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HARDNESS OF THERMALLY MODIFIED BEECH WOOD AND HORNBEAM WOOD

TVRDOĆA TOPLINSKI MODIFICIRANE BUKOVINE I GRABOVINE

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SUMMARY

There is increasing number of products made of termally modified wood (mainly floor coverings) in wood market. Thermal modification at temperatures above 160 °C in oxygen free environment is known to alter the physical and mechanical properties of wood, among others. In this work, change in Brinell hardness of beech wood and hornbeam wood subjected to 200 °C in oxygen free environment for 48 hours was investigated in relation with unmodified wood of the same species. Beech and hornbeam were selected because of the impacts of climate change as well as future predictions on the distribution of beech and hornbeam in South East Europe. Wood hardness was investigated on cross, radial and tangential sections. The dependence of wood hardness on wood density was also shown. All measurements were performed at 12% EMC (equilibrium moisture content) of wood. The average values of Brinell hardness of termally modified beech wood and hornbeam wood were significantly different and smaller than the average values of unmodified beech wood and hornbeam wood. As expected, thermal modification caused weight reduction and consequently, decrease in the density of beech wood and hornbeam wood. Applied thermal modification reduced Brinell hardness of beech wood cross section for 3%, radial section for 15%, and tangential section for 25%. Applied thermal modification reduced Brinell hardness of hornbeam wood cross section for 6%, radial section for 18%, and tangential section for 13%.

Applied thermal modification negatively influenced Brinell hardness on all three sections of investigated beech wood and hornbeam wood. The recorded decrease in hardness still does not hinder the use of such modified wood in non-load-bearing wood structures and wood flooring.

KEY WORDS: Brinell hardness, thermally modified wood, beech wood, hornbeam wood

INTRODUCTION
UVOD

Climate change is expected to have a profound effect on the forests of temperate and Mediterranean bioclimatic zones, where extreme abiotic events (e.g. drought, storm, forest fires, etc.) and associated changes in biotic disturbance regimes are supposed to be the major climate change related impacts (Hlásny et al. 2014). In such circumstances, drought-induced mortality, changes in forest growth rate and shift of species distribution range are expected across Europe (Lindner et al. 2010).

Several studies conducted for the regions of Balkan and Central Europe evidenced that climate change might significantly affect future production and distribution range of the main tree species. For example, study conducted by Stojanović et al. (2014) demonstrated possible significant change of bioclimatic niches for the most important forest tree species in Serbia before the end of 21st century. Li-

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kewise, giving a comprehensive review on potential impact of climatic changes on forest vegetation shift in Slovenia, Kutnar and Kobler (2011) stated that the share of thermophilous forests, which are less economically interesting, will increase significantly (from the present 14% to a range between 50% and 87%), replacing the currently predominant mesic forests. This situation is particularly worrying concerning European beech, which although cover an extensive natural range, and which is also known to be vulnerable to drought (Rose et al. 2009). Indeed, Lakatos and Molnar (2009) documented mass mortality of beech trees in Hungary, as a consequence of a damage chain, caused by drought period from 2000 to 2004, while Czúcz et al. (2011) found that 56-99% of existing European beech forests in Hungary might fall outside their bioclimatic niche by 2050. Finally, using Ellenberg's climate quotient (EQ) Stojanović et al. (2013) showed that 90% of beech forests in Serbia (southeast Europe) may be outside their present bioclimatic niche until the end of 21st century. Therefore, it seems that alternative forests tree species, such as hornbeam, will need to be used intensively in the future in order to meet raising demands of wood industry.

Using of hornbeam, which is known for its high density, hardness, toughness and wear-resistance (Fodor et al. 2017), would be justified from both ecological point of view, as well as taking into account projected climate change effects on forest ecosystems in Central and Southern Europe. Namely, certain studies on a long-term natural forest dynamics in a mixed stands evidenced a quantitative increase of late-successional species, such as Carpinus betulus, whereas parallel decline was observed for economically more important tree species (e.g. Picea abies, Fraxinus excelsior, Quercus robur, etc.) (Bernadzki et al. 1998). Finally, according to aforementioned EQ, European beech is dominant tree species at the areas with EQ less than 30 (Ellenberg, 1988), whereas higher EQs (i.e. regions with dryer and warmer climate) are more suitable for hornbeam growing. Although very rare, certain studies evidenced naturalization and formation of large pure stands by this species in the regions with EQ over 30, thus suggesting that climatic change might positively affect the distribution of hornbeam in the future (Jensen et al. 2004).

Thermal modification of wood at high temperatures causes permanent changes in chemical and physical properties (Aytin et al. 2015; Welzbacher et al. 2009). Thermal modification of wood increases its moisture resistance, improves dimensional stability, enhances resistance against biological deterioration, and contributes to uniform colour change from original to dark brownish tones (Kollmann et al. 1975; Stamm, 1956; Tjeerdsma et al., 1998; Kotilainen et al., 2000; Yildiz, 2002; Avadi et al., 2003; Rousset et al., 2004; Hill, 2006; Živković et al. 2008; Sinković et al., 2011; Sahin, H. T. et al. 2011; Mitani and Barboutis, 2014). Heating changes wood colour acquiring a darker tonality which is often caused by the formation of color degradation produced from hemicelluloses (Sehlstedt-Persson 2003, Sundqvist 2004). The colour of wood is important from the aesthetic point of view.

However, thermal modification decreases mechanical properties of wood. Mass loss, lower density of thermally modified wood are caused by heating regime, procedure, duration, relative humidity and wood moisture content (Vernois, 2001; Alén et al., 2002; Esteves et al., 2007; Candan et al., 2013; Laine et al., 2016; Lykidis et al., 2016; Li et al., 2017; Boruvka et al., 2018). These undesirable changes may limit application of thermally modified wood in wood construction.

Although there are scientific papers with measured reduced values of hardness of beech and hornbeam wood after heat treatment (Yildiz, 2002; Gunduz et al., 2009), their results are difficult to compare with each other due to the use of different treatment regimes. This paper aims to check and compare the decrease in the density and hardness of Brinell wood due to the equal treatment of beech and hornbeam wood with high temperature. Beech and hornbeam were selected precisely because of the aforementioned impacts of climate change as well as predictions on the distribution of beech and hornbeam in South East Europe.

The aim of this article was to investigate and compare Brinell hardness on three main sections of thermally modified and unmodified beech wood an hornbeam wood and to determine wood mass and wood density reduction after thermal modification.

MATERIAL AND METHODS
MATERIJAL I METODE

Research was carried out on beech wood and hornbeam wood. Trees selected for research came from the Papuk region and originate from the same economic unit which means they had the same conditions for growth. Trees were selected according to HRN ISO 3129:1999. One bark to bark core, length of one meter, was cut out from each tree. Then the cores were sawn in half its length. A half of core was used to make samples of unmodified beech and hornbeam wood and the other half was thermally modified at 200 ^{o}C for 48 hours. The entire process from the beginning of thermal modification to the cooling of the heath chamber lasted for 72 hours.

After the thermal modification cores were sawn into specimens 30 mm × 30 mm × 20 mm (R, T, L) for the purpose of testing wood hardness. Only the samples without any natural wood defects (bark, cracks, reaction wood) where taken in consideration. Three series of samples were prepared, depending on the investigated cross section. The hardness of wood was investigated according to Brinell (HRN ISO 3350:1999) on cross, radial and tangential section. Wood density was investigated according to HRN ISO

Table 1 Survey of statistical values for Brinell hardness on cross, radial and tangential section of unmodified and thermally modified beech wood
Tablica 1. Prikaz statističkih vrijednosti čvrstoće po Brinell-u na poprečnom, radijalnom i tangentnom presjeku recentne i toplinski modificirane bukovine

Untrated beech wood *Recentna bukovina*							Heat treated beech wood *Toplinski modificirana bukovina*					
Cross section *Poprečni presjek*		Radial section *Radijalni presjek*		Tangential section *Tangentni presjek*			Cross section *Poprečni presjek*		Radial section *Radijalni presjek*		Tangential section *Tangentni presjek*	
[a] ρ_{12}%	HB_C	$\rho_{12\%}$	HB_R	$\rho_{12\%}$	HB_T		$\rho_{12\%}$	HB_C	$\rho_{12\%}$	HB_R	$\rho_{12\%}$	HB_T
g/cm³	N/mm²	g/cm³	N/mm²	g/cm³	N/mm²		g/cm³	N/mm²	g/cm³	N/mm²	g/cm³	N/mm²
50	50	53	53	51	51	N	54	54	53	53	51	51
0,688	68,1	0,652	20,0	0,673	28,3	MIN	0,577	61,2	0,577	18,7	0,596	20,1
0,718	73,3	0,718	31,1	0,715	39,1	AVE	0,657	71,3	0,643	26,4	0,650	29,0
0,753	77,7	0,783	41,5	0,759	53,1	MAX	0,722	85,1	0,718	33,3	0,723	41,4
0,020	2,411	0,034	5,391	0,026	6,417	SD	0,038	5,325	0,036	3,705	0,039	5,427
0,000	5,813	0,001	29,063	0,001	41,183	CV	0,001	28,351	0,001	13,725	0,002	29,453

[a] $\rho_{12\%}$ – density at 12% EMC, $HB_{C\ 12\%}$ – Brinell hardness on cross section at 12% EMC, $HB_{R\ 12\%}$ – Brinell hardness on radial section at 12% EMC, $HB_{T\ 12\%}$ – Brinell hardness on tangential section at 12% EMC, N – number of samples, MIN – minimum value, AVER – mean value, MAX – maximum value, STDEV – standard deviation, CV – coefficient of variation

[a] $\rho_{12\%}$ – gustoća pri sadržaju vode od 12%, $HB_{C\ 12\%}$ – tvrdoća po Brinell-u poprečnog presjeka pri sadržaju vode od 12%, $HB_{R\ 12\%}$ – tvrdoća po Brinell-u radijalnog presjeka pri sadržaju vode od 12%, $HB_{T\ 12\%}$ – tvrdoća po Brinell-u tangentnog presjeka pri sadržaju vode od 12%, N – broj uzoraka, MIN – minimalna vrijednost, AVER – aritmetička sredina, MAX – maksimalna vrijednost, STDEV – standardna devijacija, CV – koeficijent varijacije

3131:1999. Brinell hardness was tested on "Shimadzu AG-X 100kN", universal machine for testing the mechanical properties of wood, with test load for hardwood species (1000 N) and a 10 mm diameter indenter.

Statistical analysis of the results and their comparison was carried out in specialized statistical program Statistica 8. Statistical analysis has shown the number of measured samples, minimal, maximal and average value of certain measured properties, standard deviation, as well as their coefficient of variation. Comparison study between investigated Brinell hardness of beech and hornbeam wood was carried out by Mann Whitney test.

RESULTS AND DISCUSSION
REZULTATI I RASPRAVA

Invesigated Brinell hardness of thermally modified beech wood is lower than unmodified beech wood on all three sections. Average Brinell hardness of thermally modified beech wood was lower for 3% on cross section, it was lower for 15% on radial section and it was lower for 25% on tangential section (Table 1). Statistical analysis showed there is sigificant difference between Brinell hardness of thermally modified and unmodified beech wood on all three sections (Table 2 and Figure 2).

Table 2 Mann Whitney test of difference between Brinell hardnes of thermally modified and unmodified beech wood
Tablica 2. Mann Whitney test razlike između tvrdoće po Brinell-u toplinski modificirane i recentne bukovine

Unmodified / Thermally modified	$HB_{C12\%}$ unmodified beech wood, cross section *$HB_{C12\%}$ recentna bukovina, poprečni presjek*	$HB_{R12\%}$ unmodified beech wood, radial section *$HB_{R12\%}$ recentna bukovina, radijalni presjek*	$HB_{T12\%}$ unmodified beech wood, tangential section *$HB_{T12\%}$ recentna bukovina, tangentni presjek*
$HB_{C12\%}$ thermally modified beech wood, cross section *$HB_{C12\%}$ toplinski mod. bukovina, poprečni presjek*	$p = 0.01$ $Z = 2.537$		
$HB_{R12\%}$ thermally modified beech wood, radial section *$HB_{R12\%}$ toplinski mod. bukovina, radijalni presjek*		$p < 0.001$ $Z = 4.479$	
$HB_{T12\%}$ thermally modified beech wood, tang. section *$HB_{T12\%}$ toplinski mod. bukovina, tangentni presjek*			$p < 0.001$ $Z = 6.562$

Note: Correlations are significant at $p < 0.05$
Bilješka: Razlika je signifikantna kod $p < 0,05$

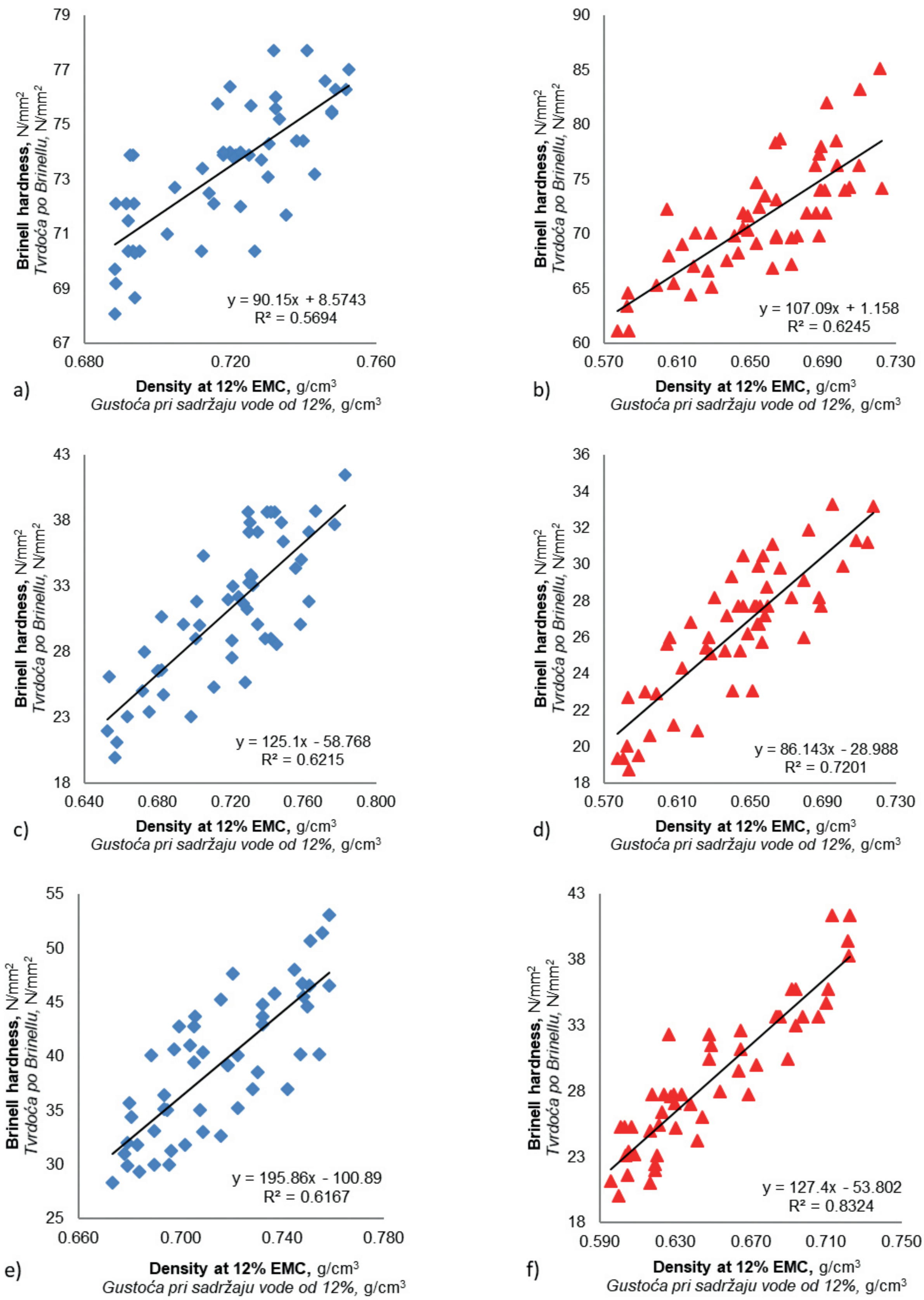

Figure 1 Relationship between Brinell hardness and density at 12% EMC; a) unmodified beech wood on cross section; b) thermally modified beech wood on cross section; c) unmodified beech wood on radial section; d) thermally modified beech wood on radial section; e) unmodified beech wood on tangential section; f) thermally modified beech wood on tangential section

Slika 1. Odnos tvrdoće po Brinell-u i gustoće pri sadržaju vode od 12%; a) recentne bukovine na poprečnom presjeku; b) toplinski modificirane bukovine na poprečnom presjeku; c) recentne bukovine na radijalnom presjeku; d) toplinski modificirane bukovine na radijalnom presjeku; e) recentne bukovine na tangentnom presjeku; f) toplinski modificirane bukovine na tangentnom presjeku

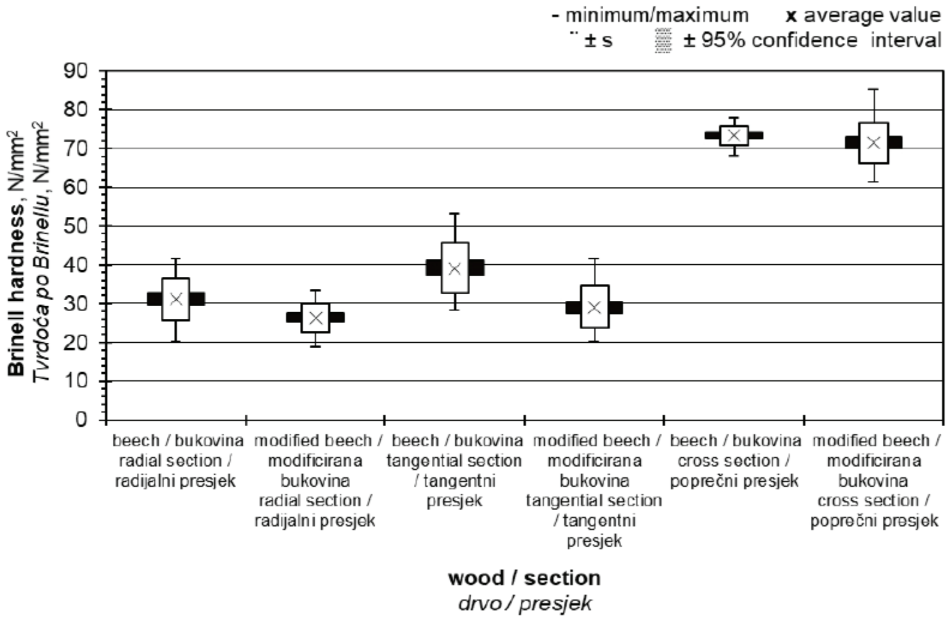

Figure 2 Statistical analyzes of Brinell hardness on cross, radial and tangential section between unmodified and thermally modified beech wood
Slika 2 Statistička analiza tvrdoće po Brinellu poprečnog, radijalnog i tangentnog presjeka, između recentne i topliski modificirane bukovine

Table 3 Survey of statistical values for Brinell hardness on cross, radial and tangential section unmodified and thermally modified hornbeam wood
Tablica 3. Prikaz statističkih vrijednosti čvrstoće po Brinell-u na poprečnom, radijalnom i tangentnom presjeku recentne i toplinski modificirane grabovine

Untrated hornbeam wood *Recentna grabovina*							Heat treated hornbeam wood *Toplinski modificirana grabovina*					
Cross section *Poprečni presjek*		Radial section *Radijalni presjek*		Tangential section *Tangentni presjek*			Cross section *Poprečni presjek*		Radial section *Radijalni presjek*		Tangential section *Tangentni presjek*	
[a] $\rho_{12\%}$	HB_C	$\rho_{12\%}$	HB_R	$\rho_{12\%}$	HB_T		$\rho_{12\%}$	HB_C	$\rho_{12\%}$	HB_R	$\rho_{12\%}$	HB_T
g/cm³	N/mm²	g/cm³	N/mm²	g/cm³	N/mm²		g/cm³	N/mm²	g/cm³	N/mm²	g/cm³	N/mm²
51	51	53	53	51	51	N	53	53	57	57	53	53
0,702	73,8	0,703	29,9	0,709	27,9	MIN	0,579	62,3	0,558	18,0	0,525	23,9
0,736	80,6	0,732	33,2	0,735	37,2	AVE	0,675	75,8	0,670	27,3	0,660	32,3
0,776	91,6	0,755	36,8	0,761	45,8	MAX	0,752	90,2	0,758	34,3	0,741	42,1
0,022	3,578	0,014	1,844	0,015	4,450	SD	0,050	7,895	0,039	4,109	0,051	4,481
0,000	12,805	0,000	3,402	0,000	19,801	CV	0,003	62,334	0,002	16,888	0,003	20,080

[a] $\rho_{12\%}$ – density at 12% EMC, $HB_{C\ 12\%}$ – Brinell hardness on cross section at 12% EMC, $HB_{R\ 12\%}$ – Brinell hardness on radial section at 12% EMC, $HB_{T\ 12\%}$ – Brinell hardness on tangential section at 12% EMC, N – number of samples, MIN – minimum value, AVER – mean value, MAX – maximum value, STDEV – standard deviation, CV – coefficient of variation

[a] $\rho_{12\%}$ – gustoća pri sadržaju vode od 12%, $HB_{C\ 12\%}$ – tvrdoća po Brinell-u poprečnog presjeka pri sadržaju vode od 12%, $HB_{R\ 12\%}$ – tvrdoća po Brinell-u radijalnog presjeka pri sadržaju vode od 12%, $HB_{T\ 12\%}$ – tvrdoća po Brinell-u tangentnog presjeka pri sadržaju vode od 12%, N – broj uzoraka, MIN – minimalna vrijednost, AVER – aritmetička sredina, MAX – maksimalna vrijednost, STDEV – standardna devijacija, CV – koeficijent varijacije

The decrease in beech wood hardness recoreded in this work was less than the decrease in beech wood hardness recorded by Yildiz (2002). He determined the greatest decrease in hardness values when beech samples were treated at 180 °C for 10 h, and hardness decrease of 25.9%, 45.1%, and 41.8% were observed for longitudinal, radial, and tangential directions, respectively.

The ratio between Brinell hardness and density at 12% EMC of thermally modified and unmodified beech wood on three sections are shown in Figure 1. It was determined that the changes in wood density significantly affect Brinell hardness on all sections of thermally modified and unmodified wood.

Invesigated Brinell hardness of thermally modified hornbeam wood is lower than unmodified hornbeam wood on all three sections. Average Brinell hardness of thermally modified hornbeam wood was lower for 6% on cross section, it was lower for 18% on radial section and it was lower for 13% on tangential section (Table 3). Statistical analysis showed there is sigifficant difference between Brinell hardness of thermally modified and unmodified hornbeam wood on all three sections (Table 4 and Figure 4).

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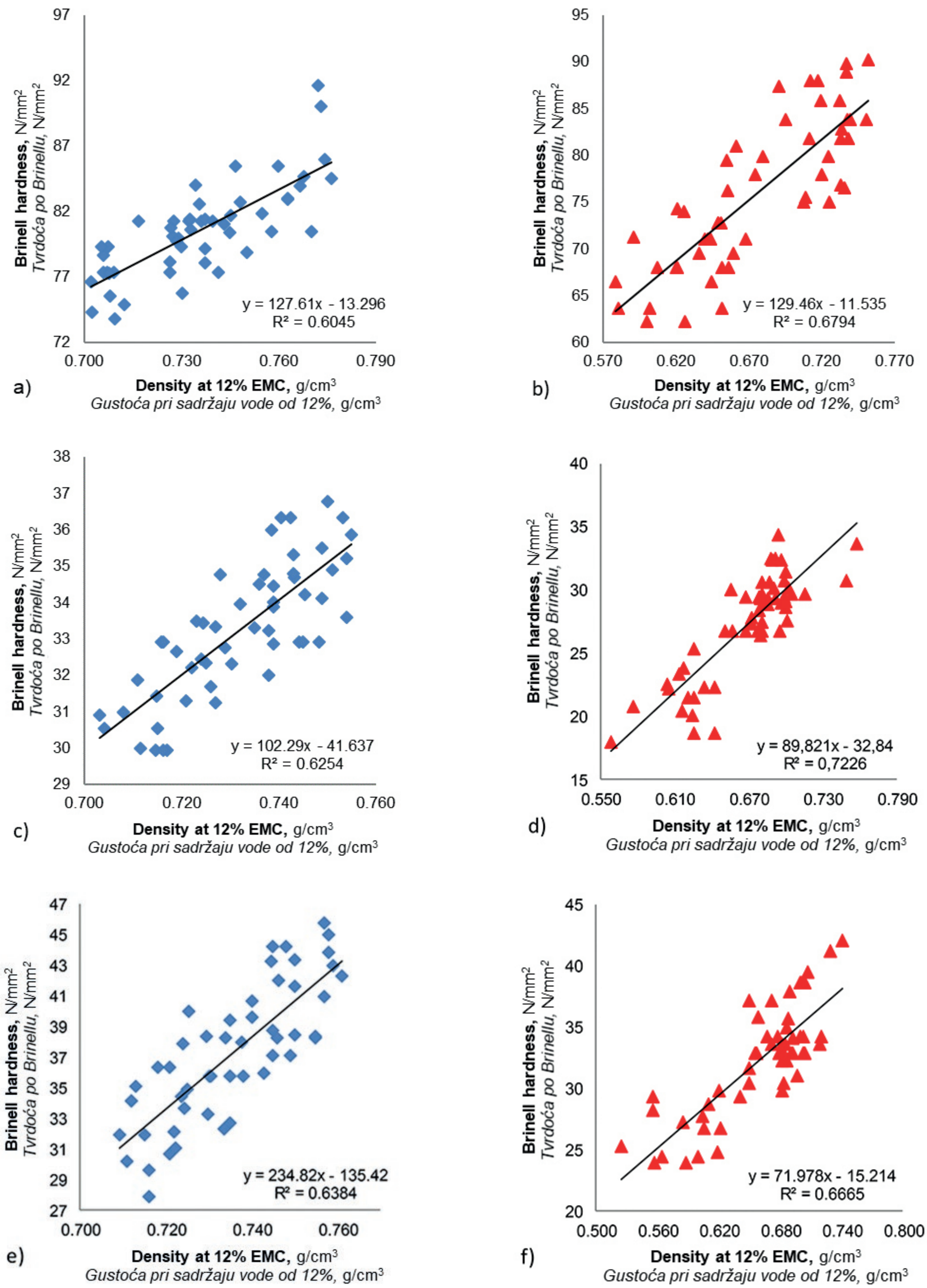

Figure 3 Relationship between Brinell hardness and density at 12% EMC; a) unmodified hornbeam wood on cross section; b) thermally modified hornbeam wood on cross section; c) unmodified hornbeam wood on radial section; d) thermally modified hornbeam wood on radial section; e) unmodified hornbeam wood on tangential section; f) thermally modified hornbeam wood on tangential section

Slika 3. Odnos tvrdoće po Brinell-u i gustoće pri sadržaju vode od 12%; a) recentne grabovine na poprečnom presjeku; b) toplinski modificirane grabovine na poprečnom presjeku; c) recentne grabovine na radijalnom presjeku; d) toplinski modificirane grabovine na radijalnom presjeku; e) recentne grabovine na tangentnom presjeku; f) toplinski modificirane grabovine na tangentnom presjeku

Table 4 Mann Whitney test of difference between Brinell hardnes of thermally modified and unmodified hornbeam wood
Tablica 4. Mann Whitney test razlike između tvrdoće po Brinell-u toplinski modificirane i recentne grabovine

Unmodified / Thermally modified	$HB_{C12\%}$ unmodified hornbeam wood, cross section *$HB_{C12\%}$ recentna grabovina, poprečni presjek*	$HB_{R12\%}$ unmodified hornbeam wood, radial section *$HB_{R12\%}$ recentna grabovina, radijalni presjek*	$HB_{T12\%}$ unmodified hornbeam wood, tangential section *$HB_{T12\%}$ recentna grabovina, tangentni presjek*
$HB_{C12\%}$ thermally modified hornbeam wood, cross section *$HB_{C12\%}$ toplinski mod. grabovina, poprečni presjek*	$p = 0.001$ $Z = 3.254$		
$HB_{R12\%}$ thermally modified hornbeam wood, radial section *$HB_{R12\%}$ toplinski mod. grabovina, radijalni presjek*		$p < 0.001$ $Z = 7.857$	
$HB_{T12\%}$ thermally modified hornbeam wood, tang. section *$HB_{T12\%}$ toplinski mod. grabovina, tangentni presjek*			$p < 0.001$ $Z = 4.821$

Note: Correlations are significant at $p < 0.05$
Bilješka: Razlika je signifikantna kod p < 0,05

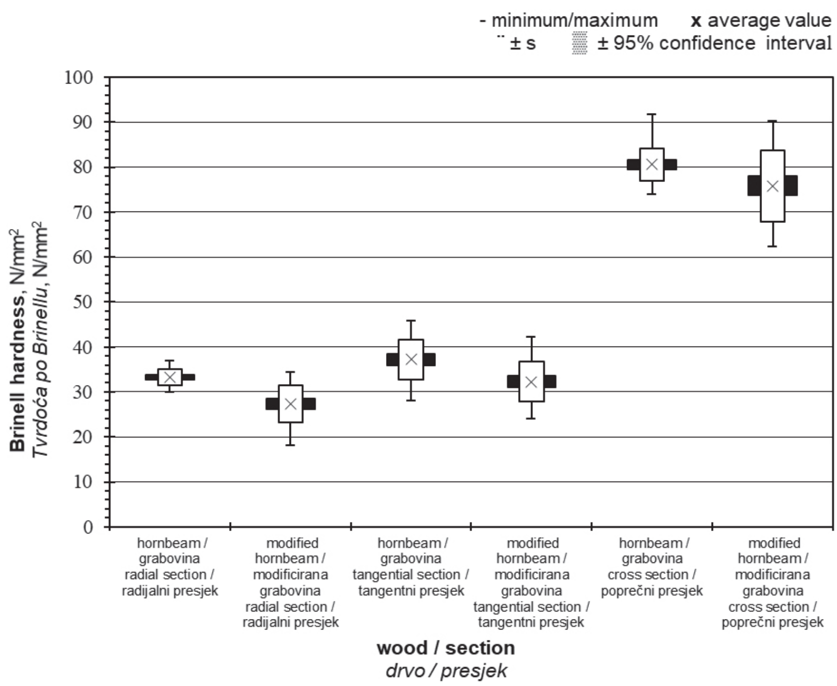

Figure 4 Statistical analyzes of Brinell hardness on cross, radial and tangential section between unmodified and thermally modified hornbeam wood
Slika 4. Statistička analiza tvrdoće po Brinellu poprečnog, radijalnog i tangentnog presjeka, između recentne i topliski modificirane grabovine

The decrease in hornbeam wood hardness recoreded in this work was less than decrease in hornbeam wood hardness recorded by Gunduz et al. (2009). He determined following decrease in hardness values of hornbeam wood samples treated at 210 °C for 12 h: 38% for longitudinal direction (cross section), 55% for radial direction (tangential section), and 54% for tangential direction (radial section).

The ratio between Brinell hardness and density at 12% of moisture content of thermally modified and unmodified hornbeam wood on three section are shown in Figure 3. It was determined that the changes in density significantly effect Brinell hardness on all sections of thermally modified and unmodified wood.

CONCLUSIONS
ZAKLJUČAK

Thermal modification at 200 °C in oxygen free environment for 48 hours expectedly reduced wood mass and caused the reduction of density in beech wood and hornbeam wood.

The density of thermally modified beech wood and hornbeam wood was about 10% lower than density of untreated wood.

Brinell hardness of thermally modified beech wood decreased for 3%, 15%, and 25% on cross, radial, and tangential section, respectively.

Brinell hardness of thermally modified hornbeam wood decreased for 6%, 18%, and 13% on cross, radial, and tangential section, respectively.

Mann-Whitney's test found that all differences in Brinell hardness between thermally modified and unmodified wood were significant.

From these results, it is apparent that thermal modification adversely affects the wood hardness on all three sections in beech wood and hornbeam wood, although the wood hardness for the nonbearing wood structures and wood flooring is satisfactory.

The thermal modification processes of wood are still being investigated. Although thermally modified wood exhibits advantages in terms of aesthetic properties such as uniformity and change of color in darker tones and some technical properties, such as increased dimensional stability and improved resistance to decaying fungus, one should be aware of its drawbacks as compared to unmodified wood. It is necessary to develop the experience of the impact of thermal modification on each type of wood individually, as it has been shown that their properties change differently.

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SAŽETAK

Na tržištu se pojavljuje velik broj proizvoda (uglavnom podnih obloga) od toplinski modificiranog drva. Poznato je da se drvu mijenjaju fizička i mehanička svojstva djelovanjem temperatura viših od 160 °C u okolišu siromašnome kisikom. U prikazanom radu istraživana je promjena tvrdoće po Brinell-u toplinski modificirane bukovine i grabovine u odnosu na recentno drvo, i to na tri glavna presjeka drva: poprečnom, radijalnom i tangentnom. Bukovina i grabovina odabrane su zbog utjecaja klimatskih promjena, kao i predviđanja na rasprostranjenost bukve i graba u Jugoistočnoj Europi. Drvo je modificirano u okolišu siromašnom kisikom 48 sati pri 200 °C. Također je prikazana i ovisnost tvrdoće drva po Brinell-u o gustoći drva. Sva su mjerenja provedena pri ravnotežnom sadržaju vode drva od 12 %. Prosječne vrijednosti tvrdoće po Brinell-u toplinski modificirane bukovine i grabovine statistički se značajno razlikuju i manje su od prosječnih vrijednosti tvrdoće recentne bukovine i grabovine. Toplinskom modifikacijom bukovine i grabovine očekivano je došlo do smanjenja mase, a time i do smanjenja gustoće ispitanih uzoraka. U ovom istraživanju utvrđeno je da se primijenjenom toplinskom modifikacijom bukovini smanjila prosječna vrijednost tvrdoće po Brinell-u za 3% na poprečnom presjeku, za 15% na radijalnom presjeku i za 25% na tangentnom presjeku. Grabovini se istovrsnom toplinskom modifikacijom smanjila tvrdoća po Brinell-u za 6% na poprečnom presjeku, za 18% na radijalnom presjeku i za 13% na tangentnom presjeku.

Primijenjenom toplinskom modifikacijom drva smanjena je tvrdoća po Brinell-u na sva tri presjeka istraživane bukovine i grabovine. Međutim, zabilježeno smanjenje tvrdoće još uvijek ne priječi uporabu tako modificirane bukovine i grabovine u nenosivim drvenim konstrukcijama i drvenim podnim oblogama.

KLJUČNE RIJEČI: tvrdoća po Brinell-u, toplinski modificirano drvo, bukovina, grabovina