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STUDY ON LASER CUTTING TECHNOLOGY OF BAMBOO

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ABSTRACT

The research advances of laser cutting technology were first stated. Then to study the performance of bamboo laser cutting and obtain the optimum technological parameters, we used a laser cutting machine with 60 W power laser tube and observed the magnified kerf shape. We found laser cutting perpendicular to the fiber direction was more difficult than other cutting directions under the same conditions. The notch depth was the deepest by parallel cutting and the notch width was the widest by oblique cutting. When the thickness of laser-cut bamboos was 3 mm, we obtained moderate kerf width, thinner carburization zone and better kerf quality under laser nozzle height 20 mm, cutting speed 30 $m \cdot min^{-1}$ and laser output power 48 W, which were the optimum technological parameters of bamboo laser cutting.

KEY WORDS: Laser cutting, bamboo, kerf quality, optimum technological parameters.

INTRODUCTION

Laser processing uses the laser-material interaction characteristics to process metals and nonmetals, including cutting, welding, surface treatment, drilling, micro-machining and identifies objects as light sources (Hecht 2010). Laser cutting technology, representative of laser processing, is a non-contact processing method that melts and vaporizes machined materials directly with high-energy laser as a tool. Laser cutting has two advantages: its rapid development and wide application can be promoted in all fields, and it has no chip pollution, tool wear, cutter replacement or noise pollution (or minimum noise) for cutting machine. Moreover, laser cutting also has excellent processing ability for machined materials, such as narrow cuts, good kerf quality, high cutting speed, small heat-affected zone (HAZ) and less distortion, and is able to cut complex geometries (Wang 2011). To ensure the cutting quality when laser cutting is applied to different materials, users only have to set appropriate process parameters. Many experiments have been done to obtain the optimum technological parameters. Patel et al. (2016) designed orthogonal experiments on laser cutting of glass fiber-reinforced plastic composites, investigated the effects of process parameters on HAZ, and optimized the process parameters on basis of artificial neural network (ANN) modeling. They found the ANN model better agreed with the prediction of HAZ with accuracy of > 97% for the given range of input parameters. Lutey et al. (2016) tested laser cutting of lithium-ion battery electrodes in terms of mechanical cutting, and obtained similar cutting quality and throughput but lower maintenance requirement. A scanning electron microscope was utilized to assess the clearance width of the upper coating layer and determine the defect dimensions, and obtain the optimum process parameters. Satoshi et al. (2016) drilled holes in the wood with short-wavelength short-pulse lasers, studied the shape of single hole and the quality of HAZ and obtained the optimum parameters. They deduced when wood cutting was attempted under the conditions of speed = 50 $mm \cdot s^{-1}$, a cutting width of approximately 20 μm at a thickness of several millimeters was achieved. They put forward the expectation to discuss machining parameters for cutting to be seen in the future. Eltawahni (2013) and Li Rongrong et al. (2016) tested laser cutting on plywood and reconstituted bamboo based on experimental design. They used mathematical models to establish the relationship between process parameters and edge quality parameters, and performed a numerical optimization to find out the optimal process setting at which both kerf would lead to a ratio of about 1 and at which low cutting cost take place. With the popularity of laser processing, more scholars tried to apply laser cutting into common materials, and compared its feasibility with the effect of mechanical cutting. Riveiro et al. (2016) cut 10-mm-thick commercial black granite boards by using a 3.5 kW CO2 laser source, assessed cutting quality by statistically-planned experiments and calculated the main influence factors on quality. They found granite boards could be a new application of CO2 laser cutting machine if a supersonic nozzle was used. Stepanov et al. (2015) investigated the pros and cons of laser cutting in different areas and applied to leather in comparison with mechanical cutting. Recent research is focused on the use of laser cutting in aviation, medicine and other high-tech fields. Mishra et al. (2017) used laser cutting into ultra-thin glass substrate for spacecraft thermal control application, and characterized microstructures by optical and scanning electron microscopy to study the laser-affected zone and cutting edge quality. They analyzed the influence of cutting parameters and made the optimization. Sealy et al. (2016) determined the effects of laser cutting conditions (e.g. peak laser power and cutting speed of a millisecond range pulsed laser) on kerf geometry, surface topography, surface roughness and microstructure, and obtained the optimal process parameters by experiments.

At present, there are many studies on laser cutting of conventional materials such as metals, plastics and wood, but little research is conducted on bamboo, which is used widely and processed by traditional methods though. Thus, we designed experiments here through automatic programming and used a CNC laser engraving machine to cut bamboo. We studied the effects of defocusing amount, laser output power and cutting speed on kerf quality of bamboo cutting, and obtained the optimum technological parameters through L25 orthogonal test. This study theoretically underlies industrial production of bamboo cutting and carving.

MATERIALS AND METHODS

Materials

Natural bamboo containing 6.5 % water was used, with the size of 100 mm (longitudinal, fiber direction) ×20 mm (width) ×3 mm (thickness).

Equipment

The traditional bamboo carving methods are slip carving and shallow graphic carving (Qin 2016). To simulate this processing mode, people usually use the laser engraving machine with rated power of 60 W in bamboo carving. Thus, a QJ6090C model laser cutting machine (Made in China) was used here (working principle shown in Fig. 1), with the maximum engraving speed at 60 m·min^{-1}, the maximum cutting speed at 100 m·min^{-1} and the maximum working range at 900×600 mm. The rated power of the provisioned CO2 laser is 60 W, the length of the laser tube is 1250 mm and the diameter is 55 mm; the diameter of the focus lens is 20 mm and the focal length is 63.5 mm. A number of experiments show the diameter of spot of laser beam left on the material surface is the smallest when the vertical distance from the laser nozzle to the material surface (hereafter, the nozzle height) is 20 mm.

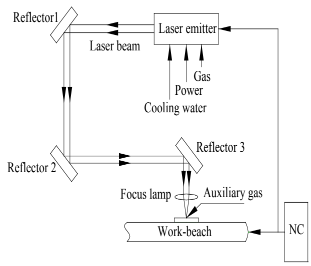


Fig.1: Working principle of laser cutting machine.

The surface quality and size of the kerf were observed under a JX13C model microscope (Made in China). The images displayed on the computer screen connected to the microscope were magnified 30 times, with the pixel of 795×596 and the resolution of 0.0002 mm.

Experimental design

Cutting test at the perpendicular direction to fiber

In the preparation stage, bamboo was laser-cut with different gas pressures (auxiliary gas was compressed air). When the gas pressure gradually rose within 0.1-0.4 MPa, the bamboo cutting depth slightly increased, so the kerf width was slightly reduced. The gas with higher pressure blew away the slag, forming better cross-sections of kerf. Therefore, we selected auxiliary gas pressure of 0.4 MPa to cut the bamboo.

We mainly discussed the influences of defocusing amount, cutting speed, and laser output power on kerf quality of bamboo cutting, as well as the superficial morphology of kerf. The defocusing amount was defined as the distance from the focus of laser focusing lens to the material surface, the focus above the materials as positive defocus, the focus on the material surface as 0 defocus, and the focus in the materials as negative defocus (Tan et al. 2011). The defocusing amount cannot be measured directly, but can be controlled indirectly by adjusting the nozzle height. The cutting speed was defined as the movement speed of laser head during the engraving. The main bases for judgement of kerf quality are the kerf sizes, including the width and depth. The essence of laser cutting bamboo was to superpose the kerf repeatedly upon the bamboo at the depth direction until the specimen was cut off. Thus, in this test, we studied the material removal mechanism of a single incision, and concluded the rules of bamboo laser cutting. Compared with vertical cutting, bamboo cutting parallel or at an angle to the fiber direction was more difficult. Thus, we mainly measured the size of kerf perpendicular to the fiber and observed the surface quality. We obtained the optimum technological parameters of bamboo cutting perpendicular to the fiber through data analysis, and then carried out parallel and oblique cutting tests. We selected the best technological parameters by comparing the sizes and surface morphology of kerf as comprehensive references.

Because of many variables, the intuitive and convenient orthogonal test was chosen to complete the test where bamboo was laser-cut perpendicular to the fiber. It was difficult to locate the focusing lens in the nozzle, so we cannot directly measure the focal position. Instead, we controlled the defocusing amount indirectly by adjusting the distance between the nozzle and the material surface. On basis of the test results, we would judge the focal position and the relationship between nozzle height and defocusing amount. The nozzle height was adjusted to ensure the parameter change was in the range of 16-20 mm. The range of cutting speed was 10-50 m·min^{-1}, and the range of laser output power was 12-60 W. The cutting surface was the side approach bamboo skin, and the cutting direction was perpendicular to the fiber of bamboo surface (Fig. 2).

This test involved 3 factors: nozzle height, laser output power and cutting speed. Each factor was tested at five levels (Tab. 1).

Tab. 1: Levels of influence factors on the kerf sizes in bamboo laser cutting.

Test factor	**Level of value**				
	1	2	3	4	5
Nozzle height/H (mm)	16	18	20	22	24
Laser output power/P (W)	12	24	36	48	60
Cutting speed/V (m·min^{-1})	10	20	30	40	50

In this 3-factor and 5-level test, we chose the orthogonal table L25 (56) and designed orthogonal Tab. 2 on the test factors.

Tab. 2: Orthogonal table of influence factors on kerf sizes in bamboo laser cutting.

Specimen number	Nozzle height H (mm)	Laser output power P (W)	Cutting speed V (m·min^{-1})
1	16	12	10
2	16	24	20
3	16	36	30
4	16	48	40
5	16	60	50
6	18	12	20
7	18	24	30
8	18	36	40
9	18	48	50
10	18	60	10
11	20	12	30
12	20	24	40
13	20	36	50
14	20	48	10
15	20	60	20
16	22	12	40
17	22	24	50
18	22	36	10

19	22	48	20
20	22	60	30
21	24	12	50
22	24	24	10
23	24	36	20
24	24	48	30
25	24	60	40

Parallel and oblique cutting tests

Due to obvious anisotropy (Keogh et al. 2015), when the process parameters were the same, the laser could more easily cut off the bamboo in parallel to the fibers under macroscopy, and inclined cutting was easier than vertical cutting. Thus, when the bamboo was repeatedly cut until being cut-off, these two cutting methods would both severely burn the cutting surfaces due to unnecessary repeated cutting, thereby reducing the quality of the cutting surface. In addition, serious carbonation of notch materials also largely enlarged the kerf width, which resulted in material loss. Thus, we should ensure the kerf shapes at vertical direction, and pay attention to the size and quality of parallel or oblique cutting kerf under the same process parameters. Therefore, we set up a reference test by cutting the bamboo surface and controlling the variables of parallel cutting (the cutting direction was in parallel with the bamboo fiber direction) and oblique cutting (the angle between cutting direction and bamboo fiber direction was 45°) (Fig.2(b) and 2(c)). Cross-section configuration of kerf perpendicular to the cutting direction was observed under a microscope enlarged by 30 times. We compared the kerf sizes and carbonization degrees under different parameters, combined the optimum parameters obtained from laser cutting perpendicular to the fiber direction, and obtained the best technological parameters of bamboo laser cutting.

(a)Vertical cutting *(b)Parallel cutting* *(c)Oblique cutting*

Fig.2: Diagram of cutting at different directions.

RESULTS AND DISCUSSION

Cutting test perpendicular to the fiber direction

Mechanism of bamboo laser cutting

There are two mechanisms for bamboo laser cutting: instantaneous gasification and combustion (Fang 2006), which are decided by both power density and irradiation time. The instantaneous gasification requires sufficiently large laser power density and thus processes the materials at the point of irradiation to form a slit. In this ideal cutting mechanism, the cutting speed is fast and the surface of the cutting seam is not carbonized, with only slight glaze or a bit dark.

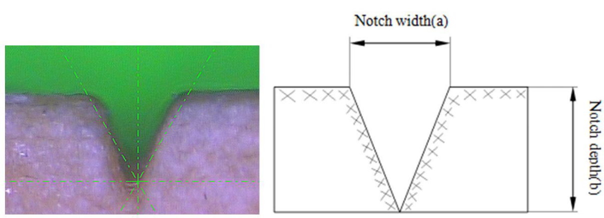
At the moment of laser irradiation, insufficient power density cannot gasify the materials instantly, but only burns to form a carburization zone. The specific phenomena were the low cutting speed, large HAZ, large notch width and unsatisfactory cutting process. Due to the influences of beam pattern and laser output power, the beam density is less than that required for evaporation in partial area of the irradiated site. In addition, flammable gases, water vapor, and coke formation during evaporation further were burnt to form heat and accelerate the cutting. As a result, the irradiated site was usually gasified with burning (Cao 1995). In the cutting, an appropriate beam mode should be used to suppress the combustion mechanism, or namely to ensure the small spot diameter by controlling the laser focus falling on the material surface. Adjusting the auxiliary gas pressure can blow away the unevaporated coke and other residues, which prevented the reduction of cutting quality due to secondary combustion. Increasing laser output power and cutting speed can ensure the large power density required for gasification and the reduction of irradiation time. We need to consider the interactions among the influential factors of bamboo laser cutting while guaranteeing the high cutting quality and suppressing the combustion mechanism (Yilbas 2004).

Shapes of kerf

Fig. 3 shows the macro-photo of a kerf, and Fig. 4 shows the micro-photo of the side and a schematic diagram of a single kerf. Clearly, the cross-section of the kerf is generally V-shaped; the notch is wider near the surface and narrows down with the increase of notch depth, until an angle appears at the lower part of the kerf. The reason for formation of kerf shape is that the laser focus fell near the material surface in the cutting process, so the laser energy was the strongest near the surface of the workpiece, which was concentrated and sufficient to ensure the larger notch width near the material surfaces. The laser energy was gradually weakened in a deeper region than an energy concentration area, and a large energy amount was consumed primarily when the upper layer of materials was removed. Therefore, the kerf width in the lower region gradually reduced to 0, and the kerf became V-shaped visually (Hua et al. 2013). The size of the cutting kerf included two parameters: (1) the notch width, defined as the maximum horizontal distance of the notch in cross-section of the kerf which was perpendicular to the cutting direction; (2) the notch depth, defined as the vertical distance from the surface of the workpiece to the lowest point of the notch.

In practical production, we hoped the cutting kerf was small in width and large in depth, so as to reduce the energy consumption. In addition, the thickness of the black carburization zone on the kerf surface after laser cutting is also an important factor that measures the kerf quality (Riveiro et al. 2016) during the process of material removal by laser. Theoretically, when the left carburization zone is thinner, the kerf quality is better. Thus, the carburization zone is thinner and the kerf quality is better.

Fig.3: Macroscopic top views of kerf perpendicular to the fiber direction.



(a)Microphotograph of the notch *(b)Diagram of the notch*

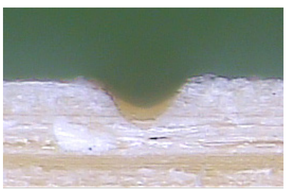
Fig. 4: Cross-section of the kerf perpendicular to the fiber direction.

Sizes of kerf

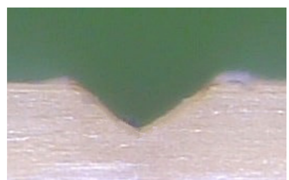
Notches of specimens under the conditions of different parameters were observed under a microscope with 30×. The notch width and depth of each specimen was measured (Tab. 3). Morphological comparison of a kerf under different parameters is shown in Fig.5.

Tab. 3: Measurements of notch sizes during bamboo laser cutting perpendicular to the fiber direction.

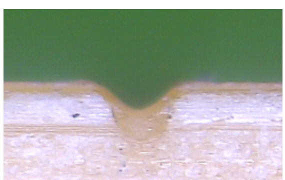
Specimen	Width a (mm)	Depth b (mm)	Specimen	Width a (mm)	Depth b (mm)
1	0.4025	0.0783	14	0.4857	0.1958
2	0.4047	0.0885	15	0.4836	0.1715
3	0.4132	0.1106	16	0.3025	0.0449
4	0.4387	0.1091	17	0.4374	0.0465
5	0.4522	0.1130	18	0.5411	0.1012
6	0.2588	0.0586	19	0.5348	0.0890
7	0.3158	0.0757	20	0.5668	0.0937
8	0.3773	0.0796	21	0.3558	0.0255
9	0.3965	0.0843	22	0.4346	0.0501
10	0.4852	0.2058	23	0.4921	0.0685
11	0.2003	0.0936	24	0.6988	0.0689
12	0.3029	0.0986	25	0.7243	0.0526
13	0.3578	0.1021	/	/	/



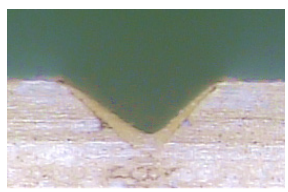
H=18 mm P=48 W V=50 m·min^{-1}



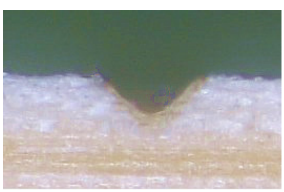
H=20 mm P=48 W V=10 m·min^{-1}



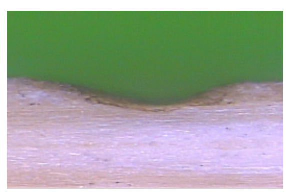
H=18 mm P=12 W V=20 m·min^{-1}



H=20 mm P=60 W V=20 m·min^{-1}



H=20 mm P=36 W V=50 m·min^{-1}



H=24 mm P=48 W V=30 m·min^{-1}

Fig.5: Morphological comparison of kerf under different parameters (From top to bottom, the dominant parameter was cutting speed, laser output power and defocusing amount, respectively)

Data analysis

Influences of various factors on the notch width

Tabs. 4 and 5 shows the angles and variances about the influences of factor-alpha level on the notch width. Figure shows the effective curve about the effects of test factors on the notch width.

Tab. 4: Variance analysis and significance test of factor-alpha level of notch width.

Parameter	Test factors	Freedom (DF)	square sum of deviation	Mean square sum of deviation	F -value	significance
Notch width	H(mm)	4	0.113	0.028	9.4	*
	P(W)	4	0.188	0.047	15.7	*
	V($m \cdot min^{-1}$)	4	0.012	0.003	1.0	

Tab. 5: Range analysis of factor-alpha level of notch width.

Parameter	Level value	Nozzle height (H)	Output power (P)	Cutting speed (V)
Notch width	K_1	0.422	0.304	0.470
	K_2	0.367	0.379	0.435
	K_3	0.366	0.436	0.439
	K_4	0.477	0.511	0.429
	K_5	0.541	0.542	0.400
	Range(R)	0.175	0.238	0.070
	Primary and secondary factors	P>H>V		
	Optimization	$P_1H_3V_5$		

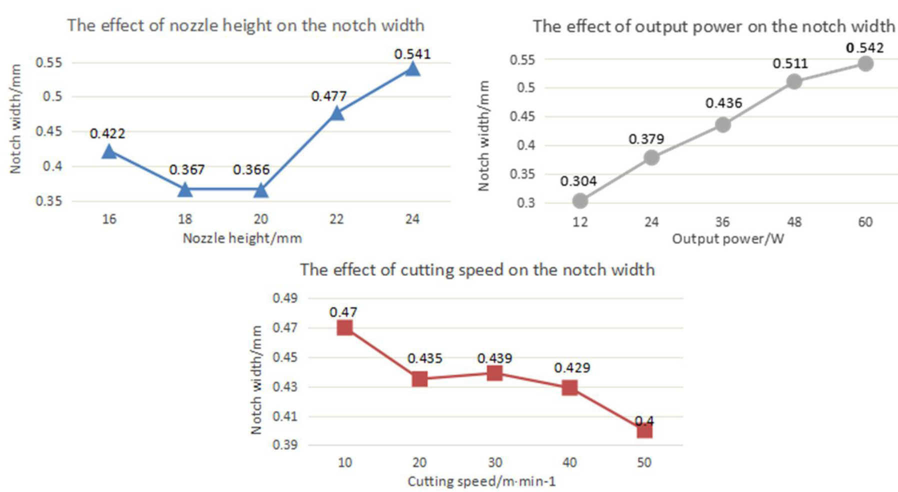


Fig.6: Effects of nozzle height (upper), output power (middle) and cutting speed (lower) on notch width.

By analyzing the significant effects of various factors on the notch width (Tabs. 4 and 5), we find effects of the three factors on the notch width rank in the order of laser output power > nozzle height (both significantly) >> cutting speed. Moreover, the notch width was the smallest when the bamboo surface was cut at downward 18-20 mm from the nozzle under the same condition (Fig. 6), indicating the focus of laser beam was felt in between downward 18-20 mm from the nozzle. In a certain range, a distance farther away from the focus led to larger spot diameter, which enlarged the kerf width. As described in conjunction with Fig. 5(c), when the defocusing amount was too large, the severely-burnt surface resulted in a wider and shallower kerf, so the material could not be cut off basically and the kerf quality was low. The result is the same with too small defocusing amount. With the increase of the output power, the laser energy rose and the kerf width was enlarged significantly. The cutting speed had little influence on the kerf width, as its increase led to reduction of width (Fig. 6).

Influences of various factors on notch depth

Tabs. 7 and 8 shows the analysis of range and variance about the influences of factor alpha level on the notch depth. Fig. 7 shows the effects of test factors on the notch depth.

Tab. 7: Variance analysis and significance test of factor-alpha level of notch depth.

Parameter	**Test factors**	**Freedom (DF)**	**Square sum of deviation**	**Mean square sum of deviation**	**F -value**	**Significance**
Notch depth	Distance	4	0.018	0.091	18	*
	Laser output power	4	0.015	0.209	15	*
	Cutting speed	4	0.009	0.004	9	*

Tab. 8: Range analysis of factor-alpha level of notch depth.

Parameter	**Level value**	**Nozzle height (H)**	**Output power (P)**	**Cutting speed (V)**
Notch depth	K_1	0.100	0.060	0.126
	K_2	0.101	0.072	0.095
	K_3	0.132	0.092	0.089
	K_4	0.075	0.109	0.077
	K_5	0.053	0.127	0.074
	Range(R)	0.079	0.067	0.052
	Primary and secondary factors	H>P>V		
	Optimizing technology	$H_3P_5V_1$		

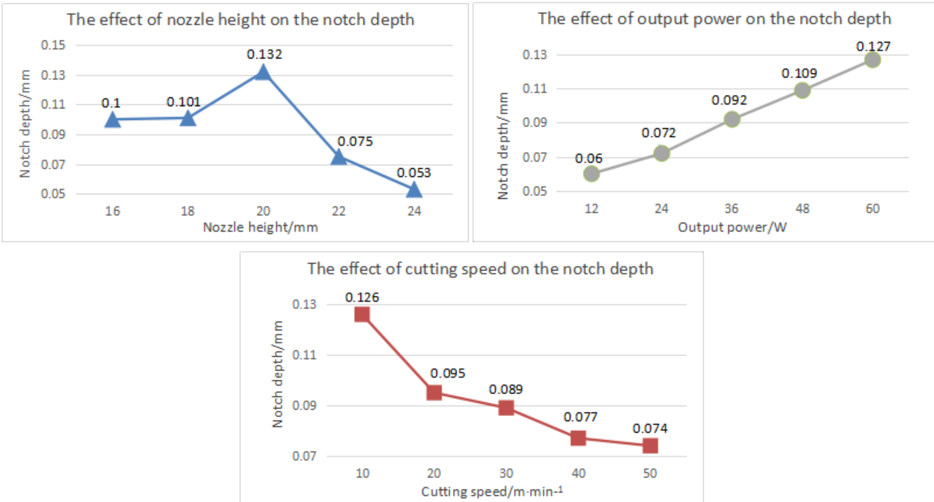


Fig. 7: Effects of (upper) nozzle height, (middle) output power and (lower) cutting speed on notch depth.

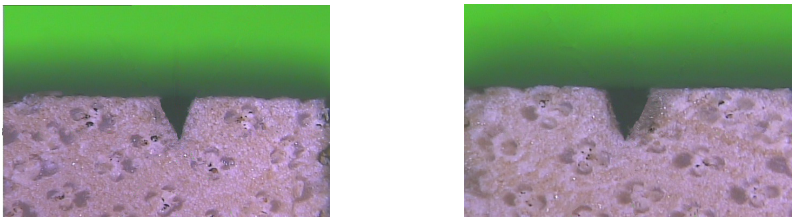
By analyzing the significant effects of various factors on notch width (Tabs. 7 and 8), we find the three factors all significantly affect the notch depth and rank in the order of nozzle height > laser output power > cutting speed. As showed in Fig. 7, the notch depth was the maximum when the bamboo surface was cut at downward 20 mm from the nozzle under the same condition, verifying that the laser focus felt near downward 20 mm from the nozzle. In a certain range, at a distance farther away from the focus, a larger defocusing amount led to shallower notch depth. When the nozzle height increased to 24 mm, the spot diameter became too large and led to the scattering of laser energy, and at this time, the laser could not cut off the material basically (Fig. 5c). In addition, the kerf depth increased obviously with the rise of laser output power. In conjunction with Fig. 5b, the kerf depth would be too shallow and had an extension of burning mark in the depth direction under too small laser output power. Moreover, too large output power would lead to a too thick carbonization zone, which reduced the cutting quality. The time of the laser beam staying on the material surface was decided by the cutting speed. Thus, in certain conditions, the kerf depths decreased with the increase of cutting speed. This obvious downtrend can be seen in Figs. 7 and 5a.

Parallel and oblique cutting test

The results of test 2.1 at the direction perpendicular to the fibers show the smallest notch width and the shallowest notch depth, so the kerf shapes are good after the bamboo has been cut at downward 20 mm from the nozzle. Therefore, the laser nozzle height of 20 mm is one major parameter of laser cutting. In addition, too slow cutting speed would lead to the formation of wide kerf while too fast speed is unable to cut off materials. Too small output power could not guarantee the appropriate cutting depth, while too large output power would cause excessive carbonization of incisions. All these conditions reduce the kerf quality. Therefore, the purpose of this check test is to verify the influences of laser output power and cutting speed on the kerf sizes. The variable controlling method was used here by maintaining the nozzle height constant at 20 mm. To verify the effect of cutting speed on cutting kerf shapes, we controlled the output power at 36 W and changed the cutting speed at 20, 30 or 40 m·min^{-1}. To verify the effect of output power, we controlled the cutting speed at 30 m/min and changed the output power at 24, 36 or 48W, the cutting direction was parallel or at 45° to the bamboo fibers, while the cutting surface was the side approach bamboo skin. Then we observed the shapes of sections perpendicular to the cutting direction, recorded the kerf sizes and analyzed the test results.

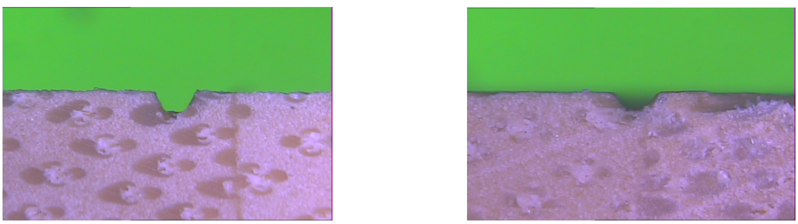
Shapes of kerf

A part of the cross-section shapes of kerf under the microscope are shown in Figs. 8 and 9, with the cutting direction parallel or at 45° to the bamboo fibers. The sizes of cutting kerf under different conditions are shown in Tab. 9.



H=20 mm P=48 W V=30 m·min^{-1}　　*H=20 mm P=36 W V=20 m·min^{-1}*

Fig.8: Morphological comparison of kerf with the cutting direction parallel to the fiber direction



H=20 mm P=48 W V=30 m·min^{-1}　　*H=20 mm P=36 W V=40 m·min^{-1}*

Fig.9: Morphological comparison of kerf with the cutting direction inclined to the fiber direction.

Tab. 9: Measurements of notch sizes that laser cutting bamboo parallel and inclined to the fiber directions.

Cutting direction	Specimen number	H (mm)	P (W)	V (m·min^{-1})	Width a (mm)	Depth b (mm)
Parallel to fiber direction	1	20	36	20	0.4112	0.2853
	2	20	36	30	0.3920	0.2513
	3	20	36	40	0.3451	0.2387
	4	20	24	30	0.3325	0.2406
	5	20	36	30	0.4026	0.2540
	6	20	48	30	0.4114	0.3068
Inclined to fiber direction	7	20	36	20	0.6248	0.1601
	8	20	36	30	0.5582	0.1424
	9	20	36	40	0.4657	0.1091
	10	20	24	30	0.5053	0.0969
	11	20	36	30	0.5629	0.1451
	12	20	48	30	0.5869	0.1712

Data analysis

1. Parallel cutting

As showed on the micrograph of parallel cutting (Fig. 8), the tip of V-type notch by parallel laser cutting is sharper than at other cutting directions, which is due to the structural anisotropy of bamboo. The bamboo is composed of parallel and tidy fiber bundles with consistent textures and no lateral contact, so its transverse intensity is only 1/30 of the longitudinal intensity (Li. 2014). Thus, when laser cutting was carried out parallel to bamboo fibers, only the transverse connection between fibers should be cut off, but not the fibers. Under the same laser cutting conditions, the bamboo fibers could be more easily cut off in the parallel direction. The difficulty of oblique cutting is in between the two directions.

When laser cutting is parallel to the fiber direction, the kerf sizes change with the output power and cutting speed and are basically consistent with the perpendicular cutting (Tab. 9), so no more reaffirmation is presented here. On the micrograph of kerf at parallel direction (Fig. 8), at the laser output power of 48 W and the cutting speed of 30 m·min^{-1}, the parallel cutting kerfs are shaped better, and superficial burning can be ignored basically. Together with the process requirements of smaller kerf width and larger kerf depth, the nozzle height of 20 mm, we decide the optimum parameters of bamboo laser cutting at parallel direction to the fibers are laser output power = 48 W and cutting speed = 30 m·min^{-1}.

2. Oblique cutting

Fig. 8 shows the notches of oblique cutting are significantly wider than at the parallel or vertical direction under the same parameter conditions. Therefore, in the actual cutting production, considering the material loss for kerf, we think oblique cutting should be avoided as much as possible. Tab. 10 shows the rules that the kerf sizes from oblique cutting change with the parameters are similar to other cutting directions, except that the larger notch widths. For the kerf at oblique cutting, we find the conditions of laser output power 48 W and cutting speed 30 m/min led to the formation of kerfs with acceptable widths, enough depths and better surface morphology (Fig. 8). Therefore, the optimum technological parameter of bamboo laser cutting are nozzle height = 20 mm, laser output power = 48 W and cutting speed = 30 m·min^{-1}.

CONCLUSIONS

1. The sections of kerfs for bamboo laser cutting were V-shaped. A layer of black carbonization materials appeared on the surfaces of the cut kerfs.
2. Under the same conditions, bamboo cutting perpendicular to the fiber direction is the most difficult, followed by oblique cutting and parallel cutting. Bamboo fiber cutting in the vertical direction consumed much more laser energy, while parallel cutting only cut the transverse connection between the fibers and thus was easier. Oblique cutting combined the characteristics of these two types, but the large notch width resulted in a waste of materials, so it was not recommended for actual production.
3. At the laser machine with output power of 60 W cutting bamboo with a thickness of 3 mm, the materials deviated further more from the laser focus (at downward 20 mm from the nozzle) along with the increase of the defocusing amount, and the kerf widths increased and the depths declined. The kerf widths and depths decreased with the acceleration of cutting speed, and increased with the enhancement of laser output power. Defocusing amount had the most significant effect on kerf width, and the most significant effect was the output

power. Gathering and analyzing the test results of laser cutting in three directions, we found the optimum technological parameters are defocusing amount = 0 (i.e., nozzle height = 20 mm), laser output power = 48 W and cutting speed = 30 $m \cdot min^{-1}$. The kerf widths are moderate and the depths are deeper under the optimum technological conditions, the kerf carburization zones are thinner and the kerf quality is higher, so the conditions are most suitable for laser cutting and will theoretically underlie the actual industrial production.

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