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ORIGINAL ARTICLE

Optimizing the delamination failure in bamboo fiber reinforced polyester composite

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Abstract Delamination is represented to be the most prevalent failure in composite structures. The use of composites in the manufacturing sector plays a very important role in the industry in general. Moreover these materials have unique characteristics when analyzed separately from constituents which are a part of them. In this paper, a partially ecological composite was made, using natural fibers as reinforcement (bamboo fiber), in the polyester resin matrix to form a composite, seeking to improve the mechanical behavior among its class of materials. The characteristics of a composite material are determined by how it behaves while machining, Drilling is the most predominant machining process because of its cost effectiveness when compared with other processes. Obviously delamination is the major problem that is focused by many researchers while selecting drilling as the machining process in polymeric composites. This research mainly emphasizes on the critical parameters by varying its speed, feed, and diameter of the cutting tool, their contribution to delamination was analyzed. Reduced delaminations were identified by varying the speed and feed rate.

1. Introduction

Composite materials have been dominant among all emerging materials because of its greater mechanical properties. The utilization of composite materials proved that it conquered new markets relentlessly. The mechanical properties of polymers have shortcomings in fulfilling many structural functions. Generally the mechanical strength of polymers is less compared with metals. However such limitations can be overcome by using treated natural fiber reinforced polymeric composites. While focusing on composite materials, the main points to be considered are cost effectiveness and environmental friendliness. The two main phases of composites are, a discontinuous phase called as "reinforcement" and a continuous phase called as "matrix" which is the major constituent of the product. The matrix separately shows less properties than when combined with reinforcement. It bears the load acting over it and distributes it evenly to the reinforcement. It helps in increasing the overall mechanical properties of the composites. Moreover factors like constituents, concentration, and geometry of the reinforcement determine the properties of the composite to a

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greater extent. Orientation of the reinforcement also has a major role in determining the mechanical properties. Volume fraction or concentration influences the contribution of individual constituents to the overall properties of the composites. Hocheng et al. (1992) concluded that a range of cutting parameters both feed rate and cutting speed should be conservative, since an increase in the feed rate can cause delamination, while an increase in the cutting speed raises the torque and consequently reduces the tool life. Won et al. (2002) observed that an increase in feed rate has an important influence on the chisel edge effect, while an increase of tool diameter decreases this effect. Delamination is mainly caused by the thrust force acting on the chisel edge. Mohan et al. (2007) have studied the influence of cutting parameters, drill diameter and thickness while machining GFRP composites and analyzing the delamination. Paulo Davim et al. (2004) have studied the influence of cutting parameters (cutting velocity and feed) while machining GFRP with two different matrices in order to study its influence along with those parameters on delamination.

Tsao et al. (2004) have studied the drilling of CFRP composite, the approach was carried out based on Taguchi techniques and analysis of variance. From the above literature, it has been identified that the delamination due to the thrust force and torque produced in drilling are important and is to be modeled. For modeling thrust force and torque in drilling a second order polynomial regression modeling is used. Various researchers developed several mathematical and predictive models to suit a particular situation but still there is a need for good predictive model persists in order to save time and labor. Therefore the present research initiative is to develop a predictive model using regression modeling to predict delamination factor for a particular cutting speed and feed rate in drilling of bamboo based polyester composite. Additionally, the results of delamination are compared with the oscilloscopic images obtained during drilling. To predict the delamination factor at the entry and exit of the hole, empirical models are developed. Production of high quality holes with minimal damage in composite materials is a key challenge. In this paper, delamination caused in bamboo fiber reinforced polyester laminate plates by drilling is evaluated.

2. Natural fiber reinforced composites

Natural Fiber-Reinforced Polymeric (NFRP) composites are quickly springing up in terms of research and industrial applications. Natural fiber serves as an important alternative to man-made fibers because they are abundantly available, economical, recyclable, biodegradable and possess a high mechanical strength. Lingo cellulosic plant fibers like bamboo, sisal, kenaf, cotton, jute, pineapple, banana, etc., are mainly used as reinforcement for NFRP composites. Nowadays they are used in various applications like transportation, defense, civil engineering applications, packaging, consumer products, etc. Natural fibers have many significant advantages over synthetic fibers. Currently, bamboo has been proved to be excellent in mechanical properties with strength and modulus (Navin chand et al., 2007). Evolution of next generation materials is only possible with polymeric composites with biodegradability. Biodegradable plastics take up the part of giving eco-friendly products that can compete with products made of petroleum feedstock and capture the changing markets. Natural or bio fiber composites are emerging as a feasible alternative to synthetic fiber reinforced composites especially in the field of automotive and civil engineering applications. Combining bio fibers such as bamboo with polymer matrices produce composite materials that are competitive with synthetic composite materials which require special attention; however bamboo fiber polyester composites are not fully eco-friendly because of the non biodegradable nature of the polymer matrix. But the utilization of natural fibers with such polymers will allow many environmental consequences to be solved. Natural fibers with unsaturated polyester matrix is highly beneficial than those of the unreinforced plastics because of the resulting strength and toughness of the composites. Moreover, cellulosic natural fibers are strong enough, light in weight, cheap, abundant, and renewable (Abdalla Rashdi et al., 2010).

3. Compression molding

Bamboo fiber reinforced polymeric composite is prepared using hand layup and compression molding. Initially NaOH is treated with bamboo fabric mesh with 10% concentration, then it is washed using distilled water till the entire chemical concentration was eliminated, it is then dried in hot air oven for 30 s and samples were weighed based on the requirement (Dhakal et al., 2006). Treating the fibers with NaOH helps in mending the interfacial bonding between the resin and fiber ensuing better mechanical properties. Several authors state that mechanical properties of composites can be improved by chemically treating the fibers (Yuhazri et al., 2011). Here the mesh is weaved with 0/90° orientation. Knitted bamboo fabric after fiber treatment is washed in water to remove the alkalinity and is dried at around 100 °C to remove completely the moisture content present in the fabric using hot air oven (Valadez-Gonzalez et al., 1999). Known amount of unsaturated polyester resin mixed with Kerox ME-50 (MEKP) catalyst and Kerox C-20 accelerator at a concentration of 0.01 w/w for rapid curing was coated on a pre-weighed bamboo fiber mat after applying resin, it was uniformly leveled with minor pressure using roller to remove the air packets within the layers. The bamboo fiber and polyester resin were left free for 2 min to allow air bubbles to escape from the surface of the resin, and then the coated layers were placed in a mold which was sealed with Teflon sheet coated with polymer release agents like silicone spray and grease all around. The mold was then closed and made compact using a hydraulic press at a temperature of 35 °C and at a pressure of 10 bar for about 3 min. After being taken out from the hydraulic press, it is kept in a vaccum furnace where high fiber bonding happens with the matrix thereby the delaminating tendency tends to reduce and then it is allowed for cooling at room temperature for few hours. After that the specimens of required dimensions were cut using a diamond tool cutter.

In compression molding the preheated polymeric composite is kept in a mold cavity with heating coils inbuilt to provide uniform heat as per the requirement. The upper cover plate of the mold is closed when the plunger of hydraulic press gets lowered and pressure is applied to act evenly on all surfaces. Uniform heat and pressure are maintained to create a homogeneous layer, and then the polymeric composite is held in a vaccum furnace which reduces the nature of debonding, it is followed by curing at room temperature for some time. Most

Table 1 Details of Parameters and Levels.

Parameters		Level-1	Level-2	Level-3
A	Dia of tool (mm)	4	6	8
B	Spindle speed (RPM)	500	860	1360
C	Feed rate (mm/min)	18	26	34

compression molding applications use thermoset as polymers nowadays; because of its ease in processing and minimization of debonding. Compression molding is best suitable for molding complex elements where high-strength is required. Because of the advantage in producing complex parts major industries choose compression molding techniques to produce parts in reduced cycle time.

4. Theoretical background

Design of experiments is a potential tool for modeling and analyzing the influence of process variables (Mohana et al., 2007). The main requirement in the design of experiment dwells in the choice of selecting the control factors. The taguchi approach provides a systematic direction to gather, examine, and understand data to meet the objectives of this research. Using taguchi approach, in design of experiments, one can gather maximum information about the experimentation carried over. By setting design parameters and their levels as shown in Table 1, taguchi parameter design can optimize the performance characteristics and reduce the source of variation (Basavarajappa et al., 2009). Taguchi method employs a peculiar design of orthogonal array to examine the entire parameter with minimum experiments conducted. The experimental results are then transformed into a signal-to-noise (S/N) ratio by considering noise factors. The S/N ratio for each level of process parameters is calculated based on the S/N analysis. Usually, there are three quality characteristics in S/N ratio analysis. They are, lower-the-better, higher-the-better, and nominal-the-better. Therefore by selecting the suitable characteristics, the optimal process parameters level is identified. Moreover, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant. With the S/N and ANOVA analyses, the optimal combination of the process parameters can be predicted. Finally, optimization is conducted to verify the contribution of each parameter and their significance in obtaining the result.

To receive higher quality yields while optimizing the process parameters, it is essential to follow some steps in selecting the factors, which mainly affect the process results. Then the selected factors should be divided into several levels based on design and ensure that all maximum combinations are taken into consideration. In this case, the number of all possible potential combinations represents the number of needed experiments. Here, orthogonal arrays make it possible to accomplish fractional factorial experiments in order to avoid number of experimental works and also to provide shortcuts for optimizing elements. The influence of orthogonal arrays depends mainly on the number of factors and process levels considered. Mostly, output factors like thrust force, torque and delamination depend mainly on the machining conditions, such as feed, cutting speed, and tool diameter. Here the experiment is carried out with three input factors at three different levels and output values are tabulated. Table 2 shows the detail design of L18 orthogonal array for input variables.

5. Machining the composite

Drilling process is conducted in SMT radial drilling machine. The drilling variables include the speed ranges of 500, 860, 1360 rpm, feed ranges of 18, 26, 34 mm/min and drill tool diameter ranges of 4, 6, 8 mm are selected based on L_{18} orthogonal array. For different cutting conditions the thrust force and torque were measured using IEICOS two-channel piezoelectric type drill tool dynamometer.

The general arrangement of the experimental set-up is shown in Fig. 1, Burrs and dust particles generated during drilling were removed using a vaccum blower. The dynamometer was connected by a data acquisition system that is assembled in a personal computer (PC) to monitor the test values and frequency waves through RIGOL DS1000D series DSO (Digital signal oscilloscope). The output signals received from the dynamometer were filtered and amplified using charge amplifiers and then the amplified signals of thrust and torque were fed as input to a personal computer through the digital storage oscilloscope for further analysis. The electrical output signals (DC volt) from strain gauges for both thrust force and torque were calibrated using thrust and torque calibration trigger in the data acquisition system for any known value. The variation

Figure 1 Radial drilling machine set-up.

Table 2 L_{18} Orthogonal Array for Input variables.

Exp. No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Tool dia (mm)	A1	A1	A1	A2	A2	A2	A3	A3	A3	A1	A1	A1	A2	A2	A2	A3	A3	A3
Spindle speed (RPM)	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3
Feed rate (mm/min)	C1	C2	C3	C1	C2	C3	C2	C3	C1	C3	C1	C2	C2	C3	C1	C3	C1	C2

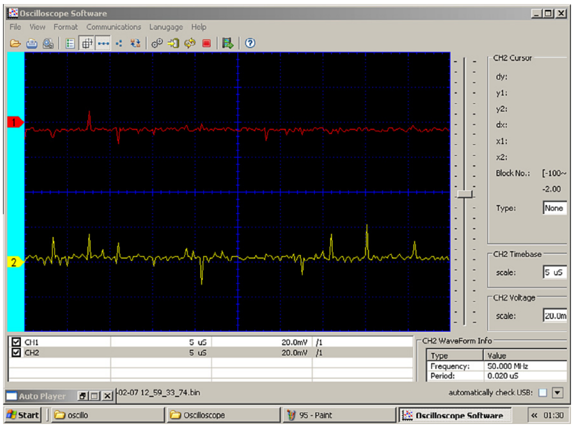

Figure 2 Frequency waves in DSO.

in values of thrust force and torque while drilling a hole with respect to machining time were plotted as frequency wave forms in the digital signal oscilloscope shown in Fig. 2, The output signals from the oscilloscope is noticed in terms of time signal and frequency amplitudes, variation in amplitudes happens because of the frictional component arising due to the phenomenon of rubbing mechanism over a larger surface area of contact is the reason for this increase. Frequency bandwidth is narrower with the lower frequency occurring from a value approximately 20 kHz and ending at 245 kHz are also observed here. Frequency plots shown in Fig. 2 reveal that the amplitudes of the time signal are very largely rising to a maximum of about 500 ms and decreasing exponentially to 2 ms, over that time the voltage is varied from 510 mV to 25 mV. The variation in signal is more conspicuous than in contact and actual drilling. Pure bamboo composite laminates should show different behavior from resin to fibers. Observing the 16th hole contact friction reveals a greater variation in amplitudes, which rise to a peak value of approximately 210 mV and reduces approximately to 25 mV at 150 ms. The presence of fibers, which have different surface characteristics compared with resin, could contribute to this behavior. The most interesting observations are made while observing 18th hole. The peak frequency occurs at 146.4 kHz with a secondary lower peak on the left occurring at 122 kHz. The time signal values do not get delayed and are sustained over the entire length of the process. The values of the amplitudes are large and no repetitions are noticed from several waveforms, which are obtained. By referring to the figure, random fluctuations in the amplitude are noticed. The reason for randomness in the amplitudes is due to the non-uniformity and irregularity in the cutting dynamics caused due to the fiber and matrix interphase meets alternately the cutting edges when drill bit is moved in the axial direction as well as during rotation. The frequency signals were used to investigate the influence of cutting variables on thrust force and torque.

6. Delamination measurements

The delamination factor is the level to categorize the damage on the test specimen at the entry and exit of the drill during the machining process. The delamination factor (F_d) is the ratio of the maximum diameter (D_{max}) of the delamination area to the drill diameter (D_0), this can be calculated as

$$F_d = \frac{D_{max}}{D_0}$$

Figure 3 Top and bottom surface of drilled specimen with dimensions.

Table 3 L_{18} Orthogonal Array with measured output.

Expt. No	Dia of tool (mm)	Spindle speed (RPM)	Feed rate (mm/min)	F_d		F_{dA}		Thrust force (N)	Torque (Nm)
				Peel up	Push out	Peel up	Push out		
1	4	500	18	1.11	1.073	1.096	1.096	4.847	1.3
2	4	860	26	1.05	1.075	1.102	1.685	4.917	1.404
3	4	1360	34	1.298	1.383	1.657	1.734	5.001	1.349
4	6	500	18	1.166	1.366	1.157	1.32	3.723	1.254
5	6	860	26	1.14	1.228	1.152	1.342	4.571	1.285
6	6	1360	34	1.292	1.387	1.563	1.838	5.041	1.261
7	8	500	26	1.062	1.122	1.485	1.838	5.07	1.389
8	8	860	34	1.248	1.337	1.593	1.937	4.988	1.405
9	8	1360	18	1.22	1.322	1.66	1.918	5.056	1.311
10	4	500	34	1.235	1.1	1.44	1.21	4.411	1.332
11	4	860	18	1.22	1	1.454	1.401	4.112	1.317
12	4	1360	26	1.257	1.111	1.584	1.378	4.988	1.365
13	6	500	26	1.197	1.1	1.315	1.21	4.225	1.311
14	6	860	34	1.283	1.283	1.307	1.316	6.295	1.577
15	6	1360	18	1.143	1.277	1.283	1.387	5.182	1.281
16	8	500	34	1.162	1.381	1.423	1.66	5.698	1.315
17	8	860	18	1.112	1.317	1.176	1.69	4.217	1.459
18	8	1360	26	1.3	1.389	1.618	1.927	5.117	1.469

F_d which is the conventional delamination factor represents the crack propagation size, whereas F_{da} represents the area of damage caused because of drilling (Paulo Davim et al., 2007). Parameters like α and β represents the weights. Davim et al. proposed an approach to find the value of the conventional (F_d) and adjusted (F_{da}) delamination factors (Rubio et al., 2008). Therefore,

$$F_{da} = \alpha \cdot + \beta \cdot F_d^2$$

$$F_{da} = \alpha \frac{D_{max}}{D_0} + \beta \frac{A_{max}}{A_0}$$

$$F_{da} = (1 - \beta) \cdot F_d + \beta \cdot F_d^2$$

$$F_{da} = F_d + \frac{A_d}{(A_{max} - A_0)} (F_d^2 - F_d)$$

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

In this paper an accurate inexpensive method for measuring the delamination size has been considered. The equipments required for this technique are PC, color flatbed scanner, DSO and image software (CorelDraw). The specimen to be tested was placed directly on the scanning bed of the scanner. The scanner used is "Canon color scanner". The image of the drilled specimen was acquired, with 400 DPI resolution, using the scanning software, delamination zone of the composite specimens was clearly observed around the drilled hole due to transmitted light passing through it.

By using the features such as contrast, brightness and focusing utilities the shadow zone can easily distinguish from the other undamaged areas. Then this image is saved in a BMP format. Then, this file was imported to the coreldraw software and the photo was magnified up to 30X. Circles were drawn to the delamination zone and to the original drill size. The dimensions of the delaminated zone were measured using ruler tool of photoshop software. Fig. 3 shows the specimens with dimensions drawn. The size of delamination is defined as the difference between the maximum damage radius and the drilled hole radius. This technique was calibrated by measuring the area of delamination using an optical microscope. Since, the error lies in the range of 0.2–0.5%. This range was accepted when compared with the measurements carried out using CCD sensor (Khashaba, 2004).

Table 3 shows the output obtained after measuring the dimensions of the drilled hole and delamination factors were calculated based on the formulas mentioned and thrust and torque values were monitored using a dynamometer while drilling was carried out.

7. Analysis of S/N ratio

The desirable value (mean) is represented by the term signal for the output characteristics and the undesirable value (S.D) is represented by the term noise for the output characteristics of taguchi method given in Table 4. Hence, S/N ratio is the ratio of the mean to the standard deviation. Taguchi method uses the S/N ratio to measure the deviation from the desired value of quality characteristics. The S/N ratio suited for this approach is lower-the-better defined as $\eta = -10\ \log_{10}$

Table 4 Analysis of S/N ratio.

Expt. No	Dia of tool (mm)	Spindle speed (RPM)	Feed rate mm/min	S/N Fd-Ent	S/N Fd-Exit	S/N Fda-Ent	S/N Fda-Exit	S/N Thrust	S/N Torque
1	4	500	18	−0.9065	−0.612	−0.7962	−0.7962	−13.7095	−2.2789
2	4	860	26	−0.4238	−0.6282	−0.8436	−4.532	−13.834	−2.9473
3	4	1360	34	−2.2655	−2.8164	−4.3865	−4.781	−13.9811	−2.6002
4	6	500	18	−1.334	−2.709	−1.2667	−2.4115	−11.4179	−1.966
5	6	860	26	−1.1381	−1.784	−1.229	−2.5551	−13.2002	−2.1781
6	6	1360	34	−2.2253	−2.8415	−3.8792	−5.2869	−14.0503	−2.0143
7	8	500	26	−0.5225	−0.9999	−3.4345	−5.2869	−14.1002	−2.854
8	8	860	34	−1.9243	−2.5226	−4.0443	−5.7426	−13.9585	−2.9535
9	8	1360	18	−1.7272	−2.4246	−4.4022	−5.657	−14.0761	−2.3521
10	4	500	34	−1.8333	−0.8279	−3.1672	−1.6557	−12.8907	−2.4901
11	4	860	18	−1.7272	0	−3.2513	−2.9288	−12.2811	−2.3917
12	4	1360	26	−1.9867	−0.9143	−3.9951	−2.785	−13.9585	−2.7027
13	6	500	26	−1.5619	−0.8279	−2.3785	−1.6557	−12.5165	−2.3521
14	6	860	34	−2.1645	−2.1645	−2.3255	−2.3851	−15.9799	−3.9566
15	6	1360	18	−1.1609	−2.1238	−2.1645	−2.8415	−14.2899	−2.151
16	8	500	34	−1.3041	−2.8039	−3.0641	−4.4022	−15.1144	−2.3785
17	8	860	18	−0.9221	−2.3917	−1.4081	−4.5577	−12.5001	−3.2811
18	8	1360	26	−2.2789	−2.854	−4.1796	−5.6976	−14.1803	−3.3404

(M.S.D) where, M.S.D is the mean-square deviation for the output characteristics. In order to obtain an optimal cutting performance, a lower-the-better quality characteristic is selected for giving minimum delamination. The optimum process design is achieved by scoring a maximum S/N ratio. Since −log is a monotonically decreasing function, it implies that we should maximize the M.S.D. Lower-the-better quality characteristic can be represented by the relation given below

$$\frac{S}{N} = -10\log\frac{1}{n}\left(\sum y^2\right)$$

Figs. 4 and 5 show the S/N ratio for F_d entry and exit. The value corresponding to −0.423 for the second experiment in Fig. 4 and the value corresponding to zero for the eleventh experiment in Fig. 5 show that the process is optimum at these levels to show a minimum delamination at entry and exit levels. Similarly Figs. 6 and 7 show the S/N ratio for adjusted delamination factors at entry and exit. The value corresponding to −0.796 for the first experiment in Fig. 6 and the value corresponding to −0.796 for the first experiment in Fig. 7 show the process is optimum at these levels to show a minimum adjusted delamination at entry and exit levels. Thrust force is optimum in the fourth experiment with S/N ratio −11.417

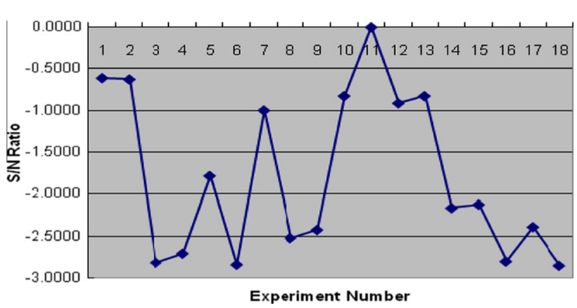

Figure 4 S/N ratio for F_d entry.

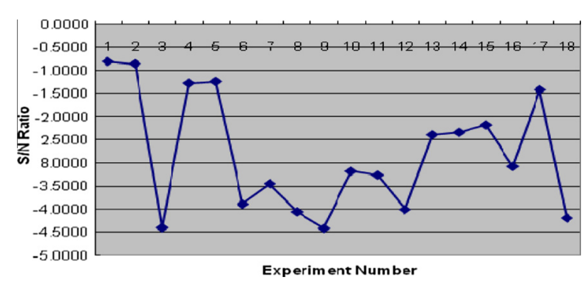

Figure 6 S/N ratio for F_{da} entry.

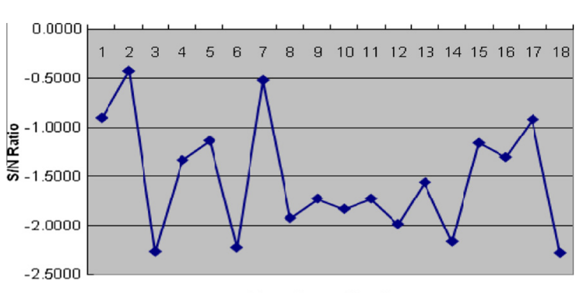

Figure 5 S/N ratio for F_d exit.

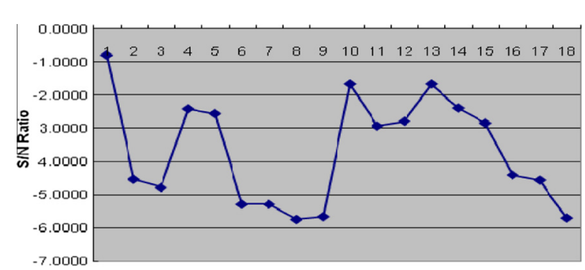

Figure 7 S/N ratio for F_{da} exit.

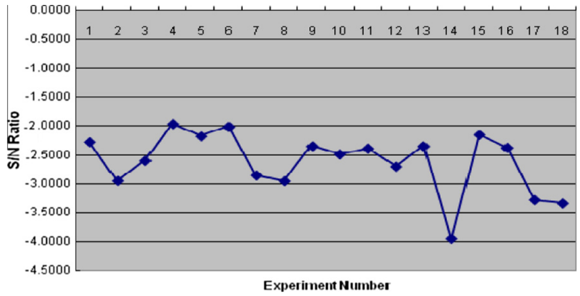

Figure 8 S/N ratio for thrust force.

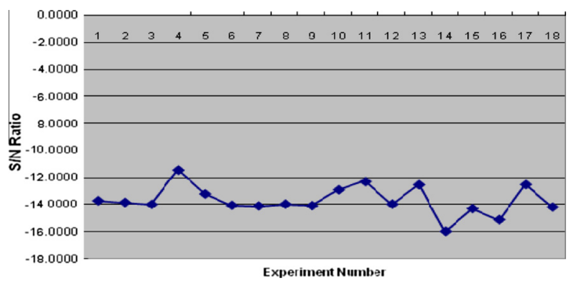

Figure 9 S/N ratio for torque.

shown in Fig. 8; moreover torque is optimum in the fourth experiment with S/N ratio −1.966 given in Fig. 9. As all these values are optimum at their single objective level by considering the taguchi approach which is not sufficient for this analysis. Hence a multifunctional objective approach grey has to be used to find the overall single optimum value of the tests conducted.

8. Grey relational analysis for S/N ratio

Table 5 shows the response table for mean. In grey relational analysis, a data preprocessing is conducted first in order to normalize the raw data. A linear normalization of S/N ratio is performed in the range of (0–1), which is called grey relation generation (Tarng et al., 2002). The normalized S/N ratio x_{ij} for the i^{th} performance characteristic in the j^{th} experiment can be expressed as

$$X_{ij} = \frac{\eta_{ij} - \min_{j}\eta_{ij}}{\max_{j}\eta_{ij} - \min_{j}\eta_{ij}}$$

Table 5 Response table for mean.

Parameters	Table for mean		
	1-MEAN	2-MEAN	3-MEAN
Speed	0.8463	0.8233	0.7585
Feed	0.8547	0.8297	0.7438
Drill dia	0.8523	0.8245	0.7513
Total	2.5533	2.4775	2.2537
Mean grey	0.8094		

Table 6 Grey relation analysis.

S/N Fd-Ent	Normalize	Coefficient	S/N Fd-Exit	Normalize	Coefficient	S/N Fd-Ent	Normalize	Coefficient	S/N Fd-Exait	Normalize	Coefficient	S/N Thurst force	Normalize	Coefficient	S/N Torque	Normalize	Coefficient	Grade
−0.9065	0.602	0.715	−0.612	0.791	0.827	−0.7962	0.825	0.851	−0.7962	0.864	0.880	−13.7095	1.393	1.649	−2.2789	0.456	0.648	0.928
−0.4238	0.814	0.843	−0.6282	0.785	0.823	−0.8436	0.815	0.844	−4.532	0.225	0.563	−13.834	1.385	1.627	−2.9473	0.413	0.630	0.888
−2.2655	0.006	0.501	−2.8164	0.036	0.509	−4.3865	0.038	0.510	−4.781	0.182	0.550	−13.9811	1.376	1.603	−2.6002	0.435	0.639	0.719
−1.334	0.415	0.631	−2.709	0.073	0.519	−1.2667	0.722	0.783	−2.4115	0.587	0.708	−11.4179	1.541	2.177	−1.966	0.476	0.656	0.912
−1.1381	0.501	0.667	−1.784	0.390	0.621	−1.229	0.730	0.788	−2.5551	0.563	0.696	−13.2002	1.426	1.743	−2.1781	0.462	0.650	0.861
−2.2253	0.024	0.506	−2.8415	0.028	0.507	−3.8792	0.149	0.540	−5.2869	0.095	0.525	−14.0503	1.372	1.591	−2.0143	0.473	0.655	0.721
−0.5225	0.771	0.813	−0.9999	0.658	0.745	−3.4345	0.246	0.570	−5.2869	0.095	0.525	−14.1002	1.368	1.583	−2.854	0.419	0.633	0.812
−1.9243	0.156	0.542	−2.5226	0.137	0.537	−4.0443	0.113	0.530	−5.7426	0.018	0.504	−13.9585	1.377	1.606	−2.9535	0.413	0.630	0.725
−1.7272	0.242	0.569	−2.4246	0.170	0.547	−4.4022	0.034	0.509	−5.657	0.032	0.508	−14.0761	1.370	1.587	−2.3521	0.451	0.646	0.728
−1.8333	0.196	0.554	−0.8279	0.717	0.779	−3.1672	0.305	0.590	−1.6557	0.717	0.779	−12.8907	1.446	1.805	−2.4901	0.442	0.642	0.858
−1.7272	0.242	0.569	0	1.000	1.000	−3.2513	0.287	0.584	−2.9288	0.499	0.666	−12.2811	1.485	1.943	−2.3917	0.449	0.645	0.901
−1.9867	0.128	0.534	−0.9143	0.687	0.762	−3.9951	0.123	0.533	−2.785	0.524	0.677	−13.9585	1.377	1.606	−2.7027	0.429	0.636	0.791
−1.5619	0.315	0.593	−0.8279	0.717	0.779	−2.3785	0.478	0.657	−1.6557	0.717	0.779	−12.5165	1.470	1.887	−2.3521	0.451	0.646	0.890
−2.1645	0.050	0.513	−2.1645	0.259	0.575	−2.3255	0.490	0.662	−2.3851	0.592	0.710	−15.9799	1.248	1.329	−3.9566	0.348	0.605	0.732
−1.1609	0.491	0.663	−2.1238	0.273	0.579	−2.1645	0.525	0.678	−2.8415	0.514	0.673	−14.2899	1.356	1.553	−2.151	0.464	0.651	0.799
−1.3041	0.428	0.636	−2.8039	0.041	0.510	−3.0641	0.328	0.598	−4.4022	0.247	0.570	−15.1144	1.303	1.435	−2.3785	0.450	0.645	0.732
−0.9221	0.595	0.712	−2.3917	0.182	0.550	−1.4081	0.691	0.764	−4.5577	0.220	0.562	−12.5001	1.471	1.891	−3.2811	0.392	0.622	0.850
−2.2789	0.000	0.500	−2.854	0.023	0.506	−4.1796	0.083	0.522	−5.6976	0.025	0.506	−14.1803	1.363	1.570	−3.3404	0.388	0.620	0.704

The grey relation coefficient is calculated based on the normalized value. The grey relational coefficient ζ_{ij} for the i^{th} performance characteristic in the j^{th} experiment can be expressed as

$$\zeta_{ij} = \frac{\min_i \min_j |\chi_i^0 - \chi_{ij}| + \zeta \max_i \max_j |\chi_i^0 - \chi_{ij}|}{|\chi_i^0 - \chi_{ij}| + \zeta \max_i \max_j |\chi_i^0 - \chi_{ij}|}$$

where χ_i^0 is the ideal normalized S/N ratio for the i^{th} performance characteristic and ζ the distinguishing coefficient which is defined in the range $0 \leqslant \zeta \leqslant 1$. Finally averaging the grey relation coefficient gives the grey relation grade. The grey relational grade γ_j can be obtained using,

$$\gamma_j = \frac{1}{m} \sum_{k=1}^{n} w_i \zeta_{ij}$$

where 'γ_j' is the grey relational grade for the j^{th} experiment, 'w_i' the weight factor for the i^{th} performance characteristic, and 'm' the number of performance characteristics. These results show that complex multiple performance characteristics can be converted into a single response grey relation grade. The grey relational coefficient is calculated to depict the relationship between the best and actual normalized values. The optimal process parameters are achieved at the level where the S/N ratio is highest. This is reliable for the optimization of single performance characteristics and for multiple performance characteristics which cannot be straightforward. Higher S/N ratio for one performance characteristic may represent lower S/N ratio for another performance characteristic. Hence, the overall evaluation of the S/N ratio is required for the optimization of the multiple performance characteristics. Therefore grey relational analysis adopted in this work is given in Table 6. The grey relational grade is calculated by averaging the grey relational coefficient corresponding to each performance characteristic. The optimal level of the process parameters is the level with highest grey relational grade as shown in Fig. 10. Furthermore, ANOVA is performed to see which process parameters are statistically significant with the grey relational analysis. Hence, optimal combination of process parameters can be predicted.

The highest grade value obtained for speed, feed, and drill diameter shown in Fig. 10 is achieved in level-1 based on the mean values given in Table 5.

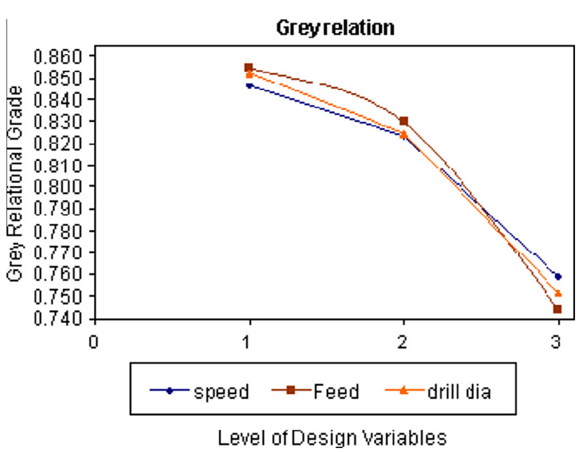

Figure 10 Grey grade vs level of variables.

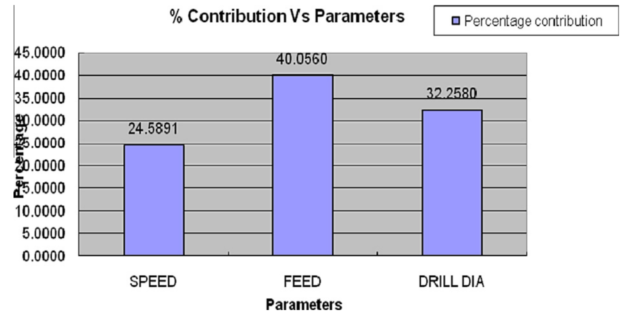

Figure 11 % Contribution vs parameters.

Table 7 ANOVA showing percentage contribution of parameters.

	SSQ	MEANSQ	F	P	%	DOF
SST	0.1013				100.0000	
Speed	0.0249	0.0041	1.3233	0.2459	24.5891	6.0000
Feed	0.0406	0.0068	2.1557	0.4006	40.0560	6.0000
Drill dia	0.0327	0.0065	2.0833	0.3226	32.2580	5.0000
Error	0.0031				3.0969	0.0000
Total					100.0000	17.0000

Table 8 ANOVA table for regression F_d entry sample-1.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	0.077143	0.077143	0.008571	2.01	0.156
Linear	3	0.059941	0.006692	0.002231	3.52	0.067
Square	3	0.010010	0.007319	0.002440	3.57	0.047
Interaction	3	0.007191	0.007191	0.002397	0.96	0.453
Residual error	8	0.038337	0.038337	0.004260	*	*
Total	26	0.192622				

Table 9 ANOVA table for regression F_d entry sample-1.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	0.250880	0.250880	0.027876	3.93	0.034
Linear	3	0.164290	0.080794	0.026931	3.75	0.058
Square	3	0.066391	0.058601	0.019534	3.79	0.042
Interaction	3	0.020199	0.020199	0.006733	0.95	0.462
Residual error	8	0.056774	0.056774	0.007097	*	*
Total	26	0.558534				

Mean grade value of 0.8094 is predicted in the analysis and higher grade value of 0.928 is achieved in level-1 where the input parameters have minimum values as shown in Table 6. The contribution of parameters for this level is formulated by ANOVA.

Table 10 Confirmation grey values.

Confirmation test	
Pred.grey value	Exp.grey value
0.809	0.928

9. Analysis of variance

Analysis of variance (ANOVA) test is performed to justify the goodness of fit in the developed model. The purpose of ANOVA is to investigate the significance of design parameters that affect the quality characteristics of a product or process. This can be achieved by classifying the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean. Contributions of each parameter are given in Fig. 11. Mean square is the ratio of sum of squares to the degrees of freedom (Gaitonde et al., 2008). The results of ANOVA justifying the closeness of fit of the developed model

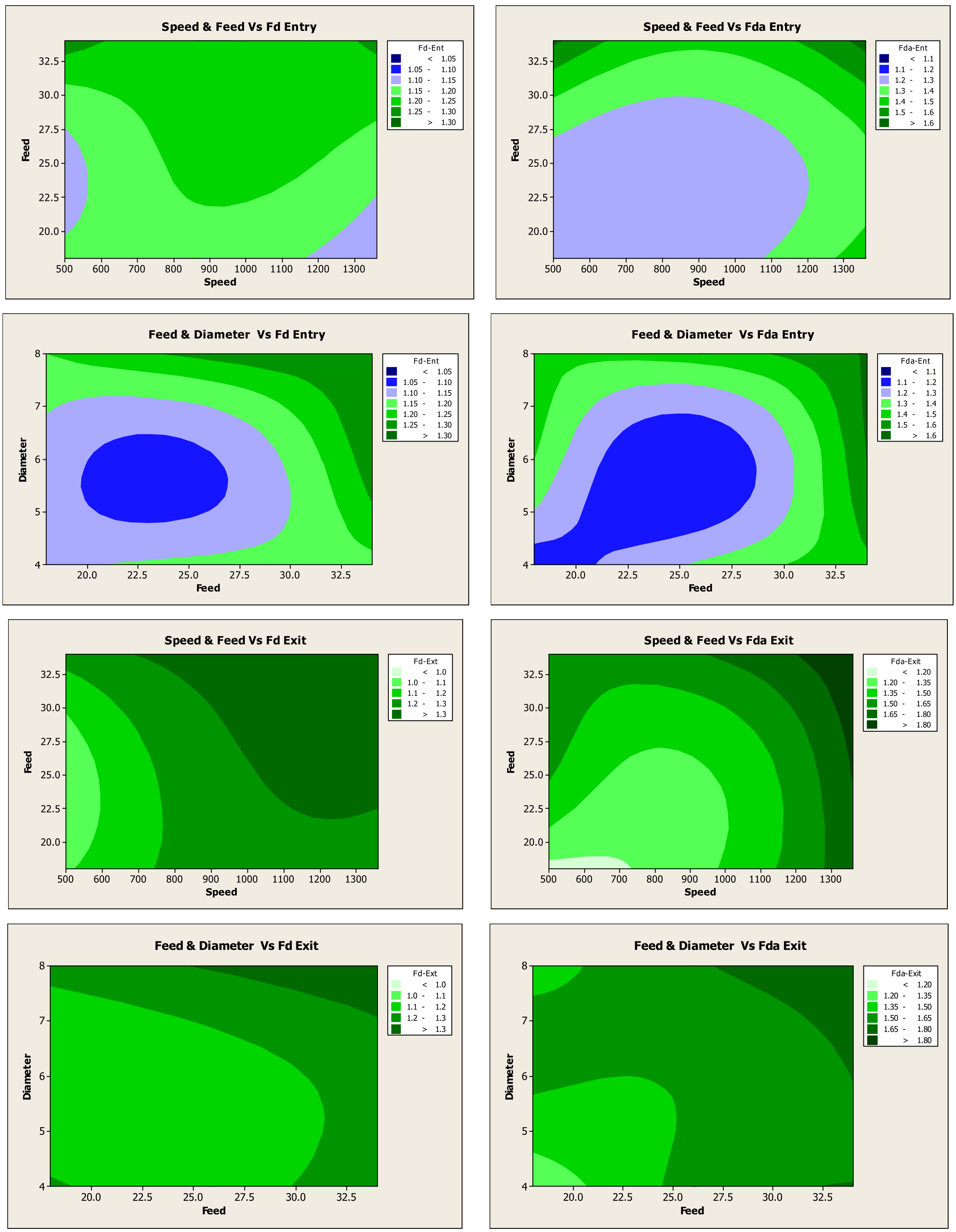

Figure 12 Response surface plots for peelup and pushout.

are presented in Table 7. It is found that the developed model is quite adequate at 95% confidence limit. The delamination related with push-out is more severe than that of peel-up and is identified by the conventional drilling process using different diameters of twist drill (Liu et al., 2012).This happens not only because of low interlaminar shear strength between the fiber and resin interface at the exit side but also, due to higher thrust force experienced during machining the specimen.

The influence of cutting speed on peel-up delamination is comparatively low to push-out delamination while the peel-up and push-out delaminations of woven bamboo/polyester composite were decreased with increasing cutting speed. The size of delamination increases with increase in feed, as a result of increase in thrust force and drill diameter. The delamination associated with push-out is more severe than that of peel-up. The axial thrust force exerted by twist drill is the major cause for delamination. The most popular way of reducing delamination damage is to support the bottom plies of the laminate while machining (Capello et al., 2004). The axial thrust force exerted by the drill point on the composite laminate is the main cause for delamination damage in the work piece, and this happens when the thrust force exceeds the critical thrust force because of the nature of weak interlaminar shear strength that happens at critical thrust force. This work outlines a methodology to optimize the process parameters in drilling of bamboo fiber reinforced polyester composite for minimum delamination damage. Taguchi experimental design and optimization were carried out using grey analysis and the significance of process parameters and their contribution based on results were analyzed with ANOVA given in Fig. 11 based on the values obtained in Table 7. It is clear that feed rate has a maximum contribution of 40.05 percentage followed by drill diameter of 32.25 percentage and then the influence of speed with 24.58 percentage.

10. Regression modeling

Quadratic equation is used to describe the functional relationship between the estimated variable (delamination factor) and the input variables {drill diameter (D), speed (S) and feed rate (F)}, with regression coefficients and coded units utilized when the response function is unknown or nonlinear. This model can predict 95% of the variance indicating that the model fits the data very well and has an adequate predictive ability. Regression coefficients, of the multivariable second order regression model for delamination factor is estimated by the method of least square shown in equations. The ‘P’ value is called as probability of determination and it varies between zero and unity.

Tables 8 and 9 show ANOVA for the full quadratic model. The second-order response surface model is used to predict whether the parameters are adequate within 95% confidence intervals. In this table, the F-value is an indicator that shows the importance of input parameters. ‘F’ value is the ratio of mean of squared deviations to the mean of the squared error. Usually, when ‘F’ value is greater than four means that the change of the design parameter has a significant effect on the quality characteristics. The interaction value shows the dependency of one parameter on the other two parameters. The probability ‘P’ value which is the deciding criteria to check whether the process is significant or not that is if $P > 0.05$ it is insignificant. By referring to the probability values of the tables, it is evident that all the ‘P’ values are less than 0.05 for the squared terms and hence all the values lie within the confidence interval.

11. Confirmation test

After selecting the optimal level of design parameters the quality characteristics have to be improved using the optimal level of design parameters. The predicted grey value can be estimated using the relation

$$\hat{\eta} = \eta_m + \sum_{i=1}^{m} (\tilde{\eta} - \eta_m)$$

where η_m is the total mean S/N ratio, $\tilde{\eta}$ the mean S/N ratio at the optimal level, m is the number of the main design parameter that affect the quality characteristics. Table 10 shows the comparison of predicted grey level and experimental grey level. Response surface analysis shown in Fig. 12 indicates the minimum delamination at the exit is obtained at a low level of feed rate at low speed and at low drill diameter. The confirmation experiments were conducted to verify the predicted optimal parameters with the experimental results. The comparison of the predicted grey value for the delamination factor with the experimental value using optimal cutting parameters is made, good agreement between the predicted and experimental results is observed.

12. Conclusions

The following observations were identified while testing the delamination in bamboo fiber reinforced polyester composites. It is interesting to compare the results of delamination properties of bamboo fiber composites with glass and royal fiber composites. While analyzing bamboo fiber composite the pushout delamination failure effect can be minimized by controlling the feed rate at 18 mm/min with a minimum speed of 500 rpm with 4 mm diameter drill bit, whereas the optimal condition for glass and royal fiber composite is around 2000 rpm with same size of drill and at a feed rate of 200 mm/min. however there is much variation in the feed and speed, for both cases delamination is getting minimized at a lower feed rate and speed.

The feed rate and drill diameter are seen to make the largest contribution to the delamination effect. Generally, the use of small diameter drills and low feed favor the minimum delamination while drilling that leads to better quality holes.

- As taguchi parameter design is applicable for single objective function, the S/N ratio obtained for each process parameters are different, therefore suitable multi objective function were carried out using grey analysis.
- Grade value of 0.928 is achieved in the first experiment where level-1 shows the input process parameters with smaller grades.
- Analysis of varience which gives the influence of input parameters and feed rate is known to have a maximum contribution followed by the drill diameter and spindle speed which has a minor part in delamination.
- By analyzing the mean squares the error percentage is found to be 3.09 percentage which is within the acceptable range.

- Confirmation test is carried out to compare the predicted grey value with the experimental grey value and found to be close. Finally experiments were conducted with the same input parameters of higher grade value and found to have the same value as obtained earlier.

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