QUADRATIC RSM MODELS OF PROCESSING PARAMETERS FOR THREE-LAYER ORIENTED FLAKEBOARDS

Kaiyuan Wang

Graduate Research Assistant

and

Frank Lam

Assistant Professor

Department of Wood Science
Faculty of Forestry
University of British Columbia
Vancouver, BC
CANADA V6T 1Z4

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ABSTRACT

Response surface method with central composite design was used to establish quadratic regression models and surface maps to relate panel properties, including static bending modulus of elasticity, modulus of rupture, internal bond strength, and thickness swelling with flake slenderness ratio, flake orientation, and panel density. A robot mat formation system was used to form the panels with predefined processing parameters. Results indicated that nonlinear models capable of including interactions were required to relate flake slenderness ratio, flake orientation, and panel density to panel properties. An optimization model was developed to obtain the best panel performance with respect to the three factors. The optimized combination of the three factors within the experimental range is: 133 for flake slenderness ratio, 8° for surface flake orientation, and 0.62g/cm^3 for board density.

Keywords: Slenderness ratio, flake orientation, density, response surface method, optimization, oriented strandboard.

INTRODUCTION

The development of acceptable bond strength in a composite mat requires that the mat be compressed to maximize flake to flake contact for bonding. The manner in which flakes are packed in the mat strongly influences the degree of flake contact and the ultimate horizontal distribution of densities in the panel. It is believed that this variable density distribution influences many of the properties of the composite product. Consequently a better understanding of the factors that influence the packing arrangement of wood elements in the mat such as flake geometry, flake orientation, and panel density may lead to enhanced procedures for controlling flake packing and ultimately to improved wood composites.

The individual influence of flake slenderness ratio (flake length to thickness ratio), flake orientation, and panel density on some composite panel properties is well documented (Lehmann 1974; Moslemi 1974; Kelly 1977; Geimer et al. 1975; Geimer 1982; Canadido et al., 1988, 1990; McNatt et al., 1992; Doyle et al., 1996). Generally speaking, most of the panel properties—bending modulus of rupture (MOR), bending modulus of elasticity (MOE), and internal bond strength (IB) improve as the three factors increase. However, there exist some inconsistencies with thickness swelling (TS), which is believed to be strongly influenced by the interaction between flake length and density (Ethington 1978). Furthermore, although it is well known that IB of a three-layer oriented strandboard (OSB) is strongly influenced by the core density, the complicated interaction of flake geometry, flake orien-

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tation, density variation, and IB is not clearly understood. The complex influence of manufacture parameters on panel properties cannot be accurately explained by simple linear regression models. Higher level models such as quadratic models should be considered to explain the complexity of interactions between factors. Finally, optimization of these variables to effectively and efficiently produce better quality OSB is imperative.

Response surface method (RSM) is a collection of mathematical and statistical (regression) techniques that are useful for modeling and optimizing a response of interest that is influenced by several variables. It encompasses experiment design, mathematical model development, and result optimization analysis (Mao 1981; Khuri and Cornell 1996). The advantage of using RSM is that it can reduce the total number of experiments and still provide reasonable explanations of the results. It can also provide highly accurate models to reflect the nature of the experiment. This method has been successfully applied to maximize veneer yield and quality (Warren and Hailey 1980) and maximize the use of paper birch in a laboratory-produced three-layer aspen oriented strandboard with minimum core resin spread (Au et al., 1992). Recently, this method was also used to reveal the interaction effect of the critical pressing and moisture parameters (platen temperature, initial creep closing position, and face moisture content) on the properties of a three-layer OSB (Hsu 1996). Even though optimized pressing parameters were obtained, the interaction relationship between panel structure and panel properties has not been fully explored.

Previous research has shown that the robot mat formation system is a very reliable tool to link the computer simulated panels with robot formed experimental panels (Wang and Lam 1998). Combined with the simulation program MAT (Lu et al., 1998), the horizontal density distribution (HDD) of a mat can be accurately determined. In this study, robot mat formation technology is applied to obtain replicate panels with high repeatability and accurate predefined surface flake orientation to study the relationship between panel structure and properties (IB, TS, MOR, MOE).

This study has two objectives:

(1) To investigate the influence of the interactions of flake slenderness ratio, flake orientation, and panel density on panel properties—MOE, MOR, IB, and TS. Regression models will be developed and three-dimensional surface response maps will be plotted by applying RSM;
(2) To explore how the combination of variables will affect the panel properties and to establish a combination of variables that exhibits optimal properties under the controlled boundary conditions.

EXPERIMENTAL

Experiment design

Three variables were selected, namely, slenderness ratio, flake orientation and panel density. Four responses were considered in this study: static bending MOR, MOE, IB, and TS. Response surface method—second order central composite design (Mao 1981; Khuri and Cornell 1996)— was used to develop the regression models. The model can be written as:

$$F(x_1, x_2, \dots, x_m) = b_0 + \sum_{j=1}^{m} b_j x_j + \sum_{\substack{i=1 \\ i<j}}^{m-1} \sum_{j=2}^{m} b_{ij} x_i x_j + \sum_{j=1}^{m} b_{jj} x_j^2 \quad (1)$$

where b_0, b_j, b_{ij}, and b_{jj} are regression coefficients; x_i and x_j are input variables in the regression function; $m=3$ is the total number of variables; and $F(x_1, x_2, \dots, x_m)$ is the response.

A central composite rotatable design[1] was applied to provide equal precision of estimation

[1] An experiment design is known as a rotatable design if the variance of the predicted response at some design point is a function only of the distance of the point from the design center and is not a function of direction.

TABLE 1. *The actual (scaled) experimental values used in the experiment design.*

Experiment No.	Slenderness ratio X_1	Flake orientation X_2 (°)	Board density X_3 (g/cm³)
1	100 (−1)	8 (−1)	0.54 (−1)
2	150 (1)	8 (−1)	0.54 (−1)
3	100 (−1)	32 (1)	0.54 (−1)
4	150 (1)	32 (1)	0.54 (−1)
5	100 (−1)	8 (−1)	0.66 (1)
6	150 (1)	8 (−1)	0.66 (1)
7	100 (−1)	32 (1)	0.66 (1)
8	150 (1)	32 (1)	0.66 (1)
9	83 (−1.682)	20 (0)	0.6 (0)
10	167 (+1.682)	20 (0)	0.6 (0)
11	125 (0)	0 (−1.682)	0.6 (0)
12	125 (0)	40 (+1.682)	0.6 (0)
13	125 (0)	20 (0)	0.5 (−1.682)
14	125 (0)	20 (0)	0.7 (+1.682)
15	125 (0)	20 (0)	0.6 (0)
16	125 (0)	20 (0)	0.6 (0)
17	125 (0)	20 (0)	0.6 (0)
18	125 (0)	20 (0)	0.6 (0)
19	125 (0)	20 (0)	0.6 (0)
20	125 (0)	20 (0)	0.6 (0)

in all directions from the center points to design points (combination of variables) on the response surface. The number of total design points (N) was calculated by the following formula:

$$N = m_c + 2m + m_0 \qquad (2)$$

where m_c = the factorial portion of the design = 2^m; m = total number of variables (these design points are distributed on a sphere with radial $r = \sqrt{m}$); 2m = the axial portion of the design (these design points are distributed on a sphere with radial $r = \gamma$ where γ depends on m_c and determines the rotatability of the central composite design; in this study $\gamma = 1.682$ was obtained from design table); m_0 = the number of the central points (these design points are distributed on a sphere with radial r = 0; in this study $m_0 = 6$ was obtained from design table).

Following a central composite rotatable design described by Khuri and Cornell (1996), $N = 2^3 + 2 * 3 + 6 = 20$; therefore, a total of 20 design points were assigned in the experiment design. Table 1 describes the detailed experiment design with actual and scaled experimental values. Three replicate mats were manufactured for each design point, except for each center point where only one panel was made. Therefore, the total number of the mats manufactured for this experiment is $14 * 3 + 6 = 48$.

Coded variables were used in place of the input variables in the fitted model to facilitate the construction of experimental designs with easy computation. Also accurate estimation of the model coefficients and enhanced interpretability of the coefficient estimates can be achieved with coded variables. A convenient coding formula for defining the coded (scaled) variable, x_j, is:

$$x_j = \frac{X_j - X_{0j}}{\Delta_j}, \qquad j = 1 \ldots m \qquad (3)$$

where

$$X_{0j} = \frac{X_{1j} + X_{2j}}{2}, \qquad \Delta_j = \frac{X_{2j} - X_{0j}}{\gamma}$$

X_{1j}, X_{2j} are the low and high levels of variable j, respectively; X_{0j} is the zero level of variable j; Δ_j is called the level distance of variable j. Therefore a set of X_j (X_{2j}, $X_{0j} + \Delta_j$, X_{0j}, X_{0j} −

Δ_j, X_{1j}) can be scaled to a set of x_j (γ, 1, 0, -1, $-\gamma$).

In this study, each of the five levels of a variable is scaled separately to -1.682, -1, 0, 1, 1.682. Combining the information obtained from the practical experience and previous research results, the zero level of the actual variable value is defined as 125 for slenderness ratio, 20° for flake orientation, and 0.6g/cm^3 for panel density. Based on Eq. (3), the conversion equations to link the actual variable values (X_j) and the scaled variable values (x_j) are:

(1) Slenderness ratio $X_1 = 125 + 25x_1$

(2) Flake orientation (°) $X_2 = 20 + 12x_2$

(3) Panel density (g/cm^3) $X_3 = 0.6 + 0.06x_3$

Materials and panel manufacturing

Fifteen kinds of three-layer oriented flakeboards (30% oriented face and bottom, 70% random core) were formed under the following conditions:
Five flake slenderness ratios, surface flake orientations, and target board densities are shown in Table 1. The slenderness ratio is controlled by fixing flake thickness as 0.6 mm and changing flake length corresponding to 50, 60 75, 90, and 100 mm.

The alignment of flakes in a flakeboard can be described by a normal distribution (Lau 1981). The mean is assumed to be zero because of the symmetry characteristics of the true distribution of the angles about the principal alignment direction, and the standard deviation of the angles of alignment is calculated by the following formula:

$$S = \left(\frac{\pi}{2}\right)^{1/2} \bar{\theta} \qquad (4)$$

where S = standard deviation of the aligned angles; $\bar{\theta}$ = the absolute range of alignment angle. The definition of flake orientation in this study is shown in Fig. 1. A random number generation program *Normal* was developed to generate the flake orientation values.

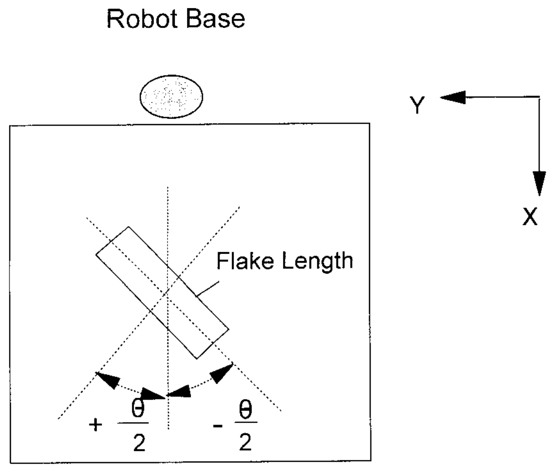

FIG. 1. Definition of flake orientation in a mat.

The inputs are the absolute range of alignment angle in a mat and the total number of flakes in surface layers. The output is the normally distributed orientation of each flake in the mat. The location of the centroid of each flake can be assumed random based on Poisson distribution (Lu et al. 1998). These values were used in the robot mat formation process to control the placement and orientation of the flakes in the surface layers.

Target panel density at 10% moisture content and mat size are also inputs to the simulation program MAT (Lu et al. 1998). Assuming that a flakeboard is made of several flake layers parallel to a plane, the panel density is controlled by the total number of flakes placed in a mat (N_f) which can be calculated from:

$$N_f = \frac{\gamma_m ABT}{\gamma_f abt} \qquad (5)$$

where A, B, T are panel length, width and thickness; a, b, t are flake length, width and thickness; γ_m is the board density; and γ_f is the flake density. Linear regression is used to adjust the real panel density to target board density.

The species of the flakes was trembling aspen (*Populus tremuloides*) with specific gravity 0.420 based on oven-dry weight and green volume. Phenol-formaldehyde powder resin CASCOPHEN W91B, 6% solids (based on the oven-dry wood weight) was used. Blended flakes were deposited into mats by a robot system and then hot pressed at 180°C to 10-mm panel thickness stop, using total 6 minutes to press including 0.8 minutes closing time by a computer-controlled 300 × 300 mm hot press. The target mat size was 250 mm × 250 mm × 10 mm (length × width × thickness), and the actual averaged mat size was 250 mm × 250 mm × 10.3 mm.

Optimization method—FIACCO AND McCORMICK (SUMT ALGORITHM)

A minimization algorithm FIACCO AND McCORMICK (SUMT ALGORITHM) was obtained from Microsoft Fortran Power Station 4.0 mathematical library to find the minimum of a multivariable, nonlinear function $F(X_1, X_2, \ldots, X_m)$ subject to inequality constraints:

$$\text{Minimize} \quad F(X_1, X_2, \ldots, X_m)$$

$$\text{Subject to} \quad G_K \leq X_K \leq H_K, \quad K = 1, 2, \ldots, m \qquad (6)$$

where X_1, X_2 ... X_m are independent variables. The upper and lower constraints H_K and G_K are either constants or functions of the independent variables (Kuester and Mize 1973). In this study m = 3 and when using coded variables, the boundary conditions for each variable are shown below:

For slenderness ratio,

$$-1.682 \leq X_1 \leq 1.682$$

For flake orientation,

$$-1.682 \leq X_2 \leq 1.682$$

For target board density,

$$-1.682 \leq X_3 \leq 1.682$$

In order to find the maximum of a multivariable, nonlinear function $F(X_1, X_2, \ldots, X_m)$, the following equation is defined:

$$\text{Max } F(X_1, X_2, \ldots, X_m) = -\text{Min}(-F(X_1, X_2, \ldots, X_m)) \qquad (7)$$

After the surface response equation of each response is obtained, Linear Combination Method can be used to optimize the combination of four responses (overall performance criterion) simultaneously (Chen et al. 1981). First the value of the objective function is normalized within the range of 0 to 1 to minimize the influence of different numerical levels of each response function on the overall response as:

$$F_j'(X) = \frac{F_j(X) - \alpha_j}{\beta_j - \alpha_j} \qquad (0 \leq F_j'(X) \leq 1) \quad (8)$$

and

$$\alpha_j \leq F_j(X) \leq \beta_j \qquad (j = 1, 2, \ldots, q)$$

where α_j, and β_j are lower bound and upper bound; $F_j(X)$ is each response function; q is the total number of responses studied. $F_j'(X)$ is the normalized response function.

The principle of this model is shown in the following equation after normalizing:

$$F(X_1, X_2, \ldots, X_m) = \sum_{i=1}^{q} W_i F_i'(X_1, X_2, \ldots, X_m) \qquad (9)$$

Here $F(X_1, X_2 \ldots, X_m)$ is the combination response function; W_i (i = 1, 2, ... q) is called combination factor determined by the importance of each response; q = 4 is the total number of the responses studied. $F'(X_1, X_2, \ldots, X_m)$ is the individual normalized response function. For example, when each response is equally important to the overall performance criterion (overall response), then W_i = 1. In this study by applying correlation analysis of the four responses MOR, MOE, IB, and TS, it is found that MOE and MOR are highly correlated (correlation coefficient equals 0.93). W_i is set to ½ for MOE and MOR to eliminate the possible dominating influence of MOE and MOR on the overall response. W_i is set to 1 for IB and −1 for TS when assuming equal importance of IB and TS and also considering the negative effect of TS on the overall response. Based on judgment and experience,

TABLE 2. *The experimental results of the four responses.*

Experiment No	MOE (MPa)	MOR (MPa)	IB (MPa)	TS (%)
1	6,158.53[a] (716.47[e])	28.95[a] (4.35)	0.545[b] (0.073)	25.83[b] (0.027)
2	6,315.90 (784.16)	29.05 (4.73)	0.402 (0.059)	24.18 (0.031)
3	4,916.99 (394.33)	23.73 (2.47)	0.428 (0.068)	27.42 (0.043)
4	4,988.56 (715.79)	24.65 (5.0)	0.387 (0.082)	25.34 (0.034)
5	8,140.38 (424.97)	44.40 (3.28)	0.546 (0.04)	48.65 (0.074)
6	8,279.95 (609.09)	49.05 (3.67)	0.535 (0.074)	40.73 (0.068)
7	6,315.90 (451.29)	36.06 (2.81)	0.518 (0.043)	49.61 (0.077)
8	6,411.24 (482.33)	37.63 (5.63)	0.539 (0.073)	39.21 (0.075)
9	5,091.60 (1142.8)	24.70 (7.61)	0.502 (0.061)	40.72 (0.074)
10	6,427.46 (407.23)	34.07 (3.07)	0.471 (0.063)	29.59 (0.060)
11	7,414.66 (665.73)	35.04 (4.03)	0.580 (0.073)	33.46 (0.063)
12	4,371.92 (646.67)	17.90 (3.16)	0.532 (0.082)	31.98 (0.078)
13	3,091.73 (401.8)	12.22 (3.14)	0.385 (0.071)	21.22 (0.05)
14	7,068.82 (774.43)	38.35 (5.45)	0.659 (0.068)	46.43 (0.051)
15	5,442.59[c] (502.46)	24.62[c] (2.43)	0.629[d] (0.101)	27.99[d] (0.05)
16	5,806.11 (348.6)	26.99 (2.25)	0.600 (0.104)	24.71 (0.041)
17	6,324.46 (650.97)	29.27 (3.65)	0.660 (0.118)	30.08 (0.049)
18	5,673.11 (538.07)	26.94 (4.33)	0.623 (0.08)	30.70 (0.031)
19	6,270.73 (362.01)	29.16 (2.71)	0.618 (0.111)	30.04 (0.06)
20	6,005.39 (745.6)	29.04 (4.08)	0.631 (0.105)	29.64 (0.015)

[a] For experiment no. 1-14, MOE, MOR data is the average of 9 specimens
[b] For experiment no. 1-14, IB, TS data is the average of 12 specimens
[c] For experiment no. 15-20, MOE, MOR data is the average of 3 specimens
[d] For experiment no. 15-20, IB, TS data is the average of 4 specimens
[e] Data in parentheses represent standard deviation.

W_i can also be adjusted to meet other special requirements of a particular property.

Testing method

The density (weight and volume at around 10% moisture content) of the panels (250 × 250 mm) was measured before cutting the panels into 230 × 230-mm size to reduce the edge effect on the performance of the panels. The boards were then cut into 3 specimens prepared for static bending MOE tests (specimen size: 230 × 40 mm), 4 for IB tests (size: 50 × 50 mm), and 4 for TS tests (50 × 50 mm). The density of each specimen was measured before testing.

The specimens for MOR and MOE tests were tested on an MTS Sintech 30/D test machine according to ASTM D 1037-93 (1994) using displacement-control at a loading rate of 6 mm/min under 3-point testing mode. A span of 200 mm rather than standard 240 mm was used due to the limitation of panel size. Then IB tests and TS tests were performed following the CSA Standard Can/CSA-O437.0-93, Standards on OSB and waferboard (1994). The ultimate strength and the failure position were recorded for each IB sample. Thickness swelling of each specimen was measured after water soaking for 24 hours at 20°C.

RESULTS AND DISCUSSIONS

Relationship between three variables and panel properties

Table 2 shows the experiment results (averaged experiment values) of the four responses. The averaged value in each experiment was used in RSM modeling. RSM-MOR, RSM-MOE, RSM-IB, and RSM-TS are the results obtained by using the scaled variable data.

MOR—Modulus of rupture in static bending

The expression of the model equation in terms of coded factors is:

RSM-MOR (MPa)

$$= 27.44 + 1.684A - 4.261\theta + 7.667D + 2.121A^2 + 1.09\theta^2 + 0.672D^2 - 0.283A \times \theta + 0.649A \times D - 1.267\theta \times D \quad (10)$$

where A refers to coded flake slenderness ratio, θ refers to coded flake orientation, and D refers to coded board density.
The expression of the model equation in terms of actual factors is:

MOR (MPa)

$$= 85.33 - 1.024A' + 0.502\theta' - 126.881D' + 0.003A'^2 + 0.008\theta'^2 + 196.84D'^2 - 0.001A' \times \theta' + 0.433A' \times D' - 1.76\theta' \times D' \quad (11)$$

where A′ refers to actual flake slenderness ratio, θ′ refers to actual flake orientation, and D′ refers to actual board density.

Equation (10) shows that the significance of factors affecting RSM-MOR was in the following order: D, θ, A^2, A, θ × D, θ^2, D^2, A × D and A × θ. In general, increase of board density and flake slenderness ratio and decrease of flake orientation resulted in increase of MOR. The coefficient of determination of this regression model is 0.924. The relationships between MOR and the three factors are shown graphically in Fig. 2.

MOE—Modulus of elasticity in static bending

The expression of the model equation in terms of coded factors is:

RSM-MOE (MPa)

$$= 5891.971 + 198.472A - 833.192\theta + 985.262D + 129.596A^2 + 176.874\theta^2 - 110.499D^2 - 16.254A \times \theta + 0.747A \times D - 140.539\theta \times D \quad (12)$$

The expression of the model equation in terms of actual factors is:

MOE (MPa)

$$= -13{,}141.01 - 43.568A' + 3.149\theta' + 56{,}592.281D' + 0.209A'^2 + 1.277\theta'^2 - 30{,}233.493D'^2 - 0.054A' \times \theta' + 0.498A' \times D' - 195.193\theta' \times D' \quad (13)$$

Equation (12) shows that the significance of factors affecting RSM-MOE was in the following order: D, θ, A, θ^2, θ × D, A^2, D^2, A × θ and A × D. In general, increasing board density and flake slenderness ratio and decreasing flake orientation resulted in an increase of MOE. The coefficient of determination of this regression model is 0.928. The relationships between MOE and the three factors are shown graphically in Fig. 3.

IB—Internal bond strength

The expression of the model equation in terms of coded factors is:

RSM-IB (MPa)

$$= 0.628 - 0.0165A - 0.0173\theta + 0.0612D - 0.0554A^2 - 0.0308\theta^2 - 0.0428D^2 + 0.0166A \times \theta + 0.0242A \times D + 0.0136\theta \times D \quad (14)$$

The expression of the model equation in terms of actual factors is:

IB (MPa)

$$= -4.11 + 0.011A' - 0.011\theta' + 13.102D' - 8.8\text{E-}05A'^2 - 2.2\text{E-}04\theta'^2 + 12.061D'^2 + 5.52\text{E-}05A' \times \theta' + 0.016A' \times D' + 0.019\theta' \times D' \quad (15)$$

Equation (14) shows that the significance of factors affecting RSM-IB was in the following order: D, A^2, D^2, θ^2, A × D, θ, A × θ, A and θ × D. In general, increase of board density resulted in increase of IB. The effects of flake slenderness ratio and flake orientation on IB are more complicated. In this study at a lower flake slenderness ratio, increasing flake ori-

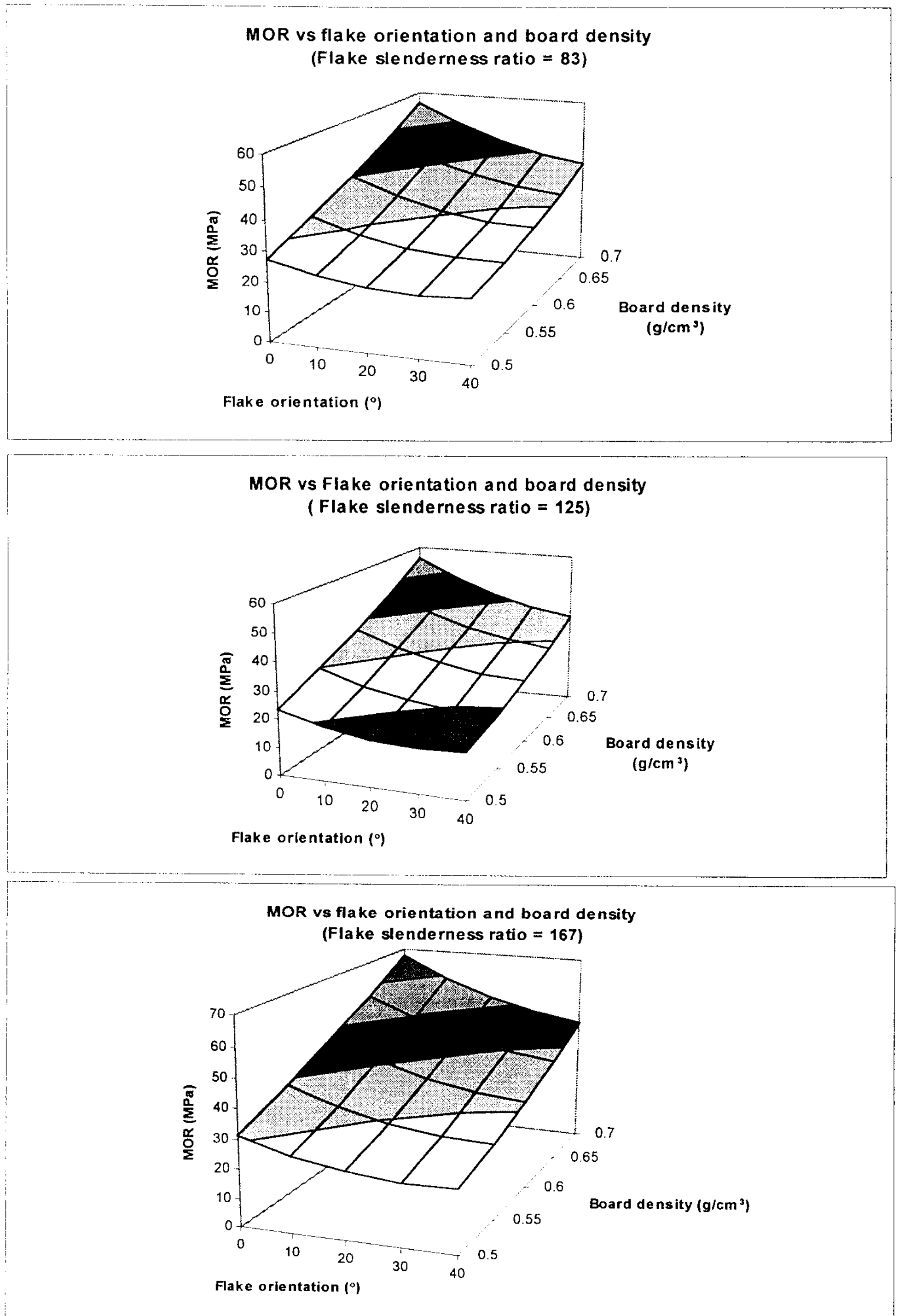

FIG. 2. 3-Dimensional response surface of static bending MOR.

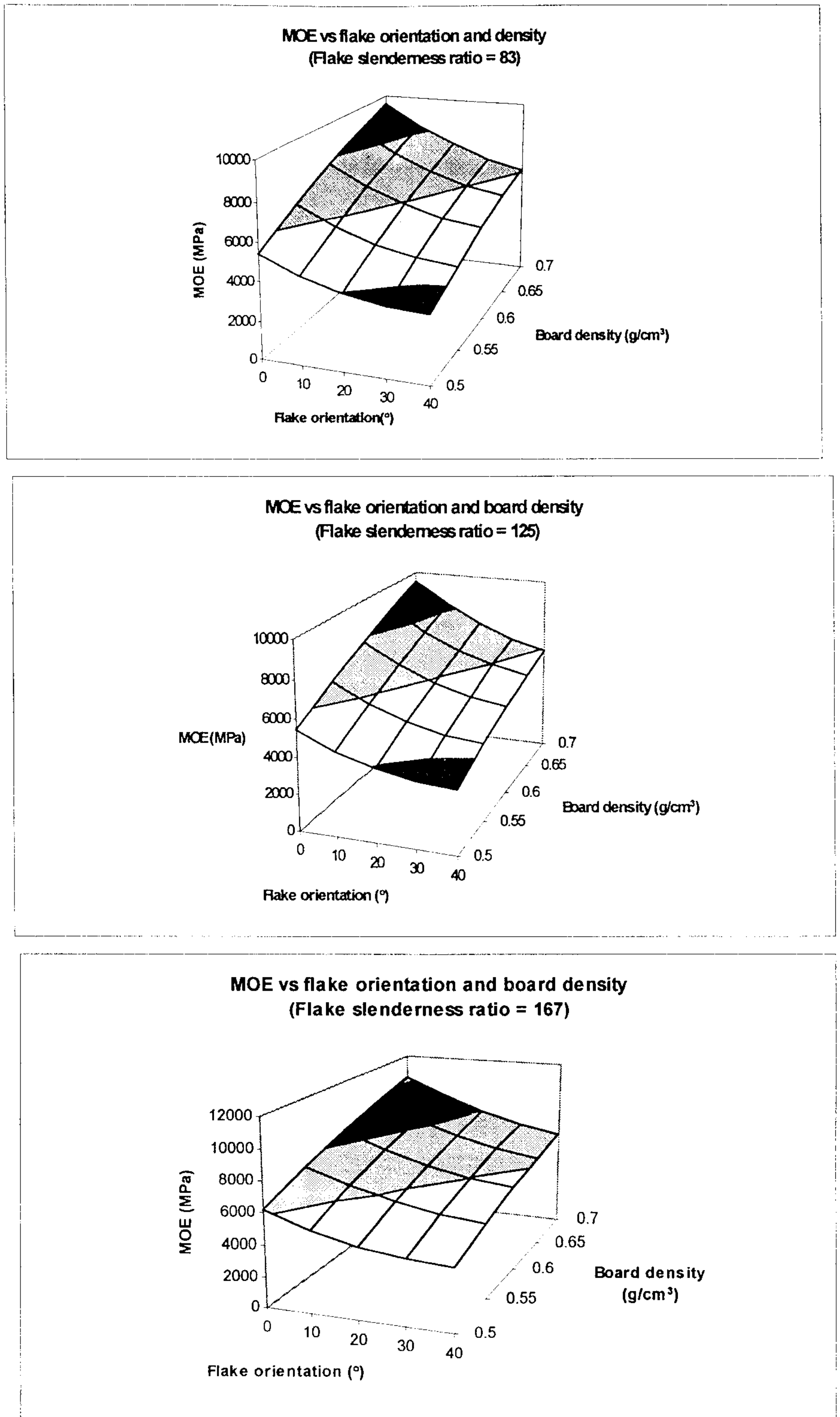

FIG. 3. 3-Dimensional response surface of static bending MOE.

entation resulted in decrease of IB. However at a higher flake slenderness ratio, the influence of flake orientation is not significant. When the surface flakes are aligned well, increase of flake slenderness ratio resulted in decrease of IB value at a lower density. At a higher density, this trend didn't exist. Although IB is strongly controlled by core density and may be flake orientation in the core layer, other parameters were not considered as variables in this study. In the case of low flake slenderness ratio and low density, the core density may be partially influenced by the interaction between flake slenderness ratio and surface flake orientation, which would in turn influence IB. The coefficient of determination of this regression model is 0.967. The relationships between IB and the three factors are shown graphically in Fig. 4.

TS—Thickness swelling 24h

The expression of the model equation in terms of coded factors is:

$$\begin{aligned}\text{RSM-TS }(\%) &= 28.831 - 2.985A - 0.022\theta + 8.627D \\ &\quad + 2.419A^2 + 1.553\theta^2 + 1.948D^2 \\ &\quad - 0.363A \times \theta - 1.823A \times D \\ &\quad - 0.414\theta \times D \qquad (16)\end{aligned}$$

The expression of the model equation in terms of actual factors is:

$$\begin{aligned}\text{TS }(\%) &= 118.036 - 0.33A' + 0.057\theta' \\ &\quad - 348.89D' + 0.004A'^2 + 0.011\theta'^2 \\ &\quad + 548.112D'^2 - 0.001A' \times \theta' \\ &\quad - 1.216A' \times D' - 0.575\theta' \times D \qquad (17)\end{aligned}$$

Equation (16) shows that the significance of factors affecting RSM-TS was in the following order: D, A, A^2, D^2, A × D, θ^2, θ × D, A × θ and θ. In general, increase of board density resulted in increase of TS. At a higher board density, increase of flake slenderness ratio resulted in decrease of TS. However, at a lower board density, the effect of flake slenderness ratio on TS was not significant. The effect of flake orientation on TS was not as significant as the effect of board density and flake slenderness ratio. The coefficient of determination of this regression model is 0.984. The relationships between TS and the three factors are shown graphically in Fig. 5.

By applying a t-test to examine the examine the significance of the coefficient factors (significant at $\alpha = 0.2$) in regression models (10), (12), (14), and (16), the sequences of the significant factors are listed in the Table 3. The results are similar to the significance testing results of the coefficient factors in Eqs. (11), (13), (15), and (17) by applying the elimination method.

Optimization of overall properties

By running the optimization program, from Eqs. (10), (12), (14), and (16), the lower bound (α_j) and upper bound (β_j) and corresponding A, θ, and D to get the optimum response of each response are shown in Table 4. As an example, for the property MOR, the minimum and maximum test values of 15.39 MPa and 67.54 Mpa were set as the lower and upper bounds, respectively. The optimization result for MOR was obtained when aspect ratio equaled 167, flake orientation angle equaled 0°, and board density equaled 0.7 g/cm³.

By applying the combination factors W_i, the overall criteria equation using scaled factors is:

$$\begin{aligned}\text{OVERALL CRITERIA} &= \tfrac{1}{2}\text{RSM-MOR}' + \tfrac{1}{2}\text{RSM-MOE}' \\ &\quad + \text{RSM-IB}' - \text{RSM-TS}'\end{aligned}$$

The optimized overall value is obtained when A = 0.299, θ = −1.00, and D = 0.415. The corresponding actual values for three variables are: A′ = 133, θ′ = 8°, D′ = 0.62 g/cm³. It is noted that the optimization process is dependent on the choice of W_i which can be selected based on experience and judgment to customize panel properties. Finally, vertical density

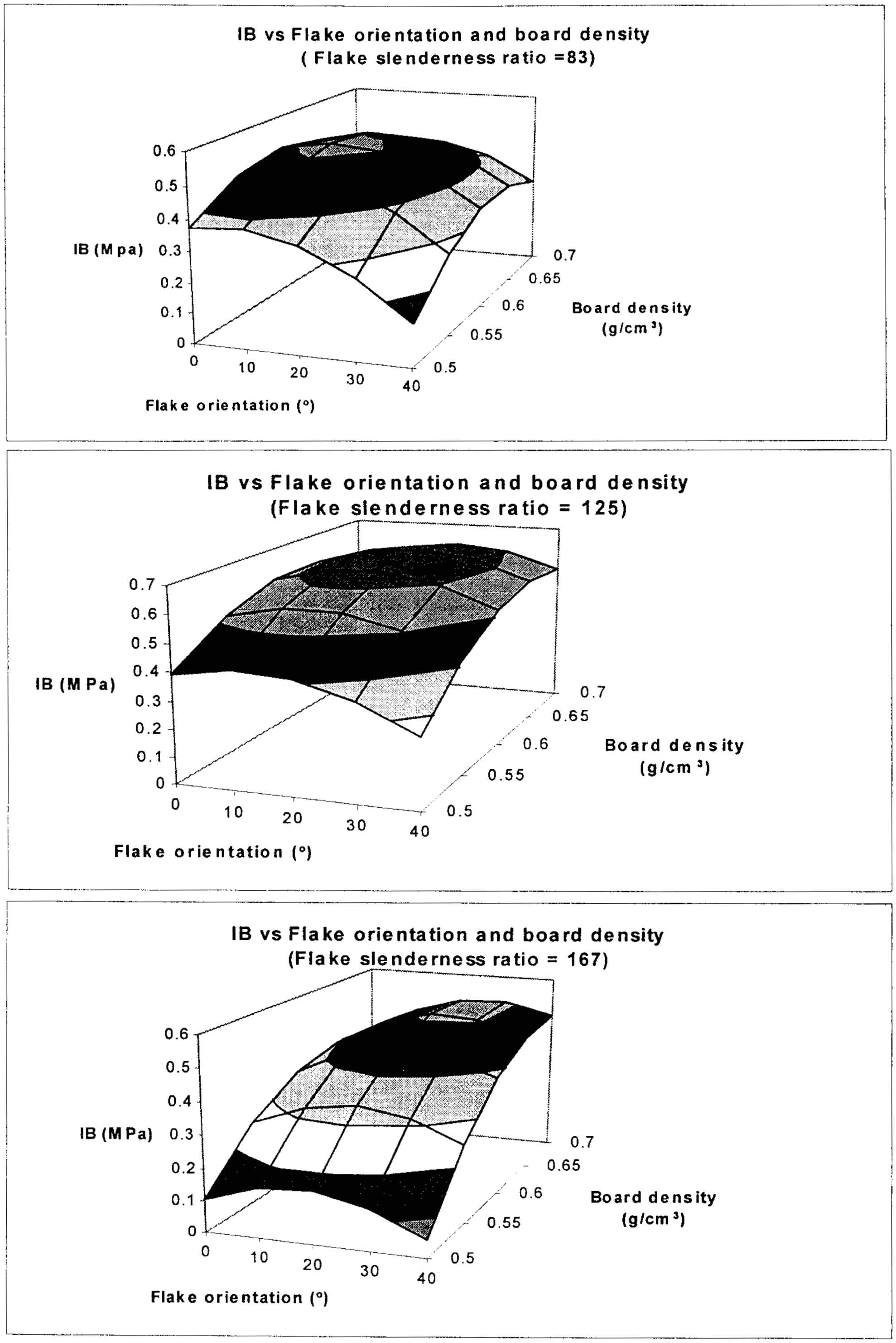

FIG. 4. 3-Dimensional response surface of internal bond strength.

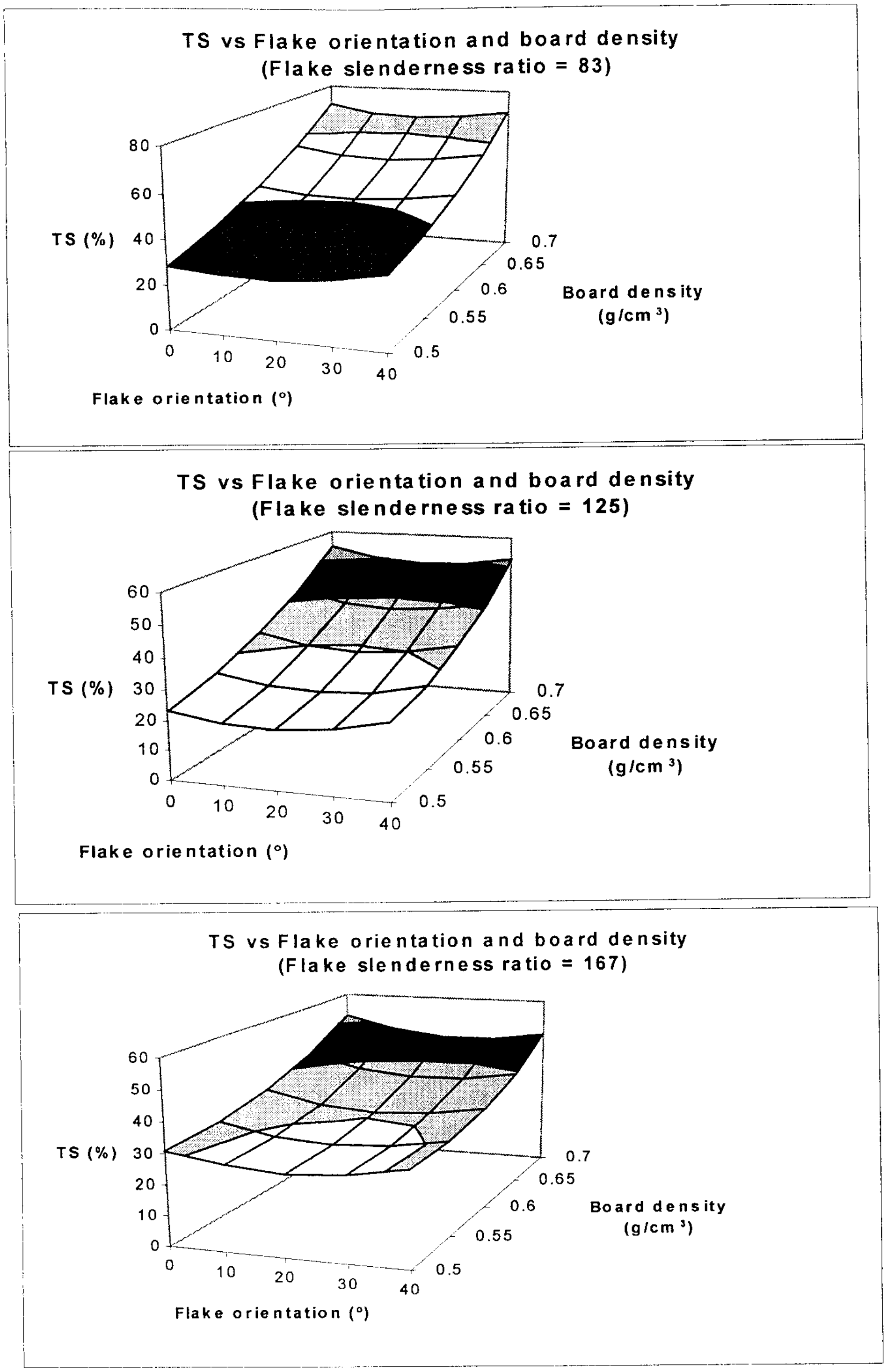

FIG. 5. 3-Dimensional response surface of thickness swelling.

TABLE 3. *Sequences of the significant factors in four responses.*

	A	θ	D	A^2	$θ^2$	D^2	A × θ	A × D	θ × D
MOR	4	2	1	3	—*	—	—	—	—
MOE	—	2	1	—	—	—	—	—	—
IB	6	—	1	2	4	3	7	5	—
TS	2	—	1	3	5	4	—	6	—

* — means not significant.

distribution and pressing parameters were not considered in this study. These parameters significantly influence panel properties and will be considered in future studies.

CONCLUSIONS

From the limited data collected in this study and the statistical analysis made using response surface method and optimizing method, the following conclusions are drawn:

1. Response surface method with central composite design provided a very effective tool to study the interaction effect of variables on target response;
2. Quadratic models provided a good fit for the relationship between the three factors—flake slenderness ratio, flake orientation, and panel density studied. In this study it was found that increase of density resulted in increase of all properties. However, the effect of flake slenderness ratio and flake orientation on panel properties is more complicated. Significant interactions exist for the three variables on each property and should be considered when providing a detailed model for in-situ OSB production;
3. An overall criteria evaluation method based on linear combination method was used. By setting ½, ½, 1, −1 as W_i for MOR, MOE, IB, and TS respectively and applying the optimization program, the best combination of the three factors that can provide best panel properties in this study are: Flake slenderness ratio = 133, Flake orientation = 8°, Board density = 0.62 g/cm³.

TABLE 4. *Optimization results of each response.*

	α_j	β_j	A	θ	D
MOR	15.39	67.54	167	0	0.7
MOE	3362	10284	167	0	0.7
IB	0	0.65	124	18	0.64
TS	19.8	70.5	124	17	0.5

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