Water-Jet Assisted Laser Cutting of Korean Pine (*Pinus koraiensis*): Process and Parameters Optimization

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In order to improve the processing quality of wood parts, an orthogonal experimental design of five factors and four levels was adopted, and a water-jet assisted laser cutting experiment on Korean pine (*Pinus koraiensis*) was conducted. Moreover, by using range analysis, the influences of the defocusing amount, cutting speed, laser power, water pressure, and water jet angle on the processing quality of Korean pine parts were evaluated, and the optimum process parameters were determined. The test results show that when the defocusing amount was -1 mm, water jet angle was 30°, laser power was 48 W, water pressure was 1.0 MPa, and cutting speed was 25 mm/s, the best processing quality of Korean pine parts was obtained.

Keywords: Water-jet assisted laser; Korean pine; Orthogonal design; Forming precision; Surface quality

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INTRODUCTION

Laser processing technology is an advanced type of manufacturing that uses the interaction between laser beam and materials to process cutting, punching, welding, and surface treatment (Yang *et al.* 2016; Pablos-Martín and Höche 2017). Laser processing technology has the advantages of being noiseless, fast, and causing no mechanical processing deformation compared with traditional processing technology (Guan *et al*. 2010). Therefore, laser processing technology is widely applied in automobile, aerospace engineering, medical treatment, mechanical manufacturing, and other fields (Li *et al*. 2007; Lorenz *et al.* 2015).

However, traditional laser processing has some shortcomings such as microcracking and a large heat-affected zone within the processing area when using a high energy beam laser. Hence, in the field of fine machining, water-jet assisted laser machining is widely used. This usually involves a combination of laser beam as the main and water jet as complementary tools to achieve material removal (Madhukar *et al*. 2013). Materials utilized in water-jet assisted laser processing are mainly concentrated in metals, ceramics, and their corresponding composite materials (Chen *et al*. 2014; Tangwarodomnukun *et al*. 2015), but wood and wood composite materials are less commonly used. As a natural and environmentally friendly renewable material, wood is widely used in furniture, building materials, wood products, and other fields (Barcikowski *et al.* 2006; Hernandez-Castaneda *et al*. 2010). Therefore, the demand for wood is increasing, which leads to excessive consumption of wood resources. Meanwhile, fine and delicate wood parts are widely needed. This research paper is the first to introduce water-jet assisted laser technology into the field of wood processing. The initial research mainly focused on the design of water-jet assisted nanosecond laser processing equipment on wood (Yang *et al*. 2018). Subsequently, research on the mechanism and technology of water-jet assisted nanosecond laser processing on northeast China ash wood was conducted, and adequate processing effects were obtained (Yang *et al*. 2019). However, with in-depth research, it was found that wood has a higher absorption rate of CO_2 laser waves and the CO_2 laser has the advantage of low price (Zhou and Mahdavian 2004). Therefore, it is necessary to study the influence of water-jet assisted CO_2 laser cutting process parameters on the quality of wood parts.

Korean pine is a typical softwood. It has some advantages in that it is light, soft, fine, uniform in texture, and having favorable structure, corrosion resistance, and water resistance. Hence, it is widely used in furniture and wood products. Therefore, this paper selected Korean pine as the raw material, and the orthogonal experimental design of five factors and four levels was adopted to evaluate the influence rule of water-jet assisted laser processing technology parameters on the forming precision of Korean pine parts. The produced Korean pine parts were of good size accuracy and surface quality.

EXPERIMENTAL

Equipment and Process Principle

Water-jet assisted laser processing experiments were conducted using water-jet assisted laser equipment, as shown in Fig. 1a. The equipment mainly consisted of a CO_2 laser cutting machine and water-jet assisted CO_2 laser device. The laser system was a CO_2 laser cutting machine (Baomei Technology Ltd., Jinan, China) equipped with a CO_2 laser generator (wavelength of 10.6 μm and laser power of 80 W). Additionally, the lens focal length was 63.5 mm. The water-jet assisted system was designed and manufactured by the researchers of this paper. The model of water pump was QL-380 (Hongyuan Company, Harbin, China). The diameter of the water jet nozzle was 0.5 mm, and the nozzle angle was adjustable. The principle of water-jet assisted laser processing on wood is to fix wood on the working table with a special fixture, move the water-jet assisted laser system to the processed area by controlling the feed system, and then turn on the power switches of the water pump and the laser switch simultaneously. The laser beam radiates from the laser to the processing area of the wood surface, the water-jet in the water pump sprays the wood surface through the nozzle, and finally wood parts with a desired geometric shape are obtained.

A process principle diagram is shown in Fig. 1b. During processing, the distance water-jet focal point lagged behind the laser focal point about 1 mm, which reduced the direct contact between water jet and laser beam and prevented the water jet from absorbing too much laser energy, thus avoiding heat loss. When processing, due to the lower ignition temperature of wood, part of the laser energy density in the processing zone was always lower than the laser energy density for the vaporization of wood, causing the burning of wood. Thus, carbonization and ablation of the heat-affected zone (HAZ) are observed, along with residuals, such as carbon granules, charring, and ash content, which has a negative impact on the surface quality of wood. The cooling and washing effect of the water jet provides a guarantee for improving the size accuracy and surface quality of wood parts processed by water-jet assisted CO_2 lasers.

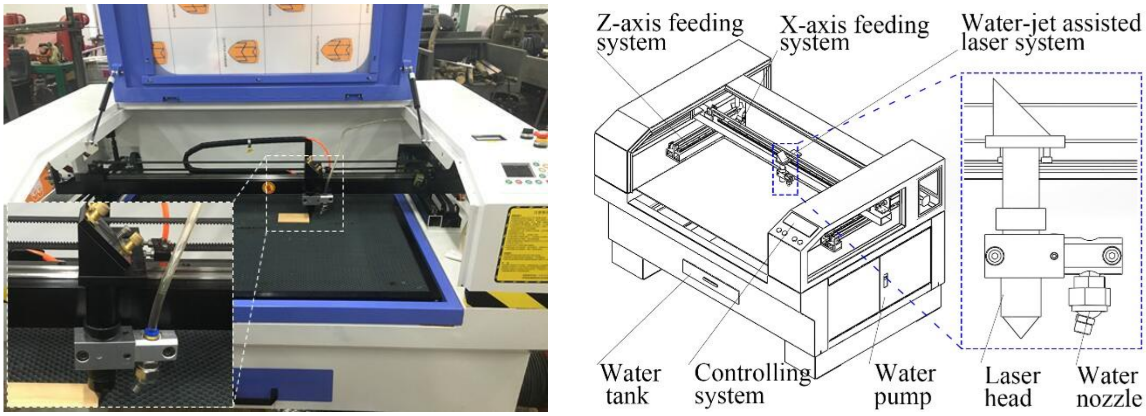

Fig. 1. Equipment and schematic diagram: (a) equipment, (b) process schematic diagram

Materials and Method

Korean pine was used as the experimental material (Haicheng Machining Factory, Harbin, China). The Korean pine had an air-dry density of 0.435 g/cm^3 and a moisture content of 12.62 %. The Korean pine was milled to the same size after processing, with the specimens being 100 mm × 60 mm × 2 mm (length × width × thickness). The process direction was along the fiber of Korean pine with a single pass. The specimen and process method are shown in Fig. 2.

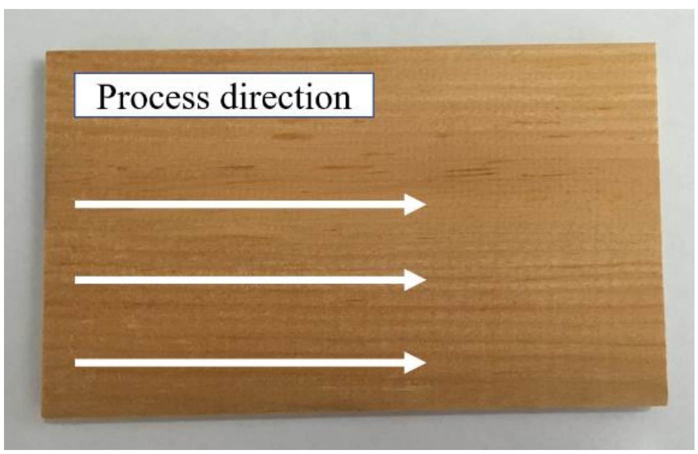

Fig. 2. Specimen and process method

Single Factor Experimental Design

Through the experiment of water-jet assisted laser processing on Korean pine, it was found that laser power, cutting speed, water pressure, defocusing amount, and water jet angle (the angle between the flow direction and the horizontal direction) were significant factors affecting the cutting width of the parts. The parameters' variation range was firstly determined to ensure the feasibility of the orthogonal experimental design, and then the orthogonal experimental design was conducted so that the optimal ranges of various parameters' influence on experimental results could be determined. The process parameters of water-jet assisted laser cutting processing on Korean pine are provided in Table 1.

Table 1. Parameters of Processing

Factors	A. Defocusing Amount (mm)	B. Cutting Speed (mm/s)	C. Laser Power (W)	D. Water Pressure (MPa)	E. Water Jet Angle (°)
$A_1/A_2/A_3/A_4/A_5/A_6$	-1.5/-1.0/-0.5/0/0.5/1.0	25	52	0.6	40
$B_1/B_2/B_3/B_4/B_5/B_6$	0	13/16/19/22/25/28	52	0.6	40
$C_1/C_2/C_3/C_4/C_5/C_6$	0	25	48/52/56/60/64/68	0.6	40
$D_1/D_2/D_3/D_4/D_5/D_6$	0	25	52	0.2/0.4/0.6/0.8/1.0/1.2	40
$E_1/E_2/E_3/E_4/E_5/E_6$	0	25	52	0.6	10/20/30/40/50/60

Orthogonal Experiment Design

In the process, the cutting width is an important factor to consider when evaluating the formability of water-jet assisted laser processing on Korean pine. It is a very complicated process. The cutting width mainly depends on the process parameters. Therefore, based on the single factor experimental results, an orthogonal experiment design method of five factors and four levels was used in the water-jet assisted laser processing experiment. The influence of the process parameters on the cutting width were studied to obtain forming rules for water-jet assisted laser processing. The test scheme of Korean pine is shown in Table 2.

Table 2. The Factors and Levels of Test

Levers	A. Defocusing Amount (mm)	B. Cutting Speed (mm/s)	C. Laser Power (W)	D. Water Pressure (MPa)	E. Water Jet Angle (°)
1	-1	19	48	0.6	30
2	-0.5	22	52	0.8	40
3	0	25	56	1.0	50
4	0.5	28	60	1.2	60

Material Characterization and Properties Test

Cutting width

The cutting width was the average of the widths on the top and bottom surfaces along the thickness direction, which were measured using an optical microscope. The cutting width value was the average value of three repeated tests.

Scanning electronic microscopy (SEM)

The tangential section of the processed parts was observed using a FEI Quanta200 scanning electron microscope (FEI Instruments, Hillsboro, OR, USA).

RESULTS AND DISCUSSION

Single Factor Analysis

The influences of laser power, cutting speed, water pressure, defocusing amount, and water jet angle on the cutting width of Korean pine were studied by a single factor method, as shown in Fig. 3.

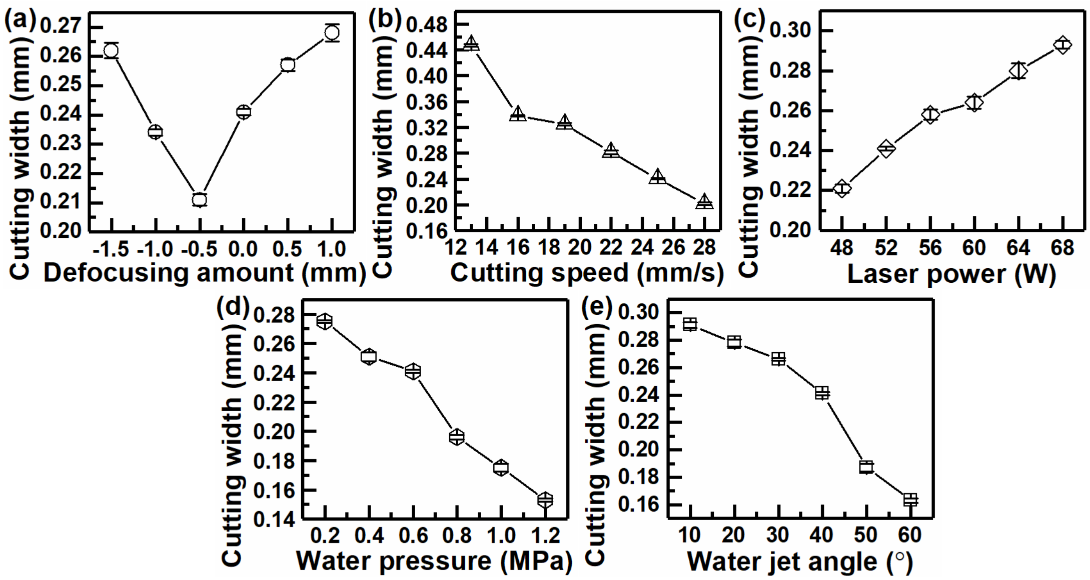

Fig. 3. The influence of process parameters on cutting width of parts: (a) Defocusing amount, (b) Cutting speed, (c) Laser power, (d) Water pressure, and (e) Water jet angle

Influence of defocusing amount on cutting width of parts

In order to explore the effect of defocusing amount on the cutting width of Korean pine parts by water-jet assisted laser, the processing was performed using various defocusing amounts. Figure 3(a) presents the effect of defocusing amount on the cutting width of Korean pine parts. It was demonstrated that with the increase of defocusing amount, the cutting width of Korean pine first decreases and then increases. When the focal point is at the bottom, the laser power density is large, thus the heat-affected zone is big and the cutting width is large. If the focal point is positioned slightly above the middle of the workpiece, the laser energy density is more uniform throughout the thickness. In this case, the kerf width is smaller and more uniform. When the defocusing amount is 0 mm, the maximum laser energy density is at the surface, so the cutting width is large. When the focal point is located above the surface of Korean pine parts, the laser spot size becomes large, and thus the cutting width is increased obviously. Therefore, the optimum defocusing range affecting the cutting width of Korean pine parts is -1 mm to 0.5 mm.

Influence of cutting speed on cutting width

Cutting speed plays an important role in determining cutting width, and thus it is necessary to study the effect rule of cutting width of Korean pine parts. The results are apparent in Fig. 3(b). With an increase in cutting speed, the cutting width gradually decreased. This is attributed to the fact that when the cutting speed is small, the interaction time between laser beam and wood is long, the heat accumulation effect of wood under the laser's action is serious, and the range of thermal influence area is large, increasing the degree of damaged wood and generating a large cutting width. When the cutting speed increases, the interaction time between the laser beam and the wood is shortened, the effective reaction area of the laser beam on the surface of wood is reduced, the gasification speed of the wood is lower than the moving speed of the laser beam, the range of thermal influence area is smaller, and the cutting width is reduced accordingly. Therefore, the optimum range of cutting speed affecting cutting width was 19 mm/s to 28 mm/s.

Influence of laser power on cutting width

Figure 3(c) depicts the influence curve of laser power on the cutting width of Korean pine parts processed by water jet assisted laser. As shown in the figure, with the increase of laser power, the cutting width of the part increased gradually. This shows that when the laser power was small, the heat generated and transferred on the wood surface by the laser action was less, and the amount of wood that can burn and sublimate was less. Additionally, the burning destruction effect of the laser on the wood during cutting was relatively weak, and the removed wood was relatively less, so the cutting width was naturally smaller. With the increase in laser power, the heat generated by the laser on the wood surface accumulated faster within the same action time, and the wood surface temperature rose rapidly. Under the action of the laser beam, the wood can reach its own sublimation faster, so that wood is consumed when cutting, making the cutting width larger. Therefore, the optimum range of laser power affecting the cutting width of Korean pine parts was found to be 48 W to 56 W.

Influence of water pressure on cutting width

Figure 3(d) shows the influence curve of water pressure on the cutting width of Korean pine parts using a water jet assisted laser. As can be seen from the figure, with the increase in water pressure, the cutting width decreased obviously. This was due to the increase of water pressure, which enhances the turbulence of water, intensifies the interference of water jet on the laser, and degrades the laser beam quality while increasing the spot diameter. At the same time, as the Reynolds number of the water jet increases, the convective heat transfer coefficient of the water jet increases, and the cooling effect of the water jet on the heat-affected zone is enhanced. Therefore, the range of the heat-affected zone is smaller and the cutting width is correspondingly reduced. This study found that the optimum range of water pressure affecting the cutting width was 0.6 MPa to 1.2 MPa.

Influence of water jet angle on cutting width

The water jet angle plays an important role in determining the cutting width of water jet assisted laser machining, and thus it is necessary to study its effects. The result is observed in Fig. 3(e), where an increase in the water jet angle caused the cutting width of the part to decrease gradually. The water jet's impact force on the workpiece can be divided into horizontal shear force parallel to workpiece surface and impact force perpendicular to workpiece surface. Under the premise of constant water jet pressure, the impact of water jet angle increased, while the horizontal shear force was small, and the impact force of the water jet in the horizontal direction decreased, creating a small cutting width. Hence, the optimum range of the water jet angle affecting cutting width was 30° to 60°.

Result and Analysis of Orthogonal Experiment

Using the range analysis method, the cutting widths of Korean pine parts in Table 2 were conducted, and the obtained range value was used to evaluate the influence of process parameters on the cutting width, as shown in Table 3. A larger range value illustrated that the process parameter's influence on forming precision was greater. Table 3 showed that the cutting width range value was ordered from large to small: defocusing amount, water jet angle, laser power, water pressure, and cutting speed. This meant that the defocusing amount had the greatest influence on cutting width, while the cutting speed had least influence on cutting width.

Table 3. Water-Jet Assisted Laser Process Scheme and Cutting Width of Parts

Serial number	A. Defocusing Amount (mm)	B. Cutting Speed (mm/s)	C. Laser Power (W)	D. Water Pressure (MPa)	E. Water Jet Angle (°)	Test Index
						Cutting width
1	-1	19	48	0.6	30	0.294
2	-1	22	52	0.8	40	0.250
3	-1	25	56	1.0	50	0.239
4	-1	28	60	1.2	60	0.216
5	-0.5	19	52	1.0	60	0.168
6	-0.5	22	48	1.2	50	0.131
7	-0.5	25	60	0.6	40	0.156
8	-0.5	28	56	0.8	30	0.155
9	0	19	56	1.2	40	0.116
10	0	22	60	1.0	30	0.142
11	0	25	48	0.8	60	0.114
12	0	28	52	0.6	50	0.102
13	0.5	19	60	0.8	50	0.148
14	0.5	22	56	0.6	60	0.142
15	0.5	25	52	1.2	30	0.238
16	0.5	28	48	1.0	40	0.225
K1	0.250	0.181	0.191	0.173	0.207	Optimum Combination: A1E1C1 D3B3
K2	0.153	0.166	0.190	0.167	0.187	
K3	0.118	0.187	0.163	0.194	0.155	
K4	0.188	0.174	0.166	0.175	0.160	
R	0.132	0.021	0.028	0.027	0.052	

In Table 3, the range of A was largest, meaning that it was the factor having the greatest influence on the test index. Level 1 was suitable for A, where the range of E was smaller than that of A; namely, the influence was less than A. Level 1 was suitable for E where the ranges of C and D were smaller than that of A and E, and the influence was less. Additionally, level 1 was suitable for C and level 3 was suitable for D, where the range of B was the smallest, thereby having the least influence. Level 3 was suitable for B. Thus, A1E1C1D3B3 was the optimum combination of various factors, where the defocusing amount was -1 mm, the water jet angle was 30°, the laser power was 48 W, the water pressure was 1.0 MPa, and the cutting speed was 25 mm/s. The optimization aims at obtain smaller cutting widths, which provides a basis for the choice of the process parameters and gives a new direction for subsequent water-jet assisted laser processing of Korean pine parts.

Experimental Verification

The cutting width of Korean pine parts using optimized process parameters was 0.1 mm, which represents a decrease by 1.96% when compared with the smallest cutting width in Table 3. The cutting width of Korean pine parts is an important index for the surface quality of parts. The smaller the cutting width, the better the forming precision of parts. Micromorphology of the cut section of the best Korean pine part in Table 3 and the optimized Korean pine part were observed under SEM (Fig. 4). Compared with Fig. 4a, Fig. 4b, by using optimized process parameters, left no residue on the inner walls of the tracheids and the kerf surface was smoother, thus creating better surface quality. This was because the water cooling erased the steam produced by the vaporization of Korean pine. At the same time, the water flow washed away the residues that remained on the surface of the kerf. Therefore, using optimized process parameters not only decreases the cutting width of Korean pine part, but also improves the machining quality of the part.

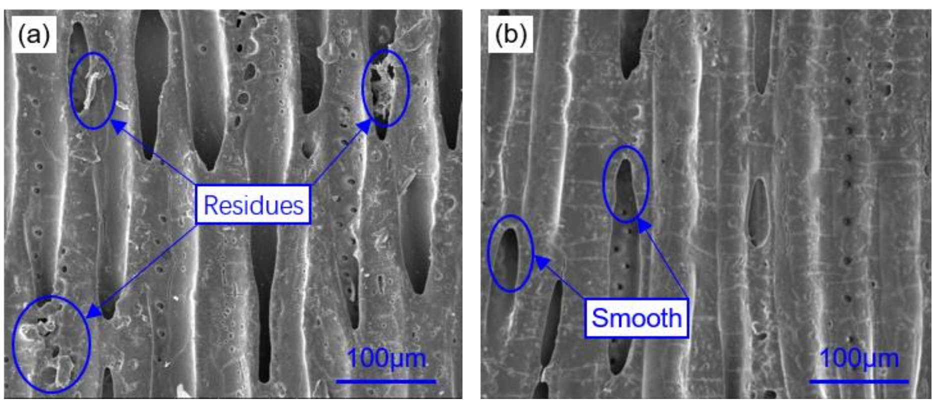

Fig. 4. Micromorphology of cut section of Korean pine part: (a) the best part, and (b) optimized part

CONCLUSIONS

1. The cutting width of Korean pine parts by water-jet assisted laser were conducted using the range analysis method, and the obtained range value was used to evaluate the influence of process parameters on the forming precision of parts. The defocusing amount had the greatest influence on cutting width, while the cutting speed had the least influence on cutting width.
2. Through an orthogonal experiment of five factors and four levels, the influence of the process parameters on the forming precision of Korean pine parts were arranged from large to small in the following order: defocusing amount, water jet angle, laser power, water pressure, and cutting speed. The A1E1C1D3B3 was the optimum combination of various factors, namely, the defocusing amount was -1 mm, the water jet angle was 30°, laser power was 48 W, the water pressure was 1.0 MPa, and the cutting speed was 25 mm/s.

3. The cutting width of Korean pine parts was decreased by 1.96% when using optimized process parameters in comparison to using the best process parameters in water-jet assisted laser processing. The optimized process parameters ensured the high-quality Korean pine parts fabricated by water-jet assisted laser and provided reference values for the choice of process parameters.

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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. Y., Yuan, G. F., and Wang, J. H. (2014). "Low-pressure water-jet and laser composite cutting on Al_2O_3 ceramic," *Infrared and Laser Engineering* 43(07), 2097-2102.

Guan, B. G., Liu, S. H., Zhang, M. L., Wang, Y. L., and Liu, H. (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

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," *International Journal of Advanced Manufacturing Technology* 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," *Applied Surface Science* 351, 935-945. DOI: 10.1016/j.apsusc.2015.06.041

Madhukar, Y. K., Mullick, S., and Nath, A. K. (2013). "Development of a water-jet assisted laser paint removal process," *Applied Surface Science* 286, 192-205. DOI: 10.1016/j.apsusc.2013.09.046

Pablos-Martín, A. D., and Höche, T. (2017). "Laser welding of glasses using a nanosecond pulsed Nd:YAG laser," *Optics and Lasers in Engineering* 90, 1-9. DOI: 10.1016/j.optlaseng.2016.09.009

Tangwarodomnukun, V., Likhitangsuwat, P., Tevinpibanphan, O., and Dumkum, C. (2015). "Laser ablation of titanium alloy under a thin and flowing water layer," *International Journal of Machine Tools and Manufacture* 89, 14-28. DOI: 10.1016/j.ijmachtools.2014.10.013

Yang, C. M., Zhu, X. L, Kim, N. H., Lee, S. H., Qi, Y., Bai, Y., Guo, M. H., 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

Yang, C. M., Jiang, T., Yu, Y. Q., Dun, G. Q., Ma, Y., and Liu, J. Q. (2018). "Study on surface quality of wood processed by water-jet assisted nanosecond laser," *Bioresources* 13(2), 3125-3134. DOI: 10.15376/biores.13.2.3125-3134

Yang, C. M., Jiang, T., Yu, Y. Q., Dun, G. Q., Ma, Y., and Liu, J. Q. (2019). "Water-jet assisted nanosecond laser microcutting of northeast China ash wood: Experimental study," *BioResources* 14(1), 128-138. DOI: 10.15376/biores.14.1.128-138

Zhou, B. H., and Mahdavian, S. M. (2004). "Experimental and theoretical analyses of cutting nonmetallic materials by low power CO_2-laser," *Journal of Materials Processing Technology* 146(2), 188-192. DOI: 10.1016/j.jmatprotec.2003.10.017

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