Effects of Thermal Modification of Oak Wood Upon Selected Properties Of Coating Systems

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In the last few years there has been an increased demand to change the natural color of valuable hardwoods without chemicals for use mainly in indoor parquet floors. In this study, wood samples from oak (*Quercus petraea* L.), one of the most used species for parquet, were heat treated (ThermoWood method) at 190 °C for 2 h and at 212 °C for 1 and 2 h. Untreated and heat treated wood surfaces were coated following two different applications: type 1, with a single layer of sealer (50 g/m^2) and type 2 with two layers (35 g/m^2) using a nanolacke varnishing system. The objective of this study was to investigate surface properties including adhesion, glossiness, pendulum hardness, and color (L^*, a^*, b^*, ΔE^*, ΔL^*, Δa^*, and Δb^*). With heat treatment the lightness decreases, and its decrease is higher for higher temperatures and treatment times. Type 2 coated wood presented a slightly lower lightness decrease. The experiment showed a slight increase followed by a decrease in redness (lower a^*) and a clear decrease in the yellow tone (b^*). The total color variation increased with the intensity of the treatment, while the glossiness decreased (more for Type 1 coated wood). The adhesion strength and surface hardness decreased with the heat treatment in both the Type 1 and Type 2 coated wood samples. The decrease in adhesion was higher for Type 2, reaching 67%, while the decrease in surface hardness reached about 18%.

Keywords: Parquet; Heat treatment; Oak; Glossiness; Color; Adhesion

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INTRODUCTION

In present day industry, wood heat treatment processes are well established. The success of heat treatment over other procedures, such as chemical modification using acetylation (Accoya®) or impregnation modification using furfurylation (Kebony®), is due to the lower cost and simplicity of the heat treatment and the fact that the alternative methods are based on the use of chemicals.

There are several heat treatment processes that follow different heating processes and operating conditions. Nevertheless, the heating processes generally have four phases: heating, treatment, cooling, and stabilization. In recent years, several processes have successfully evolved into commercial processes. Amongst these commercial processes are ThermoWood®, Plato Wood®, and Perdure®. The ThermoWood® process (Viitaniemi *et al*. 1997) uses steam to prevent contact between the wood and oxygen in the air. This process leads to a product with decreased moisture content, which improves the dimensional stability and durability of the wood against fungi, except if it is in ground contact (Rapp 2001).

The high temperatures used in thermal modification changes the chemical composition of wood, producing a new material with improved properties. The main chemical differences are as follows: decreased hemicellulose content (Sivonen *et al*. 2002; Esteves *et al*. 2008; Chen *et al*. 2012); deacetylation that leads to the release of acetic acid (Tjeerdsma *et al.* 1998) which induces further degradation; increased cellulose crystallinity due to amorphous cellulose degradation (Tjeerdsma and Militz 2005); and the crosslinking of methylene bridges during lignin formation (Tjeerdsma *et al.* 1998; Nuopponen *et al.* 2005). These chemical changes in the structural wood components induce different properties on the wood surfaces, for example, the wood will become darker (Sundqvist and Morén 2002; Esteves *et al.* 2007) with lower wettability (Pétrissans *et al.* 2003; Hakkou *et al.* 2005; Metsä-Kortelainen and Viitanen 2012) and thermal conductivity.

Heat treatment alters the way the wood surface interacts with adhesives, mainly for waterborne adhesives. The rate of absorption of these adhesives is slower than in untreated wood, which affects the adhesion process (Poncsák *et al.* 2007; Sernek *et al.* 2008). Kariz *et al.* (2013) suggested that this is due to the hydrophobic character of heat-treated wood, which affects the distribution of the adhesive on the wood surface and its penetration of the porous wood structure. Demirci *et al.* (2013) studied the effect of thermal aging on the adhesion properties of several varnishes and stated that the adhesion strength of alkyd varnishes is much better than for waterborne varnishes on aged samples.

The process of adhesive penetration has been described by Bastani *et al.* (2015) as "the movement of a fluid glue from the surface into the voids and porous structure of wood tissue". Furthermore, these authors divided penetration in two groups: gross penetration, which corresponds to the filling of cell lumens and large voids, and cell wall penetration, which occurs when the tiny voids and microstructure of the wood cell wall is filled. Also hardness is an important property in flooring materials and is known to increase or decrease after heat treatment, depending on the species and direction of the tests (Shi *et al.* 2007). However, decreases are generally under 5% (Korkut *et al.* 2008). For example Budakçı *et al.* (2016) reported that the hardness of Uludag fir, linden and black poplar decreased with the intensity of the heat treatment.

In finished wood, studies have shown that the main differences are attributable to the varnish type and that species do not have any significant effect on varnish layer hardness, except when using nanolacke varnish systems (Kaygin and Akgun 2008). Glossiness generally decreases with heat treatment (Aksoy *et al.* 2011; Karamanoglu and Akyildiz 2013; Korkut *et al.* 2013). There are several other processes that change the way adhesives interact with wood. A recent review on these methods, including plasma treatments, chemical and enzymatic modifications, application of thin films and deposition of nanoparticles by sol-gel techniques, was done by Petrič (2013).

Although heat treatment processes are generally used in low-valued softwoods, there has been an increased use of this modification to change the natural color of more valuable hardwoods without using any chemicals; these woods are mainly used on indoor parquet floors. This work presents the main differences in the surface of parquet made from untreated and heat treated oak, a commonly used species for this kind of product.

EXPERIMENTAL

Materials

Oak (*Quercus petraea* L.) wood samples came from Hasep Wood Veneer Industry and Trade Inc., in Duzce, Turkey. The samples, air dried and with an initial moisture content of around 12% measured 110 cm × 10 cm × 1.6 cm.

Heat Treatment Process

The samples were subjected to the ThermoWood® heat treatment process in the Novawood factory in Gerede-Bolu, Turkey. The ThermoWood method consists of three stages: a rapid increase of temperature by using heat and steam up to 100 °C; a milder increase up to 130 °C over 1 h; and a fast increase up to the treatment temperature (190 °C or 212 °C in this case), which is maintained for 1 h or 2 h. Afterwards, the wood is cooled and left to stabilize. The total time of treatment was around 40 h. Three different operating conditions were used, 190 °C for 2 h and 212 °C for 1 h and 2 h. Sixty samples were treated in each case. After the treatment, heat treated and untreated wood samples were conditioned at 20 ± 2 °C with a relative humidity (RH) of 65 ± 5% according to ISO 554 (1976).

Parquet Flooring Material

Parquet flooring materials were obtained from the KPS factory in Duzce, Turkey. The production methods are shown in Table 1. The varnish (N93-0910 nanolacke UV matt varnish) is a type of varnish consisting of polyacrylic-based resin and nanosilica-containing minerals. This varnish was applied in untreated and heat treated wood. After the application of the nanolacke varnish, the wood samples were cut to 10 cm × 10 cm × 1.8 cm.

Table 1. Two Different Types of Nanolacke Varnish Application Process

Varnish Application Process	Component	Value
Type 1	A. Sanding (3 cylinders) & Calibrating Machines	80-120-220 Grit Sandpaper
	1. A43-0646-UV Sanding Sealer	50 g/m^2
	B. UV lamp drying (mercury)	2 x 80 W
	C. Sanding 2 cylinders	280-320 grit sandpaper
	2. N93-0910 Nanolacke UV Matt Varnish	7.5 g/m^2
	D. UV lamp drying	2 x 80 W
	3. N93-0910 Nanolacke UV Matt Varnish	7.5 g/m^2
	E. UV lamp drying	400 W
Type 2	A. Sanding (3 cylinders) & Calibrating Machines	80-120-220 grit sandpaper
	1. A43-0646-UV Sanding Sealer	35 g/m^2
	B. UV lamp drying (mercury)	2 x 80 W
	2. A43-0646-UV Sanding Sealer	35 g/m^2
	C. UV lamp drying	400 W
	D. Sanding (2 cylinders)	280-320 grit sandpaper
	3. N93-0910 Nanolacke UV Matt Varnish	7.5 g/m^2
	E. UV lamp drying	2 x 80 W
	4. N93-0910 Nanolacke UV Matt Varnish	7.5 g/m^2
	F. UV lamp drying	400 W

All parquet flooring samples were conditioned at 20 ± 2 °C and 65 ± 5% RH according to ISO 554 (1976) for about 5 weeks until equilibrium was reached, before surface tests. The main difference between type 1 and type 2 applications is that in type 1, a single layer of sealer (50g/m^2) was used while in type 2, two layers (35g/m^2) were used (Table 1). Some properties of the chemicals used to produce this parquet flooring are given in Table 2.

Table 2. Chemicals Used to Produce Parquet Flooring

	A43-0646 - UV Sanding Sealer	N93-0910 Nanolacke UV Matt Varnish
Description	Epoxy acrylic resin, ultraviolet ray curing sealers	Polyacrylic-based resin, nanosilica-containing minerals, nanocomposites UV curing varnish
Color	Transparent	
Solids (wt.%)	95 to 97	95 to 100
Density	1:15 to 1:20 (20 °C, g/cm^3)	1:09 to 1:15 (20 °C, g/cm^3)
Application	Solid hardwood, chipboard, MDF. Formulated for surface application	

Color Measurement

The color measurements of the heat treated and untreated oak wood samples were done in an X-Rite Ci62 series portable spectrophotometer (Regensdor, Switzerland; wavelength resolution, 10 nm; measurement geometry; D/8°), with a D65 standard illuminant. The tests were made in 30 replicates. The system used to monitor color was the CIELAB system, which uses the three parameters, L^*, a^*, and b^*. The L^* axis represents lightness and varies from 100 (white) to 0 (black). The chroma coordinates a and b vary from red ($+a^*$) to green ($-a^*$) and from yellow ($+b^*$) to blue ($-b^*$). The total color difference (ΔE^*) was calculated using Eqs. 1 to 4.

$$\Delta L^* = L^*_{\text{heat treated, UV Varnishing System Applied}} - L^*_{\text{control, UV Varnishing System Applied}} \quad (1)$$

$$\Delta b^* = b^*_{\text{heat treated, UV Varnishing System Applied}} - b^*_{\text{control, UV Varnishing System Applied}} \quad (2)$$

$$\Delta a^* = a^*_{\text{heat treated, UV Varnishing System Applied}} - a^*_{\text{control, UV Varnishing System Applied}} \quad (3)$$

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \quad (4)$$

Glossiness Measurement

Glossiness measurements in coated heat treated and untreated oak wood samples were done in accordance to ISO 2813 (1994), in Gloss Meter Poly gloss GL0030 TQC (TQC BV, Neuss, Germany). The measurements were made perpendicular and parallel to the grain directions with an angle of 60°.

Adhesion Test

The adhesion strength was determined by the pull-off method in ASTM D-4541 (1995), using an electromechanical universal testing machine ALSA Laboratory Equipment Inc. (Umraniye / Istanbul, Turkey). The steel test cylinders (Ø 20 mm) were attached to the specimen surfaces at room temperature (20 °C). Samples were glued using 404 Fast Plastic Steel glue, which is composed of 2,4,6-tris(dimethylaminomethyl)phenol and fixed with tools. All test specimens were air-dried for 24 h, after which the glue residues were removed with a cutter. The adhesion X (MPa) was calculated using Eq. 5.

$$X = 4\mathrm{F} / \pi . d^2 \quad (5)$$

where F is the rupture force (N) and d is the diameter of the experiment cylinder (mm).

Pendulum Hardness

Pendulum hardness measurements were made using a König pendulum. The measurements were made for untreated and heat treated oak wood with Type 1 and Type 2 applications according to the ASTM D 4366-95 (1984) standard. The test was described before by Çakıcıer (2011). Test panels were placed on the panel table and the pendulum was placed on the panel surface and afterwards deflected through 6° and released. The number of oscillations needed for the amplitude to decrease from 6° to 3° was determined.

Statistical Analysis

A statistical analysis was made regarding glossiness, total color, color lightness, red and yellow color tone, adhesion resistance, and pendulum hardness using SPSS 17 Software (Sun Microsystems Inc., Santa Clara, CA, USA). The analysis for the adhesion tests included ten replicates of each specimen. For color lightness, red color yellow color tone, glossiness (parallel (//) and perpendicular (⊥) to the grain glossiness 60°), and pendulum hardness, the average value of thirty replicates was noted.

RESULTS AND DISCUSSION

The results of multiple comparison for the color parameters, *L**, *a**, and *b** are presented in Table 3. The main differences between the color parameters were attributed to the heat treatment.

Table 3. Test Results of Multiple Comparison for the Color Parameters (*L**, *a**, and *b**)

	Heat Treatment	Type	Mean	*HG*	Std. Deviation	Minimum	Maximum
Lightness (*L**)	Control	1	56.77	A*	1.35	52.26	58.24
		2	51.96	B	0.48	50.11	52.62
	190 °C - 2 h	1	24.72	C	0.52	23.79	26.02
		2	23.73	D	0.77	22.64	25.14
	212 °C - 1 h	1	18.71	E	0.23	18.36	19.24
		2	18.23	F	0.24	17.85	18.60
	212 °C - 2 h	1	17.89	G	0.35	17.05	18.46
		2	17.34	H	0.33	16.60	18.27
Red Color (*a**) Tone	Control	1	7.08	D	0.15	6.92	7.65
		2	7.78	C	0.10	7.64	8.06
	190 °C - 2 h	1	8.84	A*	0.22	8.31	9.17
		2	8.49	B	0.38	7.22	8.89
	212 °C - 1 h	1	6.65	E	0.17	6.28	6.99
		2	4.86	G	0.20	4.58	5.31
	212 °C - 2 h	1	4.01	H	0.09	3.83	4.22
		2	5.06	F	0.20	4.74	5.45
Yellow Color (*b**) Tone	Control	1	28.51	A*	0.19	27.91	28.73
		2	28.06	B	0.24	27.64	28.48
	190 °C - 2 h	1	12.41	C	0.68	10.77	13.72
		2	11.54	D	0.98	9.17	13.24
	212 °C - 1 h	1	6.38	E	0.17	5.99	6.68
		2	4.52	F	0.17	4.29	4.90
	212 °C - 2 h	1	2.84	H	0.14	2.66	3.09
		2	3.96	G	0.30	3.45	4.53

A clear decrease on lightness on the surface of oak boards was observed with the higher intensity of the treatment, both for higher temperatures and for longer treating times. For instance, for type 1 application *L** changed from 56.8 (control) to 24.7 for wood treated at 190 °C (2h), and 17.9 for wood treated at 212 °C (2 h). In relation to time of treatment *L** decreased to 18.7 (1 h) and 17.9 (2 h) for the treatment at 212 °C. The main differences however were between the untreated (*L** = 56.8) and the heat-treated wood (*L** = 17.9 to 24.7).

Similar results have been presented for uncoated heat treated wood. For instance, Bekhta and Niemz (2003) observed a similar decrease for heat treated spruce wood, Sundqvist (2002) for Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), and birch (*Betula pubescens*), Esteves *et al.* (2007) with pine (*Pinus pinaster*) and eucalyptus (*Eucalyptus globulus*), and Barcik *et al.* (2015) with oak (*Quercus robur*). Esteves *et al.* (2007) obtained good correlations between lightness decrease and cellulose and hemicellulose content in treated wood, evidencing that the decrease in lightness might be due to the formation of coloured degradation products from hemicelluloses as stated before (Sehlstedt-Persson 2003). Though the major differences are caused by heat treatment, the differences between the Type 1 and Type 2 coated samples were also statistically significant (Table 3). Lightness was lower for the Type 2 coated wood samples in relation to the Type 1 coated samples for both untreated and heat treated oak wood. This was probably due to the higher amount of sealer used in Type 2 application. Similar results have been presented for coated beech (*Fagus orientalis*) treated with similar temperatures and coating systems (Ayata *et al.* 2017).

There was a slight increase followed by a decrease in redness (lower *a**) as the intensity of the heat treatment increased, but the differences between the Type 1 and Type 2 coated wood samples were not consistent. As for *b**, there was a clear decrease in the yellow tone, which was more pronounced between the untreated (*b** = 28.5) and heat treated wood (*b** = 12.4 to 2.8). The variation in *a** and *b** depends on the species and on the initial color, and these values can both increase (Chen *et al.* 2012), both decrease (Guller 2014), both increase then decrease (Bekhta and Niemz 2003; Esteves *et al.* 2007), or exhibit an increase in one and decrease for the other (Srinivas and Pandey 2012).

The total color change (Δ*E**) is mainly influenced by the lightness variation (Δ*L**), which is generally higher than the *a** and *b** variations. Therefore, the total color variation increased with the intensity of the treatment. Δ*E** generally increases with the treatment (Bekhta and Niemz 2003; Chen *et al.* 2012; Guller 2014). The total color variation was smaller for Type 2 coated wood.

Table 4. Color Changes (Δ*L**, Δ*a**, Δ*b**, and Δ*E**) Between Untreated and Heat Treated Wood at 190 °C for 2 h, 212 °C for 1 h and 2 h

Duration	Type	Δ*L**	Δ*a**	Δ*b**	Δ*E**
190 °C - 2 h	1	-32.05	1.76	-16.10	35.91
	2	-28.23	0.71	-16.52	32.72
212 °C - 1 h	1	-38.06	-0.43	-22.13	44.03
	2	-33.73	-2.92	-23.54	41.24
212 °C - 2 h	1	-38.88	-3.07	-25.67	46.69
	2	-34.62	-2.72	-24.10	42.27

The results of the multiple comparisons of the glossiness perpendicular and parallel to the grain, pendulum hardness, and adhesion strength are shown in Table 5. Although the glossiness perpendicular to the grain generally decreases with heat treatment, there was a small increase in the beginning of the treatment at around 190 °C, which decreased afterwards during the more intense treatments. However, this increase was not statistically significant. In relation to the glossiness parallel to the grain, there was a decrease in all treated samples compared with the untreated wood. This decrease in glossiness has been reported for Scots pine (Aksoy *et al.* 2011), wild cherry (Korkut *et al.* 2013), Anatolian black pine, Calabrian pine, sessile oak and chestnut woods (Karamanoglu and Akyildiz 2013), and ash (Herrera *et al.* 2015).

Glossiness of Type 2 coated oak was higher than glossiness of Type 1 coating, as shown in Table 5. This is probably due to the gloss of the sealer used, since the different between the processes is that process 1 has 1 layer and process 2 two layers of sealer. This will also explain the high glossiness of the finishing once the Nanolacke varnish used was in matt version.

Table 5. Test Results of Multiple Comparison for Glossiness Perpendicular and Parallel to the Grain, Pendulum Hardness, and Adhesion Strength

Test	Heat treatment	Process Applied	Mean	*HG*	Std. Deviation	Minimum	Maximum
Glossiness 60º⊥	Control	1	17.19	A	1.15	14.60	19.10
		2	16.46	B	1.29	14.20	18.50
	190 °C - 2 h	1	15.89	C	1.12	13.70	18.00
		2	17.51	A*	0.89	15.70	18.90
	212 °C - 1 h	1	15.83	C	0.77	14.20	17.40
		2	17.27	A	0.53	15.60	18.20
	212 °C - 2 h	1	14.13	E	0.93	12.00	15.90
		2	15.05	D	0.64	13.20	16.00
Glossiness 60º //	Control	1	23.96	B	1.77	20.10	26.50
		2	25.21	A*	1.44	20.90	26.80
	190 °C - 2 h	1	21.11	D	1.58	18.30	24.60
		2	24.10	B	1.18	20.30	26.10
	212 °C - 1 h	1	22.36	C	1.02	19.70	24.20
		2	24.60	AB	1.11	22.20	26.20
	212 °C - 2 h	1	20.12	E	1.46	17.00	22.20
		2	22.17	C	2.25	16.20	24.80
Pendulum Hardness	Control	1	70.73	B	6.16	60.00	85.00
		2	77.73	A*	5.98	67.00	89.00
	190 °C - 2 h	1	63.07	C	7.72	52.00	81.00
		2	63.50	C	8.08	50.00	79.00
	212 °C - 1 h	1	62.00	C	6.61	47.00	78.00
		2	66.23	C	8.30	50.00	83.00
	212 °C - 2 h	1	57.63	D	6.61	46.00	69.00
		2	64.87	C	9.63	50.00	82.00
Adhesion Strength (MPa)	Control	1	2.680	B	0.61	1.860	3.920
		2	4.143	A*	0.28	3.866	4.761
	190 °C - 2 h	1	1.882	CD	0.50	1.016	2.764
		2	2.143	C	0.50	1.564	3.274
	212 °C - 1 h	1	1.544	DE	0.21	1.064	1.816
		2	1.403	E	0.29	1.071	1.800
	212 °C - 2 h	1	1.369	E	0.21	1.092	1.599
		2	1.436	E	0.44	0.873	2.054

Parallel glossiness (along the grain) was generally higher than perpendicular glossiness (across the grain) which is in accordance to the reported before by Bekhta *et al.* (2014).

The hardness of the Type 1 and Type 2 coated oak wood decreased with heat treatment; the decrease was around 11%, 12%, and 18% for Type 1 wood treated at 190 °C for 1 h and at 212 °C for 1 h and 2 h, respectively. The decrease for Type 2 application was a little higher 18%, 15% and 17% for similar treatments. The Type 2 coated wood samples presented a slightly higher hardness than the Type 1 coated wood samples, which is probably due to the higher amount of sealer used. Statistically, the main difference was between the untreated and the heat-treated wood samples, while the difference between the treatments was not significant. The decrease in surface hardness was most likely due to the increased brittleness of the surface after heat treatment. As reported by Shi *et al.* (2007), heat treated wood hardness increases or decreases in accordance to the species, test directions (radial, tangential, and longitudinal), and treatment schedules. Nevertheless, the hardness of wood samples treated at higher temperatures generally decreases. For example, Dilik and Hiziroglu (2012) found a decrease in Janka hardness of heat treated Eastern red cedar (*Juniperus virginiana*), while Tasdemir and Hiziroglu (2014) reported that heat treatment adversely affected the hardness of heat treated Southern pine and aspen. Bakar *et al.* (2013) reported the same for rubberwood, Eastern red cedar, and red oak.

All the samples showed cohesive delamination in the substrate. The adhesion strength decreased in both the Type 1 and Type 2 coated wood after heat treatment. The decrease is higher for higher treating times and for higher temperatures of treatment. The decreased adhesion strength after heat treatment has been reported before by Demirci *et al.* (2013) with Scots pine, Eastern beech, and Sessile oak aged woods or Ayata *et al.* (2017) for heat treated beech parquet and Gurleyen *et al.* (2017) with heat treated Scots pine laminated parquet. Opposing results were reported by Herrera *et al*. (2015); improved adherence on thermally modified ash wood was observed in samples modified at 212 °C. These authors suggested that the improved adherence is due to decreased acidic compounds on the wood surface or the influence of the sanding pre-treatment. These results show that the effects on the curing process of adhesives depend on the adhesive type used, which has been attributed to the decreased pH and wettability of heat-treated wood (Sernek *et al.* 2008; Bastani *et al.* 2015)

Bastani *et al*. (2015) tested the penetration of two waterborne adhesives, emulsion polymer isocyanate (EPI) and polyvinyl acetate (PVAc), and a one-component polyurethane (PU). They concluded that for Scots pine, increasing the treatment temperature improves the effective penetration of all adhesives. Most of the studies on wood bonding are however on shear bonding strength of the adhesive. Nevertheless, decreased shear strength with intensity of the heat treatment has also been reported, for example, for polyvinyl acetate (PVAc) and melamine-urea formaldehyde (MUF) adhesives that were applied to heat treated Scots pine and Oriental beech wood samples (Tiryaki *et al.* 2014). The same was reported by Kol *et al*. (2009) for heat treated tali (*Erythrophleum ivorense*) and iroko (*Chlorophora excelsa*) wood samples that bonded with phenol-formaldehyde (PF), melamine-urea-formaldehyde (MUF), melamine-formaldehyde (MF), and polyurethane (PUR). Nevertheless, the shear strength of the adhesive bond in the treated wood fulfilled the required value for shear strength of adhesive bonds. These results show that each case must be studied to determine the best adhesive for each treated wood.

CONCLUSIONS

1. With heat treatment, lightness decreased, and its decrease was higher for higher temperatures and treating times. Type 2 coated wood presented a slightly lower lightness decrease. The decrease in lightness is probably due to the formation of coloured degradation products during heat treatment, as stated before. There was a slight increase followed by a decrease in redness (lower *a**) and a clear decrease in the yellow tone (*b**). Total color variation increased with the intensity of the treatment, mainly due to the lightness decrease.
2. Glossiness decreased with the heat treatment. The decrease was lower for Type 2 coated wood due to having two layers of sealer which has higher gloss than treated wood.
3. The adhesion strength decreased with the heat treatment for both Type 1 and Type 2 coated wood. This decrease is possibly due to the lower wettability and pH of the heat treated wood surface.
4. Surface hardness decreased with the heat treatment for both Type 1 and Type 2 coated wood. The decrease was lower for type 2 due to the higher amount of sealer used. The decrease was smaller for wood with two layers of sealer (Type 2).
5. These results show that heat treatment affects the way adhesives relate to the wood surface forcing companies to determine the best adhesive systems for each treated wood.

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REFERENCES CITED

ASTM D 4366-95 (1984). “Standard test methods for hardness of organic coatings by pendulum test,” ASTM International, West Conshohocken, PA, USA.

ASTM D 4541 (1995). “Standard test method for pull-off strength of coatings using portable adhesion testers,” ASTM International, West Conshohocken, PA, USA.

Aksoy, A., Deveci, M., Baysal, E., and Toker, H. (2011). “Colour and gloss changes of Scots pine after heat modification,” *Wood Res.* 56(3), 329-336.

Ayata, U., Gurleyen, L., Esteves, B., and Cakicier, N. (2017). “Effect of heat treatment (ThermoWood) on some surface properties of parquet beech (*Fagus orientalis* Lipsky.) with different layers of UV system applied,” *BioResources* 12(2), 3876-3889. DOI: 10.15376/biores.12.2.3876-3889

Bakar, B. F., Hiziroglu, S., Md, and Tahir, P. (2013). “Properties of some thermally modified wood species,” *Mater. Des.* 43, 348-355. DOI: 10.1016/j.matdes.2012.06.054

Barcík, Š., Gašparík, M., and Razumov, E. Y. (2015). “Effect of thermal modification on the colour changes of oak wood," *Wood Res.* 60(3), 385-396.

Bastani, A., Adamopoulos, S., and Militz, H. (2015). "Gross adhesive penetration in furfurylated, N-methylol melamine-modified and heat-treated wood examined fluorescence microscopy," *Eur. J. Wood & Wood Prod.* 73(5), 635-642. DOI: 10.1007/s00107-015-0920-2

Bekhta, P., and Niemz, P. (2003). "Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce wood," *Holzforschung* 57(5), 539-546.

Bekhta, P., Proszyk, S., Lis, B., and Krystofiak, T. (2014). "Gloss of thermally densified alder (*Alnus glutinosa* Goertn.), beech (*Fagus sylvatica* L.), birch (*Betula verrucosa* Ehrh.), and pine (*Pinus sylvestris* L.) wood veneers," *Eur. J. Wood & Wood Prod.* 72(6), 799-808. DOI: 10.1007/s00107-014-0843-3

Budakçı, M., Pelit, H., Sönmez, A., and Korkmaz, M. (2016). "The effects of densification and heat post-treatment on hardness and morphological properties of wood materials," *BioResources* 11(3), 7822-7838.

Çakıcıer, N., Korkut, S., and Korkut, D. S. (2011). "Varnish layer hardness, scratch resistance, and glossiness of various wood species as affected by heat treatment," *BioResources* 6(2), 1648-1658. DOI: 10.15376/biores.6.2.1648-1658

Chen, Y., Fan, Y., Gao, J., and Stark, N. M. (2012). "The effect of heat treatment on the chemical and color change of black locust (*Robinia pseudoacacia*) wood flour," *BioResources* 7(1), 1157-1170.

Demirci, Z., Sonmez, A., and Budakçı, M. (2013). "Effect of thermal ageing on the gloss and the adhesion strength of the wood varnish layers," *BioResources* 8(2), 1852-1867.

Dilik, T., and Hiziroglu, S. (2012). "Bonding strength of heat treated compressed Eastern redcedar wood," *Mater. Des.* 42, 317-320. DOI: 10.1016/j.matdes.2012.05.050

Esteves, B., Graça, J., Pereira, H. (2008). "Extractive composition and summative chemical analysis of thermally treated eucalypt wood," *Holzforschung* 62(3), 344-351. DOI: 10.1515/HF.2008.057

Esteves, B., Velez Marques, A., Domingos, I., and Pereira, H. (2007). "Heat-induced colour changes of pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) wood," *Wood Sci. Technol.* 42(5), 369-384. DOI: 10.1007/s00226-007-0157-2

Guller, B. (2014). "Effects of heat treatment on density, dimensional stability and color of *Pinus nigra* wood," *Afr. J. Biotechnol.* 11(9), 2204-2209.

Gurleyen, L., Ayata, U., Esteves, B., and Cakicier, N. (2017). "Effects of heat treatment on the adhesion strength, pendulum hardness, surface roughness, color and glossiness of Scots pine laminated parquet with two different types of UV varnish application," Maderas. Ciencia y tecnología, 19(2), 213-224. DOI: 10.4067/S0718-221X2017005000019

Hakkou, M., Pétrissans, M., El Bakali, I, Gérardin, P., and Zoulalian, A. (2005). "Wettability changes and mass loss during heat treatment of wood," *Holzforschung* 59(1), 35-37. DOI: 10.1515/HF.2005.006

Herrera, R., Muszyńska, M., Krystofiak, T., and Labidi, J. (2015). "Comparative evaluation of different thermally modified wood samples finishing with UV-curable and waterborne coatings," *Appl. Surf. Sci.* 357, Part B: 1444-1453. DOI: 10.1016/j.apsusc.2015.09.259

ISO 554 (1976). "Standard atmospheres for conditioning and/or testing – Specifications," International Organization for Standardization (ISO) Geneva, Switzerland.

ISO 2813 (1994). "Paints and varnishes – Determination of specular gloss of non-metallic paint films at 20 degrees, 60 degrees, and 85 degrees," International Organization for Standardization, Geneva, Switzerland.

Kaygin, B., and Akgun, E. (2008). "Comparison of conventional varnishes with Nanolacke UV varnish with respect to hardness and adhesion durability," *International Journal of Molecular Sciences* 9(4), 476-485.

Karamanoglu, M., and Akyildiz, M. H. (2013). "Colour, gloss and hardness properties of heat treated wood exposed to accelerated weathering," *Pro Ligno* 9(4), 729-738.

Kariz, M., Kuzman, M. K., and Sernek, M. (2013). "The effect of the heat treatment of spruce wood on the curing of melamine–urea–formaldehyde and polyurethane adhesives," *J. Adhes. Sci. Technol.* 27(17), 1911-1920. DOI: 10.1080/01694243.2013.764809

Kol, H. S., Ozbay, G., and Altun, S. (2009). "Shear strength of heat-treated tali (*Erythrophleum ivorense* A. Chev.) and iroko (*Chlorophora* excelsa) woods with various adhesives," *BioResources* 4(4), 1545-1554. DOI: 10.15376/biores.4.4.1545-1554

Korkut, D. S., Hiziroglu, S., and Aytin, A. (2013). "Effect of heat treatment on surface characteristics of wild cherry wood," *BioResources* 8(2), 1582-1590. DOI: 10.15376/biores.8.2.1582-1590

Korkut, D. S., Korkut, S., Bekar, I., Budakci, M., Dilik, T., and Cakicier, N. (2008). "The effects of heat treatment on the physical properties and surface roughness of Turkish Hazel (*Corylus colurna* L.) wood," *Int. J. Mol. Sci.* 9(9), 1772-1783. DOI: 10.3390/ijms9091772

Metsä-Kortelainen, S., and Viitanen, H. (2012). "Wettability of sapwood and heartwood of thermally modified Norway spruce and Scots pine," *Eur. J. Wood Prod.* 70(1), 135-139. DOI: 10.1007/s00107-011-0523-5

Nuopponen, M., Vuorinen, T., Jämsä, S., and Viitaniemi, P. (2005). "Thermal modifications in softwood studied by FT-IR and UV resonance Raman spectroscopies," *J. Wood Chem. Technol.* 24(1), 13-26. DOI: 10.1081/WCT-120035941

Petrič, M. (2013). "Surface modification of wood," *Reviews of Adhesion and Adhesives* 1(2), 216-247. DOI: 10.7569/RAA.2013.097308

Pétrissans, M., Gérardin, P., and Serraj, M. (2003). "Wettability of heat-treated wood," *Holzforschung* 57(3), 301-307.

Poncsák, S., Shi, S. Q., Kocaefe, D., and Miller, G. (2007). "Effect of thermal treatment of wood lumbers on their adhesive bond strength and durability," *J. Adhes. Sci. Technol* 21(8), 745-754. DOI: 10.1163/156856107781362653

Rapp, A. O. (2001). "Review on heat treatments of wood," in: Proceedings of special seminar, Antibes, France, 1–66.

Sehlstedt-Persson, M. (2003). "Colour responses to heat treatment of extractives and sap from pine and spruce," in: 8th International IUFRO Wood drying conference, 459-464.

Sernek, M., Boonstra, M., Pizzi, A., Despres, A., and Gérardin, P. (2008). "Bonding performance of heat treated wood with structural adhesives," *Holz Als Roh-Werkst* 66(3), 173-180. DOI: 10.1007/s00107-007-0218-0

Shi, J. L., Kocaefe, D., and Zhang, J. (2007). "Mechanical behaviour of Quebec wood species heat-treated using ThermoWood process," *Holz Als Roh- Werkst* 65(4), 255-259. DOI: 10.1007/s00107-007-0173-9

Sivonen, H., Maunu, S. L., Sundholm, F., Jämsä, S., and Viitaniemi, P. (2002). “Magnetic resonance studies of thermally modified wood,” *Holzforschung* 56(6), 648-654. DOI: 10.1515/HF.2002.098

Srinivas, K., and Pandey, K. K. (2012). “Effect of heat treatment on color changes, dimensional stability, and mechanical properties of wood,” *J. Wood Chem. Technol.* 32(4), 304-316.

Sundqvist, B. (2002). “Color response of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birch (*Betula pubescens*) subjected to heat treatment in capillary phase,” *Eur. J. Wood & Wood Prod.* 60(2), 106-114. DOI: 10.1007/s00107-001-0273-x

Sundqvist, B., and Morén, T. (2002). “The influence of wood polymers and extractives on wood colour induced by hydrothermal treatment,” *Eur. J. Wood & Wood Prod.* 60(5), 375-376. DOI: 10.1007/s00107-002-0320-2

Tasdemir, C., and Hiziroglu, S. (2014). “Measurement of various properties of Southern pine and aspen as function of heat treatment,” *Measurement* 49, 91-98. DOI: 10.1016/j.measurement.2013.11.058

Tiryaki, S., Ozsahin S., and Yildirim, I. (2014). “Comparison of artificial neural network and multiple linear regression models to predict optimum bonding strength of heat treated woods,” *Int. J. Adhes. Adhes.* 55, 29-36. DOI: 10.1016/j.ijadhadh.2014.07.005

Tjeerdsma, B. F., Boonstra, M., Pizzi, A., Tekely, P., and Militz, H. (1998). “Characterisation of thermally modified wood: molecular reasons for wood performance improvement,” *Holz als Roh-und Werkstoff* 56(3), 149-153. DOI: 10.1007/s001070050287

Tjeerdsma, B. F., and Militz, H. (2005). “Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood,” *Eur. J. Wood & Wood Prod.* 63(2), 102-111. DOI: 10.1007/s00107-004-0532-8

Viitaniemi, P., Jamsa, S., Ek, P., and Viitanen, H. (1997). “Method for improving biodegradation resistance and dimensional stability of cellulosic products,” U. S. Patent No. 5678324.

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