

Investigation of Shear Strength of Engineered Wood Flooring Bonded with PUR by Response Surface Methodology

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The effects of process parameters (adhesive spreading rate, pressing time, and applied pressure) on the response parameter (shear strength) of engineered wood flooring bonded with polyurethane (PUR) were studied by response surface methodology. A mathematical model was established to provide a satisfying prediction for the experimental results observed. The model indicated a high degree of fitting. The results also showed that the major factors were adhesive spreading rate and pressing time. The optimized parameters for highest shear strength of engineered wood flooring were 98 g/m² adhesive spreading rate with pressing time of 24 s and applied pressure of 1.2 MPa, respectively, within certain ranges.

Keywords: PUR; Shear strength; Engineered wood flooring; Response surface methodology

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INTRODUCTION

The use of the engineered wood flooring has increased in daily life because of its natural grain, fine comfort level, and good stability (Chen *et al.* 2015). Bonding technology is key to the production of engineered wood flooring because it directly impacts the product quality and production efficiency. In the traditional bonding technology, the surface layers of engineered wood flooring are under the dual influence of water and heat, which may lead to warping deformations when using urea formaldehyde (UF) or melamine urea formaldehyde (MUF) adhesives. Polyurethane (PUR) adhesive is used to improve the engineered wood flooring because no water is used in this kind of adhesive, which solves the problem of warping deformation (Wang and Ye 2008).

For 20 years, PUR adhesive has been a versatile tool in engineered wood gluing because of its advantages, such as good strength, the absence of moisture, rapid curing at room temperature, avoidance of formaldehyde, and no mixing during processing (Kägi *et al.* 2006; Clauß *et al.* 2011). The wide use of the PUR adhesive has occurred because of its inclusion in European standards for classification and requirements (EN 15425 2008).

Blanchet *et al.* (2003) compared four adhesives used as binders in engineered wood parquet flooring. The shear strengths of the glue lines declined gradually through testing with polyvinyl acetate (PVA) and MUF/UF adhesives, but the performance of the PUR adhesive was constant. Wang *et al.* (2016) evaluated the shear strength of Scots pine wood and its glued joints in a cold climate with various adhesives. They concluded that as the temperature decreased from 20 °C to -50 °C, the shear strength of the tested PUR bond lines decreased by only 5.8%. For dynamic tests of shear strength, the PUR was the most

stable adhesive. Knorz *et al.* (2016) investigated the deformation behavior of bonded ash with the digital image correlation technique (DIC). The results showed that shear strain (SStr) distributions (SStrD) were strongly influenced by adhesive elasticity. The PUR adhesive was more elastic than the other adhesives, and SStrD was limited for PUR in the wood. Ammann and Nieme (2015a, b) studied the fracture toughness of bonded lines of PUR adhesive in European beech wood. The experimental samples were conditioned at the relative humidities (RH) of 50%, 65%, and 95%. Their results showed that the PUR adhesive was more influenced by different RH values (Kläsler *et al.* 2013), and PUR adhesive performed better under dry climatic conditions. Luedtke *et al.* (2015) also investigated PUR-bonded hardwoods for engineered wood products. The results showed that doubling the pressing time did not seem to improve the delamination behavior. However, the primer treatment, which can improve the durability of PUR adhesive (Amen-Chen and Gabriel 2015), had a much more noteworthy influence on shear strength than on delamination.

The main objective of this study was to investigate the effects of process parameters on shear strength of the engineered wood flooring bonded with PUR adhesive. Mathematical modelling *via* response surface methodology (RSM) was conducted to predict the shear strength and to find an optimum technological parameter to support practical applications.

EXPERIMENTAL

Materials

The core board and surface layer of engineered wood were all provided by Dare Parquet Co., Ltd. (Jiangsu, China). Table 1 provides an overview of the core board and surface layer used in this study.

Table 1. Properties of the Core Board and Surface Layer

Materials	Wood Species	Length (mm)	Width (mm)	Thickness (mm)	Moisture Content (%)
Surface layer	Oak	915	130	2	6-8
Core board	Poplar plywood	920	400	12	9-10

The bonding processes were performed using PUR adhesive sample (model number NP2075T, H. B. Fuller, Shanghai, China). The sample was a white solid without formaldehyde. It was a 100% solid product with melting temperature of 150 °C to 180 °C, which can reduce the deformation and warping of wood products.

A glue application machine had the function of melting the adhesive (model number HGS, OMMA corporation, Italy), and the rolling press from the union tool corporation regulated the applied pressure by controlling the distance between the pressing rolls. A fall of 1 mm of pressing rollers indicated a pressure of about 0.4 MPa, 2 mm indicated about 0.8 MPa, and 3 mm indicated 1.2 MPa. The shear strength tests were conducted on a microcomputer control electronic universal testing machine (model number CMT6104, MTS, Shenzhen, China).

Methods

The parameters studied during the continuous cold-pressing of engineered wood flooring with PUR adhesive included adhesive spreading rate, pressing time, and applied pressure, which is represented by fall distance of rollers.

First, the rollers of the gluing machine were warmed to about 150 °C. The PUR adhesive was placed over the hot rollers until it melted. The adhesive spreading rate was controlled to a fixed value and glued to the core boards. Three surface layers were placed on one core board. Afterwards, the boards were kept in laminating machines with controlled pressing pressure and pressing time. In total, 51 samples were produced, *i.e.*, 3 samples for each combination of the process parameters. After the bonding process, all samples were stored in a conditioned room at 23 °C and 50% relative humidity (RH) to reach the required moisture content.

The PUR adhesive was used to bond the surface layers and core boards. The samples preparation was based on the standard for GB/T 17517 (1998) (Fig. 1). The unit for all dimensions was mm. The engineered wood floorings were conditioned in a climate-controlled chamber at 23 °C and 50% RH until the equilibrium moisture content (EMC) was reached. The floorings were cut to size as shown in Fig. 2, which conformed to the standard mentioned above. To avoid deformation and to maintain the stress in shear during the compression test, a metal plate was glued to the surface of the samples (Fig. 3) as suggested in Lang *et al.* (2000).

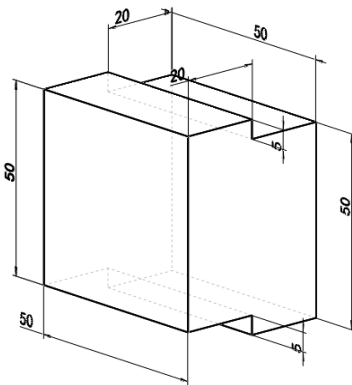


Fig. 1. Standard samples for the test of shear strength

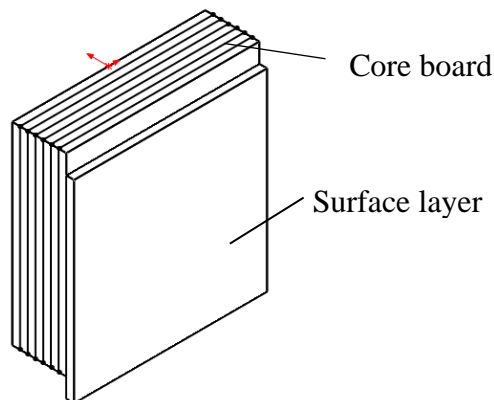


Fig. 2. Flooring samples for the test of shear strength

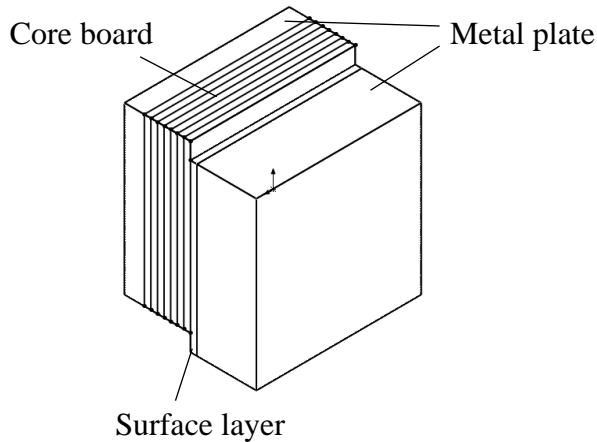


Fig. 3. Metal plate reinforced shear test

The response surface methodology (RSM) used in this study was a combination of mathematical and statistical methods. RSM can build a continuous surface model to evaluate the process parameters and to confirm the range of optimal conditions. The number of test groups is relatively small, which saves human and material resources. This method has been applied to optimize a variety of biological processes (DeMeo *et al.* 1985; Rama *et al.* 1999; Ester *et al.* 2001). In this study, a Box-Behnken design was used to arrange the testing levels (Table 2) (Box and Behnken 1960).

Table 2. Process Parameters and Corresponding Codes and Levels

Process Parameters	Code	Levels		
		-1	0	1
Adhesive spreading rate (g/m ²)	A	60	80	100
Pressing time(s)	B	10	17.5	25
Fall distance of rollers(mm)	C	1	2	3

RESULTS AND DISCUSSION

The shear strengths of engineered wood floorings are shown in Table 3. The standard order on the left-most column was created by the Design-Expert software (Stat-Ease Inc., USA), and the second column on the left was the real testing order, which was randomized to avoid the impacts of testing order on results.

Analysis of Variance (ANOVA)

According to the Box-Behnken experimental design, the corresponding codes and levels are shown in Table 2, and the experimental data is shown in Table 3. The results are shown in the Table 4. The P value of the significant levels of each model and factors used.

As shown in Table 4, the value of the model was less than 0.05, which indicated that it was statistically significant, and so were A, B, and AB. Therefore, the adhesive spreading rate and pressing time had a meaningful effect on the shear strength. In addition, the R² value of 0.94 was close to the adjusted R² of 0.87. This result further indicated that the model achieved a high degree of fit and could predict the experimental results.

Table 3. Experimental Data

Standard Order	Real Order	Process Parameters			Response Parameter
		Adhesive spreading rate (g/m ²)	Pressing time (s)	Fall distance of Rollers (mm)	Shear strength (MPa)
1	8	100	17.5	3	3.31
2	5	60	17.5	1	2.64
3	10	80	25	1	3.30
4	17	80	17.5	2	2.86
5	15	80	17.5	2	2.84
6	16	80	17.5	2	2.83
7	2	100	10	2	3.01
8	14	80	17.5	2	2.80
9	11	80	10	3	2.74
10	12	80	25	3	3.13
11	4	100	25	2	3.14
12	9	80	10	1	2.77
13	13	80	17.5	2	2.83
14	1	60	10	2	2.36
15	7	60	17.5	3	2.63
16	6	100	17.5	1	2.91
17	3	60	25	2	2.92

*Each standard order was mean value of 3 samples

Table 4. ANOVA of the Shear Strength

	Sum of Squares	Degrees of Freedom	Mean Square	F-value	Prob.>F
Model	0.89	9	0.099	13.16	0.0013
A	0.41	1	0.41	54.89	0.0001
B	0.32	1	0.32	42.95	0.0003
C	4.513E-003	1	4.513E-003	0.60	0.4646
AB	0.046	1	0.046	6.13	0.0425
AC	0.042	1	0.042	5.57	0.0503
BC	4.900E-003	1	4.900E-003	0.65	0.4468
A2	7.967E-003	1	7.967E-003	1.06	0.3383
B2	0.020	1	0.020	2.66	0.1471
C2	0.030	1	0.030	3.94	0.0876
R ² =0.94			Adjusted R ² =0.87		

Regression Models and the Accuracy of Models

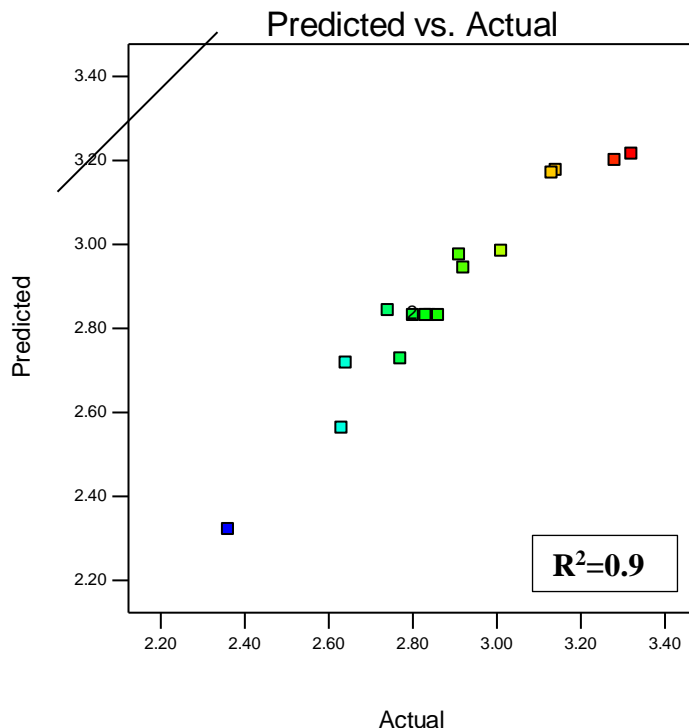
A non-linear regression analysis was adopted to establish the quadratic model of the adhesive shear strength. The regression model of adhesive is shown in Eq. 1, where A is the adhesive spreading rate, B is the pressing time, and C is the fall distance of rollers, in terms of the coded levels.

$$\text{Shear strength} = 2.83 + 0.23A + 0.2B + 0.024C - 0.11A*B + 0.1A*C - 0.035B*C - 0.044A^2 + 0.069B^2 + 0.084C^2 \quad (1)$$

Table 5. ANOVA of the Shear Strength

Process Parameters			Value	Response Parameters
A (g/m ²)	B (s)	C (mm)		Shear strength (MPa)
80	17.5	1	Actual value	2.98
			Predicted value	2.89
			Error (%)	3.2
60	25	2	Actual value	2.82
			Predicted value	2.94
			Error (%)	-4
80	10	3	Actual value	2.99
			Predicted value	2.84
			Error (%)	5.2

The accuracy of the model was verified by three groups of random experiments. The predicted values of the model and the actual values of the tests, as well as the error values are shown in Table 5. The error values in the three groups were very small, which showed that the accuracy of the quadratic model of the adhesive shear strength was high. Thus, the quadratic model could be used to predict the shear strength of the engineered wood flooring. The relevance between the predicted and actual values is shown in Fig 4. The relative coefficient was 0.94.

**Fig. 4.** Relevance graph for shear strength

The effect of shear strength is shown in Fig. 5. In the interval of selected parameters, the shear strength increased with increasing adhesive spreading rate and pressing time. The effect of adhesive spreading rate on the shear strength was due to the fact that not enough adhesive material penetrates wood when spreading was done at a low level, and it formed a starved glueline, which has a negative effect on shear strength. With the increasing

adhesive spreading rate, more adhesive penetrated the wood, which caused a continuous and stable glueline, and the shear strength increased. The shear strength decreased when the adhesive spreading rate was continually increased. Too much adhesive resulted in a thick glueline, which had a bad effect on gluing performance; hence, the shear strength decreased.

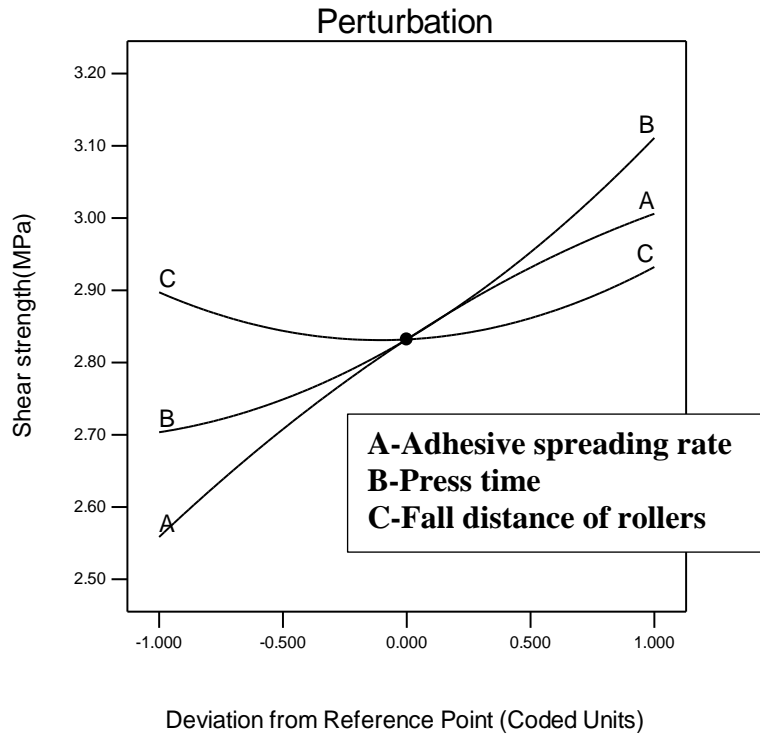


Fig. 5. Tendency showing the effect of three parameters on shear strength

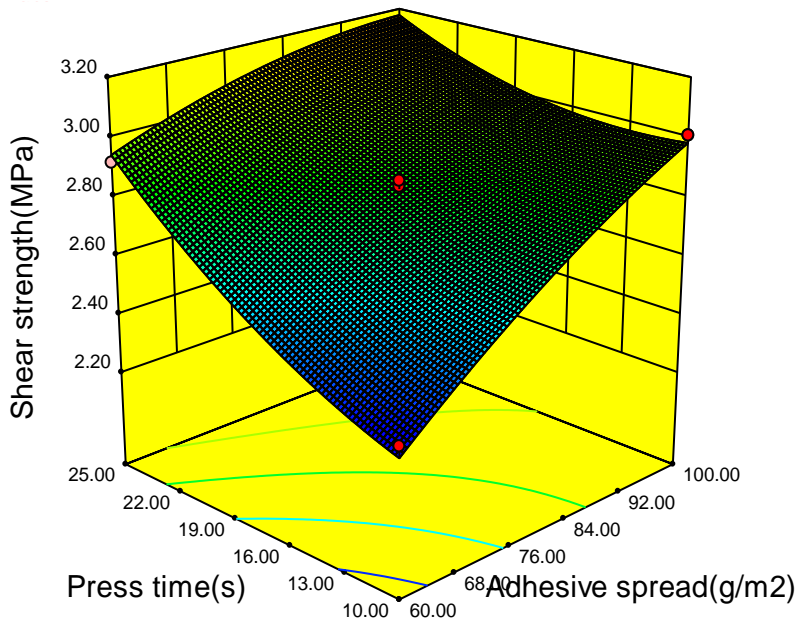


Fig. 6. Response for shear strength

The pressing time was a significant parameter. The mechanism of this effect on shear strength may be that with the extension of pressing time more adhesive penetrated the wood, which was essential to yield a good gluing performance and high shear strength. The shear strength decreased as the pressing time continued to be extended. As pressing time grew, the temperature of adhesive dropped, which may have had a negative effect on the permeation of adhesive, and the shear strength was decreased.

As functions of the major process parameters, the shear strength from mathematical models are shown in Fig. 6. The optimized process parameters to achieve the highest shear strength are shown in Fig. 6. The optimized parameters for highest shear strength were 98 g/m², 24 s, and 3 mm for adhesive spreading rate, pressing time, and fall distance of rollers, respectively. The fall distance of 3 mm represents 1.2 MPa.

CONCLUSIONS

1. The response parameter of shear strength was affected by adhesive spreading rate and pressing time. Applied pressure had insignificant effects on shear strength.
2. The shear strength of engineered wood flooring bonded with PUR adhesive increased with increasing adhesive spreading rate and pressing time.
3. The mathematical models had a high degree of fit and provided a satisfying prediction for the experimental results.
4. The optimized parameters for highest shear strength of engineered wood flooring were 98 g/m² adhesive spreading rate with pressing time of 24 s and applied pressure of 1.2 MPa.

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