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OPTIMIZATION AND ANALYSIS OF PROCESSING PARAMETERS OF WOODEN CRAFTS BASED ON ULTRA-HIGH PRESSURE WATER JET METHOD

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ABSTRACT

The investigation and application of computer-numeric-control (CNC)-based ultra-high pressure water jet technology used in the field of wood processing have been paid increasing attention. In order to further optimize the technique of processing parameters in wooden crafts processing, medium density fiberboard (MDF) and solid wood of Italian poplar (*Populus euramericana* cv.) were taken as the experimental materials. The orthogonal experiment method was applied and the influence of several processing parameters including sand regulating speed, air-dry density, water jet pressure, feeding speed and target distance was considered to analyze the surface roughness. The water jet experiments were conducted based on the patterns designed by AutoCAD software with aid of numerical control working system. By the measurement of surface roughness and calculations, the influence of each processing parameter was investigated and the optimal scheme was then proposed. This work could provide optimization of processing parameters to the manufacturing of wooden crafts including fancy wood floors, indoor decorative boards of timber structure and mahogany furniture et al., which has high application value and practical significance.

KEYWORDS: Ultra-high pressure water jet, wooden crafts, processing parameter, orthogonal experiment, surface roughness, optimal scheme.

INTRODUCTION

As a concept in accordance with green manufacturing, the ultra-high pressure water jet technology combines various techniques including CNC and hydraulic pressure (Chen et al. 2002, Franz 1972, Harris 1970). This technology has been widely used in many industries, such as aerospace engineering, automobile manufacturing, building materials and decoration, military engineering, food processing and subsurface mining (Kinga 2002, He et al. 2009, Pascuzzi et al. 1998, Wang et al. 2002). At present, ultra-high water jet machine has a pressure range of 140 to 400 MPa and has features of cold working, small swage set, no pollution, arc machining, automatic control and easy operation. In 1982, Wu called high pressure water as water jet, which indicates the power of high pressure water (Wu 1982, Xue et al. 1982, Taguchi 1987). In 1960s, Bryan (1963) found that high pressure water jet could be applied to cut wood, thus creating a precedent for its application in the field of wood processing. After that, some scholars conducted researches on cutting processing of wood and wood composites by abrasive and pure water jet techniques. There were many conclusions drawn, for example, abrasive water jet has better cutting result than pure water jet. In 2007, Wang et al.2007 applied ultra-high pressure water jet technology to process solid wood parquets and MDF crafts, which provides reference for development of new technology in wood processing industry in China (Wang et al. 2007).

In China, scarcity of forest resources results in the shortage of timber. Therefore, the optimization of cutting parameters is significantly important to the application of ultra-high pressure water jet in the fields of wood product processing and rare wood cutting. In recent years, scholars worldwide have obtained some achievements on studying water jet cutting techniques of wood. For example, through water jet experiments on tropical wood, the influence of several important parameters including air-dry density, water cutting pressure, feeding speed, abrasive grain size and cutting thickness on the roughness of processed wood surface was investigated (Chen 2005, Wang 2012). However, there is no publication about the flow speed of garnet sand which is contained in the sand control device of water jet machine, though this parameter has a great impact on the processing quality. Thus, in this work, the performance of ultra-high pressure water jet technique was investigated. MDF and solid wood of Italian poplar were taken as experimental materials. Sand regulating speed as the innovation point, combined with several parameters including air-dry density, water cutting pressure, feeding speed and target distance, the orthogonal experimental design method of L8(27) was applied for analysis. This work could provide optimization of processing parameters to the manufacturing of wooden crafts including fancy wood floors, indoor decorative boards of timber structure and mahogany furniture et al., which has high application value and practical significance.

MATERIALS AND METHODS

Materials

Four pieces of MDF and four pieces of Italian poplar were selected as specimens in the experiments. The sizes of the eight specimens were 300×300×12 mm. Tab. 1 shows the production place, air-dry density, average air-dry density and moisture content of the specimens.

Garnet sand was produced in Donghai County, Jiangsu Province, China. The sand size is 60 meshes and it has features of high hardness, thermostability, chemical stability, uniform size, high grinding efficiency and no scratches.

Tab. 1: Air-dry density and moisture content.

No.	Material	Production place	Air-dry density ρ ($kg \cdot cm^{-3}$)	Average ir-dry density ($kg \cdot cm^{-3}$)	Moisture content (%)
1	MDF	Dare Wood-based Panel Group	0.563	0.583	10.30
2	MDF	Dare Wood-based Panel Group	0.574		12.46
3	MDF	Dare Wood-based Panel Group	0.613		9.16
4	MDF	Dare Wood-based Panel Group	0.582		12.46
5	*Populus euramericana* cv	Siyang, Jiangsu	0.483		8.42
6	*Populus euramericana* cv	Siyang, Jiangsu	0.335		11.28
7	*Populus euramericana cv*	Siyang, Jiangsu	0.407		12.26
8	*Populus euramericana cv*	Siyang, Jiangsu	0.322	0.387	12.26

Equipments

The type of CNC ultra-high pressure water jet machine is WC40WA1312H, consisting of ultra-high pressure water jet generator (Type SQ-WJG44), double-column type CNC table and CNC operation system. Specifically, the water jet generator consists of pressure charging, water supply, pressure stabilizing, nozzle pipe, catchment and water circulation treatment systems, with maximum water pressure of 300 MPa, maximum working pressure of oil pump of 15 to 16 MPa and maximum jet flow of 2.7 $L \cdot min^{-1}$. The double column type CNC table comprises linear guide rail, working table and ball screw. The accuracy of screw and guide rail are IP5±0.11mm with resetting accuracy of ±0.05 mm. The maximum processing size of 2D working table is 1200×1200 mm with control accuracy of ±0.02 mm and adjusted cutting speed of 0 to 3000 $mm \cdot s^{-1}$. The jet cutting system consists of a water jet nozzle with diameter of 0.126 mm and a sand control device. The CNC operation system comprises standard industry control machine, independent control cabinet, the Windows operation platform and CAD/CAM system. The main procedures of control system are as follows:

Oil pump pressurization→ Electromagnetic directional valve→ High pressure water boosting→ High pressure accumulator→ High pressure water selector valve→ High pressure water nozzle→ MDF and solid wood cutting, as shown in Fig. 1.

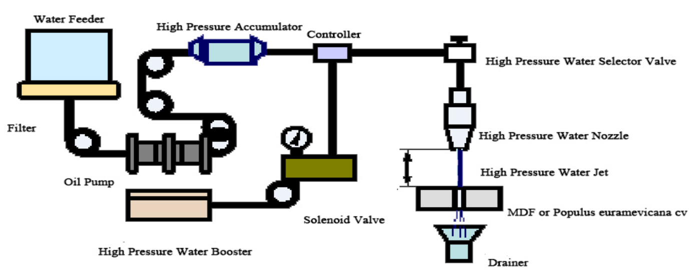

Fig. 1: Working flow of cutting wood craft specimen by ultra-high pressure water jet method.

Type TR110 pocket-size roughness tester (radius of the measuring tip of 10±2.5 μm) has operational principle as follows: The sensor moves along material surface in a straight line in a constant speed. The interior cat whisker perpendicular to the working surface produces a vertical displacement along the outline of working surface. Then the variation of displacement is transformed into the change of electric quantity by sensor. After amplification and filtering, the electric quantity is transformed into digital signal in the A/D convertor. The digital signal is processed by CPU to calculate and show the values of R_a or R_z which reflect the distance measurement of roughness.

Orthogonal experiment design

The orthogonal experiment analysis method was applied and orthogonal experiment table $L_8(2^7)$ was selected. There were two levels (MDF and *Populus euramericana* cv.) and five factors (average air-dry density, water cutting pressure, feeding speed, target distance and sand regulating speed) as shown in Tab. 2. Fig. 2 shows the pattern designed by AutoCAD.

Tab. 2: Experimental factors and levels.

Material	Level	Experimental factor						
		A	B	C	D	E	F	G
		Average air-dry density ($g \cdot cm^{-3}$)	Water cutting pressure (MPa)	Feeding speed ($mm \cdot s^{-1}$)	Target distance (mm)	Sand regulating speed ($kg \cdot h^{-1}$)	Blank	Blank
MDF	1	0.583	250	1 000	5	20		
Populus euramericana cv.	2	0.387	300	1 300	10	25		

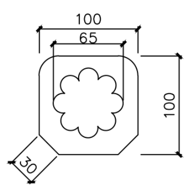

Fig. 2: Pattern designed by AutoCAD.

Experimental procedures

The experimental procedures are as follows:

1) Prepare a specimen and clamp it.
2) Design pattern by AutoCAD software.
3) Code and simulation for cutting.
4) Filter running water.
5) Pressurize the water to the maximum (250 MPa and 300 MPa) by a force pump (150 kW); send it to water jet device on the working platform.
6) Adjust sand amount by sand regulating device.
7) Cut material.

Fig. 3 and 4 show the experimental site and finished products. The processed wooden crafts were conducted with secondary drying in order to overcome the interference of water and prevent materials from deformation.

a. CAD/CAM system operation diagram

b. Water jet cutting experiment site

Fig. 3: Experiment site diagram.

a. Specimen No.4 - MDF finished product

b. Specimen No.8 - *Populus euramericana* cv. finished product

Fig. 4: Finished products of wooden crafts.

Surface roughness measurement

When the test ranges of surface roughness tester are that R_a is between 0.05 μm and 10 μm and Rz is between 0.1 μm and 50 μm, then R_a would be firstly used within commonly used numerical range (R_a is between 0.025 μm and 6.3 μm) in the assessment of parameters, according to GB/T 12472-2003 and GB/T 14495-1993. After calibration, R_a (in μm) should be selected to determine the roughness of the finished product specimens.

According to GB/T 14495-1993, sampling and evaluation lengths were selected as $l_n=5l_r$. Due to smooth surface, $l_n<5l_r$ was selected in the measurement, where ln was sampling length and lr was evaluation length. Tab. 3 shows the measurement results.

RESULTS AND DISCUSSION

Tab. 3 shows measurement results of surface roughness and Tab. 4 shows the analysis results by orthogonal experiment design. In specimen processing, wood could be out of shape because of moisture absorption, which would cause difficulty of later processing and pave. Therefore, after processing, the material was timely sent to the drying chamber (TDB=40°C; Δt=4°C) with constant temperature and moisture for secondary drying. After 24 hours, the final moisture content of specimens was controlled below 12%.

Tab. 3: Measurement results of surface roughness (μm).

Specimen No.	Measuring times					R_a average
	1	2	3	4	5	
MDF No. 1	4.29	3.98	4.19	3.82	3.45	3.95
MDF No. 2	4.29	4.53	3.86	5.01	5.2	4.58

MDF No. 3	3.12	3.36	3.02	3.24	3.21	3.19
MDF No. 4	4.29	3.98	4.13	4.03	4.45	4.18
Populus euramericana cv. No. 5	4.00	4.63	4.52	3.88	4.33	4.27
Populus euramericana cv. No. 6	4.12	3.92	4.16	3.55	4.06	3.96
Populus euramericana cv. No. 7	3.49	3.54	2.97	2.85	2.89	3.15
Populus euramericana cv. No. 8	3.28	2.89	3.18	2.99	3.09	3.09

Tab. 4: Analysis by orthogonal experiment design.

No.	A	B	C	D	E	F	G	Surface roughness Ra	Ra^2
1	1	1	1	1	1	1	1	3.95	15.60
2	1	1	1	2	2	2	2	4.58	20.98
3	1	2	2	1	1	2	2	3.19	10.18
4	1	2	2	2	2	1	1	4.18	17.47
5	2	1	2	1	2	1	2	4.27	18.23
6	2	1	2	2	1	2	1	3.96	15.68
7	2	2	1	1	2	2	1	3.15	9.92
8	2	2	1	2	1	1	2	3.09	9.55
K1	15.90	16.76	14.77	14.56	14.19	15.49	15.24	T=30.37	W=117.61
K2	14.47	13.61	15.60	15.81	16.18	14.88	15.13		
k1	7.95	8.38	7.39	7.28	7.10	7.75	7.62		
k2	7.24	6.81	7.80	7.91	8.09	7.44	7.57		
R	0.72	1.58	0.41	0.62	0.99	0.30	0.06		
Rank of influencing factors	B, E, A, D and C								

As shown in Tab. 4, the influencing factors rank as follows: *B*>*E*>*A*>*D*>*C* (water cutting pressure>sand regulating speed>average air-dry density>target distance>feed speed). Besides, the optimum scheme is $A_2B_2C_1D_1E_1$. In other words, the surface roughness would be minimum and the best cutting quality could be achieved when average air-dry density of Italian poplar is 0.387 $g{\cdot}cm^{-3}$, water cutting pressure is 300 MPa, feed speed is 1.000 $mm{\cdot}s^{-1}$, target distance is 5 mm and sand regulating speed is 20 $kg{\cdot}h^{-1}$.

Tab. 5: Variance analysis of the influencing factors to cutting quality.

Source of variance	*A*	*B*	*C*	*D*	*E*	Error	Sum
Sum of squares of deviations (SS_T)	0.256	1.240	0.086	0.195	0.495	0.050	2.320
Error degrees of freedom (f)	1	1	1	1	1	2	7
Mean square (MS)	0.128	0.620	0.043	0.098	0.248	0.025	
F Value	10.645	51.653	3.586	8.134	20.615		
Critical value	$F_{0.1}$ (1,2)=8.53 $F_{0.05}$ (1,2) =18.51						
Optimal scheme	$A_2B_2C_1D_1E_1$						

As shown in Tab. 5 , F values of water cutting pressure and sand regulating speed are larger than $F_{0.05}(1,2)$ ($F_{0.05}(1,2)$=18.51) and average air-dry density larger than $F_{0.1}(1,2)$

($F_{0.1}$(1,2)=8.53). It indicates that surface roughness of material is remarkably influenced by water cutting pressure and sand regulating speed, followed by air-dry density. Whereas, feeding speed and target distance have unremarkable influence on surface roughness.

Since Franz (1972) developed the device of ultra-high pressure water jet in 1960s, this technology has been gradually perfected. Because the device has many advantages, such as cutting various materials into different patterns and stripes, cutting wood, plastic and composite materials without pollution, no harmful gas produced and strong operability, it is commonly used in many cutting fields, including stone, metal, glass, ceramic, concrete, paper, food, glass, cloth, polyurethane, wood, leather, rubber, ammunition et al. The technology is very frontier and has vast potential for future development.

During the past years, there are some works that have some achievements in the study of water jet cutting technology. For instance, some important parameters including air-dry density, water cutting pressure, feeding speed, sand regulating speed and cutting thickness were adopted to study their influence on the cutting quality of surface of wood. However, there is not any work considering a significant parameter - flow speed of garnet sand which is contained in the sand control device of water jet machine. Moreover, there is no study on the influence of garnet sand flow speed to the optimization of water jet cutting technology in the orthogonal experimental design.

In our study of mechanism of water jet, parameters including garnet sand flow speed as an innovation point, the impact significance of each influencing factor and the optimal scheme were achieved. Besides, in this work, the orthogonal experimental design method of L8(27) was selected and applied to study processing quality and performance of wood and wood composites processing by ultra-high pressure water jet technique. Moreover, the method proposed here applies to optimal selection of processing parameters for the manufacturing of wooden crafts including fancy wood floors, indoor decorative boards of timber structure and mahogany furniture etc. by ultra-high pressure water jet. Overall, this work could provide further development to the optimization of processing parameters for wooden crafts manufacturing through ultra-high pressure water jet technology and orthogonal experiment in the field of wood processing, which has high theoretical meaning and application value.

CONCLUSIONS

1. Optimization of ultra-high pressure water jet for wooden crafts was achieved, with orthogonal experiment design selecting sand regulating speed parameter as innovation point. Influencing factors and levels were also selected reasonably and reliably.
2. Cutting performance of ultra-high pressure water jet machine was relative to the factors including air-dry density, feeding speed, water cutting pressure, target distance and sand regulating speed. These influencing factors rank as follows: water cutting pressure> sand regulating speed>average air-dry density>target distance>feeding speed. In this work, the surface roughness would be minimum and the best cutting quality would be achieved when average air-dry density of *Populus euramericana* cv. is 0.387 $g \cdot cm^{-3}$, water cutting pressure is 300 MPa, feeding speed is 1.000 $mm \cdot s^{-1}$, target distance is 5 mm and sand regulating speed is 20 $kg \cdot h^{-1}$. Surface roughness of material is remarkably influenced by water cutting pressure and sand regulating speed, followed by air-dry density. Whereas, feeding speed and target distance have unremarkable influence on surface roughness. The processing technic could be improved through increasing water cutting pressure and reducing sand regulating speed.

3. The processed wooden crafts were conducted with secondary drying in order to overcome the interference of water and prevent materials from deformation.
4. The method applies to optimal selection of processing parameters for the manufacturing of wooden crafts including fancy wood floors, indoor decorative boards of timber structure and mahogany furniture etc. by ultra-high pressure water jet.
5. The orthogonal experimental design method of L8(27) was selected and applied to study processing quality and performance of wood and wood composites processing by ultra-high pressure water jet technique.

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