Machinability analysis of drilled bamboo fibre reinforced polymer (BFRP) composite

M F A Zaharuddin[1], **P A A Yunos**[1], **Y Jiyoung**[2], **A S Mohruni**[3], **I Yani**[3], **M Yanis**[3]

[1]Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia.
[2]Technical Research Center, Hyundai Steel Company, 1480 Bukbusaneop-ro, Songak-eup, Dangjin-si, Chungcheongnam-do, 31719, South Korea.
[3]Department of Mechanical Engineering, Faculty of Engineering, Sriwijaya University, Indonesia.

*corresponding author: faridh@mail.fkm.utm.my

Abstract. In globally the technology keep improving continuously from time to time especially in materials development. Many researchers and manufacturer found interested in substituting synthetic with natural materials. By utilizing natural surrounding sources, it will impact on the product improvement and creating environmental awareness. Besides on many available natural fibres for reinforcements, bamboo fibre has been identified as one of reliable reinforcement in polymer matrix. The mechanical properties of bamboo fibre composite at moderate strength compared with another types. However, bamboo is grows naturally in the foothills or can be planted and easily to find in the Peninsular Malaysia. Further machining process on composites such as drilling will affecting strength properties of the composite, this is due to discontinuous of the fibre after drilled. This study will evaluating on influence of machining parameters and tool geometry on residual tensile strength and delamination damage of drilled bamboo fibre reinforced polymer (BFRP) composites. Fabrication of the composite using resin infusion process by vacuum assisted resin transfer moulding. The experiments were developed using Taguchi method and tested according to ASTM D3039 requirement. The results were analysed using analysis of variance (ANOVA). Finally, the optimum condition for maximizing residual tensile strength and minimizing delamination factors on the drilled bamboo fibre reinforced composite are suggested.

1. Introduction

Composite materials attracted interest among researchers and manufacturer on its comparable of mechanical properties behavior. Composite made from combination of two properties, matrix and reinforcement. The combination of two properties will be select by user that meets to their requirements. Matrix usually from thermoset or thermoplastic materials while reinforcement from synthetic or natural fibre. The improvement of high performance materials made from natural resources is the main attraction to researcher nowadays. Cost of the raw materials such as metal, iron, and plastics are expensive and leading as interest towards fabrication from natural polymer composite. Natural polymer composite has simple process of fabrication, high specific stiffness and low in cost.

Mechanical properties on natural polymer composite lower than metallic materials but it is outperformed when comparing strength to weight ratio. Natural polymer composite often use for interior application such as furniture and automotive accessories.

Fazita [1] reported, Malaysia contributes 1.9% of the world bamboo resources, approximately 7 million tons with only 6000 tons of commonly used species. The bamboo can grow in fast with maturity cycle of three to four years. Bamboo as a natural fibre uses by many researchers due to it characteristic of high strength and able to produce a high end quality sustainable product in the industrial area [1] [4] [7] [11] [12]. Natural fibre from bamboo is one of the most important sources due to its rapid growth and universality [11]. Bamboo fibre also found good in terms of economic value, light weight, high specific strength, and non-hazardous. Another characteristic, bamboo fibre have good tensile properties, provide more balanced properties, ease in handling, and high flexibility. Abdul Khalil et. all. [12] identified bamboo is dividing into two types with the different process flow and method which are natural original origin bamboo fibre and bamboo pulp fibre which so called bamboo viscous fibre or regenerated cellulose bamboo fibre. The natural original origin bamboo fibre is obtained and produced using mechanical and physical method only without any chemical treatment. The second types is coming from regenerated cellulose fibre as chemical fibre after splitting of bamboo strips and then continue with mechanical processing or chemical processing. Bamboo polymer composite has been use in making flooring, furniture, packaging, surfboards, and transportations.

Machining process needed for structural purpose and complexity of the products either from synthetic or natural fibre. Many difficulties are found after machining fibre reinforced polymer composite with several material problems due to anisotropic and non-homogenous nature which includes delamination damage, matrix burning, ply failure, fibre breakage, fibre pull-out, fibre fuzzing, fibre–matrix debonding, and matrix cracking [2]. Previous researcher reported the damage produce during drilling of composites can be detrimental towards the mechanical behaviour of the composite products [2] [3]. Research had proved the residual tensile strength and delamination damage of natural fibre can be minimized with specific setup of machining parameters. Thus, it is important to study the effect of drilling process damages on the mechanical behavior of fibre reinforced polymer composites.

Abdul Nasir et. all. [2] made the investigations on the relationship between few machining parameters such as feed rate and spindle speed as well tool geometry on residual tensile strength of flax fibres reinforced polymer as well the delamination damage factor after drilling process. A few researchers used Taguchi method in order to design the experiment and using analysis of variance (ANOVA) for analysing the percentage of each parameter effects on the specimen [1] [2] [3] [8] [9] [22]. The specimen has made according to American Society for Testing and Materials (ASTM) 3039–Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials [2] [3]. Kishore et. all. [8] results show the process drilling glass fibre reinforced epoxy composites induced damage and affects the residual tensile strength of composites and the cutting speed is significant parameter influences the residual tensile strength of the polymer composites. Karimi et al [13] mentioned that minimization of the drilling induced damage may subsequently lead to maximization of the residual tensile strength of the glass fibre reinforced composites.

Based on this literature study, the influence of machining parameters and tool geometry on residual tensile strength as well delamination damage of drilled bamboo fibre reinforced polymer (BFRP) composite will reported in this analysis. The effect of parameters on the residual tensile strength with selected parameters as feed rate, cutting speed and drilled point geometry will be analysed. Taguchi method was use for designing parametric study. Analysis of variance (ANOVA) was conducted to have a significant factor that affect the residual tensile strength and delamination damage factor of the selected fibre reinforced composite. Conventional drilling still been used and mainly as a choice to drilling a composite. However this conventional type produces damages such as delamination, micro cracks, fibre pull out and matrix burning around the hole which leading effect on the mechanical properties of composites.

2. Research method

The experimental begins with fabrication of the BFRP composite by Vacuum Assist Resin Transfer Molding (VARTM). The next procedure is to prepare the specimens according to American Society for Testing and Materials (ASTM) D3039 as shown in Figure 1. The tensile strength value obtained after tensile test made on plain specimen. The design of experiment developed using Taguchi method and the experimental begin with drilling process via CNC machine. All results obtained from the experimental were recorded for analysis.
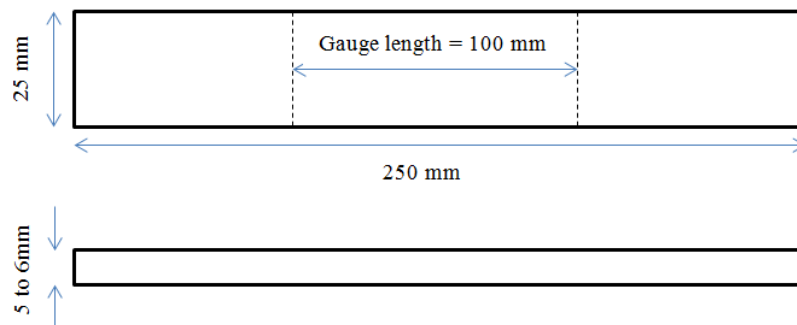

Figure 1. Specimen dimension

The experiment is design by using Taguchi methodology. Taguchi method is use to minimize number of experiments and simplify the result analysis. Orthogonal array (OA) is well reported in previous research that capable to lump in all factors that affecting parameter performance. The L8 orthogonal array was choose that contains of three independent variables at two levels every each of them for the experiment.

The results obtained from the experimental will convert to signal to noise (S/N) ratio. The S/N ratio is mainly to measure the deviation from the desired value of quality characteristic or output result. S/N ratio that matched for maximizing residual tensile strength value is "larger-the-better" as equation (1). For minimizing delamination factor at both entrance and exit drilled hole is "lower-the-better' which in equation (2).

$$(S/N) = -10 \log[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y\mathrm{i}^2}] \tag{1}$$

$$(S/N) = -10 \log[\sum_{i=1}^{n}y\mathrm{i}^2] \tag{2}$$

Abdul Nasir et. all. [2] stated direct value of tensile strength off drilled specimens may not be a true for represent residual tensile strength. From the research study suggested to use equation (3) to calculate the appropriate residual tensile strength based on observed ultimate tensile force.

$$\sigma = \frac{Fu}{(w-d)t} \tag{3}$$

In the drilling process of BFRP composite, three control factors will apply. The control factor includes are the cutting speed (rev/min), feed rate (mm/min) and drill point geometry. Two levels of the control factors are selected. The related control factors and levels are shown in Table 1. From the combination of three factors with two levels, a L8 of orthogonal array is developed. OA is used to design a minimum number of experiments which able to give optimal parameter combinations. The drilling experiments were performed on Akira Seiki Performa SR3 CNC 3 axis milling machine.

Table 1. Factors and levels for designing orthogonal array L8, drill diameter 8 mm

Level	Factor		
	A: Spindle speed (rpm)	B: Feed rate (mm/rev)	C: Drill point geometry
1	3000	0.16	Twist drill
2	6000	0.24	Step drill

Delamination is the damage produced after drilling processes on the drilled hole. The delamination will be factorized by categorizing the damage on the specimen after tested at the entrance and exit of the drilled hole. For the drilled specimen, analysis to be conducted is the delamination factor (Df). The delamination dimension is defined as the differences between the maximum diameters of delamination damage with the original drill hole. The delamination factor, Df calculated as in equation (4).

$$D_f = \frac{D_{max}}{D} \tag{4}$$

After drilling process of the specimen, tensile test will be conduct as per previously made in plain specimen setup. The result from preliminary tensile test will help to drive these tensile test activities on specimens with hole which able to prevent any abnormality on the result obtained.

3. Results and discussions

3.1 Preliminary test result
The preliminary tensile strength test of undrilled composite was conducted on the fabricated BFRP composite and having value of 27.11 MPa.

3.2 Taguchi L8 experimental results
Table 2 shows the results of residual tensile strength and delamination factor based on required equations (3) and (4). The delamination factor is calculated after measuring the dimensions of the drilled holes while the residual tensile strength calculated from the tensile test result. Results then been converted to require signal to noise (S/N) ratio based on required equations (1) and (2).

Table 2. L8 orthogonal array after conducted experiment

Experiment number	A	B	C	Residual tensile strength (MPa)	S/N ratio residual tensile strength	Top delamination factor	S/N ratio entrance delamination factor	Bottom delamination factor	S/N ratio exit delamination factor
1	1	1	1	20.62	26.29	1.28	-2.14	1.40	-2.92
2	1	1	2	23.25	27.33	1.19	-1.51	1.34	-2.54
3	1	2	1	18.89	25.52	1.33	-2.48	1.49	-3.46
4	1	2	2	18.89	25.53	1.32	-2.41	1.48	-3.41
5	2	1	1	22.86	27.18	1.22	-1.73	1.34	-2.54
6	2	1	2	22.89	27.19	1.19	-1.51	1.33	-2.48
7	2	2	1	19.65	25.87	1.31	-2.35	1.47	-3.35
8	2	2	2	20.16	26.09	1.24	-1.87	1.37	-2.73

From the tabulation result in Table 2, the maximum residual strength for BFRP composite is 23.25 MPa, which 24% lower than preliminary test result. This is proven in previous study the composite loss tensile strength from 15% to 30% with 8 mm diameter of hole after tensile test [2]. The experiment condition with 3000 rpm of spindle speed, 0.16 mm/rev of feed rate and step drill tool geometry. Table 3 clearly show the main contributor is feed rate follows by tool drill geometry and spindle speed. Table 4 showing the feed rate is at 77.14% influenced on maximizing residual tensile strength of the drilled BFRP composite with significant value of F test at 33.60 which higher than F ratio of 7.71. Base on response in Table 3, substitution of lower and higher level of all three factors, feed rate is 4.63% impact on the value while spindle speed and tool geometry only 1.2% and 1.5% respectively. On the other hand, residual tensile strength can be increase by keeping feed rate at lower level with higher level of spindle speed with step drill tool geometry. In previous study, feed rate has significant effect on the residual tensile strength. A minimum value of feed rate is preferred and the use of step drill contributed a small increase in residual tensile strength compare to twist drill for drill point geometry [1].

Table 3. Response table for residual tensile strength

Level	A: Spindle speed (rpm)	B: Feed rate (mm/rev)	C: Drill point geometry
1	26.17	27.00	26.21
2	26.58	25.75	26.53
Delta	-0.42	1.25	0.32
Rank	3	1	2

Table 4. ANOVA response table for residual tensile strength

Factor	Sum of Square	Degree of Freedom	Mean Square	Fisher test	$F_{ratio(1,4)}$	% Contribution
Spindle speed	0.35	1	0.35	3.74	7.71	8.60
Feed rate	3.10	1	3.10	33.60	7.71	77.14
Drill point geometry	0.20	1	0.20	2.21	7.71	5.08
Error	0.37	4	0.09		7.71	9.18
TOTAL	4.02	7				100

The minimum entrance delamination factor for BFRP composite is 1.19 as shown in Table 2. The spindle speed setup is 3000 rpm and 6000 rpm, 0.16 mm/rev of feed rate and step drill tool geometry. From Table 5, the feed rate is the main contributor follows by tool drill geometry and spindle speed. Feed rate is at 55.10% influenced on minimizing entrance delamination factor of the drilled BFRP composite with significant value of F test at 23.05 that higher than F ratio of 7.71 as shown in Table 6. Base on response in Table 5, substitution of lower and higher level of all three factors, feed rate having 1.33% impact on the value while spindle speed and tool geometry only 1.15% and 1.19% respectively. The entrance delamination factor can be decrease by keeping feed rate at lower level with neglecting of spindle speed with step drill tool geometry.

Table 5. Response table for entrance delamination factor

Level	A: Spindle speed (rpm)	B: Feed rate (mm/rev)	C: Drill point geometry
1	-2.14	-1.72	-2.17
2	-1.86	-2.28	-1.83
Delta	-0.27	0.55	0.35
Rank	3	1	2

Table 6. ANOVA response table for entrance delamination factor

Factor	Sum of Square	Degree of Freedom	Mean Square	Fisher test	$F_{ratio(1,4)}$	% Contribution
Spindle speed	0.15	1	0.15	5.63	7.71	13.46
Feed rate	0.61	1	0.61	23.05	7.71	55.10
Drill point geometry	0.24	1	0.24	9.15	7.71	21.88
Error	0.11	4	0.03		7.71	9.56
TOTAL	1.11	7				100

The minimum exit delamination factor for BFRP composite is 1.33. The experiment condition is 6000 rpm of spindle speed, 0.16 mm/rev of feed rate and step drill tool geometry. Feed rate is the main contributor follows by tool drill geometry and spindle speed as shown in Table 7. Table 8 show the feed rate is 61.87% influenced on minimizing exit delamination factor of the drilled BFRP composite with significant value of F test at 24.83 that higher than F ratio of 7.71. Base on response in Table 4, substitution of lower and higher level of all three factors, feed rate having 1.23% impact on the value while spindle speed and tool geometry only 1.11% and 1.18% respectively. The exit delamination factor can be decrease by keeping feed rate at lower level with higher level of spindle speed with step drill tool geometry.

Table 7. Response table for exit delamination factor

| Level	A: Spindle speed (rpm)	B: Feed rate (mm/rev)	C: Drill point geometry
1	-3.08	-2.62	-2.17
2	-2.77	-3.24	-1.83
Delta	-0.31	0.62	0.28
Rank	3	1	2

Table 8. ANOVA response table for exit delamination factor

Factor	Sum of Square	Degree of Freedom	Mean Square	Fisher test	$F_{ratio(1,4)}$	% Contribution
Spindle speed	0.19	1	0.19	6.22	7.71	15.49
Feed rate	0.76	1	0.76	24.83	7.71	61.87
Drill point geometry	0.16	1	0.16	5.09	7.71	12.67
Error	0.12	4	0.03		7.71	9.97
TOTAL	1.23	7				100

By having higher spindle speed at 6000 rpm with low feed rate of 0.16 mm/rev and step drill geometry, the minimum delamination factor is achievable. Bosco et. al. [24] stated an increase in spindle speed would decrease the entry delamination of the sandwich panels. By increase in spindle speed will soften the matrix material and removed the drilled parts with ease then the delamination could be reduced. The minimum delamination factor at exit hole found as 1.33 which higher than the entry delamination damage factor which is 1.19 as shown in Table 2. Support by previous study, this is mainly due to the reducing of the thickness of uncut plies that reduces the resisting stiffness of the laminated composite [2]. Authors also mentioned the drill bit approaches the hole exit side, the remaining ply layers flex elastically under the influence of the applied thrust force (from the drill bit) to produce the delamination damage.

3.3 Taguchi L8 experimental response analysis
The effects of changing drilling factors of spindle speed, feed rate and drill point geometry on the residual tensile strength and the delamination damage are shown in Taguchi response graph in Figure 2, Figure 3 and Figure 4. The experimental outputs influenced factor illustrated by the trend of linear slope in the graphs. Based on the trend, the effect of feed rate changes is the most influenced factor in maximizing residual tensile strength whereas minimizing the delamination damage as well. The changing of feed rate has a negative effect on the outputs which lower feed rate is needed to improve residual tensile strength and improving the delamination damage at the highest spindle speed. The step drill tool geometry was observed giving high impact on improving both required analysis. In Summary, the preferable combination of drilling parameters and factors to achieve high residual tensile strength and low delamination damage is A2B1C2.
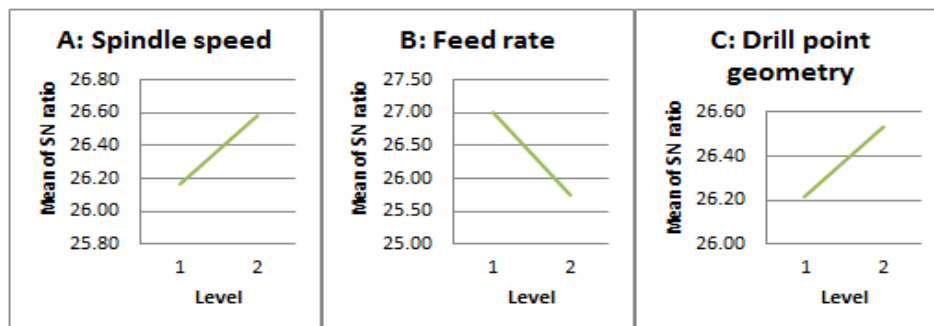
Figure 2. Taguchi response graph for residual tensile strength of BFRP composites
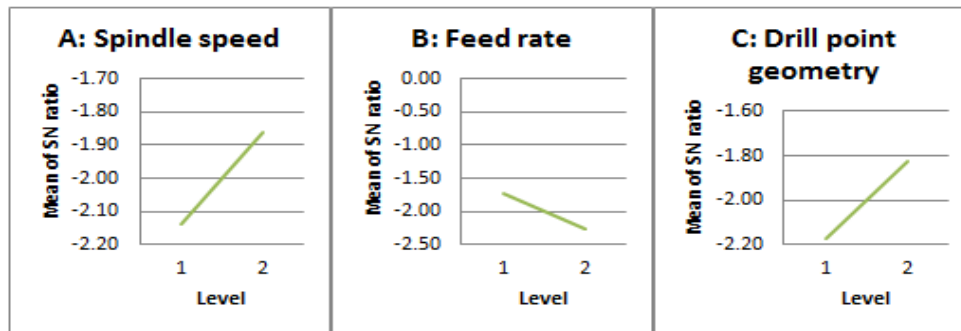
Figure 3. Taguchi response graph for entrance delamination damage of BFRP composites
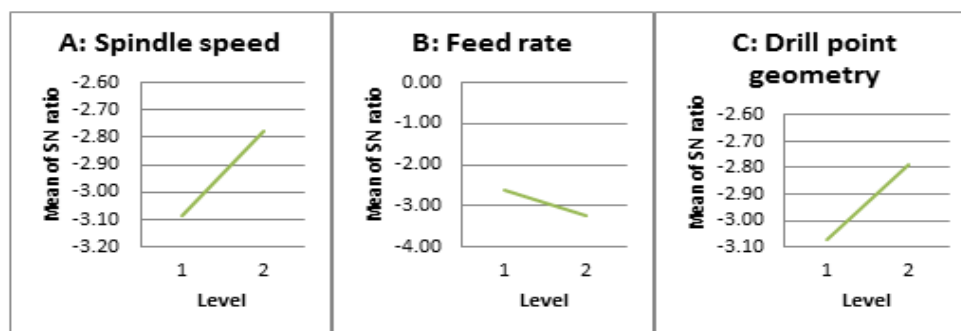

Figure 4. Taguchi response graph for exit delamination damage of BFRP composites

4. Conclusion

The influenced of drilling parameters and factors on the residual tensile strength and delamination damaged of BFRP composites were successfully analyzed using the Taguchi methodology and analysis of variance (ANOVA). In general, the strength of the researched composite found decreased once been drilled a hole. From statistical analysis, the experimental results lead to the conclusion of maximum residual tensile strength can be improved by proper selection of the feed rate, spindle speed and drill tool geometry. In specific, the feed rate should be kept at lowest level as possible, while the spindle speed at the highest level and using step drill geometry. Additionally, the same combination gives the lowest delamination damage at the entrance and exit of the hole. The delamination damaged was found more severe on the entrance hole while compare to bottom surface. Due to the behavior of the selected fibre, it gives the ability to deform under the fibre-tool interaction and having further failure due to the fibre brittle fracture. In terms of tool geometry, the changing tools give significant impact on the results especially delamination damage but may negligible to the residual tensile strength. In order to get the optimum result of getting both advantages on maximizing residual tensile strength and minimizing delamination damages, step drill geometry with the angle point of 85° was recommended.

Acknowledgments

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