Design and Experiment for a Numerical Control Nanosecond Water-jet-guided Laser Processing Test Bench

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The laser processing method was applied to wood processing, and the water-jet-guided laser processing was adopted to design a numerical control nanosecond water-jet-guided laser processing test bench, which will provide a new theory and method for laser-processing wood. The numerical control nanosecond water-jet-guided laser processing test bench was built. *Pinus sylvestris* was used as the test subject. Laser energy, cutting speed, and defocus amount were used as the experimental factors. The aspect ratio was used as a response indicator. A three-factor, three-level Box-Behnken design was studied. A regression model of the three factors and aspect ratio was established. The test results showed that laser energy and cutting speed were the significant effects ($p < 0.001$) and that defocus amount was the notable effect ($p < 0.05$). The interaction of laser energy × cutting speed and laser energy × defocus amount had a significant effect on the aspect ratio. The optimal processing parameters were as follows: laser energy of 195.24 mJ, cutting speed of 1.03 mm/s, and defocus amount of -0.69 mm. The authors compared the surface of nanosecond water-jet-guided laser processing with the surface of laser processing. The former had little slag, and the cutting processing was stable. Therefore, nanosecond water-jet-guided laser processing showed better processing quality.

Keywords: Wood; Water-jet-guided laser; Processing parameters; Processing quality

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INTRODUCTION

Traditional laser processing technology has been widely used in production because of its advantages of being quiet and it has shown good controllability in the processing direction. Wood is a green, renewable, and biodegradable material. It has wide applications in furniture and architecture. Laser processing technology used in wood processing will provide a new processing method and theory (Sun *et al*. 2017; Yang *et al*. 2017).

Li (2008) designed a stable and inexpensive water-jet-guided laser processing system. It was found that water-jet-guided laser processing systems have good processing quality and wide application. Wu *et al.* (2015) proposed a nanosecond laser processing method of wood relief surface sanding. Jiang *et al.* (2016) studied the effects of laser energy, cutting speed, and depth of cut on the processing surface. It was found that the quality of the processing surface increased with an increase in the laser energy. In the same laser energy conditions, the quality of the processing surface increased with an increase in cutting speed. Yang *et al.* (2017) proposed the nanosecond laser processing theory of micronized wood fibers. It was found that micronized wood fibers could be produced by cutting along the grain.

The nanosecond laser ensures the processing accuracy in the micron range. However, a lot of slags, micro-cracks, and heat-affected zones were produced at the processing surface, which greatly decreased the quality of the processing surface and was not significant to the actual wood processing (Yuan and Han 2010; Lu *et al*. 2015). Therefore, it is urgent to develop an effective laser processing method for wood.

EXPERIMENTAL

Theory of Laser Processing Wood

The essence of the laser processing of wood is a process in which a high-density laser carbonizes and decomposes wood fibers. The laser gasifies the tissue fluid of the cells, causing the pressure to increase inside the cell wall. The high pressure ruptures the cell wall and the processing of wood is achieved. The principle of laser processing wood is shown in Fig. 1. The surface of the wood will oxidize when the temperature exceeds 180 °C. The wood will burn when the temperature reaches above 280 °C. The principle of nanosecond water-jet-guided laser processing is a process in which a water beam is used to guide a nanosecond laser to process wood. The internal temperature of the cell was controlled between 100 °C and 180 °C to avoid oxidation and burning of the processing surface. The water beam forms a laser processing anoxic zone and destroys the basic conditions of wood burning. Sublimation takes place within wood mixed with water vapor, and various gases are discharged with the gaseous water. The water beam decreases the temperature in the non-processing area and discharges the gasified wood, which ensures that sintering is not generated during the processing of wood (Yu *et al*. 2015; Li 2016; Yang *et al*. 2017).

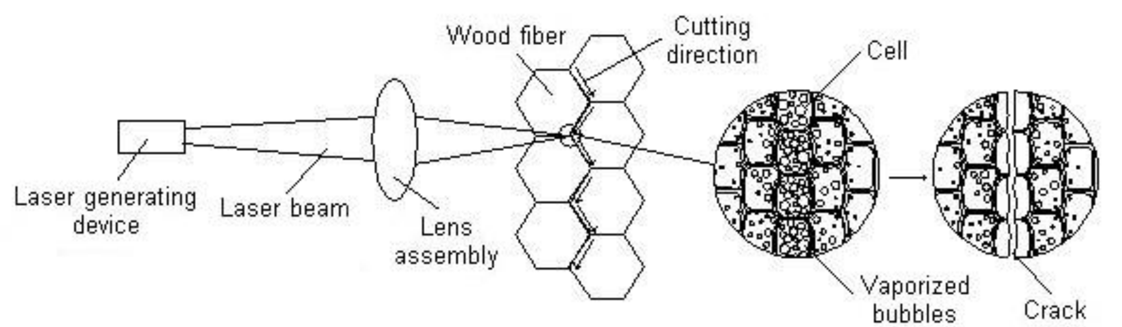


Fig. 1. The principle of laser cutting wood

Design of Numerical Control Nanosecond Water-jet-guided Laser Processing Test Bench

Analysis of movement of numerical control nanosecond water-jet-guided laser processing

A high quality of the processing surface and the small cutting force can be achieved when cutting along the fiber direction (Ren *et al*. 2014; Yang *et al*. 2016). Numerical control nanosecond water-jet-guided laser processing is the process of an envelope forming over a predetermined path. The formation of the envelope included rotation of the spindle in the axial direction of the workpiece and moving of the tool head in the fiber direction and radial direction of the workpiece. The processing is difficult to carry out due to the deformation of the workpiece and the change of the diameter gradient. The width of the laser beam can be adjusted to solve the problem. The motion diagram of nanosecond water-jet-guided laser processing is shown in Fig. 2.

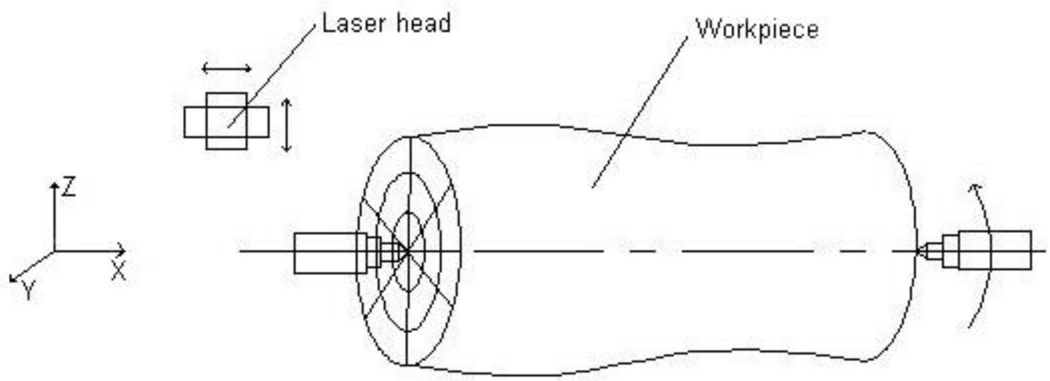


Fig. 2. Nanosecond water-jet-guided laser processing motion diagram

The configuration of the numerical control nanosecond water-jet-guided laser processing test bench

The processing of any machine tool is realized by the mating motion of the bed, moving parts, and rotating parts, and the nanosecond water-jet-guided laser processing of wood is no exception. Due to the processing characteristics of wood, the configuration of the machine tool is limited.

The configuration of the test bench can be determined by the following requirements:

1. The wood specimen must rotate around its axis during processing. Therefore, the rotating of the spindle should be the first configuration.
2. The internal structure of the wood is fibrous. The fiber bundle makes the wood have the characteristics of anisotropy. Cutting along the fiber direction will produce a better quality of the processing surface and a smaller cutting force during the processing of wood. Therefore, moving in the fiber direction is the second configuration.
3. The movement in the fiber direction and radial direction should be an adjacent cooperating movement to establish envelope cutting. Thus, moving in the radial direction should be the third configuration.

Based on the above processing requirements, the configuration of the test bench is the priority of the rotation of the spindle and the movement of the XY workbench.

Development of control system for numerical control nanosecond water-jet-guided laser processing test bench

The numerical control nanosecond water-jet-guided laser control system was a two-stage open-controlled nanosecond laser system based on an industrial personal computer (IPC) and programmable multi-axis controller (PMAC) 104, as shown in Fig. 3. The executive end was driven by three automation control (AC) servo motors (Delta, Taiwan, China). Three AC (Automation Controls) servo motors were controlled by an X-axis driver, Y-axis driver, and Z-axis driver. The laser head was controlled by the frequency converter to accurately produce laser beams of differing powers. The controller was connected to the PMAC. The dual-ported random access memory (RAM) and the conversion interface of a signal switch were connected to the PMAC to achieve a two-way exchange. Then, the industry standard architecture (ISA) bus was connected to an industrial personal computer (IPC). The system had two levels of openness, which makes it easy to extend the system to meet the processing needs (Li 2008; Yuan *et al.* 2010).

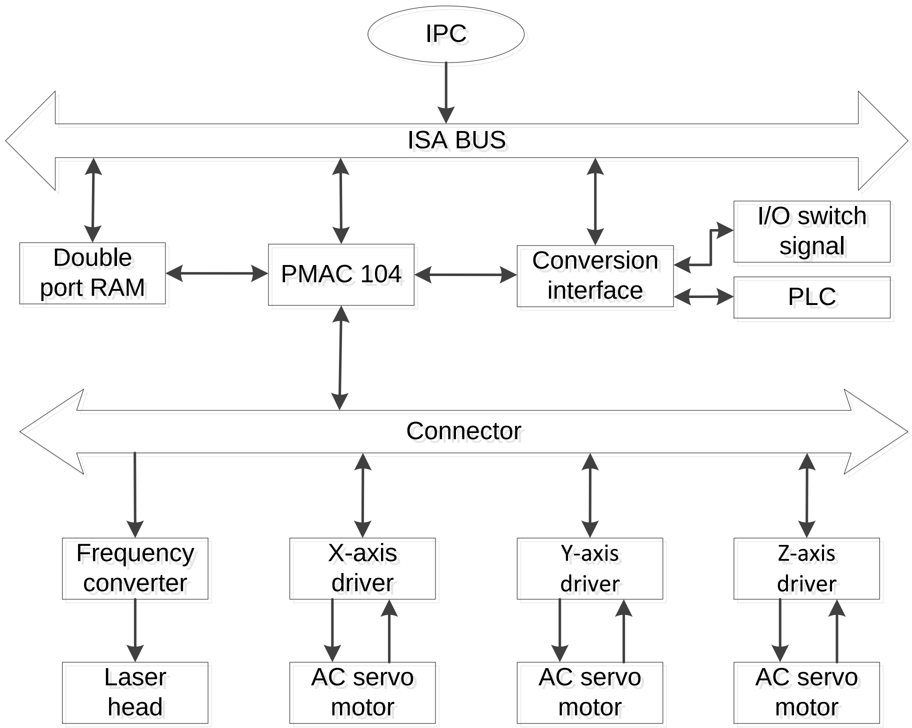


Fig. 3. Numerical control principle of the numerical control nanosecond water-jet-guided laser processing test bench

The numerical control nanosecond water-jet-guided laser processing test bench was designed as shown in Fig. 4. It meets the requirements of wood processing.

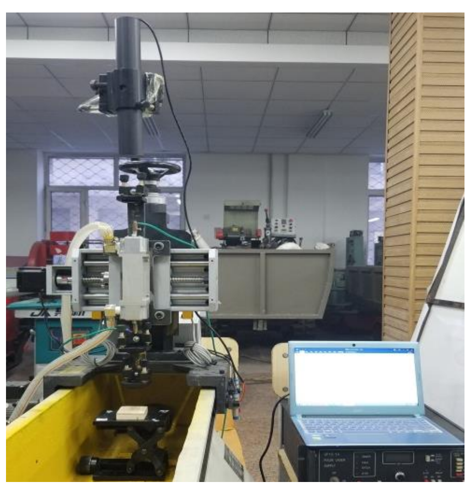


Fig. 4. The numerical control nanosecond water-jet-guided laser processing test bench

The test bench consisted of a nanosecond laser generator, a water supply system, a focusing lens, a spindle turning table system, and an XY moving table system. The rated voltage of the nanosecond laser generator was 220 V. The electric current can be adjusted within 0 mA to 3000 mA to produce different laser energy. An Nd: YAG (1064 nm) laser was employed. A YAG pulse processing angle regulator was used to adjust processing angle. The laser beam (Gaussian beam) mode was Single mode (TEM00). The pulse duration was about 200 μs, pulse frequency was 1~10 Hz, the laser spot size was 0.05 mm, and the focal length was 10 cm. The water supply system produces a high-pressure water flow. The system has a water circulatory system. The water pressure was 2 MPa, and the nozzle diameter was 0.15 mm (Li 2008).

Methods

Wood utilization should be improved to acquire maximized profits during the wood processing. Wood utilization is the ratio of the volume of raw material to the volume of finished product, as shown in Eq. 1,

$$\eta = \frac{v_c}{v_y} = \frac{v_y - v_z - v_q}{v_y} \tag{1}$$

where n is the wood utilization, v_c is the volume of finished product (mm^3), v_y is the volume of raw material (mm^3), v_z is the waste volume due to defects in wood quality (mm^3), and v_q is the waste volume due to processing (mm^3).

Wood quality problems are unpredictable and unavoidable during wood processing. To improve wood utilization, the waste of raw materials during processing should be reduced. In traditional woodworking, a wider sawing path leads to a much lower wood utilization. Especially in curvilinear cutting, the raw material is often wasted due to the limitations of the mechanical structure and the cutting principle during the wood processing. Nanosecond water-jet-guided laser processing is not limited by the traditional mechanical structure and cutting principle. The narrower cutting width will result in higher wood utilization. The cutting width of the nanosecond water-jet-guided laser system is 1/10 of the traditional cutting width (Jiang *et al.* 2016). Nanosecond water-jet-guided laser processing can acquire higher wood utilization. The deep depth of cutting is needed to meet the requirements of processing capacity. The aspect ratio defined by the ratio of cutting width to cutting depth is shown in Eq. 2,

$$\lambda = \frac{D}{h} \tag{2}$$

where λ is the aspect ratio, D is the cutting width (mm), and h is the cutting depth (mm).

The establishment of regression model

Solid wood furniture is widely used due to environmental protection being increasingly valued (Wu *et al.* 2015). *Pinus sylvestris* pine wood is widely used because of its clear texture and minimal scarring. Wood needs to be dried before processing and can be used for processing timber when its moisture content is below 10% (Hernández-Castañeda *et al.* 2011). *P. sylvestris*, with a moisture content of 9.67%, was used as the test subject (Forestry and Woodworking Machinery Engineering Technology Center, Harbin, China). The principle of water-jet-guided laser processing shows that the laser energy, the cutting speed, and the defocus amount are the main factors affecting aspect ratio (Eltawahni *et al.* 2011; Ren *et al.* 2014). The minimum aspect ratio is sought to achieve high utilization and processing capacity. A three-factor, three-level Box-Behnken

(Design Expert) design was applied for the optimization of processing parameters. The factors and levels of the test are in Table 1 and the experimental design is in Table 2.

Table 1. Three-factor Level Coding Table

Level	Factor		
	Laser Energy x_1 (mJ)	Cutting Speed x_2 (mm/s)	Defocus Amount x_3 (mm)
1	380	2.35	1
0	235	1.45	-0.5
-1	90	0.55	-2

Table 2. Test Plan and Result

No.	Factor			Aspect Ratio λ
	Laser Energy x_1 (mJ)	Cutting Speed x_2 (mm/s)	Defocus Amount x_3 (mm)	
1	90	2.35	-0.5	1.67
2	380	1.45	-2	0.43
3	235	1.45	-0.5	0.32
4	235	0.55	-2	0.40
5	380	1.45	1	0.68
6	235	2.35	-2	0.59
7	235	1.45	-0.5	0.32
8	380	0.55	-0.5	0.37
9	90	1.45	1	1.59
10	235	1.45	-0.5	0.43
11	235	2.35	1	0.73
12	90	1.45	-2	1.59
13	235	1.45	-0.5	0.32
14	235	1.45	-0.5	0.32
15	235	0.55	1	0.44
16	380	2.35	-0.5	0.69
17	90	0.55	-0.5	1.57

The regression equation of the aspect ratio is shown in Eq. 3:

$$\begin{aligned}\lambda &= 3.067 - 0.0182x_1 - 0.327x_2 - 0.0134x_3 + 4.1x_1x_2\times10^{-4} \\ &+ 2.91\times10^{-4}x_1x_3 + 0.016x_2x_3 + 3.01x_1^2 + 0.125x_2^2 + 0.044x_3^2\end{aligned} \quad (3)$$

Variance analysis is a quantitative investigation of the differences between actual and predicted values. The analysis was used to study the relationship between test results and test factors. A variance analysis of the test results is shown in Table 3. The significance test of the model coefficients is shown in Table 4.

Table 3. Variance Analysis of Test Results

Source of the Equation	Sum of Square	Degree of Freedom	Mean Square	F Value	p Value
Model	4.25	9	0.47	258.59	< 0.0001
Error	0.013	7	1.827×10^{-3}		
Misjudgment	2.618×10^{-3}	3	8.728×10^{-4}	0.34	0.7969
Pure error	0.010	4	2.543×10^{-3}		
Sum	4.27	16			
R = 0.9865, R^2 = 0.987, and R^2_{Adj} = 0.9731					

Table 3 shows that the model was significant ($p < 0.0001$), the misjudgment was not significant ($p = 0.7969$). The value of R^2_{Adj} was 0.9731, which shows that the model could explain the change of 97.31% response. The correlation coefficient value was 0.9865, which shows that the model fit well. Therefore, the model can be used to analyze and predict the aspect ratio of nanosecond water-jet-guided laser processing.

Table 4. The Significance Test of Model Coefficients

Model	Coefficient Estimates	Freedom	Mean Square	F Value	p Value
x_1	2.26	1	2.26	1236.19	< 0.0001
x_2	0.10	1	0.10	55.29	0.0001
x_3	0.022	1	0.022	12.18	0.0101
x_1x_2	0.011	1	0.011	6.27	0.0408
x_1x_3	0.016	1	0.016	8.76	0.0211
x_2x_3	1.980×10^{-3}	1	1.98×10^{-3}	1.08	0.3325
x_1^2	1.68	1	1.68	920.66	< 0.0001
x_2^2	0.043	1	0.043	23.79	0.0018
x_3^2	0.041	1	0.041	22.29	0.0022

Note: $p < 0.0001$ is a significant effect, $p < 0.05$ is a notable effect, and $p > 0.05$ is not significant effect

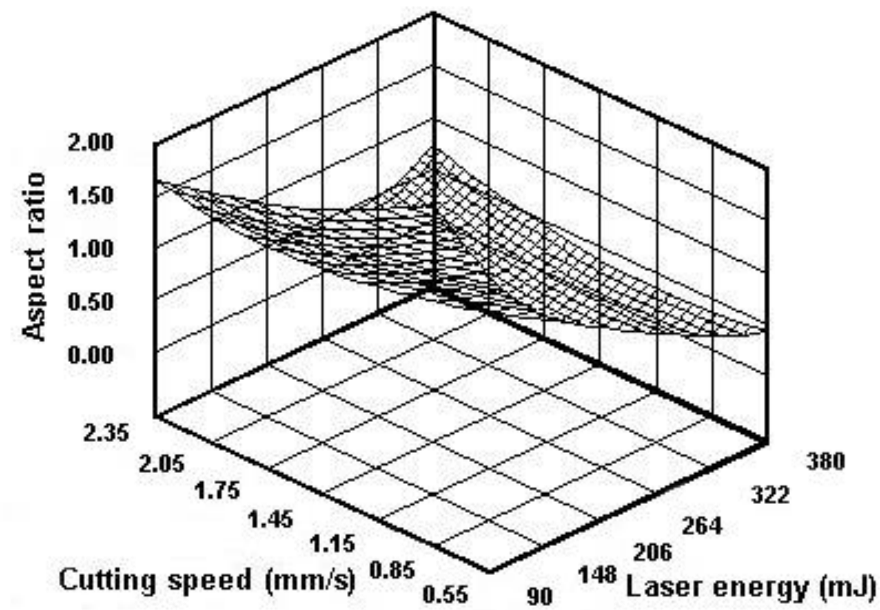
Table 4 shows that laser energy and cutting speed were significant effects ($p < 0.0001$), defocus amount was a notable effect ($p < 0.05$), square of laser energy was a significant effect ($p < 0.0001$), square of cutting speed and square of defocus amount were notable effects ($p < 0.05$), laser energy × cutting speed was a significant effect ($p < 0.0001$), and that laser energy × defocus amount was a notable effect ($p < 0.05$). Therefore, there were two nonlinear relationships and interactions between the three factors and the aspect ratio.

RESULTS AND DISCUSSION

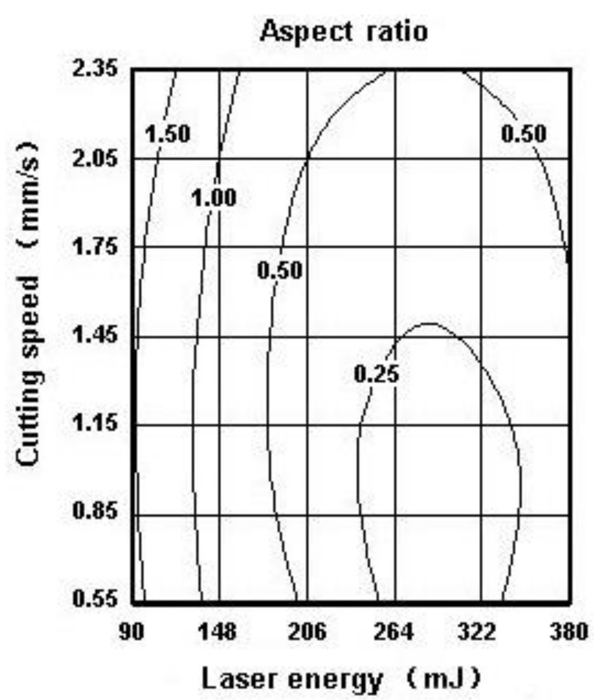
Response Surface Analysis of Nanosecond Laser Guided Laser Beam Cutting

Laser energy × cutting speed and laser energy × defocus amount were significant effects, while cutting speed × defocus amount was not significant. Therefore, the interaction of laser energy × cutting speed and the interaction of laser energy × defocus amount should be studied, and the interaction of cutting speed × defocus amount should not be studied. Once the cutting speed and the defocus amount were at level zero the results were recorded. The interaction of cutting speed × laser energy and the interaction of laser energy × defocus amount are shown in Figs. 5 and 6. The interaction of the two-factors was analyzed and evaluated by response surface methodology (Design Expert), and the optimum factor level was determined.

Figure 5 represents the interaction effects of laser energy × cutting speed when the defocus amount was -0.5 mm. The test showed a quadratic (nonlinear) relationship between the laser energy and aspect ratio and a quadratic (nonlinear) relationship between the cutting speed and aspect ratio. The interaction of laser energy × cutting speed had a significant impact on the cutting width. The aspect ratio did not change with the increase in cutting speed when the laser energy was at a low level. The aspect ratio increased with the increase in cutting speed when the laser energy was at a high level. The aspect ratio increased first and then decreased with the increase in laser energy when the cutting speed was at a low level. The aspect ratio decreased with the increase in laser energy when the cutting speed was at a high level.

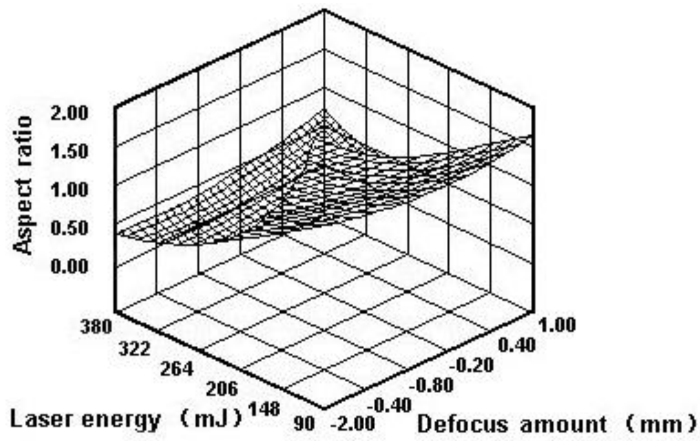


a. The response surface of interaction of laser energy × cutting speed

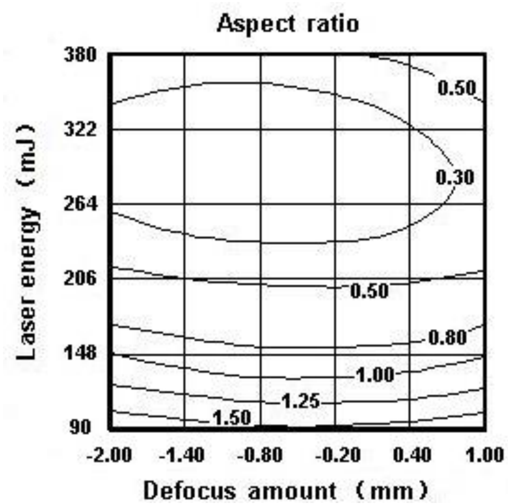


b. The contour line of interaction of laser energy × cutting speed

Fig. 5. The interaction of laser energy × cutting speed



a. The response surface of interaction of laser energy × defocus amount



b. The interaction of laser energy × defocus amount

Fig. 6. The response surface and the contour line of the laser energy × the defocus amount

Figure 6 represents the interaction effect of laser energy × defocus amount on aspect ratio when the cutting speed was 1.45 mm/s. The test showed a quadratic (nonlinear) relationship between the defocus amount and aspect ratio. The interaction of laser energy × defocus amount had a significant effect on aspect ratio. The aspect ratio increased first and then decreased with the increase in laser energy when the defocus amount was at a low level, and its trend of change was steep. The aspect ratio increased first and then decreased with the increase in laser energy when the defocus amount was at a high level, and its trend of change was slow. The aspect ratio was at a higher level and almost did not change with the increase in defocus amount when the laser energy was at a lower level. The aspect ratio decreased first and then increased with an increase in the defocus amount when the laser energy was at a high level.

Processing Parameter Optimization and Processing Quality Analysis

The processing parameters should be optimized to acquire the minimum aspect ratio. The optimal processing parameters were acquired (Design Expert). The optimization results were as follows: laser energy was 195.24 mJ, cutting speed was 1.03 mm/s, and defocus amount was -0.69 mm. The theoretical aspect ratio was 0.51 using the regression equation of the aspect ratio. At the same time, a verification test was conducted. The actual aspect ratio was 0.48, so the relative error was 5.9%. The rationality of the model was verified because the relative error was less than 10%. The response trend of the aspect ratio was the same for different kinds of wood due to the anisotropic internal fiber structure of the wood. The optimal processing parameters of different wood were acquired using the method of this study.

Nanosecond water-jet-guided laser processing of wood and laser processing of wood had obvious differences in quality. The processing quality was compared, as shown in Fig. 7. The surface of laser processing observed with SEM (Scanning Electron Microscopy) is shown in Fig. 7a. The surface of water-jet-guided laser processing observed with scanning electron microscopy (SEM) is shown in Fig. 7b. Laser processing yielded obvious signs of burning, was gully-shaped, and had more slag as shown in Fig. 7a. The quality of the processed surface was poor. The nanosecond water-jet-guided laser processing surface had a fine melting effect, was smooth, and had little carbonizing wood residues as shown in Fig. 7b. The quality of the processing of the surface was high.

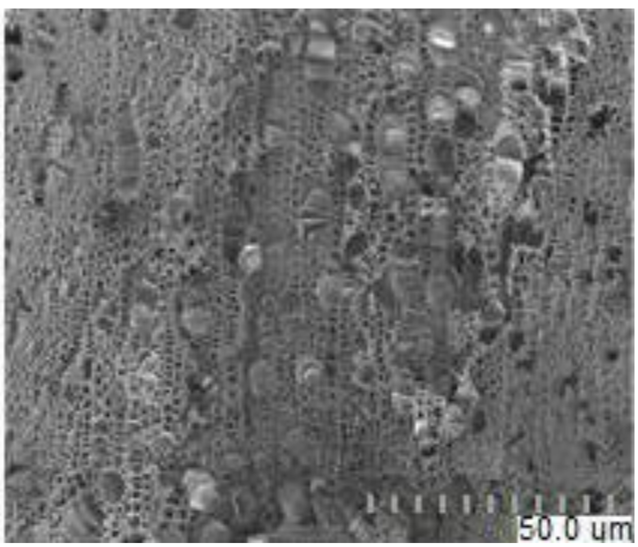


Fig. 7a. SEM image of the surface of laser processing

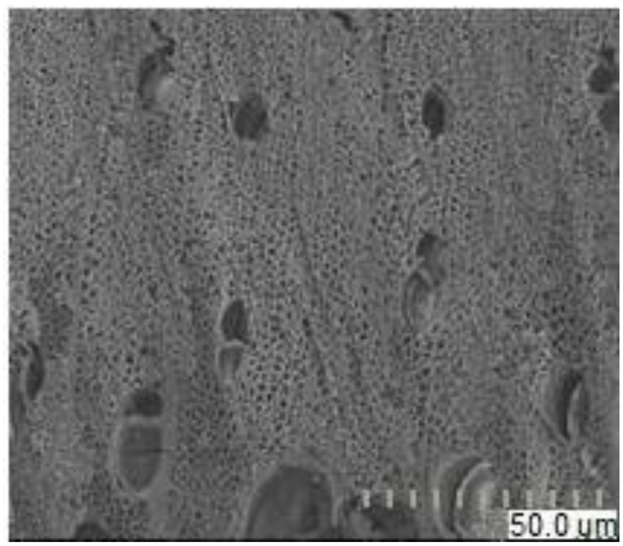


Fig. 7b. SEM image of the surface of water-jet-guided laser processing

CONCLUSIONS

1. The movement of numerical control nanosecond water-jet-guided laser processing was analyzed to determine the configuration of the test bench. The control system of numerical control nanosecond water-jet-guided laser processing test bench was developed and a numerical control nanosecond water-jet-guided laser processing test bench was built.
2. A regression model of the three factors and the aspect ratio was established. It was concluded that the laser energy and cutting speed were highly significant effects ($p < 0.001$) and the defocus amount was a notable effect ($p < 0.05$). The order of influence of the factors was laser energy > cutting speed > defocus amount. The interaction of

laser energy × cutting speed and laser energy × defocus amount had a significant effect on the aspect ratio.

3. The optimal processing parameters were acquired. The optimization results were as follows: laser energy of 195.2 mJ, cutting speed of 1.03 mm/s, and defocus amount of -0.69 mm. The rationality of optimal processing parameters was verified. The surface of nanosecond water-jet-guided laser processing was compared with the surface of laser processing. The former had a fine melting effect, was smooth, and had little slag. Therefore, nanosecond water-jet-guided laser processing resulted in a better quality of processing.

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