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Review Article

Heat-Treated Wood as a Substrate for Coatings, Weathering of Heat-Treated Wood, and Coating Performance on Heat-Treated Wood

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Heat treatment is a method of wood modification with increasing market acceptance in Europe. The major patented European commercial heat treatment processes have trade names ThermoWood, Platowood, Retiwood, Le Bois Perdure, and Oil-Heat-Treated Wood (OHT). To what extent modification of wood affects the resistance of wood to weathering is also an important aspect for wood applications, especially where appearance is important. Unfortunately, heat-treated wood has poor resistance to weathering, and surface treatment with coatings is required for both protection and aesthetic reasons. As a substrate for coating, heat-treated wood has altered characteristics such as lower hygroscopicity and liquid water uptake and changed acidity, wettability, surface free energy, and anatomical microstructure. Various wood species, heat treatment method, treatment intensity, and treatment conditions exhibited a different extent of changes in wood properties. These altered properties could affect coating performance on heat-treated wood. The reported changes in acidity and in surface energy due to heat treatments are inconsistent with one another depending on wood species and temperature of the treatments. This paper gives an overview of the research results with regards to properties of heat-treated wood that can affect coating performance and weathering of uncoated and coated heat-treated wood.

1. Introduction

Heat treatment is one of the wood modification methods for improving wood properties such as dimensional stability, water resistance, and biological durability without using harmful chemicals. In recent years, wood products with increased performance and without toxic preservatives are increasingly demanded by customers, thus contributing to the popularity of heat-treated wood. Heat-treated wood is increasingly used in many applications such as hardwood flooring, siding/cladding, decking, saunas/wall panelling, windows/doors, and garden furniture. Heat treatment or thermal modification is controlled pyrolysis of wood being treated at high temperatures between 180°C and 240°C under an oxygen-free atmosphere to avoid burning, involving either steam, nitrogen, or oil [1]. Important process variables are temperature and atmosphere. Different processes give different heat-induced chemical changes in wood [2]. The main commercial heat treatment processes in Europe are covered by patents, and wood products are treated under names such as ThermoWood, Platowood, Retiwood, Le Bois Perdure, and Oil-Heat-Treated Wood (OHT) [3].

The most used industrial process of wood thermal modification is the ThermoWood process [4]. The International ThermoWood Association defines and certifies the standard conditions of the process, and only members of the International ThermoWood Association can use the ThermoWood trademark. The ThermoWood process can be divided into three phases: Phase 1: by means of heat and steam, the kiln temperature is raised rapidly to a level of around 100°C; Phase 2: the temperature inside the kiln is increased to a level between 185°C and 230°C and then maintained at that level for 2-3 hours; and Phase 3: the final stage where temperature decreases to 80–90°C using water spray and then remoisturizing and conditioning takes place to bring the wood moisture content to a useable content over 4% [5].

The Plato process is a two-stage hydrothermal process performed in a stainless-steel reactor at relatively mild conditions with an intermediate drying stage in a conventional kiln. This process leaves high cellulose content in wood which is crucial to optimize final mechanical properties. The process was developed and is used by the Plato Company in the Netherlands for the production of flooring, cladding, decking, and rough sawn timber [3, 6].

The retification process is mild pyrolysis of wood under a nitrogen atmosphere, industrialised in France and sold under the name Retiwood. The name of the process comes from the French word rétification, which is the abbreviation of réticulation (creation of chemical bonds between polymeric chains) and torréfaction (roasting). The second French process is named Le Bois Perdure (the Perdure process). This process is relatively close to the retification process, and the properties of modified wood processed with both methods are similar. The wood is heated to 230°C in a steam atmosphere, the steam being generated from the water from the green wood [6].

The oil heat treatment process involves heating of wood in vegetable oil (sunflower, rape seed oil, or linseed oil). In a closed process vessel, wood is immersed in hot oil and heated at temperatures between 180 and 220°C to ensure good durability at acceptable strength reduction. The process was developed in Germany and is sold under the name Menz Holz OHT.

A heat treatment always results in darkening of wood (Figure 1), often explained by the formation of coloured degradation products from hemicelluloses and extractive compounds [7–9]. The formation of oxidation products such as quinones is also referred to as the reason for darker wood colour [10, 11]. This dark colour change is often seen positively, especially as it results in temperate hardwoods, resembling tropical wood species [11–13].

Besides improved stability, reduced hygroscopicity, and dimensional changes, heat-treated wood also has some shortcomings, such as loss of toughness, reduced tensile and bending strengths, unstable colour in exterior exposure, and appearance of surface cracking [14]. Unfortunately, it has been established that the resistance of heat-treated wood against weathering (UV light and moisture changes) is not changed largely when compared to untreated wood, making a surface treatment with coatings necessary [15, 16].

2. Heat-Treated Wood as a Substrate for Coatings

Heat-treated wood is a good substrate for coatings as it is dry after production and free of resin which runs out during heating. It has been established that, at the temperatures above 180°C, fats and waxes disappeared from the sapwood surface and caused no problem with adhesion [17]. Compared to the unmodified wood, heat-treated wood has altered characteristics. The chemical composition of heat-treated wood is changed by degrading the cell wall compounds and extractives [18]. The level of change depends on the wood species, type of heat treatment, treatment intensity, and process conditions, in which the temperature and the absence of oxygen play an important role [15]. As a result of these changes heat-treated wood has lower hygroscopicity [10, 14, 15], liquid water uptake [19–23], and consequently reduced dimensional changes. Besides, it was shown that the heat-treated wood has changed acidity, wettability, surface free energy, and anatomical structure. Changed properties of heat-treated wood can affect the properties of the whole wood-coating system such as the wetting of heat modified wood by coating, penetration, and adhesion of the coating.

It should be noted that contradictory results have been reported in the literature concerning the acidity of heat-treated wood. It was shown that two-stage heat treatment at temperature <200°C reduced the pH of radiata pine (*Pinus radiata* D.), Norway spruce (*Picea abies* Karst), and birch wood (*Betula pendula*) to 3.5–4 due to the production of acetic acid and formic acid [24]. Higher acidity of heat-treated wood was also reported by Miklečić and Jirouš-Rajković [25] for beech wood (*Fagus sylvatica* L.) and Pavlič [23] for Scots pine wood (*Pinus sylvestris* L.). Several studies have shown decrease in the pH of heat-treated wood depends on the heating temperature and time [26, 27]. However, Herrera et al. [20] reported that acidity values of European ash wood (*Fraxinus excelsior* L.) decreased with the intensity of treatment (pH increased gradually). Gerardin et al. [28] also reported decrease of wood acidity of heat-treated beech wood (*Fagus sylvatica* L.) and pine wood (*Pinus sylvestris* L.) at 240°C under the nitrogen atmosphere. Altgen et al. [29] reported an increase in the acidity for heat-treated Scots pine wood (*Pinus sylvestris* L.) and Norway spruce wood (*Picea abies* L.) at low treatment intensities (180°C and 2 hours). The low-intensity treatment resulted in higher acidity than a treatment at higher temperatures (212°C and 3 hours) which might be due to further release of organic acids as volatile organic compounds out of the kiln at higher temperature or due to the possible reaction of organic acids with the cell wall components. Hofman et al. [30] reported a diverse range of the pH, depending on the wood species and intensity of heat treatment. For oak wood (*Quercus robur* L.) pH increased with intensifying the treatment, while for beech wood (*Fagus sylvatica* L.) and ash wood (*Fraxinus versicolor* L.) pH decreased between untreated and medium levels. Higher treatment temperature caused the pH to increase again to the level of the untreated samples. Based on these results, it can be concluded that the method of heat modification, the wood species, and the treatment intensity have a significant influence on the changes in the chemical composition during the heat treatment and consequently on acidity of modified wood. The altered surface properties of wood could affect coating performance on heat-treated wood. Lower absorption of water of heat-treated wood could, for example, reduce the liquid water permeability of the whole system heat-treated wood-solid coating and thus influence the durability of coating. An increase in the acidity of wood surface could affect the wettability of the wood [31] and adhesion of waterborne coatings on heat-treated wood [29].

It has been shown that heat treatments also change wood wettability and surface energy of wood. These two surface

(a) (b) (c)

Figure 1: Increase of dark coloration of beech wood with increasing of treatment temperature. Untreated samples (a) and heat-treated samples at 190°C (b) and 212°C (c).

properties can also affect the coating process. Miklečić and Jirouš-Rajković [25] studied the influence of thermal modification of beech wood (*Fagus sylvatica* L.) on surface properties and reported that water contact angle on beech wood was higher and that it increased with modification temperature (Table 1). Several authors also reported a decrease in wood wettability and, consequently, increase in hydrophobicity with increasing heat treatment temperature [28,32–34]. Gérardin et al. [28] established that the hydrophobic behavior of the wood surface was due to some modified wood surface properties caused by heat treatment. Pétrissans et al. [33] suggested that an increase of cellulose crystallinity could be a possible reason for the decrease of wettability of heat-treated wood. Hakkou et al. [34] suggested that modification of the conformational arrangement of wood biopolymers due to loss of residual water or lignin plasticization may be a possible reason for wettability modification during the heat treatment of wood. However, Awoyemi et al. [19] reported that soybean oil treatment and in-treatment cooling increased surface wettability by water.

Wood wettability and surface energy are surface properties that influence the interactions between substrate and coating during the bonding process. There are discrepancies in the literature about whether thermal treatment reduces or increases surface free energy of wood (Table 2) because of the difficulties in contact angle measurements on wood and different approaches to calculating surface free energy. Gerardin et al. [28] investigated surface energy of untreated and heat-treated beech and pine sapwood using Lifshitz–van der Waals acid-base approach. The results showed that surface free energy of wood was slightly reduced after heat treatment (Table 2). After heat treatment, the Lifshitz–van der Waals component of wood surface free energy was slightly modified while the acid-base component was strongly reduced. The most significant alteration after heat treatment was shown with the electron-donating component

Table 1: Contact angle of water, formamide, and diiodomethane on untreated and heat-treated beech wood at 190°C and 212°C [25].

Type of substrate	Contact angle (°)		
	Water	Formamide	Diiodomethane
Untreated	55.9	38.3	34.2
Heat-treated at 190°C	73.0	31.1	45.7
Heat-treated at 212°C	81.1	32.4	35.6

($\gamma-$) which might be due to degradation of the hemicelluloses and the loss of predominantly oxygen-containing functional groups [37]. Wolkenhauer et al. [37] also reported slight reduction of the Lifshitz–van der Waals component of wood surface free energy and no distinct differences in total surface energy between untreated and heat-treated beech wood samples. Miklečić and Jorouš-Rajković [25] also found a reduction in total surface free energy of beech wood after heat treatments and a strong reduction of the acid-base component. Chu et al. [36] calculated the total surface free energy according to the OWRK (Owens–Wendt–Rabel–Kaelble) method and established that the surface energy of heat-treated poplar wood (Populus beijingensis W.Y.Hsu) decreased with increasing temperature and polar component of surface energy also decreased with increasing temperature. In contrast, Petrič et al. [35] reported that the thermal modification process in vacuum of spruce wood increased the surface free energy and decreased the polarity of wood, at the modification temperature of 210°C. The total surface free energy of the modified wood specimens increased from 54.4 mJ/m^2 for control specimens to 59.7 mJ/m^2 for wood modified at 210°C. At the same time, a substantial drop of the polar component of the surface free energy was observed.

A slight increase in wood surface energy and decrease of polar component were also reported by Herrera et al. [20] for

Table 2: Comparison of surface free energy of heat-treated (HT) and untreated wood samples.

	LW-AB approach							
Substrate	γ^{LW}	γ^{AB}	γ^{+}	γ^{-}	γ_{tot}	Temperature (°C)	Heat treatment	Reference
Beech untreated	49.5	9.1	1.5	13.5	58.6			
Pine untreated	46.4	8.2	1.1	15.8	54.8			[28]
Beech HT	50.9	5	2.3	2.7	55.8	240	Treatment under nitrogen	
Pine HT	50.7	1.5	0.8	0.7	52.2	240		
	OWRK approach							
Substrate	γ_S^d		γ_S^p		γ_S	Temperature (°C)	Heat treatment	Reference
Beech untreated	38.7		13.9		52.6			
Beech HT	39.9		6.8		46.7	190	Treatment under vapor	[25]
Beech HT	46.3		2.6		48.9	212		
Spruce untreated	53.4		0.97		54.4			[35]
Spruce HT	59.6		0.04		59.7	210	Vacuum treatment	
Poplar untreated	34.98		8.07		43.05			
Poplar HT	36.99		3.77		40.76	160		
Poplar HT	36.31		4.35		40.66	180	Treatment under vapor	[36]
Poplar HT	37.63		1.67		39.31	200		
Poplar HT	37.55		1.13		38.68	220		
European ash untreated	43.94		6.74		50.68			
European ash HT	52.19		0.1		52.2	192		
European ash HT	52.61		0.1		52.62	202	Treatment under vapor	[20]
European ash HT	51.58		0.1		51.59	212		

ash wood (*Fraxinus excelsior* L.) after heat treatments. As can be seen from Table 2, the surface free energy values of heat-treated woods range from 39.31 to 59.37 mJ/m^2. In general, for good wetting, coatings should have lower surface tension than the surface free energy of the substrate, or they should at least be equal [38]. Too high surface tension of the liquid coating might be the reason for insufficient substrate wetting, and reducing the surface tension of waterborne coatings could improve their adhesion and performance on heat-treated wood. Vernois [39] reported that surface energy of the retified wood is drastically affected after heat treatment and that painting and finishing usually used for untreated wood cannot be used without adjusting them to altered wood properties. Regardless, Jämsä et al. [40] reported that heat-treated wood is comparable to untreated wood as a substrate for coatings and no alterations in coating recommendations are needed when considering coating of heat-treated wood. Normal painting processes present no problems, but when electrostatic painting is used, heat-treated wood requires extramoisturising [41]. However, the increased hydrophobic character of heat-treated wood and changed polarity of wood could cause problems with adhesion of waterborne coatings. The problems with reducing of coating adhesion to heat-treated wood were established in several studies [1, 42, 43]. Petrič et al. [44] investigated the wettability of oil heat-treated Scots pine wood (*Pinus sylvestris* L.) with some commercial waterborne coatings and showed better wetting of heat-treated wood by waterborne coating than wetting of untreated wood. In contrast, Miklečić and Jirouš-Rajković [25] showed better wetting of unmodified beech wood by waterborne coatings than wetting of heat-treated wood. They also reported lower adhesion strength of waterborne coatings on heat-treated beech wood samples and higher amount of wood fracture than those on untreated wood. Altgen et al. [29] reported that penetration of waterborne coatings was not affected by the heat treatment of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L.) and adhesion strength of waterborne coatings strongly depended on the coating system that was used. The adhesion strength of one of the applied coatings was lower on heat-treated wood compared to untreated wood; irrespective of the wood species, the treatment intensity or the surface preparation technique. Kesik and Alkyldiz [45] investigated the influence of heat treatment on the adhesion strength of waterborne coatings using Calabrian pine wood (*Pinus brutia* Ten.), Anatolian black pine wood (*Pinus nigra* J.F. Arnold), sessile oak wood (*Quercus petraea* Liebl.), and sweet chestnut wood (*Castanea sativa* Mill.) and established decrease of adhesion with increasing of heat-treatment temperature and time of heat treatment. Nevertheless, when choosing waterborne coating systems for heat-treated wood, it is advisable to ask the manufacturer of heat-treated wood to recommend acceptable coating systems that can cope with altered properties of modified wood.

3. Coating Systems for Heat-Treated Wood

Due to horizontal surface, accumulation of water, and full exposure to sun and rain, finishing of heat-treated wood decking is more demanding than other wood finishing (e.g., exterior claddings). Penetrating finishes are recommended for such surfaces because they do not form a film and give better overall performance and have the easiest maintenance and refinishing [46, 47]. Finishing of heat-treated wood is very similar to finishing normal kiln-dried wood, so all requirements that have been set for standard wood protection in most cases can be applied to heat-treated wood as well. However, there are several wood properties that have been changed after thermal modification which should be considered during surface finishing of thermally modified wood:

(i) Heat-treated wood becomes more hydrophobic and more acidic [48]

(ii) Heat-treated wood absorbs moisture more gradually, and therefore, it is important to have a care to the absorption of the finish

(iii) Heat-treated wood is less prone to swelling and shrinking but still an elastic finish is recommended

(iv) Heat-treated wood has a darker colour which is prone to fading due to exposure to light

Transparent stains and oils do not protect surfaces from weathering discolouration, and they are only recommended for finishing of thermally modified wood products that are kept under a cover or away from direct sunlight and rain. Recently more and more attention is paid to the influence of the visible spectrum of sunlight on heat-treated wood because it has significant impact on the change in colour of dark wood (bleaching). The new approach for light stabilisation of dark wood species (i.e., heat-treated wood) has been developed combining selected visible light screeners with organic UV light absorbers [49]. Oils fall into the category of penetrating finishes which enhance the natural wood grain and appearance [50]. Absorption of wood surfaces as well as ingress of liquids and dirt is reduced using oil [51]. There are many oils on the market intended for outdoor application which look "natural" and are designed specifically for decks and garden furniture and formulated to resist weathering. Additionally, for thermally modified wood products that are exposed to direct sunlight for some part of a day, it is recommended to protect them with pigmented stains and oils. For thermally modified wood that is exposed to a whole range of different weather conditions, opaque coatings provide the best protection. However, coatings that form a film on the surface of the wood are not recommended for use on decking because the coating film tends to peel due to change of moisture. Generally, the pigmented finish systems slightly darken the colour of thermally modified wood.

4. Weathering of Uncoated Heat-Treated Wood

Weathering of wood is a combination of degradation by solar radiation, moisture changes, and oxidation and temperature effects [52]. Due to weathering, exterior woods discolour, erode, develop cracking, checking, and mould or mildew growth on the surface. It was reported that short-term colour stability of retified ash, beech, poplar, and pine wood exposed to artificial weathering was better than that of unmodified wood [53]. However, the original dark brown colour of the uncoated thermally treated spruce (*Picea abies* L.) and pine wood (*Pinus sylvestris* L.) panels were not stable when exposed outdoors and turned grey [40]. Thermally modified beech (*Fagus sylvatica* L.) in a nitrogen atmosphere was more resistant to natural and artificial weathering than unmodified control wood and showed a reduction of photochemical degradation and improvement of the resistance against discolouring mould fungi during natural weathering. European spruce (*Picea abies*), conversely, exhibited a minor part of these improvements [54]. However, thermal modification of either species had small but measurable effects on the performance and durability of semitransparent and film-forming stains applied to the samples. Feist and Sell [54] assumed that reduced photochemical degradation after thermal modification might be due to low equilibrium moisture content of thermally modified wood because the wood moisture content strongly influences photochemical degradation [55]. Nuopponen et al. [17] studied chemical changes of unmodified and thermally modified Scots pine samples after 7 years of natural weathering in Finland and reported that the lignin content of unmodified samples was lower than lignin content of thermally modified samples and degradation products did not leach out easily in the case of modified samples as in the case of the unmodified samples. It might be due to increased condensation of lignin induced by heat treatment. After artificial weathering, heat-treated Scots pine wood (*Pinus sylvestris* L.) showed better surface characteristics (higher gloss and lower surface roughness) than untreated Scots pine wood [56]. Deka et al. [57] found that colour changes of heat-treated spruce wood (*Picea abies* L.) were lower than untreated spruce wood after long-term artificial UV light exposure. It could be due to an increase in lignin stability by condensation at the time of heat treatment process at 210°C. Similarly, lower colour differences after one year of outdoor exposure exhibited oil-heat-treated pine wood (*Pinus sylvestris*) in comparison with colour changes of the weathered untreated wood [44]. Miklečić et al. [58] measured discolouration of untreated and heat-treated wood species (at 212°C): beech (*Fagus sylvatica* L.), ash (*Fraxinus excelsior* L.), and hornbeam (*Carpinus betulus* L.) and established that heat-treated wood samples discoloured slowly compared to untreated samples (Figure 2). Accordingly, FTIR spectra of heat-treated ash, beech, and hornbeam wood samples exposed to UV light showed similar chemical changes as untreated wood samples exposed to UV light, but less pronounced.

Heat-treated Oriental beech (*Fagus orientalis* L.) wood also showed better colour stability compared to nonreated samples after three months of natural weathering during winter. Natural weathering affected heat-treated beech wood samples less than untreated samples in terms of gloss loss and surface roughness. Also, higher temperature of the heat treatment and longer duration gave better surface properties after outdoor weathering process [59]. Photodegradation of both heat-treated and untreated Larix spp. wood was evaluated in terms of colour, microstructure, and chemical changes during accelerated weathering tests. Ultraviolet light caused a quick change of colour, and deformations and cracks in both heat-treated and untreated samples were observed using SEM. It was found that heat treatment was effective in improving colour stability only in the first stage of exposure to artificial weathering

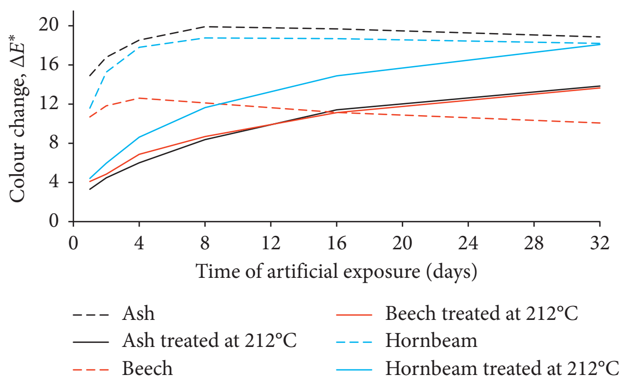

Figure 2: Colour change of untreated and heat-treated ash, beech, and hornbeam wood samples at 212°C [58].

but was ineffective in improving UV resistance of wood over long-term photodegradation conditions [60]. Yildiz et al. [61] studied colour stability and chemical changes of heat-treated alder wood (*Alnus glutinosa* L.) after natural weathering. They reported that the colour change caused by weathering factors was not prevented by heat treatment but only slowed down. Significant deformation and degradation in wood components, particularly in the hemicelluloses of heat-treated samples, were shown by FTIR-ATR spectroscopy. Increasing the time and temperature of the treatment affected degradation of hemicelluloses. There is inconsistency in the literature about whether heat-treated wood is susceptible to cracking when it is exposed outdoors. Vernois [39] reported that cracking due to dimensional changes was reduced by heat-treated wood in comparison to natural wood. On the contrary, cracking of the heat-treated spruce (*Picea abies* L.) and pine (*Pinus sylvestris* L.) wood exposed to outdoor conditions without coating was equivalent to the cracking of the untreated wood and finishing with unpigmented or low build stains, and oils did not prevent cracks to appear in heat-treated wood [40]. Feist and Sell [54] found more cracking and grain raising on thermally modified spruce wood in nitrogen atmosphere than on unmodified wood, and surfaces were noticeably rougher after 14 months of outdoor exposure. On the contrary, thermally modified beech wood (*Fagus sylvatica* L.) samples were smoother than unmodified ones with little noticeable differences in cracking. Miklečić et al. [22] reported that uncoated untreated samples of three wood species (oak, ash, and beech) had less surface cracks than heat-treated uncoated samples during accelerated weathering. The cracking of the heat-treated wood samples was reduced by oil treatment. Boonstra et al. [62] investigated effect of two-stage heat treatment process (Plato process) on the anatomical structure of softwood and reported that species with narrow annual rings and/or an abrupt transition from earlywood into latewood were the most susceptible to tangential cracks in the latewood section and that radial cracks appeared mainly in impermeable wood species such as Norway spruce (*Picea abies* L.). Altgen et al. [63] suggested that anatomical microdefects in Norway spruce (*Picea abies* L.) and Scots pine (*Pinus sylvestris* L.) wood caused by heat treatment might have an impact on the formation of cracks during the use of wood in exterior conditions.

5. Performance of Coatings on Heat-Treated Wood

Feist and Sell [54] established that, after 14 months of outdoor exposure, both semitransparent penetrating and film-forming stains performed worse on thermally heat-treated spruce samples than those on the untreated samples. The semitransparent stains performed somewhat better on heat-treated beech wood samples than on untreated samples, while the film-forming stain performed poorly on both heat-treated and untreated samples. Miklečić et al. [22] established that heat-treated wood finished with oils absorbed less water than unfinished heat-treated wood. Deka and Petrič [64] studied the effect of two waterborne acrylic coating on photodegradation of thermally modified wood and unmodified wood and established that the whole substrate-coating system exhibited better photo resistance when heat-treated wood was used as a substrate. Pavlič [23] studied compatibility of nine different coatings with heat-treated Scots pine wood (*Pinus sylvestris* L.). Coatings applied on heat-treated wood exhibited better performance than coatings on unmodified wood. This could be explained by the changed characteristics of heat-treated wood such as lower equilibrium moisture content, lower water permeability, increased dimensional stability, better resistance to blue stain fungi, and better UV stability in comparison with those of untreated wood. Better penetration of the coating into heat-treated wood and better wetting of heat-treated wood with coatings were also shown.

After one year of exterior weathering, the solvent-borne coatings exhibited better performance than waterborne coatings [23]. After more than 10 years of using ThermoWood products in a built environment, the assessment results showed that colour changed to grey and that fibre erosion and surface shakes were quite common for ThermoWood products [65]. Pigmented film-forming coating for decking had very short life span and required regular maintenance, although oil-based finishes were a better option even though the colour would not be maintained. Miklečić et al. [66] studied interaction of heat-treated beech wood with nanoparticles-modified waterborne polyacrylate coating during outdoor and artificially exposure. Results showed that colour stability of heat-treated beech wood was improved by the addition of TiO_2-rutil and ZnO nanoparticles to the coating (Figure 3). However, nanosized ZnO increased peeling and cracking of coating and caused the reduced adhesion of coating on heat-treated beech wood.

Ahola et al. [67] observed the performance of the coated heat-treated and untreated spruce wood and pine wood during five years of exposure. Even though the moisture content of heat-treated wood has been found to be lower compared to untreated wood, no decrease in surface growth of coated wood was detected. The heat treatment used did not have an influence on mould and blue stain growth on coated wood in service [67]. Jämsä et al. [40] found that acid

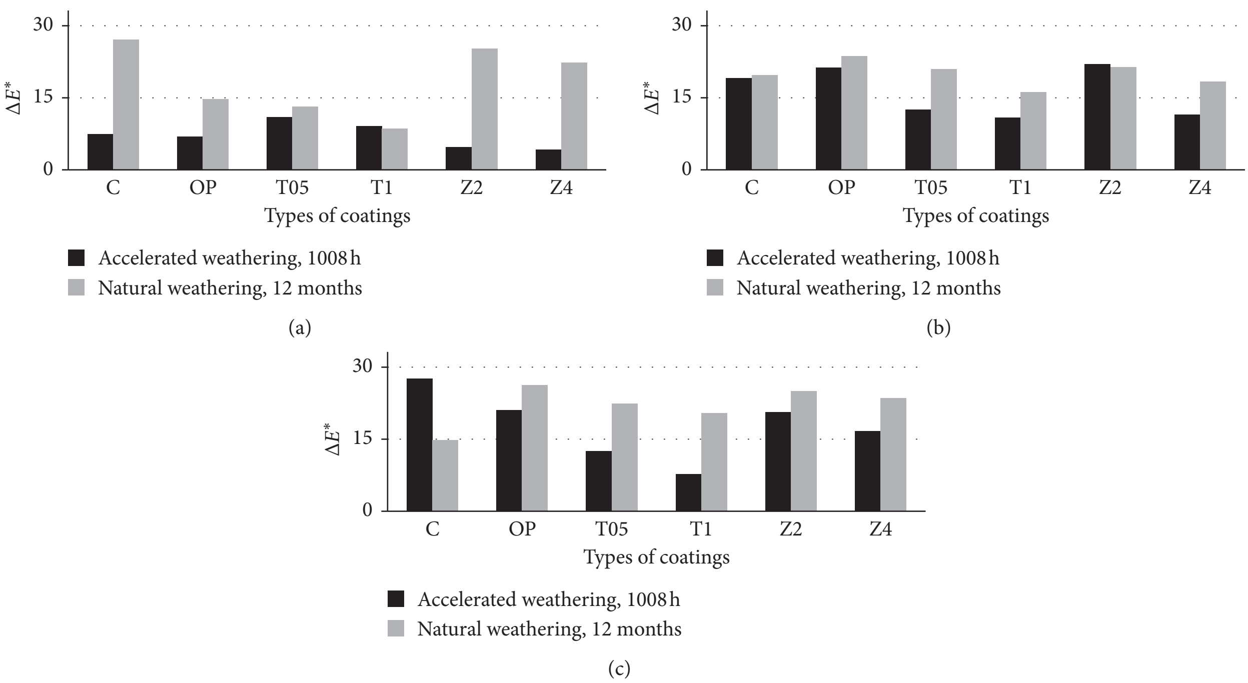

Figure 3: Colour change of untreated (N) (a) and heat-treated beech wood at 190 (b) and 212°C (c). The samples were uncoated (C), coated with net coating (OP), TiO_2 nanocoatings concentration 0.5 and 1% (T05 and T1), and ZnO nanocoatings concentration 2 and 4% (Z2 and Z4) [66].

curable and waterborne acrylic paint had better performance on heat-treated wood than on untreated spruce wood after five years of natural weathering. They also reported that the best coating systems for the heat-treated wood were the systems consisting of the oil base coat and solvent-borne alkyd and waterborne acrylic top coat.

6. Conclusions

Although moisture content of heat-treated wood and swelling and shrinkage due to moisture are greatly reduced, it has been established that heat-treated wood is not resistant to weathering. To keep attractive appearance of heat-treated wood products, it is essential to protect wood surface with appropriate coatings. Compared to unmodified wood, heat-treated wood as a substrate for coating has altered properties due to chemical changes and structural modifications in the cell wall during heating. In addition to reduced hygroscopicity and water absorption, heat-treated wood has also changed acidity, wetting properties, and surface free energy. There is discrepancy between results in the literature on the changes in these properties during the heat treatment which can be influenced by the method of heat treatment, heat treatment temperature, and wood species. The changed properties of heat-treated wood can affect coating performance and its adhesion to the heat-treated wood, especially for waterborne coatings. The performance of coatings in outdoor applications depends on many factors and is very difficult to compare results obtained using different wood species as substrate, different heat treatment process parameters, different coating systems, and different exposure conditions. However, it has been established that the protection effect of coating strongly depends on the degree of the pigmentation. To protect heat-treated wood from discolouration induced by visible part of sunlight, the now approach for light stabilisation has been developed combining selected visible light screeners with organic UV light absorbers. As with untreated wood, the selection of wood coating for heat-treated wood depends on the type of wood product, exposure conditions, and end use categories.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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