The Effect of Drilling Parameters on the Hole Quality of Hybrid Fiber-Reinforced Epoxy Composite

V. Santhanam, S. Sendhilkumar, N. Venkateshwaran, and M. Chandrasekaran

Abstract In this work, hybrid fiber-reinforced epoxy composite had been developed by using woven banana fiber and woven glass fiber as reinforcements. Laminated composite sample was developed by using hand layup method. Glass fiber was kept as top layer, and banana fiber was kept as bottom layer with the arrangement of G-B-G-B. Drilling is one of the most common and critical machining operations during the assembly operation in manufacturing. In this work, the effect of drilling parameters on the quality of the hole and delamination was studied. Three different drill speeds and feed rates were used in this study. The machining was done by using a twist drill of diameter 8 mm, and the drilling was performed at the speeds of 700, 1400 and 2100 rpm. The feed rate was kept at 0.05, 0.12 and 0.20 mm/rev. The drilled holes were scanned in a high-resolution scanner, and digital image processing was further used to compute the hole dimensions. The details of the pixel values at the entry and exit were measured digitally, and subsequently, the pixel values were used to determine the extent of damage occurred due to the drilling operation. A two-dimensional array of hole dimension with respect to the feed rate and speed was obtained from the experimental results. Finally, ANOVA technique was used to determine the most influencing drilling parameter to get better hole quality. The experimental results indicated that the damage due to machining was greater at the exit than the damage at the entry. Also, ANOVA technique showed that the drilled hole quality depends on the drilling speed and feed rate, but the feed rate is the most significant parameter than the cutting speed.

Keywords Composite drilling · Hybrid fiber-reinforced composite · Banana fiber · Glass fiber · ANOVA technique

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1 Introduction

Nowadays, the demand for the multifunctional materials is becoming prime importance in automotive applications. The main task is to develop high-performance, low-cost and low-density materials with better strength and modulus along with good thermal characteristics. This diverse and contradictory requirement for the automotive materials has brought the very complex problem of developing new types of polymer composites materials. Polymer composite materials had been increasingly used in several applications due to their advantages such as low weight to strength ratio, better wear properties, ease of manufacturing, and the properties can be easily tailor-made as per the requirements of the application. Due to the increasing environmental concerns and carbon emission regulations, recently the focus is on the use of natural fibers as a successful reinforcement in place of synthetic fibers such as glass fiber, carbon fiber and Kevlar fiber. But the natural fibers are hydrophilic, and the mechanical properties of the plant fibers are inferior to that of the synthetic fibers. Hence, attempts are being made to develop the hybrid fiber-reinforced polymer composites where both the natural fiber and synthetic fiber are used as the reinforcement to get the advantage of both the fibers. Hybridization [1] is one of the effective means of achieving desired properties of laminated composite by combining two or more types of fiber or matrix. Also, the hybridization suppresses the weakness of the constituents due to the addition of better material in it, and thereby, the compensation of properties also occurs [2]. By developing such versatile materials, the machining of the material becomes difficult to accommodate this development. Of the various available secondary process of machining the composite materials, drilling is most widely used during the assembly process. The quality of drilled holes in composite materials involves the parameters like feed rate, speed, drill wear and drill geometry. The machinability parameters include torque, thrust force, residual strength, surface roughness and damages associated.

Problems such as delamination, hole quality and excessive tool wear are frequently encountered during the drilling process of the polymer composite materials. The delamination in composite material is a significant factor as it affects the structural strength, poor assembly tolerance and micro-cracking of the components during the usage [3]. The effect of drilling parameters on the tool wear and delamination of glass fiber composite was investigated by Prakash et al. [4] with the help of vibration signal. The time domain and frequency domain analysis was carried out to determine the optimum drilling parameters, and from the experimental results, it was found that the frequency domain analysis predicted better results than the time domain analysis. The results showed that the machining speed of 951 rpm and feed rate of 1 mm/s produced the lowest delamination factor. Sumesh et al. [5] developed composite materials based on pineapple and flax fibers, and cellulose microfiber was used as filler material. Research on machinability of hybrid composite was carried out, and it was shown that the addition of filler up to 3% resulted in better machinability. Various kinds of fillers such as carbon black, coconut shell powder, fly ash and nano alumina were used as secondary reinforcement. The effect of boron nitride particle on the machinability of carbon fiber epoxy composite was carried out by Burak Kaybal et al. [6], and it was observed that the delamination factor decreased with the addition of filler. The majority of studies agree that there is a good correlation between the thrust force and the delamination. Bosco et al. [7] analyzed the influence of machining parameters on thrust force in drilling GFRP-armor steel sandwich composite and showed that the thrust force required is higher for the bottom panel due to the heat generation after drilling the armor steel composite. Rajamurugan et al. [8] studied the drilling performance of the aluminum foil reinforced sisal/flax epoxy composite. The experimental results revealed that the hole pitch and spindle speed greatly affected the circularity of drilled hole. Anand et al. [9] optimized the drilling parameters using Taguchi orthogonal array and grey relational algorithm of Ni-P coated glass fiber and aluminum oxide nano wire hybrid composite. Bukhari et al. [10] studied the influence of drilling parameters of hybrid composite and the influence of stacking sequence on the drilled hole quality. Tran et al. [11] investigated the thrust force and particle generation of drilling the miscanthus fiber with biochar and polypropylene composite. The experiments showed that the feed rate and drill tool diameter had significant effect on the fine and ultra-fine particle emission. Jaganatha et al. [12] analyzed the thrust force and delamination of glass fiber–carbon fiber epoxy composite. From the literature, it was found that the drilling of FRP composites has several undesirable effects such as spalling [13], edge chipping [14], macroscopic pitting [15], fiber breakage, debonding [16], fiber pullout [17], crack formation [18], thermal damage [19], fuzzing [20], stress concentration [21] and matrix crazing along with delamination [22]. From the literature, it was evident that most of the studies on the machining of composite materials were carried out to determine the drilling parameters and drilled hole quality. The effect of fiber loading and drilling parameters on the thrust force, delamination were studied by several researchers. The effect of drilling parameters on the hybrid fiber-reinforced composite and the measurement of hole quality using machine vision technique was not widely reported. Hence, in this work, the effect of drilling parameters on the drilled hole quality of the hybrid fiber-reinforced epoxy was analyzed using machine vision technique.

2 Materials and Methods

Banana fiber was used as the natural reinforcement in this work; processed banana fiber was purchased from Rope International Pvt Ltd., Chennai, India. The properties of banana fiber are better than most of the cellulosic fiber available in nature. It has an approximate tensile strength of 600 MPa and modulus of 17.85 GPa. The density of the fiber was estimated as 1.35 gm/cm^3. The banana fiber was dried under the sun to remove any residual water content from the fiber. E-Glass fiber was used as synthetic fiber reinforcement in this work, which is procured from Sakthi Fibers, Chennai. It has a density of 2.55 gm/cm^3, and the tensile strength is 2400 MPa. The glass fiber was mixed with the banana fiber in equal amounts to prepare the hybrid reinforcement. Epoxy resin was used as the matrix material in this work, which is procured from Sakthi fibers, Chennai. Hybrid fiber composites were fabricated by using hand layup method. A wooden mold of 300 mm × 300 mm was used for fabricating the specimens. Woven fiber arrangement had been used for the purpose. Composites were prepared by using the G-B-G-B arrangement of the woven mats. Figures 1 and 2 show the woven mats of glass fiber and banana fiber used in this study and the composite specimen used for machining operation.

Fig. 1 Woven banana fiber and woven glass fiber mats

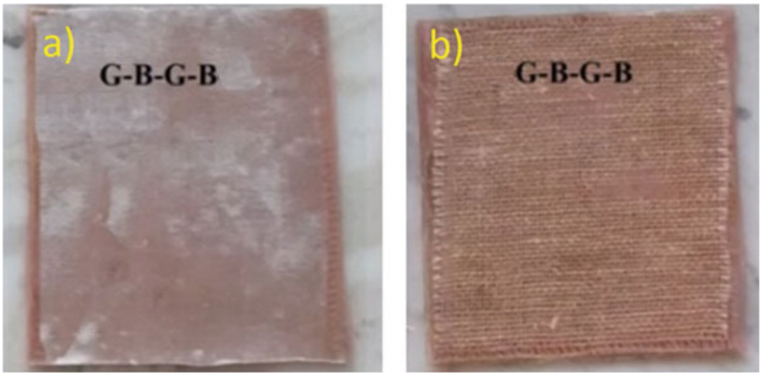

Fig. 2 Top side (**a**) and bottom side (**b**) of the banana–glass fiber-reinforced hybrid composite specimen

2.1 *Experimental*

The drilling operation was performed by using MTAB-DENFORD CNC machine which is shown in Fig. 3. A Single point HSS standard twist drill of 8 mm diameter was used as the drilling tool. The drilling operation was performed at 700, 1400 and 2100 rpm speeds. Considering the diameter of the drill tool, the tangential velocity of the operation was kept between 20 and 60 m/min. The feed rate was varied as 0.05, 0.12 and 0.20 mm/rev. The specimen size of 30 mm × 30 mm was used for the study. The quality of the drilled holes was assessed by using the delamination factor. Machine vision technique was used to measure the hole quality which is shown in Fig. 4. The ratio between the nominal diameter (D) of the hole to the largest diameter (D_{max}) of the delamination zone will give delamination factor (F_d) as shown in Fig. 5.

3 Results and Discussion

The drilled hole size at the entry and exit was determined by measuring the pixel value using the machine vision technique. Tables 1 and 2 present the pixel values at the entry (top side) and at the exit (bottom side) of the drilled holes. It can be observed from the tables that the hole size is marginally higher at high feed rate, indicating

Fig. 3 Drilling machine used in this study

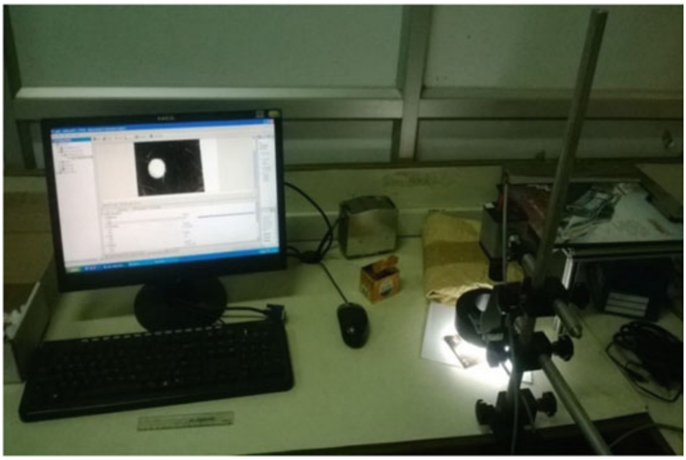

Fig. 4 Hole quality analysis using machine vision setup

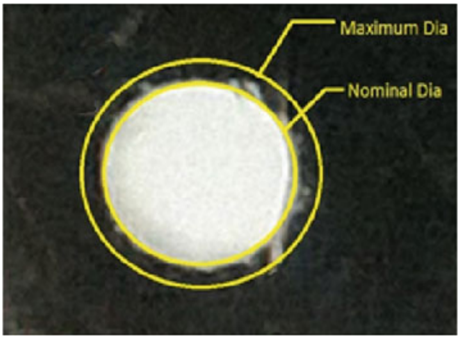

Fig. 5 Digital image processing of drilled hole

Table 1 Pixel values and equivalent hole dimension at entry

Top side												
Feed (mm/rev)	0.20				0.12				0.05			
Speed (RPM)	Pixel	mm	Pixel	mm	Pixel	mm	Pixel	mm	Pixel	mm	Pixel	mm
2100	589	10.91	595	11.02	560	10.37	554	10.26	473	8.76	468	8.67
1400	599	11.09	593	10.98	542	10.03	547	10.13	465	8.6	460	8.52
700	597	11.06	603	11.18	538	9.97	533	9.87	482	8.92	477	8.84

Table 2 Pixel values and equivalent hole dimension at exit

Bottom side												
Feed (mm/rev)	0.20				0.12				0.05			
Speed (RPM)	Pixel	mm	Pixel	mm	Pixel	mm	Pixel	mm	Pixel	mm	Pixel	mm
700	681	12.62	675	12.5	610	11.3	616	11.42	547	10.13	542	10.03
1400	656	12.14	649	12.02	612	11.33	606	11.22	533	9.87	538	9.97
2100	643	11.9	636	11.78	593	10.99	599	11.1	530	9.81	524	9.71

more damage in the drilled hole. The average values of the delamination factor are presented in Tables 3 and 4, respectively, for at the entry and exit of the drilled holes. It is noted from the tables that the maximum value of delamination factor was

Table 3 Entry delamination factor for hybrid fiber composite sample

Fiber arrangement in the composite	Speed (rpm)	Feed rate (mm/rev)	Delamination factor at entry
G-B-G-B	2100	0.20	1.37
	2100	0.12	1.29
	2100	0.05	1.09
	1400	0.20	1.38
	1400	0.12	1.26
	1400	0.05	1.07
	700	0.20	1.39
	700	0.12	1.24
	700	0.05	1.11

Table 4 Exit delamination factor for hybrid fiber composite sample

Fiber arrangement in the composite	Speed (rpm)	Feed rate (mm/rev)	Delamination factor at exit
G-B-G-B	2100	0.20	1.48
	2100	0.12	1.38
	2100	0.05	1.22
	1400	0.20	1.51
	1400	0.12	1.41
	1400	0.05	1.24
	700	0.20	1.57
	700	0.12	1.42
	700	0.05	1.26

observed for the feed rate of 0.20 mm/rev. A maximum value of delamination factor was obtained as 1.39 for entry (top side) and 1.57 at exit (bottom side). The top layer is subjected to compression at the entry of the drilling tool, and hence, less damage is observed; whereas, the bottom layer is subjected to tensile stress during the exit of the drilling tool, and hence, the damage and delamination can easily occur at the bottom. It is because of this reason; woven banana mat is placed at the bottom of the specimen. Since banana fiber has relatively lesser tensile strength than glass fiber mat, the delamination due to the damage of the banana fiber mat is lesser than that of the glass fiber mat.

The effect of drilling speed and feed rate on the entry and exit hole quality is presented in Figs. 6 and 7, respectively. It was observed from the figures that the delamination factor was largely affected by the feed rate rather than the drilling speed.

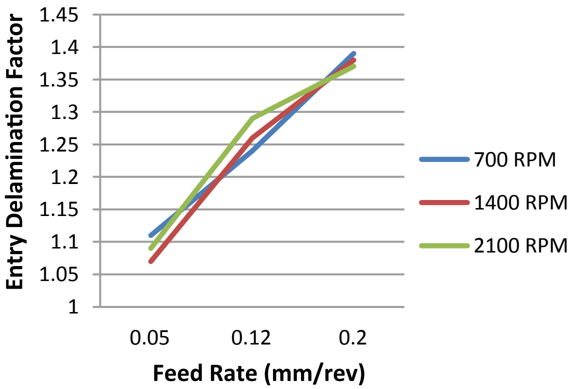

Fig. 6 Effect of feed rate and drilling speed on entry delamination

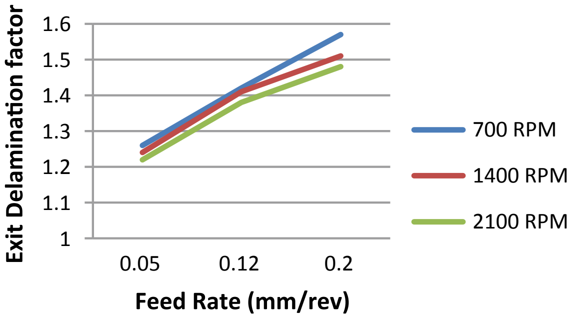

Fig. 7 Effect of feed rate and drilling speed on exit delamination

3.1 ANOVA Analysis

Analysis of variance technique was used to determine the most influential machining parameter for the drilled hole quality. The analysis was carried out by considering two factors (drilling speed and feed rate) with three variables for each factor. Minitab 6.0 software was used for the purpose of analysis. The ANOVA results are presented in Tables 5 and 6, respectively, for the entry and exit delamination. It was noted from the table that the '*p*' value is less than 0.05 at 95% confidence level for the feed rate, indicating that the feed rate has higher significant effect on the hole quality than the other parameters. It was also observed that the value of '*p*' is less than 0.05 for the drill speed at the exit indicating that both the speed and feed rate influence the exit delamination factor.

Regression equations were developed based on the experimental values of entry and exit delamination. These equations can be further used to predict the delamination factor for any value of feed rate and drill speed. Tables 7 and 8 show the values predicted by the regression equation and the values obtained experimentally for the entry and exit delamination. The error between the actual values and predicted values is also presented in Tables 7 and 8 for entry and exit delamination, respectively. The regression models showed an error of 3.96% and 1.97%, respectively, for the entry and

Table 5 ANOVA for entry delamination for woven fiber composite

Source	DF	Adj SS	Adj MS	*F*-value	*P*-value
Speed (rpm)	2	0.0002896	0.0001446	0.291	0.7611
Feed rate (mm/rev)	2	0.1277565	0.0638785	129.191	0.0000
Error	4	0.0019785	0.0004934		
Total	8	0.1300226			

Model summary

S	R-sq	R-sq(adj)	R-sq(pred)	
0.02223613	98.4	96.9%	92.3%	

Table 6 ANOVA for exit delamination for woven fiber composite

Source	DF	Adj SS	Adj MS	*F*-value	*P*-value
Speed (rpm)	2	0.0048221	0.0024111	9.232	0.0324
Feed rate (mm/rev)	2	0.1186893	0.0593442	227.283	0.0000
Error	4	0.0010442	0.0002613		
Total	8	0.1245564			

Model summary

S	R-sq	R-sq(adj)	R-sq(pred)	
0.0161587	99.2%	98.3%	95.7%	

Table 7 Comparison between experimental and regression model results at entry

Speed (rpm)	Feed rate (mm/rev)	Regression model F_d (entry)	Experimental F_d (entry)	Error (%)
2100	0.20	1.39	1.37	−1.66
2100	0.12	1.24	1.29	3.96
2100	0.05	1.10	1.09	−1.32
1400	0.20	1.39	1.38	−0.82
1400	0.12	1.24	1.26	1.78
1400	0.05	1.10	1.07	−3.08
700	0.20	1.39	1.39	0.00
700	0.12	1.24	1.24	0.00
700	0.05	1.10	1.11	0.76

Table 8 Comparison between experimental and regression model results at exit

Speed (rpm)	Feed rate (mm/rev)	Regression model F_d (exit)	Experimental F_d (exit)	Error (%)
2100	0.20	1.50	1.48	−1.54
2100	0.12	1.35	1.38	1.87
2100	0.05	1.22	1.22	0.00
1400	0.20	1.53	1.51	−1.38
1400	0.12	1.38	1.41	1.97
1400	0.05	1.25	1.24	−0.99
700	0.20	1.56	1.57	0.71
700	0.12	1.41	1.42	0.69
700	0.05	1.28	1.26	−1.61

exit delamination of the drilled holes. The negative error means that the delamination factor predicted by the regression model is higher than the experimental value.

This shows that the regression models given by Eqs. (1) and (2) had been able to predict the delamination factor with reasonable degree of accuracy.

Entry delamination = 1.00411 + 0.0000021*Speed (rpm) + 1.9222*Feed rate (mm/rev) (1)

Exit delamination = 1.21539 – 0.0000402*Speed (rpm) + 1.8569*Feed rate (mm/rev) (2)

4 Conclusion

Banana–glass hybrid fiber-reinforced composites were developed, and the drilling behavior of the composite was studied using the machine vision technique in this experiment. The effect of drilling speed and feed rate was analyzed to assess the most influencing parameter. ANOVA technique had used for the analysis. The following conclusions were drawn from the experiment.

- The delamination factor increases with both the cutting parameters (velocity and feed rate), which means that the composite damage is bigger for higher cutting speed and higher feed.
- Feed rate had been the most influencing parameter than the cutting speed which is validated by ANOVA technique.
- The delamination factor predicted by regression models was in good correlation with the experimental ones. The maximum error in prediction of entry delamination is 3.96%, and exit delamination is 1.97%.

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