Effect of Process Parameters on Cutting Forces and Surface Roughness during Peripheral Up Milling of Bamboo Scrimber

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The effects of milling process parameters on cutting forces and surface roughness were studied during peripheral up milling of bamboo scrimber. The study results indicated that the effect of feed rate on cutting force components F_x, $+F_y$, $-F_y$, and surface roughness R_a were the most significant compared to spindle speed and cut depth during longitudinal milling. F_x, $+F_y$, $-F_y$, and R_a decreased slightly with increasing spindle speed, but increased greatly with increasing feed rate. In addition, cutting direction had a great effect on the cutting force components F_x and $+F_y$, as well as the machined surface roughness R_a. F_x, $+F_y$, and R_a during longitudinal cutting were always larger than those during end-grain cutting. Decreasing the feed rate appropriately could greatly improve the quality of the machined surface.

Keywords: Bamboo scrimber; Peripheral up milling; Orthogonal test; Cutting force components; Surface roughness

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INTRODUCTION

Bamboo scrimber is similar to wood scrimber, and it exhibits many excellent properties, such as sustainable supply, high strength, and high hardness. Bamboo scrimber can greatly improve the utilization of bamboo. Although the natural structure of the bamboo has been changed, bamboo scrimber retains the good performance of bamboo itself. In the past ten years, bamboo scrimber has been a main product in the bamboo industry in China, and has gradually found use in the field of flooring and furniture (Qin 2009; Yu 2012). In addition, many countries also are showing a growing interest in the use of bamboo scrimber as an engineered material (Nugroho and Ando 2000; Sharma *et al*. 2014; Sharma *et al*. 2015).

Kivimaa (1950) developed a new method for separating the cutting force into two components, the normal cutting force and the thrust cutting force, to evaluate cutting force during cutting in woodworking and studied the effects of the cutting parameters and physical properties of birch on the cutting forces. Yang *et al*. (2006) studied the cutting forces of moso bamboo. Their investigation found that the physical properties of moso bamboo and process parameters such as cutting speed and cutting thickness had an effect on cutting forces during milling of moso bamboo. Cutting forces varied for the different milling sections. Palmqvist (2003) studied the parallel and normal cutting forces in peripheral milling of wood. The results showed that the normal force varied in both direction and magnitude when changing the process parameters. The parallel force also showed the dependence on the cutting parameters. Palmqvist *et al*. (2005) investigated the cutting-forces when up-milling in beech. The study found that the cutting force parallel to the feed direction changed from approximately 40 to 86 N/cm and the cutting force normal to the machined surface varied from approximately 14 to 51 N/cm. Cutting forces became larger with increasing average cutting thickness. There was no significant relationship between average cutting thickness and cutting forces. Hernández *et al.* (2014) studied the cutting forces and surface quality of black spruce during cutting in various cutting directions and cutting depths.

Cutting depth was shown to have a greater effect on cutting forces and surface quality than cutting direction. Guo *et al.* (2014) researched the effect of cutting parameters on cutting force components during orthogonal cutting of three types of wood-polymer composites. The research found that the influence of chip thickness on the parallel cutting force was most significantly compared to rake angle and edge radius. The influence of chip thickness and rake angle on the normal cutting force was significantly compared to edge radius.

Hiziroglu *et al.* (2014) investigated the influence of surface roughness on the bonding strength of pine, oak, and nyatoh wood species. The results showed that higher bonding strength values could be achieved with increasing surface roughness. Kiliç *et al.* (2006) studied the influence of different machining methods on surface roughness of various wood and suggested that stylus method was an effective method to evaluate the surface quality of wood. Kiliç *et al.* (2009) analyzed the bonding strength by starting from the influence of surface roughness on the tensile strength perpendicular to the surface of samples (medium density fiberboard overlaid with polyvinyl chloride). The results indicated that the surface roughness decreased with the decrease of the grit size of the abrasives when the grit size of the abrasives was smaller than 320, and the surface roughness had an effect on the tensile strength of samples; the tensile strength of samples increased in nonlinear with the decrease of the surface roughness. Malkoçoğlu (2007) studied the influence of the rake angle and feed rate on the surface roughness and machining properties. The investigation showed that the properties of the specimen increased with decreasing feed rate and rake angle. The effect of the feed rate on the surface roughness was not significant compared to the effect of the rake angle. However, there have been few studies focusing on the influence of process parameters and cutting direction on cutting force components and machined surface quality of bamboo scrimber in peripheral up milling.

Söğütlü *et al.* (2010, 2011) investigated the effect of planing parameters on surface roughness of cherry, pear woods, oriental beech, Scotch pine, and cedar wood. The results showed that tangential direction produced smoother surface compared to radial direction, and the machining surface was rougher when the feed direction of work pieces was in the direction of cutting speed compared to opposite to the cutting speed. Feed direction affected the surface roughness significantly, and surface roughness increased with an increase of feed rate.

This paper focused on the influence of spindle speed, feed rate, cutting depth, and milling direction on the cutting force components and machined surface roughness of bamboo scrimber. Experimental results and significance analysis were used to investigate the relationship between the process parameters and cutting force components and the relationship between the process parameters and machined surface roughness. Cutting in both the longitudinal and end-grain directions was considered.

EXPERIMENTAL

Materials

In this study, bamboo scrimber samples made of moso bamboo with thicknesses of 10 mm were provided by Hunan Peach Blossom River Industrial Co., Ltd. (China). The dimensions of the tested bamboo scrimber samples were 170 mm (L) × 100 mm (W) × 10 mm (T), the average moisture content was 8.3%, and the average density was 1.01 g/cm^3. Test samples were all kept in a climatization chamber that had a temperature of 20 ± 2 °C and a relative humidity of 65 ± 5% until they reach equilibrium moisture content. After the peripheral up milling in bamboo scrimber, the test pieces were once again kept in a climatization chamber to make sure that the physical properties of test samples were not changed until the surface roughness of samples were measured. A cemented carbide straight shank milling cutter with a cutting diameter of 16 mm was provided by Leitz Tooling Systems (Nanjing) Co., Ltd. The rake angle, sharpness angle, and clearance angle were respectively 15^o, 50^o, and 25^o.

Methods

The peripheral up milling experiments were performed on a CNC machine (YHM25-X, China). The machine's table size was 1900 mm × 1800 mm × 1500 mm, the maximum spindle speed was 18,000 rpm, and the maximum feed rate was 3000 mm/min. Cutting forces F_x and F_y were measured using a quartz three-component dynamometer with dynaoware software (Kistler 9257B, Switzerland).

Cutting directions and cutting forces are illustrated in Fig. 1. F_x is the parallel force, which is parallel to the feed direction. F_x is always positive, and the maximum parallel force value was recorded as F_x. F_y is the normal force, which is perpendicular to the feed direction. F_y varies from a positive maximum value to zero, and then from zero to a negative maximum value.

The positive maximum value was recorded as $+F_y$, and negative maximum value was recorded as $-F_y$. The arithmetic mean deviation of the surface roughness, R_a, was chosen as the characteristic parameter of surface roughness. R_a was measured using a surface roughness instrument (Mahr Perthometer M2, German). The experimental design and data analysis were completed with the software called Orthogonal Experiment Assistant (Version 3.1, China).

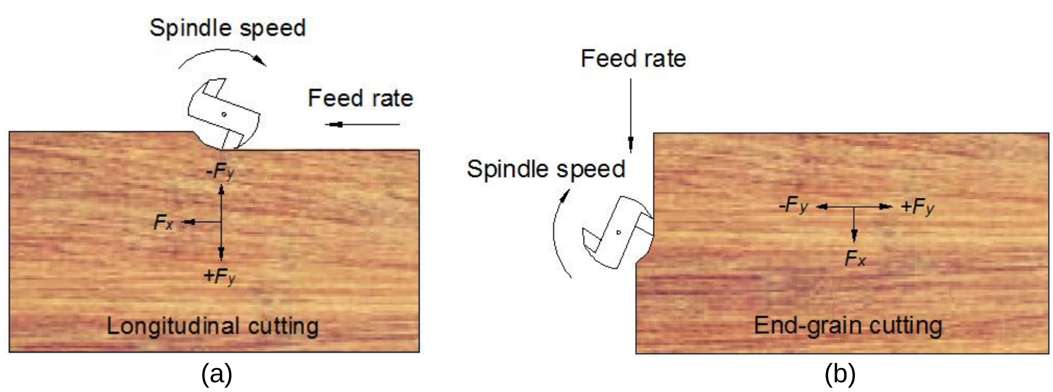


Fig. 1. Cutting directions and cutting force components F_x and F_y during up milling of bamboo scrimber: (a) longitudinal cutting, (b) end-grain cutting

Plan of the experiment

An orthogonal experimental design was used in this study. An L9(34) orthogonal array layout was chosen. Cutting direction, spindle speed, feed rate, and cutting depth were considered as process parameters. The influence of the process parameters on cutting force components and surface roughness were studied. The levels of the process parameters are shown in Table 1.

Table 1. Factors and Levels of the Experiment

Factor notation	Factors	Longitudinal cutting			End-grain Cutting		
		Levels			Levels		
		1	2	3	1	2	3
A	Spindle speed (rpm)	5000	7500	10000	5000	7500	10000
B	Feed rate (mm/min)	1000	2000	3000	1000	2000	3000
C	Cutting depth (mm)	1	2	3	1	2	3

RESULTS AND DISCUSSION

The experiments were conducted to study the influence of the process parameters on the cutting force components F_x, $+F_y$, $-F_y$, and surface roughness R_a during peripheral up milling of bamboo scrimber. Tables 2 and 3 show the experimental results for the cutting force components, F_x, $+F_y$, $-F_y$, and surface roughness R_a.

Table 2. Cutting Force Components and Surface Roughness during Longitudinal Cutting

Trial No.	Spindle speed (rpm)	Feed rate (mm/min)	Cutting depth (mm)	Cutting force components			Surface roughness
				F_x (N)	$+F_y$ (N)	$-F_y$ (N)	R_a (μm)
1	5000	1000	1	160.27	49.37	-31.69	1.384
2	5000	2000	2	178.20	77.23	-47.65	1.704
3	5000	3000	3	201.30	95.68	-63.48	1.972
4	7500	1000	2	156.87	51.15	-29.37	1.596
5	7500	2000	3	175.80	86.70	-48.52	1.950
6	7500	3000	1	200.31	74.75	-54.55	1.847
7	10000	1000	3	144.33	53.08	-27.91	1.564
8	10000	2000	1	170.60	60.60	-38.49	1.780
9	10000	3000	2	213.33	86.29	-71.26	2.130

Table 3. Cutting Force Components and Surface Roughness during End-Grain Cutting

Trial No.	Spindle speed (rpm)	Feed rate (mm/min)	Cutting depth (mm)	Cutting force components			Surface roughness
				F_x (N)	$+F_y$ (N)	$-F_y$ (N)	R_a (μm)
1	5000	1000	1	191.20	51.68	-56.31	7.079
2	5000	2000	2	231.50	77.30	-69.54	7.361
3	5000	3000	3	280.48	97.95	-90.14	6.410
4	7500	1000	2	203.18	62.86	-61.23	5.656
5	7500	2000	3	248.10	85.16	-80.39	5.238
6	7500	3000	1	254.40	73.54	-73.13	4.503
7	10000	1000	3	225.15	79.39	-79.91	5.540
8	10000	2000	1	202.30	66.42	-63.41	6.054
9	10000	3000	2	266.60	80.07	-82.87	5.702

Analysis of Results

Significance of process parameters

The cutting force has an important impact on power consumption and machining quality of products. During the peripheral up milling, the results of the analysis of the significance of the effect of process parameters on cutting force components and machined surface roughness for the L9 experimental layout are shown in Tables 4, 5, 6, and 7.

In the column indicating the significance, a blank cell in the table means the effect of the corresponding parameter on cutting forces or surface roughness was not significant, "*" in the cell of the table means the effect of the corresponding parameter on cutting forces or surface roughness was significant, and "**" in the cell of the table means the effect of the corresponding parameter on cutting force or surface roughness was extremely significant.

Table 4. Results of ANOVA for Parallel Cutting Force F_x

Control factors	Sum of square of deviations	Degrees of freedom	F-value	F-critical value	Significance
Spindle speed	22.318	2	0.172	19.000	0.853
Feed rate	3966.639	2	30.612	19.000	0.032*
Cut depth	124.330	2	0.960	19.000	0.510
Error	129.58	2			
Total	4242.867	8			

Table 5. Results of ANOVA for Normal Cutting Force $+F_y$

Control factors	Sum of square of deviations	Degrees of freedom	F-value	F-critical value	Significance
Spindle speed	83.439	2	1.423	19.000	0.413
Feed rate	1855.666	2	31.642	19.000	0.031*
Cut depth	433.753	2	7.396	19.000	0.119
Error	58.65	2			
Total	2431.508	8			

Table 6. Results of ANOVA for Normal Cutting Force $-F_y$

Control factors	Sum of square of deviations	Degrees of freedom	F-value	F-critical value	Significance
Spindle speed	17.958	2	0.187	9.000	0.842
Feed rate	1681.791	2	17.539	9.000	0.054*
Cut depth	95.010	2	0.991	9.000	0.502
Error	95.89	2			
Total	1890.649	8			

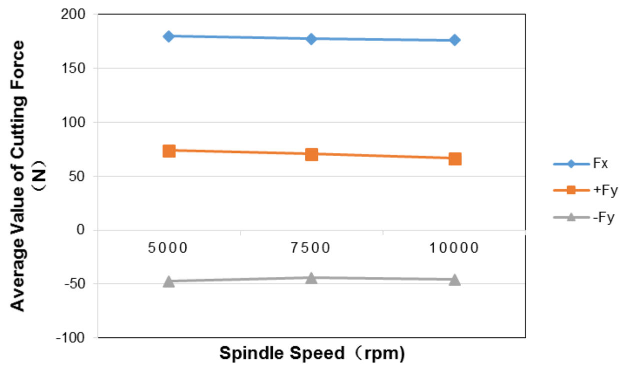
Table 7. Results of ANOVA for Surface Roughness *Ra*

Control factors	Sum of square of deviations	Degrees of freedom	F-value	F-critical value	Significance
Spindle speed	0.032	2	1.524	9.000	0.396
Feed rate	0.366	2	16.000	9.000	0.059*
Cut depth	0.045	2	2.143	9.000	0.319
Error	0.02	2			
Total	0.463	8			

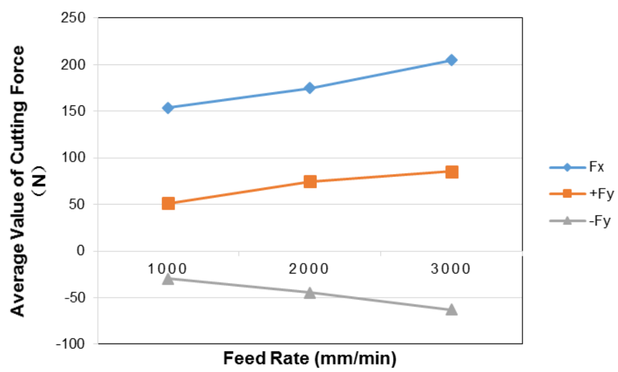
It can be seen from Tables 4, 5, and 6 that the effect of feed rate on the parallel cutting force F_x and the normal cutting force $+F_y$ was significant when measurement level α equaled 0.05. The effect of feed rate on the normal cutting force $-F_y$ and machined surface roughness R_a was significant when the measurement level α equaled 0.1. The effect of spindle speed and cutting depth on the cutting force components and machined surface roughness was not significant in this study.

Effect of process parameters on cutting force components

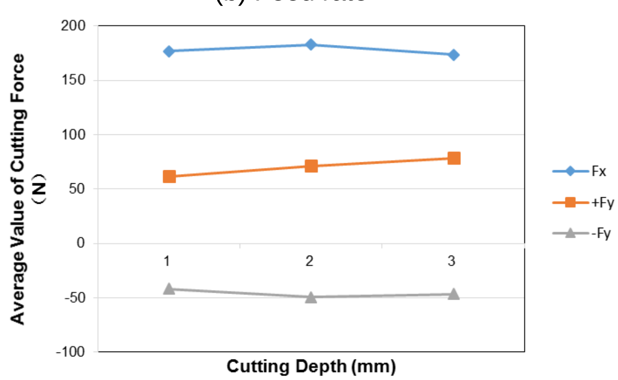
Figure 2(b) shows that feed rate had the most evident effect on cutting force components F_x, $+F_y$, and $-F_y$; the cutting force components all increased significantly with increasing feed rate. A higher feed rate would increase the cutting area and cutting volume of every cutting edge, which would lead to an increase in the cutting force of chip to cutting tool rake face. Figure 2(a) and (c) show that spindle speed and cutting depth had only a slight influence on the cutting force components compared to the feed rate. The parallel cutting force F_x and normal cutting force $+F_y$ decreased slightly with increasing spindle speed. A higher spindle speed would decrease the chip thickness, cutting area, and cutting volume of every cutting edge, leading to a decrease in the cutting force.



(a) Spindle speed



(b) Feed rate



(c) Cutting depth

Fig. 2. The effect of process parameters on cutting force components

With increasing cutting depth, the cutting volume of every cutting edge increased. However, bamboo scrimber is formed from bamboo fiber bundles saturated in phenol formaldehyde (PF) and compressed. During longitudinal cutting of bamboo scrimber, there were advanced splits on the machined surface; more advanced splits on the machined surface were generated with increasing cutting depth, and the range and depth of advanced splits became larger and deeper, which led to a decrease in cutting volume for the next cutting edge, so the cutting force components may not have increased with increasing cutting depth. This result is in agreement with Guo *et al*. (2009), who found that the length of advance splits increased with increasing milling thickness. The area of advance splits extended as the milling speed increased. The cutting direction had a significant influence on the length and width of advanced splits.

Effect of process parameters on machined surface roughness

The average value of surface roughness at every level was used to plot Fig. 3, which shows the influence of process parameters on machined surface roughness R_a. R_a increased with increasing spindle speed, feed rate, and cutting depth, and increased greatly with increasing feed rate compared to spindle speed and cutting depth. A higher feed rate led to an increase in the cutting area, as well as the friction and temperature between the cutting edge and work piece, and enhanced the vibration of the cutting system, which increased the value of R_a. Although the cutting volume of every cutting edge decreased with increasing spindle speed, the vibration of the process system was enhanced. When the effect of vibration of the process system was larger than the effect of the decrease of cutting volume on R_a, the value of R_a decreased. The larger cutting depth increased the cutting volume of every cutting edge, which increased the phenomenon of advanced splits. At the same time, advanced splits destroyed the machined surface, and R_a increased.

It can be concluded that decreasing the feed rate appropriately could greatly improve the quality of the machined surface, but it may decrease the production efficiency.

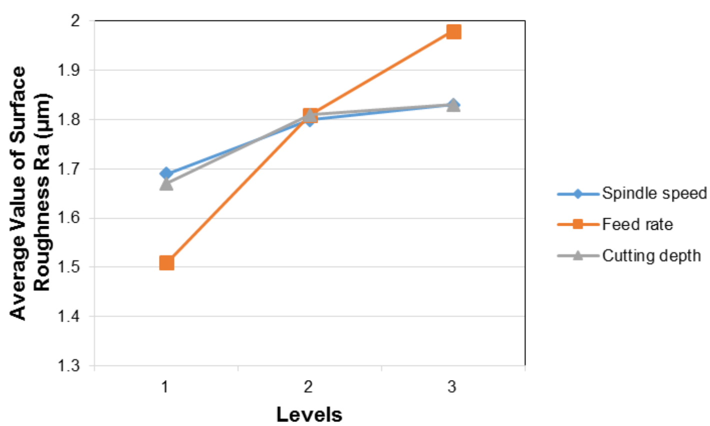


Fig. 3. The effect of process parameters on machined surface roughness

Effect of milling direction on cutting force components

Figure 4 shows that milling direction had a significant effect on the cutting force components F_x and -F_y. The parallel cutting force during end-grain milling (F_{xe}) was always larger than the parallel cutting force during longitudinal milling (F_{xl}) with the same experimental parameters. In addition, the normal cutting force during end-grain milling (-F_{ye}) was always larger than the normal cutting force during longitudinal milling (-F_{yl}) with the same experimental parameters. However, there was no obvious difference between the normal cutting forces during end-grain milling (+F_{ye}) and the normal cutting forces during longitudinal milling force (+F_{yl}) with the same experimental parameters.

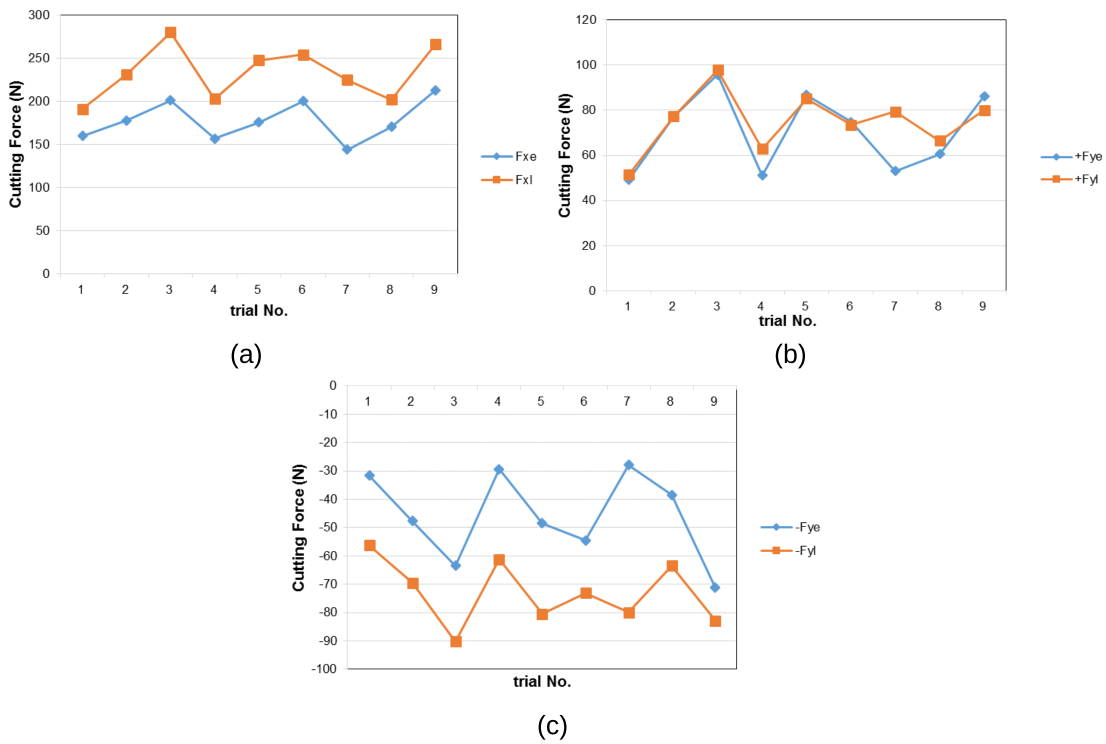


Fig. 4. The effect of milling direction on cutting force components

Effect of milling direction on machined surface roughness

Figure 5 shows that the value of machined surface roughness R_a during longitudinal milling (R_{al}) was always markedly smaller than the value of machined surface roughness during end-grain milling (R_{ae}).

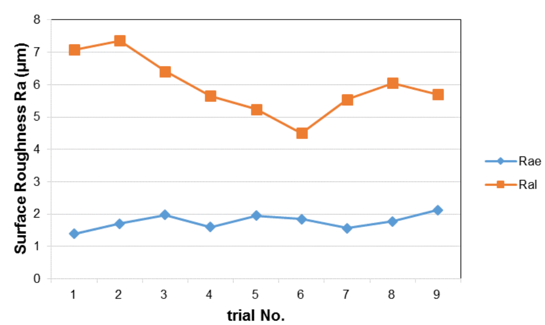


Fig. 5. The effect of milling direction on surface roughness R_a

Fig. 6. Machined surface of bamboo scrimber during (a) longitudinal milling and (b) end-grain milling

Figure 6 shows that the quality of the machined surface during longitudinal milling (Fig. 6(a)) was obviously better than the quality of machined surface during end-grain milling (Fig. 6(b)). Figure 6a shows that there were few defects generated by advanced splits, which decrease the quality of the machined surface.

Figure 6(b) shows that there were many small bumps generated by different elastico-plasticity characteristic of bamboo fiber bundles. This means that when cutting forces acted on bamboo fiber bundles of cutting surface, the fiber bundles would deform. After the cutting forces were released, a part of deformation of fiber bundles would disappear completely, some deformation would disappear partly, and some deformation would remain without any elastic recovery. The possible reasons for this phenomenon are that bamboo scrimber is a kind of anisotropic material, or that bamboo fiber bundles and the connecting material between bamboo fiber bundles had different strength and elastico-plasticity which led to different deformation of bamboo fiber bundles and the connecting material between bamboo fiber bundles. As a result, many bumps were generated on cutting surface during end-grain cutting of bamboo scrimber.

CONCLUSIONS

1. Process parameters had a great effect on cutting force components and machined surface roughness.
2. The effect of feed rate on cutting force components F_x, $+F_y$, $-F_y$, and surface roughness R_a was more significant than spindle speed and cutting depth.
3. During longitudinal milling, cutting force components F_x, $+F_y$, $-F_y$, and machined surface roughness R_a decreased slightly with increasing spindle speed. The cutting force components F_x, $+F_y$, $-F_y$, and machined surface roughness R_a increased greatly with increasing feed rate.
4. Cutting direction had a great effect on the cutting force components F_x, $+F_y$, and machined surface roughness R_a. F_x, $+F_y$, and R_a during longitudinal cutting were always larger than those during end-grain cutting.
5. In practice, decreasing the feed rate appropriately could greatly improve the quality of machined surface roughness and decrease power consumption.

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