Pressure, Feed Rate, and Abrasive Mass Flow Rate Influence on Surface Roughness for Recombinant Bamboo Abrasive Water Jet Cutting

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The effects of pressure, feed rate, and abrasive mass flow rate on surface roughness were investigated during abrasive water cutting of recombinant bamboo. Two different thicknesses (10 mm and 15 mm) of recombinant bamboo were cut in the longitudinal and transversal directions by abrasive water jet. All experiments were arranged using response surface methodology. The parameter R_a was selected to represent the surface roughness. The value of R_a increased with an increase in feed rate and abrasive mass flow rate, but decreased with an increase in pressure. The surface roughness was lower when cutting the fiber longitudinally than when cutting transversally.

Keywords: Recombinant bamboo; Response surface methodology; Abrasive water jet; Surface roughness

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INTRODUCTION

Water jet technology is a novel non-traditional industrial method that can be used for cutting operations. The material that is cut away is removed by mechanically impacted fluid on the workpiece (Oh and Cho 2014). With respect to the different fluid contents, water jet cutting can be divided into pure water jet cutting (WJ) and abrasive water jet cutting (AWJ). Compared to traditional cutting technologies, AWJ offers the following advantages: negligible thermal effects, small machining force, good working conditions and environment, long tool life, high flexibility, and high machining versatility (Yue *et al.* 2014). Currently, AWJ is widely used in various industries.

Recombinant bamboo is a wood-like material with high hardness and density that can be used indoors and outdoors (Li *et al.* 2014). Unfortunately, short tool life and high cutting heat cannot be avoided in recombinant bamboo processing with traditional cutting tools. With AWJ, these problems can be eliminated. In recent years, much attention has been paid to AWJ; this includes investigating the influence of process parameters on the kerf geometry and surface roughness. Barcík and Kvietková (2011) evaluated the impact of material thickness on the angle of the cut sides and found that increasing the thickness of the material causes an initial decrease of the angle before an increase in angle. Li *et al.* (2015) investigated the impact of varying pressure, feed rate, and abrasive mass flow rate on the efficiency of an abrasive water jet cutting process when cutting recombinant bamboo. But surface roughness is also a major quality parameter of the products manufactured using AWJ. Available literature is concentrated on researching the effects of process parameters on the surface roughness. Kvietková *et al.* (2014) investigated the effects of process parameters on surface roughness during the cutting of wood-based panels. The results showed that the feed rate and abrasive mass flow rate had significant effects on the surface quality. The cutting direction also affected the surface quality, but the tendency varied among different panels. Kminiak and Gaff (2014) used AWJ for cutting English oak (*Quercus robur*), European beech (*Fagus sylvatica*), and European spruce (*Picea abies*). The results indicated that the R_a values were greater when cutting the fibers transversally than when cutting longitudinally. Gerencsér and Bejó (2007) studied the water jet cutting of nine different wood species. Surface quality was evaluated on the basis of the mean roughness depth parameter (R_z). They found that the surface roughness values increased with an increase in feed rate, and R_z values were mostly higher when cutting the fibers transversally. Additionally, the surface roughness always stayed significantly lower than the roughness of planed or sawn surfaces. Alberdi *et al.* (2013) studied the cutting of fiber and plastic composites with AWJ. The results from this experiment indicated that the feed rate was a significant factor. Lower values of the parameter R_a were obtained with lower feed rates.

This paper describes the effect of pressure, feed rate, and abrasive mass flow rate on the surface roughness, R_a. The results were used to determine optimal cutting conditions. Experimental results and response surface methodology (RSM) were applied to study the relationship between the process parameters (pressure, feed rate, and abrasive mass flow rate) and the response parameter (R_a). Cutting in both the longitudinal and transversal directions was considered.

EXPERIMENTAL

Materials and Equipment

In this study, recombinant bamboo samples with thicknesses of 10 mm and 15 mm were selected. The recombinant bamboo was supplied by the Hunan Taohuajiang Industries Co., Ltd. (China). Some basic information of this type of recombinant bamboo is shown in Table 1.

Experiments were carried out on an abrasive water jet cutter (Dadi DWJ3020, China). The setup of the equipment and the recombinant bamboo is shown in Fig. 1. The highest operating pressure of this machine is 500 MPa. The diameter of the nozzle was 1 mm. The distance between the jet nozzle and the upper surface of the work piece was fixed at 2 mm. The grain size was 80 mesh.

Table 1. Some Basic Information of this Type of Recombinant Bamboo

Parameters		Value
Pressing parameters	Temperature	160 ℃
	Pressure	4 MPa
	Pressing time	15 min
Adhesive		Phenol formaldehyde resin
Density		1000 kg/m^3
Brinell hardness		32 HB

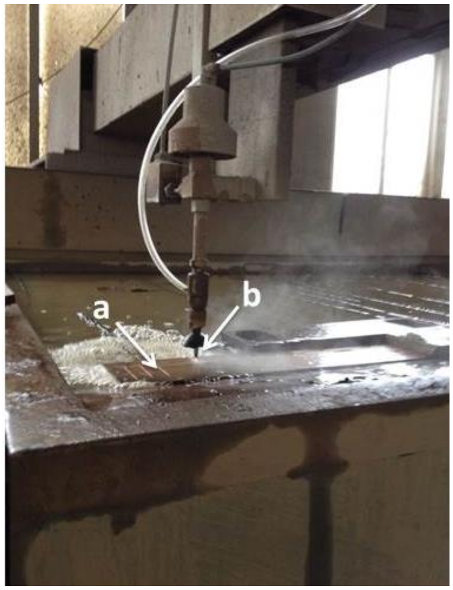

Fig. 1. Equipment setup: (a) recombinant bamboo and (b) nozzle

Methods

Samples were cut in both the longitudinal and transversal directions relative to the fiber direction. Three repeated cutting tests were used for every parameter combination in each direction (the cutting plan is shown in Fig. 2) for each sample. Every cutting length was 100 mm. The surface roughness, R_a, was measured using a surface roughness gauge (Mahr M2, USA).

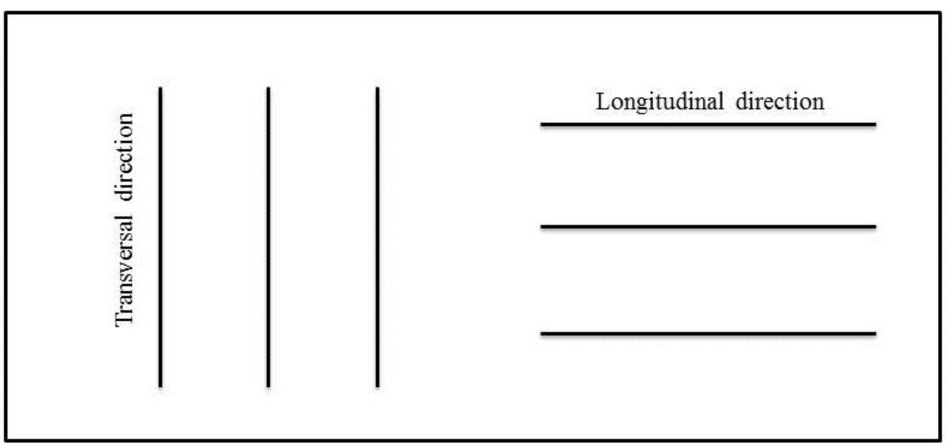

Fig. 2. Cutting plan of samples

Design of experiments

Table 2 shows the process parameters as well as their corresponding codes and levels. Normally, 3^3 (27) experiments need to be conducted when there are three process parameters, at three different levels, using a full factorial experimental design. In this study, RSM using a Box-Behnken design (Box and Behnken 1960) was applied to obtain the surface roughness of the AWJ process. It is well-known that RSM can effectively save experimental cost and time. Only 13 unique combinations were chosen, and an extra four repeated tests were added for the medium level of the process parameters. The experiment plan was developed by Version 8.0.6 of the Design-Expert Software (Stat-Ease Inc., USA), and the experimental data were also analyzed using this software.

Table 2. Process Parameters and Corresponding Codes and Levels

Process parameters	Code	Unit	Level					
			-1		0		1	
			Thickness (mm)		Thickness (mm)		Thickness (mm)	
			10	15	10	15	10	15
Pressure	A	MPa	100	200	150	250	200	300
Feed rate	B	m/min	0.2	0.2	0.4	0.4	0.6	0.6
Abrasive mass flow rate	C	g/min	200	200	300	300	400	400

RESULTS AND DISCUSSION

During the experiments, the values of response parameters were measured at three points (top, middle, and bottom) and the average values of response parameters were recorded by the standard order shown in Tables 3 and 4. All experiments were implemented in a randomized order.

Table 3. Experimentally Recorded Data for 10-mm Thickness

Standard order	Process parameters			Response parameter	
	Pressure (MPa)	Feed rate (m/min)	Abrasive flow (g/min)	Surface roughness Ra (μm)	
				Transversal	Longitudinal
1	100	0.2	300	9.17	7.58
2	200	0.2	300	7.56	5.74
3	100	0.6	300	10.18	8.33
4	200	0.6	300	9.65	7.01
5	100	0.4	200	8.73	6.85
6	200	0.4	200	8.66	6.44
7	100	0.4	400	12.50	10.90
8	200	0.4	400	12.35	10.10
9	150	0.2	200	8.22	6.44
10	150	0.6	200	8.99	7.23
11	150	0.2	400	10.53	8.89
12	150	0.6	400	14.13	12.01
13	150	0.4	300	9.00	7.89
14	150	0.4	300	9.01	7.90
15	150	0.4	300	9.02	7.90
16	150	0.4	300	9.01	7.88
17	150	0.4	300	9.00	7.88

Table 4. Experimentally Recorded Data for 15-mm Thickness

Standard order	Process parameters			Response parameter	
	Pressure (MPa)	Feed rate (m/min)	Abrasive flow (g/min)	Surface roughness Ra (μm)	
				Transversal	Longitudinal
1	200	0.2	300	10.65	7.51
2	300	0.2	300	8.36	7.15
3	200	0.6	300	11.89	10.76
4	300	0.6	300	11.61	11.22
5	200	0.4	200	9.38	8.33
6	300	0.4	200	8.01	7.35
7	200	0.4	400	12.65	13.21
8	300	0.4	400	11.98	11.69
9	250	0.2	200	8.51	7.08
10	250	0.6	200	10.41	9.33
11	250	0.2	400	11.89	10.53
12	250	0.6	400	15.89	13.87
13	250	0.4	300	10.96	9.00
14	250	0.4	300	10.99	9.01
15	250	0.4	300	10.98	9.02
16	250	0.4	300	10.99	9.01
17	250	0.4	300	10.97	9.00

Analysis of Variance

Table 5 shows the analysis of variance (ANOVA) results for the quadratic model of the response parameters. The R^2 values are close to 1 because of the high number of degrees of freedom in relation to the number of experiments.

Table 5. Summary of ANOVA

Thickness (mm)	Response parameters		Degrees of Freedom	Probability (F model)	R^2	Adjusted R^2	Predicted R^2
10	Surface roughness (Ra)	Transversal	9	<0.0001 (Sig.)	0.986	0.968	0.776
		Longitudinal	9	<0.0001 (Sig.)	0.978	0.949	0.645
15	Surface roughness (Ra)	Transversal	9	<0.0001 (Sig.)	0.988	0.974	0.821
		Longitudinal	9	<0.0001 (Sig.)	0.978	0.951	0.657

Regression Equations

In the present work, the RSM-based second order mathematical model is given by Eq. 1:

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

In Eq. 1, b_0 is the free term of the regression equation and coefficients b_1, b_2, … b_k and b_{11}, b_{22}, . . . b_{kk} are the linear and the quadratic terms, respectively, while b_{12}, b_{13}, . . . b_{k-1} are the interaction terms (Aouici *et al.* 2013).

Equations 2 through 3 show models for 10-mm-thick recombinant bamboo:

$$Ra_{Transvesal} = 10.02 - 0.55A + 0.68B + 2.18C + 0.23AB - 0.66AC + 1.19BC - 0.61A^2 - 0.23B^2 + 1.08C^2 \quad (2)$$

$$Ra_{Longitudinal} = 7.89 - 0.55A + 0.74B + 1.87C + 0.13AB - 0.10AC + 0.58BC - 0.40A^2 - 0.33B^2 + 1.08C^2 \quad (3)$$

Equations 4 through 5 show models for 15-mm-thick recombinant bamboo:

$$Ra_{Transversal} = 10.98 - 0.58A + 1.30B + 2.01C + 0.50AB + 0.18AC + 0.53BC - 0.76A^2 + 0.41B^2 + 0.29C^2 \quad (4)$$

$$Ra_{Longitudinal} = 9.01 - 0.30A + 1.61B + 2.15C + 0.21AB - 0.14AC + 0.27BC + 0.05A^2 + 0.10B^2 + 1.09C^2 \quad (5)$$

Adequacy of the Developed Models

The adequacy of the developed models was tested with two confirmation experiments carried out with different and unique process parameter combinations. Table 6 presents the actual experimental values, the predicted values, and the errors. The adequacy of the developed mathematical models for R_a is shown with two confirmation tests, which gave a maximum of 3.54% error for surface roughness. This means that the model can effectively predict the surface roughness in recombinant bamboo abrasive water jet cutting.

Table 6. Confirmation Experiments

Thickness (mm)	Process parameters			Values	Surface roughness	
	A (MPa)	B (m/min)	C (g/min)		Transversal	Longitudinal
10	120	0.45	310	Actual	10.22	8.75
				Predicted	10.55	8.44
				Error (%)	-3.23	3.54
15	250	0.5	290	Actual	11.75	9.96
				Predicted	11.51	9.62
				Error (%)	2.04	3.41

Discussion

In Figs. 3 and 4, it is easy to see that R_a increases with an increase in feed rate within the limits for this study. One possible reason for this phenomenon is that fewer particles that pass through a unit area can be used as the feed rate increase. Thus, fewer impacts and cutting edges will be available per unit area (Aydin *et al.* 2011). It is obvious that R_a increases as the abrasive mass flow rate increases. This is possibly partly because at higher abrasive mass flow rates, more particles will be mixed during the cutting process, and because of the inter-collision of particles among themselves, which leads to a loss of kinetic energy (Aydin *et al.* 2011). The same result was also found in a previous study (Kvietková *et al.* 2014). In terms of the pressure, the kinetic energy of the abrasive particles increases with a pressure increase, which enhances their capacity for material removal. As a result, R_a decreases when the pressure increases (Azmir and Ahsan 2009).

These tendencies are similar in both the transverse and longitudinal directions. However, in Tables 3 and 4, it is obvious that the values of the transverse surface roughness are higher than the values of longitudinal surface roughness when cutting with the same parameters. This result is in good agreement with those from plywood abrasive water jet cutting (Kvietková *et al.* 2014).

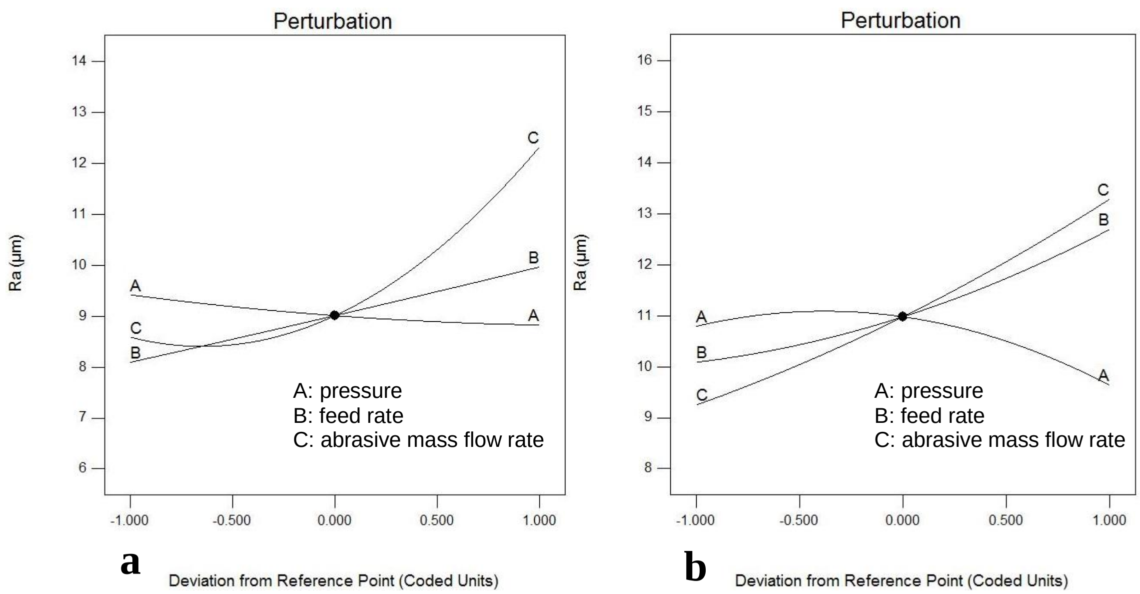

Fig. 3. The effects of (A) pressure, (B) feed rate, and (C) abrasive mass flow rate on the surface roughness (transversal direction) for thicknesses of (a) 10 mm and (b) 15 mm. In coded units, -1 represents the lowest value, 0 represents the medium value, and 1 represents the highest value; see Table 1.

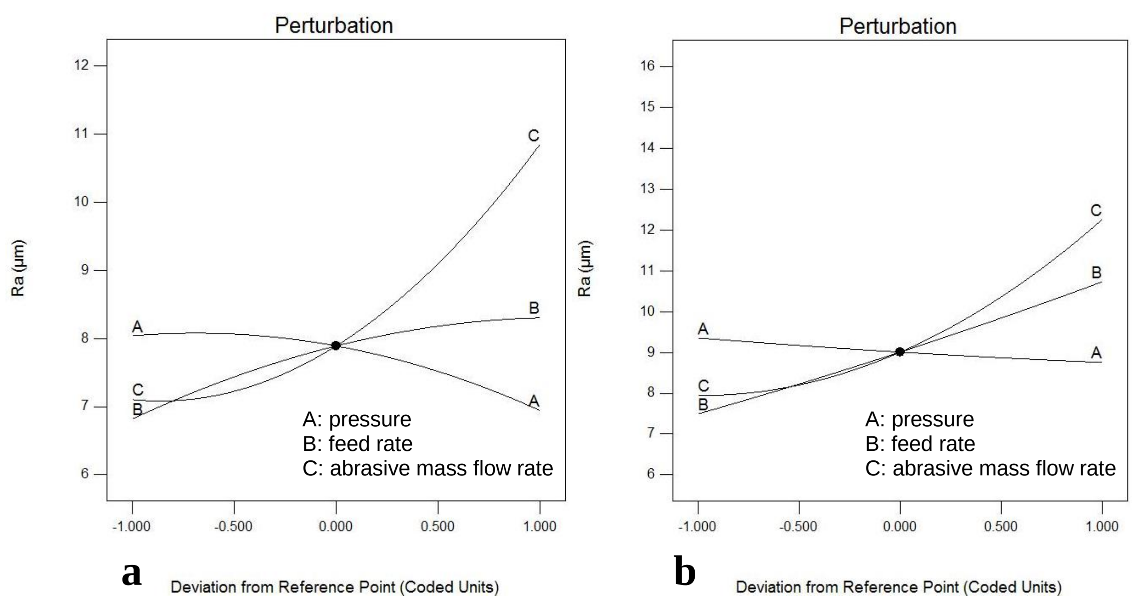

Fig. 4. The effects of (A) pressure, (B) feed rate, and (C) abrasive mass flow rate on the surface roughness (longitudinal direction) for thicknesses of (a) 10 mm and (b) 15 mm

Figures 5 and 6 are response surface graphs showing the effect of the abrasive mass flow rate and feed rate on surface roughness for each of the thicknesses tested. These figures are useful in identifying the area in which the R_a approaches the minimum value.

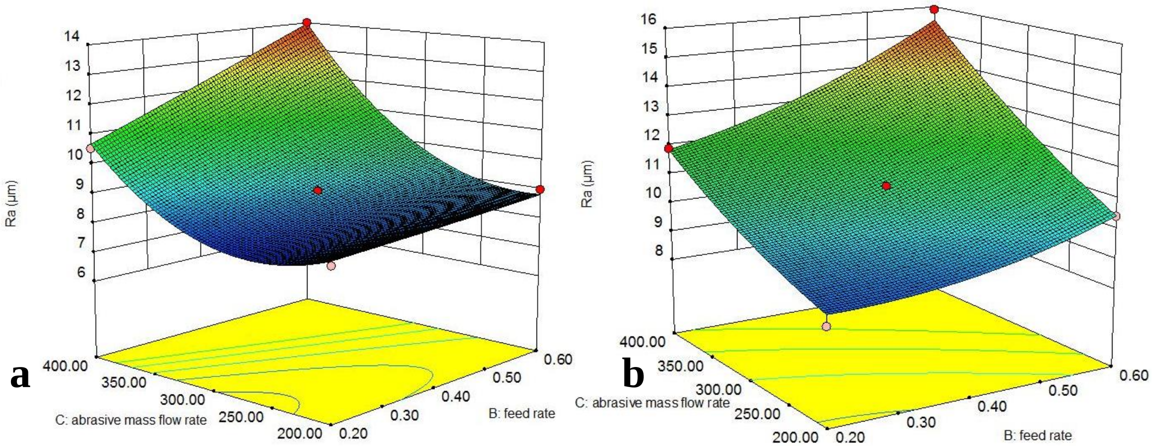

Fig. 5. Surface roughness (transversal direction) as a function of (B) feed rate and (C) abrasive mass flow rate for thicknesses of (a) 10 mm and (b) 15 mm. Units for B and C are m/min and g/min, respectively (Table 1).

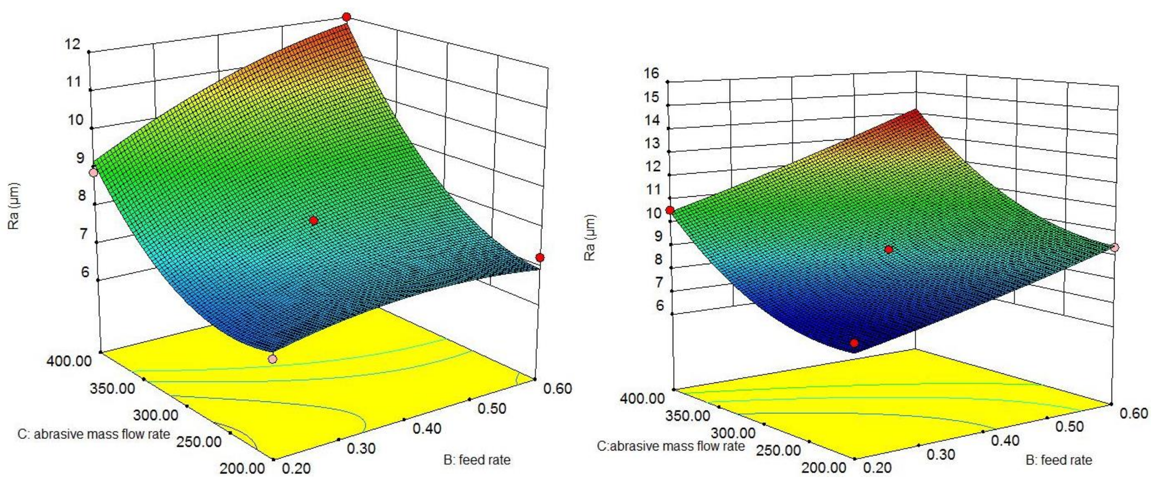

Fig. 6. Surface roughness (longitudinal direction) as a function of (B) feed rate and (C) abrasive mass flow rate for thicknesses of (a) 10 mm and (b) 15 mm

Optimization of Process Parameters

The optimal manufacturing conditions for recombinant bamboo abrasive water jet cutting can be achieved by minimizing the values of surface roughness. The goal and process parameter ranges set for this optimization process are summarized in Tables 7 and 8. The optimization results using RSM are shown in Tables 9 and 10. The optimized surface roughness was 7.46 to 7.52 μm and 5.54 to 5.71 μm for 10-mm recombinant bamboo cutting in the transversal and longitudinal directions, respectively. The optimized surface roughness was 7.56 to 7.94 μm and 6.53 to 6.91 μm for 15-mm recombinant bamboo cutting in the transversal and longitudinal directions, respectively.

Table 7. Goals and Parameter Ranges for Optimization of 10-mm Recombinant Bamboo Cutting Condition

Condition	Goal	Lower limit	Upper limit
Pressure (MPa)	Is in range	100	200
Feed rate (m/min)	Is in range	0.2	0.6
Abrasive mass flow rate (g/min)	Is in range	200	400
$R_{a;transversal}$ (μm)	Minimize	7.56	14.13
$R_{a;longitudinal}$ (μm)	minimize	5.74	12.01

Table 8. Goals and Parameter Ranges for Optimization of 15-mm Recombinant Bamboo Cutting Condition

Condition	Goal	Lower limit	Upper limit
Pressure (MPa)	Is in range	200	300
Feed rate (m/min)	Is in range	0.2	0.6
Abrasive mass flow rate (g/min)	Is in range	200	400
$R_{a;transversal}$ (μm)	Minimize	8.01	15.89
$R_{a;longitudinal}$ (μm)	minimize	7.08	13.87

Table 9. Response Optimization for 10-mm Recombinant Bamboo Surface Parameters

Number	Pressure (MPa)	Feed rate (m/min)	Abrasive mass flow rate (g/min)	$R_{a;transversal}$ (μm)	$R_{a;longitudinal}$ (μm)	Desirability
1	192.98	0.21	248.45	7.51	5.65	1.000
2	196.49	0.20	238.97	7.52	5.55	1.000
3	192.82	0.21	259.61	7.51	5.71	1.000
4	198.24	0.21	259.81	7.46	5.54	1.000
5	198.10	0.21	256.92	7.47	5.55	1.000

Table 10. Response Optimization for 15-mm Recombinant Bamboo Surface Parameters

Number	Pressure (MPa)	Feed rate (m/min)	Abrasive mass flow rate (g/min)	$R_{a;transversal}$ (μm)	$R_{a;longitudinal}$ (μm)	Desirability
1	298.90	0.28	229.34	7.56	6.91	1.000
2	278.52	0.22	202.96	7.98	6.62	1.000
3	278.22	0.20	200.29	7.94	6.53	1.000
4	283.30	0.26	200.33	7.84	6.86	1.000
5	283.98	0.25	203.20	7.83	6.80	1.000

CONCLUSIONS

1. The considered process parameters have significant effects on the surface roughness. The tendencies were similar for the two thicknesses tested.
2. The surface roughness (R_a) is higher when cutting fibers transversally than when cutting longitudinally.

3. Within the limits of this study, decreasing the feed rate and abrasive mass flow rate may improve the surface quality. Increasing pressure probably will improve the surface quality.

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