WOOD RESEARCH
63 (5): 2018
783-794

PARAMETERS OPTIMIZATION FOR ULTRAHIGH-PRESSURE PURE WATER AND ABRASIVE WATER JET OF *PTEROCARPUS MACAROCARPUS* KURZ PROCESSING

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(Received January 2018)

ABSTRACT

This work optimizes the parameters of ultrahigh-pressure water jet, with or without abrasives, for the cutting of *Pterocarpus macarocarpus* Kurz wood, a precious species. Parametric factors of cutting pressure, target distance and feed rate were analyzed with respect to the resultant surface roughness of the cuts on specimens using an orthogonal experiment. The optimal machining schemes were elected for water jets either with or without added abrasives based on microscopic evidences. The results showed that the impacts on the resultant surface-roughness of the factors with a given water jet, i.e. either with or without added abrasives, from the most to the least, are both in the order of water jet pressure>feed rate>target distance. Water jets with no added abrasives have lower cutting capacity, which was evidenced by the worse surface roughness of cuts resulted from rebound jet. Raising their kinetic energy, the probabilities of fracture from tearing would also rise, thus, inducing corrugation in the bottom with exacerbated overall surface roughness of cuts. Abrasive water jet has the feature of many ripples, decreasing the surface integrity of specimens. Therefore, to improve product quality of *Pterocarpusma carocarpus* Kurz wood, is to increase the portion that is smooth in the sections from water jet cuts by choosing carefully the process parameters. The investigation of water jet cutting in this work throws some light on the configuration of process parameters while applying ultra high-pressure water jets, both with and without added abrasives, to the cutting of wood products of precious species.

KEYWORDS: *Pterocarpus macarocarpus* Kurz, pure water jet, abrasive water jet, surface roughness, cutting mechanism, microscopic analysis.

INTRODUCTION

NC (Numerical Control) ultrahigh-pressure (UHP) water jet technology, as a new type of versatile processing technology developed in recent thirty years, embodies the idea of green manufacturing. Including pure water jet and abrasive jet, the technology has lots of advantages compared with traditional cutting technology (Kuyumcu and Rolf 2004). In processing precious wood, the use of UHP water jet technology has significant advantages of excellent cutting quality, high efficiency, low cost, environmental protection and simple system operation, which can reasonably increase utilization rate of the wood (Hou et al. 2014, Ábrahám et al. 2015). The cutting mechanism is more complicated with wood materials, since because of pressure, focus distance and feed rate, the quality of wood cutting is also under the influence of the isotropy of natural wood material.

Currently, there is much room for improvement in the research of wood processing and application in China to achieve the industrialization of water jet equipment through optimization of process parameters. He Jilong et al. (2008) adopted dynamic pressure test to analyze the cutting force of Chinese fir specimen in free state. Meanwhile, they compared the roughness of cutting surface of Chinese fir specimen with different specifications in free state and clamped state. Four-cylinder linkage pneumatic clamping device is designed to be used with SQ-WJG40 high-pressure water jet cutting machine, improving the machining accuracy (He et al. 2008). Wang et al. (2010) conducted experiments of water jet processing on the wood commonly used in flooring, analyzing the influence of air dry density, water cutting pressure, feed rate, grit size and cutting thickness on the roughness of machined surface. It is concluded that cutting water pressure has the greatest influence on the test results. The optimal cutting process is in the conditions: Density of 0.70 $g•cm^{-3}$, water pressure of 280 MPa, feed rate of 80 $mm·min^{-1}$ and grinding size of 100 sieves (Wang 2010). In 2016, Cao et al. used orthogonal test method to test water-jet cutting of medium-density fibreboard and poplar solid wood specimens. The results showed that the processing quality of poplar is the highest with minimum surface roughness in average air-dry density of 0.387 $g•cm^{-3}$, pressure of 300 MPa, feeding speed of 1,000 $mm·s^{-1}$, target distance of 5 mm, and the feed rate of sand at 20 $kg·h^{-1}$ (Cao et al. 2016).

In recent years, other countries have made lots of researches on the application of UHP water jet processing. Barcík et al. (2011) studied the abrasive water jet cutting MDF process. Meanwhile, they explored the effect on material cutting width of processing parameters, material parameters and cutting angle. The results show that water jet cutting can be applied preferentially to composite material processing when jetting and technical parameters are adopted reasonably. The incision width is more stable in lengthwise cutting. The parameters of feed rate of 400 $mm•min^{-1}$ and abrasive flow of 350 $g•min^{-1}$ are proved to be the optimal processing condition. This method is not efficient when the thickness exceeds 44 mm, due to the increase of additional work (Barcík et al. 2011). A three-phase flow phenomenological model of abrasive jet cutting nozzle was developed by Narayanan et al. (2013). After verification with relevant tests, it is proved that the cutting head geometry, pressure and abrasive flow rate have universality. Throughout the test, the average abrasive velocity in cross section of the nozzle is predicted. The results showed that the correlation between the experimental model and test results is over 95% (Narayanan et al. 2013). Abrasive jet was used to cut MDF, OSB and plywood considering the effect of material thickness, cutting depth direction, abrasive flow and feed rate (Kvietková et al. 2014). The experimental results showed that the abrasive jet cutting generates changes in longitudinal direction of the material. The water has a reaction at the bottom of the material, with an increase in cut width. The cutting effect is optimal with minimum cut width in the following conditions:

Feed rate of 400 mm·min^{-1} and abrasive flow rate of 450 g·min^{-1} (Hlaváčová and Geryk 2017). Shukla and Singh (2017) studied the abrasive waterjet machining (AWJM) techniques for type AA631-T6 aluminium alloy by the Taguchi method. Effects of parameters including feeding speed, standoff distance and mass flow rate on the kerf width and taper were analyzed. Regression models were developed based on the data from experimental results. Seven advanced optimization techniques were attempted to study AWJM process. The experimental and analysis results show that the Taguchi method and optimization techniques are useful tools in the optimization of process parameters in the AWJM process (Shukla and Singh 2017). There are few researches on cutting process of *Pterocarpus macarocarpus* Kurz with ultra-high pressure water jet. Existing researches on cutting process and mechanism of ultrahigh-pressure water jet are based on uniform materials of rock and ceramic as well as wood composites. The research in water jet processing of solid wood is rare. But it is crucial to carry out optimization design of UHP water jet cutting process to promote the modern production of *Pterocarpus macarocarpus* Kurz handicrafts.

Due to the lack of research results on microscopic analysis of pure water jet and cutting mechanism at home and abroad, this work aims to obtain referential results through parameters optimization as well as macro and micro analysis on *Pterocarpus macarocarpus* Kurz specimen with UHP pure water and abrasive jet cutting. The test scheme was designed mainly based on orthogonal analysis table L4 (2^3). Considering the influence of cutting pressure, target distance and feed rate on surface roughness of finished specimen processing, we determined the order of the influencing factors and optimal scheme of processing parameters. Cutting mechanism was analyzed with microscope, to better understand the water cutting for the production of wood crafts of precious species, e.g. mahogany wood. The advantages and disadvantages of the two types of water jets, with or without added abrasives, for *Pterocarpus macarocarpus* Kurz wood cutting were summed up to provide a basis for the further research and optimization of water jet technology for wood processing.

MATERIALS AND METHODS

Materials

1) *Pterocarpus macarocarpus* Kurz: wood samples of *Pterocarpus macarocarpus* Kurz; specifications of 275 (length)×160 (width)×11 (height) mm; origin place of Burma; flat board; air dry density 1.0 g·cm^{-3}; and dry air moisture content of 16.7%.
2) Garnet sand: 60 meshes; origin of Donghai County, Jiangsu.

Equipments

1) WC40WA1312H NC UHP water jet cutting machine, consisting mainly of SQ-WJG44-type UHP water jet generator, gantry CNC bench, jet cutting system and CNC operating system. Water jet generator is composed of supercharger, water supply, pressurized constant pressure, nozzle piping, water collection and water circulation system, with maximum water pressure of 300 MPa. NC operating system consists of standard industrial control machine, independent control cabinet and dedicated CAD/CAM system. Fig. 1 shows the work flow.

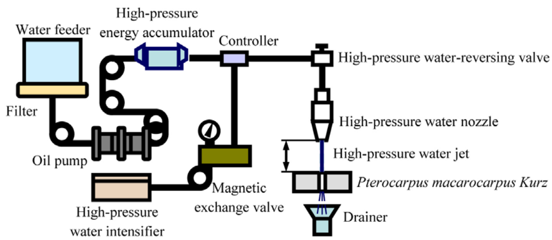

Fig. 1: UHP water jet cutting rosewood process work flow.

2) A GDS-100 constant temperature and moisture content chamber, with computer-controlled humidity and saturated gas humidification. Its temperature range includes -20, -40, -60, -70~+100°C (+150 °C), with temperature fluctuation of ±0.5°C, temperature uniformity of ±2°C and moisture content range of 38-98% RH.
3) SURFOM 1400 G roughness meter. The sampling, evaluation and scanning length are 10 mm; measurement accuracy is 1.8 µm; maximum speed of contour measurement sampling 20 mm·s^{-1}; maximum moving speed 60 mm·s^{-1}; roughness measurement speed 3 mm·s^{-1}.
4) An OLYMPUS SZX7 stereomicroscope. It is configured with OLYMPUS DP70 observation lens, connected with a computer. The micrograph of cutting surface is obtained through OLYMPUS analysis software. The magnification is 40.0×. The work uses Galilean optical system with no difference between left and right optical paths as well as parallel beam. It is configured with high-NA objective lens parallel to the observation surface, and the trestle table as focusing unit. Transmitted and reflected light belongs to LED lighting, with small color difference, good resolution and contrast.
5) An HK-30 wood moisture meter.

EXPERIMENT DESIGN AND PROCESS

Orthogonal analysis table L4 (2^3) was adopted in pure water jet test of *Pterocarpus macarocarpus* Kurz. The test factors included water jet pressure, target distance and feed rate, with 2 levels for each factor (Tab. 1).

Tab. 1: Orthogonal test table of pure water jet.

Test level	Test factors		
	A	B	C
	Pressure MPa	Target distance mm	Feed rate mm•s^{-1}
1	300	8	300
2	200	3	100

The abrasive jet test of *Pterocarpus macarocarpus* Kurz was designed according to orthogonal analysis table L4 (2^3), with adjusting sand speed of 50 kg·h^{-1}. The test factors included water jet pressure, target distance and feed rate. Two levels were selected for each factor (Tab. 2).

Tab. 2: Orthogonal test table of abrasive jet test.

Test level	Test factors		
	A	B	C
	Pressure (MPa)	Target distance (mm)	Feed rate (mm•s^{-1})
1	300	8	1000
2	200	3	500

Process route

Fig. 2 shows processing design of specimen, while Fig. 3 shows the test specimen. The processing steps include sample preparation →CAD design→ setting cutting pressure and speed→cutting coding and simulation→ tap water filtration→ generator pressurization (200 or 300 MPa) → adjusting sand feeding rate (0 or 50 kg•h^{-1})→adjusting target distance → positioning cutting → dealing with constant temperature and moisture content drying→ measurement and calculation of cutting surface roughness. Pure water cutting specimens were numbered as 1, 2, 3 and 4; abrasive cutting specimens as 5, 6, 7 and 8. Fig. 4 shows on-site processing and carving of *Pterocarpus macarocarpus* Kurz craft–"Fuwa".

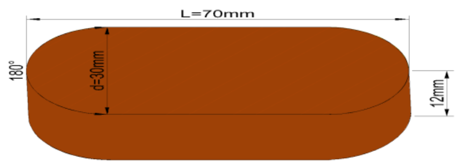

Fig. 2: Processing design of specimen.

Fig. 3: Processing specimen.

Fig. 4: Pterocarpus macarocarpus Kurz *craft "Fuwa" and carving.*

Secondary drying of temperature humidity chamber

Pterocarpus macarocarpus Kurz was obviously yellowish brown when soaked in water. The wood had characteristics of swell and shrinkage as well as anisotropy. In order to prevent micro-deformation of the specimen after water jet processing, the finished samples were timely put into temperature humidity chamber, with dry-bulb temperature 40°C and Δt = 4°C, for a 24-hour secondary drying. The final moisture content of the specimen was controlled below 12% (Wang 2012).

RESULTS AND DISSCUSION

In the past four decades, many experts and scholars carried out a plenty of work on the related optimization design based on the ultra-high pressure water jet processing technique.

By using the ultra-high pressure water jet processing technique, a lot of experiments were conducted on cutting paper, rock, ceramics, composites and other products, and basic application research including energy conversion, crushing mechanism, simulating calculation was conducted. In the area of wood and wood product processing, the influence of abrasive, density and maximum cutting speed on the processing performance such as surface roughness and kerf width was analyzed. However, there are few papers on the optimization of processing parameters and the crushing mechanism of ultra-high pressure water jet for precious wood. Based on the previous research, parameter optimization and crushing mechanism of ultra-high pressure water jet for precious wood were further studied. The effects of pure water jet and abrasive jet on the processing performance were analyzed so that the optimal processing parameters were obtained under the conditions with or without abrasive jet. Thus, numerical control machining with high precision, robustness and efficiency was achieved, which allows the limited timber resources to be more fully and rationally utilized. From both aspects of macroscopic and microcosmic, the crushing phenomenon and its mechanism of ultra-high pressure water jet for cutting precious wood was specifically analyzed so that optimization scheme was further designed. This change of processing method for precious wood can contribute to the application of ultra-high pressure water jet technique to the industries such as precious wooden furniture, sculpture, handicrafts, interior decoration boards and improvement of wood processing technique level.

After secondary drying of *Pterocarpus macarocarpus* Kurz processing specimen, the surface roughness was measured by roughness meter for calculation and analysis of orthogonal experimental design. Meanwhile, stereomicroscope was used for microscopic observation and analysis on processing surface.

Calculation and analysis of surface roughness

According to GB/T 1031-2009 Ra was preferred. Due to high density and precision of test material, Ra value was calculated to evaluate the processing surface roughness. The range of Ra was 2.0-10.0 µm, sampling length l_r=2.5 mm. Consequently, the evaluation length was $l_n=5l_r$, namely 12.5 mm. Tab. 3 shows the orthogonal experimental design analysis and roughness measurement results of pure water jet and abrasive jet.

Tab. 3: Orthogonal design analysis table L8 (2^3) of pure water jet and abrasive jet.

Factor / NO	Pure water jet			Abrasive jet			Cutting thickness (mm)		Ra (µm)		Ra average value	
	A_1	B_1	C_1	A_2	B_2	C_2	Pure water	Abrasive	Pure water	Abrasive	Pure water	Abrasive
1(5)	1	1	1	1	1	1	5.5	11	8.11	7.26	8.59	7.50
									7.35	7.21		
									10.32	8.03		
2(6)	1	2	2	1	2	2	8	11	7.67	6.94	8.04	6.99
									7.96	6.78		
									8.48	7.24		
3(7)	2	1	2	2	1	2	4.5	11	7.14	6.69	7.08	6.60
									6.92	6.72		
									7.19	6.39		
4(8)	2	2	1	2	2	1	2.5	11	7.57	6.88	7.58	6.93
									7.43	6.79		
									7.75	7.11		

K_1	16.63	15.68	16.18	14.49	14.09	14.42
K_2	14.67	15.62	15.12	13.52	13.92	13.59
k_1	8.30	7.84	8.09	7.24	7.05	7.21
k_2	7.33	7.81	7.56	6.76	6.96	6.79
Range	0.98	0.03	0.53	0.48	0.09	0.42
Optimal scheme	A_2	B_2	C_2	A_2	B_2	C_2

According to Tab. 3, the influencing factors of pure water jet and abrasive jet test of *Pterocarpus macarocarpus* Kurz are ranked as A, C and B. That is, water jet pressure>feed rate>target distance. The optimal scheme of test is $A_2B_2C_2$, namely cutting pressure of 200 MPa, target distance of 3 mm and feed rate of 100 mm·s^{-1} for pure water jet of *Pterocarpus macarocarpus* Kurz. In terms of abrasive jet, the optimal scheme is obtained under the conditions as follows: Cutting pressure of 200 MPa, target distance of 3 mm and feed rate of 500 mm·s^{-1}. Under such technological parameters, the surface of *Pterocarpus macarocarpus* Kurz under water jet cutting has the smallest roughness, with the optimum processing quality.

Cutting mechanism of microscopic analysis

The erosive action of *Pterocarpus macarocarpus* Kurz in UHP water jet cutting was mainly the shearing effect of water jet impact and lateral streaming. Vertical jet processing method was used in the test, while the erosion mainly resulted from effect (Huang et al. 2012, Liu et al. 2011). The hardness and toughness of the material had great influence on erosion effect. High hardness easily leads to process defects. Moreover, wood material belongs to viscoelastic material, which explains why the amount of removal increased with high roughness (Hlavacova and Geryk 2017, Chen et al. 2015). Microscopic observation was performed on the surface of processing specimen in water jet cutting (Fig. 5).

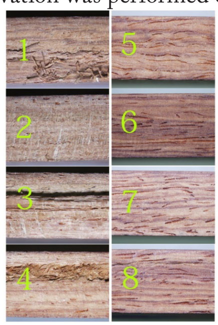

Fig. 5.Microscopic graph of cutting surface of Pterocarpu smacarocarpus Kurz *in water jet.*

The surface of the UHP water jet cutting specimen had erosion areas resulting from initial damage area, smooth area, corrugation area and jet rebound (Nouraei et al. 2014). Due to large initial kinetic energy of UHP water jet, tearing occurred easily within a certain range on the upper surface of the wood at the moment when water jet got into contact with the wood surface, namely forming initial damage area. The smooth area is the cutting surface formed by cutting wear mechanism, with low surface roughness. The erosion ability of water jet was weakened when cutting specimen was increased to the certain thickness. The wood fiber fractured due to shearing and stretching effect, forming corrugation area. When kinetic energy of water jet cutting is not enough to penetrate the specimen, the bottom of the jet flow will form erosion area, thereby increasing the surface roughness.

According to Fig. 5 and Tab. 3, specimens no. 1-4 have not been cut completely through due to low erosive capacity of water jet without abrasives. The surfaces of *Pterocarpus macarocarpus* Kurz specimens were mainly affected by the rebound of jet stream. Within large erosive areas, burrs of broken wood fibers became apparent, thus worsening the overall roughness. Specific performances are described as follows. Specimen no. 1 was cut to a depth of 5.5 mm with water jet with no added abrasives pressurized at 300 MPa, target distance at 8 mm, and feed rate at 300 mm·s^{-1}. Due to large values of all of the pressure, target distance and feed rate, lots of processing defects could be seen on the newly cut surface on specimen. As a result, specimen no.1 has the worst surface roughness. Specimen no. 2 was cut to a depth of 8 mm with pure water jet pressurized at 300 MPa, a target distance at 3 mm, and a feed rate at 100 mm·s^{-1}. High pressure and cutting kinetic energy left obvious damages and ripples on the cut surface that was processed. Specimen no. 3 was cut to a depth of 4.5 mm with pressure at 200 MPa, target distance at 8 mm, and feed rate at 100 mm·s^{-1}. This process configuration is relatively superior, with better roughness of the processed surface. Specimen no. 4 was cut with pressure at 200 MPa, target distance at 3 mm, and feed rate at 300 mm·s^{-1}. The cut depth was only 2.5 mm due to the lowest kinetic energy among all the water jets that were used.

With added abrasives in water jets, the surface roughness of processed surfaces of *Pterocarpus macarocarpus* Kurz specimens were better when compared with those cut with their non-abrasive counterparts under the same conditions. Small abrasive particles increase the erosion capacity of water jets, thus reducing the impact of reverse erosion which occurs before the water jet penetrates the specimen. Increased impact of water jet with added abrasives will increase the amount of wood removal. Irregular movement is generated under the action of high pressure water, easily reducing the integrity of wood processing surface (Alsoufi et al. 2017). With added abrasives, the cut depth reached 11 mm, and the *Pterocarpus macarocarpus* Kurz specimens were all cut completely through.

The specific performances are described as follows. Specimen no.5 was cut with processing pressure set at 300 MPa, target distance at 8 mm, and feed speed at 1,000 mm·s^{-1}. With large pressure and the high kinetic energy of abrasive cutting, damage gaps developed on the upper surface of specimen due to the instantaneous impact of the abrasives. Meanwhile, the increased target distance and feed rate led to the enlarged angle of abrasive cutting to the specimen, thus, reducing the kinetic energy of cutting but increasing the amount of wood removal. The breaking of fibers resulted in the worst surface roughness. Specimen no.6 was cut with processing pressure set at 300 Mpa, target distance at 3 mm, and feed rate at 500 mm·s^{-1}. Large pressure, small target distance and low feed rate raised the kinetic energy of abrasive particles in the cutting jet. Particles collided with their regular internal wood structure while cutting the fibers, resulting in visible corrugation at the bottom. Specimen no.7 was cut with processing pressure set at 200 MPa, target distance at 8mm, and feed rate at 500 mm·s^{-1}. Under such process condition, the cut section of the specimen was smooth with the best roughness on the whole, without obvious defects, burrs, ripples, etc. Specimen no. 8 was cut with water jet pressure set as 200 MPa, a target distance at 3 mm, and a feed speed at 1,000 mm·s^{-1}. The specimen is processed with obvious ripples and large roughness values.

Theoretically, in a water jet-cutting of a *Pterocarpus macarocarpus* Kurz specimen, the roughness of smooth area in the middle of the cut surface should be the best. Because on the upper and lower areas of the specimen, instantaneous impact leads to cracks since the reduced kinetic energy that pulls the fiber causes corrugation, and larger roughness. On the other hand, *Pterocarpus macarocarpus* Kurz belongs to diffuse porous wood with a predominant tendency of bovine-ring porous wood. The pores are large inside the growth wheel, which can be seen with the naked eye. The maximum chord wise diameter is 269 μm with an average of 127 μm (about 1-15/mm^2), often containing yellowish sediments. Axial thin-walled tissue is obvious under the naked eye, mainly presenting concentric-layer para tracheal tube, aliform-confluentand fine line shapes (width of 1-4 cells). Wood rays can be seen under a magnifying glass. The ray has isomorphous, uniserial and detailed structure, with staggered texture. Using chord wise cutting in the jet test, the *Pterocarpus macarocarpus* Kurz is distributed with lots of pores, thus affecting the results of roughness measurement. Consequently, a minor deviation is understandable between the measured roughness result and that of theory.

CONCLUSIONS

The originality of this work stems from the orthogonal experiment of the cutting of mahogany wood craft using UHP water jets both with- and without-added abrasives, telling the magnitudes of impact from the governing parametric factors for the purpose of cut-surface roughness optimization. Meanwhile, water jet cutting mechanism was analyzed in depth through microscopic analysis. The main conclusions are as follows:

1. The cutting efficiency of UHP water jet is primarily governed by the factors of jet pressure, target distance and feed rate. The order of influencing factors is: Water jet pressure>feed rate>target distance. Water jet pressure has the most significant impact, followed by feed rate and target distance.
2. The best processing quality of *Pterocarpus macarocarpus* Kurz specimen with pure water cutting is achieved in following conditions: Jet pressure of 200 MPa, target distance of 3 mm, feed rate of 100 mm·s^{-1} and surface roughness of 7.08 μm. Such parameters can be used in cutting *Pterocarpus macarocarpus* Kurz crafts with thickness of 4.5 mm. Through abrasive cutting, the optimal processing quality is achieved under the conditions: jet pressure of 200 MPa, target distance of 3mm, feeding speed of 500 mm·s^{-1}, and surface roughness 6.60 μm. These parameters can be used in cutting *Pterocarpus macarocarpus* Kurz crafts with thickness of 11 mm.
3. According to observations and measurements, the 11 mm thick *Pterocarpus macarocarpus* Kurz has not been completely cut and penetrated under the condition of pure water jet. Due to low jet erosion ability, the specimen surface is mainly affected by the rebound of the jet, with large range of erosion area. Jet rebound increases the amount of fiber burr on the surface of wood, thus enhancing the overall roughness. In contrast, abrasive jet can cut completely through 11 mm thick *Pterocarpus macarocarpus* Kurz material with different sets of parameters. The abrasive greatly improves erosion force of water jet. Removal amount of the wood is increased with relatively lower surface roughness. Meanwhile, the integrity of specimen surface is decreased, with more visible processing ripples.
4. Through microscopic observation of surface quality of the specimen, the erosive action of UHP water jet cutting is based on the shearing effect of water jet impact and lateral streaming. The surface of cutting specimen has erosion areas, resulting from initial damage area, smooth area, corrugation area and jet rebound. Due to large jet kinetic energy, there is serious tearing on the upper surface and processing ripples on the bottom, affecting the overall surface roughness of the specimen. Non-penetrated wood forms rebound to further increase the burr on material surface. To improve processing quality of *Pterocarpus macarocarpus* Kurz, it is necessary to increase the range of smooth area of processing surface through process improvement.

ACKNOWLEDGEMENTS

The study was funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX17_0840) in 2017.

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