Study on Surface Quality of Wood Processed by Water-jet Assisted Nanosecond Laser

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Water-jet assisted nanosecond laser process was used to avoid the process defects of traditional nanosecond laser on wood. Korean pine was used as the experimental material. A factorial design of experiment was performed. The influence of cutting speed and laser power on the kerf width was compared with and without the water-jet assisted system. The surface morphology of processed wood kerf was observed *via* scanning electron microscopy (SEM). The results showed that kerf width increased with increased laser power and decreased with increased cutting speed. When the cutting speed was 50 mm/s and the laser power was 6 W, the minimum value of the kerf width was 0.26 mm with the water-jet assisted system involved, and the surface quality was excellent. The experimental results were processed by analysis of variance and multi-linear regression analysis. Moreover, prediction model of process parameters and kerf width was established, and the prediction model had better prediction accuracy, providing certain theoretical basis for predicting kerf width of wood processed by water-jet assisted nanosecond laser.

Keywords: Nanosecond laser; Water-jet assisted system; Korean pine; Factorial design of experiment; Microscopic morphology

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INTRODUCTION

Laser technology is a non-traditional approach for wood processing. Its advantages over traditional processes include non-contact and high efficiency (Guan *et al*. 2010; Vidholdová *et al.* 2017). Therefore, laser technology has been widely applied in industries such as the manufacture, medical science, automobile, and aerospace fields (Li *et al.* 2007). Materials that have been considered for laser technology include metals, ceramics, wood, and their corresponding composites (Chen *et al.* 2014; Lorenz *et al*. 2015; Pablos-Martín and Höche 2016). Wood is an environmentally friendly material; thus its consumption has been gradually increasing. However, conventional cutting technology results in a substantial loss of material. Hence, highly efficient laser processes are widely applied in wood cutting and wood sculpture (Hernandez-Castaneda *et al*. 2010; Guo *et al*. 2016).

The authors have studied the micromachining process of wood (Yang *et al*. 2017). Yang *et al*. (2016) designed a test bench of nanosecond laser process. The temperature field on the wood surface by finite element analysis was analyzed to determine the process parameters. The influence of different process parameters on process quality was discussed (Ren *et al*. 2014; Wu *et al*. 2015). However, when the wood was cut with a nanosecond laser, water vapor appeared after wood gasification and carbon granules were left after burning, which affected the surface quality of wood kerf (Barcikowski *et al*. 2006; Yu *et al*. 2015).

The present work presents an innovation to nanosecond laser process by using a water jet. The water-jet has a cooling and washing effect on the wood. The vapor is cooled and the residues are washed, which avoids the process defects of traditional nanosecond laser processing of wood. It provides a new way to achieve the benefits of the micromachining of wood.

The Korean pine was processed by water-jet assisted nanosecond laser. A single factor experiment and a factorial design of experiment were performed. The influence of laser power and cutting speed on the kerf width of wood with and without the water-jet assisted system was studied. Moreover, the process theory of water-jet assisted nanosecond laser was analyzed in depth, the surface quality of kerf of wood was assessed, and the prediction model of multi-line regression was established. This research provides foundation for the prediction of kerf width of wood processed by water-jet assisted nanosecond laser.

EXPERIMENTAL

Water-jet Nanosecond Laser Process Theory

A schematic diagram of water-jet assisted nanosecond laser process is shown in Fig. 1. Wood is fixed on the workbench, and the laser is moved to the process area by a feeding system. After the pump power switch is opened, water moves through the nozzle (Fig. 1(a)) onto the process area, and a water ring forms. At the same time, the laser switch is opened, and the laser beam from the laser device radiates the process area of the wood surface. Finally, the geometry of the parts is obtained.

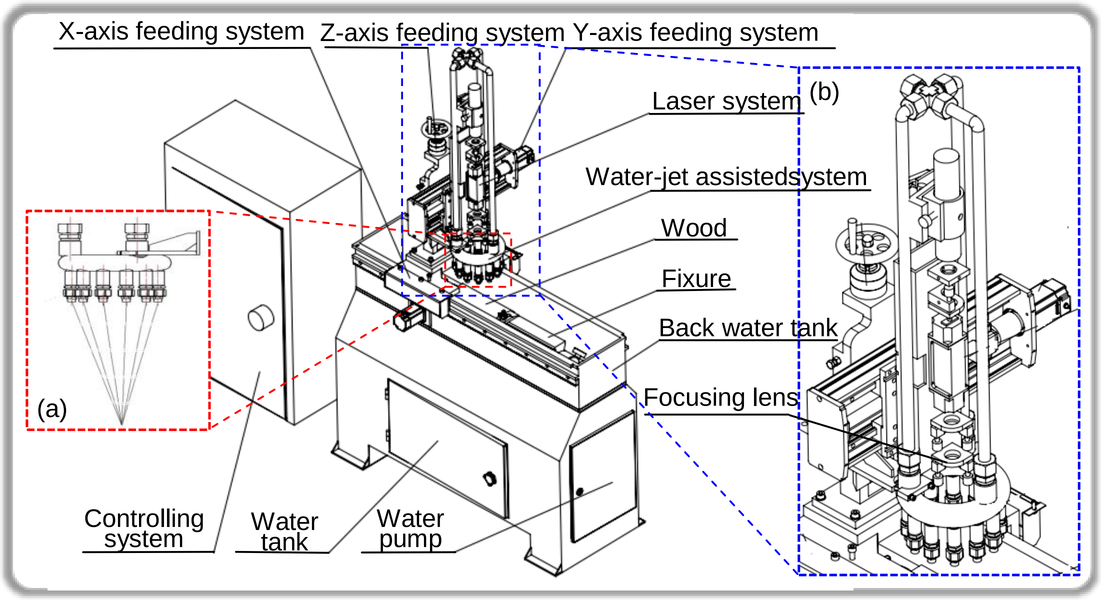

Fig. 1. Schematic diagram of water-jet nanosecond laser process. (a) Structural drawing of nozzle; (b) structural drawing of water-jet system

The water-jet system is shown in Fig. 1(b); the function of the water-jet is to cool and wash the material. The system removes the vapor generated by wood gasification, and at the same time the flowing water-jet forms a cooling temperature barrier that effectively reduces the range of the heat affected zone. The water jet also washes the residues on the wood kerf.

Equipment and Materials

Korean pine (*Pinus koraiensis*) was used as the material. This softwood material has an air-dry density of 0.45 m^3 and a moisture content of 12.32%. The wood with the same size was obtained after processing. The size was: 150mm × 20mm × 2mm (length × width × thickness). The system contained a Nd:YAG (Neodymiumdoped Yttrium Aluminum Garnet) laser, JDW3-250 laser power supply (Beijing, China), water-jet assisted system, and PH-LW06-BLP laser cooling system (Shenzhen, China). The focusing system consisted of a combination of optical lenses, pulse duration of 20 ns, pulse frequency in the range of 1 Hz to 10 Hz, and laser wavelength of 1064 nm. The focal length of the focusing lens was 100 mm. The focused beam spot size was 0.05 mm; The water-jet assisted system consisted mainly of annular nozzles. The angle of jet can be adjusted to control the range of water ring. The feeding system moves through the X-axis, Y-axis and Z-axis. The kerf width was the average of widths on top and bottom surfaces along the thickness direction, which were measured using an optical microscope (JNOEC XS213, China). Tangential section of wood after spray process with and without water-jet assist were observed using a FEI Quanta200 scanning electron microscope (Hillsboro, OR, USA).

Process Method

The water flow of the water-jet system was 8 m^3/h, and the adjustable nozzle flow pressure was set as 0.13 MPa. The water flow velocity was 5.75 m/s. A sample and process method are shown in Fig. 2. The focused beam spot located on the top surface of the wood. The process direction was along the wood fiber by a single pass. Korean pine (thickness of 2 mm) was processed by with different laser power and cutting speeds, with or without the water-jet assisted system.

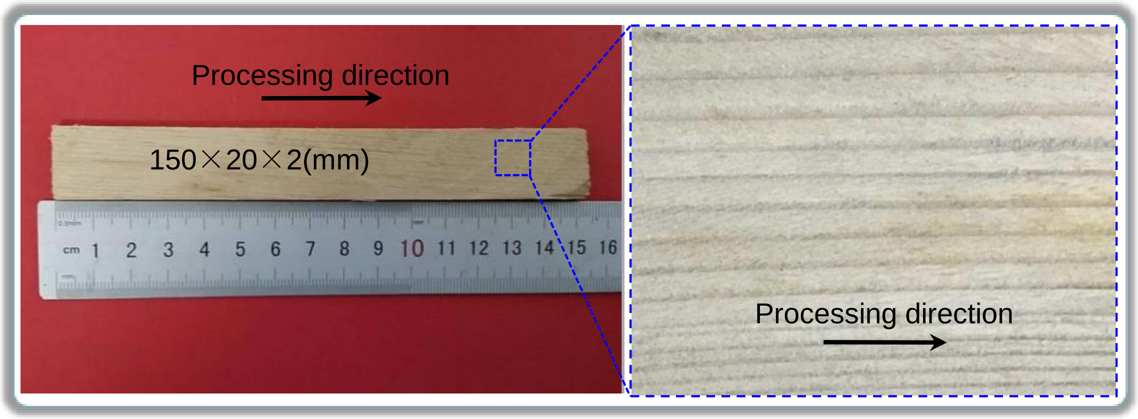

Fig. 2. Sample and process method

Experimental Design

The single factor experiment was performed, and the change tendencies of single process parameter on kerf width of wood were considered. Then, a factorial design of experiment was performed, and the influence rules of multiple process parameters and their interaction on the surface quality of wood was studied. Though a factorial design of experiment, the influence rules of laser power (three levels of high, medium, and low), cutting width (three levels of high, medium, and low), and water-jet speed (with and without) on kerf width of wood were studied. The influence of water-jet system on the surface quality of wood was also studied. A 2 × 3 × 3 factorial design was performed with 18 groups. Single factor experiment and a factorial design of experiment were performed, with three repeated cutting tests in each group.

RESULTS AND DISCUSSION

Influence of Laser Powers and Cutting Speeds on Kerf Width of Wood

In the process of water-jet assisted nanosecond laser, the process parameters of single factor experiment are shown in Table 1. Korean pine was processed by nanosecond laser with or without the water-jet assisted system. The kerf width data under different laser power and cutting speed was processed, then the change tendencies were shown in Fig. 3.

Table 1. Process Parameters of Nanosecond Laser Process

Sample number	1	2	3	4	5	6	7	8	9	10
Av. Laser power（W）	6	8	10	12	14	16	18	20	22	24
Cutting speed （mm/s）	5	10	15	20	25	30	35	40	45	50

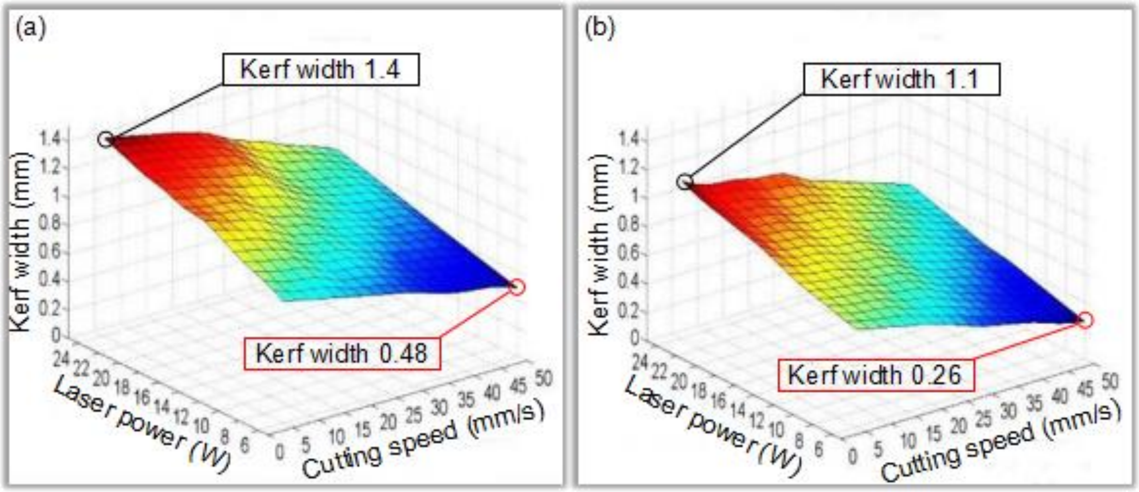

Fig. 3. The change tendencies of the kerf width with different laser power and cutting speed (a) without or (b) with the water guided system

In Fig. 3, it can be seen that, with and without the water-jet assisted system, the change tendencies of the kerf width with different laser powers and cutting speeds were consistent. When cutting speed was constant, the kerf width increased with increasing laser power. Lower laser power caused less heat on the surface of wood; with less sublimation and burning. Less wood was removed. Thus, the kerf width was small. Increased laser power generated more heat on the wood surface, causing its temperature to rise rapidly. The wood sublimated and formed kerf width; thus the large consumption of wood caused the increased kerf width. When laser power was constant, the kerf width decreased with increased cutting speed. When the cutting speed was low, a long-time interaction between laser beam and wood caused a serious heat accumulation effect on wood, then the heat-affected zone and kerf width got bigger. With the increase of cutting speed, the heat of the laser beam accumulated on wood in the unit time was less, which caused the kerf width to decrease accordingly. Figure 3 shows that, when the cutting speed of 50 mm/s and laser power was 6 W, the smallest kerf width of wood without a water-jet assisted system involved was 0.48 mm. However, the smallest kerf width of wood under water-jet assisted system involved was 0.26 mm, resulting in the minimum kerf width and highest size precision. Under the water-jet assisted system, the high temperature produced by the laser beam is cooled, and the range of the heat-affected zone is reduced. At the same time, the water-jet continuously flows, which also can clear the carbon residue on the surface of the kerf. Therefore, the minimum kerf width was smaller than that without the water-jet assisted system.

Analysis of Variance of for Kerf Width under Process Parameters

In the process of water-jet assisted nanosecond laser, factors and levels of factorial design is shown in Table 2. Factorial design of experimental results are shown in Table 3.

Table 2. Factors and Levels of Factorial Design

Levels Factors	1	2	3
A (Water-jet speed)	0m/s (A_0)	5.75m/s (A_1)	
B (Laser Power)	6W (B_1)	12W (B_2）	18W (B_3)
C (Cutting Speed)	20mm/s (C_1)	35mm/s (C_2)	50mm/s (C_3)

Table 3. Factorial Design Experimental Results for Kerf Width of Wood

A×B		C_1			C_2			C_3		
B_1	A_0	0.75	0.72	0.75	0.61	0.62	0.57	0.47	0.51	0.46
	A_1	0.53	0.58	0.57	0.44	0.37	0.39	0.23	0.29	0.26
B_2	A_0	0.89	0.88	0.93	0.73	0.81	0.74	0.57	0.62	0.61
	A_1	0.70	0.65	0.69	0.53	0.55	0.48	0.37	0.41	0.36
B_3	A_0	1.10	1.12	1.08	0.87	0.90	0.87	0.73	0.69	0.74
	A_1	0.77	0.83	0.80	0.63	0.68	0.67	0.52	0.45	0.47

The analysis of variance for the experimental results was conducted. The significant factors were determined (Table 4). It can be seen that $A*C$ (F=0.242, Sig.=0.787>α=0.05), $B*C$ (F=2.416, Sig.=0.067>α=0.05), and $A*B*C$ (F=1.933, Sig.=0.126>α=0.05) had no significant effect on kerf width of wood. In order to be convenient to calculation, these factors were not considered in multi-line regression analysis. However, the other factors (A, B, C, A*B) whose main effect is statistically significant, are considered to be the main effect factors for kerf width of wood.

Table 4. Analysis of Variance for Kerf Width under Process Parameters

Source	Sum of Squares	Degree of freedom	Mean Square	F	Sig.
Corrected Model	2.220	17	0.131	157.758	0.000
Intercept	22.118	1	22.118	26720.215	0.000
A	0.694	1	0.694	837.906	0.000
B	0.640	2	0.320	386.577	0.000
C	0.865	2	0.433	522.604	0.000
A*B	0.006	2	0.003	3.866	0.030
A*C	0.000	2	0.000	0.242	0.787
B*C	0.008	4	0.002	2.416	0.067
A*B*C	0.006	4	0.002	1.933	0.126
Error	0.030	36	0.001		
Total	24.368	54			
Corrected Total	2.250	53			

Multi-line Regression Analysis for Kerf Width of Wood

In order to further clarify the relationship between the process parameters and the kerf width of wood, a multi-linear regression method was used to establish the model of factors selected and the kerf width of wood. The multi-linear regression model can reflect the interaction effect of various factors on the kerf width of wood. Some significant factors stand out, and other non-significant factors can deleted.

Regression model established through sample data cannot be immediately used for analysis and prediction of the actual problem; thus, a variety of statistical tests need to conducted, such as goodness of fit test (Table 5), F-test (Table 6), and T-test (Table 7).

Table 5. Goodness of Fit Test

R	R^2	Adjusted R^2	Standard error of estimate
0.997	0.993	0.991	0.02

Table 6. F-test

Model	Sum of squares	Degrees of freedom	Mean square	F-value	Sig.
Regression	0.735	4	0.184	474.565	0.000
Residual	0.005	13	0.000		
Total	0.740	17			

Table 7. T-test

Model	Non-standardized coefficients		Standardized coefficient	T-value	Sig.
	B	Standard error			
Constant	0.822	0.022		37.629	0.000
A	-0.030	0.004	-0.427	-7.063	0.000
B	0.024	0.001	0.591	18.258	0.000
C	-0.010	0.000	-0.624	-27.288	0.000
*A*B*	-0.001	0.000	-0.152	-2.347	0.035

In Tables 5 to 7, regression models were processed according to a goodness of fit test, F-test, and T-test, respectively. Compared with the non-standardized coefficients of each factor, the model of the kerf width of wood under process parameters can be expressed as:

$$T = 0.822 - 0.03A + 0.024B - 0.01C - 0.001A * B \tag{1}$$

In Eq. 1, the regression coefficient of the water-jet speed had a negative value, which indicates that water-jet speed had the opposite effect on kerf width of wood. With the increase of the water-jet speed and cutting speed, the kerf width of wood decreased. A synergistic effect decreased and antagonistic effect increased in the system; the regression coefficient of the water-jet speed had a positive value, which represents that water-jet speed had a better effect on kerf width of wood. With the increase of the laser power, the kerf width of wood increased. Synergistic effects increased and antagonistic effects decreased in the system. The binary interaction effect of *A***B* on the kerf width of wood was significant; however, the ternary interaction effect was not significant. The regression coefficient of *A**B had a negative value, indicating that *A***B* had an opposite effect on kerf width of wood, which is shown as an antagonistic effect in the system.

Validation of Prediction Model

Korean pine was processed by water-jet assisted nanosecond laser, and the obtained measured value of kerf width was compared with the predicted value of kerf width. Thus, the prediction accuracy of the established multi-line regression model of the kerf width was tested. Five test samples in the process parameters of the water-jet assisted laser were selected randomly. Then these process parameters were brought to the prediction model, as shown in Eq. 1, where the model prediction value of kerf width of the corresponding process parameters can be obtained.

The comparison of the measured value and the model predictive value of kerf width is shown in Table 8. The error range of the prediction value of kerf width was within ±7%, and the average prediction error was 3.99%. This showed that the prediction model of multi-line regression of kerf width had better prediction precision. Therefore, the influence of process parameters by water-jet assisted nanosecond laser on kerf width was described better.

Table 8. Comparison of the Measured and Predicted Values of Kerf Width

Sample Number	Water-jet speed (m/s)	Laser Power (W)	Cutting Speed (mm/s)	Kerf Width (mm)		Relative Error (%)
				Measured value	Predicted value	
1	0	6	10	0.82	0.866	5.61
2	5.75	6	10	0.64	0.659	2.97
3	0	12	40	0.70	0.71	1.43
4	5.75	18	5	0.96	0.928	3.33
5	0	20	20	1.18	1.102	6.61

Micromorphology of the Kerf Surface of Wood

Dimensional precision and surface quality of machining parts are important factors that affect the performance of parts and are also the important indices for evaluation of the process technology. Thus, the dimensional precision and surface quality of parts was studied. Tangential section micromorphology of wood when kerf width was minimum with and without water-jet assisted system were observed under SEM (Fig. 4). There were some carbon granules left on the inner walls of the tracheids, and the kerf surface was rough after the laser process. Thus, the surface quality was bad. In Fig. 4(b), there were no carbon granule left on the inner walls of the tracheids and kerf surface was smooth after the laser process with water-jet assisted system, thus, surface quality of wood kerf is better. This was because the cooling of the water took away the steam produced by the vaporization of the wood. At the same time, the water flow washed away the residues that remained on the surface of the kerf. Therefore, the surface quality of the kerf processed by laser with the water-jet assisted system was better than that without the water-jet assisted system.

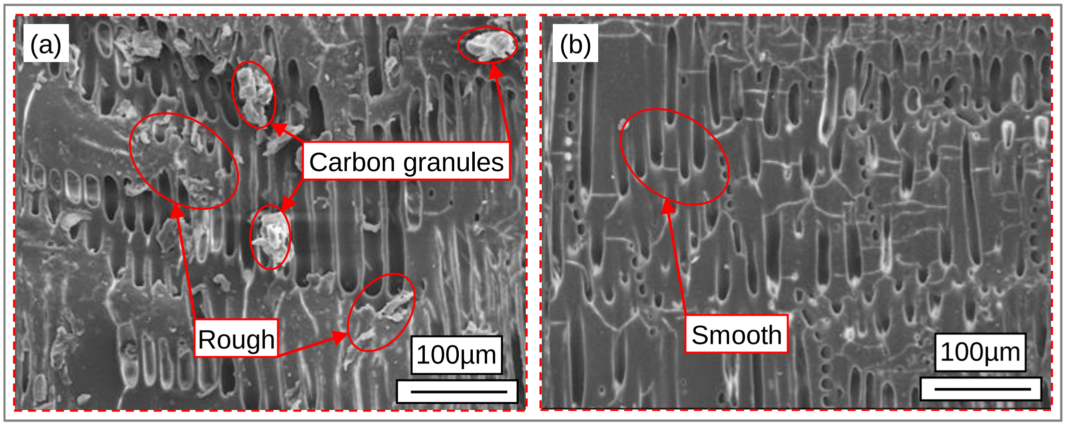

Fig. 4. Tangential section micromorphology of wood when kerf width is minimum; (a) without or (b) with the water guided system under 200 times.

CONCLUSIONS

1. A water-jet assisted nanosecond laser cutting process was used on Korean pine. The experimental results showed that the cutting speed and the laser power influenced the kerf width. When the cutting speed was constant, the kerf width increased with the increase of laser power. When the laser power was constant, the kerf width decreased with the increase of cutting speed. When the cutting speed was 50 mm/s and the laser power was 6 W, the kerf width of 0.26 mm under the water-jet assisted system was smaller than that without the water-jet assisted system.
2. Through analysis of variance of factorial design of experiment, the effects of water-jet speed, laser power, cutting speed, and the interaction of water-jet speed and laser power on kerf width were significant. A multivariate linear regression method was used to establish the model of factors selected and the kerf width of wood. The prediction model of process parameters and kerf width by water-jet assisted nanosecond laser was obtained. After validation, the prediction model had good predictive precision, which provided a theoretical foundation for predicting kerf width.

3. The kerf surfaces of Korean pine were observed *via* SEM. Without the water-jet assisted system, some carbon granules were left on the inner walls of the tracheids. The kerf surface was rough after the laser process. Thus, the surface quality was bad. With the water-jet assisted system, no carbon granules were left on the inner walls of the tracheids, and the kerf surface was smooth after laser process with water-jet assisted system. Thus, the surface quality of wood kerf was better.

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REFERENCES CITED

Barcikowski, S., Koch, G., and Odermatt, J. (2006). "Characterization and modification of the heat affected zone during laser material process of wood and wood composites," *Holz als Roh-und Werkstoff* 64(2), 94-103. DOI: 10.1007/s00107-005-0028-1

Chen, C., Yuan, G., and Wang, J. (2014). "Low-pressure water jet and laser composite cutting on Al_2O_3 ceramic," *Infrared and Laser Engineering* 43(7), 2097-2102. DOI: 10.3969/j.issn.1007-2276.2014.07.010

Guan, B. G., Liu, S. H., Zhang, M. L., *et al*. (2010). "Application and development tendency of precision laser machining," *Laser & Infrared* 40(3), 229-232. DOI: 10.3969/j.issn.1001-5078.2010.03.001

Guo, Q., Ma, Y., Wu, Z., and Cui, Y. (2016). "Experimental research and numerical simulation of heat transfer of nanosecond laser ablation wood," *Chem. Eng. Trans.* 51, 1189-1194. DOI: 10.3303/CET1651199.

Hernandez-Castaneda, J. C., Sezer, H. K., and Li, L. (2010). "Dual gas jet-assisted fiber laser blind cutting of dry pine wood by statistical modeling," *Int. J. Adv. Manuf. Tech.* 50(1-4), 195-206. DOI: 10.1007/s00170-009-2491-z

Li, J., Hu, X., and Yang, Y. (2007). "Development and application of micro manufacturing technology," *Modern Machinery* 4, 76-78. DOI: 10.3969/j.issn.1002-6886.2007.04.033

Lorenz, P., Zajadacz, J., Bayer, L., Ehrhardt, M., and Zimmer, K. (2015). "Nanodrilling of fused silica using nanosecond laser radiation," *Appl. Surf. Sci.* 351, 935-945. DOI: 10.1016/j.apsusc.2015.06.041

Pablos-Martín, A., and Höche, T. (2016). "Laser welding of glasses using a nanosecond pulsed Nd:YAG laser," *Opt. Laser Eng.* 90, 1-9. DOI: 10.1016/j.optlaseng.2016.09.009

Ren, H. E., Song, S., Bai, Y., Dong, B. Z., and Qi, H. (2014). "Study on the process technology of nanosecond laser for cutting micro-nano wood fiber," *Wood process Machinery* (1), 5-7.

Vidholdová, Z., Reinprecht, L., and Igaz, R. (2017). "The impact of laser surface modification of beech wood on its color and occurrence of molds," *BioResources* 12(2), 4177-4186. DOI: 10.15376/biores.12.2.4177-4186

Wu, Z., Yang, C. M., Ma, Y., Ren, H. E., and Ma, H. B. (2015). "Nanosecond pulse laser application in wood surface process research," *Journal of Mechanical Manufacturing* 5, 44-46. DOI: 10.3969/j.issn.1000-4998.2015.05.014

Yang, C. M., Lu, Y., Ma, Y., Ren, C.Q., Bai, Y., and Cao, F. D. (2017). "Theoretical and experimental study on the cutting of wood by nanosecond pulse laser," *Scientia Silvae Sinicae* 53(9), 151-156. DOI: 10.11707/j.1001-7488.20170918

Yang, C. M., Zhu, X. L., Kim, N. H., Lee, S. H., Qi, Y., Bai, Y., Guo, M., and Ma, Y. (2016). "Experimental design and study of micro-nano wood fiber processed by nanosecond pulse laser," *BioResources* 11(4), 8215-8225. DOI: 10.15376/biores.11.4.8215-8225

Yu, M., Song, S., Jiang, S. H., Ma, Y., and Ren, H. E. (2015). "Theory research of wood surface cells explosion heated by nanosecond laser," *Forestry Machinery & Woodworking Equipment* 43(2), 30-32. DOI: 10.3969/j.issn.2095-2953.2015.02.012

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