Prediction of the Color Variation of Moso Bamboo during CO_2 Laser Thermal Modification

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Thermal modification is widely used for bamboo materials as an efficient modification method. CO_2 laser with the advantages of high energy density, short process period, non-pollution, *etc.* could be applied as a novel thermal treatment for wooden and bamboo materials processing. The laser intensity argumentation of power, motion arguments of feed rate, and sweep width for laser emitter were selected as input arguments for treating the Moso bamboo surface. The lightness variation and total color variation (ΔL^* and ΔE^*) were collected using a portable colorimeter to describe the bamboo surface color variation after laser irradiation. Response surface methodology was chosen for designing experiments and modeling. The results showed that the increase of laser power had a positive influence on increasing the absolute values of ΔL^* and ΔE^*, but the feed rate of laser emitter and sweep width increasing had opposite effects on absolute values of ΔL^* and ΔE^*. The quadratic models of ΔL^* and ΔE^* created by response surface methodology were competent for describing the relationship between laser processing arguments and color indexes of ΔL^* and ΔE^*. This approach will be useful for selecting suitable and desirable processing arguments to get the surface color of bamboo productions.

Keywords: Bamboo; Laser; Color; Thermal treatment; Response surface methodology

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INTRODUCTION

As a natural fiber material, bamboo has advantages such as excellent mechanical properties, short growth cycle, and renewable utilization (Chen *et al.* 2017; Lv *et al.* 2019; Fang *et al.* 2020). It is widely applied for producing bamboo-based composites, glue-laminated bamboo, and further used to manufacture construction, furniture, floorings, handiwork, architectural structure, *etc.* (Li *et al.* 2018a).

Moso bamboo (*Phyllostachys pubescens*) is a common species of bamboo and is widely distributed in China. It is composed of cellulose, hemicellulose, lignin, carbohydrates, *etc.* (Meng *et al.* 2016). The chemical composition of carbohydrates is normally higher than wood, which makes bamboo susceptible to mold, fungal decay, and insect attack (Gao *et al.* 2018; Lee *et al.* 2018; Yu *et al.* 2018; Mo and Zhang 2019). Because of the presence of hydrophilic groups in bamboo, dimensional instability is significantly affected by absorption and desorption of water or vapor, which directly affects the application field of bamboo materials (Chen *et al.* 2018; Lou *et al.* 2020). Thermal treatment is a common and effective method to improve the performance of bamboo, such as its shape stability and durability (Ding *et al.* 2017; Jiang *et al.* 2017; Cheng *et al.* 2018).

However, the appearance qualities of thermally treated wood, such as color, were also altered after thermal treatment (Ding *et al.* 2017; Jiang *et al.* 2017). It is important to consider the value of this process for enhancing bamboo appearance.

In traditional thermal treatments, bamboo is modified by exposure to hot oil, steam, or other shielding gases at a temperature of 160 to 260 °C. The processing parameters have a significant influence on the color variation of bamboo. Gürgen *et al.* (2019) applied two kinds of statistical algorithms (neural network and multivariate linear regression) to predict the colorimetric parameters of heat-treated bamboo. The results revealed that the variation of color difference was positively correlated with a rise in temperature and an increase in heat treatment duration (Gürgen *et al.* 2019). The color changes occurred due to the changes in functional groups of bamboo chemical components. Different treatment temperatures and processing times were applied as independent variables to treat moso bamboo to reveal the modified surface properties (color and contact angle) and chemical properties changes after thermal modification. The color of the heat-treated bamboo surface was a dark or dark brown color. In addition, the discoloration of the moso bamboo surface was aggravated by the higher treatment temperature (Lee *et al.* 2018). Lv *et al.* (2019) studied the color variation of round bamboo after different microwave-vacuum drying (MVD) conditions. The surface color of round bamboo changed from green to yellow after MVD. For bamboo scrimber, the color was also varied after different media treatments, and it became darker after all the selected treatment conditions. The more homogenous color of bamboo scrimber was easier to achieve by oil-treatment than the other treatments (Li *et al.* 2018a).

The thermal treatment parameters have significant effects on bamboo surface color. Color is one of the important quality indexes of bamboo products that affect consumer preference and added value of bamboo-based products. Laser processing as a kind of thermal process can be used for cutting, surface treating of metal, plastic, wood, and so on. In this study, the CO_2 laser was selected for bamboo surface thermal treatment and the color variation of the bamboo surface after laser thermal treatment will be studied. In the previous studies, results revealed that the laser parameters (power and focal length) and motion parameters (feed rate) have directly influences on performance of processed wooden materials (Kubovský and Kacik 2013; Gurau *et al.* 2017; Li *et al.* 2018b). This study aims to reveal the color variation of moso bamboo surface under different modification conditions. The response surface methodology (RSM) will be chosen to model the relationship between laser parameters and color indexes.

EXPERIMENTAL

Materials

Moso bamboo (*Phyllostachys pubescens*) with large stand volume in China, was applied for making experimental samples. The selected bamboo with the age of 6 years, was taken in Jinzhai, Anhui province, China. Firstly, the round bamboo was cut to bamboo strips. Then the outer and inner part of bamboo strips were planed by planer to achieve flat surfaces for the following laser processing experiments. The detailed processing is shown in Fig. 1. The size of the samples was 150 × 30 × 3 mm^3 (Length × Width × Thickness). Before laser treatment, the samples were dried to a moisture content of 11%. After drying, the surface of the material underwent a sanding treatment.

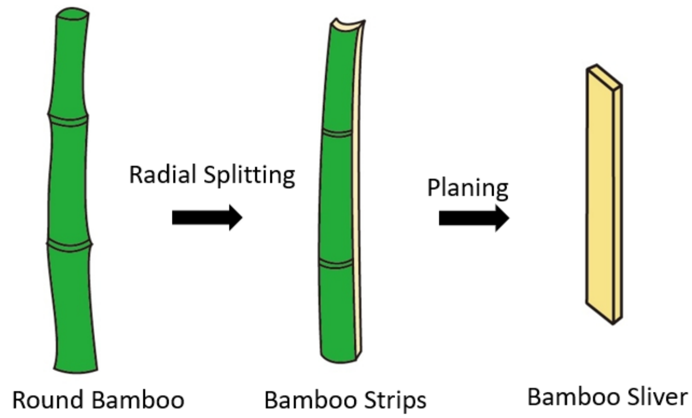

Fig. 1. Schematic diagram of specimen preparation

Experiment Setup and Procedure

The CO_2 laser had a wavelength of 10.6 μm, which is widely used for non-metallic material (such as plastic, wood, bamboo, *etc.*) processing. Light with a wavelength of 8.30 to 10 μm, has maximum absorption in a cellulose molecule. Therefore, the CO_2 laser could be efficiently absorbed by moso bamboo, which is composed of cellulose as the principal chemical component (Martinez-Conde *et al.* 2017). The experiments were carried out by a computerized numerical controlled laser machine, which is a commercial product supplied by Shandong Minglong technology Co., Ltd. (China). The maximum power output of the machine was 100 W. The width of two adjacent scan paths was defined as weep width and the detailed laser scanning roadmap is shown in Fig. 2.

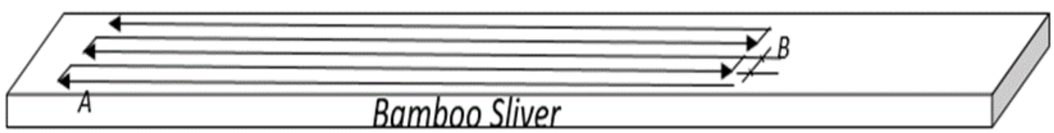

Fig. 2. The scan paths of a laser transmitter

The color of untreated and treated samples surface was measured by colorimeter (Puxi, Shanghai, China). The measurement and calculation of Moso bamboo surface color were based on the standard of chromaticity system recommended by the international commission on illumination (Kubovský and Kacik 2013; Teacă *et al.* 2013). To evaluate the color variation of the bamboo surface after laser irradiation, the total color difference ΔE^* was calculated using Eq. 1,

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

where ΔE^* is the total color difference, ΔL^* is lightness difference, Δa^* is the difference of red-green index, and Δb^* is the difference of yellow-blue index.

Experimental Plan

RSM is a modeling and data regression analysis method for creating a functional relationship between input variables and response values and finding the significance of input parameters on the coupled response parameters. RSM is also competent for optimizing the responses (Bhushan 2013). The Box-Behnken design (BBD) of RSM was selected to research and analysis the influences of laser processing parameters on color index variation and arrange the experiments. Equation 2 presents the selected model for color variation of the bamboo surface after laser processing,

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i,j}^{k} b_{ij} X_i X_j + \sum_{i=1}^{k} b_{ii} X_i^2 \quad (2)$$

where b_0 is the free term of the regression equation. The coefficients b_i and b_{ii} are the linear and quadratic terms, respectively. The coefficient b_{ij} represents the interacting terms. The experimental plan was developed to evaluate the influences of feed rate, sweep width, and laser power on color index variation after thermal laser treatment (Rajamurugan *et al.* 2012; Valarmathi *et al.* 2013). In this research, the laser processing parameters and their levels are shown in Table 1. Design Expert software (Ver. 8.0.6, Stat-Ease Inc., Minneapolis, MN, USA) was selected to arrange the experiments and analyze the experimental data.

Table 1. Input Variations and Levels

Parameters	Code	Level		
		-1	0	1
Laser power/ P (W)	A	16	18	20
Feed rate/ V (mm/s)	B	300	400	500
Sweep width/ W (mm)	C	0.10	0.15	0.20

RESULTS AND DISCUSSION

The color indexes of ΔL^*, Δa^*, and Δb^* were evaluated by colorimeter and the value of total color difference (ΔE^*) were counted by Eq. 1. The experimental arrangement and recorded data of response variations are shown in Table 2.

Table 2. The Results of Color Indexes

Standard	Run	Factors			ΔE^*	ΔL^*	Δa^*	Δb^*
		Laser power/ P (W)	Feed rate/ V (mm/s)	Sweep width/ W (mm)				
1	8	16.00	300.00	0.15	11.6	-9.8	3.3	5.3
2	10	20.00	300.00	0.15	17.0	-16.3	5.9	3.4
3	14	16.00	500.00	0.15	10.7	-6.9	6.1	5.4
4	1	20.00	500.00	0.15	11.9	-10.6	6.1	2.8
5	9	16.00	400.00	0.10	13.3	-9.1	5.2	8.2
6	16	20.00	400.00	0.10	17.9	-15.3	6.3	6.8
7	15	16.00	400.00	0.20	10.8	-8.3	5.5	4.2
8	5	20.00	400.00	0.20	13.3	-11.2	5.3	4.8
9	17	18.00	300.00	0.10	21.2	-18.6	4.4	9.2
10	6	18.00	500.00	0.10	14.9	-10.3	6.0	8.9
11	2	18.00	300.00	0.20	12.6	-13.6	4.6	6.9
12	13	18.00	500.00	0.20	11.0	-8.9	4.6	4.6
13	3	18.00	400.00	0.15	10.1	-7.5	4.0	5.4
14	4	18.00	400.00	0.15	10.1	-7.5	4.0	5.4
15	12	18.00	400.00	0.15	10.1	-7.5	4.0	5.4
16	11	18.00	400.00	0.15	10.1	-7.5	4.0	5.4
17	7	18.00	400.00	0.15	10.1	-7.5	4.1	5.4

Influences of Laser Processing Parameters on Δ*L** and Δ*E**

The results of bamboo surface color indexes are shown in Table 2 and analyzed by Design Expert software. For wooden materials, the lightness index and total color difference significantly varied after laser irradiation (Gurau *et al.* 2017; Li *et al.* 2018b). Both wood and bamboo are natural fiber materials and have similar chemical components. In this paper, only the main indexes Δ*L** and Δ*E** were studied. The effect graphs of Δ*L** and Δ*E** are shown in Fig. 3. It is obvious that the value of Δ*L** was negative, which means that the color lightness of the bamboo surface decreased after laser irradiation. The increasing of the absolute value of Δ*L** was positively correlated with the enhancement of laser power, but the value of Δ*L** was reduced when the feed rate of laser nozzle and sweep width augmented. The laser processing parameters had similar effects on total color difference, as shown in Fig. 3(b). The total color difference increased with the enhancement of laser power, but the augment of feed rate and sweep width had negative effects on total color increasing.

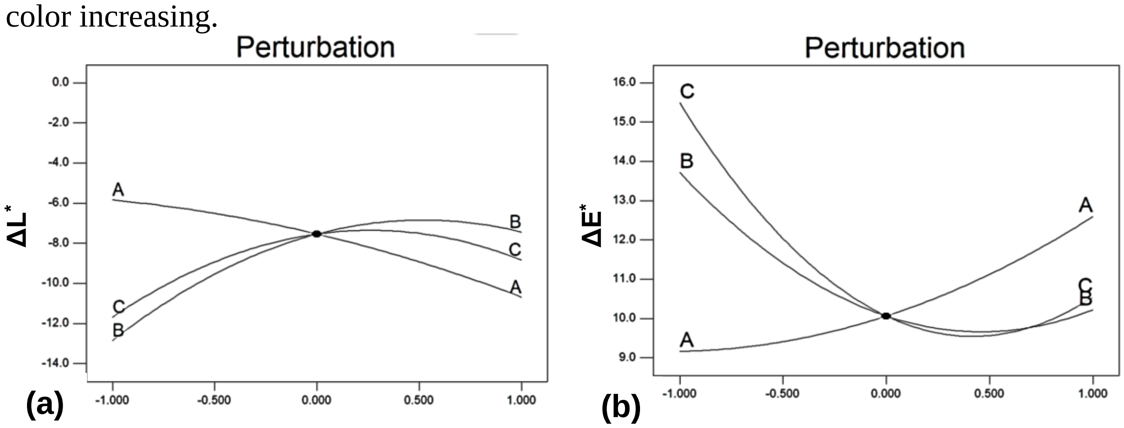

Fig. 3. The effect graphs of Δ*L**(a) and Δ*E**(b)

Analysis of Variance

To reveal the significance of laser processing arguments and evaluate the adequacy of the BBD model of RSM, analysis of variance (ANOVA) was adopted. The detailed results of ANOVA for Δ*L** and Δ*E** are shown in Table 3.

Table 3. Results of ANOVA for Δ*L** and Δ*E**

Source	Sum of Squares		df		Mean Square		F Value		P-Value Prob > F	
	Δ*L**	Δ*E**	Δ*L**	Δ*E**	Δ*L**	Δ*E**	Δ*L**	Δ*E**	Δ*L**	Δ*E**
Model	197.36	166.31	9	9	21.93	18.48	53.04	30.46	< 0.0001	< 0.0001
A	46.75	23.49	1	1	46.75	23.49	113.09	38.72	< 0.0001	0.0004
B	58.32	24.34	1	1	58.32	24.34	141.06	40.13	< 0.0001	0.0004
C	16.19	48.75	1	1	16.19	48.75	39.16	80.36	0.0004	< 0.0001
AB	1.99	4.31	1	1	1.99	4.31	4.81	7.10	0.0644	0.0323
AC	2.99	1.08	1	1	2.99	1.08	7.24	1.78	0.0311	0.2234
BC	3.35	5.58	1	1	3.35	5.58	8.10	9.20	0.0248	0.0190
A^2	2.25	2.71	1	1	2.25	2.71	5.43	4.46	0.0525	0.0726
B^2	28.69	15.02	1	1	28.69	15.02	69.40	24.75	< 0.0001	0.0016
C^2	31.28	36.29	1	1	31.28	36.29	75.65	59.82	< 0.0001	0.0001
Cor Total	200.25	170.56	16	16						

When the values of "prob > F" are less than 0.0500, it indicates that model variations are significant. In the circumstances, model terms A, B, and C were significant for the color indexes, which made a significant contribution to bamboo surface color indexes of Δ*L** and Δ*E**. The probability of selected quadratic models for Δ*L** and Δ*E** were < 0.0001, which meant the selected models were significant. In Table 4, the values of R^2 for quadratic models were very close to 1.

Table 4. ANOVA Analysis Results for the Adopted Quadratic Models

Responses	Source	Standard Deviation	R^2	Adjusted R^2	Predicted R^2
ΔL^*	Quadratic	0.64	0.9855	0.9670	0.7704
ΔE^*	Quadratic	0.78	0.9751	0.9431	0.6062

Regression Analysis

The functional relationship between inputted laser modification arguments and response arguments requires a statement of a statistical model. The Design Expert software was selected to establish response surface equations for Δ*L** and Δ*E** of the bamboo surface after laser modification. Because of the high values of R^2, the quadratic models were qualified to describe the functional relationship between Δ*L**, Δ*E**, and laser modification arguments. The values R^2 were quite close to 1, indicating the selected quadratic models were suitable for predicting the values of Δ*L** and Δ*E** of bamboo surface color after CO_2 laser treatment. The graphs of model-predicted and actual values Δ*L**(a) and Δ*E**(b) are shown in Fig. 4. It is easy to find that model-predicted values of Δ*L**(a) and Δ*E**(b) were quite close to the actual experimental measurements. The detailed models in terms of coded factors were shown in Eqs. 3 and 4,

$$\Delta L^* = -7.52 - 2.42 \times A + 2.70 \times B + 1.42 \times C + 0.71 \times A \times B + 0.86 \times A \times C - 0.91 \times B \times C - 0.73 \times A^2 - 2.61 \times B^2 - 2.73 \times C^2 \quad (3)$$

$$\Delta E^* = 10.10 + 1.71 \times A - 1.74 \times B - 2.47 \times C - 1.04 \times A \times B - 0.52 \times A \times C + 1.18 \times B \times C + 0.80 \times A^2 + 1.89 \times B^2 + 2.94 \times C^2 \quad (4)$$

where model term *A* is laser power in (W), term *B* is feed rate in (mm/s), term *C* is sweep width in (mm).

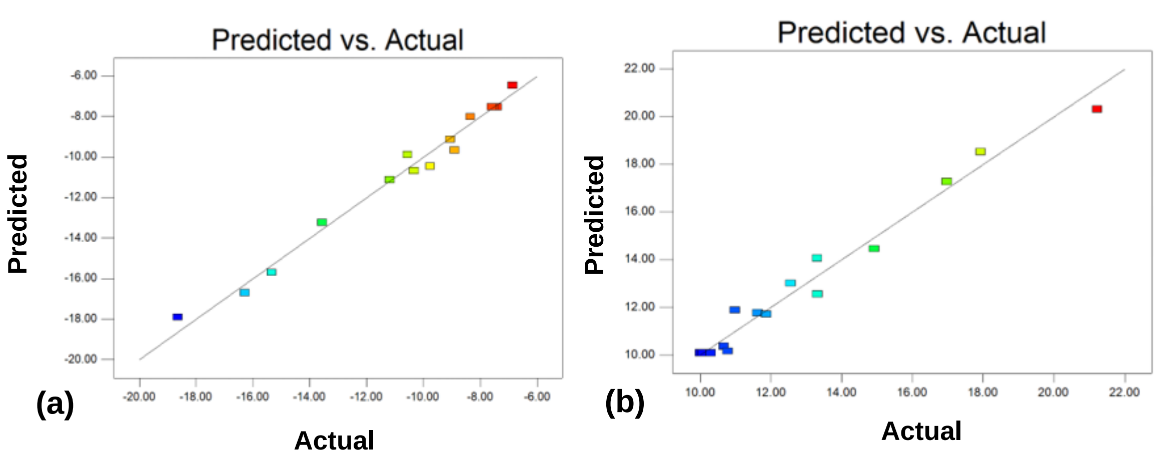

Fig. 4. The graph of predicted and actual values of Δ*L**(a) and Δ*E**(b)

Discussion

The increasing of the absolute value of ΔL^* was positively correlated with the enhancement of laser power, but the value of ΔL^* decreased when the feed rate of laser nozzle and sweep width was augmented. Since bamboo is a type of natural fiber materials, with cellulose as one of its main components, the absorption of CO_2 laser light is efficient (Martínez-Conde *et al.* 2017). When carrying out the slower feeding speed and decreasing sweep witdth, the values of ΔL^* and ΔE^* increase, due to the more CO_2 laser energy absorped by bamboo surface. With the enhancement of laser power, the total heat exchange on the surface of bamboo will increase per unit time. The irradiation period and irradiation intensity have a direct impact on the color indexes variation. A darker surface was achieved by a longer irradiation period and higher irradiation intensity. The variation of chemical functional groups of bamboo is the key cause of color variation of the bamboo surface (Meng *et al.* 2016).

The quadratic models were created by RSM to establish the functional relationship between the laser processing arguments and color indexes. The values of R^2 of these two models were very close to 1, which meant the selected models gave a good prediction of the values of ΔL^* and ΔE^*. The color of bamboo products has a direct influence on its appearance aesthetics. Different customs have different color preferences. The functional relationships were revealed by the adopted models, which gave a quantitative evaluation of color variations. It is important to pick suitable laser modification parameters to obtain the expected color of different products

CONCLUSIONS

1. The CO_2 laser, which is in widespread use, could be used for bamboo surface modification. The CO_2 laser processing arguments (laser power, feed rate, and sweep width) have significant actions on bamboo surface color indexes of ΔL^* and ΔE^*.
2. The bamboo surface color became dark after laser irradiation. The absolute values of ΔL^* and ΔE^* increased with the enhancement of laser power but were reduced when the feed rate of the laser nozzle and sweep width augmented.
3. The quadratic models of ΔL^* and ΔE^* were created by RSM, and were competent in describing the relationship between laser processing parameters and color indexes of ΔL^* and ΔE^*. The approach employed in this work will be useful in achieving the desired color to cater to the needs of a different color preferences.

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