Optimization Design of Bamboo Filament Decorated Board Process Based on Response Surface

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Bamboo filament decorated board is a new kind of bamboo and wood composite material. In this material, melamine-urea-formaldehyde (MUF) modified resin impregnated paper is used as the bonding material between bamboo filament decoration material and finger joint plate. This research investigated the effects of hot pressing temperature, time, and pressure on surface bonding properties of bamboo filament decorated board, and the optimum process parameters were determined. With the surface bonding strength as the evaluation index, the response surface analysis was used to optimize the design of the optimal hot pressing process. The optimum surface bonding strength of 1.13 MPa was achieved with the process parameters of 130 s (hot pressing time), 148 °C (hot pressing temperature), and 2.00 MPa (hot pressing pressure). The experimental values were in good agreement with the predicted ones, and the relative error was less than 5%, showing the optimized result.

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Keywords: Bamboo filament decorated board; Surface bonding strength; Hot pressing process; Strain; Response surface method; Optimization

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INTRODUCTION

Bamboo filament has the visual characteristics of straight texture and elegant color, which evokes the feeling of being streamlined and elegant (Chen *et al*. 2020; Lian and Wu 2022). The processing and application of bamboo filament has a long history in Chinese culture, especially the artistic style of weaving (Min *et al*. 2020; Wu *et al*. 2020; Zheng and Zhu 2021). Many designers have used bamboo wire in the veneer of flat and frame furniture design, but it cannot be realized on an industrial scale because of the lack of technology (Chen *et al*. 2016a,b; Xu 2019). For fluid or liquid adhesive, it is difficult to control the amount of glue in the production; the overflow of glue affects the visual effect of the plate. Although the mechanical properties of the decorative board are up to standard, the most important decorative effect is lost. To solve this problem, a new type of bamboo filament decorated board has been developed using impregnated paper instead of liquid adhesive. This method simplifies the process and improves the efficiency, which is of great significance to the innovation of bamboo decorative material.

In previous studies, joinery and plywood were used as substrates to produce bamboo filament decorated board (Li *et al*. 2020, 2021). The present study took an innovative structure of the bamboo filament decorated board. The finger joint plate was used as the base material directly, which saved the upper and lower 4 layers of wood veneer and reduced the glue content of the base material. This innovation reduces production costs and the amount of adhesive used, thereby reducing the release of free formaldehyde by reducing the amount of adhesive used. In addition, the strong bending performance of bamboo solves the problems of easy deformation and poor bearing capacity of finger joints in the length direction by means of composite, which is a new idea for the use of finger joints.

The single factor method and orthogonal experiment method have been used to optimize the process in various fields. Single factor test method has a large number of experimental groups and cannot investigate the interaction between factors. The orthogonal experiment method has the characteristics of uniform dispersion and neat comparability, which can seek the best horizontal combination of factors (Wei *et al*. 2017; Wu *et al*. 2020; Shen *et al*. 2020; Xiao *et al*. 2021; Li *et al*. 2022). However, it cannot get the best combination and response value in the region. The response surface method can use multiple quadratic regression equation to fit the functional relationship with the reduction of the number of experimental groups in advance. It can be used to find the optimal parameters by analyzing the regression equation. Response surface methodology (RSM) has been applied to optimize the processing technology of wood and bamboo composites by domestic and foreign scholars (Wang *et al*. 2017; Du *et al*. 2018; Huang *et al*. 2018; Wang *et al*. 2020; Wang *et al*. 2021). For example, the hot-pressing process of reconstituted bamboo, the hot pressing process of floor balance paper, the hot-pressing process parameters of rice straw molding material, and so on, were optimized by the response surface method. Therefore, the Box-Behnken Design (BBD) method was adopted in this study to obtain the hot pressing process parameters of the material efficiently and scientifically.

By fitting the regression equation, drawing the response surface and contour line, and predicting and simulating the horizontal interaction of various factors, the optimal process parameter scheme was obtained, which provided a theoretical model and method guidance for the serial manufacturing of bamboo filament decorative materials.

EXPERIMENTAL

Materials

Decorative bamboo filament (DBF) was made from 4-year-old moso bamboo (*Phyllostachys edulis* (Carr.) J. Houz.) of Xianning, Hubei Province, China. The average length and diameter of the moso bamboo culms obtained were 17 m and 10 cm at breast height, respectively. The density of bamboo culms was 0.842 g/cm^3, and the thickness was 10 mm. The most straight part in the middle of the bamboo culms was used to make bamboo filament. The moisture content of DBF was 7%, and the dimensions were 10 mm (tangential) × 1000 mm (longitudinal) × 1.6 mm (radial). The Chinese fir finger-joint was used as the base material, which was purchased from Shandong Laidian Technology Co., Ltd. The thickness and the horizontal splicing strip of the finger-joint was 12 mm and 52 mm, respectively. The moisture content and density were 10% and 0.685 g/cm^3, respectively. The gram weight, pre-curing degree, and thickness of MUF impregnated adhesive paper was 20 g/m^2, 30%, and 0.5 mm, respectively, which was provided by Hubei Honglian industrial Co., Ltd.

Response Surface Methodology and Box-Behnken Design

Decorative bamboo filament, Chinese fir finger-joint, and MUF impregnated adhesive paper (Hubei Honglian industrial Co., Ltd, Xiaogan, China) were formed according to Fig. 1, and then glued using the hot press (BY100, Qingdao Guosen Machinery Co. LTD, Qingdao, China). To explore the effect of variables on the response in the region of investigation, a BBD with three factors and three levels was performed. Hot pressing time, temperature, and pressure were set as independent variables, and the range and level of the variables are shown in Table 1. The surface bonding strength was taken as the response. Three samples were pressed under each group of parameters as parallel tests. The results of the experimental design were analyzed by Design Expert software V8.0.6 (Stat-Ease Inc, Minneapolis, MN, USA).

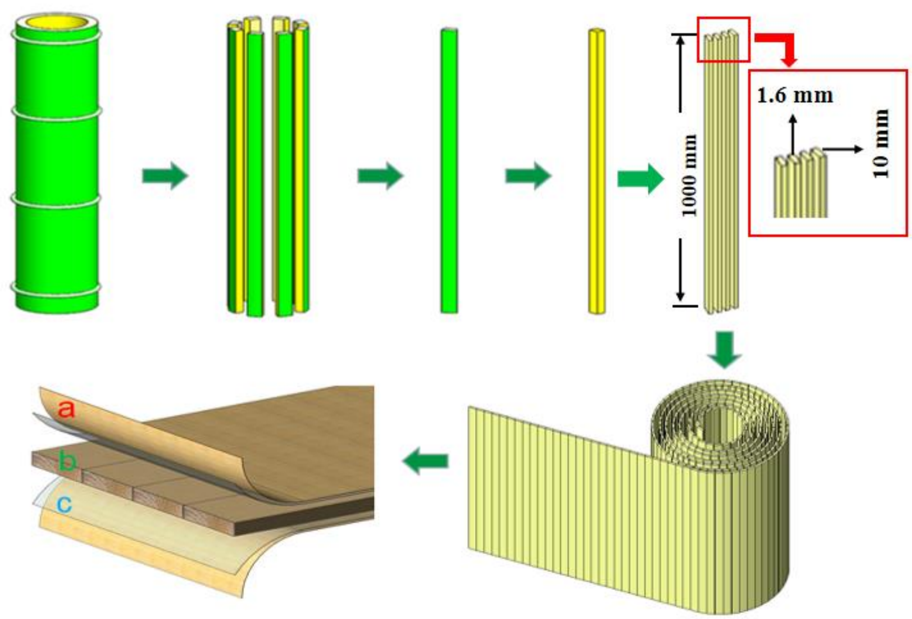

Fig. 1. The composition unit and structure of bamboo filament decorative board. (a) Decorative bamboo filament; (b) Chinese fir finger-joint; (c) MUF impregnated adhesive paper

Table 1. The Range and Level of the Variables

Factor	Variable	Unit	Range and level of actual and coded values		
			-1	0	1
X_1	hot pressing time	s	130	155	180
X_2	hot pressing temperature	°C	130	155	180
X_3	hot pressing pressure	MPa	2	3.5	5

Surface Bonding Strength Test

The surface bonding strength tests were conducted in accordance with the Chinese National Standard for wood-based panels and surface decorated wood-based panels (GB/T 17657-2013) with a universal mechanical testing machine (WDW-100, Jinan Huaheng Equipment Co., Ltd, Jinan, China) to assess the performance of adhesive interface of bamboo filament decorated board. The dimensions of the specimen for the test were 50 mm × 50 mm (length × width). All specimens were conditioned at 20 ± 2 °C and RH of 65

± 2% for 14 days before testing. Six replicates were performed in each group. The specimen was placed and stretched down according to Fig. 2, and the falling speed was set at 1.0 mm/min.

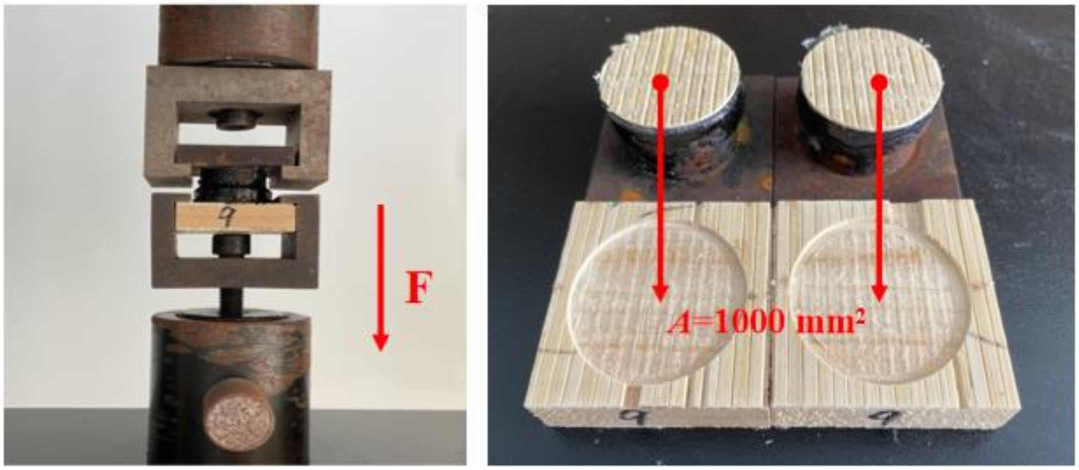

Fig. 2. The surface bonding strength test of bamboo filament decorative board

The surface bonding strength was calculated by Eq. 1,

$$\sigma = \frac{F_{\max}}{A} \tag{1}$$

where σ represents the surface bonding strength (MPa), $F_{\max}$ represents the maximum failure load of the specimen surface (N), and A stands for the bonding area between specimen and clamp head, which was a constant of 1000 mm^2.

Static Bending Strength Test

The samples for three-point bending were tested according to the same standard (GB/T 17657-2013) using a mechanical testing machine (WDW-100), as shown in Fig. 3.

Fig. 3. The Static Bending Strength Test of bamboo filament decorative board

The span was set at 280 mm. The dimensions of the specimen for the test were 300 mm × 50 mm × 50 mm(length × width× thickness). All specimens were conditioned at 20 ± 2 °C, and RH of 65 ± 2% prior to testing. Twelve replicates were performed in each group. The static bending strength was calculated by Eq. 2,

$$P = \frac{3 \times F_{\max} \times l}{2 \times b \times h^2} \quad (2)$$

where P represents the static bending strength (MPa) and F_{max} represents the maximum failure load (N), while l, b, and h represent the measured value of span (mm), width (mm), and thickness (mm) of the specimen, respectively.

Water Absorption and Thickness Expansion Rate Test

The tests were conducted in accordance with GB/T 17657-2013, in which the dimensions of the specimen were 50 mm × 50 mm (length × width). All specimens were conditioned at 20 ± 2 °C and RH of 65 ± 2%, and prior to testing, the thickness and weight of the specimen at marked lines were recorded with an accuracy of ± 0.01 mm and ± 0.01 g, respectively. The specimens were immersed in a water tank for 24 h, and the temperature was controlled at 20 ± 1 °C. After that, the thickness and weight of the specimens were measured, and the thickness expansion and water absorption rate were calculated by Eqs. 3 and 4,

$$T = \frac{t_2 - t_1}{t_1} \times 100 \quad (3)$$

$$W = \frac{m_2 - m_1}{m_1} \times 100 \quad (4)$$

where T represents the thickness expansion rate (%), t_1 and t_2 represent the thickness of the specimen before and after the water absorption test, respectively, W represents the water absorption rate (%), while m_1 and m_2 represent the weight of the specimen before and after the test, respectively.

RESULTS AND DISCUSSION

Response Surface Test

Results of the surface bonding strength test are presented in Fig. 4.

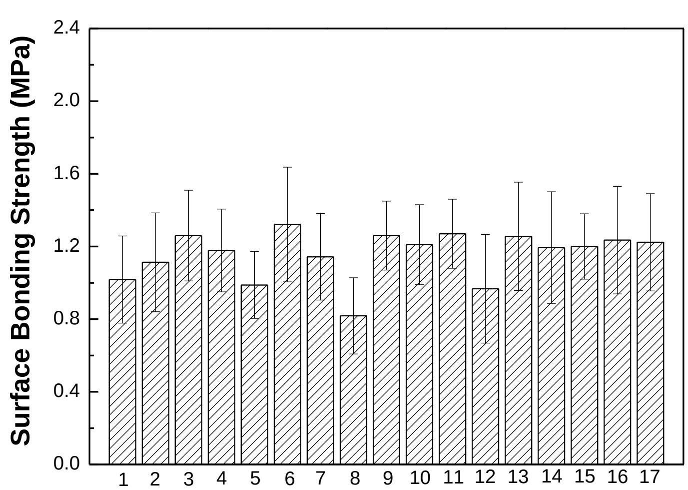

Fig. 4. The results of the surface bonding strength test

The data were measured in parallel 18 times and averaged, and 6 samples were selected from each board for testing. The plan of BBD in coded and actual levels of the three independent variables and test results are shown in Table 2.

Table 2. Experimental Designs and Results

Run	Code Value			Actual Value			Response Value *Y*
	X_1	X_2	X_3	t (s)	T (°C)	P (MPa)	SBS (MPa)
1	0	-1	-1	155	130	2.00	1.018
2	0	-1	1	155	130	5.00	1.113
3	0	0	0	155	155	3.50	1.260
4	-1	0	1	130	155	5.00	1.178
5	1	0	-1	180	155	2.00	0.988
6	1	0	1	180	155	5.00	1.321
7	1	1	0	180	180	3.50	1.143
8	-1	-1	0	130	130	3.50	0.818
9	0	0	0	155	155	3.50	1.260
10	0	0	0	155	155	3.50	1.210
11	0	0	0	155	155	3.50	1.270
12	1	-1	0	180	130	3.50	0.967
13	0	1	1	155	180	5.00	1.256
14	-1	0	-1	130	155	2.00	1.194
15	0	0	0	155	155	3.50	1.200
16	-1	1	0	130	180	3.50	1.235
17	0	1	-1	155	180	2.00	1.223

Note: *T*, *t*, *P*, and SBS refer to hot press temperature, hot press time, hot press pressure, and surface bonding strength, respectively.

According to the above results, a second-order regression equation model fitting *Y* and each factor can be obtained by Design Expert Software, as follows:

$$Y= 0.051781X_1+0.07491X_2 - 0.32482X_3 - 0.0000964X_1X_2 - 0.0232667X_1X_3 - 0.00041333X_2X_3 - 0.0001452X_1^2 - 0.0001736X_2^2+0.00933333X_3^2 - 8.43728 \quad (5)$$

where *Y* represents the surface bonding strength， X_1, X_2 and X_3 represent the actual value of the hot pressing time, temperature, and pressure, respectively.

To test the validity of Eq. 5, the mathematical model of surface bonding strength was subjected to variance analysis, and the results are shown in Table 3.

Table 3. ANOVA for Apparent Evaluation

Source	Sum of Squares	DF	Mean Square	F-value	P-value	Sig.
Model	0.27	9	0.030	11.72	0.0019	*
X_1	4.5*E*-006	1	4.5*E*-006	1.753*E*-003	0.9678	
X_2	0.11	1	0.11	43.12	0.0003	*
X_3	0.025	1	0.025	9.64	0.0172	*
$X_1 X_2$	0.015	1	0.015	5.66	0.0490	*
$X_1 X_3$	0.030	1	0.030	11.86	0.0108	*
$X_2 X_3$	9.610*E*-003	1	9.610*E*-003	0.37	0.5600	
X_1^2	0.035	1	0.035	13.51	0.0079	
X_2^2	0.050	1	0.050	19.31	0.0032	*
X_3^2	1.857*E*-003	1	1.857*E*-003	0.72	0.4232	
Residual	0.018	7	2.567*E*-003			
Lack of Fit	0.014	3	4.589*E*-003	4.37	0.0941	
Pure Error	0.0042	4	1.050*E*-003			
Cor Total	0.29	16				
R^2	0.9377		Adjusted R^2	0.8577		

According to the ANOVA test results (Table 3), R^2 and adjusted R^2 were 0.9377 and 0.8577, respectively. These results indicated that the equation had a good correlation and 85.77% of the variability of the experimental data could be explained by the regression model. The F value of the model was 11.72, and the P-value (P=0.0019) was less than 0.05, which indicated that the regression model reached a significant level (Wang *et al*. 2017). The P-value (P=0.0941) of lack of fit was greater than 0.05, which illustrated that the experimental error was small and the model fit was high. Thus, the regression model can be used to predict and analyze the surface bonding strength in actual production.

In addition, the P-value of X_1 in Table 3 was greater than 0.05, indicating that the factor was not significant, while the other two factors (X_2 and X_3) were significant. It can be concluded that the effect of hot pressing temperature and pressure on surface bonding strength was greater than that of hot pressing time. According to the mean square of all factors in the square difference table, the descending order of the influence on surface bonding strength can be hot pressing temperature, hot pressing pressure, and hot pressing time. For the interaction terms, the P values of $X_1 X_2$, $X_1 X_3$, and $X_2 X_3$ were 0.049, 0.0108, and 0.56, respectively. It was shown that the cross terms $X_1 X_2$ and $X_1 X_3$ had significant effect on the surface bonding strength, while $X_2 X_3$ was the opposite. The interaction between hot pressing time and temperature, hot pressing time, and pressure had a significant influence on the response value. The correlation of quadratic terms (X_1^2, X_2^2 and X_3^2) can also be judged by the P-value, which indicates that only X_2^2 had a significant correlation with the change of surface bonding strength. In summary, the factors with significant correlation in ANOVA were marked with * in Table 3.

Interaction Analysis of Process Factors

The response surface figure is a contour map of three-dimensional space on the two-dimensional horizontal plane composed of the response value and the value of each test factor. The response surface and contour of the influence of the interaction of the two factors on the surface bonding strength are shown in Figs. 5 through 7.

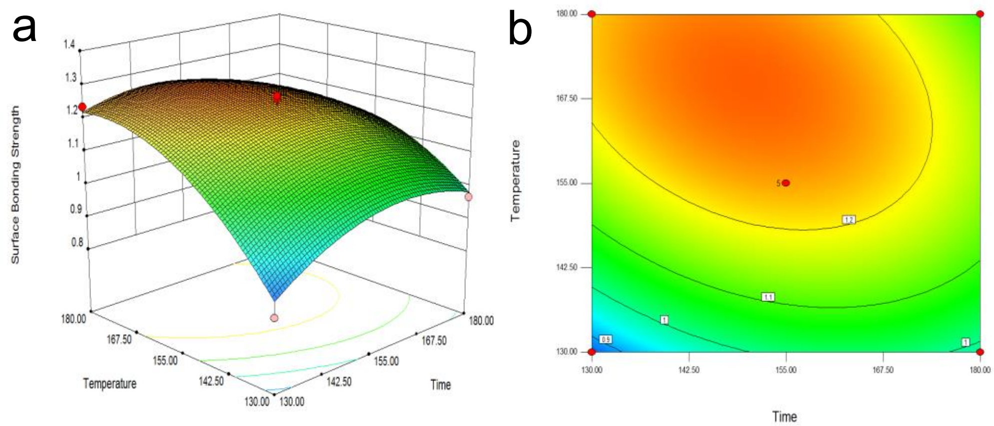

Fig. 5. Response surface and contour plot for hot pressing time and temperature on the surface bonding strength of bamboo filament decorated board

In Fig. 5, the response surface graph (Fig. 5a) has a vertex in the selected horizontal range, which indicated that the optimal value was in the selected range. Similarly, the contour line (Fig. 5b) presents an ellipse, which showed that the two factors of hot pressing time and the hot pressing temperature had obvious interaction (Tang *et al.* 2011).

In Fig. 5a, the curve of hot pressing time-surface bonding performance showed a trend of first rising and then decreasing, and the maximum response value appeared at about 155 s. The reason for the inflection point was that a shorter time would be not conducive to adhesive curing, and a longer time would cause adhesive aging, which could also cause the decline in the adhesive performance (Zuo *et al.* 2016). Furthermore, the increase in energy consumption and the decrease in production efficiency would be caused by the longer hot pressing time in the actual production process. Another curve on the graph is the curve of hot pressing temperature−surface bonding strength, which was relatively flat. With the increase in hot pressing temperature, the surface bonding strength increased first and then decreased slowly, and the curve reached the maximum response value at about 170 ℃. When the hot pressing temperature was at a lower level, the flow ability and cementation ability of the adhesive were weak, which could not lead to the forming of a firm bonding interface. As the temperature rose to the ideal curing temperature of MUF adhesive, the cementation performance was improved and the adhesive could penetrate into bamboo and wood cells to form bonding interface well (Wu *et al.* 2020; Fang *et al.* 2016). At this time, the macroscopic performance was that the surface bonding strength value increased. Conversely, extremely high temperatures also made bonding difficult. This was because high temperatures would accelerate the evaporation of water in the adhesive, which would reduce the fluidity of the adhesive and prevented the adhesive from entering the interface cells to form the interface (Sheng *et al.* 2019).

The response surface 3D diagram and contour diagram of hot pressing time and pressure are shown in Fig. 6. According to the results of ANOVA (Table. 3), the interaction between the two factors was significant. The law of the hot pressing time was consistent with that in Fig. 5, which still rose first and then fell gently and the inflection point was about 155 s. The curve of hot pressing pressure-surface bonding strength was very gentle, and the surface bonding strength showed an increasing trend with the increase of pressure. This indicated that the Chinese fir finger-joint and bamboo filament had not been subjected to overload pressure to destroy the permeable space of glue (Huang 2016; Dong *et al*. 2018).

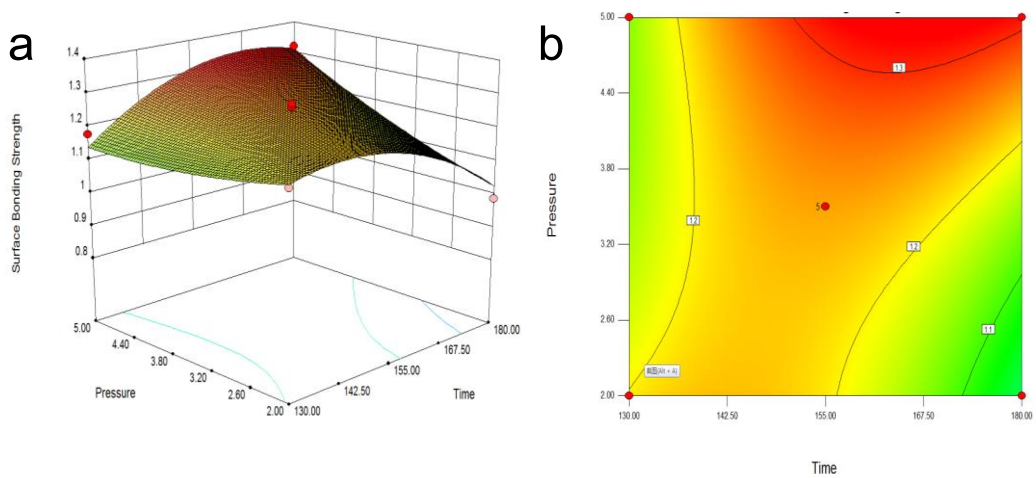

Fig. 6. Response surface and contour plot for hot pressing time and pressure on the surface bonding strength of bamboo filament decorated board

As shown in Fig. 7, both hot pressing temperature and pressure had a curving relationship with surface bonding strength, and the interaction between the two factors was not significant, as shown in Table 3. The slope of the pressure-surface bonding strength curve was significantly lower than that of the temperature-surface bonding strength curve. The influence of hot pressing pressure on surface bonding strength was less than that of hot pressing temperature within the set parameter range.

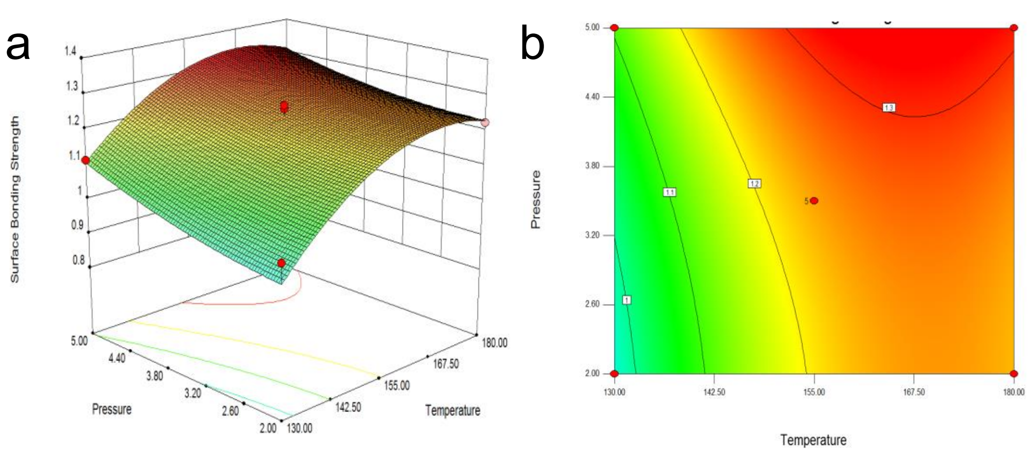

Fig. 7. Response surface and contour plot for hot pressing pressure and temperature on the surface bonding strength of bamboo filament decorated board

Validation of Response Surface Optimization Process

Considering the requirements of energy consumption and production efficiency in actual production, the adjustment of thermal pressure parameters was set as small as possible, which could reduce production costs by increasing production capacity and reducing energy consumption. Based on this premise, the process was optimized using Design Expert. The optimized process parameters and the predicted values of surface bonding strength were 130 s (hot pressing time), 148 °C (hot pressing temperature), 2.00 MPa (hot pressing pressure), and 1.14 MPa (surface bonding strength), respectively. This predicted value was conformed to the standard (GB/T 34722-2017 Surface decorated plywood and blockboard with paper impregnated thermosetting resins), which defined the surface bonding strength of decorative panels as not less than 0.6 MPa.

To verify the accuracy of the predicted optimization results, three repeated tests were conducted according to the modified optimal process parameters. The comparison between the measured and predicted values is shown in Table 4.

Table 4. Comparison and Verification of Response Surface Optimization Results

No.	Hot Pressing Time (s)	Hot Pressing Temperature (℃)	Hot Pressing Pressure (MPa)	Surface Bonding Strength (MPa)	Relative Error (%)
Predicted Value	130	148	2.00	1.14	—
Measured Value 1	130	148	2.00	1.11	2.63
Measured Value 2	130	148	2.00	1.09	4.39
Measured Value 3	130	148	2.00	1.18	3.51
Average Measured Value	130	148	2.00	1.13	0.88

According to Table 4, the surface bonding strength of bamboo filament decorated board was 1.13 MPa, which was close to the predicted value, and the relative error was less than 5%. The regression model obtained by the response surface method was correct and had a good predictive effect on actual production.

Static Bending Strength and 24 h Water Absorption

Static bending strength

The test results and process are shown in Fig. 8. The test results shown in Fig. 8a indicate the static bending strength of bamboo filament decorated board was much higher than the national standard of GB/T 34722-2017 (The limit is not less than 15 MPa). In Fig. 8b, the mean value and standard deviation of the preferred group were 55.67 and 4.95 MPa, respectively. This is due to the mechanical contribution of bamboo on the upper and lower surfaces. At the same time, it also showed that the optimized process could be applied to production practice.

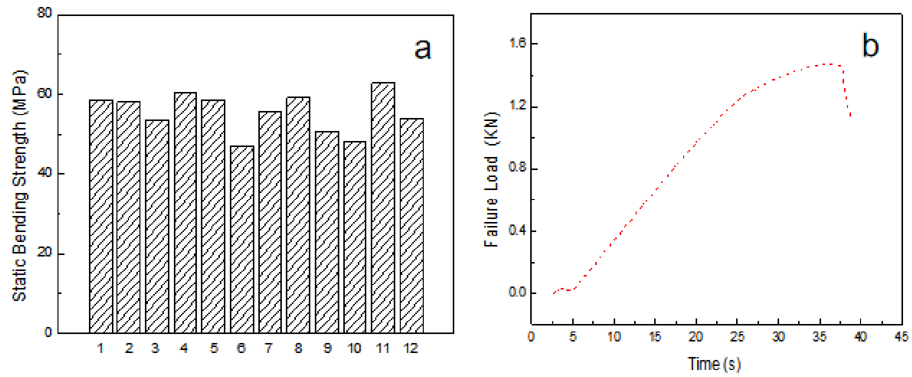

Fig. 8. Static bending strength test results of bamboo filament decorated board

Water absorption and thickness expansion rate

The test results of water absorption quality and water absorption thickness expansion after 24 h of water absorption are shown in Fig. 9. The mean value and standard deviation of water absorption quality were 6.26 g and 0.68, respectively. And the mean value and standard deviation of water absorption thickness expansion were 3.82% and 0.64, respectively. The results show that the 5-layer structure of bamboo filament decorated board has excellent dimensional stability after the composite process.

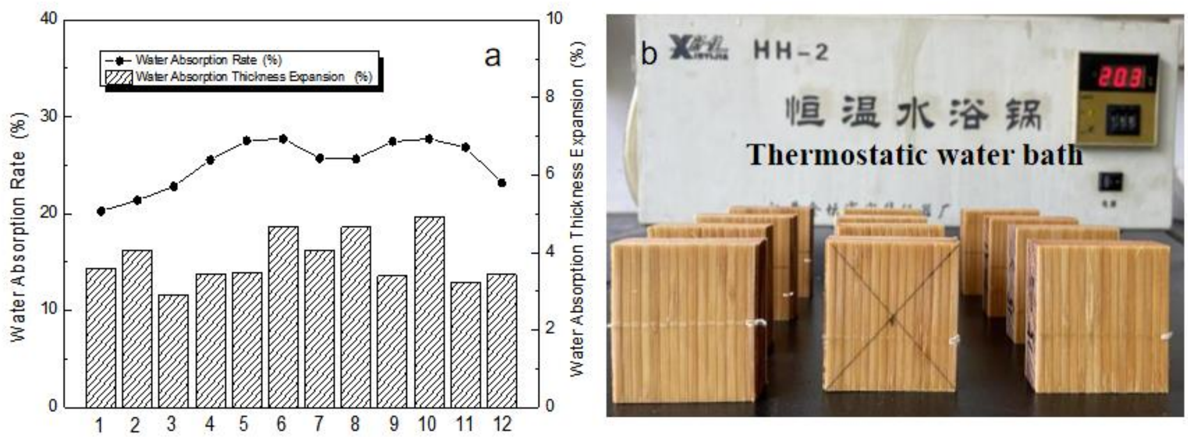

Fig. 9. Water absorption and thickness expansion rate test

CONCLUSIONS

1. Response surface methodology was successfully applied to optimize the production process of bamboo filament decorated board. A quadratic model in terms of *t*, *T*, and *P* was developed, which was as follows:

$$Y = 0.051781X_1 + 0.07491X_2 - 0.32482X_3 - 0.0000964X_1X_2 - 0.0232667X_1X_3 - 0.00041333X_2X_3 - 0.0001452X_1^2 - 0.0001736X_2^2 + 0.00933333X_3^2 - 8.43728.$$

The model was highly significant with a *P*-value of 0.0019. Most of the single factors and interactions of independent variables had a significant influence on the surface bonding strength. But the independent variable of *t*, quadratic term of *t* and *P*, and interactions between *T* and *P* were negligible.

2. The optimum process parameter of surface bonding strength of bamboo filament decorated board optimized by response surface method were 130 s (hot pressing time), 148 ℃ (hot pressing temperature), 2.00 MPa (hot pressing pressure), with a surface bonding strength of 1.13 MPa. The experimental values were in good agreement with the predicted ones and the relative error is less than 5%. The bamboo filament decorated board has excellent bending strength and dimensional stability under optimized process.
3. Bamboo filament decorated board is a new bamboo-wood composite product, and it has excellent mechanical properties and dimensional stability. However, there is no corresponding test standard at present. To facilitate the quality control and promotion of products, a large number of experiments should be combined to complete the construction of a performance evaluation system for the further study.

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