Effects of Heat Treatment on the Machining Properties of *Eucalyptus urophylla×E. camaldulensis*

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The lumber of *Eucalyptus urophylla×E. camaldulensis* was heat-treated at either 180, 190, 200, or 210 ºC for 3 h. According to the national forestry standard methods for evaluating the machining properties of lumber, the machining properties (including planing, sanding, boring, mortising, shaping, and turning) of heat-treated and untreated control samples were investigated. The results indicated that the machining properties of the lumbers were improved after heat treatment. In the machining comprehensive evaluation system (top score is 10 points), the scores of the control and heat-treated samples at 180, 190, 200, and 210 ºC were 4.74, 7.76, 8.08, 7.46, and 6.96 points, respectively. A temperature of 190 ºC was thus optimal for the comprehensive machining properties when heat-treatment was used to modify the machinability of *E. urophylla×E. camaldulensis* wood.

Keywords: Heat-treated wood; Machining properties; Planing; Shaping; Turning; Mortising; Sanding

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INTRODUCTION

Commercial natural wood has excellent physical, mechanical, and appearance properties and is highly used in markets all over the world. However, the supply of these natural wood species is declining and the prices are rapidly rising, with an imbalance between supply and demand. In this scenario, fast-growing wood is necessary to meet the demand.

Eucalyptus urophylla×E. camaldulensis, which has beautiful appearance and high strength, is one of the primary fast-growing woods in the south of China. It grows very quickly and can be used after 5 to 6 years after planting, but it is not highly value-added due to poor stability, poor machinability, and difficult drying. In recent years, much research had been performed to solve these problems. Su *et al.* (2012) studied the drying schedule for 40-mm-thick *Eucalyptus urophylla*, while Huang *et al*. (2013) studied the drying schedule for 60-mm-thick lumber of *E. urophylla×E. camaldulensis*. Liao *et al.* (2013) made a comparative study on two kinds of drying processes for 20-mm-thick lumber of *E. urophylla×E. camaldulensis* and improved its stability using heat treatment.

Heat treatment of wood is a process in which the wood is heated to temperatures in the range of 180 to 260 ºC, depending on the desired material properties (Kocaefe *et al*. 2008a). It has attracted attention in Europe and more recently in North America as an environmentally friendly method for the improvement of wood durability (Boonstra 2008; Enjily and Jones 2006; Korkut and Budak 2009; Mayes and Oksanen 2002). Thermally modified wood provides better resistance to fungi and weathering, higher dimensional stability, and lower hygroscopicity. This material is therefore suitable for outdoor and indoor areas of high humidity that do not involve high mechanical stresses (de Moura *et al*. 2011).

Over the last 50 years, many researchers in different countries have conducted studies of the heat treatment of wood and have primarily reported on chemical changes (Bekhta and Niemz 2003; Kocaefe *et al*. 2008b; Repellin and Guyonnet 2005; Tjeerdsma and Militz 2005), physical and mechanical properties (Shi *et al*. 2007; Tu *et al*. 2010; Unsal *et al*. 2003; Yildiz 2002), and decay resistance (Kamdem *et al*. 2002); however relatively little information is available on the effect of heat treatments on the machinability of wood. De Moura *et al.* (2011) investigated the planing and sanding properties of relatively low-value wood (*Eucalyptus grandis* and *Pinus caribaea* var. *hondurensis*) that had undergone a variety of thermal modification treatments (from 140 to 200 ºC). Budakçı *et al.* (2013) performed research on the determination of the surface roughness of heat-treated wood planed by the cutters of a horizontal milling machine. Though the research can provide some guidance, the data on machinability of heat-treated wood is still insufficient.

This study aimed to determine the optimal-treatment temperature that can be used to improve the machinability and value of *E. urophylla*×*E. camaldulensis* by characterizing the machining properties according to Chinese National Forestry criterion LY/T 2054-2012 (National Forestry Administration 2012).

EXPERIMENTAL

Materials

E. urophylla×*E. camaldulensis* was selected in this study due to the large amounts available in the south of China. Logs obtained from each trunk ranging from 2 to 4 m in height were sawn into boards with the dimensions of 1300 (L) × 150 (W) × 25 (T) mm. Specimens 20 mm in length were cross-cut from each board to determine the density and the average annual ring width.

The specimens selected randomly without any defects (clear, well-manufactured, and consistent with their natural structure) were heat-treated at 180, 190, 200, or 210 ºC for 3 h and sawn into boards with different dimensions based on standard LY/T 2054-2012 (National Forestry Administration 2012), as illustrated in Fig. 1. The mean oven-dried density of the specimens (control, 180 ºC, 190 ºC, 200 ºC, and 210 ºC) were 0.560 g/cm^3, 0.554 g/cm^3, 0.545 g/cm^3, 0.536 g/cm^3, and 0.530 g/cm^3, respectively. The average annual ring width was 9.1 mm.

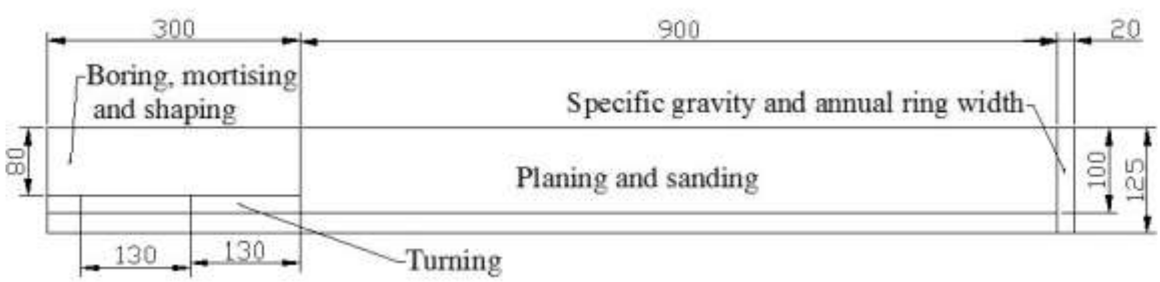

Fig. 1. Dimensions (mm) of the samples for machining tests

Methods

Heat treatment

The boards were heat-treated in an electrical resistance oven equipped with an air circulation system and a nominal chamber volume of 0.50 m^3. Each matched sample underwent a different level of heat treatment. Fifty specimens were not treated (control), while the same number of specimens in each group were treated as follows: (a) dried to 5% moisture content in the drying chamber; (b) after steam saturation in the chamber the temperature was increased at 15 ºC/h to either 180, 190, 200, or 210 ºC for 3 h; (c) cooled to 60 ºC and then removed from the chamber. The specimens were then placed in the conditioning chamber at 20 ± 2 ºC at 90 ± 5% relative humidity until they reached an equilibrium moisture content of 12%. This heat-treatment process is followed by companies to produce manufactured flooring in China (Gu *et al*. 2007). The maximum temperatures (180, 190, 200, and 210 ºC) were chosen based on previous studies (Prša *et al*. 2007; Zhou *et al*. 2013).

Evaluation of machinability

A total of 50 specimens were considered for each group for each type of machining test. Based on the amount and severity of defects present (fuzzy grain, raised grain, torn grain, chip marks, and crushing) and surface roughness, the machining quality of each individual sample was examined both visually and by touch and classified into five grades: (1) excellent (no defect), (2) good (few slight defects), (3) fair (lots of slight defects), (4) poor (serious defects), and (5) very poor (very serious defects and cannot be used anymore). Consecutive grades merge gradually without any abrupt change in quality or any sharp dividing line. Any given grade is not completely uniform in quality, but has some range between the best and the poorest examples within the grade. (National Forestry Administration 2012). The specimens from the five groups were consecutively machined with different tools to ensure consistent machining and balance the effect of the gradual dulling of knives. The knives and cutterheads used for the experiments were kept sharpened.

To compare the quality between treated and control specimens on each machining project, the integral weighted method was used as follows: 5, 4, 3, 2, 1 points were attributed to the 1st, 2nd, 3rd, 4th and 5th grade, respectively.

Similarly, the comprehensive processing performance of treated and control specimens were evaluated by the integral weighted method. The planing, sanding, shaping, and turning were given 2 points, and the mortising and boring were given 1 point. The percentages of the qualified grade were used to calculated. The qualified grade given in the standard (National Forestry Administration 2012) are listed in Table 1.

Table 1. Specimen Size for Machining Testing and Resultant Qualified Grade

Processing item	Dimensions L × W × T (mm)	Number of specimens	Qualified grade
Planing	900 × 100×20	50	1，2
Sanding	900 × 100×18	50	1，2
Boring	300 × 80×20	50	1，2
Mortising	300 × 80×20	50	1，2，3
Shaping	300 × 80×20	50	1，2
Turning	150 × 20×20	50	1，2，3

Planing test

The planing test was done using only the top spindle of the machine with three knives whose cutting angles were 30º. The machine operated at a spindle rotation of 5000 rpm. Specimens were cut with a depth of 1.6 mm and at a feed speed of 8 m/min. All the specimens were cut along the grain and run butt to butt to eliminate the occurrence of possible defects such as burn marks due to overheating of the knife edges. Specimens were graded based on the presence of fuzzy grain, raised grain, torn grain, and chip marks.

Sanding test

The sanding specimens were identical to those used in the planing test. They were sanded on a belt-type sander with two heads. The sanding sequence included a 60-grit cloth-backed aluminum oxide belt on the first head and a 120-grit cloth-backed aluminum oxide belt on the second head. The feed rate was adjusted to 5 m/min, the speed rate of the belts was 22 m/s, and the sanding depth was 0.6 mm. The quality of sanded surfaces was assessed by the presence of fuzzy grain, raised grain, and surface roughness. Roughness measurements were made with a portable stylus-contacting type roughness meter. The pick-up travel length and cut-off length were set to 15 mm and 2.5 mm. The measurements were performed at 0.5 mm/s. Roughness parameters were calculated as an average of five consecutive cut-off lengths for each pick up travel length. The roughness average ($Ra_{\perp}$) was measured across the grain according to ISO 4287-1 (1984).

Boring test

A single spindle boring machine with a rotation speed of 2800 rpm and feed speed of about 0.6 m/min was used for this test. Two holes were bored across the grain in the same specimen with a brad point bit with a diameter of 25 mm. A smooth board was set under the specimens to ensure that they were closely touching. The boring properties of different woods were evaluated based on the examination of the holes. Transverse and lateral faces of each hole were visually examined for the smoothness of cut. Surfaces were evaluated for crushing, torn grain, and fuzzy grain.

Mortising test

The specimens used for the mortising test were the same as those for the boring test. The tests were done with a drilling machine equipped with a 12.5 mm × 12.5 mm hollow chisel operating at a rotational speed of 3600 rpm. A piece of plywood was placed under each specimen to prevent damage on the outgoing side of the hollow chisel. The specimens were manually fed at 0.3 m/min. Two mortises with two sides parallel to the grain and the other two sides perpendicular to grain were cut for each specimen. Specimens were graded for the presence of torn grain or crushing inside the mortise.

Shaping test

The specimens used for the shaping test were the same as those for the boring test. The shaping test was performed on a single spindle shaper at a spindle speed of 6000 rpm. The specimens were first cut by a band saw according to the standard LY/T 2054-2012 (National Forestry Administration 2012). The specimens were fed manually at a speed of about 2.4 m/min and cut to a depth of 1.6 mm. A plywood jig was used to keep the specimens stationary during the shaping process. The rake and the back clearance angles were 10º and 20º, respectively. The specimens were graded for the presence of fuzzy grain, raised grain, torn grain, and chip marks.

Turning test

The specimens were used on a manual copy lathe equipped with a conical knife. The rotating speed and the feed speed were 3200 rpm and about 5 m/min, respectively. All the specimens were manually fed into the machine while the knife moved along the length of the rotation specimens on the template guide. Specimens were visually examined and graded for the presence of torn grain and surface roughness.

RESULTS AND DISCUSSION

Results from the machining of treated and control specimens are given in Table 2.

Table 2. Machining Properties of Treated and Control Specimens (%)

Items	Treatment	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Qualified grade
Planing	Control	0	36	58	6	0	36
	180 ºC	8	82	10	0	0	90
	190 ºC	18	72	10	0	0	90
	200 ºC	14	78	8	0	0	92
	210 ºC	14	62	24	0	0	76
Sanding	Control	0	10	80	10	0	10
	180 ºC	0	34	66	0	0	34
	190 ºC	0	40	60	0	0	40
	200 ºC	0	44	56	0	0	44
	210 ºC	0	48	54	0	0	48
Boring	Control	44	22	34	0	0	66
	180 ºC	64	36	0	0	0	100
	190 ºC	80	20	0	0	0	100
	200 ºC	58	42	0	0	0	100
	210 ºC	68	32	0	0	0	100
Mortising	Control	0	30	70	0	0	100
	180 ºC	16	58	26	0	0	100
	190 ºC	20	40	40	0	0	100
	200 ºC	14	30	50	6	0	94
	210 ºC	20	46	26	8	0	92
Shaping	Control	0	14	70	16	0	14
	180 ºC	60	18	16	6	0	78
	190 ºC	80	20	0	0	0	100
	200 ºC	74	12	8	6	0	86
	210 ºC	88	12	0	0	0	100
Turning	Control	0	14	80	6	0	94
	180 ºC	0	12	74	14	0	86
	190 ºC	0	20	54	20	6	74
	200 ºC	0	8	46	40	6	54
	210 ºC	0	0	28	40	32	28

Planing and sanding properties

In terms of planing properties, the percentage of qualified grade among the treated samples was larger (180 ºC, 90%; 190 ºC, 90%; 200 ºC, 92%; 210 ºC, 76%) than that of control samples (36%). The planing properties of *E. urophylla×E. camaldulensis* were improved after heat treatment. The highest percentage of qualified grade were for the samples treated at 200 ºC (92%), followed by the samples treated at 180 ºC and 190 ºC (90%). The points calculated by the integral weighted method for the samples (control, 180 ºC, 190 ºC, 200 ºC, and 210 ºC) were 3.30, 3.98, 4.08, 4.06, and 3.90, respectively. The best planing results were the samples treated at 190 ºC, but samples treated at 180, 200, and 210 ºC had similar results. The primary defects observed after planing were the presence of fuzzy and raised grain. The defects may be caused by feed speed, which plays an important role in processing. High feed speed can cause a poor surface, especially for hardwood (Malkoçoğlu and Özdemir 2006). It is recommended that the feed speed of planing should be slow, but capacity should also be considered.

For sanding properties, the average roughness measured across the grain ($Ra_{\perp}$) of the control and treated woods are shown in Table 3.

Table 3. Average Value of Roughness of the Control and Treated Specimens*

Treatment	$Ra_{\perp}$/µm	Standard deviation
Control	5.98	0.89
180 ºC	4.95	1.41
190 ºC	4.70	0.68
200 ºC	4.76	1.13
210 ºC	4.80	0.81

* Average of 50 specimens

The roughness ($Ra_{\perp}$) decreased after heat treatment, but it was similar in treated wood at the different temperatures. Statistically significant differences were highlighted by the ANOVA method with an F value of 28.7 compared to a 0.01% significance value of 3.4, so the treatment temperature has a significant effect on the roughness of the wood. The score calculated by the integral weighted method for the samples (control, 180 ºC, 190 ºC, 200 ºC, and 210 ºC) were 3.00, 3.34, 3.40, 3.44, and 3.54, respectively. The sanding scores increased as the maximum temperature of treatment increased. It should be noted that the qualified grade were less than 49% (control, 10%; 180 ºC, 34%; 190 ºC, 40%; 200 ºC, 44%; 210 ºC, 48%) in both the control and treated samples due to fuzzy grain.

Boring and mortising properties

In terms of the boring properties, the wood after heat treatment showed excellent performance; the percentage of qualified grade in all treated wood was 100%, while in the controls only 66%. The points calculated by the integral weighted method for the samples (control, 180 ºC, 190 ºC, 200 ºC, and 210 ºC) were 4.10, 4.64, 4.80, 4.58, and 4.68, respectively. The 190 ºC treated samples were the best. Defects typically observed for all samples were torn grain, and to a lesser extent, fuzzy grain, which generally occurred on the transverse side of the hole.

For mortising properties, the control and samples treated at 180 and 190 ºC had a higher percentage (100%) than the samples treated at 200 ºC (94%) and 210 ºC (92%); the samples treated at 190 and 210 ºC had the highest percentage (20%) in grade 1. The points calculated by the integral weighted method for the samples (control, 180 ºC, 190 ºC, 200 ºC, and 210 ºC) were 3.30, 3.90, 3.80, 3.52, and 3.78, respectively. Severely torn and crushed grain was present on the transverse face of the mortises. The quality of the surface was better than the transverse face. Therefore, mortises with no transverse grain are recommended.

Shaping and turning properties

The shaping properties of all treated samples considered have shown excellent performance with a high percentage of qualified grade (from 78% to 100%), while the control samples show a poor performance with a lower percentage (14%). The points calculated by the integral weighted method of the samples (control, 180 ºC, 190 ºC, 200 ºC, and 210 ºC) were 2.98, 4.32, 4.80, 4.54, and 4.88, respectively. It was obvious that the shaping property was greatly improved after heat treatment. Raised grain was the principal defect on end grain of the samples where the knife cut against the grain. Torn grain was present, but to a lesser extent, on the end grain of the samples.

In terms of the turning property, the best result was obtained for the control samples, with the highest proportion of 94%; the samples treated at 180 and 190 ºC had a good performance, with a proportion of 86% and 74%, respectively. The samples treated at 200 and 210 ºC showed a poor performance, with a low percentage of 54% and 28%, respectively. The points calculated by the integral weighted method of the samples (control, 180 ºC, 190 ºC, 200 ºC, and 210 ºC) were 3.08, 2.98, 2.88, 2.56, and 1.96, respectively. The tuning properties were different from other machining properties. Turning quality decreased as the maximum temperature of treatment increased; since the strength of the wood decreased as the maximum temperature of treatment increased, the treated wood was easier to rupture when rotating at a high speed. Torn grain was main defect observed after turning, generally occurring on the curved edge of the samples where the knife cut against the grain. Raised and fuzzy grain were also present, but to a lesser extent.

Comprehensive comparison of machining properties

The general marks for machining properties of control and heat-treated samples are listed in Table 4. It can be seen that the total scores improved from 4.74 to 8.08, so the machining properties of the wood were improved, except mortising and turning properties, after heat treatment. Finally, samples treated at 190 ºC showed the best machining properties. Therefore, this is the optimal temperature when modifying *E. urophylla*×*E. camaldulensis* wood.

Table 4. Summary of the Scoring Marks for Machining Properties of Control and Heat-treated Samples

Treatment	Planing	Sanding	Boring	Mortising	Shaping	Turning	Total
Control	0.72	0.20	0.66	1.00	0.28	1.88	4.74
180 ºC	1.80	0.68	1.00	1.00	1.56	1.72	7.76
190 ºC	1.80	0.80	1.00	1.00	2.00	1.48	8.08
200 ºC	1.84	0.88	1.00	0.94	1.72	1.08	7.46
210 ºC	1.52	0.96	1.00	0.92	2.00	0.56	6.96

CONCLUSIONS

1. Within the range of the temperatures studied, heat treatment had a positive effect on the machinability of samples. The heat treatment can be applied to enhance the machining properties of *E. urophylla×E. camaldulensis* wood.

2. The treatment temperature at 190 ºC was optimal to modify the machinability of *E. urophylla×E. camaldulensis* wood.

3. The sanding properties were poor in the control and treated samples. Wood of *E. urophylla×E. camaldulensis* should not be transverse when boring or mortising and should not be processed by turning following heat treatment.

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