WOOD RESEARCH doi.org/10.37763/wr.1336-4561/67.6.10321045
e-ISSN 2729-8906
67(6): 2022 1032-1045 pp.

STUDY ON MACHINING PROPERTIES AND SURFACE COATING PROPERTIES OF HEAT TREATED DENSIFIED POPLAR WOOD

AOKAI CHENG, DENGYUN TU, ZHIPENG ZHU, QIAOFANG ZHOU, WEI WEI, CHUANSHUANG HU
SOUTH CHINA AGRICULTURAL UNIVERSITY
CHINA

XIANGHAO LIU
GUANGDONG XIANGTONG SUPPLY CHAIN MANAGEMENT CO., LTD
CHINA

(RECEIVED MAY 2022)

ABSTRACT

In this study, a modification combining densification and heat treatment of poplar wood (*Populus tomentosa* Carr.) was carried out, and the machining properties of the unmodified poplar wood (control) and the heat treated densified wood (HTD) were tested and evaluated. In addition, the water-based UV paint was covered on the control and HTD respectively, and the surface coating properties of them were evaluated. The results showed that: *(1)* The machining properties of poplar wood were improved after the heat treatment-densification modification. The score of comprehensive machining properties of the HTD was 45 (excellent grade), while the score of the control was 36 (good grade). *(2)* The abrasion resistance, hydrophobicity and adhesion were improved after heat treatment-densification modification. Therefore, the modification combining densification and heat treatment played a significant role in enhancing the value of wood.

KEYWORDS: Poplar wood, densification, heat treatment, machining properties, surface coating properties.

INTRODUCTION

Poplar (*Populus tomentosa* Carr.) wood is one of the most widely distributed fast-growing species in China with several benefits including light color, straight texture and ease of processing. Nevertheless, poplar wood has a few natural defects, such as loose structure, low density, low strength and poor dimensional stability (Candan et al. 2013), and it is easy to have shrinkage deformation and veneer fluffing after processing, which restricts its application in furniture or engineering materials. Therefore, poplar wood must be modified when it is utilized in some high value-added applications. Physical modification - densification, heat treatment (Lykidis et al. 2020, Liu et al. 2018, Sandberg et al. 2013, Wang et al. 2014), chemical modification - acetylation and furfurylation (Taghiyari et al. 2017, Yang et al. 2019), and so on are some of the most common modified procedures.

The combination of densification and heat treatment for wood has been demonstrated to be a cost-effective and ecologically beneficial solution. After densification, the physical and mechanical properties of fast-growing soft wood are improved, and the material is homogeneous and easy to process (Tu et al. 2021, Sikora et al. 2021, Kariz et al. 2017). Morever, the compression recovery of densified wood can be effectively fixed by the following heat treatment. In addition, the dimensional stability, biological durability and acoustic performance may all be significantly enhanced (Cirule et al. 2021, Hill et al. 2021, Gu et al. 2019). At present, the research on densification and heat treatment mainly focuses on physical and mechanical properties. There are, however, few reports on the wood's machining and surface coating properties.

Machining properties and surface coating properties constitute the foundation for further processing and utilization of wood. Evaluation of machining properties and surface coating properties is of great significance for expanding the range of wood applications (Malkoçoğlu 2007, Tsvetkova et al. 2019). A multitude of tests and evaluations on the machining properties of wood are reported (Malkoçoğlu et al. 2006, Sofuoğlu and Kurtoğlu 2014, Zhou et al. 2021, Zhu et al. 2019), but the research is primarily focused on comparing the machining properties of different wood species, with relatively few studies on the machining properties of modified wood (Sun et al. 2020). Surface coating for wood can not only preserve the wood, but also improve the durability and stain resistance, while also serving as a vital decorative and aesthetic feature(Niu et al. 2021, Pavlič et al. 2021). Current researches include pure wood coating properties and modified wood coating properties: pure wood coating properties researches mainly focus on the effects of different tree species and different coatings on coating properties (Huang et al. 2020); modified wood coating properties researches mainly focus on heat treatment on wood coating properties (Pelosi et al. 2021, Deng et al. 2010, Li et al 2017). What appears to be undeniable is that little study has been done on the machining and surface coating properties of heat treated densified wood (HTD).

In this study, the modification combining densification and heat treatment of poplar wood was conducted, and machining and surface coating properties of heat treated densified wood were examined and assessed in comparison to unmodified poplar wood (control). The purpose of this study is to provide theoretical guidance for the effective use of poplar wood, as well as to expand the usage of heat treatment-densification combination modification. The team has conducted in-depth research on the physical and mechanical properties of HTD in the early stage and the current research is based on the prior study (Wang et al. 2021, Zhou et al. 2019, Tu et al. 2014).

MATERIAL AND METHODS

Wood material

Poplar wood sawn timber were collected from Zhoukou, Henan, with an average air-dry density of 450 ± 30 kg·m^{-3}. The size of the board is 400 mm (longitudinal) × 150 mm (radial) × 25 mm (tangential), without any visible defects. A total of 2 sets of test pieces were prepared, one was prepared for HTD, and the other was used as control. Each set of test pieces had 20 repeated plate samples. Their moisture contents were adjusted to 3-5% at 70°C in the drying oven (ZHYICO-0231, Guangdong Zhengyi Experimental Equipment Co., LTD, China).

Densification process

A hot-pressing machine (BY302X2/2150, Suzhou Xinxieli, China) was used to prepare tangentially densified poplar wood. According to the densification process given by Dengyun Tu (2014), the densified poplar wood was prepared, and the densification process parameters and schematic diagram were shown in Fig. 1a and Tab. 1.

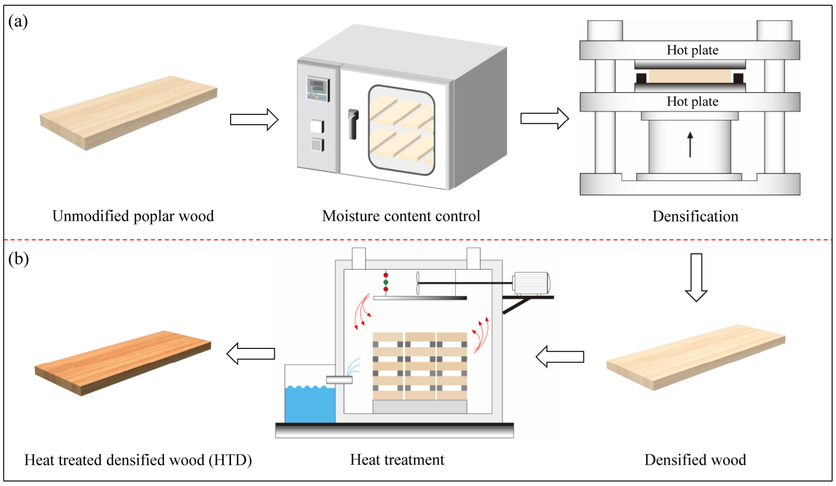

Fig. 1: Schematic diagram of densification (a) and heat treatment (b).

Tab. 1: Densification process.

Technological parameter	Parameter values
Tangential initial thickness (mm)	25
Tangential target thickness (mm)	20
Temperature of platens (°C)	180
Pressure (MPa)	1.0-2.7
Closing speed (mm·min^{-1})	3
Preheating time (s)	400
Holding time (s)	480
Cooling time (s)	900

Heat treatment process

A heat treatment tank (ZKY-JS2400, Guangzhou Energy Institute, China) was used for heat treatment of densified poplar wood. The heat treatment process included heating stage, high temperature heat treatment stage, cooling and humidity adjustment stage. According to the study by Xianju Wang (2021), under the heat treatment temperature conditions of 190°C for 3 h, the wood samples exhibited a higher storage modulus and the lowest loss factor in the colloidal phase, and the wood products had a longer service life. Therefore, the heat treatment conditions for 3 h at 190°C were used to prepare the HTD in this experiment. The specific heat treatment process was referred to Fig. 2 and the schematic diagram was shown in Fig. 1b.

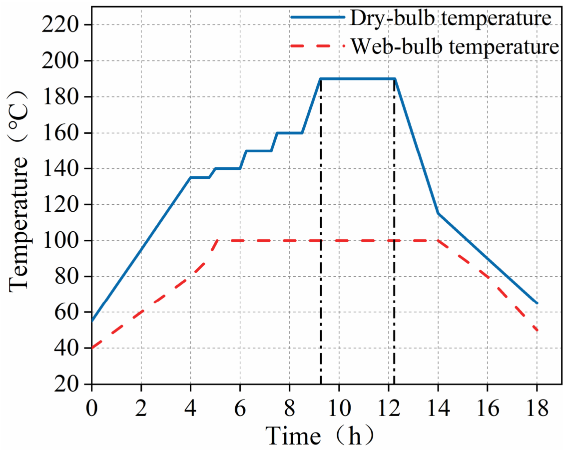

Fig. 2: Heat treatment procedure.

Vertical density profile measurements

The vertical density profile curves of the control and HTD samples were measured with an X-ray profile densitometer (DPX-300LT, IMAL, Italy), with the scanning step of 0.05 mm. The size of samples was 50 mm × 50 mm (L × T) and each sample was measured 3 times.

Micromorphology and energy dispersive spectrometer (EDS)

The scanning electron microscope (EVO 18, Carl Zeiss, Germany) was used to observe the microscopic morphology of the control and HTD. The type and content of component elements near the interface between paint film and wood were analyzed by energy dispersive spectrometer. Each sample was measured 3 times.

Machining properties measurement and evaluation method

Referring to the ASTM D1666-17 and LY/T 2054-2012, 6 main machining properties including planing, sanding, boring, mortising, shaping and turning have been tested and evaluated. The planning was prepared on a Single-sided planer (S630, SCM Company, Italy), with the speed of 5000 r·min^{-1} and the wedge angle of 30°, and the planing process was smooth texture processing. The sanding was carried out with a roller belt sander (225R-SR, Dongguan Jincheng Woodworking Machinery Co., Ltd., China), which the sanding thickness was 0.5 mm. An electric drilling machine (Z9026A, Zhongshan Machinery Factory, China) with a rotation speed of 500 r·min^{-1} was used for the boring test. The mortising equipment was a vertical single-axis tenon and groove machine (MS362, Shanghai Leban Woodworking Machinery Co., Ltd., China), and the speed was 3600 r·min^{-1}. A vertical single-axis milling machine (MX5117B, Guangdong Ma Shi Woodworking Machinery Factory, China) was adopted to shaping, and the shaping depth was 17 mm. The turning equipment was a lathe (MCL3022, Foshan Shengmu Woodworking Machinery Factory, China), and the lathe speed was 3200 $r \cdot min^{-1}$. Results of all machining properties were expressed as the percentage of Grade 1 and 2.

According to the main types and degrees of processing defects produced during processing, the processed test pieces were evaluated according to a five-grade classification method (LY/T 2054-2012): Grade 1 - excellent, 5 points; Grade 2 - good, 4 points; Grade 3 - medium, 3 points; Grade 4 - poor, 2 points; Grade 5 - very poor, 1 point. Determine the percentage of the number of test pieces of different processing performance levels, and use the weighted integral method to obtain the quality level values of different processing performances. Finally, referring to LY/T 2054-2012, a weighted integral method was used to evaluate the individual processing performance, the corresponding scores were calculated, the total scores were obtained by adding them, and the wood machining properties was comprehensively evaluated according to the scores.

Surface coating process and properties measurement

The control and HTD were coated the water-based UV paint on the surface. The surface coating properties, including the surface glossiness, surface roughness, the abrasion resistance, adhesion and hardness, were characterized by the gloss meter (KGZ-C-4, Chengdu Besta Instrument Co., Ltd., China), the roughness tester (Waveline W5, Waveline, Germany), the paint film abrasion meter (JM-IV, Shanghai Pushen Chemical Machinery Co., Ltd., China), the hundred-grid knife (SZZW-BGD-001, Zhixin Technology Co., Ltd., China), paint film hardness measuring instrument (HK-QHQ, Dongguan Huaguo Precision Technology Co., Ltd., China), in accordance to GB/T 4893.6-2013, ISO 4287:1997, GB/T 4893.8-2013, GB/T 4893.4-2013 and GB/T 6739-2006.

Water contact angle (WCA) measurement

Using a droplet shape analyzer (DSA100, Klusch, Germany), the water contact angle test was performed on the surface of the control and HTD before and after coating. The size of samples was 50 mm × 50 mm (L × T) , each group included 6 samples, and each of which was tested three times.

RESULTS AND DISCUSSION

Vertical density profile curves and micromorphology

Vertical density profile curves and SEM micrographs of the control and HTD were showed in Fig. 3. As could be seen from Fig. 3a, the density of control was uniform, with an average density of 450 $kg \cdot m^{-3}$. After modification, the density of HTD was increased to 510 $kg \cdot m^{-3}$ and was evenly distributed, which was 13.3% higher than that of the control (Fig. 3b). From the SEM micrographs of HTD, the cell was deformed, the cell wall collapsed, the cell lumen volume reduced, and also no significant cleavage of the cell walls could be observed, which were the explanation for the increased density of poplar wood.

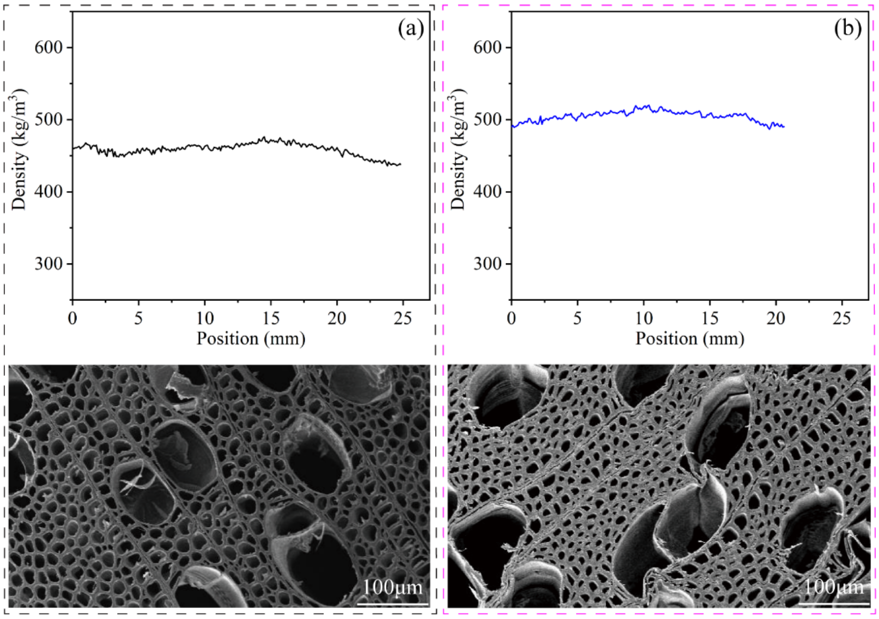

Fig. 3: Vertical density profile curves and SEM of the control (a) and HTD (b).

Machining properties

The percentages of different machining properties grades of the control and HTD were shown in Fig. 4. As could be seen from Fig. 4, the HTD showed superior attributes than the control, and the HTD's compliance rate was better than that the control's all in all. The planing, sanding, boring, mortising, and shaping performance were enhanced, and the proportion of Grade 1 were increased by 54.2%, 10%, 20%, and 21.7%, respectively. Meanwhile the Grade 1 proportion of boring performance risen to 100%. The Grade 2 ratio of the turning performance increased as well after modification. Equally, Grade 2 samples had only minor flaws after sanding, which could be removed by secondary sanding. Through the calculation of the weighted integral method, the quality grades of the planing performance of the control and HTD were 4.17 and 4.88 respectively, the quality grades of sanding performance were 4.65 and 4.75 respectively, the quality grades of boring performance were 4.80 and 5.00 respectively, the mortising performance quality grade values were 3.83 and 4.43 respectively, the shaping performance grade values were 4.20 and 4.67 respectively, and the turning performance grade values were 2.90 and 3.45 respectively. According to the relevant standards, the planing, sanding, mortising and shaping properties of the two samples were all excellent and the four machining properties were better following modification. The mortising performance of the control was good but the HTD was excellent; the turning performance of the control was medium, while the HTD had good turning performance.

The six processing defects in the machining process were depicted in Fig. 5. Overall, the HTD had fewer defects than the control. This might be because the density of poplar wood improved after modification (Fig. 3) and the compressive strength along the grain of poplar wood increased with heat treatment (Li et al. 2010).

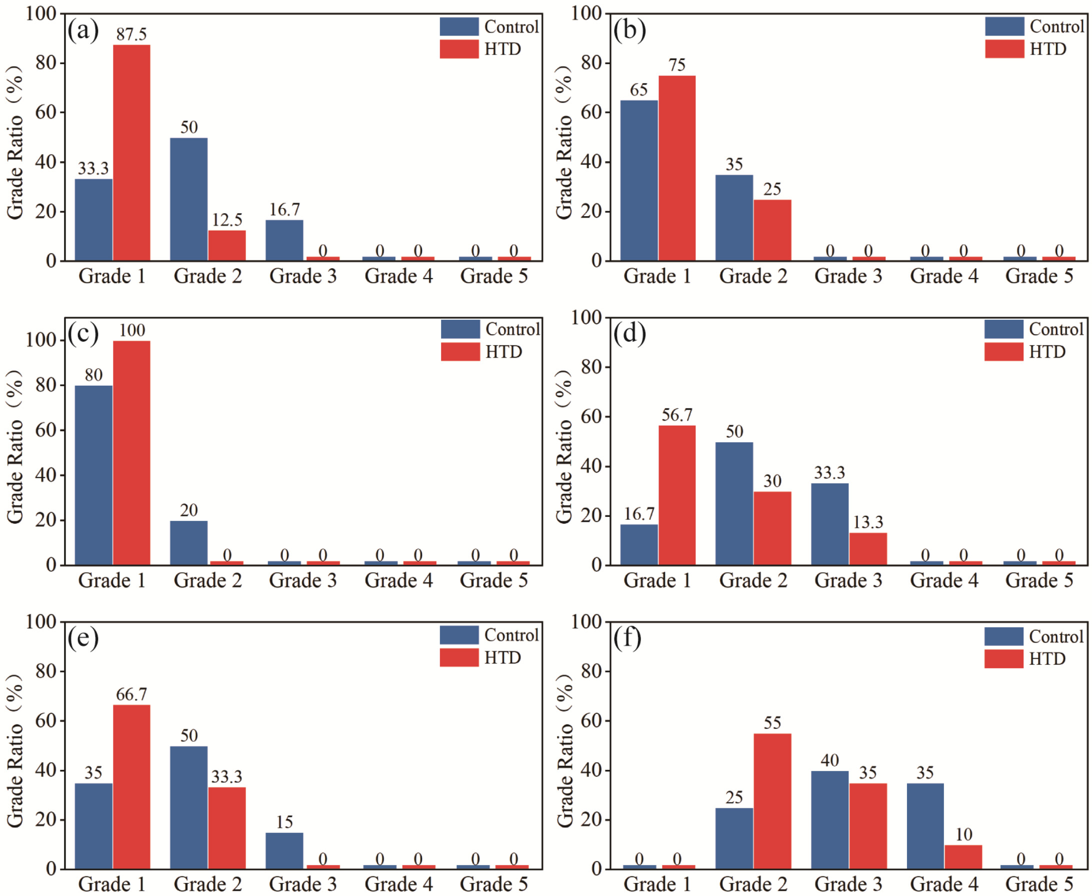

Fig. 4: Proportion of machining performance grade of the control and HTD: (a) planing performance; (b) sanding performance; (c) boring performance; (d) mortising performance; (e) shaping performance; (f) turning performance.

During the planing process, the most common surface defects of poplar wood were indentation and burr. Uneven density distribution of poplar wood and different tool pressures on the surface of poplar wood might be the cause of these defects. Burrs, groove marks and surface roughness were the most typical processing flaws during boring and mortising. Because the lower edge of the processing hole of the samples had more defects than the upper edge, it was recommended that the backing plate be applied to decrease defects such as burrs during processing. In addition, the control's inner wall was rougher than the HTD's. This might be because during the heat treatment of poplar wood, the cellulose microfibrils were aggregated due to the degradation of hemicellulose components, and some mechanical properties were improved (Gu et al. 2019). Despite the fact that the control's density and hardness were low, the surface fiber was more likely to be torn by the bit during boring and mortising. And the degree of mortising defects was more serious than that of boring, which might be caused by the rotating speed of the tenoning machine being higher than the electric drilling machine. The defects in the shaping process were mainly burrs and groove marks, the burrs were mainly located at the edge of the milling plane, and groove marks was mainly created by poplar fiber rupture during blade processing. Due to the rotation of the tool used to cut the poplar fiber, the defects in the turning process were mainly burr and groove marks. The poplar fiber's orientation was perpendicular to the saw's rotation, so it was easier to tear during processing than planing.

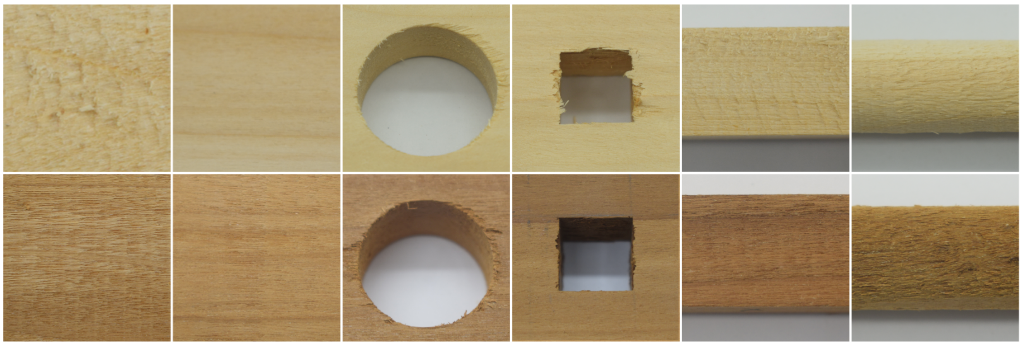

Fig. 5: Machining performance defect photos of the control and HTD.

Comprehensive analysis of machining properties of the control and HTD were displayed in Tab. 2. Based on weighted integrals, the comprehensive score of the control and HTD were 36 and 45, resp. After modification, the machining properties and the comprehensive score of machining properties was significantly improved, and the comprehensive score was excellent.

Tab. 2: Comprehensive scoring results of various machining properties of 2 kinds of poplar specimens.

Sample	Individual points (Weighted)						Total score
	Planing	Sanding	Boring	Mortising	Shaping	Turning	
Control	8	10	5	3	8	2	36
HTD	10	10	5	4	10	6	45

Surface glossiness and roughness of paint film

The capacity of wood to reflect light is measured by its surface glossiness. The surface glossiness of GZL (incident light parallel to the grain direction)and GZT (incident light perpendicular to the grain direction) was determined by the gloss meter. Due to the cell structure of the wood surface, the glossiness of the two wood surfaces in the parallel grain direction was better than the glossiness in the vertical grain direction after the water-based UV coating finished (Fig. 6a). Most of the light was refracted by the cell wall and other tissues when the incident direction of the light was parallel to the wood surface, and the reflected light dispersed less, the reflected light ability was larger, and the gloss was greater. When the direction of light incidence was perpendicular to the surface of the wood, however, portion of the light entering the cell cavity was blocked by the inner cell wall, the reflected light might be scattered more widely, and the glossiness was diminished accordingly (He et al. 2016, Zhu et al. 2021). Furthermore, the surface glossiness of the HTD was found to be lower than that of the control, implying that heat treatment could promote the decomposition of structural chemical components of the wood. The likelihood of incident light being absorbed on the wood surface raised, resulting in a reduction in glossiness.

Roughness is also an essential consideration in wood finishing (Bekhta et al. 2022). Surface roughness test was performed on the control and HTD (Fig. 6b). Ra (arithmetic average roughness) and Rz (average roughness depth) were found to diminish to a considerable level following modification, with Ra decreasing by 9.93% and Rz decreasing by 13.61%. This might be because poplar wood have a more uniform surface after densification. The degradation of materials produced by heat treatment had an influence on roughness as well.

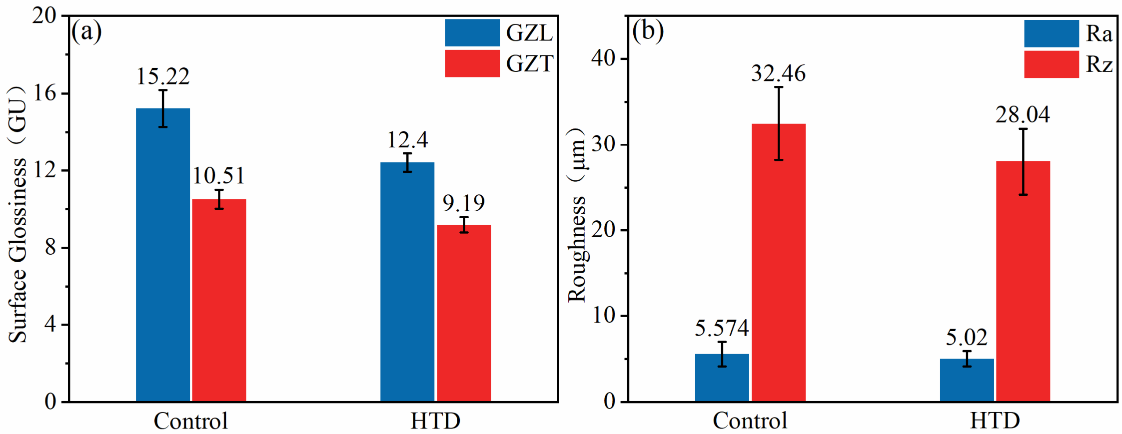

Fig. 6: Surface glossiness (a) and roughness(b) of the control and HTD after water-based UV paint coating.

Abrasion resistance, adhesion and hardness of paint film

The abrasion resistance, adhesion and hardness of the paint film could be used to evaluate the ability of the paint film surface to resist wear. As shown in the Tab. 3, the paint film hardness grades of the control and HTD were both 4H, which were classified as good. In terms of paint film adhesion, the paint film adhesion of the control was Grade 2 while the HTD was Grade 1. This might be due to the unevenness and grooves formed on the poplar surface after sanding, which could result a better connection with the coating. In addition, when compared to the control, the weight loss of the paint film of the HTD was reduced by about 20% after 500 rpm grinding by grinding wheel, and the paint film's abrasion resistance was improved. According to the analysis of the special element Si element in the water-based UV paint, the mass percentage of the Si element at the interface between the water-based UV paint and the HTD was 7.32% (Fig. 7b), while the mass percentage of the Si element at the interface with the control was 1.58% (Fig. 7a). This meant that part of the surface material of poplar wood was decomposed following heat treatment, the penetration depth of the water-based UV paint increased, and the water-based UV paint formed a stronger interface with the wood surface covalent bond.

Tab. 3: Surface abrasion resistance, adhesion and hardness of the two samples after coating with water-based UV paint.

	500 rpm paint film weight loss (g)	Adhesion (Grade)	Hardness
Control	0.1998	2	4H
HTD	0.1596	1	4H

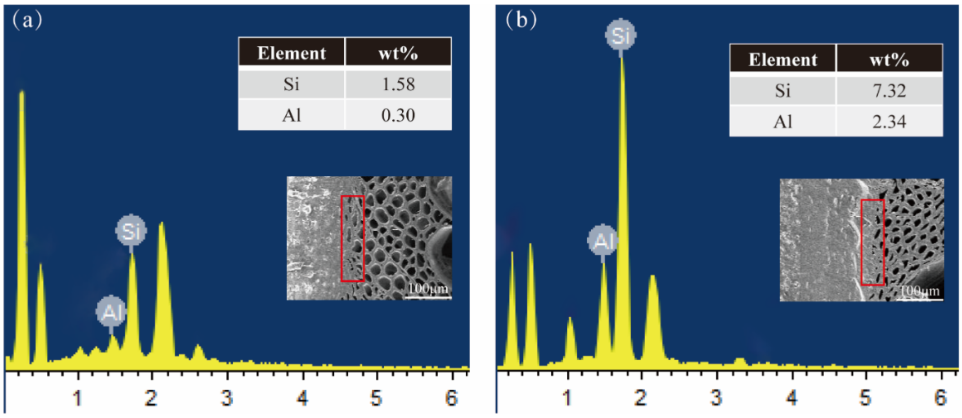

Fig. 7: The EDS spectra for the control (a) and HTD (b).

Water contact angle (WCA)

Pre- and post-coating water contact angles (WCA) between the control and HTD surfaces were measured (Fig. 8). The HTD's hydrophobicity was greatly improved when compared to the control. Without coating, the control's WCA gradually fell from 63° at 1s to 23.4° at 40 s. After 40 s, the WCA could not be determined, however the HTD's could be recorded after 120 s, which is 41.2°. The WCA between the control and HTD rose after coating, and the WCA varied minimally over time owing to the action of the paint film. Wood was a naturally hydrophilic substance, its surface was very easy to absorb water. Densification resulted in surface cell densification and pore reduction. At the same time, heat treatment reduced the concentration of hydrophilic groups (such as hydroxyl) on wood surfaces. Densification and heat treatment acted together to improve the hydrophobicity of wood surfaces.

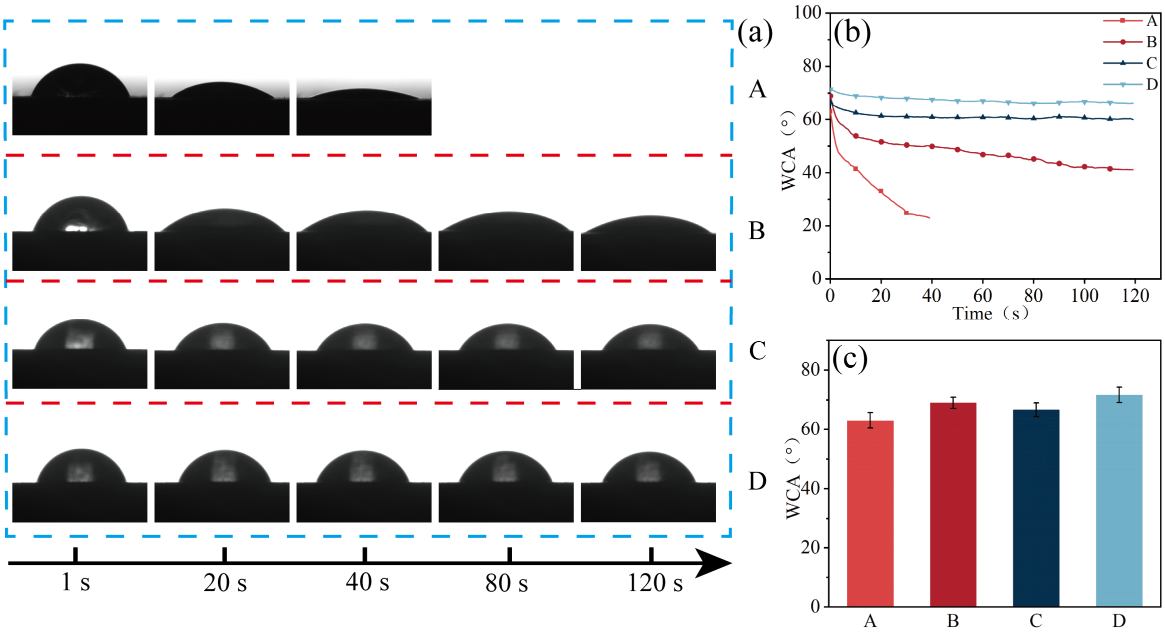

Fig. 8: Control and HTD's contact angles, (a) graphs of water droplets at different times of contact, (b) contact angle curves, (c) contact angle maxima; Where A and B are uncoated control and HTD respectively, and C and D are coated control and HTD.

CONCLUSIONS

In this work, the machining properties and surface coating properties of the HTD were studied, and the following conclusions were obtained: *(1)* The HTD was superior to the control in the fields of planing, sanding, boring, and shaping. The performance of planing, sanding, boring, and shaping were all full marks. The HTD received a 45 comprehensive score, and the comprehensive evaluation grade was excellent. While the comprehensive score of the control was 36 points, with good grade. *(2)* Compared with the control, the surface glossiness and roughness of the HTD was decreased after water-based UV paint coating, but the abrasion resistance, hydrophobicity and adhesion of the paint film were improved. *(3)* Heat treatment-densification combination modification could improve poplar's machining and surface coating properties, which is critical for improving the effective exploitation of poplar wood.

ACKNOWLEDGEMENT

This research was financially supported by the Special Funding Project for Guangdong Provincial Industrial Science and Technology Commissioners (GDKTP2021058500), the National Natural Science Foundation of China (Grant No. 31770601) and the Project of Guangdong Xiangtong Supply Chain Management Co., Ltd. (Grant No. HXKJHT20212443).

REFERENCES

1. ASTM D1666, 2017: Standard test methods for conducting machining tests of wood and wood-base panel materials.
2. Bekhta, P., Lis, B., Krystofiak, T., Bekhta, N., 2022: Surface roughness of varnished wood Pre-Treated using sanding and thermal compression. Forests 13(5): 777.
3. Candan, Z., Korkut, S., Unsal, O., 2013: Thermally compressed poplar wood (TCW): physical and mechanical properties. Drvna Industrija 64(2): 107-111.
4. Cirule, D., Sansonetti, E., Andersone, I., Kuka, E., Andersons, B., 2021: Enhancing thermally modified wood stability against discoloration. Coatings 11(1): 81.
5. Deng, S., Chen, H., Lin, J., Bian, L., 2010: Effect of high temperature heat treatment on the color and coating properties of Chinese fir plantation wood. (In Chinese). Journal of Fujian Agriculture and Forestry University (Natural Science Edition) 39(5): 484-489.
6. ISO 4287, 1997: Geometrical product specifications (GPS) - surface texture: profile method – terms, definitions and surface texture parameters.
7. GB/T 4893.4, 2013: Test of surface coatings of furniture. Part 4. Determination of adhesion. Cross cut.
8. GB/T 4893.6, 2013: Test of surface coatings of furniture. Part 6. Determination of gloss value.
9. GB/T 4893.8, 2013: Test of surface coatings of furniture. Part 8. Determination of wearability.
10. GB/T 6739, 2006: Paints and varnishes. Determination of film hardness by pencil test.

11. Gu, L., Ding, T., Jiang, N., 2019: Development of wood heat treatment research and industrialization. (In Chinese). Journal of Forestry Engineering 4(4): 1-11.
12. He, T., Luo, J., 2016: Study on the color and luster of twenty species of rosewood. (In Chinese). Journal of Forestry Engineering 1(2): 44-48.
13. Hill C., Altgen M., Rautkari L., 2021: Thermal modification of wood - a review: Chemical changes and hygroscopicity. Journal of materials science 56(11): 6581-6614.
14. Huang, Q., Huang, Y., Zhang, W., Lin, X., Wang, X., 2020: Film properties of waterborne paint based on *Fraxinus mandshurica* substrate. (In Chinese). Journal of Beijing Forestry University 42(7): 140-146.
15. Kariz, M., Kuzman, M.K., Sernek, M., Hughes, M., Rautkari, L., Kutnar, F.A., Kamke, A., 2017: Influence of temperature of thermal treatment on surface densification of spruce. European Journal of Wood and Wood Products 75(1): 113-123.
16. Li, F., Yan, Y., Gu, X., Guo, M., Sun, W., 2017: Coating properties of high temperature heat-treated larch and bending strength of high temperature heat-treated larch after coating. (In Chinese). Journal of Northeast Forestry University 45(10): 49-52.
17. Li, Y., Tang, R., Bao, B., Sun, H., 2010: Mechanical properties and dimensional stability of heat-treated Chinese fir. (In Chinese). Journal of Beijing Forestry University 32(4): 232-236.
18. Liu, H., Shang, J., Kamke, F., Guo, K., 2018: Bonding performance and mechanism of thermal-hydro-mechanical modified veneer. Wood Science and Technology 52(2): 343-363.
19. Lykidis, C., Moya, R., Tenorio, C., 2020: The effect of melamine formaldehyde impregnation and hot-pressing parameters on the density profile of densified poplar wood. European Journal of Wood and Wood Products 78(3): 433-440.
20. LY/T 2054, 2012: Methods for evaluating machining properties of lumber.
21. Malkoçoğlu, A., Özdemir, T., 2006: The machining properties of some hardwoods and softwoods naturally grown in Eastern Black Sea Region of Turkey. Journal of Materials Processing Technology 173(3): 315-320.
22. Malkoçoğlu, A., 2007: Machining properties and surface roughness of various wood species planed in different conditions. Building and Environment 42(7): 2562-2567.
23. Niu, K., Song, K., 2021: Surface coating and interfacial properties of hot-waxed wood using modified polyethylene wax. Progress in Organic Coatings 150: 105947.
24. Pavlič, M., Petrič, M., Žigon, J., 2021: Interactions of coating and wood flooring surface system properties. Coatings 11(1): 91.
25. Pelosi, C., Rubino, G., Capobianco, G., Lanteri, L., Agresti, G., Bonifazi, G., Serranti, S., Picchio, R., Lo Monaco, A., 2021: A multi-technique approach to evaluate the surface properties of heat-treated chestnut wood finished with a water-based coating. Coatings 11(6): 706.
26. Sandberg, D., Haller, P., Navi, P., 2013: Thermo-hydro and thermo-hydro-mechanical wood processing: An opportunity for future environmentally friendly wood products. Wood Material Science and Engineering 8(1): 64-68.
27. Sikora, A., Gaff, M., Sethy, A.K., Horáček, P., Fantuzzi, N., 2021: Bending work of laminated materials based on densified wood and reinforcing components. Composite Structures 274: 114319.

28. Sofuoğlu, S.D., Kurtoğlu, A., 2014: Some machining properties of 4 wood species grown in Turkey. Turkish Journal of Agriculture and Forestry 38: 420-427.
29. Sun, Z., Wang, H., Yang, L., Yuan, H., Yu, S., 2020: Study on machining properties of resin impregnation reinforcement modified wood for poplar and radiata pine. (In Chinese). China Forest Products Industry 57(03): 41-46.
30. Taghiyari, H.R., Rassam, G., Ahmadi-DavazdahEmam, K., 2017: Effects of densification on untreated and nano-aluminum-oxide impregnated poplar wood. Journal of Forestry Research 28(2): 403-410.
31. Tu, D., Chen, C., Zhou, Q., Ou, R., Wang, X., 2021: Research progress of thermo-mechanical compression techniques for wood products. (In Chinese). Journal of Forestry Engineering 6(1): 13-20.
32. Tu, D., Su, X., Zhang, T., Fan, W., Zhou, Q., 2014: Thermo-mechanical densification of *Populus tomentosa var. tomentosa* with low moisture content. Bioresources 9(3): 3846-3856.
33. Tsvetkova, I.N., Krasilnikova, L.N., Khoroshavina, Y.V., Galushko, A.S., Yu, Frantsuzova, Y.V., Kychkin, A.K., Shilova, O.A., 2019: Sol-gel preparation of protective and decorative coatings on wood. Journal of Sol-Gel Science and Technology 92(2): 474-483.
34. Wang, X., Deng, Y., Wang, S., Min, C., Meng, Y., Pham, T., Ying, Y., 2014: Evaluation of the effects of compression combined with heat treatment by nanoindentation (NI) of poplar cell walls. Holzforschung 68(2): 167-173.
35. Wang, X., Tu, D., Chen, C., Zhou, Q., Huang, H., Zheng, Z., Zhu, Z., 2021: A thermal modification technique combining bulk densification and heat treatment for poplar wood with low moisture content. Construction and Building Materials 291: 123395.
36. Yang, T., Ma, E., Cao, J., 2019: Synergistic effects of partial hemicellulose removal and furfurylation on improving the dimensional stability of poplar wood tested under dynamic condition. Industrial Crops and Products 139: 111550.
37. Zhou, F., Gao, X., Fu, Z., Zhou, Y., 2021: Evaluation of machining performance of *Acacia melanoxylon* and *Michelia macclurei* wood. (In Chinese). Chinese Journal of Wood Science and Technology 35(5): 7-11.
38. Zhu, Z., Zhong, K., Chen, C., Tu, D., Hu, C., Yin, G., 2019: Effect of tree age on the machining properties of *Mytilaria laosensis*. (In Chinese). Journal of Southwest Forestry University (Natural Science Edition) 39(1): 184-188.
39. Zhou, Q., Chen, C., Zhao, X., Tu, D., Li, K., 2019: The effect of thermal modification by hot pressing on the some physical and mechanical properties in rubberwood (*HeveaBrasiliensis*). Wood Research 64(2): 361-372.
40. Zhu, Z., Tu, D., Chen, Z., Chen, C., Zhou, Q., 2021: Effect of hot pressing modification on surface properties of rubberwood. Wood Research 66(1): 129-140.

AOKAI CHENG, DENGYUN TU*, ZHIPENG ZHU, QIANGFANG ZHOU, WEI WEI,
CHUANSHUANG HU
SOUTH CHINA AGRICULTURAL UNIVERSITY
COLLEGE OF MATERIALS AND ENERGY
GUANGZHOU
CHINA
*Corresponding author: tudengyun@scau.edu.cn

XIANGHAO LIU
GUANGDONG XIANGTONG SUPPLY CHAIN MANAGEMENT CO., LTD
DONGGUAN
CHINA