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Plasma Treatments to Improve the Bonding of Thermo-Treated Cherry Wood

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Abstract: Thermal treatment can significantly improve the dimensional stability of wood, but it will decrease the bonding strength. In this work, the bonding strength of thermo-treated cherry wood boards was improved by plasma treatment. The change of wettability, surface morphology, and surface chemical property of cherry wood before and after plasma treatment was investigated by water contact angle measurement, Scanning Electron Microscopy (SEM), Atomic Force Microscopy (AFM), and X-ray photoelectron spectroscopy (XPS). The plasma treatment significantly improved the wettability of thermo-treated cherry wood by decreasing its water contact angle from 109.95° to 53.18°. N₂ or O₂ was used as the plasma atmosphere, and it was found that N₂ plasma treatment afforded cherry wood a rougher surface. The AFM roughness of cherry wood was increased from 19 nm to 31.9 nm after N₂ plasma treatment. XPS results revealed an additional C–N group for N₂ plasma treatment and the content of C=O, O–C–O, and O–C=O increased for O₂ plasma treatment, respectively, indicating that the surface chemical property of cherry wood was modified. Due to the surface character, the bonding strength increased by 21.17% for N₂ plasma treatment and 15.32% for O₂ plasma treatment.

Keywords: thermal treatment; plasma treatment; cherry wood; bonding strength; surface chemical property

1. Introduction

Wood is a renewable, wide spread, low cost, environmental enhancing resource with great potential to improve economic development. On the one hand, wood can be used as structural material due to its high strength. On the other hand, it can be used as furniture and decoration material because of its multitude of colors, grains, and fragrance. Although there are so many advantages of wood, the polar groups in the surface of wood result in it having a hydrophilic surface. Additionally, the dimensional stability and durability of wood have to be addressed [1]. To make the wood more hydrophobic, chemicals such as silanes, oils, silicones, resin, and waxes have been used and applied to solid wood and wood-based materials, such as fiberboard and particleboard, to reduce their water absorption and improve their dimensional stability [2–6].

Thermal treatment has been considered as an environmentally friendly and efficient method for improving the dimensional stability of wood in recent years [7–9]. These beneficial changes are due to chemical changes in the cell wall polymers and the loss of hydroxyl groups leads to increased hydrophobicity, reduced surface wettability, and reduced water absorption. However, these alterations adversely affect the adhesion or penetration of water-based adhesives, finishes, or modification agents and make further processing more difficult [10–12].

Plasma treatment is considered to be a promising technology for rapidly modifying the surface of materials due to its solvent-free, well-controlled, and short processing cycle [13,14]. Cold plasma treatments can cause physical and chemical changes to depths of several microns, without changing the volume. In recent years, plasma modification technology has been applied to the surface modification of wood and wood-based materials in order to enhance the surface properties of the wood component and mechanical strength of the wood-based materials [15–17]. Plasma treatment can result in the formation of free radicals and active sites in the poplar wood surface [18].

In this paper, the cherry wood employed for cabinets is selected as a raw material. This wood was thermo-treated at 160 °C for 3 h. Then, the effect of plasma treatment with different gas atmospheres on wood surface properties was tested. The thermal treatment temperature was 160 °C, which falls in the lower range of commonly used treatment temperatures, while the treatment time was short and the strength loss of wood was small. However, this not only improved the dimensional stability of the wood, but also improved the adhesion of the Poly (vinyl acetate) film. In this study, the wettability, surface morphology, and surface chemical properties of cherry wood before and after plasma treatment were analyzed and discussed to some extent. Thereby, this research can provide a good reference for wood in the field of plasma modification. Furthermore, this research has great potential to be applied to all wood products.

2. Materials and Methods

2.1. Materials

Cherry wood, *Prunus serotina*, Ehrh., with dimensions of $210 \times 25 \times 10 \text{ mm}^3$, was obtained from Xiamen Golden Kitchen Cabinet Co., Ltd. (Xiamen, China). Cherry wood was thermo-treated at 160 °C for 3 h, making sure that there was enough water in this process. Cherry wood used for surface wettability was first thermo-treated, and then cut into $100 \times 18 \times 10 \text{ mm}^3$ pieces. However, cherry wood used for the bonding strength test was cut into $30 \times 25 \times 5 \text{ mm}^3$ pieces (according to GB/T 17517-1998 [19]) and this wood included thermo-treated and non-thermo-treated samples.

2.2. Wettability

The contact angle of the treated specimens was determined using a contact angle meter (HARKE-SPCA-1, Beijing, China), in order to evaluate the wettability of the specimen surfaces. Four points were measured for each group and the average value was then calculated. The static sessile drop method used distilled water as test liquid and a drop size of 3 μL . The test interval time was selected for 1 h, 3 h, 6 h, 9 h, 12 h, 1 d, 2 d, 3 d, 4 d, 5 d, 6 d, 7 d, and 8 d to record the time. Additionally, the gases used as plasma atmosphere were nitrogen and oxygen (Fuzhou Huaxinda Industrial Gas Co., Ltd., Fuzhou, China), and their purity was 99.99%. The plasma treatment device was the OSKUN-PR60L Plasma processor (Shenzhen OKSUN technology Co., Ltd. Shenzhen, China). The plasma treatment power was 100 W, the treatment time was 30 s, and the gas pressure was 40 Pa.

2.3. Surface Morphology

The surface morphologies of plasma-treated and untreated wood were tested using scanning electron microscopy (SEM Z500, ZEISS, Oberkochen, Germany) and atomic force microscopy (AFM). Before the scanning process, the specimen surfaces were gold-coated to enhance the electron conductivity. The plasma treatment parameters were set as 100 W, 30 s, and 40 Pa.

2.4. X-ray Photoelectron Spectroscopy (XPS)

Surface characterization of wood was performed with ESCALAB 250 (Thermo Fisher Scientific, Waltham, MA, USA). Spectra were recorded using a monochromatic Al $K\alpha$ radiation source. X-ray photoelectron spectroscopy (XPS) survey spectra were collected in constant analyzer energy (CAE) mode with a pass energy of 150 eV for elemental quantification purposes and the spot size was 400 μm .

2.5. Bonding Strength

The bonding strength was determined by a CMT-6104 microcomputer-controlled electronic universal testing machine (Shenzhen new thought measurement technology Co., Ltd., Shenzhen, China), according to GB/T 17517-1998 (Adhesives—Wood to wood adhesive bonds—Determination of shear strength by compression loading) [19]. The Poly (vinyl acetate) adhesive was applied on the longitudinal tangential surface with approximately 150 g/m² after the 6 h plasma treatment. The pressure was set as 2 MPa and lasted for 14 h. The specimens were tested after the pressure was removed for at least 24 h. The bonding strength test included 30 specimens. Five specimens were tested for every group and the average value was then calculated. Furthermore, the test temperature was room temperature.

3. Results and Discussion

3.1. Wettability of Cherry Wood

Wettability is very important for the spreading of adhesive on a wood surface, which can be represented by the water contact angle. Figure 1 reveals the change in water contact angle of cherry wood as a function of test time after being treated by plasma. The data results were processed by SPSS 22.0 statistical software. Significant differences were investigated by ANOVA and an least-significant difference (LSD) test as a post-hoc test, and the significance was set at $p < 0.05$. In particular, the difference in wettability between non-treated and nitrogen-plasma treated wood after 1 h was investigated ($p = 0.000$). As can be seen from Figure 1, the water contact angle without plasma treatment was 109.95°. After 1 h of nitrogen plasma treatment, the contact angle was reduced to 23.4°, which was 78.72% lower than that of the untreated sample. At the same time, the contact angle of oxygen plasma treatment was 64.66° and it decreased by 41.19%. Obviously, the water contact angle after nitrogen plasma treatment exhibited a greater difference. The contact angle of untreated wood represented the contact angle of wood without plasma treatment. After 4 d, it made a clear difference, and even after 8 d, the water contact angle of nitrogen plasma treatment was 53.18° and still decreased by 51.63%, but the water contact angle of oxygen plasma treatment was 101.35 and only decreased by 7.82%. This shows that the water contact angle treated with nitrogen plasma is still better than that treated with oxygen after 8 d. At the same time, the contact angle of the cherry wood increased with time, indicating that the effect of plasma treatment gradually fades away. All the specimens displayed a lower contact angle after plasma treatment within one day, which explained why plasma treatment had a significant effect on the wetting properties of thermo-treated wood specimens.

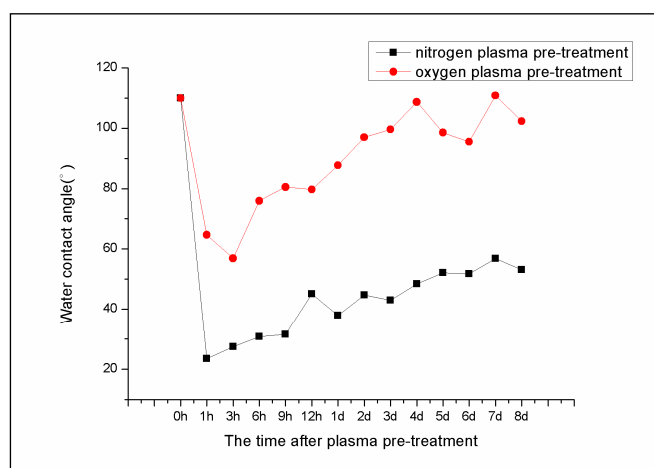


Figure 1. Contact angle of treated nitrogen plasma and treated oxygen plasma.

The contact angle of wood specimens treated by nitrogen was lower than that treated by oxygen, which was different from the results presented in a previous study [20]. Oxygen plasma has been previously used to improve the surface properties of wood. Oxygen plasma-treated wood specimens have been reported to exhibit higher surface polarity due to the formation of hydroxyl, carboxyl, aldehyde, and other polar functional groups [21–24]. Contact angles on such complex materials such as wood show dependencies on various parameters and include quite diverse effects. One major factor determining the wetting behavior and contact angles are the morphology and surface structures. Our findings demonstrated that the morphology roughness is greatly improved and the polarity is also increased due to changes in chemical groups after oxygen and nitrogen plasma treatments. Therefore, such treatment also has an important effect on the water contact angles. These groups were hydrophilic, so they were useful for improving the wetting property. However, the lower contact angle treated by nitrogen than by oxygen in this study may have resulted from the groups containing nitrogen atoms, which contributed more to the reduction of the contact angle. It is suggested that enhanced wettability through plasma treatment is due to the polar part of the surface free energy. The high effectiveness of plasma treatment on thermo-treated wood might thus be explained by its relatively high proportion of lignin. The changes in the contact angle due to the plasma treatment are more pronounced on thermo-treated wood [23].

3.2. Change in the Chemical Property

The chemical surface composition was also evaluated by X-ray photoelectron spectroscopy. The effects initiated by plasma treatment could be experimentally verified by XPS analysis.

XPS was used to reveal the surface changes in chemical elements and functional groups after plasma treatment. Figure 2 is an XPS full spectrum of untreated, nitrogen plasma-treated, and oxygen plasma-treated wood. Figure 3 presents a general survey of the surface chemical compositions of plasma-treated wood.

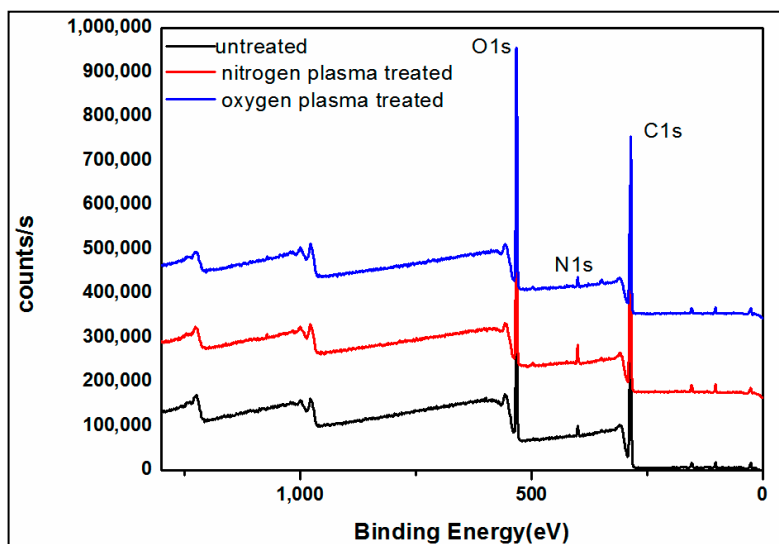


Figure 2. XPS full spectrum of untreated, nitrogen plasma-treated, and oxygen plasma-treated wood.

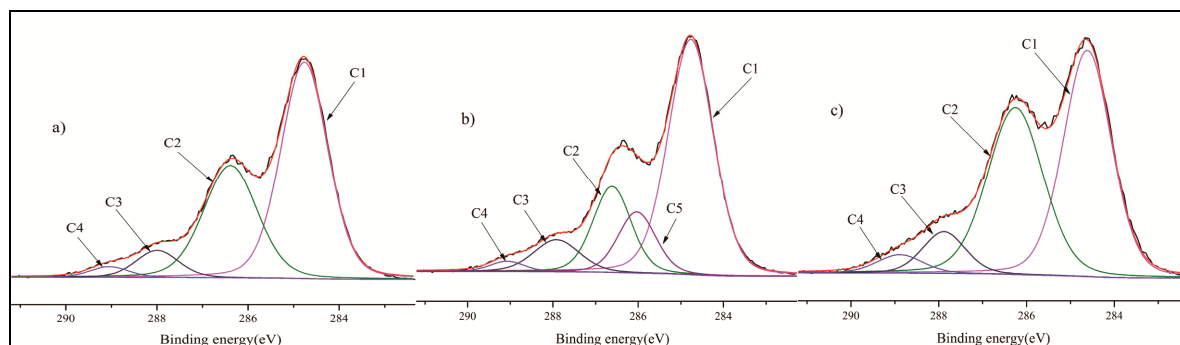


Figure 3. X-ray photoelectron spectroscopy (XPS) of thermo-treated cherry wood: (a) untreated, (b) nitrogen plasma treated and (c) oxygen plasma treated.

The C1 peak represents C–C and C–H bonds, which mainly exist in lignin and extractives; the C2 peak is assigned to C–O, which is mainly found in hydroxyl and other groups of lignin and polysaccharides; the C3 peak corresponds to O–C–O or C=O, which is found in cellulose, hemicelluloses and lignin; and the C4 peak is assigned to O=C–O, and is present in hemicelluloses [25].

The nitrogen element content and oxygen element content were both increased after plasma treatment, which was closely related to the decline of the C1 peak content (Table 1 and Table S1).

Table 1. Contribution of functional groups (%) on the surface of cherry wood.

Plasma Treatment	Element Concentration (%)			O/C Ratio	Content				
-	C	O	N	-	C–C/C–H	C–O	C=O/O–C–O	O–C=O	C–N
ref	72.58	25.62	1.8	0.35	57.33%	33.95%	6.43%	2.29%	-
nitrogen	69.49	27.24	3.27	0.39	59.05%	18.15%	8.12%	1.93%	12.75%
oxygen	66.86	31.26	1.89	0.47	47.87%	40.76%	7.74%	3.63%	-

For nitrogen plasma treatment, there was a new peak, C5. The appearance of the C5 peak improved the content of C–N, which was 12.75%. After nitrogen plasma treatment, the N concentration increased from 1.8% to 3.27%. This increase can enhance the wettability of a wood surface. For cherry wood, it increased a little, which was the opposite result. This observation could be explained by its internal structure, because the effects of different wood species were different.

Plasma treatment can lead to the generation of free radicals, and it can react with active sites on the surface of treated specimens, thus resulting in the stable incorporation of oxygen-containing groups [26]. Free radicals created by low-pressure gas plasma may have four major effects on surfaces. Each is always present to some degree; however, one effect may be favored over another, depending on the substrate chemistry, reactor design, gas chemistry, and processing conditions. The effects are the cleaning of organic contamination from the surfaces, material removal by ablation (micro-etching) to increase the surface area or to remove a weak boundary layer, crosslinking or branching to cohesively strengthen the surface, and surface chemistry to improve chemical physical interactions at the bonding interphase [27].

3.3. Surface Morphology

Evidently, after plasma treatment, especially after nitrogen plasma treatment, many small holes appeared on the surface and became rough, but the surface of the untreated wood specimen had a few small holes (Figure 4a). After plasma treatment, the holes were bigger. This may have been caused by plasma, because plasma can make the surface rougher (Figure 4b). The nitrogen plasma-treated cherry wood specimens had more grooves and tiny grains than the oxygen plasma-treated samples due to the higher etching tendency of the nitrogen plasma. It may be revealed by the observation that the

nitrogen plasma was more invasive than the oxygen plasma, and this result is in accordance with the XPS result.

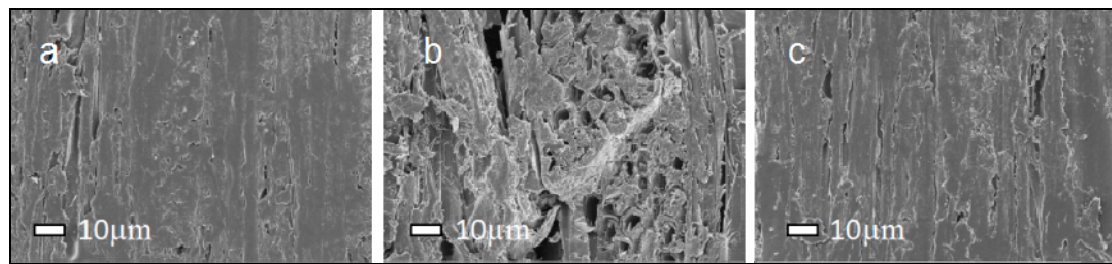


Figure 4. Scanning Electron Microscopy (SEM) images of thermo-treated cherry wood: (a) untreated, (b) nitrogen plasma treated, and (c) oxygen plasma treated.

In Figure 5, atomic force microscopic (AFM) images of untreated and plasma-treated specimens revealed differences in the surface topography, demonstrating the same result as that obtained with SEM. AFM images of the untreated cherry wood surface seem to exhibit particles, which can be assigned to amorphous hemicelluloses and extractives in the wood surface. The surface roughness increased after the plasma treatment, which is reflected in the figure of R_q (root mean square deviation). Additionally, evidently, the surface treated by nitrogen plasma looks rougher in the images, which may be associated with the second cell wall. The second cell wall is etched or degraded, leading to the exposure of the S2 layer [28]. The rougher surface is beneficial for bonding, because it can provide better interface bonding between the wood surface and the adhesive.

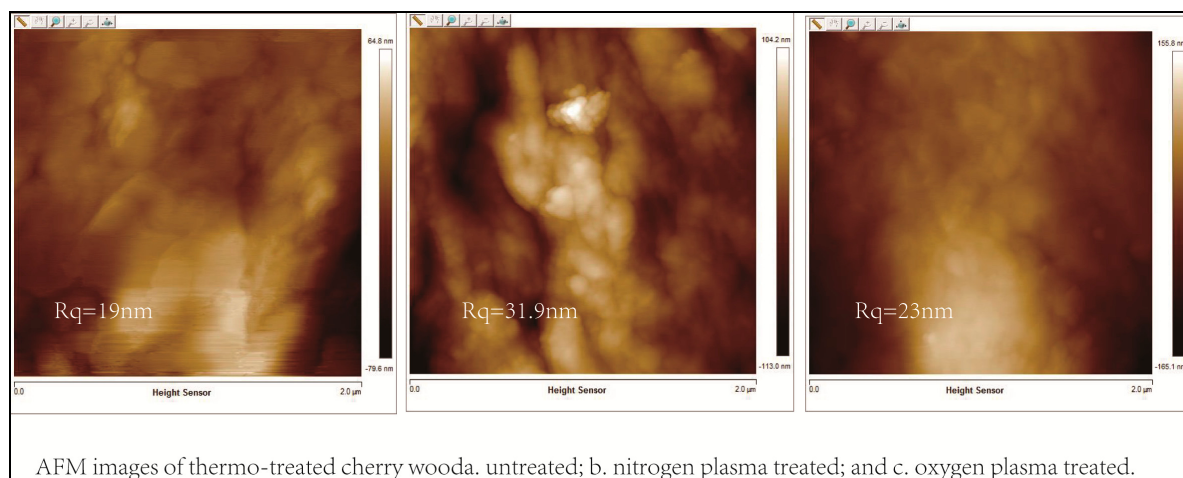


Figure 5. Atomic force microscopic (AFM) images of thermo-treated cherry wood: (a) untreated, (b) nitrogen plasma treated, and (c) oxygen plasma treated.

3.4. Bonding Strength

Figure 6 shows the influence of plasma treatment on the bonding of thermo-treated and non-thermo-treated wood. We selected 30 specimens to test the bonding strength; five specimens were tested for every group and we then took the average value. In the experiment, the wood breakdown rate of the specimens was relatively low, and most of the bonding surface of the specimens did not appear to display a fracture phenomenon. Almost all of them were affected by the bonding strength, so the issue of fiber release was not considered. In the absence of plasma treatment, the bonding strength of thermo-treated wood was 5.81 MPa, while the non-thermo-treated had a bonding strength of 6.34 MPa and decreased by 6.36%. This may be related to extractives in the wood. Extractives are common and important sources of surface contamination which are harmful to wood adhesion [29]. Bonding is adversely affected by the degree of wood surface contamination. The deposition of extractives on

the surface may reduce the adhesive bond strength in many ways. A high extractives concentration on the surface increases the possibility of contaminating and reducing the cohesive strength of the adhesive. Extractives may block reaction sites on wood surfaces and prevent adequate wetting by the adhesive [16]. Wood surface characteristics, e.g., wettability and bonding ability, benefit from the degradation and removal of extractives by removing the weak boundary layer and revealing wood's main components [30]. Thermal treatment can lead to a significant decrease of the O/C ratio, and this results from hemicellulose degradation. At the same time, the amount of hydrophilic hydroxyl reduces after thermal treatment. Furthermore, the binding ability is weakened and the binding property is decreased. As is well-known, the hydrophilic hydroxyl is essential for the bonding strength [12].

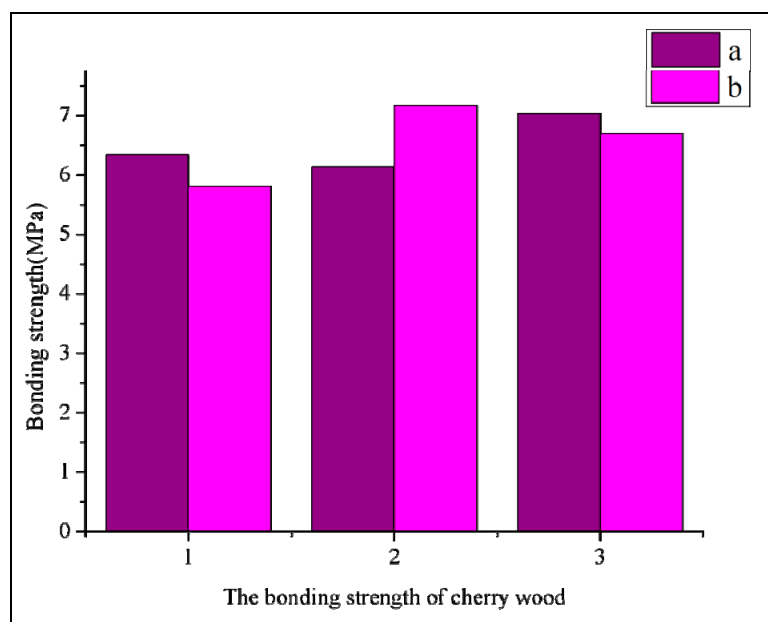


Figure 6. Bonding of thermo-treated cherry wood: (a) non-thermo-treated and (b) thermo-treated. 1: non-treated, 2: nitrogen plasma treated, and 3: oxygen plasma treated.

The bonding increased to different extents with oxygen plasma treatment in comparison with the control specimens. For the non-thermo-treated specimens, the bonding strength after nitrogen plasma treatment and without nitrogen plasma treatment was 6.34 MPa and 6.13 MPa, respectively. There was not much difference in their bonding strength. After thermal treatment, the bonding strength of specimens without nitrogen plasma treatment was 5.81 MPa, while that for specimens treated with nitrogen enhanced to 7.17 MPa, which was 23.41% higher than that without nitrogen treatment. For the non-thermo-treated specimens, the bonding strength after oxygen plasma treatment was increased by 11.04% compared with that without treatment, and the bonding after thermal treatment was increased by 13.28%. For the thermo-treated specimens, a significant difference of oxygen plasma treatment was not obvious, while differences were investigated by ANOVA and an LSD test as a post-hoc test, and the significance of nitrogen plasma treatment was set at $p < 0.05$. This indicated that there was a significant difference between nitrogen plasma treatment and non-treatment. Peculiarly, the bonding strength after thermal treatment was significantly increased ($p < 0.05$) compared with that for non-thermal treatment for the nitrogen plasma-treated specimens. It can be seen that nitrogen treatment can achieve better results. Some wood species had an increased adhesion property after plasma treatment, which was the result of the improved adhesive bonding quality [31]. This may also be associated with the functional groups introduced to the surface. After oxygen plasma treatment, the O/C was higher and there were more oxygen-containing groups in the surface, which was helpful for the adhesive to improve the bonding property.

4. Conclusions

1. The contact angle of thermo-treated cherry wood significantly decreased after plasma treatment, and the result of nitrogen plasma was better than that of oxygen, indicating that nitrogen plasma treatment is more helpful for improving the wettability of wood surfaces.
2. The morphological characteristics of wood are associated with the type of gas, but when they are plasma treated, all the wood surfaces are rougher than before treatment, explaining that plasma can etch the surface of wood and is beneficial for enhancing the bonding property.
3. The XPS showed that plasma treatment can introduce functional groups, leading to an enhancement of the wettability and bonding property, especially the oxidization on the surface. Besides, nitrogen plasma treatment can introduce C–N and make important contributions.
4. The thermo-treated cherry wood, when plasma treated, resulted in an increased bonding strength, which shows that plasma treatment can enhance the bonding of thermo-treated wood.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2079-6412/9/10/656/s1>, Table S1: Binding energies and peak width of XPS.

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Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Avramidis, G.; Militz, H.; Avar, I.; Viöl, W.; Wolkenhauer, A. Improved absorption characteristics of thermally modified beech veneer produced by plasma treatment. *Eur. J. Wood Wood Prod.* **2012**, *70*, 545–549. [\[CrossRef\]](#)
2. Mai, C.; Militz, H. Modification of wood with silicon compounds. Inorganic silicon compounds and sol-gel systems: A review. *Wood Sci. Technol.* **2014**, *37*, 339–348. [\[CrossRef\]](#)
3. Donath, S.; Militz, H.; Mai, C. Creating water-repellent effects on wood by treatment with silanes. *Holzforschung* **2006**, *60*, 40–46. [\[CrossRef\]](#)
4. Donath, S.; Militz, H.; Mai, C. Weathering of silane treated wood. *Holz Als Roh-Und Werkst.* **2007**, *65*, 35. [\[CrossRef\]](#)
5. Militz, H.; Mai, C.; Ghosh, S.C. Combined effect of hydrophobation and durability improvement of wood treated with silicone emulsions. In Proceedings of the Cost action E37 Final Conference in Bordeaux: Socio-economic Perspectives of Treated Wood for the Common European Market, Bordeaux, France, 28–30 September 2008.
6. Banks, W.B. Water uptake by scots pine sapwood, and its restriction by the use of water repellents. *Wood Sci. Technol.* **1973**, *7*, 271–284. [\[CrossRef\]](#)
7. Tjeerdsma, B.F.; Militz, H. Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood. *Holz Als Roh-Und Werkst.* **2005**, *63*, 102–111. [\[CrossRef\]](#)
8. Boonstra, M.J.; Rijdsdijk, J.F.; Sander, C.; Kegel, E.; Tjeerdsma, B.; Militz, H.; Stevens, M. Microstructural and physical aspects of heat treated wood. Part 1. Softwoods. *Maderas Cienc. Tecnol.* **2006**, *8*, 193–208. [\[CrossRef\]](#)
9. Boonstra, M.J.; Rijdsdijk, J.F.; Sander, C.; Kegel, E.; Tjeerdsma, B.; Militz, H.; Stevens, M. Microstructural and physical aspects of heat treated wood. Part 2. Hardwoods. *Maderas Cienc. Tecnol.* **2006**, *8*, 209–218. [\[CrossRef\]](#)
10. Petrič, M.; Knehtl, B.; Krause, A.; Militz, H.; Pavlič, M.; Pétrissans, M.; Gérardin, P. Wettability of waterborne coatings on chemically and thermally modified pine wood. *J. Coat. Technol. Res.* **2007**, *4*, 203–206. [\[CrossRef\]](#)
11. Pétrissans, M.; Gérardin, P.; Serraj, M. Wettability of heat-treated wood. *Holzforschung* **2003**, *57*, 301–307. [\[CrossRef\]](#)
12. Gérardin, P.; Petrič, M.; Pétrissans, M.; Lambert, J.; Ehrhardt, J.J. Evolution of wood surface free energy after heat treatment. *Polym. Degrad. Stab.* **2007**, *92*, 653–657. [\[CrossRef\]](#)

13. Baysal, E.; Tomak, E.D.; Topaloglu, E.; Pesman, E. Surface properties of bamboo and Scots pine impregnated with boron and copper based wood preservatives after accelerated weathering. *Maderas Cienc. Tecnol.* **2016**, *18*, 253–264. [\[CrossRef\]](#)
14. Yuan, Z.; Wang, X.; Bin, J.; Wang, M.; Peng, C.; Xing, S.; Chen, H. Controllable fabrication of lotus-leaf-like superhydrophobic surface on copper foil by self-assembly. *Appl. Phys. A* **2014**, *116*, 1613–1620. [\[CrossRef\]](#)
15. Xie, L.; Tang, Z.; Jiang, L.; Breedveld, V.; Hess, D.W. Creation of superhydrophobic wood surfaces by plasma etching and thin-film deposition. *Surf. Coat. Technol.* **2015**, *281*, 125–132. [\[CrossRef\]](#)
16. Aydin, I.; Demirkir, C. Activation of spruce wood surfaces by plasma treatment after long terms of natural surface inactivation. *Plasma Chem. Plasma Process.* **2010**, *30*, 697–706. [\[CrossRef\]](#)
17. Demirkir, C.; Özşahin, Ş.; Aydin, I.; Colakoglu, G. Optimization of some panel manufacturing parameters for the best bonding strength of plywood. *Int. J. Adhes. Adhes.* **2013**, *46*, 14–20. [\[CrossRef\]](#)
18. Chen, W.; Zhou, X.; Zhang, X.; Bian, J.; Shi, S.; Nguyen, T.; Wan, J. Fast enhancement on hydrophobicity of poplar wood surface using low-pressure dielectric barrier discharges (DBD) plasma. *Appl. Surf. Sci.* **2017**, *407*, 412–417. [\[CrossRef\]](#)
19. *Adhesives—Wood to wood adhesive bonds—Determination of shear strength by compression loading*. GB/T 17517-1998; Standardization Administration of China: Beijing, China, 1998.
20. Du, G.; Cui, H. Advances in Plasma Modification of Wood. *World Forestry Res.* **2008**, *21*, 51–55.
21. Hippler, R.; Pfau, S.; Schmidt, M.; Schoenbach, K.H. *Low Temperature Plasma Physics: Fundamental Aspects and Applications*, 1st ed.; Wiley-VCH: Weinheim, Germany, 2001; p. 530.
22. Park, B.D.; Frihart, C.R.; Yu, Y.; Singh, A.P. Hardness evaluation of cured urea–formaldehyde resins with different formaldehyde/urea mole ratios using nanoindentation method. *Eur. Polym. J.* **2013**, *49*, 3089–3094. [\[CrossRef\]](#)
23. Altgen, D.; Avramidis, G.; Viöl, W.; Mai, C. The effect of air plasma treatment at atmospheric pressure on thermally modified wood surfaces. *Wood Sci. Technol.* **2016**, *50*, 1227–1241. [\[CrossRef\]](#)
24. Wang, X.M.; Zhou, X.Y. Surface modification of poplar veneer by means of radio frequency oxygen plasma (RF-OP) to improve interfacial adhesion with ureaformaldehyde resin. *Holzforschung* **2015**, *69*, 193–198.
25. Thomas, E.A.D. High energy and spatial resolution XPS of polymers and polymer blends. Ph.D. Dissertation, Kent State University, Kent, OH, USA, 1999.
26. Nguyen, T.P.; Chen, W.; Cao, Y.; Wang, X.; Shi, S.; Chen, M.; Nguyen, Q. Improving Bonding Strength of Oven-dried Poplar Veneers Using Atmospheric Cold Plasma Treatment. *BioResources* **2018**, *13*, 1843–1851. [\[CrossRef\]](#)
27. Yilmaz, O. A thesis submitted to the graduate school of natural and applied sciences of middle east technical university. In Proceedings of the Workshop on Computational Natural Language Learning, Edmonton, AB, Canada, 31 May–1 June 2003.
28. Panshin, A.J.; Zeeuw, C.D. *Textbook of Wood Technology*; McGraw-Hill Book Company: New York, NY, USA, 1970; Volume 1, pp. 75–76.
29. Hse, C.Y.; Kuo, M.L. Influence of extractives on wood gluing and finishing—a review. *For. Prod. J.* **1988**, *38*, 52–56.
30. Avramidis, G.; Klarhöfer, L.; Maus-Friedrichs, W.; Militz, H.; Viöl, W. Influence of air plasma treatment at atmospheric pressure on wood extractives. *Polym. Degrad. Stab.* **2012**, *97*, 469–471. [\[CrossRef\]](#)
31. Wolkenhauer, A.; Avramidis, G.; Hauswald, E.; Militz, H.; Viöl, W. Sanding vs. plasma treatment of aged wood: A comparison with respect to surface energy. *Int. J. Adhes. Adhes.* **2009**, *29*, 18–22. [\[CrossRef\]](#)

