Properties of Thermally Modified Scots Pine (*Pinus sylvestris* L.), Kazdağı Fir (*Abies equi-trojani* Asch. et Sint.), and Eastern Beech (*Fagus orientalis* Lipsky)

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Surface roughness and discoloration of thermally modified Scots pine (*Pinus sylvestris* L.), Kazdağı fir (*Abies equi-trojani* Asch. et Sint.), and Eastern beech (*Fagus orientalis* Lipsky) were evaluated. The surface roughness and discoloration of the samples sanded with 60, 80, and 120-grit grades were evaluated at temperature levels of 160, 180, 200, and 220 °C. Findings were subjected to multiple analysis of variance and Duncan's homogeneity tests; using the SPSS package program, single, double, triple, and quadruple interactions were analyzed. The highest surface roughness values were found in Eastern beech samples with radial cross-section (12.4 µm) finished with 60-grit sandpaper. The lowest roughness value was found in Kazdagi fir samples that were heat-treated in 200 °C and processed with 120-grit sandpaper (2.03 µm). The lowest discoloration evaluation (ΔE) value was found eastern beech samples 32.43, and highest ΔE values 46.86 found at Scots pine.

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INTRODUCTION

Wood material is a biomass-derived material that is easily accessible, natural, renewable, non-toxic, and affordable. Wood has been used in construction sites and the furniture industry for over 2,500 years, meaning that a particular species of tree was utilized to achieve the best performance of physical properties of wood (Sandberg *et al.* 2017). In recent years, various new materials have been used instead of wood in construction sites and furniture production. Wood material is sustainable and part of natural life. It has many applications including furniture and interior decoration. There are three basic functions that highlight the use of wood in furniture production, surface quality, adhesion resistance, and paint varnish holding ability.

In recent years, considering the environment and human health, different methods have been developed to eliminate or minimize the unfavorable properties of wood and wood-based materials (Kacikova *et al.* 2013; Sandberg *et al.* 2017, 2021). For example, in recent decades, a popular wood modification method, thermal modification, has been used to improve wood's resistance to biological attacks. Wood drying and thermal modification has been used since ancient times. After the process of TM (thermal modification) of wood material, TM augments the physical and color properties of the wood (Sandberg *et al.* 2017). High temperature changes the chemical and anatomical properties of wood (Esteves and Pereira 2009). For example, thermal modification of wood at temperatures above 150

°C causes permanent changes in the molecular structure (Wang and Cooper 2005; Boonstra *et al.* 2007; Boonstra 2008). Furthermore, mechanical strength properties may also decrease depending on the treatment conditions, differences in cellular anatomy, environment-controlled growth patterns, and the chemical structure (Esteves and Pereira 2009; Karlsson *et al*. 2010; Kačíková *et al.* 2013; Emmerich *et al.* 2019; Bytner *et al.* 2021). Without chemical additives and with a limited supply of oxygen to prevent oxidative combustion, TM is a commonly accepted and commercialised procedure for improving some characteristics of wood (Barcik *et al.* 2014; Alfredsen *et al.* 2015; Shmulsky and Jones 2019). According to the CEN (European Committee for Standardization 2008), thermally modified timber is a wood-based material in which the composition of the cell-wall material and its physical properties have been modified by exposure to a temperature higher than 160 °C with limited access to oxygen. There are various processes to achieve TM, different statements could occur in the way to exclude air/oxygen during TM (Rapp 2001; Navi and Sandberg 2012; Pelaez-Samaniego *et al.* 2013; Candelier *et al.* 2016; Gérardin 2016).

At temperatures of 160 °C and above, the color of the wood material can be changed, and dimensional stability can be improved. However, the mechanical properties of the wood are reduced, and chemical structure is changed upon TM. To maintain dimensional stability in wood material and to protect the material against biological pests, applying TM of wood is an alternative method to the use of toxic substances (Hill 2006; Esteves *et al*. 2011; Garcia *et al.* 2012; Wentzel *et al.* 2018).

Forest Products Laboratory researcher Harry Tiemann, who is a kiln specialist, discovered thermal modification of wood in 1915. He heated air-dried wood in superheated steam at 150 °C and saw a decreased hygroscopicity of the TMT (Thermally Modified Timber) (Stamm and Hansen 1937; Stamm *et al.* 1946; Callum and Hill 2006). The thermal modification of wood was first scientifically developed by Stamm and Hansen in Germany in the 1930s and continued to be studied by White until the 1940s in the USA. It is important to note that the majority of wood modification processes developed or currently being tested have full or partial origins in the ground-breaking studies and seminal work of Alfred J. Stamm and his colleagues at the Forest Products Laboratory in Madison, Wisconsin (USA), in the 1940s and 1950s (Stamm *et al.* 1946; Bekhta and Niemz 2003; Alén *et al.* 2002; Hill 2006; Esteves and Pereira 2009; Sandberg and Kutnar and Hill 2016; Jones *et al.* 2019; Hill *et al* 2021). In 1967, Kollman, Schneider, and Bohner investigated heating and drying wood with infrared radiation. In the 1970s, published information began to be discussed by scientists.

After the 1990s, Finland became the pioneer of commercial TM of wood, known as “ThermoWood®”. Currently, the latest research on wood modification is conducted in France. The TM method has various names depending on the country that is being used. For example, thermal modification method is referred as (ThermoWood®) method in Finland, PLATO (Providing Lasting Advanced Timber Option Wood) method in the Netherlands, the (Rectification) method in France that uses inert gas and hot oil, and the OHT (Oil Heat Treatment Wood) method in Germany performed with heated oil (Mayes and Oksanen 2002). There are some advantages of thermally modified wood, such as greater dimensional stability, lower thermal conductivity, greater durability against decay, and lower equilibrium moisture content. However, not all changes are desirable, such as decreased hardness (Brinell hardness), decreased impact strength, decreased modulus of rupture (MOR), and to some extent modulus of elasticity (MOE), and increased brittleness

(Borrega and Karenlampi 2008; Korkut and Hiziroğlu 2009; Allegretti *et al.* 2012; Ulker *et al.* 2012, 2018; Bakar *et al.* 2013; Imirzi *et al.* 2014; Kutnar and Hill 2014).

Thermal modification changes the molecular structure of wood cells. Hemicelluloses begin to degrade first with increasing temperatures because they have the lowest molecular weight. Degradation of hemicelluloses causes reduction of OH bonds and association of O-acetyl groups. With the formation of crosslinks between wood fibers, wood becomes more hydrophobic. The reduction in absorption results in a reduction in swelling and shrinkage of the wood and improved dimensional stability (Bhuiyan *et al.* 2000; Kocaefe *et al.* 2008; Navi and Sandberg 2012; Poletto *et al.* 2012; Srinivas and Pandey 2012; Neyses and Scharf 2022).

In addition, after thermal treatment of wood species, low quality tree species are converted into higher quality wood species. This method increases the marketability of low-density wood species. Thus, the application of thermal treatment is an ecological alternative to low density wood species (Wikberg 2004; Wikberg and Maunu 2004; Nuopponen *et al.* 2005; Korkut and Kocaefe 2009; Olek and Bonarski 2014; Obataya and Higashihara 2017). The color of wood is also important from the viewpoint of aesthetic and hedonic concepts for the consumers. Depending on culture, country, and income level, wood products may have higher market volume solely due to its color. Heat treatment would also provide an inexpensive alternative method to darken wood to imitate more expensive exotic species (Korkut *et al.* 2013).

Wood material darkens upon heat treatment, where the degree of color change depends on the duration and the temperature of the thermal modification. During the thermal modification of wood material, enzyme-mediated reactions occur between sugars, phenolic compounds, and amino acids (Fengel and Wegener 1983; Saka 1993; Montero *et al.* 2012). This enzyme-mediated reaction of wood material can cause hydrolysis and oxidation of components, thus changing the color of the wood (Bekhta and Niemz 2003; Lamason and Gong 2007; Chen *et al.* 2020; Ulker *et al.* 2012; Mitani *et al.* 2013).

The use of wood material in furniture manufacturing and interior design depends on the physical and mechanical properties of the wood material. Furthermore, the most important part of furniture production is surface finishing and wood dimensional stability (Korkut *et al.* 2013). In this study, three types of wood were selected, Scots pine (*Pinus sylvestris* L.), Kazdağı fir (*Abies equi-trojani* Aschers et Sint.), and Eastern beech (*Fagus orientalis*).

A lot of information regarding the mechanical and physical characteristics of these species is included in the literature. To the best of the authors' knowledge, there is not enough information available on surface properties thermal modified and sanded samples of these species. Thus, the purpose of this study was to ascertain how thermal modification affected the color and surface roughness of sanded Scots pine, Kazdağı fir, and Eastern beech wood specimens. The TM wood species may be suitable for high-value applications like siding and construction thanks to their improved performance.

EXPERIMENTAL

Materials

A total of 630 specimens (160 × 50 × 10 mm^3) were prepared to evaluate surface roughness and color changes. Defect-free samples were prepared from lumber with an average of 45 cm diameter at breast height and were crosscut into 1.5 m long sections.

Specimens of Kazdağı Fir (*Abies equi-trojani* Aschers et Sint.-210 specimens), Scots pine (*Pinus sylvestris* L., 210 specimens), and Eastern beech (*Fagus orientalis* Lipsky, 210 specimens), were obtained from Siteler District Ankara-Turkey. All specimens were oven-dried at 103 ± 2 °C until a constant weight was obtained prior to thermal modification.

Selected wood species Kazdağı fir (*Abies equi-trojani* Aschers et Sint.), Scots pine (*Pinus sylvestris* L.), and Eastern beech (*Fagus orientalist* Lipsky) are mostly used as a raw material in the furniture industry in Turkey.

Until recently, there has been a debate as to whether Kazdağı fir is a unique species. In 1883, researchers Ascherson and Sinten found Kazdağı fir on the Kaz Mountains of Turkey and named it *Abies alba* Mill. In the following years, Ascherson stated that Kazdağı fir was a species related to *A. alba* and *A. cephalonica* Loudon and named it as Kazdağı fir *Abies equi-trojani*. However, according to Mattfeld, because of the unique morphological properties of Kazdağı fir, it should be accepted as a unique species of its own (Ata 1975).

Scots pine (*Pinus sylvestris* L.) is an economic and well investigated tree species of the northern hemisphere. Its growth conditions are moderate in terms of climate and soil and its morphological variation is high. Scots pine (*Pinus sylvestris* L.), the most common species of the genus *Pinus* reaches on average 23 to 27 m in height, 50 to 80 cm in diameter, and 200 to 300 years in age. It was reported for a single tree in northeastern Lapland that the maximum values were 45 m height, 150 cm diameter, and approximately 780 years old. Scots pine (*Pinus sylvestris* L.) is the most widely spread species within the genus *Pinus*. It covers a range of 10,000 km longitudinally, from the westernmost occurrence in Spain at 8 °W to the far east of Russia at 141 °E. Scots pine can be found in northern Scandinavia (70 °N) reaching to the mountains of the Sierra Nevada in Spain (37 °N), representing 3,700 km of land (Wallenius *et al.* 2010).

Eastern beech, belonging to the *Fagus* genus, was first described by C. Linnaeus (Schneider 1904) as one of the most important seven genera of the Fagaceae family (Rehder 1927). One of these species is in Bulgaria, Turkey (Marmara surrounding, Western and Eastern Black Sea Region, locally Aegean, Amanos Mountains, and around Kahramanmaras in the south, the Caucasus), and northern Iran. In the work of Duhamel (1825) “Seeds of this genus”, it is stated that the plants are “oily”, and the name is taken from an ancient Greek word according to “Virgile and Pline”, and this word means “edo” or “eat” in Latin. The French name “le Hetre” also means “the seeds are edible” (Sanlı 1977).

The TM Process

The TM of the test samples was performed in three stages (drying at high temperature, heat treatment, and cooling and conditioning). In the first stage, the temperature was raised to 100 °C for 5 h, then to 130 °C for 5 h, and then to the target temperature for 5 h. In the second stage, heat treatment was applied in four different temperatures (160, 180, 200, and 220 °C) for two hours. In the third stage, the temperature was decreased to room temperature (20 ± 2 °C). The total thermal modification period took 35 h for each temperature value. After the heat treatment process, the samples were rested in a suitable place under atmospheric conditions for three weeks. The process of thermal modification was conducted at Indem KD 200 laboratory oven in Kirikkale University wood mechanics laboratory. Thermal modification process is illustrated in Fig. 1 and surface roughness set-up is depicted in Fig. 2.

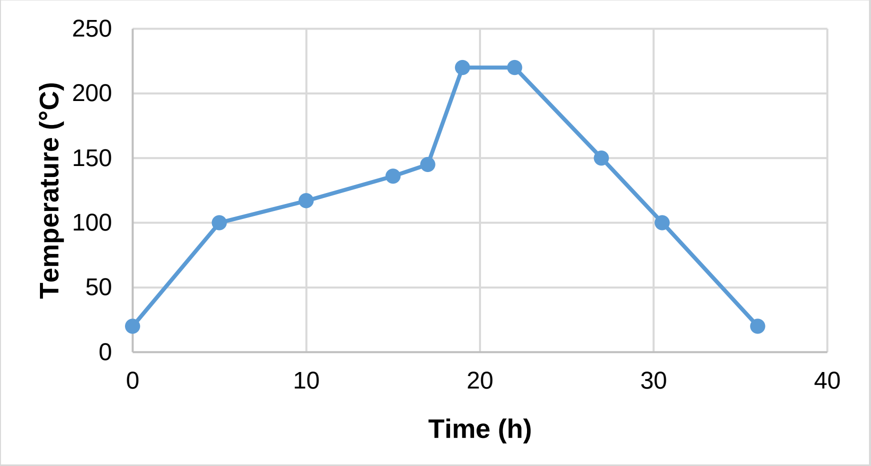
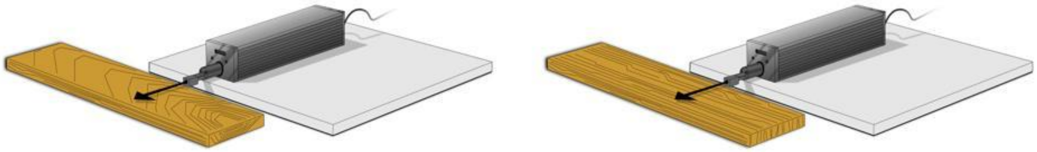


Fig. 1. Representation of thermal modification process at 220 °C

Roughness Measurement of Samples

The skid-type diamond stylus on the Mitutoyo Surftest SJ-210 (Mitutoyo Corporation, Kanagawa, Japan) has a surface-mounted 115 × 23 × 26 mm^3 drive unit. The stylus method is a popular method for determining how rough the wood's surface is on a sample's surface in terms of quantitative numerical values. Six measurements were randomly taken from both surfaces of each sample using the above profilometer across the grain orientation and a 15 mm tracing length. The tracing speed, stylus tip diameter, and tip angle were 10 mm/min, 4 µm, and 90°, respectively. The surface can be used to calculate surface roughness metrics including average roughness (R_a), mean peak to valley height (R_z), and maximum roughness (R_{max}) ISO 4287:1998 described in the Appendix of Grau *et al.* (2007).

For random roughness measurements, all samples prepared from hearth wood part of logs, during surface roughness measurement late wood areas of samples with 15 mm tracing length were employed. A total of 7 specimens were chosen for roughness groups. The surface roughness measurement set-up is illustrated in Fig. 2.



a.) Tangential Surface Roughness set-up **b.)** Radial Surface Roughness set-up

Fig. 2. Surface roughness (radial and tangential) set-up of wood specimens

Discoloration Evaluation of Samples

The CIELab color system was proposed by the International Lighting Association to assess the uniformity of color difference. To determine the heat-treatment effect on color change, a spectrometric test was conducted according to DIN 5033 (2017). Before and after thermal modification, every change was measured with a Spectro-colorimeter PCE-XXM-

20 model; (PCE Instruments UK Ltd., Southampton Hampshire United Kingdom). CIELab parameters L^*, a^*, and b^* were measured. Lightness was represented by L^*; pure white $L^* = 100$, and blackness $L^* = 0$, red was represented by $+a^*$; green was represented by $-a^*$, and yellowness was represented by $+b^*$, and blue was represented by $-b^*$. The total color change, ΔE^*, was computed using Eq. 1,

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{½} \quad (1)$$

where ΔL^*, Δa^*, and Δb^* are the color difference between the thermally modified and non-modified specimens. To determine the color changes colorimeter PCE-XXM-20 was utilized. The drawback in plotting rectangular coordinates is that the most important color characteristic, the hue, is not explicitly shown. However, this drawback can easily be eliminated by drawing in the lines of constant b^*/a^* ratios, which define the hue (Csanády *et al.* 2015).

Evaluation of Statistical Analysis

Significant variations in each of the study’s parameters were examined using the multiple analysis of variance (MANOVA). The groups were compared using the Duncan range test. Finally, IBM-International Business Machines Corp -SPSS software (Version 28.0.0, Armonk, NY, USA) was used to analyse the study results.

Sanding of the Heat-Treated Surfaces

Before the specimens were sanded, the new sanding belts were worn by continuous sanding for 30 min to remove the initial sharpness of the abrasive grits. Fresh belts result in high roughness values, which are not representative of the process (Cotta *et al.* 1982; Carrano 2000). Three different wood species, Scots pine (*Pinus sylvestris* L.), Kazdağı fir (*Abies equi-trojani* Aschers et Sint.), and Eastern beech (*Fagus orientalis* Lipsky), were sanded. After thermal modification, the species were sanded with P60, P80, and P120-grit grades, which are commonly used in the furniture industry. Samples were sanded in long, light, even strokes along the grain of the species with Helberg sandpaper. In some studies, the measurements are deliberately made in areas less affected by wood anatomy, such as latewood areas (Cotta *et al.* 1982; Costes and Larricq 2001; Gurau *et al.* 2005, 2006). Other approaches involve mechanically separating the anatomy by using a variety of sizes and shapes of styli (Peters and Mergen 1971; Gurau *et al.* 2007).

RESULTS AND DISCUSSION

In this study, two different types of hypotheses were evaluated, namely, H_0: There is no significant change in the surface roughness and discoloration after thermal modification, and H_1: Thermal modification of species improves surface roughness and discoloration, as opposed to non-thermal modification.

Surface Roughness of TM Specimens

Before thermal modification, specimen surfaces in tangential and radial grain orientations were sanded sequentially with P100 grit sandpaper with several light stokes to remove the irregularities from sawing and planing operations. All specimens were sanded with P200 grit sandpaper parallel to the grain, after P100 grit sandpaper. Statistical values of the Scots pine specimens (*Pinus sylvestris* L.), Kazdağı Fir (*Abies equi-trojani* Aschers et Sint.) and Eastern beech (*Fagus orientalis* Lipsky) are depicted in Table 1. Surface roughness of the specimens were decreased substantially with increased temperature exposure levels.

Table 1. Average Surface Roughness of Control and Thermal Modified Samples

Species	Wood Surface / Orientation Temperature	Average Surface Roughness Values (µm)		
		R_a (µm)	R_q (µm)	R_z (µm)
Scots Pine (*Pinus sylvestris* L.)	Radial / Control	10.49	14.28	77.93
	Radial / 160 °C	9.28	11.76	63.70
	Radial / 180 °C	8.66	11.02	61.94
	Radial / 200 °C	7.42	10.91	69.77
	Radial / 220 °C	6.55	10.29	63.53
	Tangential/ Control	7.61	9.99	47.30
	Tangential/ 160 °C	6.26	8.05	46.70
	Tangential/ 180 °C	5.53	8.94	55.30
	Tangential/ 200 °C	4.56	6.54	43.25
	Tangential/ 220 °C	3.38	4.94	38.27
Kazdağı Fir (*Abies equi-trojani* Aschers et Sint.)	Radial / Control	7.78	10.65	63.85
	Radial / 160 °C	6.53	9.36	59.21
	Radial / 180 °C	6.22	9.15	62.13
	Radial / 200 °C	5.54	7.77	59.49
	Radial / 220 °C	5.24	7.00	53.24
	Tangential/ Control	7.02	9.32	53.14
	Tangential/ 160 °C	6.15	9.02	58.31
	Tangential/ 180 °C	6.03	7.74	58.01
	Tangential/ 200 °C	5.45	7.14	55.38
	Tangential/ 220 °C	5.39	7.14	32.11
Eastern Beech (*Fagus orientalis* Lipsky)	Radial / Control	14.43	19.11	104.99
	Radial / 160 °C	13.32	17.31	88.14
	Radial / 180 °C	11.62	14.36	69.74
	Radial / 200 °C	10.55	14.27	70.21
	Radial / 220 °C	10.33	13.24	67.47
	Tangential/ Control	13.29	17.01	89.65
	Tangential/ 160 °C	11.52	14.38	67.21
	Tangential/ 180 °C	10.63	12.27	71.22
	Tangential/ 200 °C	9.50	13.21	65.25
	Tangential/ 220 °C	9.35	11.48	58.36

According to Table 1, average roughness values were decreased after thermal modification. Maximum surface roughness decrease was evaluated at Scots Pine tangential direction (55.5%), and minimum surface roughness was evaluated at tangential direction (23.1%) for the Kazdagi fir samples. The R_q/R_a ratio is important and has a definite physical meaning: it characterizes the slenderness of irregularities with the same height. Kazdagi fir and Scots pine are evergreen coniferous trees in the family Pinaceae, but eastern beech is a genus of deciduous trees in the family Fagaceae. The average R_q/R_a ratio were reported as the following: Scots pine 1.40, Kazdagi fir 1.37, and eastern beech 1.27. Eastern beech has a different behavior compared to the other two species as a function of temperature. This behavior could be explained by the density and anatomic structure of eastern beech. Budakci *et al.* (2011) researched four different wood species (pine, beech, oak, fir). In that study, beech samples had the highest surface roughness after thermal modification (Budakci *et al.* 2011).

Surface Roughness of the TM Applied and Sanded Specimens

According to the statistical analysis, the control samples of three species showed a significant improvement in their roughness characteristics when they were exposed to a temperature of 160, 180, 200, and 220 °C. After thermally treated specimens were compared to control specimens, the sample's overall roughness values indicated a considerable improvement.

Table 2. Average Surface Roughness Sanded Control and TM Samples

		Scots Pine (μm)			**Kazdagi Fir (μm)**			**Eastern Beech (μm)**		
Grain Orientation / Temperature Level	Sandpaper Grit No.	R_a	R_q	R_z	R_a	R_q	R_z	R_a	R_q	R_z
Radial / Control	P60	9.46	12.14	66.13	5.76	9.40	57.14	12.41	15.41	79.37
	P80	8.40	10.77	59.55	4.49	6.26	41.26	11.30	14.39	85.21
	P120	7.32	9.73	56.19	3.25	5.21	35.27	10.56	13.33	68.48
Tangential / Control	P60	6.20	8.37	48.65	4.21	6.19	40.49	11.29	14.54	69.23
	P80	5.42	6.92	33.17	3.35	4.26	38.41	10.61	13.15	6714
	P120	4.51	6.62	45.60	2.82	4.21	29.59	9.461	12.36	65.12
Radial / 160 °C	P60	7.09	8.43	43.96	5.84	8.55	57.46	12.39	15.31	79.54
	P80	5.74	7.35	43.13	4.32	5.88	39.60	10.20	13.36	75.32
	P120	4.39	6.15	42.01	3.38	4.26	33.25	9.67	12.25	67.36
Tangential/ 160 °C	P60	5.29	6.55	36.25	4.26	5.99	39.51	9.29	12.22	66.01
	P80	4.92	6.42	34.26	3.53	5.00	36.96	8.51	11.02	62.35
	P120	3.77	5.13	31.83	2.45	4.52	29.18	7.26	9.43	47.32
Radial / 180 °C	P60	7.14	10.96	54.25	4.36	5.98	40.27	10.33	13.21	68.17
	P80	6.45	9.34	51.24	3.65	5.11	38.15	9.47	11.31	67.15
	P120	4.33	8.55	38.56	2.40	4.32	20.26	7.51	10.47	57.14
Tangential/ 180 °C	P60	4.45	5.95	39.47	4.48	5.15	38.23	9.67	11.11	66.19
	P80	3.52	5.376	40.16	3.43	4.96	28.15	8.26	10.32	61.71
	P120	3.01	4.10	28.14	2.40	4.26	26.14	6.39	8.70	51.33
Radial / 200 °C	P60	6.29	9.26	58.25	4.54	5.11	41.25	9.22	11.14	58.12
	P80	5.19	7.36	45.21	3.54	5.00	37.11	8.32	10.91	53.14
	P120	4.18	6.58	41.26	2.76	4.20	27.32	7.22	9.25	48.32
Tangential/ 200 °C	P60	3.30	5.47	40.26	3.09	4.20	28.11	8.40	10.36	49.26
	P80	2.84	4.26	31.26	2.55	3.44	24.34	7.55	8.91	48.21
	P120	2.71	4.14	28.46	2.03	3.00	21.06	6.87	8.72	46.22
Radial / 220 °C	P60	5.42	9.36	59.15	3.69	5.05	38.15	9.44	12.31	61.22
	P80	4.30	5.66	42.37	3.11	4.31	28.22	7.60	9.24	50.32
	P120	3.30	5.02	39.25	2.07	3.04	19.25	6.53	7.60	45.70
Tangential/ 220 °C	P60	2.75	4.03	26.55	3.44	4.22	30.05	8.25	10.03	49.69
	P80	2.67	3.64	26.46	2.39	3.01	20.48	7.39	9.98	49.37
	P120	2.04	3.91	21.12	2.10	2.94	18.87	6.14	7.01	47.15

Results indicated that there was a major change in roughness values (Trisna and Hiziroglu 2013). In previous studies, there was a major change in roughness values associated with samples exposed to 190 °C for 8 h (Ulker *et al.* 2018). In another study, stylus type equipment was employed to evaluate surface roughness of the sample across grain orientation on tangential surface of samples (Trisna and Hiziroglu 2013). Wood degrades faster when heated by steam or water (Hillis and We 1975). It seems that the anatomical structure of wood samples was affected by thermal modification. Under these conditions, the hemicelluloses are hydrolyzed, and the crystallinity index of cellulose increases, but lignin is only slightly affected (Pelaez Samaniego *et al.* 2013). Statistical analysis related to effectiveness of the temperature on the surface roughness of the specimens is displayed at Table 3.

Table 3. Variance Analysis of Specimens

Source	Mean Square	F-value	Significance P < 0.005
Cutting Direction	274.101	3558.45	0.000
TM Temperature	151.376	1965.207	0.000
Sandpaper Type	319.455	4147.255	0.000
Wood Species	1611.574	20921.912	0.000

Based on Table 3, all variables (cutting direction, thermal modification, sandpaper type, and wood species) were found to be effective relative to surface roughness. Significant differences were observed between surface roughness, cutting direction in both radial and tangential orientations, thermal modification temperature, sandpaper type, and wood species. Homogeneity tests were performed to determine whether the differences in surface roughness of the effective variables were significant. Table 4 gives the results.

Table 4. Comparative Test Results for Average Surface Roughness Values and Homogeneity Groups According to Duncan Test

Parameters	Groups	H.G.* A	H.G.* B	H.G.* C	H.G.* D	H.G.* E
Sandpaper Type (Grit size)	Control				8.188	
	P60 Grit			6.72		
	P80 Grit		5.76			
	P120 Grit	4.76				
Parameters	Groups	H.G.* A	H.G.* B	H.G.* C	H.G.* D	H.G.* E
Wood Species	*Scots Pine*		5.40			
	Kazdagi Fir	4.12				
	Eastern Beech			9.55		
Parameters	Groups	H.G.* A	H.G.* B	H.G.* C	H.G.* D	H.G.* E
Thermal Modification Temperature	Control					7.97
	160 °C				6.89	
	180 °C			6.25		
	200 °C		5.57			
	220 °C	5.12				

*Homogeneity Groups

According to Korkut *et al.* (2013), heat treatment showed an interesting potential to increase the wood quality regarding color and its value for solid timber products from wild cherry. Increasing the severity of thermal treatment resulted in smoother surfaces. In other words, surface quality of the samples was enhanced noticeably as a result of heat treatment (Korkut *et al.* 2013). In the literature, there are more studies which support the results of our study. Heat treatment provides smoother surfaces (Bakar *et al.* 2013).

Discoloration of TM Wood Specimens

It is well known that wood discoloration is caused by thermal modification (Sirinivas and Pandey 2012; Mitani and Barboutis 2014; Pelit *et al.* 2015; Ulker *et al.* 2018). After thermal modification, all average lightness values (*L**) of species decreased.

Table 5. Average Discoloration Effects of TM of Wood Species

Temperature Level	Scots Pine			Kazdagi Fir			Eastern Beech		
	Color Characteristics			Color Characteristics			Color Characteristics		
	L*	***a****	***b****	***L****	***a****	***b****	***L****	***a****	***b****
Control	78.78	2.18	11.46	73.16	1.24	9.41	68.97	1.02	10.60
160 °C	61.52	3.47	12.80	64.88	2.51	11.76	59.96	1.31	12.30
180 °C	55.47	10.22	24.41	50.98	10.70	23.69	55.08	6.28	14.55
200 °C	50.57	13.18	19.40	46.15	14.81	20.13	51.58	9.03	19.23
220 °C	43.41	13.33	18.74	37.12	15.41	21.19	50.44	16.56	24.91

Based on Table 5, discoloration values showed a high effect on color changes due to the thermal treatment of wood species. Kazdagi fir had the greatest decrease with a value of 49.2%, followed by Scots pine 44.9%, and finally Eastern beech 26.9%. Therefore, it appears that the lightness values were adversely influenced for wood specimens. Discoloration of wood after thermal modification is a result of the chemical deterioration in the cell wall of wood specimens (Budakci *et al.* 2011). Kazdagi fir and Scots pine specimens showed relatively similar levels of discoloration values compared to Eastern beech. As stated, eastern beech samples that have mainly hardwood portions would be reason for such a finding. Discoloration evaluation of specimens (Δ*E*) values are given in Table 6.

Table 6. Discoloration Evolution of Specimens

Temperature Level	Scots Pine	Kazdagi Fir	Eastern Beech
	Color Characteristics	Color Characteristics	Color Characteristics
	Δ*E* *ab	**Δ*E* *ab**	**Δ*E* *ab**
160 °C	17.35	8.70	9.17
180 °C	32.07	28.76	16.48
200 °C	39.67	36.03	22.93
220 °C	46.86	45.14	32.43

Discoloration values (*L**, *a**, *b**) of beech specimens were significantly changed after thermal modification (Babiak *et al.* 2004; Vidholdová *et al.* 2017). During the heat treatment, color space exhibited major modifications. The color spaces of wood exposed to different modes of heat modifications were disjunctive at different temperatures (Kudela and Andor 2018). After thermal modification at 160 °C, the total color difference was $\Delta E = 8.70$, which, is a noticeable color change according to the scale conveyed in Allegretti *et al*. (2009). In the authors' study, all specimens had noticeable color change after thermal modification. All the discoloration of samples after thermal modification is shown at Fig. 3.

Scots Pine Samples Kazdagi Fir Samples Eastern Beech Samples

Fig. 3. Thermal modified Scots pine, Kazdagi fir, and Eastern beech species, control, 160 °C, 180 °C, 200 °C, and 220 °C respectively

Table 7. Color Hue Values of Specimens

Temperature Level	Scots Pine	Kazdagi Fir	Eastern Beech
	Color hue	Color hue	Color hue
	b/a	***b/a***	***b/a***
Control	5.256	7.588	10.392
160 °C	3.688	4.685	9.389
180 °C	2.388	2.214	2.316
200 °C	1.471	1.359	2.129
220 °C	1.405	1.375	1.504

Table 8. Density Values of Specimens

Temperature Level	Scots Pine (g/cm^3)	Kazdagi Fir (g/cm^3)	Eastern Beech (g/cm^3)
Control	0.53	0.42	0.65
160 °C	0.46	0.40	0.63
180 °C	0.39	0.38	0.59
200 °C	0.36	0.37	0.54
220 °C	0.33	0.35	0.54

The lightness and color hue relationship is generally observed as linear after heat treatment on specimens. This explains why the range of color change is smaller and, therefore, the measurement points can be approximated with a straight line. In the study of Bekhta and Niemz, color hue for Spruce is investigated and a linear relationship is found at $L* - h*$ values (Bekhta and Niemz 2003). The color hue interpreted in rectangular or polar coordinates is uniquely the same, although the numerical values are different, color hue values of specimens given in Table 7. The change was highest of all specimens at 160 °C when the initial yellowish color turns into light brown and then into a brownish red color at 220 °C. Density values of specimens given in Table 8.

CONCLUSIONS

1. In the conducted study, surface roughness of thermal modified wood samples Scots pine (*Pinus sylvestris* L.), Kazdağı fir (*Abies equi-trojani* Aschers et Sint.), and Eastern beech (*Fagus orientalis* Lipsky) were researched. As the result of the analyses, factors of grit size, wood species, and thermal modification temperature were statistically important and significant regarding the surface roughness value after thermal modification of wood.
2. Color change of wood species after thermal modification were investigated. Based on discoloration data, at the temperature 180 °C, Kazdagi fir color change was threefold among other species. The temperature increase to 200 °C resulted in a fourfold effect in the total color difference (ΔE =36.0 compared to 8.70) in Kazdagi fir specimens. Discoloration evolution showed that color change of Scots pine and Kazdagi fir was more prominent after thermal modification.
3. This theoretical model could be a guide study for researchers, which could enable them to work easily and economically decide the optimum temperature levels for desired color of wood species and grit size for working parameters of smooth surfaces.
4. In further studies, it would be desirable to research machining properties of thermally modified wood species (milling process, circler table, and bandsaw) to gain a better understanding of technological behaviors of different wood species.

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