

Article

Improvement of Surface Coating and Interfacial Properties of Hot-Waxed Wood Using Maleic Anhydride Grafted Polypropylene Wax

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Abstract: Beeswax is used on wood furniture surfaces in China. Beeswax is expensive and has a low melting temperature, and the wax film is easily softened and destroyed. To overcome these problems, a modified polypropylene wax grafted with maleic anhydride, with a high melting temperature and low price, was used in hot-waxed wood. The adhesion, hardness, hydrophobic properties, heat resistance, color, and gloss of hot-waxed woods were also examined. The surface and interfacial properties were characterized by FTIR, XRD, and SEM. The modified polypropylene wax showed a higher melting temperature than beeswax by DSC, and the heat resistance of hot-waxed wood using it was revealed by TG. The adhesion for the modified polypropylene wax hot-waxed wood surface was shown to achieve grade 1. In addition, it maintained original grades in adhesion after soaking in water and was greater than beeswax hot-waxed wood. The hot-waxed wood surfaces become hydrophobic compared with untreated wood, and the hydrophobicity of the modified polypropylene wax hot-waxed wood surfaces, with a decreased water contact angle, were slightly weaker than beeswax hot-waxed wood and polypropylene wax hot-waxed wood. Moreover, in hardness, the modified polypropylene wax hot-waxed wood surfaces (2H) were harder than beeswax hot-waxed wood (3B), representing stronger scratch resistance and performing well in decorative characteristics, such as color and gloss. The results of SEM, FTIR, and XRD showed mechanical and weak chemical bonding between the waxes and the surface of the wood with the presence of wax in a wood structure. Therefore, the modified polypropylene wax could be used in hot-waxed wood with great heat resistance, adhesion, and surface performance. The study is beneficial for the application of wood coatings using synthetic wax in the future.

Keywords: polypropylene wax; maleic anhydride grafted; wood; hot-waxed wood; surface coating properties; interfacial properties



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1. Introduction

As a hydrophilic material, uncoated wood is vulnerable to environmental factors resulting in performance losses [1–3]. Waxes have exhibited great potential applications in wood. Natural waxes (beeswax, insect wax, carnauba wax, paraffin wax, and montan wax) have been used as coatings in the field of wood for a long time. Beeswax and insect wax hot-waxed woods are needed in wood furniture production as protective coating [4–6]. By impregnating carnauba wax emulsion, the hydrophobicity of wood is significantly increased, with a reduced water absorption rate in the study [7–9]. Natural fossil waxes (paraffin wax and montan wax) have been applied to wood in recent years. Pure and modified paraffin is the most widely used due to its excellent performance in water repellency, dimensional stability, strength, corrosion resistance, mold and termite resistance, and resistance to decay and fungi [10–15]. Montan wax can enhance wood durability [16–18]. Although natural waxes have many advantages, they lack high heat-resistance properties.

Lately, synthetic waxes (Fischer-Tropsch wax, polyethylene wax, and polypropylene wax (PPW)) have attracted the attention of researchers with their strong strength, high ductility, and low prices. Researchers have focused on synthetic waxes and wood flour composites; among them, polyethylene wax is a common wax [19–22]. Polypropylene wax, with high thermal stability, great strength, and nontoxic properties, has been widely utilized in many fields, such as hot melt adhesive [23], medium-density fiberboard [24], asphalt [25], etc. The use of polypropylene wax to treat wood products is rarely studied. The composite emulsion of PPW and silica is used in wood by heating permeation and hot pressing, providing good hydrophobic performance in the wood, and the water contact angle on the surface can reach 140.3° [26].

Hot waxing is one of the facile surface treatment methods. In this work, the method using polypropylene wax was performed. The adhesion mechanism was attributed to both mechanical and chemical bonding [27,28]. Polarity is important, and polar particles show stronger adhesion [29]. There are different methods to improve the polarity of polymers. The methods of oxidized wax blends [30,31], oxidized waxes [32], and grafting monomer waxes [33] have been developed to improve polarity. Grafting maleic anhydride (MAH) is one of the widely used methods, and the number of grafted MAH molecules greatly influences the wood surface and wax adhesion [34]. In addition, a hot-waxed wood surface with graft-modified polyethylene wax is thermally stable, with enhanced adhesion, gloss, and hydrophobicity properties [34]. Therefore, the work of this paper is to investigate the surface coating and interfacial properties of hot-waxed wood. The research can elucidate the performance of hot-waxed wood and be beneficial for the application of artificial waxes.

2. Materials and Methods

2.1. Materials

Polypropylene wax (PPW) was obtained from Qingdao Zhongsu High-tech Materials Co., Ltd. (Qingdao, China). Beeswax (BW) was obtained after filtering and purification and was purchased from a beekeeping farm in Yichun, Heilongjiang Province. Maleic anhydride (MAH, >99.0%, AR) was obtained from Tianjin Guangfu Technology Development Co., Ltd. (Tianjin, China). Dibenzoyl peroxide (BPO, >99.0%, AR) was obtained from Shanghai Maclin Biochemical Technology Co., Ltd. (Shanghai, China); xylene (>99.0%, AR) and methanol (>99.0%, AR) were purchased from Tianjin Fuyu Fine Chemical Co., Ltd. (Tianjin, China).

Elm (*Ulmus davidiana* Planch var. *japonica* (Rehdance.) Nakai) is a hardwood from the Greater Khingan Range of China. Elmwood, for a long time, has been one of the most common woods in furniture products in China. Its sapwood was studied, and its air-dry density is 0.581 g/cm³. The size of the specimen was 50 mm (L) × 50 mm (R) × 5 mm (T), and there were no obvious defects on the surface.

2.2. Preparation of Modified Polypropylene Wax by Grafting Maleic Anhydride

The modified polypropylene wax by grafting maleic anhydride (PMAH) was prepared using a solution method in a nitrogen atmosphere at a 20 mL/min flow rate. A certain amount of PPW and xylene were added into a four-mouth flask under stirring, followed by heating at 100 °C, and held for 30 min to make it swell. The rotation speed was 300 rpm, and the temperature was raised to 120 °C and held for 2.5 h. The weight ratios of PPW:MAH (*w/w*) were 95.3:4.7, 90.9:9.1, 83.3:16.7, and 76.9:23.1; the weight ratio of MAH/BPO (*w/w*) was 5:1; the ratio of PPW:xylene was 1:2. After the reaction, the products were extracted, filtered three times, and dried in a vacuum drying oven for 24 h at 50 °C. Dried products were labeled PMAH1, PMAH2, PMAH3, and PMAH4. The acid value of PMAH was determined by standard ASTM D1386-15.

$$\text{Acid number}(\%) = (A - B) \times N \times 56.1 / C \quad (1)$$

A is milliliters of alkali solution required for titration of the sample; B is milliliters of alkali solution required for titration of the blank sample; N is the normality of the alkali solution; and C = grams of sample used.

2.3. Preparation of Hot-Waxed Woods

To remove burrs, wood surfaces were polished along the grain using sandpapers with 180, 240, and 320 grit in turn. Waxes were melted and then coated on the wood surface through a heater at, respectively, 100 °C for BW and 180 °C for PPW and PMAH, with a certain fluidity keeping 5~10 min. The wood surface was wiped at a constant speed with a clean white cloth to apply the wax evenly on the surface of the wood. The samples were cooled naturally. Finally, BW, PPW, and PMAH hot-waxed woods were achieved and were called W-BW, W-PPW, and W-PMAH, respectively. From this analogy, W-PMAH1, W-PMAH2, W-PMAH3, and W-PMAH4 were obtained.

2.4. Properties of Hot-Waxed Woods

2.4.1. Melting Behaviors of Waxes and Heat Resistances of Hot-Waxed Woods Tests

Experiments were done using the differential scanning calorimeter DSC Q20 (TA Instruments, New Castle, DE, USA). Baseline calibration was performed in the empty furnace body first. The temperature and heat flow were calibrated using indium as standard. Each sample (3–5 mg) was heated and cooled two times according to a temperature program of 10 °C/min in the range of room temperature to 200 °C. The experimental data achieved the second melting curves of beeswax, PPW, and PMAH.

The thermogravimetric curves and the derivatives mass loss (DTG) of waxes and hot-waxed wood samples were characterized using a thermal gravimetric analyzer TGA Q50 (TA Instruments, New Castle, DE, USA) under a nitrogen atmosphere with a flow rate of 30 mL/min and heating the sample from room temperature to 600 °C at a constant heating rate of 10 °C/min. The weight of the sample was about 5–10 mg inside a platinum pan in the device.

2.4.2. Adhesion Strength and Scratch Hardness Tests

The adhesions of hot-waxed woods were measured according to the adhesion cross-cutting method in GB/T 4893.4-2013. The adhesions were investigated again after soaking in water for 24 h. The adhesion grade was obtained according to the area of the wax film falling off, and the average of five values was also obtained. Grade 0 represents the strongest adhesion of samples, while grade 5 represents the weakest adhesion of samples.

The hardness of hot-waxed woods was tested by evaluating the scratch value using a pencil hardness tester (QHQA-A, AIPLI, Quzhou, China) according to GB/T 6739-2006. The pencil was held at 90° to the sandpaper, and the tip of the pencil core was smoothed. The pencil was fixed on the hardness tester at 45° on a film surface. The test was performed by repeatedly moving the pencil and observing the marks on the surface more than three times, and taking the average of the results. From 9H to 6B, the grade represents the hardness of the film. The grade with 9H represents a harder film, while the grade with 6B represents a softer film.

2.4.3. Water Contact Angle Test

The water resistance of hot-waxed wood surfaces was measured by the water contact angle test using a video optical contact angle meter (Dataphysics-OCA20, Filderstadt, Germany). The volume of deionized water droplets in each test was 4 µL in the needle. The level of wood specimens was adjusted, and the water contact angle of deionized water droplets falling on the surface of untreated and hot-waxed wood for 60 s was recorded. Three points were selected for each test piece, and the average value was taken.

2.4.4. Surface Color and Gloss Tests

Color testing of the surface of the hot-waxed and reference wood samples was obtained by spectrophotometer in the CIELAB system. The color was characterized by three parameters, L^* , a^* , and b^* . The ΔL , Δa , and Δb values were obtained by calculating the difference before and after hot waxing, and the total color difference ΔE was obtained according to Equation (1).

$$\Delta E = \sqrt{(L_2 - L_1)^2 + (a_2 - a_1)^2 + (b_2 - b_1)^2} \quad (2)$$

The gloss of the surface of reference and hot-waxed wood samples was tested with a WGG60-Y4 gloss meter (Quanzhou keshijia Photoelectric Instrument Co., Ltd., Quanzhou, China) according to GB/T 4893.6-2013. The gloss was characterized by gloss along the grain GZL (%) and gloss across the grain GZT (%).

2.4.5. Characterization of Hot-Waxed Wood

The interface between wax and wood was investigated by ATR-FTIR using a Nicolette 6700 FTIR spectrometer (Thermo, Waltham, MA, USA). The powder sample was achieved by cutting a thin slice about 100 μm from the surface of the hot-waxed wood surface using a sharp blade and grinding the sample in an agate mortar. The spectra of samples were obtained in the range of 500–4000 cm^{-1} . The scan number was 32 times, and the resolution was 4 cm^{-1} .

X-ray diffractometer XRD-6100 (Shimadzu, Kyoto, Japan) was used to test the crystallization peaks of waxes and hot-waxed woods. The scanning range was 5–40°, the scanning speed was 5°/s, and the step size was 0.0200°. The maximum power was 2 kW, the rated voltage was 20–60 kV, and the rated current was 12–50 mA. The sample was ground to a powder. The Turley method was adopted to calculate the measured data according to Equation (2).

$$C_r I(\%) = (I_{200} - I_{am}) \times 100 / I_{200} \quad (3)$$

$C_r I$ represents the relative crystallinity, I_{200} is the intensity of the lattice diffraction peak at $2\theta \approx 22^\circ$, and I_{am} is the intensity of amorphous background diffraction.

Scanning electron microscopy (SEM, QUANTA200, FEI, Eindhoven, The Netherlands) was used to examine the microstructure of reference and hot-waxed wood samples. Radial sections and cross-sections of the sample were cut and exposed with a blade, and slices were fixed on a sample holder with conductive glue, followed by gold treatment. The distribution and morphology of wax in wood were observed by a scanning electron microscope with a 5.0 kV accelerating voltage.

3. Results and Discussion

3.1. Acid Value and Characterization of MAH-Modified PPW

Figure 1 shows the acid values and characterization of PMAH. Figure 1a shows the acid values of PMAH. The acid value of PMAH continues to increase with the weight ratio of PPW/MAH because an increased number of MAH groups are grafted on PPW with the increased content of maleic anhydride.

As shown in Figure 1b, the infrared spectra of BW, PPW, and PMAH were achieved. The peak at 1736 cm^{-1} for beeswax represented ester carbonyl functional groups, while 2916 cm^{-1} and 2848 cm^{-1} reflected fatty acid chains [35]. Compared with PPW, new peaks at the wavelengths of 1776 cm^{-1} and 1716 cm^{-1} in PMAH reflect C=O vibrations of the cyclic anhydride ring and C=O of the carboxyl group [36]. Thus, MAH groups have been successfully grafted on PPW. The former peaks of PMAH are more shaped as the acid value increase.

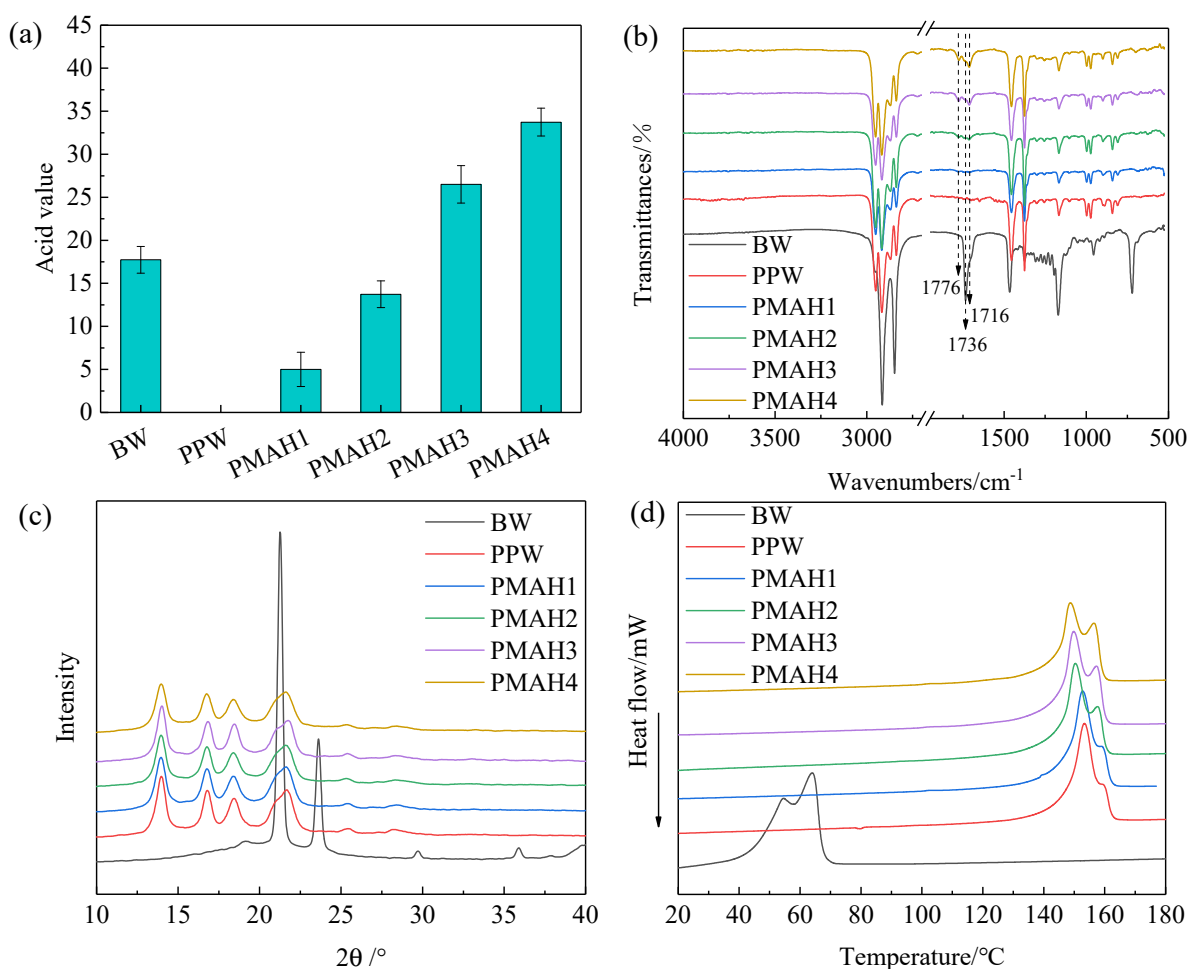


Figure 1. Characterization of waxes: (a) acid values, (b) FTIR, (c) XRD, (d) DSC.

Figure 1c shows the crystallization of the waxes. The peaks at 21.3° and 23.6° represented the BW pattern, and both intensities of the diffraction were very high. The PPW pattern shows peaks at 14.0°, 16.8°, 18.4°, and 21.6°, indicating its typical α form of crystalline structure [37]. No new peaks occur in PMAH compared to PPW, but the intensities of PMAH are lower than PPW. The result shows that the structure of PMAH may be rearranged and grain size reduced due to the presence of MAH groups [38,39].

The melting curves of the different waxes were revealed by DSC in Figure 1d. During the melting process, there were two phase-change peaks of BW, which occurred at 54.5 °C and 64.1 °C [40]. The principal peak can be ascribed to the solid–liquid transition and the other to a solid–solid transition [41,42]. It was observed that the PPW shows two melting peaks at 153.3 °C and 159.5 °C, and the melting temperature (T_{mp}) is higher than beeswax. In comparison with PPW, the melting temperature (T_{mp}) for PMAH moves towards lower values with the increased weight ratio of PPW/MAH. The structure of PPW was changed and led to increased distance and low interactions between the macromolecules because of the presence of MAH groups. Moreover, degradation may have occurred during the reaction. Therefore, the melting temperatures (T_{mp}) of PMAH are slightly lower than that of PPW. However, the intensity of the first melting peak for PMAH is weaker, while the intensity of the second melting peak is stronger because of the increased length of PMAH chains leading to increased molecular weight.

3.2. Adhesion and Hardness of Hot-Waxed Wood

Figure 2 shows the adhesion and hardness of hot-waxed woods. Before the tests, the specimens should be placed in an environment with a temperature of $(23 \pm 2)^\circ\text{C}$ and relative humidity of $(50 \pm 5)\%$ for at least 7 days.

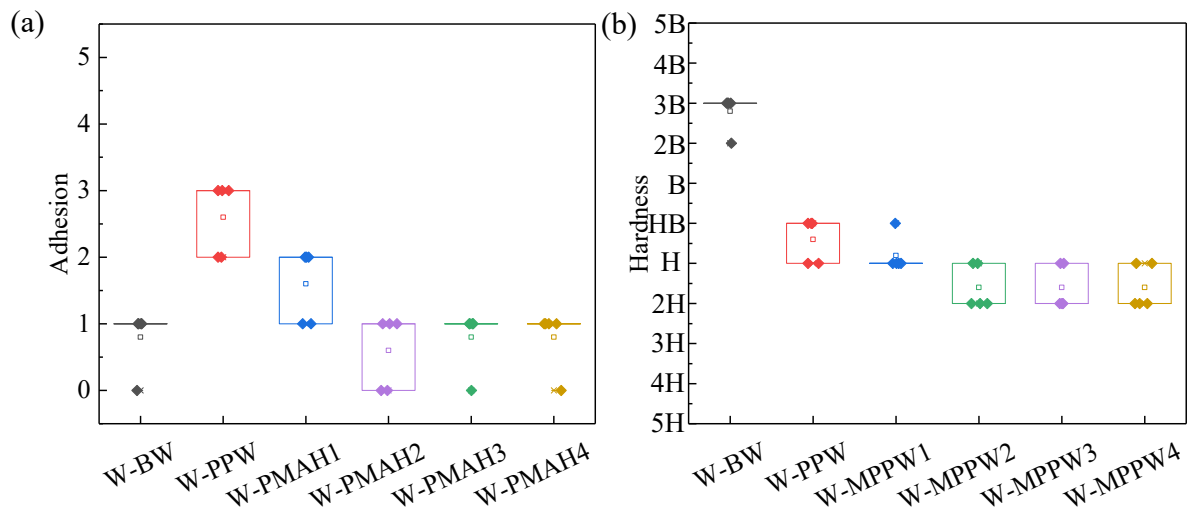


Figure 2. Adhesion and hardness of hot-waxed woods: (a) Adhesion of hot-waxed woods, (b) hardness of hot-waxed woods.

As Figure 2a shows, the adhesion of W-BW was grade 1, and that of W-PPW was grade 3, lower than W-BW. PMAH showed higher adhesion grades than W-PPW, in agreement with a previous report [43]. Moreover, W-PMAH adhesion was grade 1 and similar to W-BW when the PMAH acid value was 14 mg KOH/g. This was most likely due to the reaction between polar and hydroxyl groups in the cellulose molecules of the wood, generating ester bonds. As the acid value of PMAH continued to increase, the W-PMAH adhesions remained in grade 1. Because the steric repulsion effect occurs with MAH groups, the involved groups were blocked in the reaction. It can be concluded that the acid value was an important factor that influenced the adhesion of the hot-waxed wood.

Figure 2b shows the hardness of the hot-waxed woods. A higher hardness represents better scratch resistance. The W-BW hardness grade was 3B, and W-PPW was HB; the hardness grade of W-PMAH was harder than W-PPW. The hardness was in the order W-PMAH > W-PPW > W-BW. The cross-linking reaction occurred between carboxyl groups, and the PMAH film on the surface of the wood hardened during hot waxing, as reported [44].

3.3. Hydrophobicity of Hot-Waxed Wood

Figure 3a shows the water contact angles of uncoated wood and the hot-waxed woods. The water contact angles of the waxed wood were higher than uncoated wood (59°). The water contact angle of W-BW (122°) was the highest, followed by W-PPW (119°). As the acid value increased, the water contact angles of W-PMAH decreased from 116° to 105° , below W-PPW. Surface free energy may have been an important factor in the water contact angles. Due to the number of MAH groups introduced in PPW, the surface free energy steadily increased in W-PMAH. Hence, the water contact angles of W-PMAH presented a decreasing trend.

To further study the water resistance of hot-waxed wood, the adhesions of hot-waxed woods after soaking in water for 24 h are illustrated in Figure 3b. The state of the sample before soaking was consistent with Figure 2a. It is obvious that the adhesions of W-BW and W-PPW after soaking in water decreased, while the adhesions of PMAH maintained their original level compared to Figure 2a. This evidence proves that the adhesion of W-PMAH

is stronger than W-PPW and W-BW after soaking in water. That can be explained through the weak chemical reaction that occurred between the PMAH and the wood.

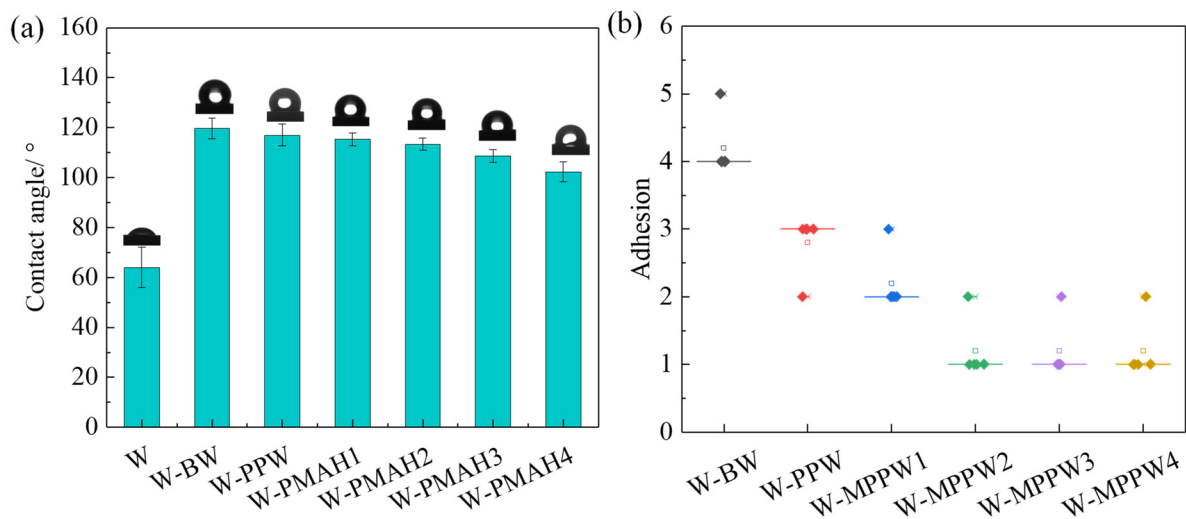


Figure 3. Hydrophobicity of uncoated wood and hot-waxed woods: (a) The water contact angles of uncoated wood and hot-waxed woods; (b) Adhesion of hot-waxed woods after soaking in water for 24 h.

3.4. Color and Gloss Measurement of Hot-Waxed Wood

Decorative performance is also important for hot-waxed wood, including color and gloss in Figure 4. As shown in Figure 4a, variations of color in untreated and hot-waxed wood surfaces were measured. Compared with the untreated wood, there were apparent changes in the hot-waxed wood surface, as indicated by the reduced L^* value and the increased a^* and b^* values. The Δa values and Δb values increased, and ΔL decreased from W-PPW to W-PMAH4. The color of the W-PPW surface was close to uncoated primary wood due to the slight color changes with the lowest ΔE . The color values of W-PMAH2 and W-PMAH3 were like W-BW, which tended to be low-brightness red and yellow.

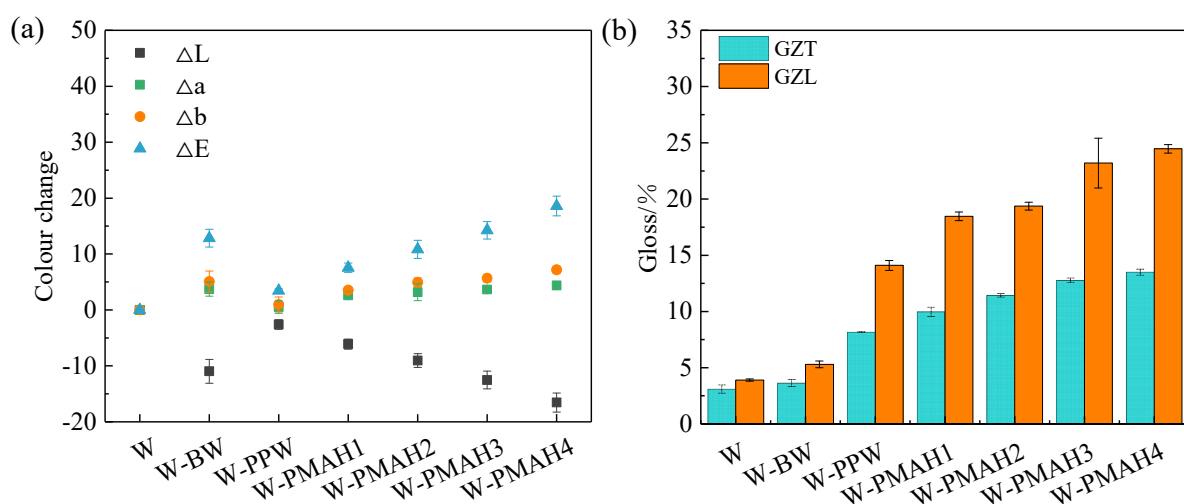


Figure 4. The color and gloss on the surface of uncoated wood and hot-waxed wood: (a) The color on the surface of uncoated wood and hot-waxed wood; (b) The gloss on the surface of uncoated wood and hot-waxed wood.

Figure 4b shows the gloss of untreated and hot-waxed wood surfaces, including gloss parallel (GZT) and perpendicular (GZL) to the wood. Compared with W-BW, W-PPW and

W-PMAH tended to have greater gloss, and the order of gloss was W-PMAH > W-PPW > W-BW. For W-BW, the roughness of the substrate may be a key factor in the gloss, resulting in a poor gloss of the hot-waxed wood. Moreover, this phenomenon may be related to the typical α form of the crystalline structure of PPW and PMAH. The presence of the branched-chain grafted MAH group disrupts the PPW crystal structure, leading to a decrease in grain size [38,39]. However, there was no noticeable improvement in the gloss as the acid value of PMAH increased.

3.5. Thermal Stability of Hot-Waxed Wood

The determination of resistance to heat of hot-waxed wood surface referenced the standard in GB/T 4893-2020. As a heat source, a cup filled with hot water at 100 °C was placed on the surface of hot-waxed wood for 30 min. After removing the heat source block and waiting until it cools completely, the change of damage on the surface of the specimen can be observed. As shown in Figure 5, the schematic diagram of heat resistance on the surface of hot-waxed wood shows changes after testing in the W-BW, W-PPW, and W-PMAH2 samples. The cups were separated from the samples, and a white ring appeared on the surface of the W-BW; nevertheless, W-PPW and W-PMAH2 showed little change. The reason was that, with its molecular weight, beeswax more easily enters the pore structure of the wood, as reported in the literature [45]. Due to the ambient temperature being higher than the melting temperature of beeswax, the beeswax melted and overflowed from the pores of the wood. As the temperature cooled, the beeswax slowly changed from liquid to solid, forming protrusions and firmly holding the bottom of the cup to the surface of the wood. After separating the cup from the sample, there was a damaged mark on the surface of the W-BW where it was in contact with the bottom of the cup. Hence, in heat resistance, W-PPW and W-PMAH were higher than W-BW, as shown in Figure 1d.

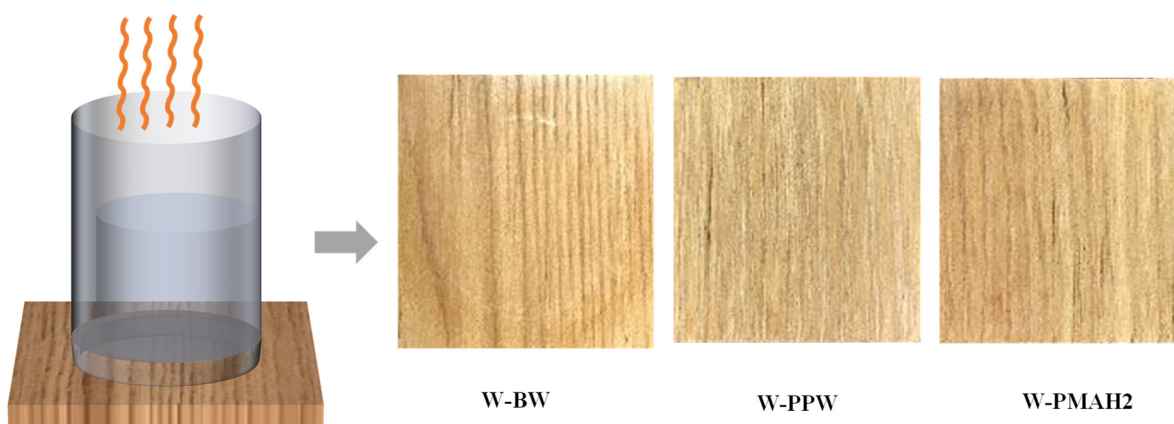


Figure 5. The schematic diagram of heat resistance on the surface of hot-waxed woods.

In Figure 6, the TG and TGA curves of the waxes and hot-waxed wood were investigated to represent their thermal stability. Figure 6a shows the lower initial thermal degradation temperature ($T_{5\%}$) at 239.67 °C for beeswax. The maximum peak temperature of beeswax (383.4 °C) is lower than that of PPW (444.6 °C) in Figure 6b. Compared with PPW, that of PMAH2 (451.2 °C) is slightly increased. To explain the thermal stability of the samples, the TG and DTG curves of untreated wood and hot-waxed wood are reported in Figure 6c,d. In Figure 6c, untreated wood's initial thermal degradation temperature ($T_{5\%}$) was 195.69 °C, which is lower than hot-waxed wood. In Figure 6d, only one peak (285.6 °C) in untreated wood is visualized, representing the degradation of the wood. There were two peaks in hot-waxed woods; the first peak mostly represented wood degradation, and the second peak represented degradation of the waxes. Hot-waxed woods improved the temperature of the degradation of wood [18], and the improvement may be beneficial for thermal degradation in application. Indeed, it was evident that the second peak of W-PPW (451.9 °C) and PMAH2 (453.1 °C) were higher than W-BW (384.71 °C). The reason was that

the waxes formed a protective layer for the wood, which slowed down the heat transfer in the wood to protect the wood, thus reducing the degradation rate of the wood. It can be concluded that hot waxing increases the initial thermal degradation temperature and the maximum exothermic temperature of the wood, and the thermal stability of W-PMAH2 is higher than W-PPW.

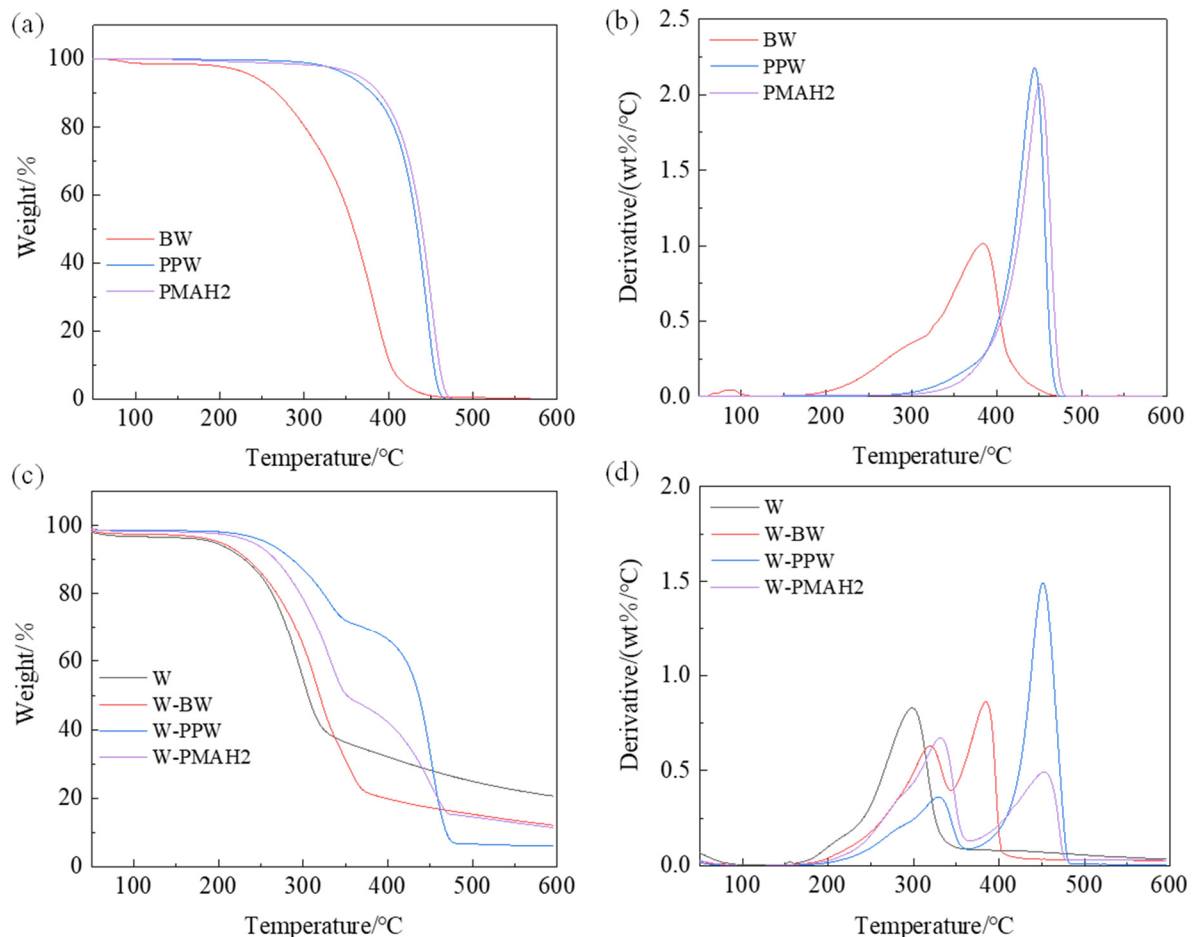


Figure 6. The TG and DTG curves of waxes and hot-waxed woods: (a) The TG curves of waxes; (b) The DTG curves of waxes; (c) The TG curves of hot-waxed woods; (d) The DTG curves of hot-waxed woods.

3.6. Characterization

3.6.1. Fourier Transform Infrared Spectra (FTIR) Analysis

FTIR spectra of uncoated and hot-waxed woods are presented in Figure 7a. The peak at 3330 cm^{-1} reflects the stretching vibration of hydroxyl groups in wood, and W-BW was close to untreated wood. However, the vibration band of hydroxyl groups for W-PPW was broadened and weakened. The FTIR spectra of W-PMAH2 were weakened compared to W-PPW due to the decreased number of hydroxyl groups during hot waxing. The W-PMAH2 1736 cm^{-1} band was broadened and sharpened, and the band at 1593 cm^{-1} relatively decreased. Moreover, the peak at 1716 cm^{-1} was not observed in W-PMAH2 in Figures 1b and 7a. That can be attributed to the change in MAH groups. The reason is that MAH hydrolyzed to carboxylic acid, and the C=O vibrations band for the cyclic anhydride ring decreased. At the same time, this may be due to a partial cross-linking reaction and esterification between carboxyl groups in the PMAH during hot waxing [34,44]. Therefore, the vibration peak of the ester base was more prominent and broadened in W-PMAH2. The bands at 1453 cm^{-1} and 1378 cm^{-1} were vibration peaks of the carbon skeleton of the wood. Both bands were sharper in W-PMAH2 than in W-BW and W-PPW. It was concluded that the combination of PMAH2 and wood was useful. The FTIR spectra revealed that a weak

chemical reaction may occur between MAH groups and the wood and be related to the adhesion of PMAH2. The result is consistent with the great adhesions of W-MAH after soaking in water for 24 h in Figure 3b.

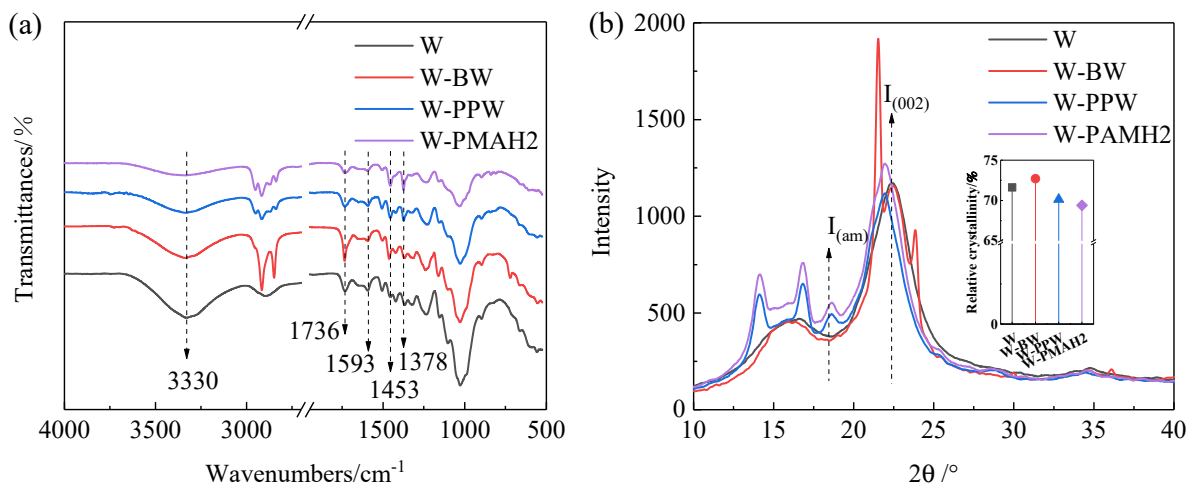


Figure 7. The FTIR and XRD on the surface of uncoated wood and hot-waxed woods: (a) The FTIR on the surface of uncoated wood and hot-waxed woods; (b) The XRD on the surface of uncoated wood and hot-waxed woods.

3.6.2. X-ray Diffraction (XRD) Analysis

As shown in Figure 7b, the peak at around 22° in the XRD pattern of untreated wood represents the diffraction peak of cellulose, and the peak around 18° presents the background peak. The diffraction peaks of BW, PPW, and PMAH2 are all observed in the W-BW, W-PPW, and W-PMAH patterns for hot-waxed woods, as in Figures 1c and 7b. The result shows that the waxes could attach to the surface of the wood. Moreover, Figure 7b showed the relative crystallinity of untreated wood and hot-waxed woods calculated by the Turley method. The relative crystallinity of cellulose in W-BW (72.7%) is higher than in untreated wood (71.6%), while W-PPW (70.1%) and W-PMAH2 (69.4%) are lower.

3.6.3. Scanning Electron Microscope (SEM) Analysis

The surface morphology of the coating and inner structures of the hot-waxed woods were characterized using scanning electron microscopy, as shown in Figure 8.

Figure 8a shows the surface of untreated wood and W-BW. The surface structure of untreated wood includes vessels, fiber, and rays in the red box of Figure 8a. In Figure 8a–f, the wood's structures were coated with waxes on the surface of hot-waxed woods. The structure on the surface of W-BW was relatively clear, representing a rough surface because beeswax is soft, and the rough surface of W-BW was close to untreated wood (Figure 8a). Thus, the water contact angle of W-BW was the largest, and the gloss of W-BW was the lowest. The surface morphology of W-PPW was relatively smooth (Figure 8b). Compared with W-PPW, the surfaces of W-PMAH showed no noticeable difference (Figure 8c–f). The result may correlate with the crystal structure of the waxes in the XRD pattern rather than with the roughness of the wood substrate. The presence of waxes in the cross-section, radial section, and tangential section of W-PMAH2 are presented in Figure 8g–i. Figure 8g shows that the wax filled in pores, rays, and so on in the cross-section of the wood. Figure 8h shows that PMAH2 was nonuniformly distributed on the spiral thickening of the vessels, and some pits were coated with wax in the radial section of the wood [46,47]. Moreover, the pores of rays were partly filled with wax in the tangential section of the wood (Figure 8i). Consequently, the presence of wax in the wood confirmed that grafted polypropylene wax with MAH groups could be embedded into the wood's structure to improve adhesion.

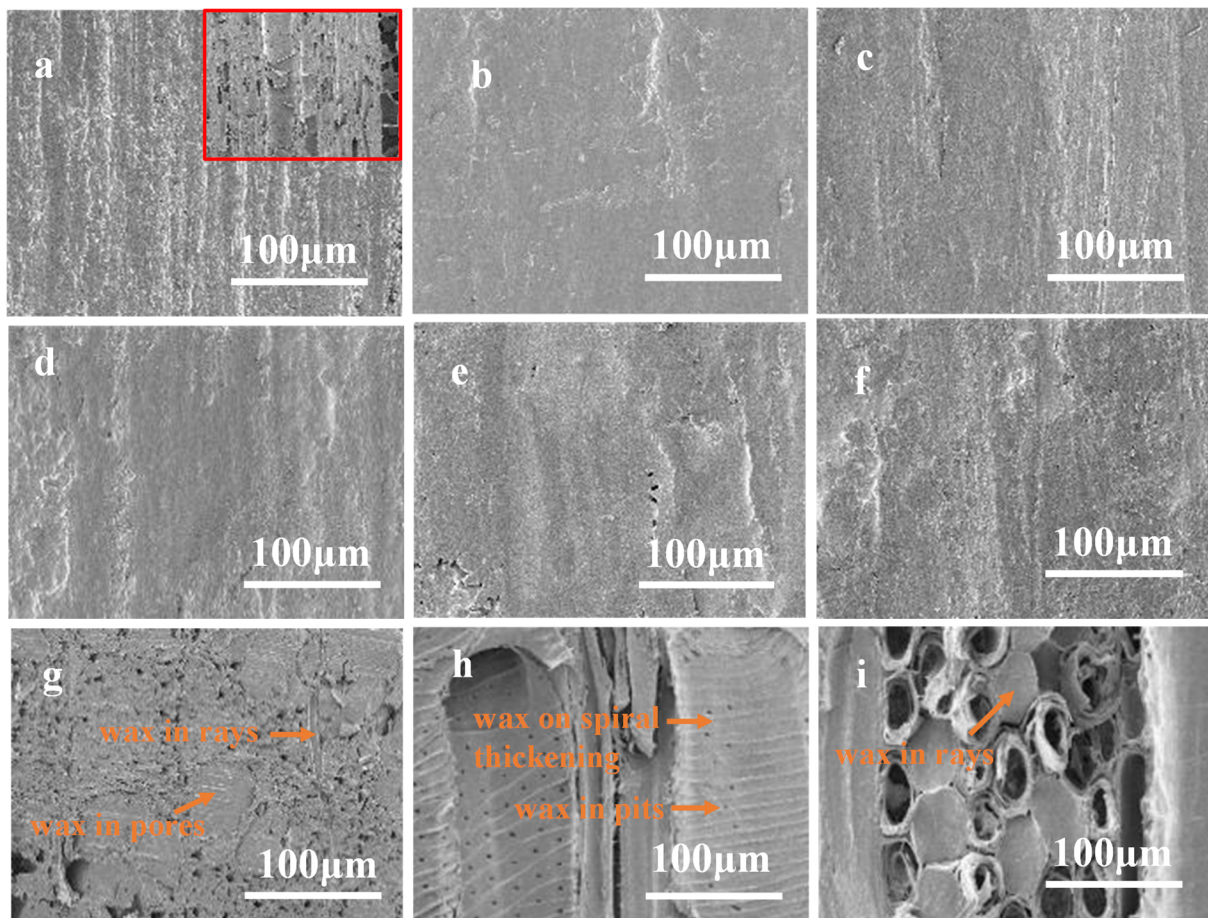


Figure 8. The SEM of the surface and inner structure of hot-waxed woods: (a) The surface morphology of untreated wood and W-BW; (b) The surface morphology of W-PPW; (c) The surface morphology of W-PMAH1; (d) The surface morphology of W-PMAH2; (e) The surface morphology of W-PMAH3; (f) The surface morphology of W-PMAH4; (g) The cross-section of the hot-waxed wood; (h) The radial section of the hot-waxed wood; (i) The tangential section of the hot-waxed wood.

4. Conclusions

Hot waxing is a promising and simple method for protecting wood. Waxes were successfully used on the surface of the wood. W-PMAH showed great heat resistance, adhesion, and surface decoration properties. The heat resistance of W-PMAH revealed that the DSC pattern showed higher melting temperatures of PMAH, and the TG pattern showed the maximum exothermic temperature of W-PMAH. W-PMAH improved the adhesion of W-PPW and achieved the same effect as W-BW in adhesion with grade 1. In addition, it still maintained its original grades in adhesion after soaking in water. W-PMAH surfaces became hydrophobic, and the water contact angles were slightly lower than W-BW and W-PPW due to the combination with the rough surface and the number of MAH groups grafted on the PMAH. Moreover, W-PMAH surfaces (2H) were superior to W-BW (3B) in hardness, representing stronger scratch resistance. At the same time, they performed decorative performances similar to W-BW. The results of SEM, FTIR, and XRD showed mechanical and weak chemical bonding between the waxes and the surface of the wood with the presence of wax in the wood structure. Therefore, PMAH could be applied in hot-waxed wood like beeswax. This work provides a facile strategy for PMAH hot-waxed wood with higher thermal performance and great surface properties and a paradigm for broadening the utilization of synthetic wax in the field of wood surface coatings.

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