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Novel Approach on Characterization of Inter-laminar Failure in Glass Fiber Reinforced Composite

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Abstract
Drilling is most widely applied to composite materials; nevertheless, the damage induced by this operation may reduce drastically the component performance. A comparison between the proposed refined delamination factor (F_{DR}) along with the conventional (F_D) and adjusted (F_{DA}) delamination factor is presented. The accuracy of the proposed criteria is validated using experimental results and analysis of variance (ANOVA) approach. It was found that the refined delamination factor works efficiently in the characterization of delamination failure.

Keywords
Composites, delamination, ANOVA

Nomenclature

$\tau_{xz_{max}}$	–	Inter-laminar shear stress
A_0	–	Nominal hole area
A_D	–	Damaged area
A_H	–	Heavily damaged area
A_M	–	Medium damaged area
A_L	–	Light damaged area
A_{max}	–	Maximum damaged area
b	–	Width of the specimen
D_0	–	Drill diameter
D_{max}	–	Maximum diameter
F_D	–	Delamination factor
F_{DA}	–	Adjusted delamination factor
F_{DR}	–	Refined delamination factor
p_{max}	–	Maximum failure load
T	–	Thickness of the specimen

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1. Introduction

Application of composite materials is dominating in the engineering field due to good specific strength, stiffness, fatigue limit, light weight and near net shape production technology available for the processing, moulding and curing of fiber reinforced plastics (FRPs), to achieve the desired tolerances [1]. One of the main difficulties associated with the drilling of composite material is delamination failure. According to Khashaba [2], delamination is mainly responsible for the rejection of approximately 60% of the composite components produced in aircraft industries. When the stress induced in the layers of the laminate during the drilling operation exceeds the inter-laminar strength of the laminate, delamination failure occurs. The influence of factors such as tool geometry and machining parameters on delamination has been studied by several researchers. However, few authors have approached both tool geometry and high speed machining (HSM) when drilling composites, more specifically glass fiber composites. The authors Davim and Reis [3] compared the influence of different drill geometries on the delamination of hand lay-up carbon fiber reinforced plastic (CFRP) laminates. A toolmaker's microscope was used to evaluate the damage as the machining parameters were altered. The delamination factor was considered as the ratio of maximum diameter in the damage zone to the drill diameter. The results indicated that the damage increases with both cutting speed and feed rate. Arul *et al.* [4] induced axial vibrations in the feed direction and studied the influence of the vibration frequency and amplitude when drilling GFRP composites. In order to establish the extent of the defects caused by drilling, specimens were examined using an optical microscope coupled to an image analyzer. Aoyama *et al.* [5] investigated the damage after drilling holes of small diameter in printed wiring boards and concluded that delamination (which leads to ion migration) is generated along with the fiber in the hole wall surface as the surface roughness increases. According to these authors, the thickness of the fiber bundle affects the internal damage of the hole, which increases together with the thickness of the fiber bundle for the same edge position angle. Nonetheless, few works have been conducted using high speed machining (HSM) and obtaining a relationship between the various controllable parameters and their influence on the quality of hole. Owing to the fact that HSM leads to lower cutting forces and energy consumption together with higher removal rates, less damage in the work piece is expected. In order to reduce tool wear when drilling composite materials, Kao [6] investigated the tribological properties of coated drills against glass fiber reinforced epoxy resin. The results indicated that by coating microdrills with 5% MoS_2–Cr, a two-fold increase in tool life was observed compared to uncoated drills. In addition, the quality of the holes was not impaired during high speed drilling at 100 000 rpm. The investigators [7] discussed the performance of HSM drilling of glass/epoxy composite material with minimal damage.

In general, delamination and surface finish in drilling composite materials have been found to be influenced by a number factors, such as feed rate, cutting speed, drill geometry, tool wear and tool material [8–12]. This delamination failure in the drilling operation can exist either at drill bit entry, known as peel-up, or at the exit of the bit, termed as push-out. Out of these two delamination mechanisms associated with drilling of fiber reinforced plastics (FRPs), push-out at the drill exit presents more severe damage. Optical microscopy, scanning and digital photography are the techniques employed to measure the delamination qualitatively. The same can be measured quantitatively as follows [13]. The delamination factor (F_D) may be calculated from the ratio of the maximum diameter (D_{max}) of the delamination zone to the drill diameter (D_0).

$$F_D = \frac{D_{max}}{D_0}. \quad (1)$$

Alternatively, the ratio of the delaminated area to the hole area may also been used. In this case, the adjusted delamination factor (F_{DA}) [13] is calculated from equation (2), in which the first part of equation (2) represents the size of the crack contribution (conventional delamination factor — F_D) and the second part represents the damage area contribution.

$$F_{DA} = F_D + \frac{A_D}{(A_{max} - A_0)}\left(F_D^2 - F_D\right), \quad (2)$$

where A_D is the damage area, A_{max} is the area related to the maximum diameter of the delamination zone (D_{max}) and A_0 is the area of the nominal hole which corresponds to D_0.

Even though delamination is estimated quantitatively by various researchers using either a delamination factor or adjusted delamination factor, in the current work it was observed that the specimen with a lower adjusted delamination factor fails more quickly than the specimens with a higher adjusted delamination factor. This creates the need for a revision in the current form of the adjusted delamination factor. Hence, in the revised form of delamination factor equation, in addition to damage zone size, drill diameter and area corresponding to nominal diameter, importance was given to severity of damages.

2. Experimental Procedure

Drilling experiments were conducted on a CNC machining centre with 5 kW power. The spindle speed range was 200–2500 rpm with a resolution of 1 rpm. The feed range was between 5 and 200 mm/min. The laminates were produced by the hand lay-up technique and were made up of epoxy matrix reinforced with 62% weight of woven glass fiber with a laminate signature of $[0/\pm 45]_5[0/90]_2$. Fourteen layers of glass fiber were used resulting in a laminate 9.57 mm thick. Table 1 shows the mechanical properties of composite material produced used for testing [14].

The composite laminate was fixed on the machining centre using an appropriate clamping device and back plate. Then the laminate was drilled with 10 mm diameter using three different drill bits, namely twist drill, end mill cutter and router and the

Table 1.
Mechanical properties of composite material used for testing

Fiber type	E-glass 21xK43 Gevetex
Matrix type	LY556/DY063 epoxy
Fiber volume fraction, V_f	0.62
Longitudinal modulus, E_{11} (GPa)	34.41
Transverse modulus, E_{22} (GPa)	6.53
In-plane shear modulus, G_{12} (GPa)	3.43
Major Poisson's ratio, ν_{12}	0.217

Figure 1. Various types of drilling cutters of 10 mm diameter: (A) router; (B) end mill cutter; (C) twist drill. This figure is published in color in the online version.

Table 2.
Range of feed rates for a spindle speed of 1000 rpm

Test no.	1	2	3	4	5	6
Spindle speed (rpm)	1000					
Feed rate (mm/min)	25	50	75	100	125	150

details are shown in Fig. 1. Drilling was performed by varying spindle speeds and feeds and Table 2 shows the range of feed rates for a spindle speed of 1000 rpm used in the experimental work. The same set of feed rates was used for different spindle speeds of 1200 and 1400 rpm.

Eighteen holes were drilled for the specified cutting parameters for a single cutting tool of an individual size. The total number of holes needed for various drill bits required for this study was worked out to be fifty-four. In order to account for unforced errors and damages induced during machining operation, three holes with the same parameters were drilled.

3. Results and Discussion

The damage at the push-out was captured qualitatively using a Nikon 300 digital camera with ST 800 flash. The size of the damage zone was measured quantitatively [5, 15–18] using the concept of neural network MATLAB 7.0 software. Using equations (1) and (2), delamination factor (F_D) and adjusted delamination factor (F_{DA}) proposed by various researchers were calculated and this is presented in Table 3.

On the other hand, the drilled specimens were tested by the following tests to confirm and validate the value of F_D and F_{DA}. The American Society for Testing and Materials (ASTM) has proposed two test standards, (a) 3-point bend test (3PT) — (D2344) to measure inter-laminar shear stress of laminated composites subjected to transverse loads, and (b) the modified short beam shear test (MSBS) — (ASTM D790), which is used to estimate the inter-laminar shear stress. Both of these tests offer failure load of the specimen in kN. Using this failure load, the inter-laminar shear stress can be computed using the following equation [19].

$$\tau_{xz_{\max}} = \frac{3p_{\max}}{4bT}, \quad (3)$$

Table 3.
Calculated delamination factor and adjusted delamination factor for holes drilled with 10 mm end mill for different conditions

Speed (rpm)	Feed (mm/min)	Max. length of damage, D_{max} (mm)	Total damage area, A_D (mm^2)	Maximum damage area, A_{max} (mm^2)	F_D	F_{DA}
1000	25	13.5	62.22	143.07	1.350	1.804
	50	15.43	80.50	186.90	1.543	2.166
	75	13.08	61.17	134.30	1.308	1.750
	100	13.81	42.47	149.71	1.381	1.688
	125	12.62	25.82	125.02	1.262	1.446
	150	13.92	69.36	152.11	1.392	1.907
1200	25	13.58	17.20	144.77	1.358	1.484
	50	16.66	53.95	217.88	1.666	2.096
	75	13.75	51.59	148.41	1.375	1.756
	100	14.22	34.62	158.73	1.422	1.681
	125	12.62	40.67	125.02	1.262	1.551
	150	13.87	101.96	151.02	1.387	2.140
1400	25	14.16	62.34	157.40	1.416	1.882
	50	12.61	59.63	124.82	1.261	1.685
	75	14.12	37.81	156.51	1.412	1.694
	100	13.00	52.34	132.67	1.300	1.677
	125	14.07	49.18	155.40	1.407	1.773
	150	13.59	91.05	144.98	1.359	2.027

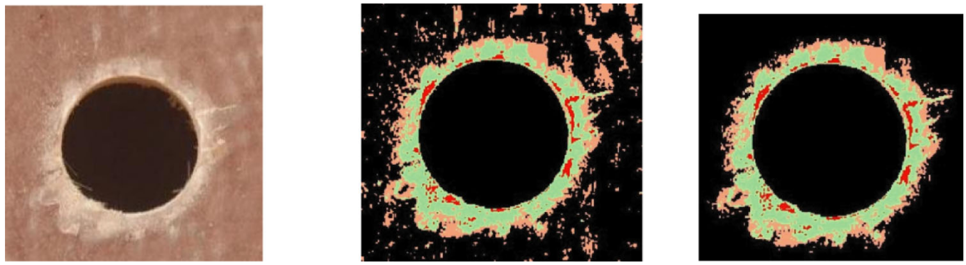
Table 4.
Failure load and inter-laminar shear stress by 3PT and MSBS tests, for holes drilled with 10 mm end mill for different conditions

Test	Parameters	Trial	Failure load (kN)	Inter-laminar shear stress (MPa)
Three-point bend test (3PT)	1000 rpm 25 mm/min feed	1	298.42	352.54
		2	299.67	354.89
		3	296.56	351.99
		Average	298.21	353.14
	1000 rpm 150 mm/min feed	1	373.07	452.61
		2	371.65	453.78
		3	372.48	450.12
		Average	372.40	452.17
Modified short beam shear test (MSBS)	1000 rpm 25 mm/min feed	1	242.49	294.19
		2	243.57	295.95
		3	241.11	292.67
		Average	242.39	294.27
	1000 rpm 150 mm/min feed	1	309.41	375.38
		2	307.84	373.69
		3	308.45	374.92
		Average	308.56	374.66

where p_{max} is the maximum failure load, b is the width of the specimen and T is the thickness of the specimen. The results of both of these tests and the computed inter-laminar shear stress are given in the Table 4.

From the above validation tests, the following observations have been made.

- Average failure load estimated using 3PT for holes drilled with 1000 rpm and 25 mm/min feed rate is 298.21 kN.
- Corresponding inter-laminar shear stress is 353.14 MPa.
- Average failure load estimated using MSBS test is 242.39 kN and corresponding inter-laminar shear stress is 294.27 MPa.
- Average failure load estimated using 3PT for holes drilled with 1000 rpm and 150 mm/min feed rate is 372.40 kN.
- Corresponding inter-laminar shear stress is 452.17 MPa.
- Average failure load estimated using MSBS test is 308.56 kN and corresponding inter-laminar shear stress is 374.66 MPa.
- Holes drilled with 25 mm/min feed rate are more prone to failure than those with 150 mm/min feed rate.



Captured Image

Segregation of pixels depends on its intensity

Final image for measuring of data

Red: Heavily Damaged. Green: Medium Damaged. Light Red: Lightly damaged.

Figure 2. Steps in neural network in MATLAB for the calculation of D_{max} and area of damage. This figure is published in color in the online version.

The test values obtained by 3PT and MSBS tests are not correlated with the values of F_D and F_{DA} obtained through the MATLAB 7.0 software [20], so it is necessary to fine tune the image process, and this has been done using the following method. It is a three-stage process and importance is attached to the depth of damage, which is called severity of damage. Steps involved in the processing of a 10 mm hole made by an end mill cutter for the calculation of maximum length of damage (D_{max}) and area of damage (A_D) using the concept of neural network in MATLAB 7.0 are shown in Fig. 2. Depending upon the depth or severity of damage, the intensity of reflected light from the damaged zone is varied. By capturing this light through machine vision technique and training the image by neural training with the MATLAB 7.0 programme, the affected area is divided into three zones, namely, heavily (A_H), medium (A_M) and lightly (A_L) affected areas. These three zones are colored as follows: heavily affected area by red colour, medium affected area by green colour and lightly affected area by light red colour.

The existing delamination factor and adjusted delamination factor depend on maximum length of damage (D_{max}), maximum damage area (A_{max}) and area of damage zone (A_D), respectively. Various researchers calculate the value of maximum damage area (A_{max}) only by considering the maximum diameter of the delamination zone (D_{max}).

It can be observed from Table 5, that the total area of damage (A_D) for a hole drilled with 25 mm/min feed rate and 1000 rpm (case 1) is 62.22 mm^2, whereas the total area of damage (A_{max}) for hole drilled with 150 mm/min feed rate and for the same speed (case 2) is 69.36 mm^2 only. The magnitude of F_{DA} for the hole mentioned in case 1 is 1.804 and for case 2 it is only 1.907 as indicated in Table 3. Based on the concept proposed in the literature, it can be decided

Table 5.
Split up values of damage area depends on severity and its corresponding refined delamination factor for holes drilled with 10 mm end mill for different conditions

Speed (rpm)	Feed (mm/min)	Max. length of damage, D_{max} (mm)	Total damage area, A_D (mm^2)	Heavily damaged area, A_H (mm^2)	Medium damaged area, A_M (mm^2)	Lightly damaged area, A_L (mm^2)	F_{DR}
1000	25	13.5	62.22	13.03	23.02	26.17	1.709
	50	15.43	80.5	9.37	36.96	34.17	1.917
	75	13.08	61.17	10.36	24.84	25.97	1.616
	100	13.81	42.47	6.30	10.75	25.42	1.539
	125	12.62	25.82	2.44	8.02	15.36	1.325
	150	13.92	69.36	4.92	35.34	29.10	1.650
1200	25	13.58	17.2	11.92	2.78	2.50	1.630
	50	16.66	53.95	13.02	22.2	18.73	2.019
	75	13.75	51.59	6.73	22.2	22.66	1.586
	100	14.22	34.62	4.04	12.66	17.92	1.533
	125	12.62	40.67	2.31	12.06	26.30	1.333
	150	13.87	101.96	6.91	57.29	37.76	1.929
1400	25	14.16	62.34	7.81	20.99	33.54	1.647
	50	12.61	59.63	3.91	23.04	32.68	1.414
	75	14.12	37.81	4.14	12.29	21.38	1.524
	100	13	52.34	2.81	16.72	32.81	1.399
	125	14.07	49.18	4.66	12.01	32.51	1.532
	150	13.59	91.05	5.50	36.36	49.19	1.646

that the hole considered in case 2 is more prone to damage when compared with case 1. When these holes were processed using the concept described earlier, it was observed that the damages were distributed in case 2 when compared with case 1.

Hence, the measurement of total area of damage (A_{max}), which is mainly concentrated around the vicinity of the drilled hole, is not sufficient by itself to quantify the delamination factor because, from both validation tests, it is observed that the holes drilled with 1000 rpm and 25 mm/min feed rate (failure load of 298.21 kN, inter-laminar shear stress of 353.14 MPa by the 3PT test; failure load of 242.39 kN, inter-laminar shear stress of 294.27 MPa by MSBS test) are more prone to failure than the holes drilled with 1000 rpm and 150 mm/min feed rate (with failure load of 372.40 kN, inter-laminar shear stress of 452.17 MPa by 3PT test; failure load of 308.56 kN, inter-laminar shear stress of 374.66 MPa by MSBS test). Hence, it is essential to refine the formula mentioned in equation (2) for the calculation of adjusted delamination factor to correlate with the test values.

This process of refining should include the effect of damage severity. In order to refine the adjusted delamination factor (F_{DA}), in addition to the variables D_{max} and A_{max}, the severity of damage should also be accounted for.

From the Table 5, it can be observed that the heavily damaged area (A_H) for the hole drilled with 25 mm/min feed rate and 1000 rpm is 13.03 mm^2, whereas it is only 4.92 mm^2 for the hole drilled with 150 mm/min feed rate at the same speed. Hence, in the formulation of a refined delamination factor, importance should be given to the severity of damage in addition to the maximum length of damage, total damage area and size of the hole. Keeping these points in mind, it is proposed that the delamination failure can be effectively characterized using Buckingham's π theorem [21, 22].

Buckingham's π theorem states: 'If there are n variables in a physical phenomenon and if these variables contain m fundamental dimensions, then the variables are arranged into $(n - m)$ dimensionless terms'. Each term is called a 'π term'. Accordingly, as discussed earlier, in the expression for delamination factor, due importance should be given to severity of damage in addition to D_{max} and D_0. Here the terms $(\frac{D_{max}}{D_0})$, $(\frac{A_H}{A_0})$, $(\frac{A_M}{A_0})$ and $(\frac{A_L}{A_0})$ were identified as dimensionless π terms. The procedure for the development of the proposed refined delamination factor F_{DR} can be summarized as follows: $F_{DR} = f(D_{max}, D_0, A_0, A_H, A_M, A_L)$. This equation can also be expressed in terms of π terms as $f(\pi_1, \pi_2, \pi_3) = 0$. The π terms are expressed as

$$\pi_1 = \frac{D_{max}}{D_0}.X\left(\frac{A_H}{A_0}\right)^{a1}.Y\left(\frac{A_M}{A_0}\right)^{b1}.Z\left(\frac{A_L}{A_0}\right)^{c1}.$$

Similarly,

$$\pi_2 = \frac{D_{max}}{D_0}.X\left(\frac{A_H}{A_0}\right)^{a2}.Y\left(\frac{A_M}{A_0}\right)^{b2}.Z\left(\frac{A_L}{A_0}\right)^{c2}$$

and

$$\pi_3 = \frac{D_{max}}{D_0}.X\left(\frac{A_H}{A_0}\right)^{a3}.Y\left(\frac{A_M}{A_0}\right)^{b3}.Z\left(\frac{A_L}{A_0}\right)^{c3}.$$

Solving the above and the refined delamination factor F_{DR} can be expressed as

$$F_{DR} = \frac{D_{max}}{D_0} + 1.783\left(\frac{A_H}{A_0}\right) + 0.7156\left(\frac{A_M}{A_0}\right)^2 + 0.03692\left(\frac{A_L}{A_0}\right)^3. \quad (4)$$

(See Nomenclature for designation of symbols.)

Calculated values of F_{DR} for the holes drilled by a 10 mm end mill with the required variables for the calculation are tabulated in Table 5 that shows the variation of F_{DR} with feed rates for different spindle speeds.

To validate the refined delamination factor, additional laminate specimens were drilled using an 8 and 12 mm end mill cutter with existing drilling parameters and two other different tools, namely, router and twist drills each with sizes of 8, 10 and 12 mm at the spindle speeds of 1000, 1200 and 1400 rpm for the feed rate 25, 50, 75, 100, 125 and 150 mm/min, with three trials, resulting in a total of 486 holes drilled and analyzed. One such set is shown in Fig. 3.

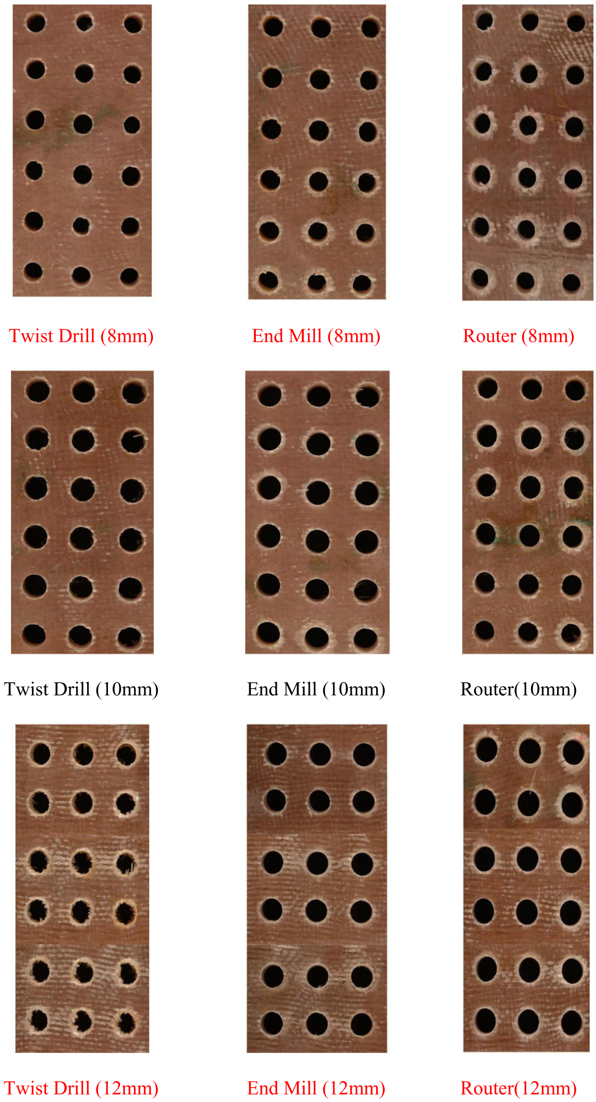


Figure 3. Photographic view of one set of drilled holes (push outside). This figure is published in color in the online version.

Figures 4–6 show the variation of the conventional delamination factor, adjusted delamination factor and refined delamination factor in different drilling conditions for the holes drilled with an 8 mm twist drill, end mill and router respectively. Similar graphs are plotted for 10 mm twist drill, end mill and router and are shown in Figs 7–9. The remaining three Figs 10–12 show the variation of F_D, F_{DA} and F_{DR} at various feed and spindle speeds for the holes drilled with 12 mm cutting tools considered for the present work.

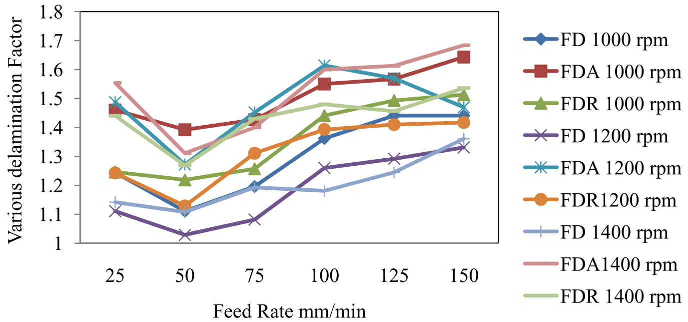


Figure 4. Plot of various delamination factors with different drilling condition for holes drilled with 8 mm twist drill. This figure is published in color in the online version.

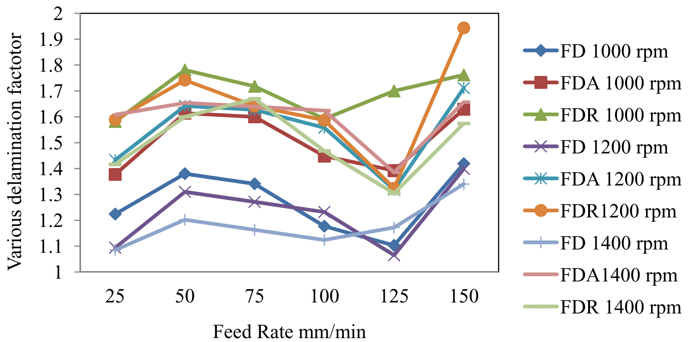


Figure 5. Plot of various delamination factors with different drilling condition for holes drilled with 8 mm end mill. This figure is published in color in the online version.

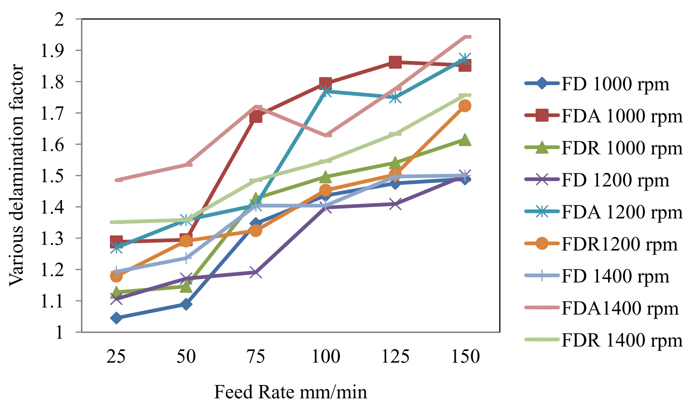


Figure 6. Plot of various delamination factors with different drilling condition for holes drilled with 8 mm router. This figure is published in color in the online version.

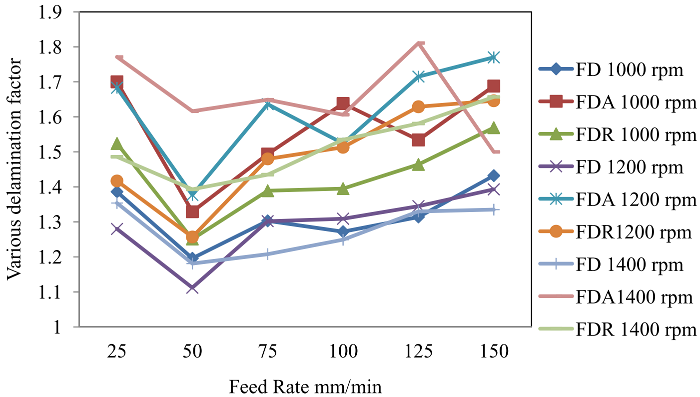


Figure 7. Plot of various delamination factors with different drilling condition for holes drilled with 10 mm twist drill. This figure is published in color in the online version.

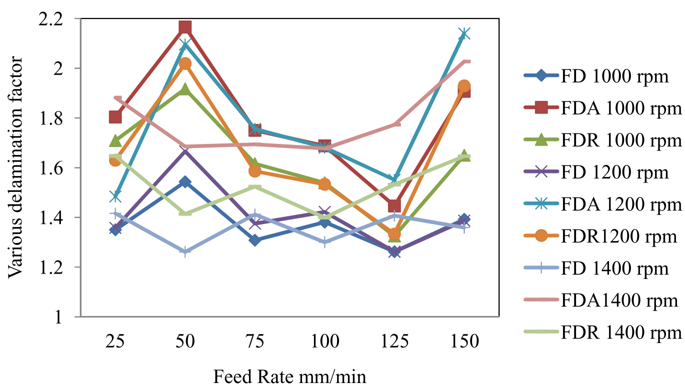


Figure 8. Plot of various delamination factors with different drilling condition for holes drilled with 10 mm end mill. This figure is published in color in the online version.

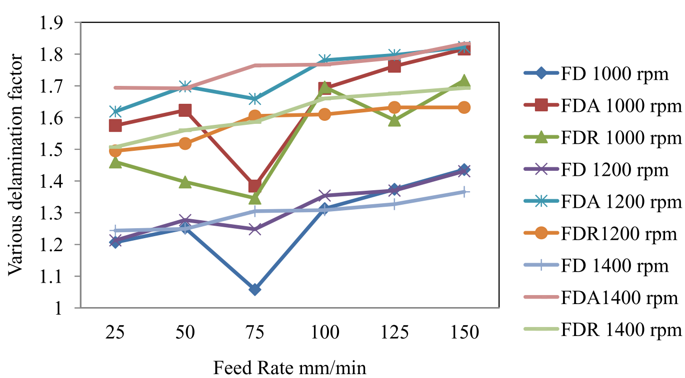


Figure 9. Plot of various delamination factors with different drilling condition for holes drilled with 10 mm router. This figure is published in color in the online version.

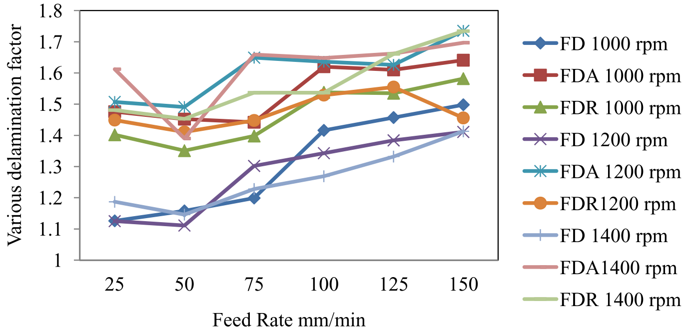


Figure 10. Plot of various delamination factors with different drilling condition for holes drilled with 12 mm twist drill. This figure is published in color in the online version.

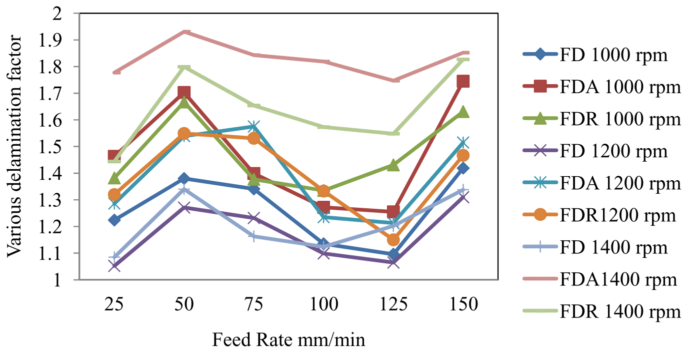


Figure 11. Plot of various delamination factors with different drilling condition for holes drilled with 12 mm end mill. This figure is published in color in the online version.

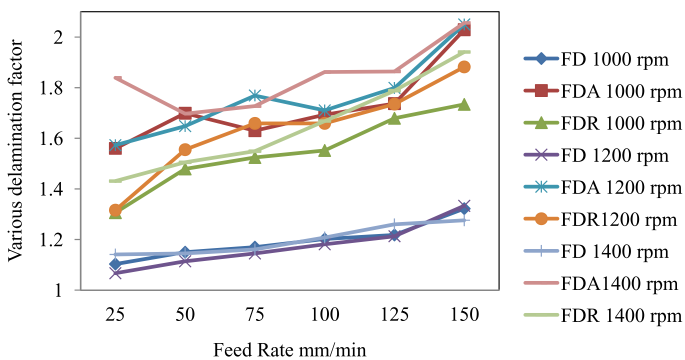


Figure 12. Plot of various delamination factors with different drilling condition for holes drilled with 12 mm router. This figure is published in color in the online version.

3.1. Analysis of Variance (ANOVA)

Taguchi's approach is based totally on statistical design of experiments, and this can economically satisfy the needs of problem-solving and product/process design optimization. By applying this technique one can significantly reduce the time required for experimental investigation, as it is effective in investigating the effects of multiple factors on performance as well as to study the influence of individual factors to determine which factor has more influence and which has less [22]. Some of the previous works that used the Taguchi method as a tool for designing experiments in various areas, including metal cutting, are listed in Refs [23–29]. The Taguchi method adopts a set of standard orthogonal arrays to determine parameters, configuration and analyze results. These kinds of arrays use fewer experimental runs but obtain maximum information and, hence, high reproducibility and reliability. The ANOVA [30, 31] is performed to find whether the process parameter has statistical and physical significance or not. Here the purpose of the ANOVA is to investigate which drilling process parameters significantly affect the performance characteristics.

Table 6 shows the different levels of drill test factors and corresponding F_D, F_{DA} and F_{DR} values for the three tools. The feed rate used for the present analysis ranges from 25–150 mm/min in steps of 25 mm/min as stated in Section 2. This range is divided into 3 levels taking minimum, average and maximum feed rates of 25 mm/min as level 1, 75 mm/min as level 2 and 150 mm/min as level 3, respectively. In order to observe the influence of drill test factors (feed rate, spindle speed and drill diameter) in drilling, three factors, each at three levels, are considered as shown in Table 6. With this data, ANOVA Tables 7–15 are formed.

Tables 7–9 illustrate the results of the ANOVA with the conventional delamination factor (F_D) in the laminate of composite material when the holes are drilled with a twist drill, end mill and router respectively.

From Table 7, it can be observed that the most important variable affecting the delamination factor is the feed rate ($P = 55.77\%$), and the spindle speed ($P = 28.05\%$) also has significant role in the determination of delamination factor. As

Table 6.
Calculated F_D, F_{DA} and F_{DR} for different tool sets

SL no.	A (mm/min)	B (rpm)	C (mm)	F_D			F_{DA}			F_{DR}		
				Twist drill	End mill	Router	Twist drill	End mill	Router	Twist drill	End mill	Router
1	25	1000	8	1.244	1.224	1.045	1.460	1.370	1.288	1.240	1.582	1.127
2	25	1200	10	1.280	1.358	1.213	1.683	1.484	1.619	1.417	1.630	1.495
3	25	1400	12	1.187	1.085	1.141	1.612	1.777	1.839	1.481	1.444	1.431
4	75	1000	10	1.303	1.308	1.058	1.494	1.750	1.384	1.389	1.616	1.346
5	75	1200	12	1.302	1.232	1.145	1.649	1.575	1.769	1.448	1.631	1.659
6	75	1400	8	1.193	1.163	1.404	1.400	1.639	1.720	1.430	1.670	1.485
7	150	1000	12	1.498	1.419	1.322	1.641	1.745	2.029	1.582	1.578	1.734
8	150	1200	8	1.331	1.399	1.500	1.470	1.711	1.873	1.512	1.944	1.723
9	150	1400	10	1.335	1.359	1.366	1.500	2.027	1.833	1.657	1.646	1.693

Table 7.
ANOVA for conventional delamination factor (F_D) with twist drill

Factor	Level (S/N)			DF	SS	V	*F* (%)	*P* (%)
	1	2	3					
A	−1.614	−2.783	−3.883	2	1.711	0.86	22.18925	55.77
B	−2.414	−2.788	−3.324	2	0.861	0.43		28.05
C	−2.524	−2.831	−3.193	2	0.419	0.21		13.67
Error				2	0.077	0.04		2.51
Total				8	3.068			100.00

Table 8.
ANOVA for conventional delamination factor (F_D) with end mill

Factor	Level (S/N)			DF	SS	V	*F* (%)	*P* (%)
	1	2	3					
A	−2.558	−3.044	−3.683	2	2.284	1.14	13.75	52.10
B	−3.637	−3.255	−2.371	2	1.313	0.66	7.91	29.95
C	−3.859	−2.985	−2.388	2	0.621	0.31	3.74	14.17
Error				2	0.166	0.08		3.79
Total				8	4.383			100.00

Table 9.
ANOVA for conventional delamination factor (F_D) with router

Factor	Level (S/N)			DF	SS	V	*F* (%)	*P* (%)
	1	2	3					
A	−1.933	−2.742	−3.266	2	5.153	2.58	7.00	53.68
B	−2.574	−2.806	−2.661	2	2.378	1.19		24.77
C	−3.171	−2.668	−2.144	2	1.332	0.67		13.88
Error				2	0.736	0.37		7.67
Total				8	9.599			100.00

shown in Tables 8 and 9, similar results are obtained in the determination of the conventional delamination factor F_D for the holes drilled with two other cutters.

Similar tabulations are plotted for the adjusted delamination factor (F_{DA}) in Tables 10–12. From Table 10, it can be seen that drill diameter plays a significant role in the determination of adjusted delamination factor for the holes drilled with a twist drill. For the end mill, both feed rate as well as spindle speed is significant whereas feed and drill diameter are significant for the router in the determination of the adjusted delamination factor, as shown in Tables 11 and 12.

Table 10.
ANOVA for adjusted delamination factor (F_{DA}) with twist drill

Factor	Level (S/N)			DF	SS	V	F (%)	P (%)
	1	2	3					
A	−4.514	−5.640	−5.816	2	0.242	0.12		9.52
B	−5.944	−4.797	−5.264	2	0.467	0.23		18.38
C	−5.870	−5.984	−3.940	2	1.779	0.89	34.89	70.09
Error				2	0.051	0.03		2.01
Total				8	2.539			100.00

Table 11.
ANOVA for conventional delamination factor (F_{DA}) with end mill

Factor	Level (S/N)			DF	SS	V	F (%)	P (%)
	1	2	3					
A	−4.514	−5.640	−5.816	2	3.162	1.58		42.83
B	−5.944	−4.797	−5.264	2	2.317	1.16		31.39
C	−5.870	−5.984	−3.940	2	1.471	0.74	3.41	19.93
Error				2	0.431	0.22		5.84
Total				8	7.382			100.00

Table 12.
ANOVA for conventional delamination factor (F_{DA}) with router

Factor	Level (S/N)			DF	SS	V	F (%)	P (%)
	1	2	3					
A	−4.401	−5.110	−5.569	2	4.378	2.19	3.59	42.32
B	−5.036	−4.896	−5.220	2	1.709	0.85		16.51
C	−5.454	−5.026	−4.640	2	3.040	1.52		29.38
Error				2	1.220	0.61		11.79
Total				8	10.346			100.00

From Tables 13 and 15, it can be observed that feed rate has a significant role in the determination of the refined delamination factor (F_{DR}), if the holes are drilled with twist drill and router, since the significance levels are 62.12 and 61.48%, respectively, for these cutters. If the holes are drilled with an end mill, all three variables make a contribution to the determination of F_{DR}.

3.2. *Establishment of Process Model*

The objective of the multi-variable regression analysis is to construct a model that explains as far as possible, the variability in dependent variables, using several in-

Table 13.
ANOVA for refined delamination factor (F_{DR}) with twist drill

Factor	Level (S/N)			DF	SS	V	*F* (%)	*P* (%)
	1	2	3					
A	−2.963	−2.928	−2.320	2	2.307	1.15	88.88	62.12
B	−1.423	−2.879	−3.653	2	0.680	0.34	26.20	18.31
C	−1.836	−2.854	−3.408	2	0.701	0.35	27.00	18.87
Error				2	0.026	0.01		0.70
Total				8	3.714			100.00

Table 14.
ANOVA for refined delamination factor (F_{DR}) with end mill

Factor	Level (S/N)			DF	SS	V	*F* (%)	*P* (%)
	1	2	3					
A	−2.860	−3.859	−4.775	2	1.302	0.65	7.36	31.28
B	−4.616	−3.853	−3.103	2	1.230	0.61		29.53
C	−3.909	−4.343	−3.401	2	1.455	0.73		34.94
Error				2	0.177	0.09		4.25
Total				8	4.164			100.00

Table 15.
ANOVA for refined delamination factor (F_{DR}) with router

Factor	Level (S/N)			DF	SS	V	*F* (%)	*P* (%)
	1	2	3					
A	−2.860	−3.826	−4.624	2	6.181	3.09	8.19	61.48
B	−3.631	−3.922	−3.928	2	2.046	1.02		20.35
C	−4.110	−3.771	−3.590	2	1.072	0.54		10.66
Error				2	0.755	0.38		7.51
Total				8	10.053			100.00

dependent variables [32, 33]. The general form of linear multi-variable regression equation is

$$Y_i = \beta_0 + \beta_1 X_{1i} + \cdots + \beta_m X_{mi} + e_i,$$

where Y_i is the dependent variable and $X_{1i}, \ldots, X_{mi}$ are the independent variables. $\beta_0, \beta_1, \ldots, \beta_m$ are referred to as parameters of the model. e_i is the random variable referred to as the error term. The error term accounts for variability in Y that can be explained by the linear effect of independent variables. R^2 is the multiple coefficient of determination as the measure of goodness of fit of the estimated multiple regression equation.

From the ANOVA results, we can come to a conclusion that feed rate (F), spindle speed (N) and drill diameter (D) contribute significantly to the characterization of the delamination factor. The establishment of a process model can also be called as either an empirical relationship or a multi-variable regression model for the delamination factor as a function of F, N and D. It would be useful to predict how much the effect of delamination can be affected for a given set of process parameters.

The multi-variable regression model for conventional delamination factor F_D for a twist drill, end mill and router can be represented as follows.

$$F_D = 1.341 + 1.241 \times 10^{-3} F - 2.75 \times 10^{-4} N + 1.825 \times 10^{-2} D, \quad R^2 = 0.91, \tag{5}$$

$$F_D = 1.55 + 1.419 \times 10^{-3} F - 2.87 \times 10^{-4} N - 4.17 \times 10^{-3} D, \quad R^2 = 0.66, \tag{6}$$

$$F_D = 0.863 + 2.142 \times 10^{-3} F + 4.05 \times 10^{-4} N - 2.84 \times 10^{-2} D, \quad R^2 = 0.81. \tag{7}$$

Similar regression model equations for adjusted delamination factor F_{DA} are as follows.

$$F_{DA} = 1.179 - 3.3 \times 10^{-4} F - 6.92 \times 10^{-5} N + 4.76 \times 10^{-2} D R^2 = 0.71, \tag{8}$$

$$F_{DA} = 0.594 + 2.275 \times 10^{-3} F + 4.817 \times 10^{-4} N + 3.142 \times 10^{-2} D, \quad R^2 = 0.71, \tag{9}$$

$$F_{DA} = 0.157 + 2.732 \times 10^{-3} F + 5.75 \times 10^{-4} N + 6.33 \times 10^{-2} D, \quad R^2 = 0.77. \tag{10}$$

Equations (11)–(13) are the regression model equations for refined delamination factor F_{DR}.

$$F_{DR} = 0.704 + 1.661 \times 10^{-3} F + 2.925 \times 10^{-4} N + 2.692 \times 10^{-2} D, \quad R^2 = 0.94, \tag{11}$$

$$F_{DR} = 1.994 + 1.346 \times 10^{-3} F - 1.33 \times 10^{-5} N - 4.52 \times 10^{-2} D, \quad R^2 = 0.66, \tag{12}$$

$$F_{DR} = 0.468 + 2.926 \times 10^{-3} F + 3.35 \times 10^{-4} N + 4.075 \times 10^{-2} D, \quad R^2 = 0.82, \tag{13}$$

where F is the feed rate in mm/min, N is the spindle speed in rpm and D is the tool diameter in mm.

3.3. Performance Evaluation of Process Model Equations

The next step in the process model generation is to validate the regression equation generated in equations (5)–(13). The regression equations were generated using various levels of drill test factors mentioned in Table 6. But the experiments were conducted for various feed rates, spindle speeds and drill diameters stated in Section 2. The predictive capability of a regression equation for the determination of F_D, F_{DA} and F_{DR} will be considered as good if these evaluations are used for non-defined test factors in the generation of equations (5)–(13) matches with experimental values. The following Table 16 shows the calculated values of F_D, F_{DA} and F_{DR} and the values determined using experimental means when the holes are drilled with twist drill. Percentage deviation in the determination of F_D, F_{DA} and F_{DR} is also calculated and is tabulated in Tables 16–18. The standard error in the determination of F_D, F_{DA} and F_{DR} for various test factors is calculated using the following equation.

$$\mathrm{SE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(1 - \frac{\text{Process Model Equation Value}}{\text{Experimental Value}}\right)^2}. \qquad (14)$$

From Table 16, it can be seen that the standard error in the determination of F_{DR} is minimum (0.0499) when compared with the other values, 0.0983 for F_D and 0.0886 for F_{DA}. Table 17 shows the corresponding table plotted for an end mill. In this case it can also be found that the values of standard error in increasing order are obtained as $F_{DR} < F_D < F_{DA}$. For the case of holes drilled with a router (refer to Table 18), the same is minimum for a refined delamination factor and the next highest value is obtained for a conventional delamination factor and the standard error is maximum for the adjusted delamination factor.

3.4. Summarized Results

1. The refined delamination factor (F_{DR}) characterizes the delamination in an effective manner, since the formulation of F_{DR} considers the severity of damage.
2. The above fact was validated from the experimental results. In order to validate this, 3PT and MSBS tests were carried out.
3. Optical means associated with the concept of a neural network in MATLAB 7.0 software were employed to estimate the severity of damage.
4. Buckingham's π theorem was used in the formulation of a refined delamination factor (F_{DR}).
5. The feed rate and speed are seen to make the largest contribution to the overall performance in the determination of the conventional delamination factor (F_D).
6. The feed rate and speed are significantly important in the determination of an adjusted delamination factor (F_{DA}), if the holes are drilled with an end mill.

Table 16.
Standard error in determination of F_D, F_{DA} and F_{DR} for holes drilled with twist drill

Type of cutter	Feed	Speed	Cutter diameter	Experimental values			Model equation values			Deviation in %			Best result (based on minimum deviation)
				F_D	F_{DA}	F_{DR}	F_D	F_{DA}	F_{DR}	F_D	F_{DA}	F_{DR}	
Twist drill	50	1200	8	1.029	1.272	1.290	1.219	1.461	1.353	15.59	12.93	4.69	F_{DR}
	100	1400	8	1.181	1.600	1.480	1.226	1.430	1.495	3.68	11.85	1.00	F_{DR}
	125	1000	8	1.441	1.567	1.493	1.367	1.450	1.419	5.40	8.08	5.18	F_{DR}
	50	1200	10	1.112	1.377	1.257	1.256	1.556	1.407	11.43	11.51	10.68	F_{DR}
	100	1400	10	1.249	1.606	1.535	1.263	1.526	1.549	1.08	5.25	0.89	F_{DR}
	125	1000	10	1.314	1.534	1.464	1.404	1.545	1.473	6.39	0.73	0.63	F_{DR}
	50	1200	12	1.111	1.491	1.411	1.292	1.652	1.461	14.01	9.72	3.43	F_{DR}
	100	1400	12	1.269	1.648	1.537	1.299	1.621	1.603	2.32	1.66	4.10	F_{DA}
	125	1000	12	1.457	1.610	1.535	1.440	1.641	1.527	1.17	1.86	0.51	F_{DR}
Standard error										0.0983	0.0886	0.0499	

Table 17.
Standard error in determination of F_{D}, F_{DA} and F_{DR} for holes drilled with end mill

Type of cutter	Feed	Speed	Cutter diameter	Experimental values			Model equation values			Deviation in %			Best result (based on minimum deviation)
				F_{D}	F_{DA}	F_{DR}	F_{D}	F_{DA}	F_{DR}	F_{D}	F_{DA}	F_{DR}	
End mill	50	1200	8	1.310	1.642	1.742	1.243	1.537	1.684	5.37	6.82	3.46	F_{DR}
	100	1400	8	1.124	1.624	1.468	1.257	1.747	1.748	10.56	7.05	16.04	F_{DA}
	125	1000	8	1.103	1.392	1.700	1.407	1.611	1.787	21.61	13.62	4.89	F_{DR}
	50	1200	10	1.666	2.096	2.019	1.235	1.600	1.593	34.92	31.00	26.71	F_{DR}
	100	1400	10	1.300	1.677	1.399	1.248	1.810	1.658	4.13	7.35	15.62	F_{D}
	125	1000	10	1.262	1.446	1.325	1.399	1.674	1.697	9.77	13.63	21.92	F_{D}
	50	1200	12	1.271	1.539	1.549	1.227	1.663	1.503	3.63	7.45	3.06	F_{DR}
	100	1400	12	1.124	1.819	1.573	1.240	1.873	1.568	9.36	2.88	0.35	F_{DR}
	125	1000	12	1.096	1.255	1.431	1.390	1.737	1.607	21.17	27.75	10.93	F_{DR}
Standard error										0.1689	0.1753	0.1541	

Table 18.
Standard error in determination of F_D, F_{DA} and F_{DR} for holes drilled with router

Type of cutter	Feed	Speed	Cutter diameter	Experimental values			Model equation values			Deviation in %			Best result (based on minimum deviation)
				F_D	F_{DA}	F_{DR}	F_D	F_{DA}	F_{DR}	F_D	F_{DA}	F_{DR}	
Router	50	1200	8	1.171	1.358	1.291	1.229	1.489	1.344	4.71	8.77	3.95	F_{DR}
	100	1400	8	1.404	1.628	1.546	1.417	1.740	1.559	0.92	6.45	0.85	F_{DR}
	125	1000	8	1.475	1.862	1.541	1.309	1.578	1.499	12.72	17.98	2.78	F_{DR}
	50	1200	10	1.277	1.698	1.518	1.172	1.615	1.426	8.95	5.17	6.48	F_{DA}
	100	1400	10	1.308	1.767	1.660	1.360	1.866	1.641	3.84	5.32	1.18	F_{DR}
	125	1000	10	1.374	1.762	1.592	1.252	1.704	1.581	9.77	3.39	0.71	F_{DR}
	50	1200	12	1.179	1.648	1.555	1.115	1.741	1.507	5.71	5.32	3.18	F_{DR}
	100	1400	12	1.208	1.862	1.668	1.303	1.992	1.722	7.32	6.54	3.15	F_{DR}
	125	1000	12	1.218	1.737	1.679	1.195	1.830	1.662	1.93	5.10	1.01	F_{DR}
Standard error										0.0674	0.0781	0.0306	

Feed rate and drill diameter are significantly important using a router. If the hole is drilled with a twist drill, it seems that drill diameter is much more important than the other two parameters.

7. The spindle speed and drill diameter have their significance when using twist drill and end milled holes in the determination of a refined delamination factor (F_{DR}) and for the router, feed rate is more significantly important.
8. Process model equations are generated to characterize a wide range of operating conditions.
9. Performance evaluation of these process model equations are carried out with the help of experimental values in the determination of F_D, F_{DA} and F_{DR}.
10. From this evaluation, it was found that a conventional delamination factor (F_D) offers the best result in two out of 27 test samples (7.41%). The adjusted delamination factor (F_{DA}) offers the best result in three out of 27 test samples (11.11%). But the percentage rating of best result for the refined delamination factor is worked out to be 81.48%.
11. Similarly standard error comparison between the process model equation values and the experimental values are made. In this case also, standard error is a minimum for F_{DR} when compared with F_D and F_{DA}.
12. Hence, it can be concluded that the delamination failure in the glass fiber reinforced composite material can be best characterized by a refined delamination factor (F_{DR}).

4. Conclusion

It was found from the literature that delamination could be characterized by either the delamination factor or adjusted delamination factor, but the effect of depth of the damage (severity of damage) was not taken into consideration. Hence, the delamination factor is refined by including the terms that were much affected by severity of damage. A refined delamination factor was calculated using the concept of neural network in MATLAB and Buckingham's π theorem for various holes drilled with different tool bits. Experiments were conducted according to ASTM standards to validate the results presented in the refined delamination factor. Furthermore, a process model equation was developed using ANOVA and its performance for various working conditions were evaluated.

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