The Effect of Heat Treatment on the Pull-off Strength of Optionally Varnished Surfaces of Five Wood Materials

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This study investigated the effects of heat treatment, following optional treatment with synthetic, water-based, and alkyd varnishes, on the pull-off strength of wooden materials sampled from oriental beech (*Fagus orientalis* L.), oak (*Quercus petraea* Liebl.), black poplar (*Populus nigra* L.), pine (*Pinus sylvestris* L.), and fir (*Abies bornmulleriana* M.). The test samples were subjected to heat treatment at temperatures of 165 °C and 175 °C for periods of 2 and 4 h with a total of 4 variations. With respect to the wood type, the samples of beech wood yielded the highest results for pull-off strength, while fir wood yielded the lowest. With respect to the varnish types, the highest pull-off strength was found in the samples of synthetic varnished beech (5,452 with a 37.2% improvement) at 175 °C heat treatment for 4 h, while the lowest results were obtained in the samples of fir (0.991 with a 48.5% decrease) at 175 °C heat treatment for 4 h. In conclusion, heat treatment significantly decreased the pull-off strength of the woods.

Keywords: Heat treatment; Wood materials; Varnishes; Pull-off strength

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INTRODUCTION

The performance of wood after heat treatment is an important factor affecting the performance of wood products and their markets. Thermal wood improvement processes have been developed and optimized over a considerable time, and many studies have been done on heat treatment.

The use of heat treatments to modify the properties of the wood is not new. The earliest studies focused on drying at high temperatures and resulted in a decrease of the equilibrium moisture and the consequent swelling of wood. Kolmann (1936) used high temperatures and densification by hot-press and called this process "Lignostone". Seborg *et al*. (1945) created a similar product that was called "Staypack". Stamm *et al*. (1946) reported a heat treatment to improve wood dimensional stability without densification and called the process "Staybwood". In the following years, in thermally treated wood, with a process that reduces content, such reduction was demonstrated to have a significant impact on the biological resistance of wood (Buro 1954) and lower equilibrium moisture content (Buro 1955). However, none of these products had much success in the market, probably due to the availability of high quality wood.

Other aspects of the thermal treatment of wood were pursued in subsequent years. Interests often focused on the chemical changes of heat-treated wood (Sandermann and Augustin 1963; Kollmann and Fengel 1965; Topf 1971, Bourgois and Guyonnet 1988; Tjeerdsma *et al.* 1998; Obataya *et al.* 2000; Zaman *et al*. 2000; Nuopponen *et al* 2004; Poncsak *et al.* 2005; Yıldız and Gümüşkaya 2007; Boonstra 2008; Esteves and Pereira 2008). Other interests (Zaman *et al.* 2000; Alén *et al.* 2002; Mazela *et al*. 2003; Esteves *et al.* 2007a) concentrated on mass loss of wood, which is one of the most important features in heat treatment and commonly referred to as an indication of quality and increases in dimensional stability of wood (Kollmann and Schneider 1963; Sailer *et al.* 2000; Yıldız 2002; Weiland and Guyonnet 2003; Wikberg 2004; Esteves *et al*. 2007a, 2008a; Enjily and Jones 2011) and changes in strength properties (Schneider 1973; Rusche 1973; Winandy 1996; Esteves *et al.* 2008; Bruno *et al.* 2009; Ozdemir and Arslan 2011).

In addition, heat treatment may also increase the competitive status of lower-quality wood types compared to higher-quality ones by presenting the possibility of new markets and supporting sustainable forest practices (Yıldız 1999). For example, heat-treated wood may gradually be applied for more exterior uses, such as siding, doors, windows, garden furniture, and interior applications, such as floor coverings, wainscoting, bathroom floors, and saunas (Ozcifci *et al*. 2009).

Several studies have also investigated the effect of heat treatment on the mechanical properties of wood. In general, these studies report a considerable reduction in the shear modulus of rupture (de Moura *et al.* 2011) and bending (Kamdem *et al.* 2002; Awoyemi and Westermark 2005), mainly at temperatures above 200 °C. It was expected that these changes in mechanical properties may have had an effect on the machining properties and surface quality of machined wood. Boonstra *et al*. (2006) observed that some cracks appeared at the annual rings, parenchyma cells, tracheids, and epithelial cells around the resin ducts in sapwood of heat-treated pine species. Funaoka *et al.* (1990) have found that lignin mainly suffers from biphenyl methane-type condensation during heat treatment at 120 to 220 °C when the timber specifically contains moisture. Esteves *et al*. (2007b) reported that steam heat-treated pine wood (*Pinus pinaster*) showed a small increase until about 4% mass loss, followed by a decrease for higher mass losses. In a static bending test, Kim *et al.* (1998) showed that there was a close relation between the decrease of bending properties and the process conditions (time and temperature) with *Pinus ratiata* wood treated at 120 °C, 150 °C, and 180 °C during 6 to 96 h. Shi *et al.* (2007) studied the mechanical behavior of Quebec wood species heat treated using the ThermoWood process and concluded that the modulus of rupture decreased between 0% and 49% for heat-treated spruce, pine, fir, and aspen, while in the case of birch the modulus increased slightly (6%) after the heat treatment.

Other studies were carried out with the purpose of minimizing the negative properties of wood and increasing its positive properties to a higher degree. According to the results of these studies, "wood modification methods" were adopted in a general sense (Korkut *et al.* 2008a). Wood modification methods may be grouped as chemical, physical, thermal, or enzymatic modification (Tomak and Yıldız 2010). With reference to thermal modification, heat treatment can be understood as keeping wood in a normal atmosphere with nitrogen or any inert gas between 100 to 250 °C for a certain time (Korkut *et al.* 2008a). In accordance with the chemical modification for the analysis of beech wood, carbohydrates underwent degradation reactions more than lignin in the heating process when the heat treatment was applied to the beech wood samples at 180 to 225 °C for 2 to 8 h (Alén *et al.* 2002). This may result in an increase in color change, biological resistance, and dimensional stabilization of wood, while additional losses in mechanical properties and chemical structure at heat treatments of 150 °C or above were also reported (Aydemir and Gunduz 2009).

However, according to Yilgor (1999), significant changes may occur in the physical and chemical properties of the woods because of the temperature of the heat treatment and other factors, such as ambient pressure, application period, moisture content of the material, and physical properties, as well as the wood temperature. In addition to this, Hakkou *et al*. (2005) found that the hygroscopicity of wood abruptly changes after heat treatment. Wettability variations may be observed between 100 to 160 °C; however, when heat treatment is performed at higher temperatures, the hygroscopicity of the wood remains unaffected. Korkut *et al.* (2008b) argued that the technological properties of the wood material decrease with increasing temperature (from 120 to 150, and 180 °C) and increasing time of the treatment (from 2, to 6, and 10 h).

A few studies investigated the effect of heat treatment on surface roughness and wood varnishing (Yildiz 2002; Ozalp *et al.* 2009; de Moura *et al.* 2014). The surface roughness of heat-treated *Eucalyptus grandis* wood after peripheral planning and sanding performed in the direction of the grain and against the grain was evaluated by de Moura *et al.* (2014), who claim that the heat treatment could minimize the occurrence of machining defects when planning against the grain of the wood.

A few studies were carried out to investigate the effects of varnishes on the surfaces of heat-treated woods. Cakicier *et al* (2011) studied the effects of different heat treatment and varnish application combination on hardness, scratch resistance, and glossiness of wood materials sampled from limba (*Terminalia superba*), iroko (*Chlorophora excelsa*), ash (*Fraxinus excelsior* L.), and Anatolian chestnut (*Castanea sativa* Mill.) woods. The heat treatment was applied at two levels (150 and 180 °C) for both 3 and 6 h periods. According to their results, glossiness increased for all of four woods species treated with cellulose lacquer and synthetic varnish and across all heating treatments, while glossiness values were decreased for all the wood species depending on heating temperature and time. Ozalp *et al.* (2009) studied the effects of heat treatment of wooden materials on hardness, brilliance, and resistance of stick of varnishes. According to them, Scotch pine (*Pinus sylvestris* L.) and chestnut (*Castanea sativa* Mill.) woods were heat treated at the temperatures of 100, 150, and 200 °C for 2, 4, and 6 h. After heat treatment, samples were varnished by water-based varnishes. The result of their study shows that the hardness, brightness, and resistance of adhesion were improved for both wooden types which were kept for 2 h at the temperatures of 100, 150, and 200 °C.

The perspective drawn from the literature reveals that there has been no specific study focused on investigating the effects of heat treatment on the pull-off strength of optionally varnished surfaces of the five wood materials of oriental beech (*Fagus orientalis* L.), oak (*Quercus petraea* Liebl.), black poplar (*Populus nigra* L.), pine (*Pinus sylvestris* L.), and fir (*Abies bornmulleriana* Mattf.), which are commonly used in the Turkish furniture and wood industries.

EXPERIMENTAL

Materials and Methods

Woods

Test samples of oriental beech (*Fagus orientalis* L.), oak (*Quercus petraea* Liebl.), black poplar (*Populus nigra* L.), pine (*Pinus sylvestris* L.), and fir (*Abies bornmulleriana* Mattf.) were chosen randomly from timber merchants of Ankara for the experimental design.

Preparation of test samples

The test samples were prepared in compliance with TS 2470 (1976) and TS 53 (1981) from regular woods, without rots and knots, and the samples were randomly chosen from first class timbers, without color differences or density variations. A total of 750 test samples were prepared from a combination of five wood types, three varnish types, four heat treatment temperatures and durations (165 °C / 2 h, 165 °C / 4 h, 175 °C / 2 h, and 175 °C / 4 h), and 10 control samples (0 °C) for each treatment category.

The test samples were initially cut into 110 mm × 110 mm × 10 mm boards and air-dried to equilibrium humidity prior to the heat treatment. The samples were re-shaped to the dimensions of 100 mm × 100 mm × 8 mm and brought to equilibrium humidity after the heat treatment. Then, the samples were subjected to a sanding process with 80 and 100 grit sandpapers after the first wetting, and 120 grit sandpaper following the last wetting. The dust from the surface of the samples was cleaned using a brush and vacuumed in preparation for surface varnishing.

Varnishes

Synthetic (Sn), water-based (Wb), and alkyd resin basis single-component wood varnishes (Al) were used in coating the surface of the samples for the experiments. The testing principles, ASTM D-3023 (1998) and ASTM-D 3924 (1991), were applied for varnishing the samples. Varnishes were applied to the test samples with medium-hard brushes.

The synthetic and alkyd resin basis single-component wood varnishes, with a solution of 120 g/m^2 by adding 10% synthetic thinner, and the water-based varnish, with a solution of 140 g/m^2 by adding 5% water, were applied in both the vertical and horizontal directions, with the primary purpose of filling in the gaps on the samples' surfaces with each layer for coating. The filling-coated samples were held in a conditioning room at 20 °C for drying in clean air circulation for 24 h. Then, the dried samples were subjected to a sanding process with 400 grit (on Norton scale) sandpaper. After cleaning, the dust from the surfaces was removed with a smooth brush and vacuumed. Then, the samples were weighed on a sensitive analytical scale (± 0.01 g), (FX-3000). The samples were subjected to a topcoat application and were set aside to dry for 3 weeks. The dry film thickness of the varnish layer was determined using a comparator (Erichsen 233, Germany), which measures the thickness with a sensitivity of 5 μm by conforming to the principles of ASTM D-1005 (2001).

Heat treatment

Heat treatment was carried out in a heat treatment oven under a normal atmosphere controlled in ±0.1 °C temperature sensitivity under the protection of hot water vapor. The air-dried wood underwent 100 ±3 °C of water vapor spraying at 1 bar time of 5 sec at intervals of 200 sec. The total heat treatment was performed in three continuous stages. In the first stage, heat and steam were used to increase the temperature of the oven to 100 °C for 6 h and then to 130 °C for 12 h. In the second stage, after the moisture content of the wood decreased to approximately zero and high temperature drying was established, the temperature was increased from 130 °C to 165 °C (or 175 °C) in 6 h, and the samples were kept at these temperatures for 2 or 4 h. In the third stage, the temperature of the wood was reduced using a water spray, and this was continued until the moisture of the wood had reached 4 to 6%. This conditioning stage continued for 12 h. Then, the materials were taken out of the oven, cut to their net dimensions, and kept in the laboratory to attain an air-dried humidity. The heat treatment was carried out in a total of 4 variations: two different temperatures (165 °C and 175 °C) with two different time periods (2 h and 4 h).

Test methods

Pull-off strength of the varnished samples was determined using an adhesion test device in accordance with the principles of ASTM D-4541 (1995) and TS EN 24624

(1996). The fully dried and varnished samples were prepared for testing by conditioning for a time period of 24 h in the conditioning cabinet at a temperature of 23 ± 2 °C and 50 ±5% relative humidity. 20 mm steel test cylinders were adhered on the surfaces of the samples (Budakci 2003). During the tests, glue was used in the amount of 150 ±10 g/m^2 on the double-component epoxy resin protected layers, according to ASTM D-4541 (1995).

The excess glue was removed after 2 h using a spatula, and the samples were left to dry for 24 h. Then, the varnish layer was cut. An upward tensile force was applied in the adhesion device operating with 2 bars of compressed air to the cylinders adhered to the sample surfaces which caused the cylinders to shear off the varnished surfaces (Atar 1999).

Data evaluation

In the evaluation of the data, the MSTAT-C statistic package software program was used. In the analysis, the values of the factor effects of wood type, heat treatment, and varnish type were determined using the analysis of variance (ANOVA) procedure, and the differences in the means were accepted at a significance of P <0.05. The least significant differences (LSD) of the means were used, and the causation factors were determined. The results of the heat-treated and varnished samples were compared to the control (Co) samples. The data obtained was analyzed at a 95% confidence level. The letters, A, B, C, and D, indicate the classification level of the LSDs for mean factor values according to the highest pull-off strength, represented by A, and the lowest pull-off strength, represented by D.

RESULTS AND DISCUSSION

The thickness values of the varnish layers were measured using a comparator device with a sensitivity of 5 μm. The dry film thicknesses of the varnish types are shown in Table 1.

Table 1. Dry Film Thickness of Varnish Types

Layer Thickness	Varnish types		
	Alkyd	Synthetic	Water-based
Dry Film (μm)	85	83	82
Amount of Solution (g/m^2)	120	120	140

The highest mean value of thickness was observed in alkyd varnished samples, with a thickness of 85 μm. The lowest dry film thickness of 82 μm was obtained from water-based varnished samples. The mean values for the effect of the wood type and varnish type on pull-off strength, with or without heat treatment (N/mm^2), are shown in Table 2.

According to Table 2, the mean values for the pull-off strength were different, depending on the wood type, heat treatment, and varnish type. The highest pull-off strength was found in the samples of synthetic varnished beech (5.452) at 175 °C heat treatment for 4 h, while the lowest results were obtained in the alkyd varnished samples of fir (0.991) at 175 °C heat treatment for 4 h. With the exception of beech wood, the results of the control samples for the pull-off strength were higher than the heat-treated wood samples.

Table 2. Pull-off Strength Before and After Heat Treatment (N/mm^2)

Wood Species	Varnish Types	Heat treatment types (°C / h) Control (Co)	165 / 2 (I)	165 / 4 (II)	175 / 2 (III)	175 / 4 (IV)
Beech (B)	Water-based	4.268	**5.043**	3.784	3.415	4.649
	Synthetic	3.974	3.268	**4.833**	**4.327**	**5.452**
	Alkyd	3.705	2.796	4.084	2.790	2.968
Oak (O)	Water-based	4.015	4.502	3.634	1.259	3.374
	Synthetic	**5.995**	3.412	1.228	1.415	2.137
	Alkyd	4.793	3.324	4.387	2.100	1.825
Poplar (P)	Water-based	2.462	1.903	2.456	1.475	1.568
	Synthetic	4.134	1.878	1.622	1.871	1.206
	Alkyd	**1.606**	2.106	1.887	1.387	1.578
Pine (Pn)	Water-based	2.909	2.340	1.244	1.656	2.934
	Synthetic	3.243	2.559	2.362	2.231	2.103
	Alkyd	2.715	1.653	2.337	1.906	2.256
Fir (F)	Water-based	2.359	1.159	**1.022**	**1.072**	1.422
	Synthetic	3.481	2.387	1.468	1.740	1.165
	Alkyd	1.925	**1.047**	2.196	1.553	**0.991**

The interactions of wood type, heat treatment, and varnish type were found to be statistically significant ($P \leq 0.05$). Single comparison analysis for the factors of wood type, heat treatment, and varnish type are shown in Table 3.

Table 3. Single Comparison Analysis of Wood, Varnish, and Heat Treatment Types on Pull-off Strength (N/mm^2)

Factors	Types	$\bar{x}$	HG
Wood	Beech	3.957	A*
	Oak	3.160	B
	Poplar	1.942	D
	Pine	2.296	C
	Fir	1.666	E
Heat treatment (°C/ h)	Control	3.439	A
	165 / 2	2.625	B
	165 / 4	2.569	C
	175 / 2	2.375	D
	175 / 4	2.013	E
Varnish	Synthetic	2.780	A
	Water-based	2.637	B
	Alkyd	2.396	C

*LSD: ±0.043; **LSD: ±0.033; *Highest pull-off strength; $\bar{x}$: Mean value; HG: Homogeneous group

With respect to the means in Table 3, during the single comparison of the factor types, the effect of wood type on the pull-off strength values was found to be significant. Regarding heat treatment levels, the highest pull-off strength value (2.625) was found in the samples heat-treated at 165 °C for 2 h, while the lowest pull-off strength (2.013) was observed in the samples heat-treated at 175 °C for 4 h. Regarding the wood type, the pull-off strength was found to be highest in the beech samples (3.957) and the lowest in the fir samples (1.666). According to the varnish type, the results for pull-off strength were the highest (2.780) in the synthetic varnished samples and the lowest (2.396) in the alkyd varnished samples. It is possible that the heat treatment process reduced the pull-off strength because of the high values for the control samples.

The results of the Duncan test double comparison analysis, according to wood and heat treatment types, are shown in Table 4. The highest pull-off strength (4.356) was found in the samples of beech that were heat-treated at 175 °C for 4 h, while the lowest value (1.192) was obtained in the samples of fir that were heat-treated at 175 °C for 4 h. However, in comparison to the control samples, the beech samples produced the best results. On the other hand, the other woods exhibited the worst results for the reduction of pull-off strength in decreasing order: oak, pine, polar, and fir. The results of the Duncan test for double comparison analysis, according to the wood and varnish types, are shown in Table 5.

Table 4. Double Comparison Analysis of Wood and Heat Treatment Types on Pull-off Strength (N/mm^2)

	Heat treatment types (°C / h)									
	165 / 2		165 / 4		175 / 2		175 / 4		Control	
Wood types	$\bar{x}$	HG	$\bar{x}$	HG	$\bar{x}$	HG	$\bar{x}$	HG	$\bar{x}$	HG
Beech	3.702	E	4.233	C	3.511	F	**4.356**	B*	3.982	D
Oak	3.746	E	3.083	G	1.591	N	2.445	K	4.934	A
Poplar	1.962	M	1.988	M	1.578	N	1.451	O	2.734	I
Pine	2.184	L	1.981	M	1.931	M	2.431	K	2.956	H
Fir	1.531	NO	1.562	N	1.455	O	**1.192**	P	2.588	J

LSD: ± 0.096; *Highest pull-off strength; $\bar{x}$: Mean value; HG: Homogeneous group

Table 5. Double Comparison Analysis of Wood and Varnish Types on Pull-off Strength (N/mm^2)

	Varnish types					
	Water-based		Synthetic		Alkyd	
Wood types	$\bar{x}$	HG	$\bar{x}$	HG	$\bar{x}$	HG
Beech	4.231	B	**4.371**	A*	3.269	D
Oak	3.357	C	2.837	E	3.286	CD
Poplar	1.973	I	2.142	G	1.713	J
Pine	2.216	G	2.499	F	2.173	G
Fir	**1.407**	L	2.048	H	1.542	K

LSD: ± 0.0745; *Highest pull-off strength; $\bar{x}$: Mean value; HG: Homogeneous group

According to the wood and varnish types, the highest result for pull-off strength was obtained in the synthetic varnished beech wood samples (4.371), and the lowest result was obtained in the water-based varnished fir samples (1.407). The synthetic varnish yielded the highest results for pull-off strength in beech, poplar, pine, and fir, while the water-based varnish yielded the highest result in oak. The results of the Duncan test for the double comparisons analysis, according to heat treatment and varnish type, are shown in Table 6.

According to Table 6, the highest result for pull-off strength was obtained for the specimens heat-treated for 2 h at 165 °C with water-based varnished samples (2.989), and the lowest was found in the specimens heat-treated 175 °C for 4 h, in the case of water-based varnished samples (1.775). The difference between the control and heat-treated samples was highly significant.

Table 6. Double Comparison Analysis of Heat Treatment and Varnish Types on Pull-off Strength (N/mm^2)

Heat treatment types (°C / h)	Varnish types					
	Water-based		Synthetic		Alkyd	
	$\bar{x}$	HG	$\bar{x}$	HG	$\bar{x}$	HG
Control	3.202	B	4.165	A	2.949	C
165 / 2	**2.989**	C*	2.701	E	2.185	H
165 / 4	2.428	F	2.303	G	2.978	C
175 / 2	**1.775**	J	2.317	G	1.947	I
175 / 4	2.789	D	2.412	F	1.923	I

LSD: ± 0.0745; $\bar{x}$: Mean value; HG: Homogeneous group

Results of the Duncan test for the total comparison of the wood type, heat treatment, and varnish type on the pull-off strength are shown in Table 7.

Table 7. Total Comparison Analysis of Wood Type, Heat Treatment, and Varnish Type on Pull-off Strength (N/mm^2)

Process types	$\bar{x}$	HG	Process types	$\bar{x}$	HG	Process types	$\bar{x}$	HG
O-Co-Sn	5.995	A	Pn-IV-Wb	2.934	O	P-III-Sn	1.871	V
B-IV-Sn	5.452	B*	Pn-Co-Wb	2.909	O	O-IV-Al	1.825	VW
B-I-Wb	5.043	C	B-I-Al	2.796	OP	F-III-Sn	1.740	VWX
B-II-Sn	4.833	D	B-III-Al	2.790	OP	Pn-III-Wb	1.656	WXY
O-Co-Al	4.793	DE	Pn-Co-Al	2.715	PQ	Pn-I-Al	1.653	WXY
B-IV-Wb	4.649	EF	Pn-I-Sn	2.559	QR	P-II-Sn	1.622	XY
O-I-Wb	4.502	FG	P-Co-Wb	2.462	RS	P-Co-Al	1.606	XYZ
O-II-Al	4.386	GH	P-II-Wb	2.456	RS	P-IV-Al	1.578	XYZ
B-III-Sn	4.327	GH	F-I-Sn	2.387	RST	P-IV-Wb	1.568	XYZ
B-Co-Wb	4.268	HI	Pn-II-Sn	2.362	ST	F-III-Al	1.553	XYZ
P-Co-Sn	4.134	IJ	F-Co-Wb	2.359	ST	P-III-Wb	1.475	YZ
B-II-Al	4.083	J	Pn-I-Wb	2.340	ST	F-II-Sn	1.468	YZ
O-Co-Wb	4.015	J	Pn-II-Al	2.337	ST	F-IV-Wb	1.421	Z
B-Co-Sn	3.974	J	Pn-IV-Al	2.256	TU	O-III-Sn	1.415	Z
B-II-Wb	3.783	K	Pn-III-Sn	2.231	TU	P-III-Al	1.387	a
B-Co-Al	3.705	K	F-II-Al	2.196	TU	O-III-Wb	1.259	b
O-II-Wb	3.634	KL	O-IV-Sn	2.137	U	PN-II-Wb	1.244	b
F-Co-Sn	3.480	LM	P-I-Al	2.106	U	O-II-Sn	1.228	c
B-III-Wb	3.415	MN	Pn-IV-Sn	2.103	U	P-IV-Sn	1.206	d
O-I-Sn	3.412	MN	O-III-Al	2.100	U	F-IV-Sn	1.165	e
O-IV-Wb	3.374	MN	F-Co-Al	1.925	V	F-I-Wb	1.159	e
O-I-Al	3.324	MN	Pn-III-Al	1.906	V	F-III-Wb	1.072	e
B-I-Sn	3.268	N	P-I-Wb	1.903	V	F-I-Al	1.047	f
PN-Co-Sn	3.243	N	P-II-Al	1.887	V	F-II-Wb	1.022	g
B-IV-Al	2.968	O	P-I-Sn	1.878	V	F-IV-Al	0.9906	h

LSD: ± 0,1666; *: Highest pull-offstrength; $\bar{x}$: Average value; HG: Homogeneous group

According to Table 7, the total comparison of the wood type, heat treatment, and varnish type yielded the highest bonding strength in the synthetic varnished beech samples that were heat-treated at 175 °C for 4 h (5.452) with the exception of control samples, while the fir samples that were varnished with alkyd resin single-component vanish and heat-treated at 175 °C for 4 h yielded the lowest bonding strength (0.9906).

This research determined the effects of heat treatment on the pull-off strength of optionally varnished surfaces of five wood materials of oriental beech (*Fagus orientalis* L.), oak (*Quercus petraea* Liebl.), black poplar (*Populus nigra* L.), pine (*Pinus sylvestris*

L.), and fir (*Abies bornmulleriana* Mattf.), in comparison to control samples, which were not heat-treated. The pull-off strength values were highly different; however, and this was not a result of the heat treatment only. The varnish and wood types also contributed to the differences in the pull-off strength values.

Pull-off strengths before and after heat treatment were different in terms of wood type, heat treatment, and varnish type. With respect to the varnish film thickness, the results show that the pull-off strength was related to the adhesion and wood types but not related to the dry film thickness, which was observed in alkyd varnished samples as the highest mean value with a thickness of 85 μm. The lowest dry film thickness of 82 μm was obtained from water-based varnished samples. However, with respect to the pull-off strength for varnishes, the highest pull-off strength was found in the samples of synthetic varnished beech (5.452) at 175 °C heat treatment for 4 h, while the lowest results were obtained in the alkyd varnished samples of fir (0.991) at 175 °C heat treatment for 4 h. The reason for the highest pull-off strength in synthetic varnish may depend on the structural properties of the varnish as reported by Sonmez and Budakci (2004).

Regarding to heat treatment levels, the highest pull-off strength value (2.625) was found in the samples heat-treated at 165 °C for 2 h, while the lowest pull-off strength (2.013) was observed in the samples heat-treated at 175 °C for 4 h. There was a significant correlation expressed for temperature and pull-off strength, since as the temperature decreased, there was a reduction of the pull-off strength ranging from 1.7% to 9.5%, depending on the temperature and time. The temperature is known to play a significant role in the change in bonding strength of wood (Schneider 1973; Rusche 1973; Winandy 1996; Yilgor 1999; Hakkou 2005; Ozdemir and Arslan 2011). In actuality, the heat treatment decreases the polarity of wood surfaces, and the heat-treated wood has the capability of being less wettable compared to non heat-treated wood (Korkut *et al.* 2008ab). It is possible say that the heat treatment process reduced the pull-off strength because of the high values in the case of the control samples.

With the exception of beech wood, the results of the control samples for the pull-off strength were higher than the heat-treated wood samples. On the other hand, the other woods exhibited the worst results for pull-off strength in order: oak, pine, polar, and fir. This result may be due to the homogenous structure and smooth texture of Oriental beech and varnish adhesion by forming smoother surfaces because of its structure of distributed small vessels (Atar 1999).

In general, this situation may arise from wood modification by heat treatment, which effects and causes changes in the mechanical properties of the wood as reported in a number of studies. These studies report a considerable reduction in the shear modulus of rupture (de Moura *et al.* 2011) and bonding (Kamdem *et al*. 2002; Awoyemi and Westermark 2005), mainly following heat-treatment at temperatures above 200 °C. Another reason might be the appearance of some cracks at the annual rings, parenchyma cells, tracheids, and epithelial cells around the resin ducts in sapwood of heat-treated pine species (Boonstra *et al*. 2006). Also it is known that lignin mainly suffers from biphenyl methane-type condensation during heat-treatment at 120 to 220 °C when the timber specifically contains moisture (Funaoka *et al.* 1990; Shi *et al.* 2007). The cited authors concluded that the modulus of rupture decreased between %0 and 49% for heat-treated spruce, pine, fir, and aspen, while birch the modulus increased slightly (6%) after the heat treatment. Another possible reason could be surface roughness and wood varnishing (Yildiz 2002; Ozalp *et al.* 2009; De Moura *et al.* 2014). Moreover planing and sanding performances in the direction of the grain and against the grain could minimize the occurrence of machining defects when planing against the grain of the wood, as evaluated by de Moura *et al.* (2011).

In conclusion, it is possible to conclude that the heat treatment significantly decreases the pull-off strength of the woods.

CONCLUSIONS

1. Alkyd varnished samples exhibited the highest mean value with a thickness of 85 µm, while water-based varnished samples presented the lowest dry film thickness of 82 µm.
2. According to results after and before heat treatment, the means for the pull-off strength were different in terms of wood type, heat treatment, and varnish type. The highest pull-off strength was found in the samples of synthetic varnished beech (5.452) at 175 °C heat treatment for 4 h, and the lowest results in the alkyd varnished samples of fir (0.991) at 175 °C heat treatment for 4 h.
3. With respect to the single comparison of the factor types, regarding the heat treatment levels, the highest pull-off strength value (2.625) was found in the samples heat-treated at 165 °C for 2 h, while the lowest pull-off strength (2.013) was observed in the samples heat-treated at 175 °C for 4 h. Regarding to the wood types, the pull-off strength was found to be highest in the beech samples (3.957) and the lowest in the fir samples (1.666). According to the varnish types, the results for pull-off strength were the highest (2.780) in the synthetic varnished samples and the lowest (2.396) in the alkyd varnished samples.
4. With respect to the double comparison analysis for wood and heat treatment types, the highest pull-off strength (4.356) was found in the samples of beech that were heat-treated at 175 °C for 4 h, while the lowest value (1.192) was obtained in the fir samples which were heat-treated at 175 °C for 4 h. For the wood and varnish types, the highest result for pull-off strength was obtained in the synthetic varnished beech samples (4.371), and the lowest result was obtained in the water-based varnished fir samples (1.407). The synthetic varnish yielded the highest results for pull-off strength in beech, poplar, pine, and fir, while the water-based varnish yielded the highest result in oak. For the heat treatment and varnish type, the highest result for pull-off strength was obtained in the 165 °C for 2 h heat-treated, water-based varnished samples (2.989), and the lowest was found in the 175 °C for 4 h heat-treated, water-based varnished samples (1.775).

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