{-}06\, N^2$$

where d denotes diameter of drill-bit; f , the feed; and N , the Spindle speed. Table 1 presents Box –Behnken (BB) experimental design with the experimental results.

3 Results and Discussion

3.1 Analysis of Variance

The analysis of variance (Table 2) shows statistical analysis of drilling parameters. The experimental result was calculated at the level of 95%. The P-value lower than 0.05 suggests that the thrust force mode is significant. The F value for the ―lake of the fit" model is 5.83 which shows that the model is not significant and this proves that the suggested models fit well[15]. The R^2 value for coefficient of determination model is found 0.9956. Thus, it shows that the experimental data for the thrust force model is fit and satisfied. It is noted from Table 1 that the diameter and rate of feed for the model are significant.

Figure 3(a) gives the uniformity acceptance[16,17] in the development of thrust force model related with the internally stuentized residual. Further, the collected data from the model are spreading in a linear fashion, thus confirming the efficiency of the developed model. The relationship between the actual thrust force and the predicted thrust force is shown in Fig. 3 (b). The results indicate that the observed values

Table 1 — Box Behnken experimental design with the experimental result

Expt No.	Work order	Diameter of drill bit, mm	Rate feed mm/min	Cutting speed rpm	Thrust force, N
1	2	6	20	1800	45.21
2	16	12	20	1800	49.04
3	11	6	60	1800	74.23
4	12	12	60	1800	102.9
5	14	6	40	1200	55.21
6	10	12	40	1200	71.84
7	7	6	40	2400	54.87
8	4	12	40	2400	73.01
9	15	9	20	1200	47.09
10	1	9	60	1200	95.91
11	8	9	20	2400	47.77
12	17	9	60	2400	92.86
13	3	9	40	1800	65.61
14	13	9	40	1800	63.55
15	9	9	40	1800	63.14
16	5	9	40	1800	63.89
17	6	9	40	1800	64.74

Table 2 — Analysis of variance for thrust force factor in drilling of cotton / bamboo woven fabric composite

Source	Sum of squares	DF	Mean square	F value	Prob > F
Model	4773.44	9	530.38	176.35	< 0.0001 *
D	565.66	1	565.66	188.08	< 0.0001
F	3906.84	1	3906.84	1299.02	< 0.0001
N	0.2964	1	0.2964	0.0986	0.7627
d^2	154.26	1	154.26	51.29	0.0002
f^2	0.5700	1	0.5700	0.1895	0.6764
N^2	3.48	1	3.48	1.16	0.3179
Df	13.01	1	13.01	4.33	0.0761
dN	123.55	1	123.55	41.08	0.0004
fN	7.17	1	7.17	2.38	0.1666
Residual	21.05	7	3.01		
Lack of fit	17.13	3	5.71	5.83	0.0608 **
Pure error	3.92	4	0.9802		
Cor total	4794.49	16			
Std. Dev.	1.73		R^2	0.9956	
Mean	66.52		Adjusted R^2	0.9900	
C.V. %	2.61		Predicted R^2	0.9416	
			Adeq precision	45.8730	

* Significant, ** not significant.

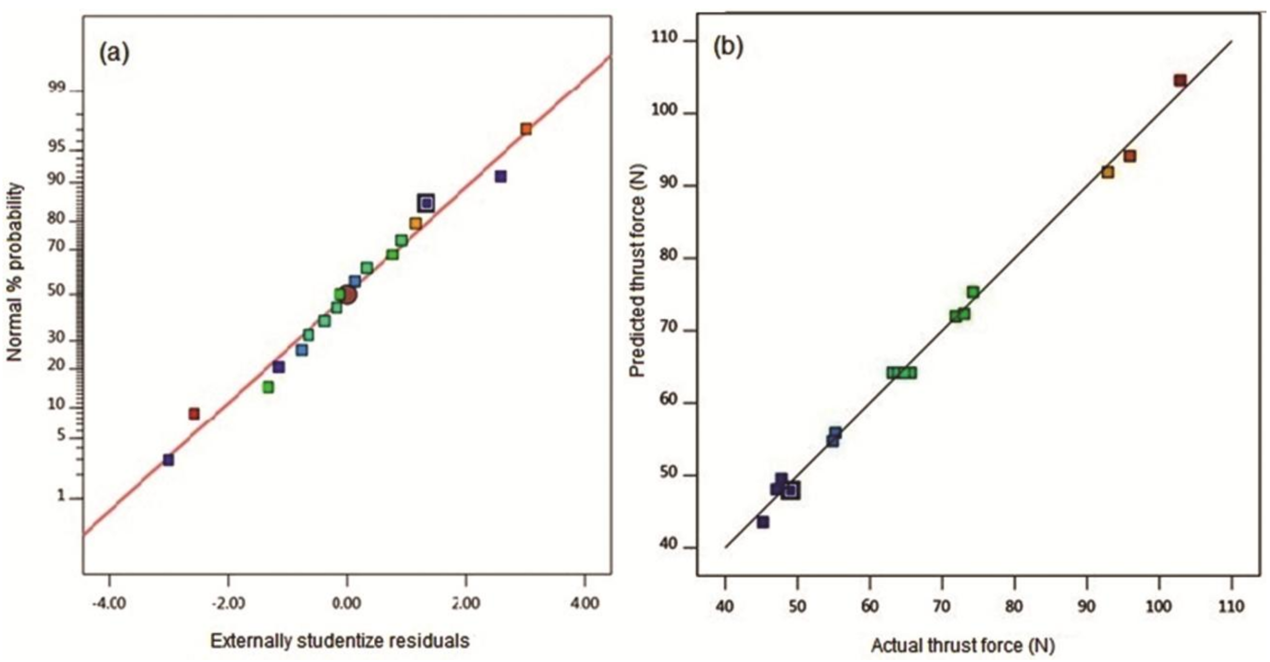

Fig. 3 — Normal probability of residuals (a) and predicated thrust force (b) in drilling of cotton / bamboo woven fabric composite

closely match with the experimental relationships developed and the thrust force is easily predicted.

The development of thrust force in drilling polymer matrix composite laminates is shown in graphical representation. The effect of the diameter of the drill-bit to the thrust force is given in Fig. 4 (a). The results show that whenever there is increase in drill diameter, the thrust force also gets increased[18]. Because of the increase in drill diameter, the contact area between drill bit and laminates is more and hence there is increase in heat generation and thrust force. The effect of feed rate on the thrust force is shown in Fig.4 (b) which indicates that whenever feed rate increases, thrust force also shows increase [19]. As the drill diameter (*D*) and the feed (*F*) increase, the thrust force also experiences increase because of increase in cross- section area (*A*) due to under formed chip area (*A*=*D F*/4). Therefore, the axial thrust is enhanced due to resistance of chip developed[20]. Figure 4 (c) presents that when the cutting speed steadily increases the thrust force gets slightly decreased and because of the high spindle speed, the chip formation is softening which minimizes the material heat. The thrust force also has increased and this research observes that at equal operating environment, feed rate and cutting speed show minimal changes, whereas thrust force gets changed at equal operation environmental condition[21].

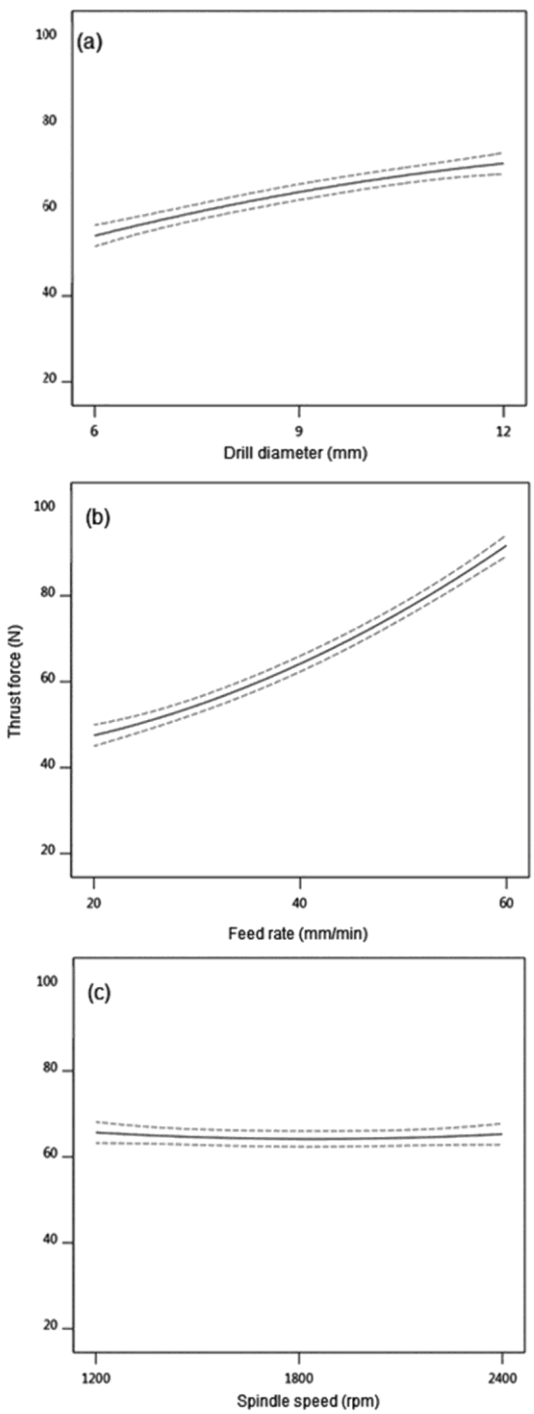

Fig. 4 — Effect of thrust force with respect to various cutting parameters :(a) diameter of drill bit *vs* thrust force, (b) rate of feed *vs* thrust force, and (c) cutting speed *vs* thrust force

While drilling of cotton\bamboo reinforced polymer composite laminate, BBD model observed the thrust force through various 3D response surface plots. Figure 5 shows the interactions effect of the rate of feed and the cutting speed on the thrust force with 3 different types of drill diameter. The figure also shows that the rate of feed increases the thrust force in drilling. Generally, it is observed that the thrust force is generated because of improper parameters, namely rate of feed, spindle speed and shape of drill. While drilling, the drill bit has movement opposite to the workplate and experiences a compressive thrust force on the workplate. In the process of their compressive force, the composite plate gets pierced and removed from the interfacial bond around the hole.

Three dimensional response graphs are used to analyse the parameters and the interaction between the effect of thrust force. In this method, there are three parameters, but two are varying and third parameter is constant. From Fig. 5 (a), it is noted that the thrust force in the drilling of composite laminate increases when the rate of feed and the diameter of drill rise. Figures 6 (b) and (c) show increase in the diameter of drill, the cutting speed and the thrust force. The machining criterion like diameter of drill-bit and rate of feed are mainly influencing the thrust force of composite material. The rate of feed which affects the thrust force is also noted. From the above observation, it is clearly evident that the poor selection of cutting parameter increases the thrust force but proper machining criterion minimizes the thrust force of the composite material.

Figure 6 (a) shows the micrograph of the drilled hole produced at a lower feed rate of 20 mm/min, drill-bit diameter of 6 mm and highest cutting speed of 2400 rpm. Further, it is observed that the drilled hole experiences less fibre pullout, torn fibre , microcrake etc. The fibre pullout is lower. Because of lower rate of feed, the thrust force is minimum and hence the drill bit does not damage the composite. Figure 6 (b) shows that the surface of the drilled hole produced at higher feed rate of 60 mm/min, higher drill diameter of 12 mm and lower cutting speed of 1200 rpm is more damaged. The damage occurs as a result of increased thrust force and there is broken fibre because of the internal adhesive

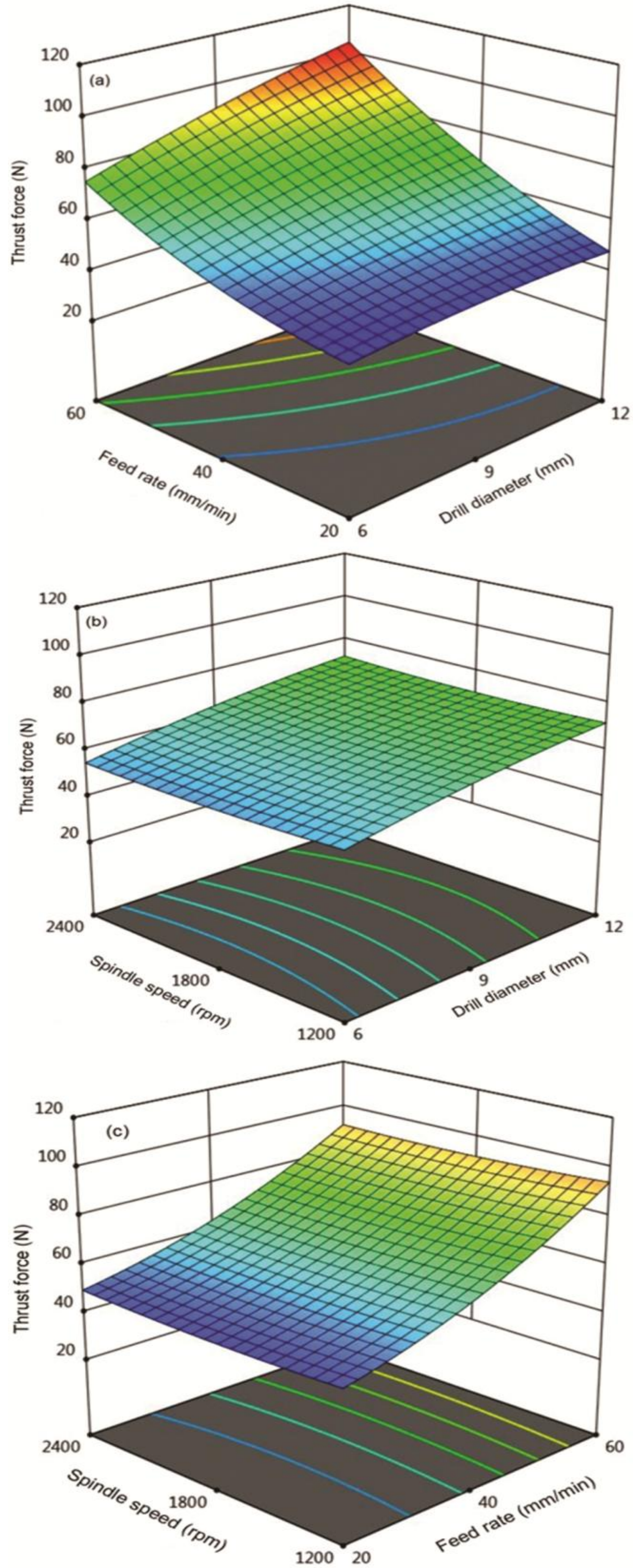

Fig. 5 — Influence of (a) drill diameter & rate of feed, (b) drill diameter & cutting speed and (c) feed rate & cutting speed thrust force in drilling of cotton / bamboo woven fabric composite

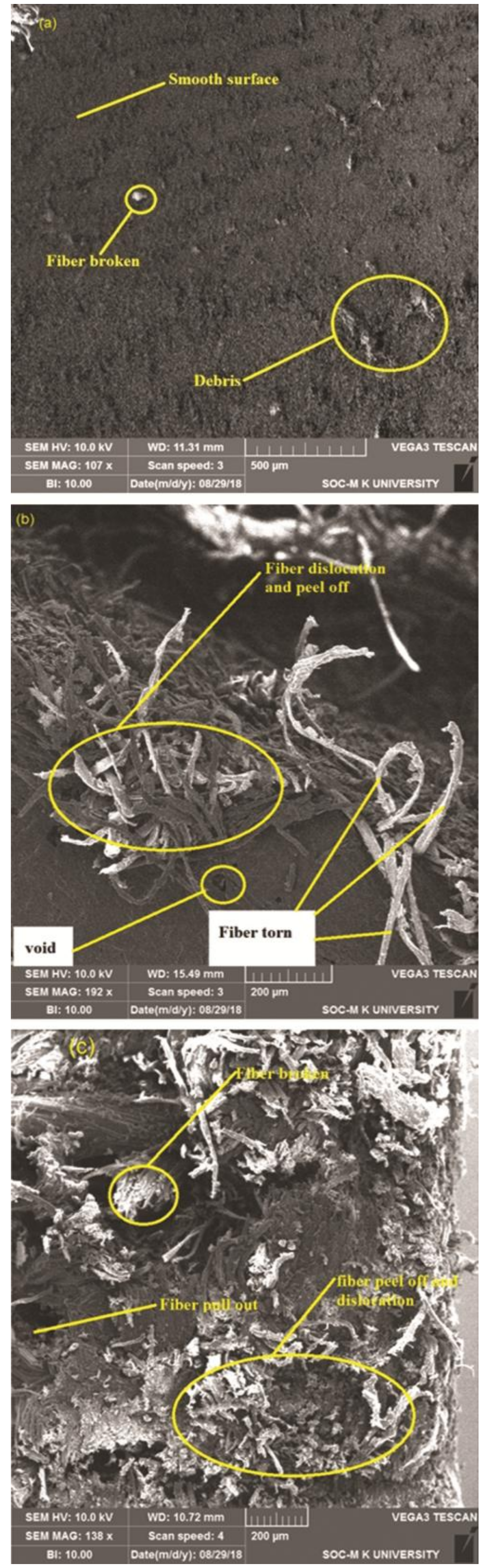

Fig. 6 — SEM images of the drilled holes (a) low feed rare at High speed, (b) High feed rate at low speed, and (c) median feed rate at median speed

bonding between the fibre and the matrix. From Fig. 6 (c), it is found that the damage is less when feed rate is 40mm/min with 9mm diameter of drill and 1800 rpm cutting speed. Observation shows that the less damage is evident at moderate condition, owing to less thrust force.

4 Conclusion

In the present study, woven cotton/ bamboo fabric laminates have been developed. The effect of drilling nature of composite laminate is investigated at various drilling process parameters. 3D graphs have been used to analyse the thrust force and the cutting parameters in drilling of composite laminate.

4.1 The result indicates that with the increase in drill diameter and feed rate the thrust force also gets increased. However, when the cutting speed increases, the thrust force gets slightly decreased in the drilling of composite laminates.

4.2 The thrust force increase depends on variation in diameter of drill-bit and rate of feed but due to increase in spindle speed of the spindle, thrust force does not have any fluctuation.

4.3 An experimental regression is developed for predicting the thrust force. From the outcome , the model is proved suitable for finding the thrust force on composite material. It is found that cutting speed 2400 rpm , drill diameter of 6mm and feed rate 20 mm/min are suitable for cotton /bamboo composite.

4.4 The thrust force is low when the diameter of drill-bit is minimum, with maximum cutting speed and minimum rate of feed.

4.5 The thickness of the composite laminates plays important role in the development of thrust force.

4.6 The SEM image of the drilled holes of cotton / bamboo composites shows, fibre and matrix debonding, fibre broken, fibre pullout, fibre dislocation, void and surface roughness in the holes.

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