Changes Caused by Heat Treatment in Color and Dimensional Stability of Beech (*Fagus sylvatica* L.) Wood

Utjecaj toplinske obrade na promjenu boje i dimenzijsku stabilnost bukovine (*Fagus sylvatica* L.)

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ABSTRACT • *Thermal modification of wood permanently alters several of its chemical and physical properties. Beech wood is one of the most important hardwoods in Central and Eastern Europe and is extensively used in furniture production. In this study the effects of thermal modification of beech wood (Fagus sylvatica L.) on hygroscopic properties were examined and the color changes of the treated wood were determined. Beech wood has been subjected to a heat treatment at the temperature of 180 °C for five different durations ranging from 2 to 10 h. A more intense, gradual color change of the treated samples was observed after 4-h treatment, whereas in some other cases the recorded alterations were less intense. The most pronounced color differentiations compared to untreated samples occurred in 8-h and 10-h treatments. Dimensional stability and absorption were measured after 1-h, 3-h, 6-h, 1 day and 3 days immersion in water. The 8-h treatment duration exhibits the greatest reduction of swelling and absorption percentage.*

Key words: *beech wood (Fagus sylvatica L.), heat treatment, color change, hygroscopic properties*

SAŽETAK • *Toplinska modifikacija drva trajno mijenja neka njegova kemijska i fizikalna svojstva. Bukovina je jedna od najvažnijih vrsta tvrdog drva u srednjoj i istočnoj Europi, a uvelike se upotrebljava za proizvodnju namještaja. U ovoj su studiji predstavljeni rezultati istraživanja utjecaja toplinske modifikacije bukovine (Fagus sylvatica L.) na neka higroskopna svojstva i promjene boje toplinski obrađenog drva. Bukovina je podvrgnuta toplinskoj obradi pri temperaturi 180 °C i tijekom pet različitih trajanja procesa obrade, od dva do deset sati. Intenzivnije promjene boje toplini izlaganih uzoraka uočene su nakon četiri sata, dok su u drugim slučajevima zabilježene manje intenzivne promjene. Najintenzivnije razlike u boji u usporedbi s netretiranim uzorcima dogodile su se nakon osam i deset sati obrade. Dimenzijska stabilnost i apsorpcija mjerene su nakon jedan sat, tri sata, šest sati, jedan dan i tri dana potapanja uzoraka u vodi. Nakon potapanja uzoraka u vodi u trajanju od osam sati zabilježeno je najveće smanjenje bubrenja i postotka apsorpcije.*

Ključne riječi: *bukovina (Fagus sylvatica L.), toplinska obrada, promjena boje, higroskopna svojstva*

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1 INTRODUCTION
1. UVOD

Improvement of wood material properties and the increase of its lifespan have occupied scientists for numerous years as wood is an omnipresent and indispensable material for a very wide range of applications such as furniture production and building constructions. For this reason, ways to tackle its basic drawbacks such as dimensional stability, low resistance to microorganisms and volatility structure have been continuously elaborated. The most popular methods applied to improve timber are based on toxic substances and complicated recycling processes, and therefore many European countries have banned their use. Thermal modification of wood is a process that provides the improvement of some wood properties without imposing an extra burden on the environment, as preservatives apparently do. Specifically, thermal modification seems to enhance dimensional stability and biological durability of wood, although some mechanical properties appear to deteriorate. This change of properties is mainly induced by thermal degradation of hemicelluses and, generally, the changes continue as the temperature is increased. Due to moisture content decrease, swelling and shrinkage occur, color darkens, several extractives flow from the wood, ph decreases and thermal insulation properties are improved (Hill, 2006).

Several studies involving thermally modified beech wood, as well as other hardwood species, have been conducted so far. Yildiz *et al.* (2002b) conducted research into the effects of heat treatment on mechanical and chemical behavior of *Fagus orientalis* at various temperatures (130 ºC, 150 ºC, 180 ºC, 200 ºC) and durations (2, 6 and 10h). Predictably, mechanical properties decreased when the treatment duration and temperature were increased, whilst, regarding chemical properties, it was observed that hemicelluloses was the wood-cell component mostly degraded by the heat treatment. Reppelin *et al*. (2005) evaluated the swelling of heat treated beech wood in relation to chemical composition, and Hakkou *et al.* (2006) studied the fungal durability of heat treated *Fagus sylvatica* in the temperature range of 200 to 280 ºC, and the results indicated a considerably good correlation between the process temperature and wood durability. Moreover, they demonstrated a sufficient correlation between decay resistant and mass loss measurements, which are directly correlated to hemicellulose degradation. Mohebby *et al*. (2005) studied the influence of thermal treatment on physical properties of beech wood at 160 ºC, 180 ºC and 200 ºC for 4, 5 and 6 hours. The highest absorption was determined in beech wood treated at 180 ºC for 4 and 6 hours, while the lowest moisture absorption was measured in the samples treated at 160 ºC for 4 h. Charani *et al.* (2007) studied the effects of thermal treatment on dimensional stability and water absorption of beech wood (*Fagus orientalis)* applied in three different temperatures (150 ºC, 160 ºC and 170 ºC) and four different durations (1 h, 3 h, 5 h and 7 h). The results indicated that the best anti-swelling efficiency value was achieved at higher temperature, whereas water absorption decreased in all heat modified samples. Arnold (2007) investigated the anisotropy, hardness, shear strength parallel to grain, swelling, tensile strength perpendicular to grain of thermally modified beech and spruce wood subjected to 180 ºC and 220 ºC. The results indicated that thermal modification has a negative impact on mechanical and physical properties, while swelling improved. Govorcin *et al*. (2009) studied certain physical properties of Ash (*Fraxinus excelsior* L.) after thermal treatment at 200 ºC. They ascertained that the mean value of density in absolutely dry conditions of recent ash was higher by 8.4 % than density of heat treated ash. In addition, shrinkage in radial and tangential direction and volume shrinkage of recent ash were higher than shrinkage in heat treated ash. Dimensional stability of ash under such procedure of heat treatment resulted in increased dimensional stability, and yet, the investigated mechanical properties were significantly lower. Arnold (2009) studied the effect of moisture on bending properties of thermally modified beech wood at 180 ºC, 220 ºC for 4 hours. Gonzalez-Pena and Hale (2009) conducted experiments on the effect of heat on the chemical composition and dimensional stability of beech wood at 190, 210, 230 and 245 for 30 min, 1, 4, 8 and 16 hours. They concluded that ΔE^* in thermally modified wood originates from chemical changes in the main wood polymers, more so in lignin than in polysaccharides, due to the darkening of the lignin itself. Sinković *et al*. (2011) studied particular physical properties of treated and untreated beech and hornbeam wood. They inferred that the average value of density in completely dry conditions of heat treated beech wood was smaller by 8.5 % than the untreated one, whereas, the reduction of average values of maximum shrinkage of heat treated beech wood was even bigger in relation to the untreated wood. Maximum radial shrinkage of heat treated beech wood was smaller by 7 %, maximum tangential shrinkage by 23.5 % and maximum volumetric shrinkage by 19.3 % compared to the same physical properties of untreated beech wood. Todorović *et al*. (2012) estimated the beech wood properties by color change at 170 ºC, 190 ºC and 210 ºC for four hours. This study demonstrated that higher temperatures led to a rise in mass loss and a decrease in mechanical properties, whereas the effect on modulus of elasticity (*MOE*) was negligible.

This study was conducted to assess the variation of dimensional stability (swelling, absorption) after immersion in water for 1 h, 3 h, 6 h, 24 h and 72 h, the weight loss caused by heat treatment, weight increase after 7, 14, 21 days and 5 months of air conditioning at 20 ± 3 °C and 60 ± 5 % relative humidity, and the color changes (ΔL, Δa, Δb, ΔE, ΔC) after heat treatment of beech (*Fagus sylvatica)* wood at 180 ºC for 2, 4, 6, 8 and 10 hours.

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

Beech sawn timber used in this research was of Greek origin, obtained from the market. The timber was air dried for 1 year. Initially, lumber was cut in sawn samples of dimension 50 x 25 mm in cross section. The average density (oven dry weight/volume at 10.26 % moisture) of timber used was 0.68 g/cm^3 (Standard Deviation = 0.02), while the average moisture content was 10.26 % (Standard Deviation = 0.15) after conditioning at 20 ± 2 °C and 60 ± 5 % relative humidity. Thermal treatment of the specimen applications was carried out in a temperature-controlled, small, laboratory, heating unit (80 x 50 x 60 cm), where five different durations (2 h, 4 h, 6 h, 8 h and 10 h) were applied at 180 °C under atmospheric pressure in the presence of air. The specimens were placed in the unit after the desired temperature had been reached. Immediately after that, the weight loss of the specimens of each heat treatment was measured by weighing them and comparing their weight to the initial one. The measurements of weight increase were conducted after reconditioning of the heat treated specimens at 20 ± 2 °C and 60 ± 5 % relative humidity for 7, 14 and 21 days.

All specimens color measurements were recorded on the surface of wood specimens before and after heat treatments in radial, tangential and longitudinal directions with a colorimeter Minolta Croma-Meter CR-400. The color system CIE*Lab** was used for the measurements. L^* describes the lightness, a^* and b^* describe the chromatic coordinates on the green-red and blue yellow axis, respectively. From the $L^*a^*b^*$ values, the difference in the lightness (ΔL^*) and chroma coordinates (Δa^* and Δb^*), saturation (C^*) (ΔC^*) and total color differences (ΔE) were calculated using the following equations:

$$\Delta L^* = L^*_t - L^*_{ut} \quad (1)$$

$$\Delta a^* = a^*_t - a^*_{ut} \quad (2)$$

$$\Delta b^* = b^*_t - b^*_{ut} \quad (3)$$

$$C^* = (a^{*2} + b^{*2})^{1/2} \quad (4)$$

$$\Delta E = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{1/2} \quad (5)$$

$$\Delta C^* = C^*_t - C_{ut} \quad (6)$$

Were L^*_t, a^*_t, b^*_t are L^*, a^* and b^* of the heated specimens and L^*_{ut}, a^*_{ut}, b^*_{ut} are L^*, a^* and b^* of the control specimens, respectively.

The color measurements were determined according to ISO 7724/3:1984 and the values reported are the average values with standard deviation.

The samples for hygroscopic properties were cut in final cross section dimensions (2 cm x 2 cm x 3 cm), according to the respective standard ISO 4859: 1982. For each experiment, 10 specimens were prepared. The swelling (in radial and tangential directions) and the absorption percentage were conducted after the immersion of samples in the water of 20 ± 3 °C for 1 h, 3 h, 6 h, 24 h and 72 h. Additionally, after conditioning at 20 ± 2 °C and 60 ± 5 % relative humidity, EMC (Equilibrium Moisture Content) and density of the specimens were estimated.

The swelling percentage was calculated with the use of the following equation:

Percentage swelling = ((*Swollen Dimension* - *Oven Dry Dimension*)/(*Oven Dry Dimension*))×100

Absorbed water percentage was calculated according to the following equation:

$$M\% = ((M_{wet} - M_{dry}) / M_{dry}) \times 100$$

Where M_{wet} the wetmass after immersion in water, M_{dry} the initial dry mass.

Twelve replicates for each variable (treatment) were performed to compute the color changes and hygroscopic properties.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

So as to estimate the color change of the specimens, the three color coordinates, L^*, a^*, and b^* were recorded before and after heat treatment. Figure 1 shows the changes in lightness of beech wood for tangential, radial and longitudinal direction with respect to

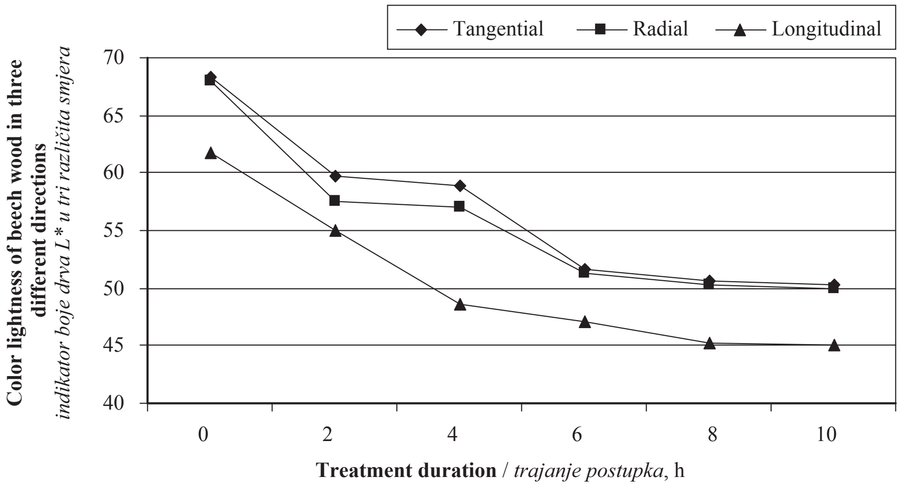

Figure 1 Effect of heat treatment duration in three different directions on L^*
Slika 1. Utjecaj trajanja toplinske obrade na indikator boje drva L^* u tri različita smjera

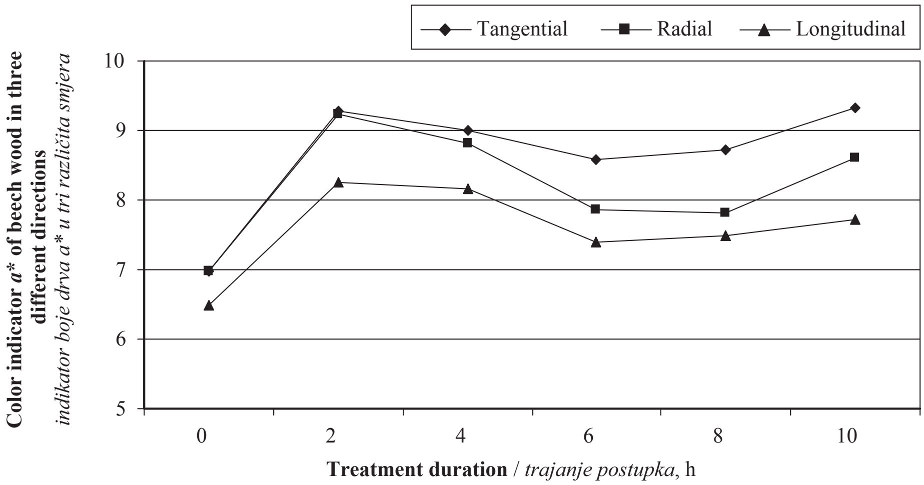

Figure 2 Effect of heat treatment duration in three different directions on *a**
Slika 2. Utjecaj trajanja toplinske obrade na indikator boje drva *a** u tri različita smjera

treatment duration. The resulting darkening was clearly observable and it intensified with treatment duration. Since *L*=0 is for black and *L*=100 is for white, it is evident that the lower *L* value, the darker color is observed. Heat treated beech wood exhibits a decrease of *L** indicator as the duration increases gradually. Additionally, tangential and radial directions show higher decrease compared to longitudinal direction. Concerning a* coordinate (Figure 2), which positions the color in a scale of green to red, it appears to be lower in untreated specimens, while it increases abruptly in specimens heat treated for 2 h and then it tends to decrease slowly with further increasing of treatment duration until 8-h treatment. Regarding coordinate *b** (Figure 3), which demonstrates the scale of yellow to blue, referring to longitudinal direction, it appears to increase till 4-h treatment unlike the radial and tangential direction.

The color coordinates, *L**, *a** and *b** were used in order to calculate the total color change (ΔE) and the color saturation (ΔC^*) (Table 1). A low value of ΔE corresponds to a low color change for the treated sample, compared to untreated specimens. According to the results, ΔE value of the specimens seems to increase, meaning that the color change of wood surface and the heat treatment intensity are proportional, while ΔC^* value seems to decrease, as the duration of the thermal treatment increases up to 6 h, where it appears to increase again until 10-h treatment, exceeding the values of 2-h treatment. The negative values of lightness (ΔL^*) indicated that the color became increasingly darker with the increase of treatment duration. The extent of thermal degradation is directly related to color darkening, therefore, the color can be used as an indicator of the process conditions (Guller, 2012).

Table 2 shows the average values of swelling of the treated and untreated specimens after immersion in water. Referring to swelling, all heat treatments in this study seem to enhance the hygroscopic behavior of beech wood. Swelling in tangential direction proved to be much higher than in radial direction. Nevertheless, thermal treatment proved to enhance tangential swelling more efficiently than radial swelling. As the duration of heat treatment is extended, tangential swelling tends to decrease and this tendency is similar to the case of swelling in radial direction, with the difference that when the treatment duration exceeded 8 h, the

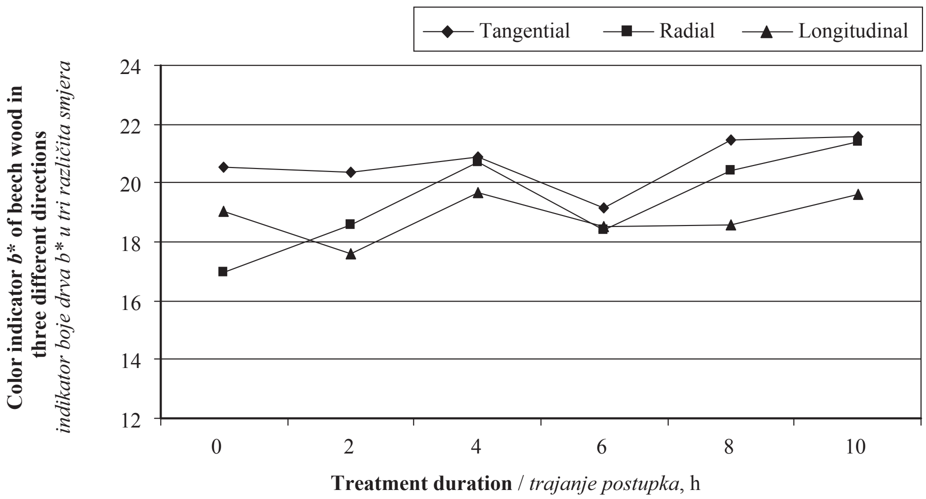

Figure 3 Effect of heat treatment duration in three different directions on *b**
Slika 3. Utjecaj trajanja toplinske obrade na indikator boje drva *b** u tri različita smjera

Table 1 Effect of heat treatment for three different durations on color changes of beech wood
Tablica 1. Utjecaj različitog trajanja toplinske obrade drva na promjene boje bukovine

Heat treatment time, h *Trajanje toplinske obrade, h*	**Direction** *Smjer*	**Unit**	**Color change values** /*Vrijednosti promjene boje*				
			ΔE	ΔL	Δa	Δb	ΔC
2 h	Tangential *tangencijalno*	Avg.	**9.09**	**-8.77**	**2.31**	**-0.3**	**0.70**
		±s	0.89	0.94	0.24	0.06	0.12
		s²	0.80	0.89	0.06	0.004	0.01
		CV	0.09	0.10	-0.10	-0.22	0.17
	Radial *radijalno*	Avg.	**11.27**	**-10.44**	**2.27**	**1.64**	**1.77**
		±s	0.99	0.84	0.37	0.21	0.23
		s²	0.99	0.72	0.14	0.04	0.05
		CV	0.08	-0.08	0.16	0.13	0.13
	Longitudinal *longitudinalno*	Avg.	**7.06**	**-6.74**	**1.78**	**-1.48**	**-0.59**
		±s	0.89	0.93	0.32	0.24	0.16
		s²	0.79	0.88	0.10	0.06	0.02
		CV	0.12	-0.13	0.18	-0.16	-0.27
4 h	Tangential *tangencijalno*	Avg.	**9.48**	**-9.42**	**2.02**	**0.34**	**1.07**
		±s	1.30	1.31	0.27	0.08	0.08
		s²	1.70	1.73	0.07	0.007	0.008
		CV	0.13	-0.13	0.13	0.25	0.08
	Radial *radijalno*	Avg.	**11.58**	**-10.92**	**1.85**	**3.76**	**3.70**
		±s	0.51	0.51	0.26	0.45	0.42
		s²	0.26	0.26	0.07	0.20	0.17
		CV	0.04	-0.04	0.14	0.12	0.11
	Longitudinal *longitudinalno*	Avg.	**13.37**	**-13.25**	**1.68**	**0.61**	**1.27**
		±s	0.62	0.61	0.19	0.18	0.15
		s²	0.38	0.37	0.03	0.03	0.02
		CV	0.04	-0.04	0.11	0.30	0.11
6 h	Tangential *tangencijalno*	Avg.	**16.84**	**-16.73**	**1.69**	**-1.29**	**-0.65**
		±s	0.90	0.87	0.46	0.15	0.11
		s²	0.82	0.76	0.21	0.02	0.01
		CV	0.05	-0.05	0.27	-0.11	-0.17
	Radial *radijalno*	Avg.	**16.84**	**-16.75**	**0.88**	**1.45**	**1.19**
		±s	0.87	0.87	0.16	0.19	0.11
		s²	0.76	0.76	0.02	0.03	0.01
		CV	0.05	-0.05	0.18	0.13	0.09
	Longitudinal *longitudinalno*	Avg.	**14.44**	**-14.40**	**0.91**	**-0.52**	**-0.17**
		±s	0.63	0.63	0.09	0.09	0.07
		s²	0.40	0.40	0.008	0.008	0.005
		CV	0.04	0.04	0.10	-0.17	-0.42
8 h	Tangential *tangencijalno*	Avg.	**17.68**	**-17.78**	**1.76**	**0.92**	**1.48**
		±s	0.83	0.89	0.18	0.11	0.15
		s²	0.69	0.80	0.03	0.01	0.02
		CV	0.04	-0.05	0.10	0.12	0.10
	Radial *radijalno*	Avg.	**18.14**	**-17.66**	**0.83**	**3.46**	**2.91**
		±s	0.78	0.94	0.09	0.25	0.258
		s²	0.61	0.89	0.009	0.06	0.06
		CV	0.04	-0.05	0.11	0.07	0.08
	Longitudinal *longitudinalno*	Avg.	**16.61**	**-16.58**	**0.99**	**-0.44**	**-1.10**
		±s	0.69	0.69	0.11	0.10	0.07
		s²	0.48	0.48	0.01	0.01	0.005
		CV	0.04	-0.04	0.11	-0.23	-0.69
10 h	Tangential *tangencijalno*	Avg.	**18.19**	**-18.01**	**2.35**	**1**	**1.73**
		±s	0.57	0.56	0.22	0.22	0.16
		s²	0.33	0.32	0.05	0.04	0.02
		CV	0.03	-0.03	0.09	0.22	0.09
	Radial *radijalno*	Avg.	**18.65**	**-18.04**	**1.63**	**4.44**	**4.13**
		±s	0.65	0.69	0.17	0.15	0.15
		s²	0.43	0.48	0.02	0.02	0.02
		CV	0.03	-0.03	0.10	0.03	0.03
	Longitudinal *longitudinalno*	Avg.	**16.80**	**-16.74**	**1.23**	**0.57**	**0.98**
		±s	0.57	0.58	0.14	0.09	0.10
		s²	0.32	0.33	0.01	0.009	0.01
		CV	0.03	-0.03	0.11	0.17	0.10

(Avg – Average / *srednja vrijednost*; ±s – Standard error / *standardna pogreška*, s² – Standard Deviation / *standardna devijacija*, CV – Coefficient of variation / *koeficijent varijacije*)

Table 2 Effect of heat treatment on dimensional stability (swelling) in tangential and radial direction of beech wood
Tablica 2. Utjecaj toplinske obrade na dimenzijsku stabilnost (bubrenje) bukovine u tangencionalnom i radijalnom smjeru

Treatment Duration *Trajanje obrade*	**Unit**	**Tangential swelling, %** *Tangencijalno bubrenje, %*					**Radial swelling, %** *Radijalno bubrenje, %*				
		Time of immersion in water / *Vrijeme potapanja u vodi*									
		1 h	3 h	6 h	24 h	72 h	1 h	3 h	6 h	24 h	72 h
0 h	Avg.	**1.10**	**2.06**	**2.91**	**6.40**	**8.04**	**1.12**	**1.54**	**2.04**	**3.52**	**3.99**
	±s	0.45	0.51	0.52	0.67	1.22	0.84	1	1.11	1.44	1.48
	s²	0.20	0.26	0.27	0.44	0.48	0.70	1	1.23	2.07	2.19
	CV	0.40	0.24	0.17	0.10	0.15	0.75	0.64	0.54	0.40	0.37
2 h	Avg.	**0.81**	**1.55**	**2.05**	**2.29**	**3.11**	**0.63**	**1.17**	**1.63**	**1.93**	**2.57**
	±s	0.36	0.44	0.50	0.58	0.72	0.20	0.28	0.39	0.58	0.63
	s²	0.13	0.19	0.25	0.34	0.51	0.04	0.07	0.15	0.34	0.40
	CV	0.44	0.28	0.24	0.25	0.23	0.32	0.47	0.24	0.30	0.24
4 h	Avg.	**0.87**	**1.39**	**1.93**	**2.30**	**3.17**	**0.76**	**1.13**	**1.54**	**1.85**	**2.73**
	±s	0.15	0.28	0.18	0.21	0.40	0.24	0.20	0.18	0.29	0.26
	s²	0.02	0.08	0.03	0.04	0.16	0.05	0.04	0.03	0.08	0.07
	CV	0.18	0.20	0.09	0.09	0.12	0.31	0.17	0.12	0.15	0.09
6 h	Avg.	**0.72**	**1.10**	**1.90**	**2.50**	**3.33**	**0.75**	**0.99**	**1.43**	**1.75**	**2.48**
	±s	0.16	0.11	0.21	0.19	0.28	0.13	0.14	0.28	0.33	0.30
	s²	0.02	0.01	0.04	0.03	0.08	0.02	0.02	0.08	0.11	0.09
	CV	0.22	0.10	0.11	0.07	0.08	0.14	0.14	0.19	0.18	0.12
8 h	Avg.	**0.67**	**1.01**	**1.49**	**1.98**	**2.58**	**0.73**	**0.98**	**1.33**	**1.71**	**2.51**
	±s	0.10	0.15	0.22	0.34	0.44	0.17	0.16	0.12	0.18	0.35
	s²	0.01	0.02	0.05	0.12	0.20	0.03	0.02	0.01	0.03	0.12
	CV	0.15	0.15	0.15	0.17	0.17	0.24	0.17	0.09	0.10	0.14
10 h	Avg.	**0.72**	**1.08**	**1.70**	**2**	**2.65**	**0.51**	**0.75**	**0.61**	**1.50**	**2.09**
	±s	0.26	0.33	0.45	0.51	0.58	0.14	0.18	1.31	0.58	0.57
	s²	0.06	0.11	0.20	0.26	0.33	0.02	0.03	1.72	0.34	0.33
	CV	0.36	0.30	0.26	0.25	0.21	0.28	0.25	2.12	0.38	0.27

(Avg – Average / *srednja vrijednost*; ±s – Standard error / *standardna pogreška*, s² – Standard Deviation / *standardna devijacija*, CV – Coefficient of variation / *koeficijent varijacije*)

swelling values slightly increased only in tangential direction, without reaching the swelling values of the untreated specimens.

The absorption of the treated specimens was affected positively compared to untreated specimens (Table 3). As the treatment duration increases, absorption decreases; however when exceeding 8 hours of treatment, absorption percentage values record a slight increase. This fact may be attributed to permanent changes typically occurring during heat treatments of long duration, namely in the chemical composition of wood and physical properties, such as mass loss, density loss, thermal degradation of polysaccharides and lignin, etc.

The dominant effect of heat treatment is the decrease in equilibrium moisture content. This, along with the oven dry density of all heat-treated samples, decreased in relation to the untreated wood except for density specimens treated for 2 h, whose values slightly increased, which is compatible with previous studies. Yildiz (2002b) reported a minor density increase of beech wood (2.25 %) after 2-h treatment at 130 ºC, but mentioned that for more intense treatments the density decreased by 10 %. Regarding equilibrium moisture content, the 10-h treatment was the most effective, decreasing the equilibrium moisture by 47.12 %. This EMC reduction suggests that thermal treatment affects the dimensional stability

Table 3 Absorption percentage of thermally treated and untreated beech wood
Tablica 3. Postotak apsorpcije toplinski obrađenoga i neobrađenog drva

Treatment duration *Trajanje obrade*	**Time of immersion in water** *Vrijeme potapanja u vodi*				
	1 h	3 h	6 h	24 h	72 h
0 h	9.78 (1.40)	14.05 (1.80)	18.18 (1.74)	30.06 (1.88)	48.79 (1.73)
2 h	6.53 (1.23)	12.45 (1.58)	16.20 (1.61)	27.63 (1.28)	49.29 (1.35)
4 h	6.13 (0.70)	10.34 (0.94)	14.99 (1.09)	25.34 (1.59)	47.15 (1.39)
6 h	6.11 (0.28)	10.12 (0.56)	13.73 (1.02)	24.04 (1.19)	43.70 (1.09)
8 h	5.46 (0.47)	8.33 (0.81)	12.56 (1.42)	22.65 (1.24)	42.80 (1.200
10 h	5.82 (0.78)	8.62 (1.14)	12.84 (0.71)	22.71 (0.95)	42.72 (1.04)

*Standard Deviation is quoted in parenthesis. / *Standardna devijacija navedena je u zagradi.*

Table 4 Equilibrium moisture content obtained after heat treatment and conditioning at 20 ºC and 65 % relative humidity
Tablica 4. Ravnotežni sadržaj vode postignut nakon toplinske obrade i kondicioniranja bukovine pri 20 ºC i relativnoj vlažnosti zraka 65 %

Treatment duration *Trajanje obrade*	**EMC** **%**	**Percentage of decrease, %** *Postotak smanjenja, %*	**Density, g/cm³** Gustoća, g/cm³	**Percentage of decrease, %** *Postotak smanjenja, %*
Untreated	10.26	-	0.68	-
2 h	6.53	36.32	0.71	-5.81
4 h	6.40	37.53	0.64	4.89
6 h	6.11	40.42	0.62	7.93
8 h	5.60	45.37	0.62	7.80
10 h	5.42	47.12	0.61	10.15

*EMC – Equilibrium moisture content / *ravnotežni sadržaj vode*

Table 5 Mean values of weight loss and weight increase of heat treated beech wood
Tablica 5. Srednje vrijednosti gubitka mase i povećanja mase toplinski obrađene bukovine

Treatment duration at 180 °C *Trajanje obrade pri 180 °C*	**Mean weight loss directly after heat treatment** *Srednja vrijednost gubitka mase odmah nakon toplinske obrade* %	**Mean weight increase after 7 days** *Prosječni porast mase nakon 7 dana* %	**Mean weight increase after 14 days** *Prosječni porast mase nakon 14 dana* %	**Mean weight increase after 21 days** *Prosječni porast mase nakon 21 dan* %
2 h	11.25	4.92	1.05	0.19
4 h	11.68	4.45	0.97	0.13
6 h	12.09	4.50	0.87	0.13
8 h	13.41	3.93	0.85	0.12
10 h	13.34	4.21	0.78	0.10

and water adsorbing capacity of wood to a great extent (Table 4). Esteves *et al*. (2009) concluded that the water adsorption of beech wood decreased at treatment temperatures higher than 100 ºC, decreasing with the increase in treatment time. The reason of the decrease in the equilibrium moisture content is that less water was absorbed by the cell walls after the heat treatment as a result of chemical change (Jamsa and Viitaniemi, 2001). Additionally, the polycondensation reactions in lignin result in further cross-linking that might also contribute to the reduction of equilibrium moisture content (Tjeerdsma, 2005).

The weight loss of the heat treated specimens, measured directly after each treatment, (Table 5) are an indicator of treated wood quality (Esteves *et al*., 2009). The higher the treatment duration, the more weight loss is recorded. This can be attributed not only to moisture content loss but also to evaporation of volatile extractives and other chemical constituents such as hemicelluloses. In this research, the specimens that were conditioned at 20 ± 2 ºC and 60 ± 5 % relative humidity, for three different periods, present an increase of their weight due to regaining moisture as shown in Table 4. The specimens treated at mild treatments exhibited higher weight increase compared to the specimens exposed to more intense treatment. Furthermore, as the conditioning period was extended, the weight increase was reduced.

4 CONCLUSIONS
4. ZAKLJUČAK

Assessment of color changes and hygroscopic properties leads to the following conclusions.

The color coordinates L^*, a^* and b^* of the heat treated specimens changed, meaning that the color of the wood surface was modified. The color difference (ΔE) appears to increase depending on treatment intensity unlike color saturation (ΔC), which decreases proportionally to treatment severity. The most intense color differences occurred in 8-h and 10-h treatments, the difference between them not being significant.

The EMC and density decrease abruptly in the initial treatments, whereas as the duration increases, this decrease tends to be slower and more gradual. Among different treatment durations, the 8-h at 180 ºC combination provided the most effective results with the largest EMC percentage decrease. Swelling and absorption percentage were positively affected by heat treatment. The swelling values increased only in tangential direction after 8-h treatment and generally the tangential direction proved to be better than the radial one.

It can be concluded heat treatment modification enhances some of the most significant wood features such as hygroscopic properties and color change. According to the dimensions of the treated specimens and conditions used in this investigation, it can be stated that 8 h was the best treatment duration, as it showed the largest decrease in the hygroscopic properties with an attractive dark color approaching tropical species, providing an optimization of beech wood in a wide range of applications.

5 REFERENCES
5. LITERATURA

1. Arnold, M., 2007: Transverse Anisotropy in Thermally Modified Beech and Spruce. 3rd European Conference on

Wood Modification. October 15-16th 2007, Bangor (UK).

2. Arnold, M., 2009: Effect of moisture on the bending properties of thermally modified beech and spruce. Journal of Materials Science, 45, 669-680. http://dx.doi.org/10.1007/s10853-009-3984-8
3. Charani, P. R.; Mohammadi Rovshandeh, J.; Mohebby, B.; Ramezani, O., 2007: Influence of hydrothermal treatment on the dimensional stability of beech wood. Caspian Journal of Environmental Sciences, 5 (2): 125-131.
4. Esteves, M. B.; Pereira, H. M., 2009: Wood Modification by heat treatment: A Review. Bio resources, 4 (1): 370-404.
5. Gonzalez, P.; Hale, M., 2009: Colour in thermally modified wood of beech Norway spruce and Scots pine, part1: Colour evolution and color changes. Holzforschung, 63: 385-393.
6. Govorčin, S.; Sinković, T.; Hrčka, R., 2009: Some physical and mechanical properties of recent and heat treated Ash-Fraxinus excelsior L. Šumarski list, 133(3-4): 185-191.
7. Guller, B., 2012: Effects of heat treatment on density, dimensional stability and color of Pinus nigra. African journal of biotechnology, 11(9): 2204-2209.
8. Hakkou, M.; Petrissans, M.; Gerardin, P.; Zoulalian, A., 2006: Investigations of the reasons for fungal durability of heat-treated beech wood. Elsevier, Polymer Degradation and Stability, 91 (2): 393-397. http://dx.doi.org/10.1016/j.polymdegradstab.2005.04.042
9. Hill Callum, A. S., 2006: Wood modification, Chemical, Thermal and other Processes. Wiley series renewable resources. School of agricultural and forest sciences, University of Wales, Bangor, p.p. 260-262.
10. Mohebby, B.; Sananei, I., 2005: Infuences of hydro-thermal treatment on physical properties of beech wood (Fagus orientalis). The international research group of wood protection. Section 4. Processes and properties. 36th annual meeting. Noor, Iran.
11. Jamsa, S.; Viitaniemi, P., 2001: Heat treatment of wood - Better durability without chemicals. In Proceedings of specialseminar held in Antibes, France.
12. Repellin, V.; Guyonnet, R., 2005: Evaluation of heat treated wood swelling by different scanning calorimetetry in relation to chemical composition. Holzforschung, 59: 28-34. http://dx.doi.org/10.1515/HF.2005.005
13. Sinković, T.; Govorčin, S.; Sedlar, T., 2011: Comparison of physical properties of untreated and heat treated Beech and Hornbeam. Drvna industrija, 62 (4): 283-290.
14. Tjeerdsma, B. F.; Militz, H., 2005: Chemical changes in hydrothermal treatedwood: FTIR analysisof combined hydrothermal and dry heat-treated wood. Holz Roh-Werkst 63:102-111. http://dx.doi.org/10.1007/s00107-004-0532-8
15. Todorović, N.; Popović, Z.; Milić, G.; Popadić, R., 2012: Estimation of heat treated beechwood properties by color change”. BioResources 7(1): 798-815.
16. Yildiz, S., 2002: Physical, mechanical, technological and chemical properties of beech and spruce wood treated by heating. PhD dissertation, Karadeniz Technical University, Trabzon, Turkey.

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