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Analysis of Harvesting Methods of Moso Bamboo

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Abstract: Bamboo is widely used as an excellent engineering material in construction and furniture. The harvesting equipment and the bamboo application process need to be integrated better. According to the application requirements of the original bamboo structure building, the mechanism and practical experience of bamboo harvesting were analyzed using field experiments in bamboo forests and the finite element method. The operation stability and the side-face planeness of the saw were the direct factors affecting bamboo cutting quality. Further, the indirect factors were the clamp saw effect on the cutting surface, the hollow structure and diaphragm of bamboo, the density and moisture, and the swarf pocket.

Keywords: bamboo; harvesting; saw; mechanism; field experiments

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1. Introduction

Sustainable material is in high demand to mitigate the global resources crisis [1,2]. Bamboo is considered an attractive natural material in terms of cost and performance due to its strength, sustainable utilization, rapid growth and significant carbon fixation capacity [3–5]. The physical properties of bamboo and wood, which can be directly used for buildings or processed into composite materials, are similar [6,7]. In industrial production, the round bamboo is split into bamboo units to produce various engineering materials or synthetic bamboo-based composites [8,9]. Using bamboo products as substitutes for plastics and wood has become one of the directions of industrial development in recent years [10,11]. The processing methods of bamboo require detailed research to help and promote the application of bamboo products in the modern world [12,13].

In China, 837 species of bamboo cover an area of about 6.41 million hectares, of which Moso bamboo accounts for 73% of the total area of bamboo forests in China. Bamboo is also one of the most important raw materials for bamboo construction [14]. Moso bamboo forests in China are mainly distributed in hilly areas with complex topography [15]. During the initial processing of bamboo, harvesting, pruning and other operations are generally carried out in the forest. Bamboo harvesting in the forest land mainly includes vertical cutting and cutting off after toppling [16]. In addition, it is difficult to cut bamboo with =existing machinery and equipment [17,18]. The high labor intensity and low production efficiency has caused a large amount of mature bamboo to be unable to come down from the mountains, resulting in serious wastes [19]. As a result, portable hand-held saws, such as the reciprocating saw, chain saw, etc., became popular cutting tools. [20].

In terms of wood cutting practices, previous research has been completed in machining methods, cutting surface quality, virtual simulation, etc. [21–24]. Because of the tapered hollow cone shell structure of bamboo, the processing method of bamboo is different from that of wood [25]. Moreover, the density distribution and microstructure have great differences between the internode and node parts of Moso bamboo in the radial, tangential and longitudinal directions [26]. Due to the limited harvesting time, the bamboo cutting position is prone to mildew or split, resulting in low bamboo yield and slow assembly.

Thus, it is desired that smooth cutting sections and high cutting efficiency are ensured during the harvesting [27].

Yang et al. designed a new V-shaped double round milling cutter for bamboo cutting, which improved the cutting efficiency of the complex terrain region [28]. Li et al. (2020) developed a hand-held bamboo harvester, which improved the harvesting efficiency, but caused bamboo splitting easily [17]. Using the finite element method, Guan et al. studied a spiral cutting mechanism, which could effectively solve the splitting problem during the bamboo harvesting [19]. Following the principle of the ecological design, Mariana et al. designed a portable bamboo cutting tool. This tool was easy to disassemble and assemble, and the tool would not twist during cutting [29]. Yu et al. developed a cluster bamboo selective cutting machine based on the reciprocating saw, which improved the smoothness of the cutting surface [30]. Based on response surface methodology (RSM), Liu et al. studied the effect of cutting parameters on the surface quality of bamboo plywood during milling. In addition, the operation parameters of the machine were optimized in the study [27]. Yang studied the mechanism of surface damage during bamboo planning [31].

Previous research has mainly focused on the design and innovation of new equipment. There are very limited studies on the comparison of tools and methods for bamboo cutting and the cutting mechanism in the bamboo forest [32]. This study focused on the mechanism of bamboo sawing to evaluate the influence of bamboo structure on cutting performance. The purpose was to provide a theoretical basis for the design of structural engineering bamboo harvesting machinery. The findings and results can be used for reference in practical forest operations.

2. Materials and Methods

2.1. Test Materials and Equipment

In this study, the age of the Moso bamboo (*Phyllostachys edulis*) was 5 years. The moisture contents of the bamboo sections were 52–63%. The bamboo growing site was located in Huajiashan Forest Farm, Nanping City, Fujian Province, China. The harvesting time was July 2022, which was the local bamboo cutting season. The cut-off position of vertical bamboo was 150–250 mm from the ground, and the average thickness of bamboo was about 10–15 mm. The experiment materials are shown in Figure 1.

Figure 1. Experiment in bamboo forest.

The main parameters and structures of the bamboo cutting tools are shown in Figure 2 and Table 1.

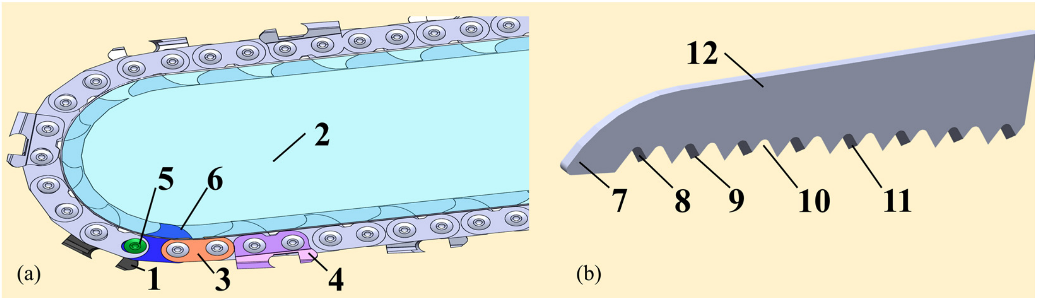

Figure 2. Structure of bamboo cutting tools. (**a**) Saw chain. 1. Left cutting tooth chain piece; 2. Guide bar; 3. Connection strap; 4. Right cutting tooth chain pieces; 5. Chain pin; 6. Driving strap. (**b**) Saw blade; 7. Saw corner; 8. Sawtooth; 9. Blade; 10. Tooth pocket; 11. Tooth surface; 12. Side surface.

Table 1. Main parameters of tools (unit: mm).

	Height	**Width**	**Thickness**	**Height of Tooth**	**Pith of Tooth**
Chain Saw	100	400	5	5	20
Reciprocating Saw	27	220	1	4	3

2.2. Method of Experiments

According to the actual production conditions and local technical requirements for bamboo cutting, the type of saw, state of bamboo, cutting direction and cutting position were selected as experiment factors, and the roughness of the cutting surface *Ra* (unit: µm) and the efficiency of cutting η (unit: cm/s) were selected as evaluation indicators.

The assembly of bamboo buildings requires bamboo to be sawn into different shaped parts, as shown in Figure 3. The types of saw include reciprocating saw, chain saw and hand saw, the weights of which are about 4.2 kg, 8 kg and 0.45 kg, respectively. In the process of bamboo cutting, there were two processes, namely, laying down bamboo and truncating bamboo. The cutting states were selected as two test levels: free-standing and chop down. The material density and water content were two important factors affecting the cutting performance in the cutting operation. The density of bamboo nodes was higher than that of internodes due to the influence of vascular bundles and vessels. Moso bamboo's density often varies as a function of its position and orientation [26]. Therefore, the cutting position was selected as the upper and near culm node, the lower and near sheath node and the middle of the bamboo internode, as indicated by L_1–L_3 in Figure 3. There are mainly two types of cutting surfaces in bamboo harvesting, i.e., horizontal and inclined. Therefore, three cutting directions were selected, i.e., horizontal, obliquely upward and inclined down. The quasi-level method was adopted to design the Taguchi Experiment with four factors and three levels, as shown in Table 2. After the experiment, the data were processed using intuitionistic evaluation (range analysis) and variance analysis. According to the analysis results, the regularity and importance of each influencing factor were obtained. By importing the formula into the Maple and Excel software that were used in this paper, we could directly generate curves.

The roughness of the bamboo cutting surface affects the component strength, adhesive quality, decoration quality, etc. of bamboo components. Poor surface roughness easily causes bacteria breeding and mildew on the cutting end surface. The direct influence of the roughness of the cutting surface is the structure and operating parameters of the saw [33–35]. The cutting surface is measured with a roughness meter at six points along the circumference of the cut surface, and then the average value is obtained as the surface roughness of the cut surface, as shown in Figure 4 and Equation (1). Bamboo cutting efficiency refers to the average velocity at which the saw finishes cutting bamboo, as shown in Equation (2).

$$Ra = \frac{\sum_{i=1}^{6} Ra_i}{i} \tag{1}$$

$$\eta = \frac{\sum_{i=1}^{6} R_i}{it} \tag{2}$$

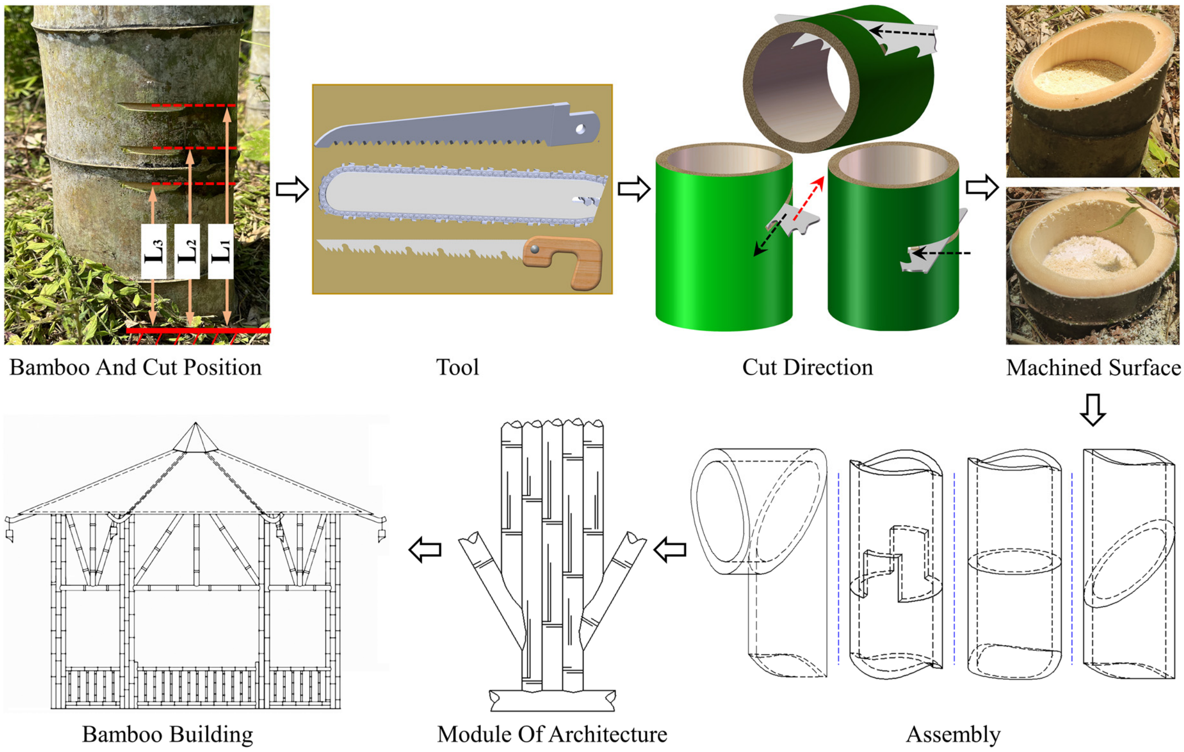

Figure 3. The experiment parameter setting and process of utilizing after bamboo cutting (Note: The red arrow indicates an oblique upward cutting direction, not a reciprocating motion).

Table 2. Factors and levels of experiment.

Level	Experiment Factors			
	A	**B**	**C**	**D**
1	Reciprocating Saw	Free-Standing	Horizontal	Upper and Near Sheath Node
2	Chain Saw	Chop Down	Obliquely Upward	Lower and Near Culm Node
3	Hand Saw		Inclined Down	Middle of Bamboo Internode

Where A, B, C and D, respectively, represent the type of bamboo cutting saw, state of bamboo, cutting direction and cutting position.

The primary aim of the in-situ trials described in this paper was to compare the performance of commonly used cutting tools and methods in the actual production process. The tools used in the experiments are shown in Figure 5. In order to select the operation and work intensity as close to the actual production as possible, operation tools for skilled forest farm workers were selected. Two male workers (36–42 years old) worked six hours a day. All the tools were hand-held.

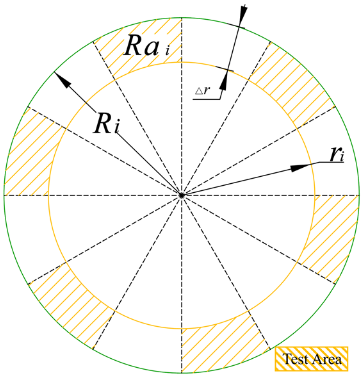

Figure 4. Surface roughness test method.

Figure 5. Test specimens and tools. (**a**) Cutter. (**b**) Test specimens. (**c**) Surface roughness meter. (**d**) Electron microscope.

The surface roughness meter (Model: ACCRETECH HANDYSURF E-35A) was used to measure the roughness of the sawn surfaces. In order to analyze the formation mechanism of the surface roughness, the electron microscope (Model: KEYENCE DIGITAL MICROSCOPE VHX-500F) was used to collect microscopic images of the sawn surface, as shown in Figure 5.

3. Results and Discussion

3.1. Experiment Results

The Taguchi experiment table L_9 (3^4) was selected to arrange the experimental scheme. The protocol and results based on the Taguchi experiment are shown in Table 3. The intuitionistic evaluation and variance analysis of the test results are shown in Tables 4 and 5.

Table 3. Experiment schemes and results.

NO.	Factors				Evaluation Indices	
	A	B	C	D	*Ra*	η
1	1	2	1	3	6.81	1.28
2	1	3 (2)	3	2	7.49	0.97
3	1	1	2	1	7.87	0.71
4	2	3 (2)	2	3	11.62	1.66
5	2	1	1	2	9.17	1.32
6	2	2	3	1	10.33	1.76
7	3	2	2	2	15.34	0.24
8	3	1	3	3	12.10	0.42
9	3	3 (2)	1	1	13.22	0.63

Note: The numbers in parentheses represent an alternative level for the quasi-level method.

Table 4. The intuitionistic analyzing of the experiment.

Indicator	Results	A	B	C	D
Surface Roughness (Ra)	K_1	22.2	29.1	29.2	31.4
	K_2	31.1	64.8	34.9	32.1
	K_3	40.6		29.8	30.4
	k_1	7.40	9.70	9.73	10.47
	k_2	10.37	10.80	11.63	10.70
	k_3	13.53		9.93	10.13
	R_1	6.16	1.09	1.88	0.49
Cutting Efficiency (η)	K_1	2.96	2.45	3.23	3.1
	K_2	4.74	6.54	2.61	2.53
	K_3	1.29		3.15	3.36
	k_1	0.99	0.82	1.08	1.03
	k_2	1.58	1.09	0.87	0.84
	k_3	0.43		1.05	1.12
	R_2	1.15	0.27	0.21	0.28

K_i (i = 1,2,3) indicates the sum of the test results corresponding to a level number i on any column. k_i (i = 1,2,3) indicates the arithmetic mean of the results obtained when the factor on any column is taken at level i. R_i (i = 1,2) indicates range.

Table 5. ANOVA results of regression model.

Items	Source of Variance	Sum of Squares	df	Mean Square	F-Value	p-Value	Significant
Surface Roughness	A	56.999	2	28.5	7599.914	0.008	***
	C	6.258	2	3.1295	834.421	0.025	**
	D	0.365	2	0.183	48.732	0.101	-
	B	2.369	1	2.369	631.717	0.025	**
	Pure Error	0.00375	1	0.00375			
	Cor Total	65.996	8	65.996			
Cutting Efficiency	A	1.984	2	0.992	14,883.17	0.0057	***
	D	0.121	2	0.06	901.167	0.0235	**
	B	0.15	1	0.15	2241.333	0.0134	**
	C	0.076	2	0.038	568.667	0.0296	**
	Pure Error	6.67×10^{-5}	1	6.67×10^{-5}			
	Cor Total	2.33	8				

Note: "***" means extremely significant ($p < 0.01$); "**" means very significant ($0.01 \leq p < 0.05$); "-" means not significant.

Based on the results of the intuitionistic analysis, the trend of the influence of each experiment factor on the indicator was obtained. Figure 6a,b demonstrates the influence of each test factor on roughness and cutting efficiency, respectively. The weight of the factors affecting the roughness is types of cutting saws > cutting direction > state of bamboo > cutting position. For roughness of surface, the optimal level is $A_1B_1C_1D_3$ (Reciprocating Saw, Free-Standing, Horizontal, Middle of Bamboo Internode). The weight of the factors affecting the efficiency of cutting is types of cutting saws > cutting position > state of bamboo > cutting direction. For efficiency of cutting, the optimal level is $A_2B_2C_1D_3$ (Chain Saw, Chop Down, Horizontal, Middle of Bamboo Internode).

According to the ANOVA results, the significance values p of each influencing factor in the test could be determined. For the evaluation index Surface Roughness, the factor " the type of bamboo cutting saw " had extremely significant influence, while the factors "state of bamboo, and cutting direction" had significant influence. The influence of cutting position on the cutting surface roughness was not significant. For the evaluation index Cutting Efficiency, the factor " the type of bamboo cutting saw " had extremely significant influence, while the factors "state of bamboo, cutting position, and cutting position " had significant influences.

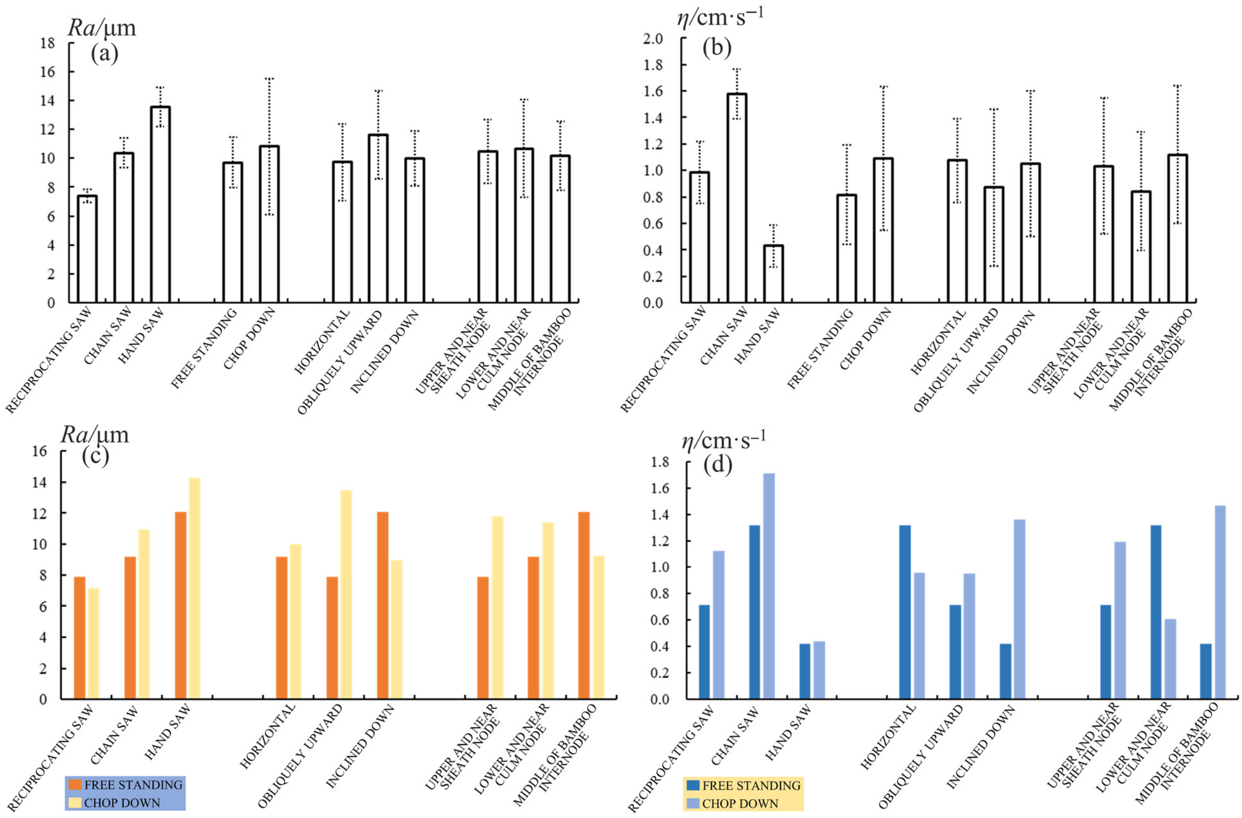

Figure 6. The influence of each factor on experiment indicators. (**a**,**b**) demonstrates the influence of each test factor on roughness and cutting efficiency, respectively. (**c**,**d**) demonstrates the influence of various factors on the surface roughness and bamboo cutting efficiency when the bamboo state was fixed to the free-standing and chop down states.

When the bamboo state was fixed to the free-standing and chop down states, the influence of various factors on the surface roughness and bamboo cutting efficiency is shown in Figure 6c,d. For the bamboo in free-standing state, the optimal level of surface roughness was $A_1C_2D_1$ (Reciprocating Saw, Obliquely Upward, Upper and Near Culm Node), and the optimal level of the bamboo cutting efficiency was $A_2C_1D_2$ (Chain Saw, Horizontal, Lower and Near Sheath Node). For bamboo in the chop down state, the optimal level of surface roughness was $A_1C_3D_3$ (Reciprocating Saw, Inclined Down, Middle of Bamboo Internode), and the optimal level of the bamboo cutting efficiency was $A_2C_3D_3$ (Chain Saw, Inclined Down, Middle of Bamboo Internode).

3.2. Mechanism Analysis

In order to intuitively understand the deformation effect of materials, the finite element simulation of the bamboo cutting process was carried out using the Finite Element Analysis software, as shown in Figure 7. In Figure 7, the relative action of the saw on bamboo fibers (micro) and the relative action of the saw on the bamboo structure (macro) are simulated, respectively. The deformation and stress nephogram during sawing was obtained.

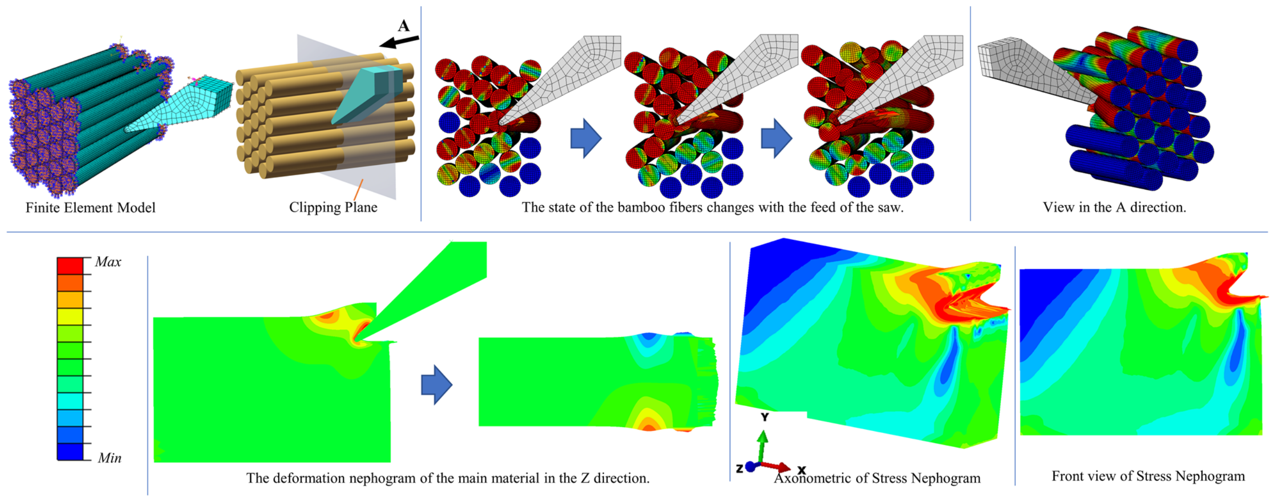

Figure 7. Finite element analysis of bamboo cutting(the direction of movement of the knife is horizontally to the left).

According to the observation of the micrograph (for example, Figure 8) of the cutting surface and reference [36], the destructive unevenness caused during bamboo cutting is the main factor causing surface roughness. The direct external factor of the ladder-shaped damage on the bamboo surface is the dislocation and offset of the cutter cutting path. Ideally, the force on the saw is balanced during the process of cutting bamboo. The saw feeds in a uniform and unidirectional state, and the chip is stressed stably. The swarf formed has a uniform size and an orderly fracture.

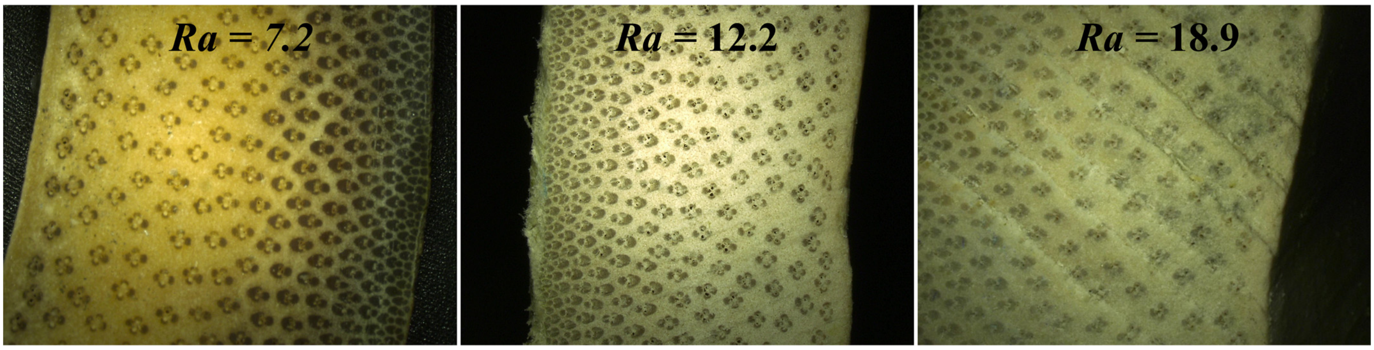

Figure 8. Microscopic view of the cutting surface formed after sawing of bamboo (tenfold magnification).

Bamboo cutting force refers to the forces caused by the resistance of wood acting on the tool. The sawing process of bamboo was analyzed according to the description of the finite element model, as shown in Figure 7. When the bamboo was sawn, the major cutting edge of the saw was parallel to the fiber direction, and the feed direction was perpendicular to the fiber direction. When the bamboo saw moves forward, the interaction between the sawtooth and the bamboo tissues is generally as follows. The major cutting edge bends the bamboo fibers forward and extrudes the bamboo fiber to both sides [37]. The front tooth surface moves forward to squeeze the bamboo tissues so that the bamboo tissues of unit volume are tensioned and then broken, which makes the bamboo tissues curl forward and upward, forming swarf when they are separated from the original position of the bamboo body. The side cutting edge shears the fibers, and both sides of the tooth surface squeeze the saw kerf walls. The swarf is concentrated in the tooth gullet area. After the front part of the flank tooth surface contacts the bamboo, the fibers are squeezed downward, resulting in an increase in the thickness of the swarf. A continuous contact arc is formed between the tooth corner and the bamboo. The bamboo is microscopically bent, squashed, sheared and stretched to form swarf. Therefore, the main forces acting on the saw tooth are shown in Figure 9.

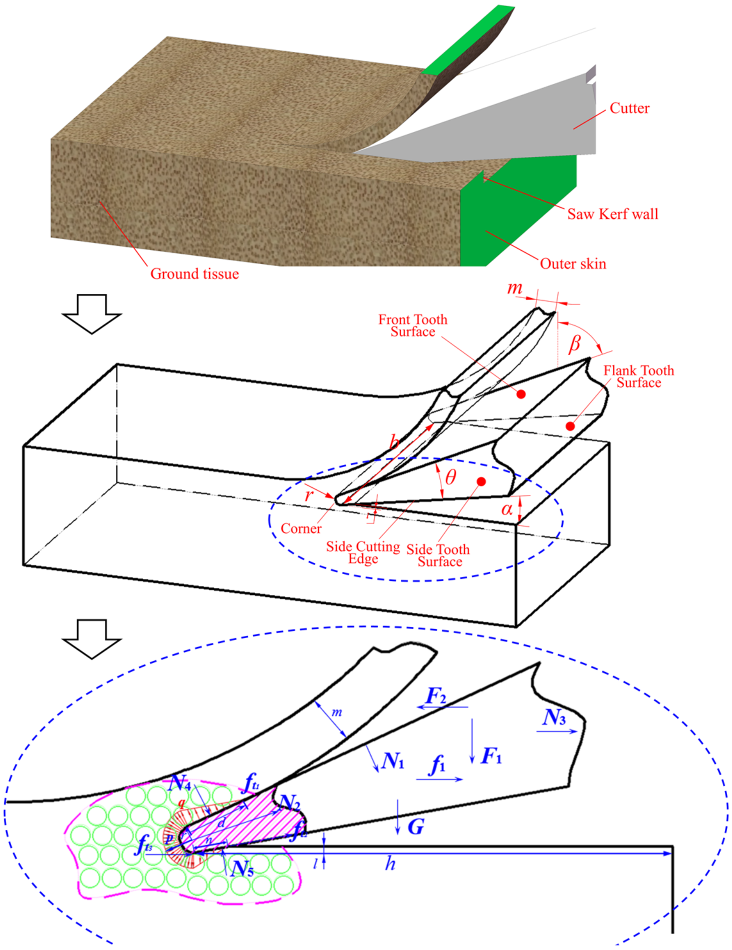

Figure 9. Mechanical analysis of bamboo cutting process.

Ideally, the contact mechanics model of the saw cutting bamboo is shown in Equations (3)–(12). From the perspective of bamboo structure parameters, the direct factors affecting surface roughness are swarf thickness and the contact size between the side edge and the saw kerf wall. Because they cause the fluctuation of saw surface pressure and friction, such as N_1, N_2, N_3 and f_1, instability of the movement state of the saw is produced. Eventually, the stress of the bamboo tissue to be cut is uneven, and the cutting surface appears as strip pits or bulges.

$$\Sigma F_x = N_2 \cos\left(\alpha + \frac{\theta}{2}\right) + (N_1 + N_4)\sin(\alpha + \theta) + f_{t_2} cos\alpha + f_{t_1}\cos(\alpha + \theta) - N_5 \sin\alpha - F_2 + f_{t_3} + N_3 + f_1 = 0 \quad (3)$$

$$\Sigma F_y = N_2 \sin\left(\alpha + \frac{\theta}{2}\right) - (N_1 + N_4)\cos(\alpha + \theta) + N_5 \cos\alpha + f_{t_2}\sin\alpha + f_{t_1}\sin(\alpha + \theta) - G - F_1 = 0 \quad (4)$$

$$N_1 = hmbp \quad (5)$$

$$N_2 = \int_0^{\pi+\beta} P(\varphi) q \mathrm{d}\varphi - \frac{qR^2\varphi}{2} \quad (6)$$

$$N_4 = \frac{1}{2} dq \quad (7)$$

$$N_5 = \frac{1}{2} nq \quad (8)$$

$$f_1 = AQ\mu \tag{9}$$

$$f_{t_1} = N_4\mu \tag{10}$$

$$f_{t_3} = N_2 \sin\left(\alpha + \frac{\theta}{2}\right)\mu \tag{11}$$

$$f_{t_2} = N_5\mu \tag{12}$$

The original shape of Moso bamboo should be kept as much as possible when it is used as a building material after harvesting [38]. The structure of bamboo resembles a hollow ring. The actual contact area between the saw and kerf wall is continuously changing, as shown in Figure 10. With the feeding of the saw, the areas of A_1 and A_2 are successively contacted. When entering area A_2, the contact area of the saw includes both area A_1 and area A_2. The bamboo structure forms two fulcrum-like structures on the saw. The positions of the force points of the whole saw change with respect to the center of mass of the saw, and saw vibration happens easily.

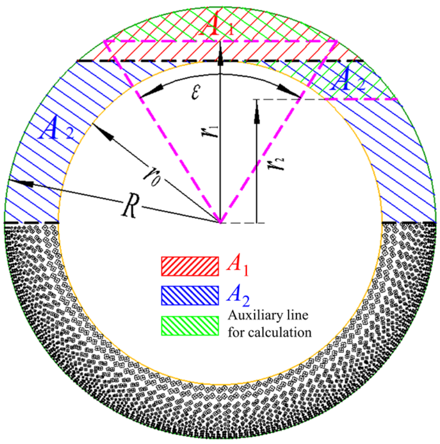

Figure 10. Schematic diagram of saw kerf wall changes in the cutting process.

With the feeding of the saw, the changing law of the saw kerf area is shown in Equations (13) and (14).

$$A_1 = \frac{1}{2}\varepsilon R^2 - r_1\sqrt{R^2 - r_1{}^2} \tag{13}$$

$$A_2 = 2\int_{r_2}^{r_0} \sqrt{R^2 - r^2} - \sqrt{r_0{}^2 - r^2}dr \tag{14}$$

The outer radius of the bamboo tube was set to 50 mm and the inner radius to 40 mm. The variation trend of the saw kerf wall was obtained, as shown in Figure 11. The function image of the equation was established by the Maple software. The rate of change was greater in an interval of about 9 mm (37–46 mm) at the junction of A_1 and A_2. The step-like rough surface appeared easily in this position, which accorded with the experimental phenomenon.

In terms of structural parameters, the thickness of the cutting affected the swarf removal ability of the sawtooth. After the bamboo cutting was completed, the most serious blockage was observed in the sawtooth gullet area of the reciprocating saws, as shown in Figure 12. The swarf was produced in the sawtooth gullet area and moved with the sawtooth movement. The swarf that was not discharged smoothly gradually compacted under the friction and vibration with the saw and bamboo. In addition, because the fresh bamboo contained a lot of extract similar to that of plant glue, the swarf was compacted and glued in the gullet area. Different gullet areas had different blockage degrees, resulting in uneven thickness of swarf. After that, the force on the saw would be uneven. At the same time, the contact length between the bamboo tissues and the side edge was decreased in the blocked position. The shear capacity of the side edge decreased.

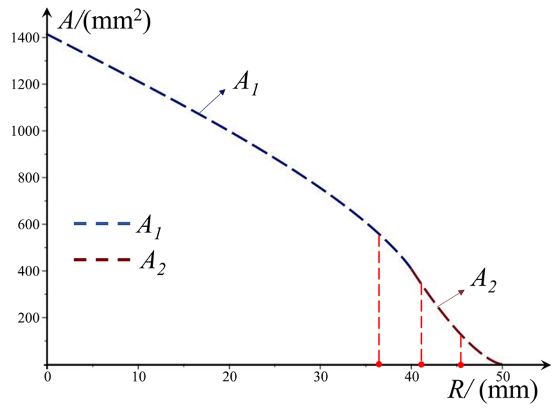

Figure 11. The variation trend of saw kerf wall area with sawing feed.

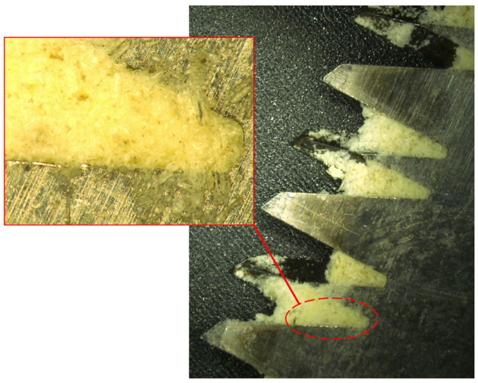

Figure 12. Micrograph of blocking phenomenon of gullet area.

3.3. Discussion

The type of saw was the most significant factor affecting the surface roughness and the efficiency of bamboo cutting, i.e., the tools. Chainsaws have larger sizes of tooth and tooth pitch than reciprocating saws [39]. The size of the swarf generated by the chain saw cutting was larger, and the sags and crests left on the surface after cutting were larger. When the movement of the sawtooth from the bamboo tissue transitioned to the bamboo cavity, the impact area between the sawtooth and the main tissue was larger, and uneven force was more likely to occur. In particular, the chain saw was heavy, and the hand-held sawing was not stable enough. However, due to the strong power, the cutting efficiency of the chain saw was higher.

In addition, for the same cutting position, the reciprocating saws and hand saws cut more times. Moreover, with the increase in the depth of the sawing, the smooth side surface of the saw would rub the side surface of bamboo that had been cut, and the microscopic sags and crests were further smoothed. The disadvantage of a handsaw was that its lateral motion was not as stable as that of an automatic tool. Therefore, the cutting surface quality of the hand saw was worse than that of the reciprocating saw.

The key difference between free-standing and chop down was the weight difference between the two sections above and below the cutting line. When the state of bamboo was free-standing, the weight of the bamboo was top-heavy, that is, prone to clamping the saw. In other words, the lateral pressure of the saw and its friction increased. In cases of the saw being clamped, the cutting efficiency decreased. When the clamping force was stable, the force pulling the saw out of its initial position was relatively small. Meanwhile, when the feed speed was reduced, the thickness of the swarf was reduced and the size was more stable. Thus, the surface roughness was lower.

There was an obvious interaction between the bamboo pose and cutting direction, as shown in Figure 6. When the bamboo was standing, it was prone to tipping over during the cutting process. For the inclined-down cutting direction, the feed direction was the same as the tipping trend. If the rollover side was unrestrained, the inclining quantity increased gradually. When excessive incline occurred, bamboo tissues would be split rather than cut. Natural splitting of the bamboo tissue was faster than cutting. However, the splitting direction and size of bamboo tissue were relatively irregular, resulting in higher surface roughness. When the bamboo was standing, the feeding direction of the saw was opposite to the tipping trend. The saw was prone to be clamped in the process of oblique upward cutting. The quality of the cutting surface was improved, but the cutting efficiency was lowered.

When the bamboo was harvested after the chop down, the clamping force of the saw was less. When the bamboo was cut in the inclined-down direction, the bending direction of the bamboo was the same as the sawing direction. A small tensile force was produced on the bamboo fibers. Microscopically, it was equivalent to pulling but not breaking bamboo fibers during cutting. This indicates that appropriate clamping force of the saw and smaller bamboo tissue elasticity are beneficial to the cutting performance.

The influence of cutting position on evaluation indicators was mainly caused by the density and moisture content. The effect of density of the middle section was lower than that of the end of the bamboo joint, and the moisture content was larger. Therefore, the strength and hardness of bamboo tissue were low in this section. During the cutting, the micro sags and crests in the middle of the bamboo joint were easier to smooth. Moreover, the force required for truncation was smaller. The diaphragm of bamboo was equivalent to a mechanical ribbed plate added to the hollow cylinder. The axial bending resistance and circumferential flattening or tearing resistance of the bamboo culm section were improved. This resulted in the interaction between the cutting position and the bamboo state, as shown in Figure 6.

For the free-standing Moso bamboo, when cutting the upper part of the bamboo node, the bamboo tissues of the upper part of the saw were far away from the bamboo diaphragm. The resulting deformation was converted into the clamping action of the saw. When cutting the lower part of the bamboo node, the bamboo culm on the upper part of the saw had a stable shape. The downward clamp force of the saw generated by the upper bamboo culm was small. Therefore, the upper part of the bamboo node was selected as the cutting position and the surface roughness was lower, but the cutting efficiency was not the highest.

However, when the harvesting state of bamboo was chop down, the axial and circumferential deformation force of the bamboo was very small, and the effect of the bamboo diaphragm was weakened. The cutting efficiency of the middle of the bamboo internode was higher, and the surface quality was better.

4. Practical Experience

(1) When the original bamboo is used for construction after harvesting, the distance between the cutting section and the bamboo diaphragm should be reasonably chosen according to the requirements of the end strength of the bamboo pole.
(2) If a clamped saw occurs, or the bamboo cutting saw enters the bamboo cavity from the bamboo skin, reducing the feed speed to obtain a higher surface quality is suggested.
(3) Clogging of the bamboo sawtooth gullet area often occurs, which is an unfavorable factor affecting cutting. In the cutting operation of bamboo, it is expected that chips be cleaned up in time.
(4) The hand-held tools are inevitably unstable during applications. Therefore, the bamboo cutting mechanism needs a stable support device to achieve stability of feed speed and direction, such as a multi-functional chassis.
(5) In order to improve the quality of the cutting surface of the reciprocating saw, the number of swarf pockets and the width of the spring set tooth shall be appropriately increased.
(6) The cutting efficiency of the chain saw is higher, and the surface roughness of the reciprocating saw is worse. For thick and strong bamboos, the operation shall be carried out with chain saws under the condition of low roughness requirements. However, for complex terrain, the chain saw operation is inconvenient and hand-held

operation is unstable. The reciprocating saw is more portable and precise. At the same time, reciprocating sawing has more advantages for cutting bamboo branches.

5. Conclusions

(1) The weight of the factors affecting the roughness is in the order of types of cutting saws > cutting direction > state of bamboo > cutting position. The weight of the factors affecting the efficiency of cutting is in the order of types of cutting saws > cutting position > state of bamboo > cutting direction.
(2) The direct external factor of the ladder-shaped damage on the bamboo surface is the dislocation and offset of the cutter cutting path, as well as the planeness of the side surface of the saw. It is important to design a structure with cutting path stability on the cutter.
(3) From the perspective of bamboo structure parameters, the direct factors affecting surface roughness are the swarf thickness and the contact size between the side edge and the saw kerf wall. When designing the cutter structure, the hollow structure of bamboo should be considered because it causes instability of the above factors.
(4) There are interactions between the state of bamboo and the cutting direction, bamboo state and cutting position.
(5) For bamboo in the free-standing state, the optimal level of surface roughness is $A_1C_2D_1$ (Reciprocating Saw, Obliquely Upward, Upper and Near Sheath Node), and the optimal level of bamboo cutting efficiency is $A_2C_1D_2$ (Chain Saw, Horizontal, Lower and Near Culm Node). For bamboo in chop down state, the optimal level of surface roughness is $A_1C_3D_3$ (Reciprocating Saw, Inclined Down, Middle of Bamboo Internode), and the optimal level of bamboo cutting efficiency is $A_2C_3D_3$ (Chain Saw, Inclined Down, Middle of Bamboo Internode).

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Nomenclature

G	Gravity
F_1	The downward thrust of the saw
F_2	The forward thrust of the saw
N_1	The pressure of swarf on the front cutter surface
N_2	The pressure on corner (contact arc)
N_3	The pressure on the side edge
f_1	The friction of sawing kerf wall
f_{t1}	The friction on the front tooth face
f_{t2}	The friction on the flank tooth surface
f_{t3}	The friction on the corner of the tooth
N_4	The pressure on the front tooth surface
N_5	The pressure on the flank tooth surface
α	The relief angle of saw
θ	The wedge angle of saw
β	The anterior angle of saw
b	The width of swarf

r	The radius of saw corner
m	The thickness of swarf
h	The length of swarf
l	The elasticity recovery of bamboo
n, d	The length of contact
q	Load collection degree
p	The curvature radius of contact arc
Ra	Roughness of surface
η	The efficiency of cutting
t	Time
R_i	The outside diameter of bamboo
r_i	The inner diameter of bamboo
Δr	The thickness of the bamboo
r_1, r_2	The distance from the tooth corner to the bamboo center
r_0	The inner diameter of bamboo
R	The outside diameter of bamboo
ε	The circular arc angle

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