Research Progress and Prospects of Wood High-temperature Heat Treatment Technology

Shuai Cao,[a] Shuai Cheng,[a] and Jiabin Cai [a,b,*]

High temperature heat treatment is one of the main technologies with the highest market conversion rate and broad future prospects in the functional technology of wood. Chemical reagents are not added in the production process. The treatment improves the dimensional stability, biological durability, wood color, and acoustic properties without reducing the environmental performance of the product. However, there are some problems in heat treatment, such as the reduction of mechanical properties and surface wettability of wood, high production energy consumption, and large exhaust emissions. Therefore, understanding the influence and mechanism of high temperature heat treatment technology on wood properties is of guiding significance to further improve the quality of heat-treated wood, improve production process, and develop new equipment. This article reviews the effects of heat treatment on the properties of wood and the mechanism of heat treatment. Then, some applications of heat treatment of wood are introduced. Finally, the development direction and prospect of high temperature heat treatment technology in the future are forecasted.

DOI: 10.15376/biores.17.2.Cao

Keywords: High-temperature heat treatment; Performance; Mechanism; Development prospects

Contact information: a: Nanjing Forestry University, Nanjing 210037 China; b: Co-Innovation Center of Efficient Processing and Utilization of Forest Resources, Nanjing 210037 China;
** Corresponding author: nldfloor@163.com*

INTRODUCTION

As one of the traditional four major materials, wood is the only one of them that is renewable and environmentally friendly. Due to its unique visual characteristics, high specific strength, natural degradation, beautification of the indoor environment, and other natural characteristics, as well as its strong plasticity, high practicability, good processing performance, low processing energy consumption, and recyclability, it has become one of the engineering materials with great development prospects. It plays an indispensable role in construction, decoration, furniture manufacturing, and road transportation. With the development of society, population growth, and improvement of living standards, the areas of application continue to expand. The demand for heat-treated wood, such as outdoor products, underfloor heating, and home manufacturing is showing a growing trend. Meanwhile, forest harvesting is restricted because of strengthening and increasing national forest protection. Under the pressure of increasingly rigid demand for wood, the development of fast-growing forests is an important measure to solve the shortage of timber supply. However, compared with natural forests, the wood from fast-growing forests has many inherent shortcomings, such as poor dimensional stability and poor decorative effects, which greatly limit the efficient use of fast-growing timbers. Therefore, researchers have carried out thermal modification treatment of fast-growing wood to improve all aspects of its performance, achieve better use of inferior wood, and increase the use value of fast-growing timbers.

Wood thermal modification involves physical methods, and it is meant to improve or change the physical, mechanical, chemical properties, and structural characteristics of wood. The purpose is to improve natural degradation (decay) resistance, acid resistance, alkali resistance, mechanical strength, and dimensional stability, such that the performance of the wood will meet people's requirements. At present, heat treatment technology has been widely used in industrialization, and a variety of heat-treated wood products have been sold in the domestic market.

Heat treatment is a relatively environmentally friendly modification method that partly affects the chemical composition. Compared with chemical modification, the heat treatment process is simpler and relatively pollution-free. Common heat treatment technologies are carried out in gaseous media such as steam. An example is the Finnish "Thermowood" patented technology (Viitanen *et al.* 1994), and it can also be carried out in a nitrogen environment, such as the "Rectification" thermal modification method invented in France (Michel 2007), and the heat treatment in the smoking state that was first developed and researched in Japan. In addition, there are hydrothermal methods that use water as the medium, typical of which is the "Plato" process developed by Shell in the Netherlands (Xie *et al.* 2002). In addition, the oil thermal method for heat treatment is carried out in oil. The modification of timber by simple heat treatment method can improve its dimensional stability and resistance to decay, but the chemical degradation after heat treatment will also reduce the mechanical strength of wood, which limit its application.

This article focuses on the performance changes of modified wood by high temperature heat treatment and its mechanism of action. Finally, the research and application of heat treatment technology are summarized and prospected.

THE EFFECT OF HEAT TREATMENT ON PROPERTIES

Appearance (Color) Change

Research on color mainly has been carried out for light-colored woods and color-changing woods. Through heat treatment, the overall color of the wood is deepened to make the light-colored wood surface darker, for instance as “teak color,” which enhances the appearance of the wood. The surface of color-changing wood is rendered more uniform, to achieve the effect of eliminating discoloration. Color change is the most intuitive effect of heat treatment on wood properties. The color change after heat treatment can be determined according to the CIE standard color measurement method specified by the International Commission on illumination (CIE). This system is composed of 3 basic indicators: L^* (lightness index), a^* (red-green index), and b^* (yellow-blue index), from which are derived the saturation difference ΔC^* and color difference index ΔE^* to characterize the color change of the treated wood. The treatment process is an important parameter that affects the color change of wood. In addition, the color changes exhibited by different species are also different.

Temperature has a significant effect on wood color indicators. With the increase of processing temperature, the color changes more obviously. The lightness index L^* decreases significantly, the color saturation difference ΔC^* decreases, and the total color difference ΔE^* increases, which is manifested as the visual color of specimen deepening (Kamperidou *et al.* 2013). Hidayat *et al.* (2017) studied the color characteristics of Korean pine (*Pinus koraiensis*) and paulownia (*Paulownia tomentosa*) by heat treatment for 2 h at 160, 180, 200, and 220 °C, and obtained a similar conclusion. Through consumer preference testing, it is known that heat-treated wood with a darker color is more popular with consumers than wood without heat treatment with a lighter color. In order to achieve a deeper "teak color," Jiang *et al.* (2020) used the CIE $L^*a^*b^*$ system to determine the effect of heat treatment process parameters (temperature, duration, and heating rate) on the color of rubber wood (*Hevea brasiliensis*) before and after heat treatment in order to obtain the best process parameters. The results showed that the temperature significantly affected the colorimetric parameters of the heat-treated rubber wood, while the duration and heating rate had no significant effect. The effect order of the three parameters was temperature>duration>heating rate. The optimum process conditions were obtained as follows: 190 °C, duration 4 h, heating rate 10 °C•h^{-1}.

Gonzalez-Pena and Hal (2009) used a colorimeter to analyze the surface color changes and evolution of three thermally modified wood species of beech (*Fagus sylvatica* L.), spruce (*Picea abies* L.) and Scots pine (*Pinus sylvestris* L.). During the heat treatment process, all the three wood species first turned orange and then approached gray. At the same time, the lightness L^* was gradually decreasing. Ayata *et al.* (2017) performed 1 and 2 h high temperature heat treatments on Afrormosia (*Pericopsis elata*), Doussie (*Afzelia bipindensis*), Frake (*Terminalia superba*) and Iroko (*Chlorophora excelsa*) by steam heat treatment at 212 °C to study the color changes. The results showed that the color difference between untreated wood and treated wood was much higher than that between tree species. The total color difference ΔE^* of Frake was the highest, and that of Doussie was the smallest. The lightness L^* of all species decreased after treatment, and the magnitude of the decrease increased with the increase of treatment time. Heat treatment caused a slight decrease in a^* of Doussie, a slight increase in b^* of Frake, and the other three wood specimens were opposite.

Light-colored woods such as poplar (*Populus tomentosa* Carr.) and birch (*Betula alnoides*) will darken after heat treatment. Cao *et al.* (2021) heat-treated poplar at 180 ℃ for 3 h. The result is shown in Fig. 1. The color changed from off-white to dark brown, and the change was obvious. The L^* of the heat-treated samples was 40.97, which was 38.18% lower than the L^* of the control, which indicated the lightness of poplar wood decreased after heat treatment. The a^* of the heat-treated samples increased by 71.97% compared to the a^* of the control and the b^* were 18.10% lower than the b^* of the control, which indicated that the heat treatment increased the red-green index and decreased the yellow-blue index of the poplar wood. Banadics and Tolvaj (2019) studied the color change of poplar sapwood and heartwood after heat treatment. The initial redness (a^*) of heartwood and sapwood was low, and it increased with time. After 20 days of treatment at 110 ℃, the redness value can reach 4.5 times of the initial value. The redness of sapwood increased more than that of heartwood and visible chromatic aberration was produced. The increase of the yellow color coordinate (b^*) was similar to the increase of the a^* value, up to 1.9 times of the initial value, and the change of redness is more obvious than that of yellowness. The color change of birch after heat treatment is similar to that of poplar. Yang *et al.* (2015) heat-treated birch at -0.08 MPa vacuum at 160 to 200 ℃ for 1 to 4 hours. They found that the color changed from light white to dark brown and uniform after vacuum heat treatment. The wood clearly showed darker tones in all heat-treated conditions. The higher the treatment temperature, the longer the treatment time, the smaller the ΔL^* value, the larger the ΔE^* value, and the darker the color.

Fig. 1. Surface colors of the different samples

It should be pointed out that the wood's color can change with the passage of time. This is true for heat-treated wood, just as it is true for the untreated wood. So the effects on color of heat treatment cannot be regarded as permanent.

Dimensional Stability and Moisture Absorption

Shrinkage and swelling are the inherent characteristics of lumber, in response to various forms of water. When lumber is transported to different places and made into furniture or heated floors, the moisture content will change, and the appearance and main physical properties of wood will change, which will cause defects in the application of wood. The most prominent improvement effect of wood heat treatment is to improve the dimensional stability of the treated wood, such as increasing its hydrophobicity and decreasing its equilibrium moisture content. Heat treatment significantly reduces the moisture absorption of wood, which can play a fundamental role in stabilizing the comprehensive performance of wood in the application process. It is also important for the use of heat-treated wood in places where water resistance is important, such as lowlands, fences, and for changing the indoor climate conditions for furniture, wall panels, or slats. Bytner *et al.* (2021) heat-treated black poplar (*Populus nigra* L.) at 160, 190, and 220 °C for 2 h and at 160, 190 °C for 6 h in a nitrogen atmosphere and measured the changes of the equilibrium moisture content of the heat-treated wood under the conditions of relative humidity of 34%, 65% and 98% in the simulated situation. It was observed that as the relative humidity increased, the EMC decreased, and the water absorption rate of the heat-treated wood at 190 and 220 °C decreased during the first 7 h of soaking in water.

Studies have shown that the heat treatment temperature and time have significant impacts on the dimensional stability of wood; the hygroscopic property of wood decreases gradually with the increase of temperature. When the temperature rises to a certain level, the improvement of dimensional stability tends to be slow. With the extension of heat treatment time, the dimensional stability of wood is improved (Priadi *et al.* 2019). Heat treatment can significantly reduce the moisture absorption equilibrium moisture content, and the higher the treatment temperature, the greater the decrease in equilibrium moisture content (Hidayat *et al.* 2018). Zhou *et al*. (2020) heat-treated mahogany wood (*Swietenia macrophylla* King) at 150 to 210 °C at 15 °C intervals for 4 h to study the fiber saturation point and surface wettability. The results showed that heat treatment reduced the fiber saturation point (measured by nuclear magnetic resonance spectroscopy) and surface wettability of the wood, resulting in a decrease in the hygroscopicity of the heat-treated wood. The wood treated at a higher temperature showed a more significant decrease in hygroscopicity. Both Zhang *et al.* (2017) and Nourian and Avramidis (2021) reached similar conclusions.

The surface wettability of heartwood and sapwood samples of teak (*Tectona grandis*) were measured after heat treatment at 180 and 200 °C. The surface wettability of the heartwood and sapwood decreased after the heat treatment, and the wettability of the heartwood was lower than sapwood (Lopes *et al.* 2018). Chang *et al.* (2019) tested the hygroscopicity of air-dried, kiln-dried, and heat-treated yellow poplar (*Liriodendron tulipifera*) lumbers, and the results showed that kiln-dried wood had the highest adsorption/desorption value, followed by air-dried wood. The heat-treated wood had the lowest hygroscopicity. The decrease of hygroscopicity and the improvement of stability are the most basic and important performance improvement of heat-treated wood. Other performance changes of heat-treated wood are more or less related to the improvement of hygroscopicity.

Physical and Mechanical Properties

The mechanical properties of wood are of great significance to the furniture and felling industries. So far, the regularities found in the research on heat-treated wood have shown that heat treatment has a significant impact on the mechanical properties of wood (Guntekin *et al.* 2017; Icel and Beram. 2017; Rasdianah *et al.* 2018; Lo Monaco *et al.* 2020). The three components of wood, namely cellulose, hemicellulose and lignin, are degraded and changed in different degrees by high temperature heat treatment, which results in the change of its physical and mechanical properties. Durmaz *et al.* (2019) tested the physical and mechanical properties of Scots pine (*Pinus sylvestris* L.) that was heat-treated at 120, 150, 180, and 210 °C for 4 and 6 hours on a laboratory scale. It was concluded that the compressive strength, bending strength, and modulus of elasticity (MOE) of wood decreased with the increase of treatment temperature and time, and it was suggested that the wood used in furniture, perches, and decoration projects exposed to external influence areas should be subjected to long-term heat treatment at low temperature.

The temperature and time parameters of heat treatment have a decisive influence on the mechanical properties of wood, but the degree of influence is different. Percin *et al.* (2015) heat-treated oak (*Quercus petraea* Liebl.) wood at 160, 190, and 220 °C for 2 and 4 h, and tested some mechanical properties. The results showed that the bending strength (MOR), modulus of elasticity (MOE), tensile strength parallel to the grain (TS), and shear strength parallel to the grain (SS) were all reduced after heat treatment, and the shear strength decreased more than the tensile strength. It was pointed out that the influence of heat treatment temperature on mechanical strength was greater than that of time. The results of Sabino *et al.* (2021) also pointed out that compared with heat treatment time, temperature has a greater impact on mechanical properties.

For heat treatment in open (atmospheric pressure) and closed (under pressure) systems, Can *et al.* (2021) compared the effect of heat treatment at 190 and 212 °C for 2 h on the shear strength of Scots pine (*Pinus sylvestris* L.) wood. The results showed that the shear strength value of heat-treated wood all decreased, and the maximum reduction was 40% when heat treatment at 212 °C for 2 h at atmospheric pressure.

Compared with other mechanical properties of heat-treated woods, the surface hardness of the treated woods is not greatly affected. Appropriate heat treatment conditions will improve the modulus of elasticity and make the wood have higher rigidity. After heat treatment, the compressive strength parallel to grain will also improved. Herrera-Diaz *et al.* (2019) found that after steam heat treatment on radiata pine (*Pinus radiata* D. Don) at 190 °C for 3 h, the modulus of elasticity increased by about 15 to 32%. Wu *et al.* (2019) studied the hardness (*H*) and reduced elastic modulus (E_r) of larch (*L. gmelinii*) and red oak (*Q. rubra*) wood cell walls after heat treatment at seven temperatures including 200 to 500 °C for 10 minutes *via* nanoindentation. The randomly selected valid data concerning reduced elastic modulus (E_r) and hardness (*H*) in the secondary cell walls of the larch and red oak wood are summarized in Fig. 2. Within the temperature range of 200 to 225 °C, for larch wood, the modulus of elasticity (E_r) value increased with the increase of temperature. The maximum value was 22.4 GPa (225 °C), but it dropped sharply to 5.7 GPa when the temperature exceeded 300 °C. The hardness value (*H*) increased with an increasing temperature.

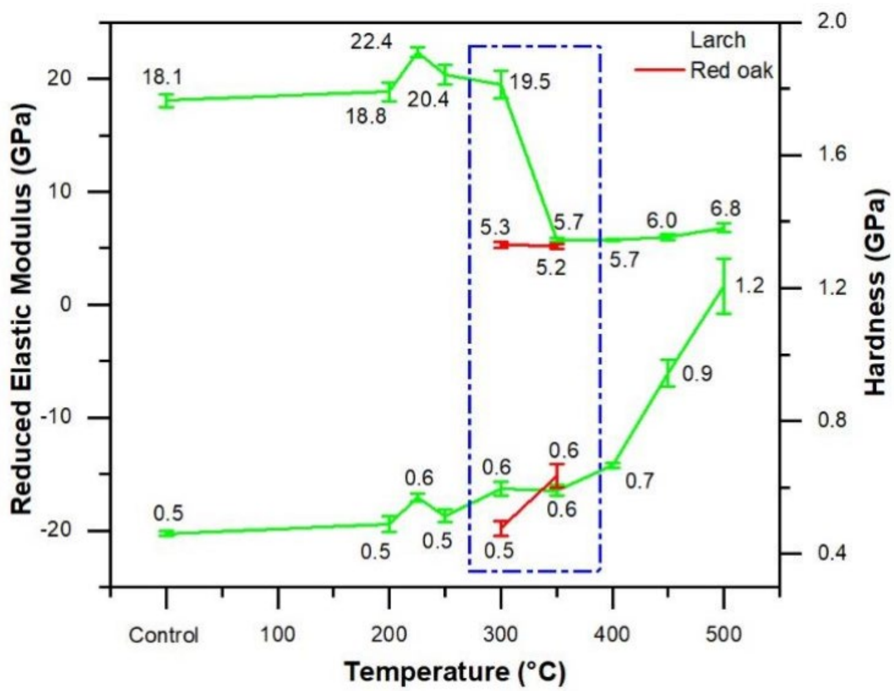

Fig. 2. E_r-temperature and *H*-temperature curves of larch and red oak wood specimens at different temperatures

Biological Durability and Weather Resistance

Under certain conditions, wood cell wall components and various carbohydrates contained in the cell cavity are susceptible to decay by various wood-rot fungi under certain conditions, causing wood to rot and degrade. The free radicals produced in the course of heat treatment have a certain inhibitory effects on fungi and molds, and the decay resistance of wood is improved. Relevant studies have shown that heat-treated rubber wood has improved decay resistance to brown rot fungi and white rot fungi (Shukla and Sharma 2018). The resistance of light red meranti (*Shorea spp.*) and Kedondong (*Canarium spp.*) to white rot bacteria is improved after steam heat treatment (Dahali *et al.* 2020). Wang *et al.* (2016) conducted oil bath heat treatment of poplar and Mongolia Seoteh pine (*Pinus sylvestris* var. *mongolica* Litv.) with vegetable oil as heat conduction medium and studied the decay resistance of heat-treated wood in room. The results showed that after oil heat treatment, the mass loss rate of poplar decreased from 19.4% to 5%, and that of Mongolia Seoteh pine decreased from 8.2% to 3.2%. Oil heat treatment effectively improved the decay resistance of wood.

However, although wood heat treatment imparts good resistance to both white rot fungi and brown rot fungi, and strong resistance to blue rot fungi, it cannot prevent or reduce the mildew on the wood surface. This is because the growth of mold mainly depends on proteins and low-molecular-weight sugar of wood, and its pyrolysis products (such as reducing sugar) may accelerate the growth of mold. In addition, high-temperature thermally modified wood generally cannot resist termite attack, thus limiting its applications. Candelier *et al.* (2020) tested the anti-termite activity of compounds extracted from heat-treated ash wood and found that the anti-termite activity of heat-treated ash wood extract was not significant. Esteves *et al.* (2021) also pointed out that heat treatment did not increase *Paulownia tomentosa* wood durability against termites.

Compared with untreated wood, heat-treated wood has better UV resistance. After the wood is treated at high temperature, it produces phenolic compounds that are resistant to light aging. These compounds can inhibit the fading of the wood to a certain extent, so after a period of strong sunlight, the heat-treated wood is better than the untreated wood in terms of color stability. Tomak *et al.* (2018) studied the effect of 48 months of weathering on the color of ash, iroko, Scots pine, and spruce wood relative to their heat-treated counterparts. It was found that surface roughness increased as the weathering time increased, surface quality and color stability were enhanced with the thermal modification for all wood species, and hardwood performed better. However, they concluded that thermal modification might not adequately protect the surface appearance and color stability in long-term outdoor conditions. Godinho *et al.* (2021) also summarized and pointed out that thermal modification was ineffective for restricting light-induced color changes and the photodegradation of wood polymers. Cai *et al.* (2020) quantified the amount of bound water, fiber saturation point (FSP), cell wall pores, and free water distribution of thermally modified Scots pine, Norway spruce, and European ash. The above thermally modified woods showed better performance than the unmodified woods after weathering.

Acoustic Properties

Long-term natural aging will reduce the hygroscopicity of wood and improve its acoustic quality. It was found that the specific dynamic elastic modulus of wood increases, the loss factor decreases, and the transmission performance of wood mechanical vibration is improved (Obataya 2016). Heat treatment can play a similar role of natural “aging”, which improves the acoustic properties of wood and at the same time shortens the long period required for normal “aging”. As a new interior material, the sound absorption performance of heat-treated wood should be considered.

Chung *et al.* (2017) heat-treated *Larix kaempferi* wood commonly used in construction at 200, 220, and 240 °C for 9, 12, 15, and 18 h. The sound absorption coefficients of heat-treated wood samples were measured in a reverberation chamber at 250, 500, 1000, 2000, and 4000 Hz, respectively. The results showed that the sound absorption coefficient increased with the increase of processing temperature and time. The increased rate of the sound absorption coefficient in the high frequency range was higher than that in the low frequency range. The sound absorption coefficient in the high frequency range of wood can be significantly improved by heat treatment. The results laid the foundation for the future research of heat-treated wood as indoor materials.

The acoustic vibration energy of wood directly determines the acoustic quality of wood as a musical instrument to a large extent. The energy loss of wood caused by friction loss is expressed by logarithmic attenuation rate $\ln(A_1/A_2)=\alpha \times T_0$. The lower the logarithmic attenuation coefficient of wood, the greater the acoustic vibration energy and the better the acoustic performance. The specific dynamic elastic modulus is the ratio of elastic modulus to density, which is one of the physical quantities representing the vibration efficiency and quality of musical instrument soundboards. The greater the dynamic elastic modulus of wood, the lower the density, that is, the greater the specific elasticity and the vibration efficiency of wood. Therefore, the soundboard of a musical instrument with excellent performance generally has a high specific dynamic modulus of elasticity. Kang *et al.* (2016) evaluated the resonance frequency and logarithmic attenuation rate of untreated and heat-treated Yezo spruce (*Picea jezoensis*), Northern red oak (*Quercus rubra*), and Japanese red pine (*Pinus densiflora* S. et Z.) by the free vibration method. The changes in the resonance frequency of the 1st mode and other modes caused by the heat treatment were evaluated, and the changes in the logarithmic attenuation rate caused by heat treatment were evaluated. The results showed that the resonant frequencies of the 1st mode of all specimens were decreased after heat treatment. In the case of the specimen with a higher resonant amplitude at the 2nd mode resonance frequency, the resonant amplitude of the 1st mode resonance frequency was increased more by heat treatment, so that the sound became more stable. Karami *et al.* (2020) treated spruce wood specimens at mild temperatures of 130 and 150 °C and different relative humidities of 0% to 25%, and found that the vibration characteristics of the specimens improved with the decrease of damping (tan δ). However, this type of heat treatment also has certain requirements with respect to the environmental humidity, and the modification effect was better within the relative humidity range of 60% to 75%. On the contrary, higher environmental humidity will significantly reduce the acoustic quality of wood (Endo *et al.* 2016).

Surface Finishing Properties and Processing Properties

The finishing property of the wood surface after heat treatment decreases, which is due to the resin and other extracts inside the wood that ooze out and solidify on the surface during the heat treatment process. Generally speaking, the bonding strength of wood and adhesive will be reduced due to heat treatment (Kariz and Sernek 2010). Although the improvement of the dimensional stability of wood after heat treatment may reduce the stress caused by the shrinkage or expansion of the adhesive layer, the adhesion between adhesive and wood will also change. The distribution of water-soluble adhesive on wood surface, wettability, and penetration of pores will be weakened due to the decrease of hygroscopicity of heat-treated wood. In addition, with the change of heat treatment time and temperature, the pH value of wood will also change, thus affecting the finishing performance of heat-treated wood. The decrease of pH value on the surface of heat-treated wood may also affect the curing of the adhesive (Miklecic and Jirous-Rajkovic 2016). An increase in the acidity of wood surface could affect the wettability of the wood and adhesion of waterborne coatings on heat-treated wood (Altgen *et al.* 2014).

After heat treatment, the surface roughness values and toughness of the wood decrease and the brittleness increases, which has a significant impact on its processing performance (Budakçı *et al.* 2013; Shukla 2019). It is easy to produce local splits during the cutting process, resulting in edge processing defects such as chipping, and the dust generated during the cutting process is also smaller.

MECHANISM OF HIGH-TEMPERATURE HEAT TREATMENT

The main components of wood contain chromophoric groups such as carbonyl groups, carboxyl groups, unsaturated double bonds and conjugated systems, and auxochrome groups such as hydroxyl groups. During the heat treatment of wood, polysaccharides are degraded to generate more carbonyl and carboxyl groups, resulting in the gradual darkening of wood color (Hu *et al.* 2012; Vybohova *et al.* 2018). Similar to ordinary wood, the color of heat-treated wood will be also affected by the environment in which it is used. Under the influence of factors such as temperature, humidity, light, and rain, the lignin content gradually decreases, the holocellulose becomes the dominant component of the cell wall, and the surface color gradually turns gray and white (Huang *et al.* 2012).

Wood cellulose and hemicellulose molecules have a large number of hydroxyl groups, and these are the most active and hygroscopic groups in chemical reactions. Heat treatment can reduce the hydroxyl content, causing the wood to lose some of its moisture exchange capacity, while also reducing the equilibrium moisture content of wood. During heat treatment, certain polysaccharides of hemicellulose are first cracked into products such as furfural, and these substances can be repolymerized as the heat treatment continues. It is a water-insoluble polymer that improves the hydrophobicity of wood and reduces the swelling and shrinkage of wood. Changes in the crystallinity of cellulose and chemical changes or plasticization of lignin will also reduce the swelling properties of wood after treatment. In addition, heating within a certain temperature range can eliminate the internal growth stress of the wood and reduce the deformation of the wood in response to moisture changes. Thus, the dimensional stability of the heat-treated wood is significantly improved.

The cross-linking reaction of cellulose, lignin, and xylan in the S2 layer of wood cell wall will aggravate the pyrolysis reaction of high molecular polymers. This will reduce the hygroscopic property of heat-treated wood but increase the brittleness and reduce the mechanical strength. Due to the different contents of pentoses, which have a great impact on the mechanical properties in hemicellulose in different wood species, the tensile strength, impact bending strength and wood toughness of hardwood with more pentosan in hemicellulose were significantly reduced in comparison to those of softwood with the same treatment after heat treatment. Yin *et al.* (2011) used imaging Fourier Transform Infrared (FT-IR) microscopy and nanoindentation to track changes in the chemical structure and the micromechanical properties of the secondary cell wall. It was found that the changes in hygroscopicity and micromechanical properties that occur with the increase of steam temperature were closely related to the degradation of polymer (hemicellulose and lignin) components in the cell wall (Wang *et al.* 2018).

The reasons for the decay resistance of heat-treated wood are as follows: 1) After heat treatment, the hygroscopicity decreases and the hydrophobicity increases, making the humidity of the living environment of decay bacteria unsuitable for its growth; 2) Hemicellulose is degraded during heat treatment process, making decayed bacteria lack food for survival; 3) Heat treatment causes permanent chemical changes in wood cell wall materials, which makes the enzymes involved in fungal degradation unable to recognize it as a suitable substrate; 4) New extracts that can be used as fungicides are produced during the heat treatment. The study of Hao *et al.* (2018) showed that the hydrolysis of cellulose in wood decreases at higher heating temperature, which explains why the decay resistance increases with increasing degree of heat treatment.

APPLICATION OF HIGH-TEMPERATURE HEAT-TREATED WOOD

After the wood is modified by heat treatment, it is not easy to be deformed, the water absorption rate is reduced (Bytner *et al.* 2021), and the dimensional stability and the weather resistance are improved (Shukla and Sharma 2018). These changes expand the application field of wood. To a certain extent, the imbalance between the supply and demand of wood in China has been alleviated, and its added value has been increased. The modified wood has superior performance in architectural decoration. Whether it is for ordinary interior architectural decoration or for special architectural decoration, there is a large application space. In addition, high temperature heat-treated wood also shows many advantages as packaging materials in trade transportation.

Decorative Materials

Heat-treated wood generally has the advantages of beautiful appearance, good dimensional stability, and uniform moisture content. It is a preferred building material for interior construction and decoration such as doors, windows, floor panels, and furniture. After heat treatment, the wood color will change from light brown to dark brown, which can play a better role in adjusting the color in architectural decoration, so as to achieve the antique visual effect, and enhance the overestimated elegance of the building. For this reason, heat-treated wood is also widely used in architectural decoration of floors and walls to enhance the warmth of the interior (Cao *et al.* 2021).

Heat-treated wood has superior decay resistance and dimensional stability, so it is also widely used in swimming pools, kitchens, and buildings with heavy water vapor, such as the decorative materials in the sauna must have small shrinkage, good dimensional stability, no bad smell, and good thermal insulation properties. The resin in fir and pine wood is basically discharged to the surface of the wood and then gradually decomposes under high-temperature heat treatment. At the same time, heat-treated fir and pine have the characteristics of low water absorption, good dimensional stability, and high resistance to biological degradation. These attributes meet the needs for sauna room materials, such that heat-treated wood has become the first choice for sauna interior decoration (Domingos *et al.* 2018). In addition, the construction of outdoor pavilions, tables and chairs, as well as fences, is also extensively made of heat-treated wood.

Packaging Materials

As a common packaging material, wood is widely used in the transportation, trading, and preservation of products. It plays a very good role in protection, support, and loading. Especially in international trade, wood packaging has many advantages. It is very suitable for the logistics of mechanical and electronic products. First of all, wood packaging has a high strength, can resist certain mechanical damage, and can perform as part of a buffer system during unloading. Secondly, the cost of wood packaging is lower and it has better economic efficiency. Finally, wood packaging can be recycled and reused without causing white pollution. It is an environmentally friendly natural green material. These advantages are irreplaceable by other materials, especially cardboard and plastic. As packaging materials, especially in cross-border trade and transportation, the emphasis should be on the treatment of pest wood, diseased, and dead wood, because once pests are spread through trade and transportation, they will have a serious impact on the local ecology. For a long time, fumigation treatment has been an important method for pests treatment (Fu *et al.* 2012). However, the residues of the fumigation treatment may affect the environment. At the same time, insects may also develop resistance to the drugs, which may lead to problems such as incomplete elimination. Therefore, some scholars believe that safe and efficient heat treatment technology also has considerable advantages in the treatment of pest wood.

PROSPECTS OF HEAT TREATMENT TECHNOLOGY

With the continuous improvement of environmental protection awareness, the wood industry is developing rapidly in the direction of green and environmental protection. Heat treatment is a physical modification method. Compared with chemical modification, the heat treatment process is simpler and it generates relatively little pollution. Only temperature and water vapor are involved in the heat treatment of wood, and no chemical agents are added. Therefore, heat treatment is quite environmentally friendly and safe. Heat-treated wood is an environmentally friendly material. At the same time, heat-treated wood has anti-decay and insect-proof functions, prolongs its service life, and greatly improves its performance, such as reduced water absorption and moisture swellability, improved dimensional stability, and almost no deformation or cracking of its products.

Although wood heat treatment has been continuously and deeply studied, and the products have been widely used, there are still some problems that need to be solved at present, and there is room for further improvement in basic research and product performance:

1) Generally speaking, the improvement of wood durability by heat treatment is not as significant as the improvement of dimensional stability. It is necessary to avoid contact with the soil during use, and this improvement is at the expense of mechanical strength. Related applications are mainly applied to non-structural applications. In terms of mechanism, the improvement in stability and durability of heat-treated wood and the decrease in strength are closely related to the degradation of hemicellulose, so this contradiction is irreconcilable. But through process innovation and optimization, this problem can be improved to a large extent. The heat treatment process can be finely adjusted according to specific tree species and uses to further optimize product performance. It is also possible to explore the combination of heat treatment and wood surface densification to improve the mechanical properties and surface hardness of wood (Cai *et al.* 2013).

2) There is a need to establish a comparison model and system of heat treatment parameters and performance indicators. The goal is to predict and control the treatment effect of the product, so as to design the high temperature treatment process more clearly and efficiently.

3) The object of the heat treatment process is not limited to logs or sawn timber, but it can also be used to promote the application of various wood-based panels and veneer products. For example, heat-treated thin wood is applied to the surface veneer of composite wood-based panels, or the surface of wood-based panels is carbonized to give a certain surface hydrophobicity, decoration, and other properties and effects.

4) There are opportunities to make comprehensive use of various micro-analysis instruments, further explore the modification mechanism of high temperature heat treatment technology, optimize the modification process of high temperature heat treatment, improve the quality of heat treatment materials, and establish a unified evaluation standard for heat treatment materials to standardize the heat treatment product market.

5) The release level of volatile organic compounds during high temperature heat treatment is much higher than that of conventional drying. Along with the heat treatment modification, the exhaust gas pollution purification treatment and absorption device is equipped to prevent the release of organic volatile compounds to pollute the air and harm human health.

ACKNOWLEDGMENTS

The authors acknowledge the fundings of Key Scientific and Technological Project of Anhui Province (CN)(No.1704a070076) and Scientific and Technological Project of Jiangsu Province (CN)(SZ SQ2019023). Additional thanks go for Prof. Jiabin Cai for his helpful advice and critical reading of the manuscript.

REFERENCES CITED

Altgen, M., Ala-Viikari, J., Hukka, A., Tetri, T., and Militz, H. (2014). "Performance of water-borne coating systems on thermally modified wood," *7th European Conference on Wood Modification.*

Ayata, U., Gurleyen, L., and Esteves, B. (2017). "Effect of heat treatment on the surface of selected exotic wood species," *Drewno* 60(199), 105-116. DOI:10.12841/wood.1644-3985.198.08

Banadics, E. A., and Tolvaj, L. (2019). "Colour modification of poplar wood by steaming for brown colour," *European Journal of Wood and Wood Products* 77(4), 717-719. DOI:10.1007/s00107-019-01397-9

Budakçı, M., İlçe, A. C., Gürleyen, T., and Utar, M. (2013). "Determination of the surface roughness of heat-treated wood materials planed by the cutters of a horizontal milling machine," *BioResources* 8(3), 3189-3199. DOI: 10.15376/biores.8.3.3189-3199

Bytner, O., Laskowska, A., Drozdzek, M., Kozakiewicz, P., and Zawadzki, J. (2021). "Evaluation of the dimensional stability of black poplar wood modified thermally in nitrogen atmosphere," *Materials* 14(6), 1491. DOI:10.3390/ma14061491

Cai, C. Y., Javed, M. A., Komulainen, S., Telkki, V. V., Haapala, A., and Herajarvi, H. (2020). "Effect of natural weathering on water absorption and pore size distribution in thermally modified wood determined by nuclear magnetic resonance," *Cellulose* 27(8), 4235-4247. DOI:10.1007/s10570-020-03093-x

Cai, J. B., Yang, X., Cai, L. P., and Shi, S. Q. (2013). "Impact of the combination of densification and thermal modification on dimensional stability and hardness of poplar lumber," *Drying Technology* 31(10), 1107-1113. DOI:10.1080/07373937.2013.775147

Can, A., Krystofiak, T., and Lis, B. (2021). “Shear and adhesion strength of open and closed system heat-treated wood samples,” *Maderas: Ciencia y Tecnología* 23(34), 1-19. DOI:10.4067/s0718-221x2021000100432

Candelier, K., Thevenon, M., Collet, R., Gerardin, P., and Dumarcay, S. (2020). “Anti-fungal and anti-termite activity of extractives compounds from thermally modified ash woods,” *Maderas: Ciencia y Tecnología* 22(2), 223-240. DOI:10.4067/S0718-221X2020005000209

Cao, S., Cai, J. B., Wu, M. H., Zhou, N., Huang, Z. H., Cai, L. P., and Zhang, Y. L. (2021). “Surface properties of poplar wood after heat treatment, resin impregnation, or both modifications,” *BioResources* 16(4), 7562-7577. DOI:10.15376/biores.16.4.7562-7577

Chang, Y. S., Park, J. H., Park, Y., Lee, J. H., and Yeo, H. (2019). “Evaluation of hygroscopic property of thermally treated yellow poplar (*Liriodendron tulipifera*) wood,” *Journal of the Korean Wood Science and Technology* 47(6), 761-769

Chung, H., Park, Y., Yang, S. Y., Kim, H., Han, Y., Chang, Y. S., and Yeo, H. (2017). “Effect of heat treatment temperature and time on sound absorption coefficient of *Larix kaempferi* wood,” *Journal of Wood Science* 63(6), 575-579. DOI:10.1007/s10086-017-1662-z

Dahali, R., Lee, S., Ashaari, Z., Bakar, E., Ariffin, H., Khoo, P., Bawon, P., and Salleh, Q. (2020). “Durability of superheated steam-treated light red meranti (*Shorea* spp.) and Kedondong (*Canarium* spp.) wood against white rot fungus and subterranean termite,” *Sustainability* 12(11), article no. 4431. DOI:10.3390/su12114431

Domingos, I., Ferreira, J., Cruz-Lopes, L., and Esteves, B. (2018). “Water-related properties of *Pinus pinaster* wood treated by different methods,” *Drewno* 61(202):69-80. DOI: 10.12841/wood.1644-3985.270.07

Durmaz, E., Ucuncu, T., Karamanoglu, M., and Kaymakci, A. (2019). “Effects of heat treatment on some characteristics of scots pine (*Pinus sylvestris* L.) wood,” *BioResources* 14(4), 9531-9543. DOI:10.15376/biores.14.4.9531-9543

Endo, K., Obataya, E., Zeniya, N., and Matsuo, M. (2016). “Effects of heating humidity on the physical properties of hydrothermally treated spruce wood,” *Wood Science and Technology* 50(6), 1161-1179. DOI:10.1007/s00226-016-0822-4

Esteves, B., Ferreira, H., Viana, H., Ferreira, J., Domingos, I., Cruz-Lopes, L., Jones, D., and Nunes, L. (2021). “Termite resistance, chemical and mechanical characterization of *Paulownia tomentosa* wood before and after heat treatment,” *Forests* 12(8), article no. 1114. DOI:10.3390/f12081114

Fu, C. H., Hu, B. Y., Chang, T. T., Hsueh, K. L., and Hsu, W. T. (2012) “Evaluation of dazomet as fumigant for the control of brown root rot disease,” *Pest Management Science* 68(7), 959-962. DOI: 10.1002/ps.3303

Godinho, D., Araujo, S. D., Quilho, T., Diamantino, T., and Gominho, J. (2021). “Thermally modified wood exposed to different weathering conditions: A review,” *Forests* 12(10), article no. 1400. DOI:10.3390/f12101400

Gonzalez-Pena, M., and Hale, M. (2009). “Colour in thermally modified wood of beech, Norway spruce and Scots pine. Part 1: Colour evolution and colour changes,” *Holzforschung* 63(4), 385-393. DOI:10.1515/HF.2009.078

Guntekin, E., Aydin, T., and Usner, B. (2017). “Physical, mechanical and bonding performance of calabrian pine (*Pinus brutia* Ten.) as influenced by heat treatment,” *Drvna Industrija* 68(2), 99-106. DOI:10.5552/drind.2017.1533

Hao, Y. N., Pan, Y. F., Du, R., Wang, Y. M., Chen, Z. J., Zhang, X. T., and Wang, X.,M. (2018). "The influence of a thermal treatment on the decay resistance of wood via FTIR analysis," *Advances in Materials Science and Engineering* 2018, article no. 8461407. DOI:10.1155/2018/8461407

Herrera-Diaz, R., Sepulveda-Villarroel, V., Torres-Mella, J., Salvo-Sepulveda, L ., Llano-Ponte, R., Salinas-Lira, C., Peredo, M., and Ananias, R. (2019). "Influence of the wood quality and treatment temperature on the physical and mechanical properties of thermally modified radiata pine," *Eur. J. Wood. Wood. Prod.* 77(4), 661-671. DOI:10.1007/s00107-019-01424-9

Hidayat, W., Qi, Y., Park, B., Banuwa, I., Febrianto, F., and Kim, N. (2017). "Color change and consumer preferences towards color of heat-treated korean white pine and royal paulownia woods," *Journal of the Korean Wood Science and Technology* 45(2), 213-222. DOI:10.5658/WOOD.2017.45.2.213

Hidayat, W., Febrianto, F., Purusatama, B., and Kim, N. (2018). "Effects of heat treatment on the color change and dimensional stability of *Gmelina arborea* and *Melia azedarach* woods," *E3S Web of Conferences* 68: 03010. DOI:10.1051/e3sconf/20186803010

Hu, C. S., Jiang, G. F., Xiao, M., Zhou, J. H., and Zhao, Y. (2012). "Effects of heat treatment on water-soluble extractives and color changes of merbau heartwood," *Journal of Wood Science* 58, 465-469. DOI:10.1007/s10086-012-1265-7

Huang, X. A., Kocaefe, D., Kocaefe, Y., Boluk, Y., and Pichette, A. (2012). "A spectrocolorimetric and chemical study on color modification of heat-treated wood during artificial weathering," *Applied Surface Science* 258(14), 5360-5369. DOI:10.1016/j.apsusc.2012.02.005

Icel, B., and Beram, A. (2017). "Effects of industrial heat treatment on some physical and mechanical properties of iroko wood," *Drvna Industrija* 68(3), 229-236. DOI:10.5552/drind.2017.1720

Jiang, H. C., Lu, Q. J., Li, G. J., Li, M., and Li, J. N. (2020). "Effect of heat treatment on the surface color of rubber wood (*Hevea brasiliensis*)," *Wood. Research* 65(4), 633-644. DOI:10.37763/wr.1336-4561/65.4.633644

Kamperidou, V., Barboutis, I., and Vasileiou, V. (2013). "Response of colour and hygroscopic properties of Scots pine wood to thermal treatment," *Journal of Forestry Research* 3(24), 571-575. DOI:10.1007/s11676-013-0389-y

Kang, H. Y., Kang, C. W., Hong, S. H., and Matsumura, J. (2016). "Effect of heat treatment on the acoustic properties of a wooden xylophone keyboard," *Journal-Faculty of Agriculture Kyushu University* 61(1), 157-163. DOI:10.5109/1564098

Karami, E., Bardet, S., Matsuo, M., Bremaud, I., Gaff, M., and Gril, J. (2020). "Effects of mild hygrothermal treatment on the physical and vibrational properties of spruce wood," *Composite Structures* 253(2), article no. 112736. DOI:10.1016/j.compstruct.2020.112736

Kariz, M., and Sernek, M. (2010). "Bonding of heat-treated spruce with phenol-formaldehyde adhesive," *J. Adhesion Sci. Technol.* 24(8-10), 1703-1716. DOI:10.1163/016942410X507768

Lo Monaco, A., Pelosi, C., Agresti, G., Picchio, R., and Rubino, G. (2020). "Influence of thermal treatment on selected properties of chestnut wood and full range of its visual features," *Drewno* 63(205), 5-24. DOI:10.12841/wood.1644-3985.344.10

Lopes, J., Garcia, R., and Nascimento, A. (2018). "Wettability of the surface of heat-treated juvenile teak wood assessed by drop shape analyzer," *Maderas Ciencia y Tecnología* 20(2), 249-256. DOI:10.4067/S0718-221X2018005002801

Michel, V. (2007). "Heat treatment of wood in France-state of the art," Centre Technique du Bois et de l'Ameublement, Paris, France.

Miklecic, J., and Jirous-Rajkovic, V. (2016). "Influence of thermal modification on surface properties and chemical composition of beech wood (*Fagus sylvatica* L.)," *Drvna Industrija* 67(1), 65-71. DOI:10.5552/drind.2016.1520

Nourian, S., and Avramidis, S. (2021). "Exploratory thermal modification of western hemlock," *Wood Mater. Sci. & Eng.* 16(4), 221-228. DOI: 10.1080/17480272.2019.1694979

Obataya, E. (2016). "Effects of natural and artificial ageing on the physical and acoustic properties of wood in musical instruments," *Journal of Cultural Heritage* 27, S63-S69. DOI:10.1016/j.culher.2016.02.011

Percin, O., Sofuoglu, S., and Uzun, O. (2015). "Effects of boron impregnation and heat treatment on some mechanical properties of oak (*Quercus petraea* Liebl.) wood," *Bioresources* 10(3), 3963-3978. DOI:10.15376/biores.10.3.3963-3978

Priadi, T., Sholihah, M., and Karlinasari, L. (2019). "Water absorption and dimensional stability of heat-treated fast-growing hardwoods," *Journal of the Korean Wood Science and Technology* 47(5), 567-578. DOI:10.5658/WOOD.2019.47.5.567

Rasdianah, D., Zaidon, A., Hidayah, A., and Lee, S. (2018). "Effects of superheated steam treatment on the physical and mechanical properties of light red meranti and kedondong wood," *Journal of Tropical Forest Science* 30(3), 384-392. DOI:10.26525/jtfs2018.30.3.384392

Sabino, T., Surdi, P., Vilela, A., Metzker, S., Coelho, N., Oliveira, T., and Mendes, R. (2021). "Effect of the post-heat treatment on the properties of medium density particleboard of *Eucalyptus* sp," *Floresta e Ambiente* 28(3), article no. e20200079. DOI:10.1590/2179-8087-floram-2020-0079

Shukla, S. R. (2019). "Evaluation of dimensional stability, surface roughness, colour, flexural properties and decay resistance of thermally modified *Acacia auriculiformis*," *Maderas. Ciencia y Tecnología* 21(4), 433-446. DOI: 10.4067/S0718-221X2019005000401

Shukla, S., and Sharma, S. (2018). "Effect of high temperature treatment of *Hevea brasiliensis* on density, strength properties and resistance to fungal decay," *J. Indian. Acad. Wood. S* 15(1). 87-95. DOI:10.1007/s13196-018-0213-6

Tomak, E., Ustaomer, D., Ermeydan, M., and Yildiz, S. (2018). "An investigation of surface properties of thermally modified wood during natural weathering for 48 months," *Measurement* 127, 187-197. DOI:10.1016/j.measurement.2018.05.102

Viitanen, H., Jämsä, S., Paajanen, L., Nurmi, A., and Viitaniemi, P. (1994). "The effect of heat treatment on the properties of spruce. A preliminary report," *Document-the International Research Group on Wood Preservation* (Sweden) 146(6), 829-833. DOI:10.1016/S0163-4453(82)92731-1

Vybohova, E., Kucerova, V., Andor, T., Zaneta, B., and Vekova, V. (2018). "The effect of heat treatment on the chemical composition of ash wood," *BioResources* 13(4), 8394-8408. DOI:10.15376/biores.13.4.8394-8408

Wang, X. Z., Chen, X. Z., Xie, X. Q., Wu, Y., Zhao, L. G., Li, Y. J., and Wang, S. Q. (2018). "Effects of thermal modification on the physical, chemical and micromechanical properties of Masson pine wood (*Pinus massoniana* Lamb.)," *Holzforschung* 72(12), 1063-1070. DOI:10.1515/hf-2017-0205

Wang, Y. M., Fan, H. Q., and Du, R. (2016). "Study on decay resistance of oil heat-treated wood with cellulose contents tested by Fourier infrared spectrum analysis," *Oxidation Communications* 39(1.pt.1), 83-90.

Wu, Y., Zhang, H., Zhang, Y., Wang, S., Wang, X., Xu, D., and Liu, X. (2019). "Effects of thermal treatment on the mechanical properties of larch (*Larix gmelinii*) and red oak (*Quercus rubra*) wood cell walls via nanoindentation," *BioResources* 14(4), 8048-8057. DOI:10.15376/biores.14.4.8048-8057

Xie, Y. J., Liu, Y. X., and Yao, X. (2002). "Heat-treated wood and its development in Europe," *Journal of Forestry Research* 13(3), 224-230. DOI:10.1007/BF02871703

Yang, Y., Zhan, T. Y., Lu, J. X., and Jiang, J. H. (2015). "Influences of thermo-vacuum treatment on colors and chemical compositions of alder birch wood," *BioResources* 10(4), 7936-7945. DOI:10.15376/biores.10.4.7936-7945

Yin, Y. F., Berglund, L., and Salmén, L. (2011). "Effect of steam treatment on the properties of wood cell walls," *Biomacromolecules* 12(1), 194-202. DOI:10.1016/j.carbpol.2014.08.040

Zhang, Y., Xu, D. L., Ma, L. B., Wang, S. Q., and Liu, X. (2017). "Influence of heat treatment on the water uptake behavior of wood," *BioResources* 12(1), 1697-1705. DOI:10.15376/biores.12.1.1697-1705

Zhou, F., Fu, Z. F., Gao, X., and Zhou, Y. D. (2020). "Changes in the wood-water interactions of mahogany wood due to heat treatment," *Holzforschung* 74(9), 853-863. DOI:10.1515/hf-2019-0192

Article submitted: February 22, 2022; Peer review completed: March 20, 2022; Revised version received and accepted: April 2, 2022; Published: April 6, 2022.
DOI: 10.15376/biores.17.2.Cao