Experimental Design and Study of Micro-nano Wood Fiber Processed by Nanosecond Pulse Laser

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A new processing technology using a nanosecond pulse laser to process micro-nano wood fiber is proposed in this paper. A test bench was designed and manufactured for the technology. The digital design process, experimental methods, and general layout principle of the test bench are introduced. When the factors that affected the results of the experiment were analyzed, it was found that cutting width and cutting depth were affected by cutting direction, cutting speed, and cutting power. The wood underwent thermal degradation near the point of processing. The results of the experiment showed that the technology is feasible.

Keywords: Nanosecond pulse laser; Micro-nano wood fiber; Test bench; Design and studies; Digital analysis

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INTRODUCTION

The nanosecond laser has the characteristics of small thermal effect, high processing efficiency, high speed, and little influence on the surface of the work piece. In recent years, laser technology has been used more widely.

Liu (2008) designed the nanosecond pulse laser micro-machining system. By analyzing the effects of different parameters of processing, it was determined that the laser pulse repetition rate, laser cutting speed, and the energy of the laser pulse had an effect on the results of micro-machining. Li (2008) conducted research to test a model of water-jet guided laser micro-machining. They found that the water-jet guided laser micro machining system that they manufactured for machining micro parts had excellent properties and extensive applications. Zhi (2014) discussed in detail the application of a laser in material welding, punching, and forming. Luo *et al*. (2015) analyzed and investigated polymer materials that were processed by pulsed laser. Wu *et al*. (2015) applied nanosecond laser into the sanding of relief furniture and carved wooden doors. Yu *et al*. (2015) studied a model of the explosion of wood surface cells when heated by a nanosecond laser, and derived a formula for the heat of the nanosecond laser generator. This laser has been shown to play an important role, whether in the field of information, military, material processing, medical science, life science, or another.

In this work, a new technology for the processing of micro-nano wood fiber by a nanosecond pulse laser is proposed. In order to master the technological rules of processing, a test bench was designed and manufactured. The effects of various factors on the results of the processing were studied.

EXPERIMENTAL

Hypothesis

It was hypothesized that when the wood cells were exposed to repeated cutting by a nanosecond laser at a high power density, the liquid inside the cells would evaporate instantly and cause the cells to burst, disconnecting the fibers from the surrounding tissue in such a way as to generate long micro-nano wood fibers (Yang *et al*. 2008; Juan *et al.* 2011).

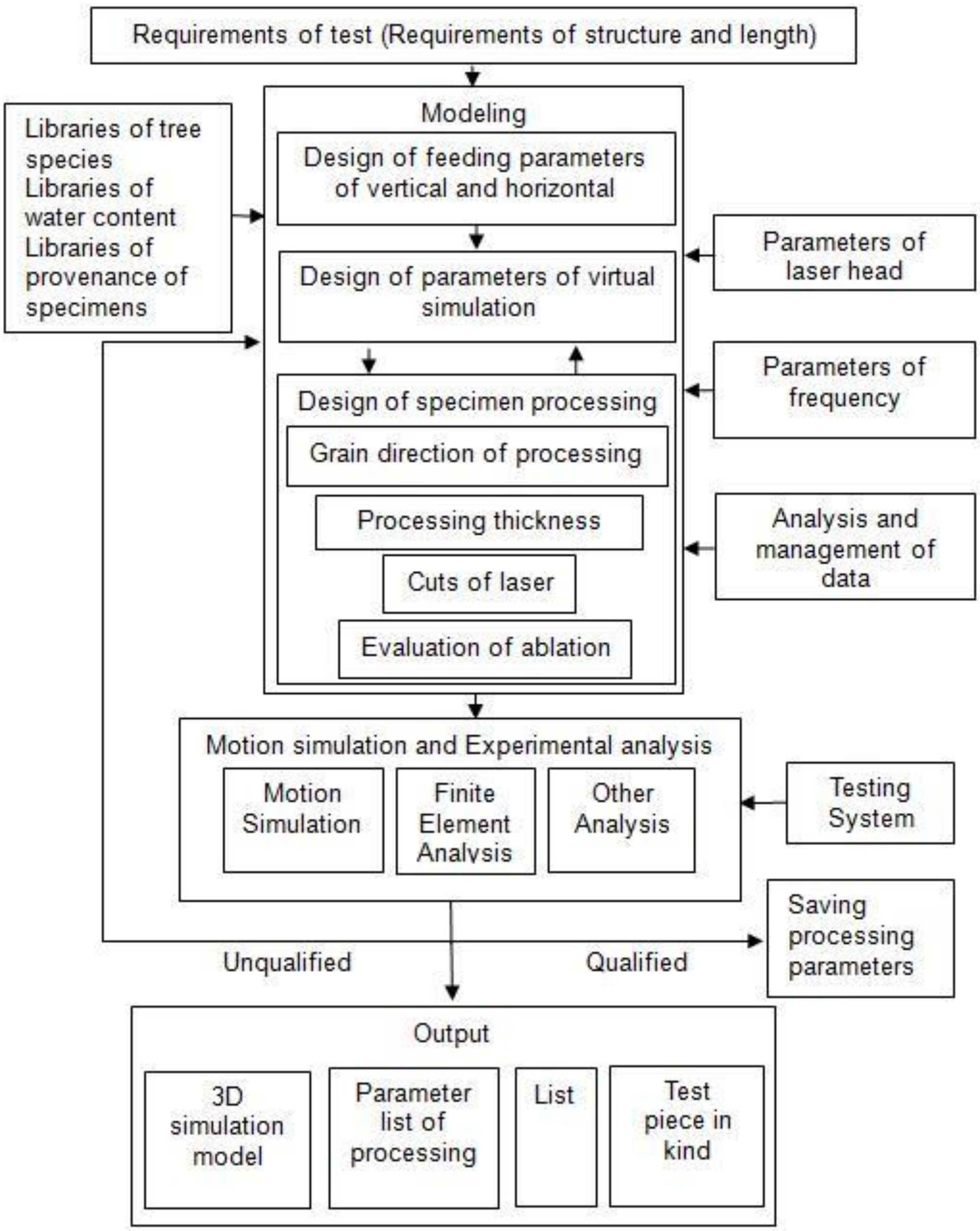

Fig. 1. General flow chart of digital design process of test bench

Design of the Test Bench

Digital design process of test bench

Computer-aided design (CAD) and computer-aided manufacturing (CAM) have been widely applied to design and develop machinery, including scheme design of the overall process, functional design, structural analysis, 3D modeling and simulation, and manufacturing (Duan and Gu 2007). The digital design of the test bench allowed the integrated and intelligent design of the structural elements and raw materials of the test bench, and it also reduced the cost of the experiment. Moreover, the length of time for the development and optimization of the test bench was shortened, and the processing quality and production efficiency of the test bench were also improved. Thus, digital design provided a solid foundation for obtaining the experimental data. Figure 1 contains a flow chart of the digital design process of the test bench.

In the digital design of the test bench, first the components and parts of the test bench, the parameters of virtual simulation (Matlab), and the processing technology of the test-piece were designed based on the requirements of the test bench. Next, a kinematic simulation (Adams) and dynamic analysis (Ansys) of the important parts were carried out. The deficiencies of the test bench were investigated. The cycle and optimal design of the test bench was developed, which made the test bench meet the requirements of the experiment. Finally, the simulation model, list (the sample library form, the experimental results, *etc*.) and test piece in kind were obtained.

Hardware structure of test bench

The objectives for the general layout of test bench were that it conform to the principles of simplicity of operation, reasonability of structure, economy, and practicality; that the layout meet the demands of the experiment; and that the components of the test bench be able to be combined together reasonably. It was also important that the numbers of motion and kinetic property and the relative positional relationship between the parts and the components be made clear. The general layout of test bench played an important role in the basic form of the test bench, which not only affected the structure, appearance, shape, volume, and weight of the bench, but also affected the operability and processing quality of the bench. The hardware structure of the test bench consisted of a printer, a nanosecond laser NC test bench, an upper computer, a video camera, and a lower computer. A schematic diagram of the hardware structure of the test bench is shown in Fig. 2.

The upper computer could be either an industrial PC or an ordinary PC depending on the conditions and requirements of the experiment. The main functions of the upper computer were the collection and processing of video data and the display and output of the results. The lower computer used the single chip test bench. The processing time, parameters of the laser, cutting angle of laser, *etc*., were controlled and adjusted from the lower computer. The upper computer and the lower computer were connected by a serial port (COM) to transmit information. The initial processing of the wood surface and the adjustment of the position between the wood and camera were managed from the nanosecond laser NC test bench. The camera was able to use industrial video camera and optical microscopy as needed. The video image of wood surface was magnified by a microscope and then recorded by an industrial camera; the S-video signal transmitted the video files to the upper computer. The printer printed the sample library form, the report with the test's results, and other experimental results that were delivered by the upper computer.

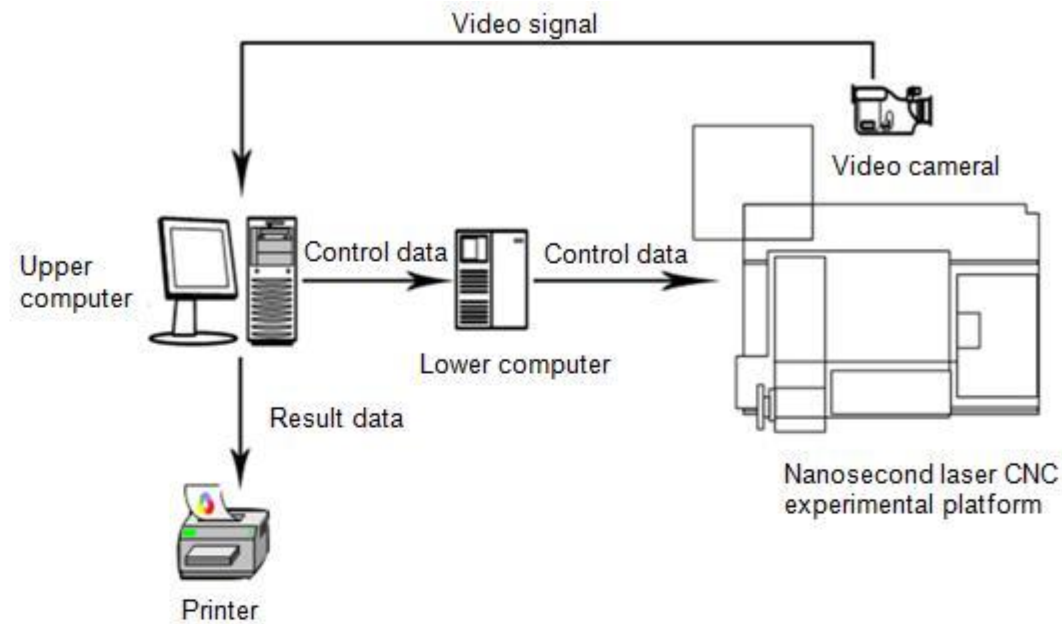

Fig. 2. Schematic diagram of the hardware structure of test bench

Mechanical system structure of the nanosecond laser NC test bench

The nanosecond laser NC test bench consisted of a laser frequency controller, processing angle regulator, nanosecond laser generator, nanosecond controller, and several other components. The structural frame of the nanosecond laser NC test bench is shown in Fig. 3.

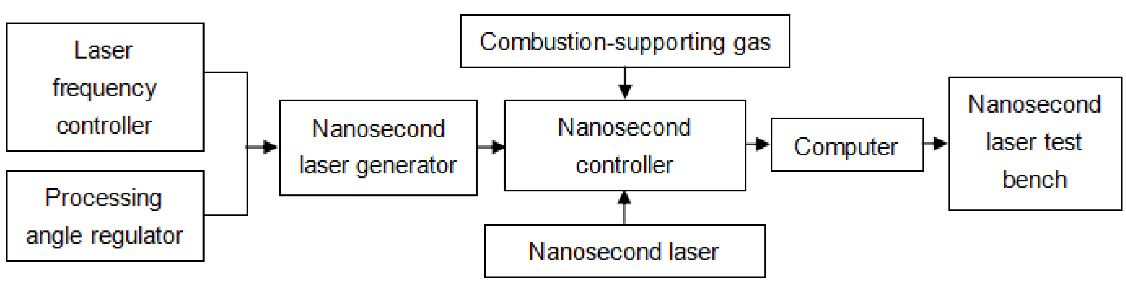

Fig. 3. The structural frame of the nanosecond laser NC test bench

The nanosecond laser NC test bench was mainly controlled by a computer to ensure that the range of variation of radial and axial velocity was large enough and that it had a high frequency resolution. The determination of the laser beam diameter, the setting of the laser angle and frequency, the pretreatment of the processing plan of wood fiber, and the generation of the processing data were the main functions of the nanosecond laser NC test bench. The laser frequency was adjusted using a laser frequency controller. The processing angle was adjusted using a processing angle regulator. Nanosecond laser pulses with a certain number of modulated pulses were emitted by the nanosecond laser generator.

The processing angle regulator used the CO_2 processing angle regulator or the YAG pulse processing angle regulator, both of which were able to meet the demands of experiment and were also cheaper than other options. The following experiment uses an Nd:YAG laser.

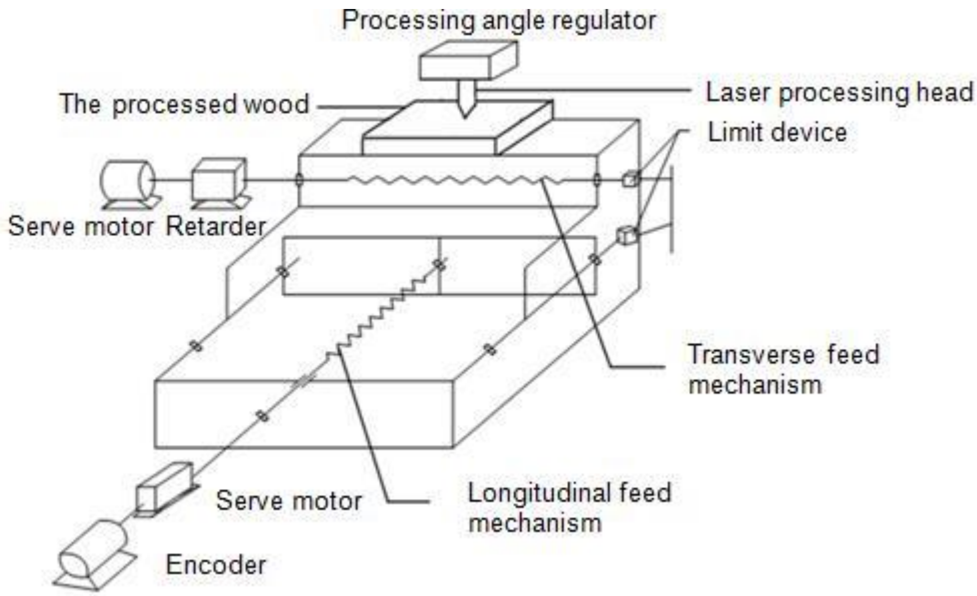

Fig. 4. Schematic of the wood fiber special NC transmission test bench

The nanosecond laser generator was composed of a fixed or removable light guide focusing test bench and a wood fiber special NC test bench. The removable light guide focusing test bench was used for the experiment, because although its technology was complicated, its volume was minimal and exquisite. The wood fiber special NC test bench was composed of a processing angle regulator, servo motor, longitudinal and transverse feed mechanism, reducer, encoder, limit device, and several more components. A schematic of the wood fiber special NC transmission test bench is shown in Fig. 4.

Methods

To ensure the precision and quality of the micro-nano wood fiber processed by the nanosecond pulse laser, the surface of wood was processed, because the degree of fragmentation of the wood cells was affected by the surface roughness of the wood.

In the course of the experiment, the voltage was maintained at a constant 220 V; the cutting power varied in the range of 0 to 6.6W. The adjustment range of the feed speed was in the range of 1 to 10 cm/s, and the distance from the laser head to the test piece was maintained at a constant 50 mm. The wood species was aspen.

The beam profile was Gaussian beam, the wavelength of the laser was 1064 nm, beam mode was Single mode (TEM00), the focal length of the focusing lens was 10 cm, pulse duration was 20 nm, the focused beam spot size was 0.05mm, and pulse frequency varied in the range of 1 to 10Hz. The wood fiber machining test bench is shown in Fig. 5.

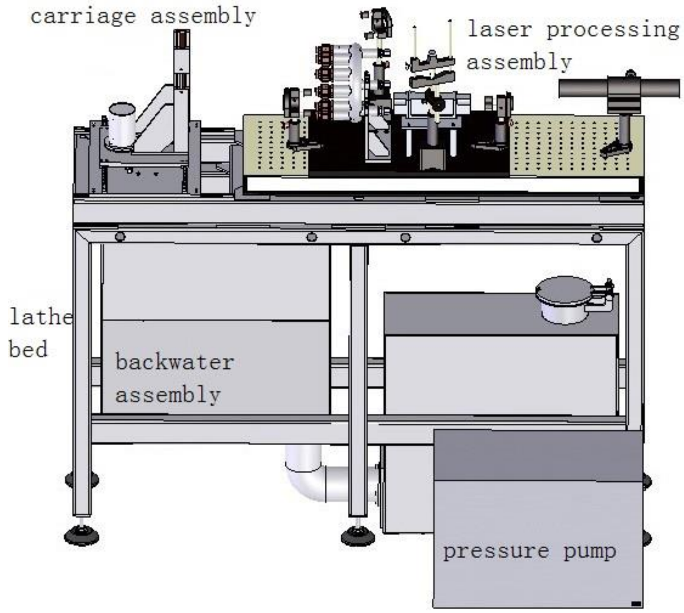

Fig. 5. The wood fiber machining test bench

The test bench consisted of a carriage assembly, laser processing assembly, backwater assembly, pressure pump, and lathe bed. The transverse and longitudinal feed of the wood was driven by the stepping motor in the carriage assembly. The laser processing assembly and backwater assembly were fixed on the lathe bed, and the processing distance of laser beam and wood was regulated by the carriage assembly. The machining precision could be adjusted by the water guide nozzle assembly in the laser processing assembly, so as to realize the water guide laser processing of the wood. The laser processing assembly is shown in Fig. 6.

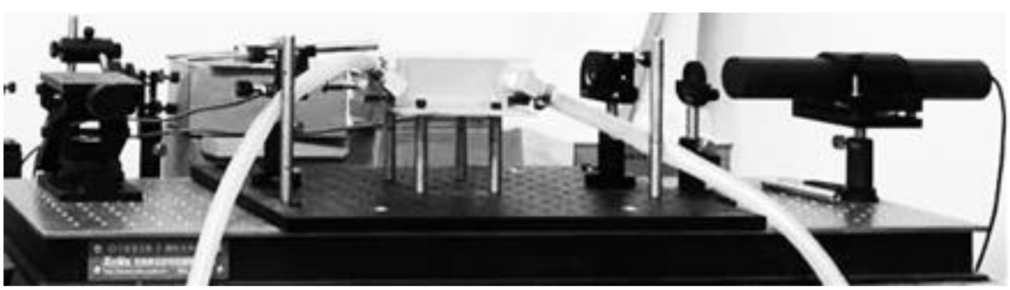

Fig. 6. The laser processing assembly

RESULTS AND DISCUSSION

The results of the processing of micro-nano wood fiber using a nanosecond pulse laser were affected by many factors, such as the grain of the wood, the quality of the wood, the species of the wood, the duration of the laser action, the direction of processing, the power density, the model of the processing angle regulator, *etc*. (Ma 2002; Eltawahni *et al*. 2011; Ren *et al*. 2014).

Table 1. Cutting Depth Along the Grain Direction

Cutting Power (W)	Cutting Speed (cm/s)			
	1	3	5	10
1.1	0.30	0.18	0.04	0.00
2.2	0.68	0.21	0.04	0.16
3.3	1.19	0.39	0.17	0.19
4.4	1.58	0.34	0.24	0.19

The results generated during the processing were recorded. Cutting depth was measured, and the average was obtained. This variable was affected by the current, cutting speed, and grain direction of the wood. The cutting depth along grain direction is shown in Table 1. The cutting depth across grain direction is shown in Table 2.

Table 2. Cutting Depth Across Grain Direction

Cutting Power (W)	Cutting Speed (cm/s)			
	1	3	5	10
1.1	0.35	0.16	0.00	0.00
2.2	0.82	0.45	0.29	0.27
3.3	1.08	0.54	0.39	0.25
4.4	1.25	0.54	0.39	0.26

The relationships between cutting depth and cutting speed along grain direction (Fig. 7), between cutting depth and cutting speed across grain direction (Fig. 8), and between cutting power and cutting depth (Fig. 9) were drawn according to the results displayed in Tables 1 and 2 (details below).

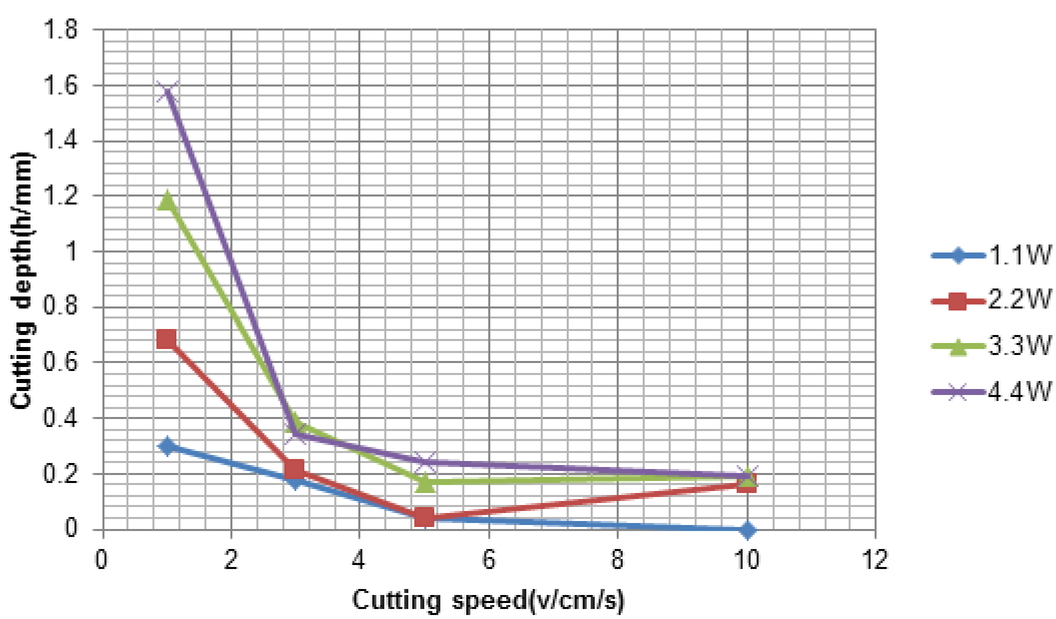

Fig. 7. The relationship between cutting depth and cutting speed along the grain direction

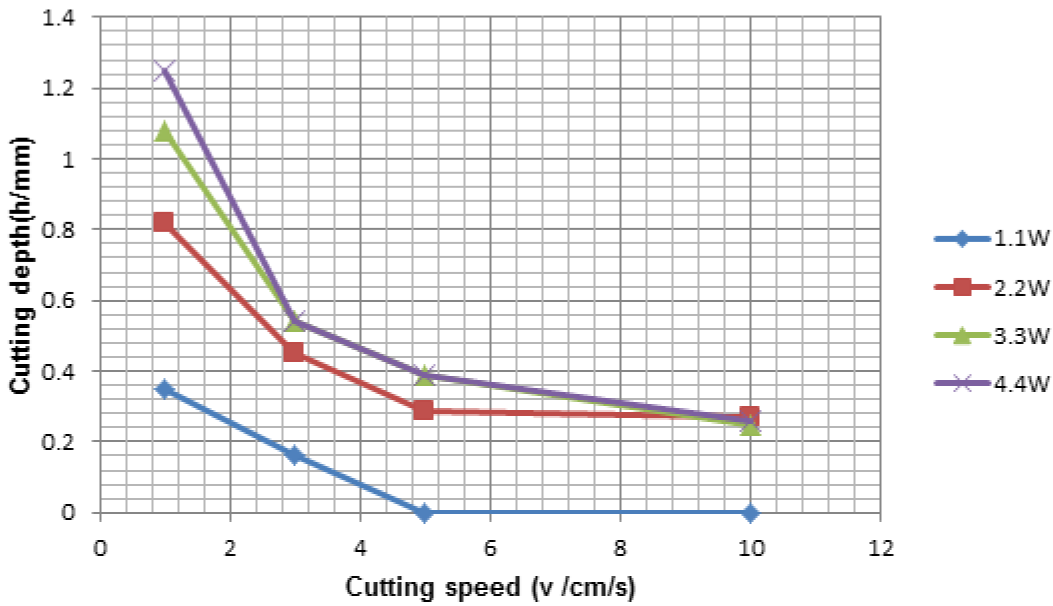

Fig. 8. The relationship between cutting depth and cutting speed across the grain direction

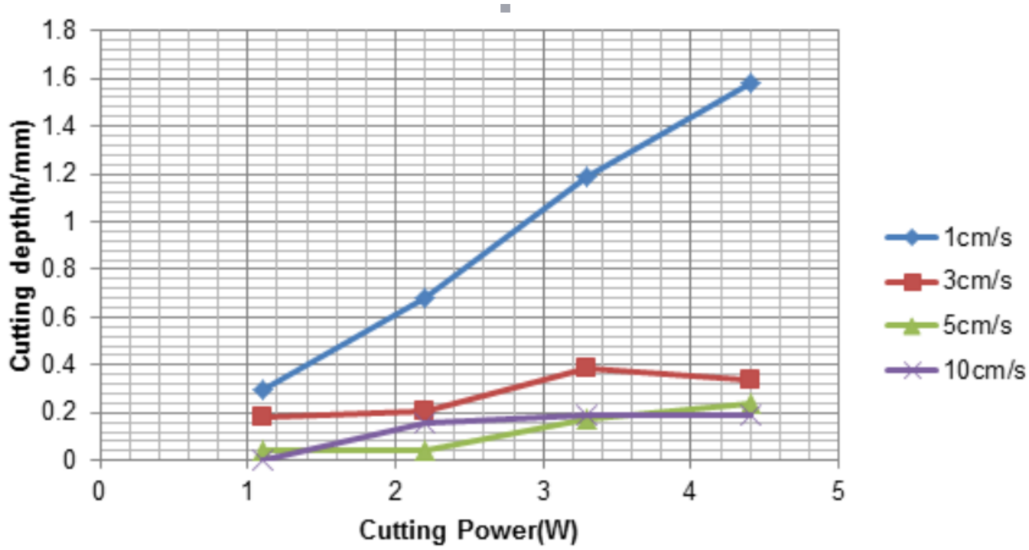

Fig. 9. The relationship between cutting power and cutting depth

Effect of cutting speed and direction on cutting depth

Cutting speed had an obvious effect on cutting depth when cut along the grain direction of the wood (Fig. 7). When the cutting power (current) was held constant, cutting depth decreased with the increase in cutting speed, reflecting the law of hyperbolic reduction. When cutting across the grain direction of the wood (Fig. 8), the effect of cutting speed on cutting depth was similar to that along the grain direction, but the effect was relatively small.

Effect of cutting speed and cutting power on cutting width

In the course of experiment, when the cutting speed was less than 500 mm/min, the cutting speed had an effect on the cutting width when cutting occurred radially, but when the cutting speed was greater than 500 mm/min, its impact on the cutting width was negligible.

Effect of cutting power on cutting depth

In the exploration of the relationship between cutting depth and cutting power, to ensure the best experimental results the test voltage was kept constant, and different cutting powers were obtained by changing the current. As shown in Fig. 9, when the cutting speed was kept constant, the cutting depth increased with increasing cutting power. However, when the cutting speed was high, the cutting depth was less affected by the increase in cutting power.

Effect of power density on cutting

In the course of the experiment, the size of the power density caused the instant evaporation of intracellular fluid along the grain direction of the micro-nano wood fiber and the tangential cleavage of the micro-nano wood fiber. However, the magnitude of the power density that produced this phenomenon was less than the power required to cut the wood fiber. The instant evaporation of intracellular fluid occurred when the wood tracheid was larger than the depth of focus of the light guide. Under the combined action of the laser beam mode and the cutting power, the tangential cleavage of the micro-nano wood fiber occurred when the power density of the liquid instantaneous evaporation was greater than the power density of the local contact area. Figure 10 shows the results of microstructure of test bench processing.

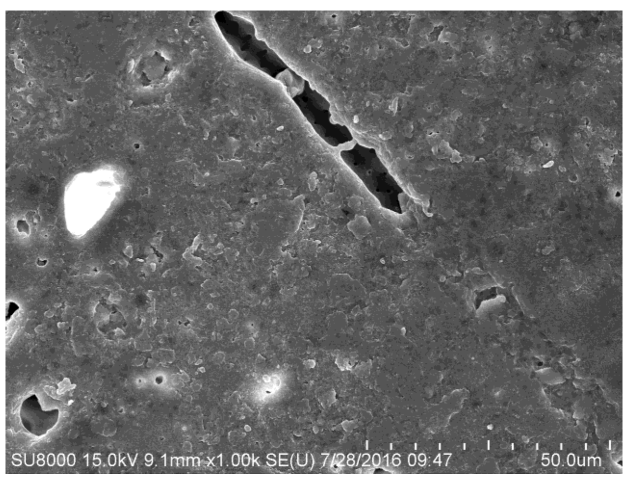

Fig.10. Results of microstructure of test bench processing

Effect of thermal degradation on cutting

During the cutting process, the thermal degradation of wood may take place near the point of processing. The part that underwent thermal degradation was called the heat-affected layer. The heat-affected layer was divided into three layers based on degree of thermal degradation: the charring layer, the thermal decomposition layer, and the initial thermal decomposition layer. The charring layer was characterized by black carbon powder, which was formed by hot carbonization; the thermal decomposition layer was deep brown in color, indicating a relatively light degree of carbonization; and lastly, the initial decomposition layer was similar in color to the unaffected wood, but its density was lower than that of unaffected wood. The degree of carbonization increased as the cutting speed decreased and the cutting depth increased.

CONCLUSIONS

1. A nanosecond pulse laser was designed, manufactured, and used to process a test bench of micro-nano wood fiber. The digital design of the test bench reduced the cost of design and development, and it also provided a good basis for further design and improvement.
2. The relationships between various factors that affected the results of the experiment were clarified. Cutting depth decreased with increasing cutting speed and increased with the increasing in cutting power. Cutting depth was also affected by the direction of cutting. Cutting width was affected by cutting speed and cutting power. Thermal deterioration, the instant evaporation of intracellular fluid along the grain direction, and the tangential cleavage of the micro-nano wood fibers were all implicated as components of the processing.
3. These experiments showed that the processing of micro-nano wood fiber using a nanosecond pulse laser is a feasible technology. The technology will certainly contribute to the development of the processing of wood fiber.

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