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Effect of Heat Treatment and Densification Temperature on Roughness, Hardness and Spring-back in Cylindrical Wood Densification

Utjecaj toplinske obrade i temperature ugušćivanja na hrapavost, tvrdoću i elastični povrat pri cilindričnom ugušćivanju drva

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ABSTRACT • *In this research, black pine (Pinus nigra Arnold) was shaped into cylindrical forms through a turning process and then underwent surface densification. The densification process was performed on a lathe using a spinning roller specifically designed and produced for this purpose. Heat-treated (3 hours at 160 °C) and untreated specimens (a large diameter of 33 mm and a small diameter of 21 mm) were used as test material. Two feed rates, low (0.05 mm/rev) and high (0.405 mm/rev), were used in the study. The lathe speed was kept constant at 800 rpm. During densification, the temperature of 600 °C was applied with a temperature blower. This was followed by rapid cooling in an environment of -18 °C. Surface roughness (Ra), hardness, and spring-back measurements were conducted on both densified and undensified areas of the cylindrical solid wood samples. After densification, the Ra value decreased for all specimens and densification conditions, and the radial and tangential hardness increased. The temperature applied during densification (600 °C hot air) did not have much effect on the spring-back in 33 mm diameter specimens, while the application of temperature in 21 mm diameter specimens reduced the spring-back. At low feed rates (0.05 mm/rev) in densification, lower spring-back was obtained.*

KEYWORDS: *surface densification; spinning roller; roughness; hardness; spring-back; heat treatment*

SAŽETAK • *U ovom je istraživanju drvo crnog bora (Pinus nigra Arnold) tokarenjem oblikovano u cilindrične uzorke, a potom podvrgnuto ugušćivanju površine. Postupak je proveden na tokarskom stroju uz pomoć posebno dizajniranoga i proizvedenoga rotirajućeg valjka. Istraživanje je provedeno na toplinski obrađenim (tri sata na 160 °C) i neobrađenim uzorcima (velikog promjera 33 mm i malog promjera 21 mm). U istraživanju su primijenjene dvije posmične brzine: mala (0,05 mm/okr.) i velika (0,405 mm/okr.). Brzina vrtnje tokarskog stroja održavana je konstantnom na 800 okr./min. Tijekom ugušćivanja potrebna je temperatura od 600 °C postignuta uz pomoć*

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grijalice, nakon čega je slijedilo hlađenje pri temperaturi od –18 °C. Mjerenja hrapavosti površine (Ra), tvrdoće i elastičnog povrata provedena su na ugušćenim i neugušćenim cilindričnim uzorcima drva. Nakon ugušćivanja smanjila se vrijednost Ra svih uzoraka i pri svim uvjetima ugušćivanja, a povećala se tvrdoća drva u radijalnome i tangentnom smjeru. Temperatura primijenjena tijekom ugušćivanja (600 °C, vrući zrak) nije znatnije utjecala na elastični povrat u uzoraka promjera 33 mm, dok se u uzoraka promjera 21 mm elastični povrat smanjio. Pri manjoj posmičnoj brzini (0,05 mm/okr.), postignut je manji elastični povrat.

KLJUČNE RIJEČI: *ugušćivanje površine; rotirajući valjak; hrapavost; tvrdoća; elastični povrat; toplinska obrada*

1 INTRODUCTION
1. UVOD

Low-density woods are generally inadequate in terms of hardness, durability and strength. Either high-density or densified materials can be preferred when these properties are required in wood materials (Sandberg *et al.*, 2021). The density of the wood material directly affects the mechanical properties (Blomberg and Persson, 2004). Density can be increased by applying additional treatments to low-density wood. Several environmentally friendly methods have been used to increase density.

There are densification methods where temperature, pressure, steam and one or more of these are used as pretreatment. These are called: thermo-mechanical (TM) process (Salca *et al.*, 2021; Tosun and Sofuoglu, 2021; Sofuoglu, 2022; Sofuoglu *et al.*, 2022), thermo-hygro-mechanical (THM) process (Korkut and Kocaefe, 2009; Navi and Sandberg, 2012; Senol and Budakci, 2016), Viscoelastic-Thermal Compression (VTC) and Thermo-Vibro-Mechanical (TVM) process (Şenol and Budakci, 2016; Bekhta *et al.*, 2017; Senol, 2018). In addition to these methods, there are studies on densification of cylindrical materials (Kaya and Sofuoglu, 2023a; Kaya and Sofuoglu, 2023b; Yesil *et al.*, 2023). In general, mechanical properties such as Young's modulus (*MOE*), modulus of rupture (*MOR*), hardness and surface hardness, *MOR* and Janka hardness were found to increase in densified wood (Laskowska, 2017; Pertuzzatti, 2018; Gao *et al.*, 2019; Senol and Budakci, 2019; Wehsener *et al.*, 2023). Radial and tangential hardness values in densified wood increased with the compression ratio, while scanning electron microscopy analysis revealed that the heat treatment and densification processes led to deformations in the cell walls (Budakci *et al.*, 2016). Studies have also been conducted to identify and reduce the extent of spring-back occurring during the densification process (Kariz *et al.*, 2017; Neyses *et al.*, 2020; Scharf *et al.*, 2023). Wettability analysis revealed that the surfaces densified through the TM process exhibited increased hydrophobicity (Bekhta and Krystofiak, 2016). The effects of densification on surface treatments have also been investigated. Densified samples showed a decrease in surface roughness and an increase in surface brightness (Pelit *et al.*, 2015). Surface brightness and hardness values increased with increasing densification rate (Sofuoglu, 2022). Thermo-mechanical densification significantly affected the color change of beech and oak wood (Laskowska, 2020). The finite element method is also used for densification analysis.

In recent years, heat treatment has become a preferred and widespread modification application to minimize the negative properties and enhance the positive properties of wood materials (Icel and Simsek, 2017). Heat treatment is a widely used modification method that effectively enhances the properties of wood materials (Hill, 2006). Heat treatment was defined by Boonstra (Boonstra, 2008) and Rowell *et al.* (2009) as a physical process that causes permanent changes in the chemical content of cell wall components (cellulose, hemicellulose, lignin, etc.). Heat treatment improves the performance of wood by causing a change in its structure. Heat treatment has many advantages, such as reduced equilibrium moisture content, biological resistance to fungi and insects, and improved dimensional stability due to the reduction of woodworking, increased resistance to external weather conditions, decorative color diversity and extended service life (Wikberg, 2004; Jones and Enjily, 2006). Heat treatment of wood is an effective method of improving dimensional stability and resistance to biodegradation, but at the same time, mechanical properties are reduced (Percin *et al.*, 2024). Densified wood, especially when exposed to water and moisture, tends to return to its previous size. This is due to the spring-back (Pelit, 2014). Various studies are conducted to prevent or minimize the spring-back. Spring-back has been tried to be reduced by heat treatment applied before and after densification (Skyba *et al.*, 2009; Esteves *et al.*, 2017; Fu *et al.*, 2017). Heat-treated wood is becoming increasingly popular for both interior and exterior applications (Jirouš-Rajković and Miklečić, 2019).

In cylindrical specimens, the steam and temperature applied during heat treatment and surface densification led to a reduction in brightness. The steam and temperature used in the surface densification process decreased the *L* and *b* color values while increasing the *a* value (Yeşil *et. al.*, 2023). Under all densification conditions, there was an increase in hardness and brightness values and a decrease in roughness (*Rz*) values (Kaya and Sofuoglu, 2023a). The lowest spring-back ratio was observed in larch wood species, with a value of 0.121

mm per revolution at a feed of 0.121 mm/revolution, a spindle speed of 400 rpm, and a densification depth of 1 mm (Kaya and Sofuoglu, 2023b). Turned wood materials are used in various applications, from furniture parts to tool handles, banisters and wooden toys. The smooth surfaces produced by the turning process also enhance the success of lacquering and painting processes. This enables economical production with lower material and labor costs (Gurleyen, 1998). Surface roughness is one of the valid parameters for making economic evaluations regarding wood materials (Sogutlu, 2005). When the literature is examined, it is seen that the studies on cylindrical densification of wood are limited. There is a lack of data on the improvement of surface properties of wood by cylindrical densification and additional surface modification processes. The densification process reduces the porosity of wood materials and produces smoother surfaces. Especially in low-density wood materials, the overall density is not much affected as only the surfaces are densified. In this case, the material becomes more suitable for surface treatments while retaining its lightness and other advantages. Surface densification can also improve the surface quality of high-density wood materials.

In this study, spring back and surface roughness changes were evaluated in preheated test samples and test samples to which heat treatment was applied during densification. In addition, the success of minimizing the spring back effect and reducing surface roughness in the densification process and heat treatment application of test samples with diameter differences in the same wood species was investigated. The applied densification method is practical and easy to apply since it consists of basic equipment. The method will allow the use of cylindrical wood in places where better surface quality is desired. Considering the effect of heat treatment and temperature on the densification of wood materials by various methods, the effect of radial and tangential hardness, surface roughness and spring-back on the densification of cylindrical wood materials with a spinning roller is important. This study investigated the effect of heat treatment and temperature on the surface densification of large and small-diameter cylindrical specimens of black pine wood species and evaluated the results obtained.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Black pine (*Pinus nigra* Arnold), which grows naturally in Turkey and has a wide range of uses, was used as the test material in the study. The specimens were obtained by a random sampling method from the timber sales company in the Simav district of Kutahya, from the timber obtained from the logs grown in the Simav region. The dried samples were kept in an air-conditioned cabinet set at appropriate temperature and relative humidity levels in accordance with the ISO 13061 (ISO 13061-1, 2014) (ISO 13061-2, 2014) standard and they reached a moisture content of 12 %.

Some of the conditioned and roughly sized black pine samples were subjected to heat treatment by applying high temperatures under atmospheric pressure. The heat treatment conditions were defined as 3 hours at 160 °C, considering literature guidelines, and the application was carried out in a laboratory-type heating chamber (Nüve FN 120) controlled to an accuracy of ±1 °C. The heat-treated specimens were re-conditioned in a climatic chamber (Nüve ID 501) and brought to clear dimensions with the other specimens before turning.

Samples were cut from the lumber with a size of 33 mm × 33 mm × 390 mm and 21 mm × 21 mm × 390 mm. The remaining 60 mm test specimens on the lathe bearer clamping area were left as a square. This square section was fixed to the four-legged lathe chuck. It was fixed between the chuck and the lathe tailstock and processed until reaching the average diameters of 33 mm and 21 mm. After turning, a grooving tool was used to create 5 mm wide channels, dividing the experimental specimens into six 50 mm long cylindrical sections. Four sections were treated with experimental parameters, while the sections at the sample tip and end were retained as controls. A configuration was created on the test specimen, enabling the application of different test parameters in each section. The specimens were burnished using 400-grit sandpaper following the completion of the turning and grooving operations. The experiments were conducted three times for each parameter, distributed across different sections of various test specimens, and their averages were recorded. In total, 24 test specimens were used (Figure 1).

For the densification process, axis of the apparatus and tailstock axis were precisely lined up. Based on experience from previous studies, the surface densification depth was determined to be 1.5 mm for each diameter.

2.1 Densification equipment
2.1. Oprema za ugušćivanje

The location of the heat source, the test specimen, the densification direction and the spinning roller set in the universal lathe are shown schematically in Figure 2. The spinning roller is specially designed and manufactured for surface densification studies. Table 1 summarizes the densification parameters and their levels. Feed, one of the process parameters, is the distance in millimeters that the densification apparatus moves for each revolution of the specimen. In the study, two feed rates, one low (0.05 mm/rev) and one high (0.405 mm/rev), determined by the authors based on their experiences

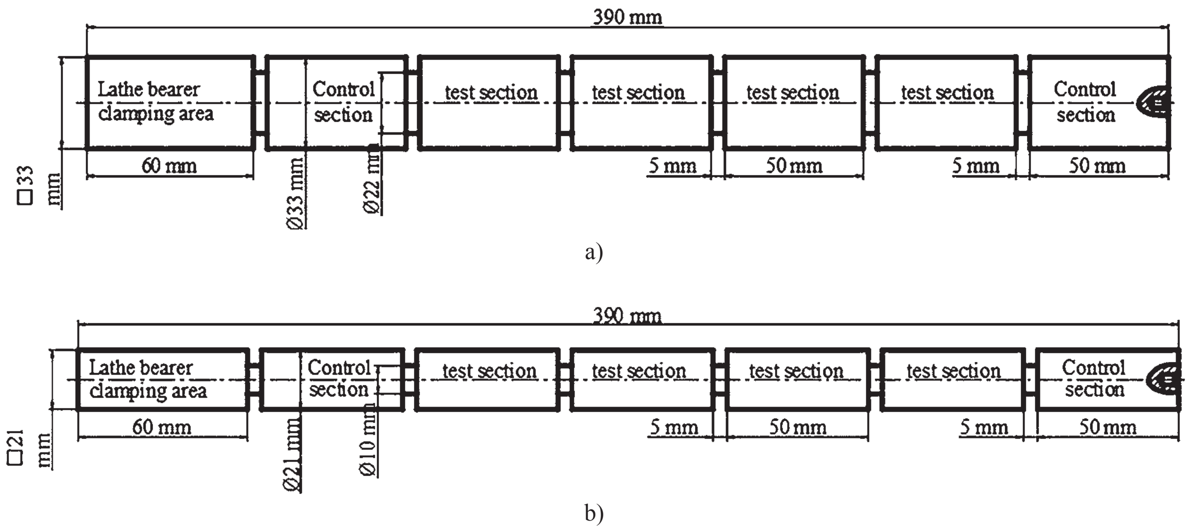


Figure 1 Technical drawing of test specimens: a) test specimen with large diameter, b) small diameter test specimen
Slika 1. Tehnički crtež ispitnih uzoraka: a) ispitni uzorak velikog promjera, b) ispitni uzorak malog promjera

from their previous studies, were used. The authors have conducted experiments under experimental conditions close to these experimental conditions in their previous studies. Progression difference of approximately 10 times allows the change in experimental results to be clearly seen (Kaya and Sofuoğlu, 2023a; Kaya and Sofuoğlu, 2023b). The lathe speed was kept constant and selected as 800 rpm. 800 rpm is again an average spindle speed used efficiently in previous studies (Yesil *et al.*, 2023). Experiments were carried out with and without heat treatment during densification. The temperature application procedure during surface densification consists of two stages. First, while the test specimen is connected to the lathe, the temperature blower is switched on for 10 minutes to reach the set temperature (600 °C). In the second stage, the blower is fitted to the clamping apparatus prepared for it on the lathe and the experiment is completed. The temperature source was set to remain at the same distance from the test speci-

Table 1 Process parameters used in black pine turning
Tablica 1. Parametri primijenjeni pri tokarenju drva crnog bora

Parameter / *Parametar*	**Coded levels** *Oznaka*	
	Level 1	Level 2
Heat treatment / *toplinska obrada*	Yes	No
Densified diameter, mm *promjer ugušćivanja,* mm	21	33
Heat in densification *zagrijavanje tijekom ugušćivanja*	Yes	No
Feed rate, mm/rev *posmična brzina,* mm/okr.	0.05	0.405

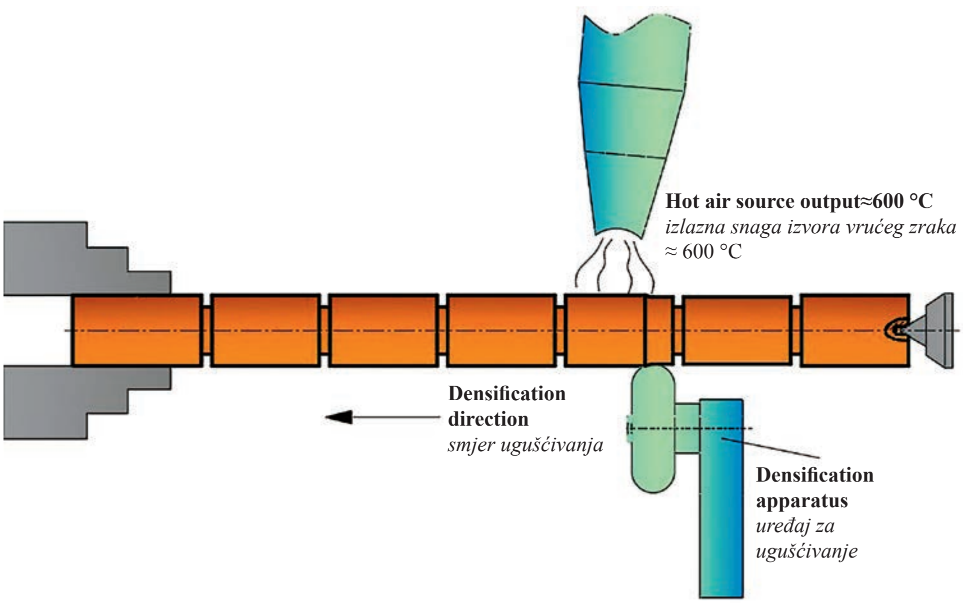


Figure 2 Densification system elements
Slika 2. Elementi sustava za ugušćivanje

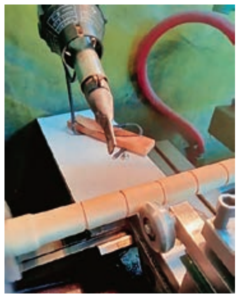
		
a) Air conditianed cabinet *a) Komora za kondicioniranje*	b) TOS-GALANTA SUIL 40A Lathe *b) Tokarski stroj* TOS-GALANTA SUIL 40A	c) Surface densification *c) Ugušćivanje površine*
		
d) Heat-Treatment *d) Toplinska obrada*	e) Spinning roller *e) Rotirajući valjak*	f) Cooling *f) Hlađenje*

Figure 3 Steps of experimental process
Slika 3. Dijelovi eksperimentalnog procesa

mens in all experiments. Due to the positioning of the clamping apparatus on the lathe sport, the automatic feed mechanism of the lathe carriage was used to move on the part at the speeds set as the experimental parameters. The specimens to which heat was applied during the experiment were removed from the lathe as soon as the experiment was completed and suddenly exposed to a shock cooling at -18 °C. Lignin and hemicellulose, the main components of wood, are sensitive to temperature changes. Sudden cooling causes the structure of these components to solidify, which reduces the spring back. With limited resources available, experiments were only conducted at -18 °C, the temperature of a refrigerator deep freezer. More efficient results will be obtained at lower temperatures. The test samples were also grouped as preheated and unheated. Each test group included large diameter (33 mm) and a small diameter (21 mm). The steps of the test process are also given in Figure 3.

2.2 Determining surface roughness and hardness
2.2. Određivanje hrapavosti i tvrdoće površine drva

Hardness was measured with Tronic PD800 model Shore D tester. Surface roughness was measured with surface roughness tester (Time TR200, Time Group Inc., China). Measurements were made parallel to the grain in three repetitions on each sample in accordance with ISO 24118-1:2023 standard. The measurement parameter (*Ra*) was defined according to ISO 24118-1:2023. The probe speed was set to 10 mm/min and the measuring needle was 4 µm in diameter with a tip angle of 90°. Tronic brand Shore D hardness measuring device was used to measure the surface hardness of the samples. In this method, the depth of the needle inserted into the wood sample with a certain force is measured to determine the relative hardness of the wood. The spring behind the tip is stretched according to the hardness of the material and the hardness of the wood can be determined depending on the tension of the spring (Kaya and Sofuoglu, 2023b). Measurement images taken before and after the experiments are shown in Figure 4.

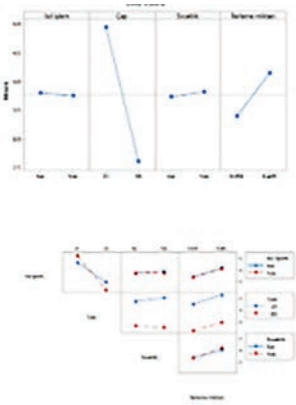
For hardness and roughness, measurements were taken three times, and their averages were used. The same measurements were taken on control sections of the test samples and compared with the test measurements. In the area where hardness measurements were made, attention was paid to the earlywood and latewood regions. Measurements were made on the same line on both test and control sections.

2.3 Calculation of spring-back
2.3. Izračun elastičnog povrata

In the study, instantaneous spring-back effects were evaluated depending on the densification parameters. Each diameter before the test was measured from 4 different points and their averages were taken as D_1. Following the application of the densification parameters, the same measurement procedure was conducted, and the average diameters were recorded after the process was concluded (D_2). A surface densification depth of 1.5 mm was used in the study. To obtain the theoretical diameters (D_3), the densification depth is sub-

a) Spring-back
a) Elastični povrat

b) Surface roughness (*Ra*)
b) Hrapavost površine (Ra)



d) Statistical evaluation
d) Statistička obrada

c) Surface hardness
c) Tvrdoća površine

Figure 4 Measurements as a result of experiments
Slika 4. Mjerenja provedena u istraživanju

tracted from the initial diameter. The spring-back, as shown in equation 1, is calculated by taking the percentage of the difference between D_2 and D_3.

$$\text{Spring}-\text{back}\,(\%)=\frac{(D_2-D_3)}{(D_3)}\times 100 \qquad (1)$$

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The roughness, hardness and spring back values measured on the densified surfaces and the experimental parameters are shown in Table 2.

Table 2 Hardness, roughness and spring back values for black pine
Tablica 2. Vrijednosti tvrdoće, hrapavosti i elastičnog povrata drva crnog bora

No Br.	**Heat treatment** *Toplinska obrada*	**Diameter** *Promjer*	**Heat** *Zagrijavanje*	**Feed rate, mm/rev** *Posmična brzina, mm/okr.*	**Hardness** / *Tvrdoća*, Shore D				**Roughness** *Hrapavost*		**Spring back** *Elastični povrat*	
					Radial *Radijalni smjer*	**ST. DEV.**	**Tangent** *Tangentni smjer*	**ST. DEV.**	***Ra*, µm**	**ST. DEV.**	**%**	**ST. DEV.**
1	Yes	21	Yes	0.050	56.44	6.09	70.67	5.61	0.96	0.10	4.25	0.59
2	Yes	21	Yes	0.405	52.67	3.94	69.11	8.30	0.92	0.28	4.63	0.48
3	Yes	21	No	0.050	60.89	5.71	76.89	7.44	0.66	0.08	4.22	0.36
4	Yes	21	No	0.405	56.78	5.49	78.33	3.39	1.21	0.47	5.53	0.26
5	Yes	33	Yes	0.050	57.22	5.02	72.89	7.42	0.86	0.29	2.68	0.53
6	Yes	33	Yes	0.405	56.67	3.84	72.33	5.66	0.98	0.17	3.24	0.49
7	Yes	33	No	0.050	57.11	7.93	71.22	6.30	1.16	0.50	2.47	0.52
8	Yes	33	No	0.405	50.00	1.94	70.22	8.36	0.85	0.13	3.40	0.36
9	No	21	Yes	0.050	57.67	3.16	67.89	3.55	1.08	0.14	4.62	0.78
10	No	21	Yes	0,405	52.78	5.80	68.89	4.17	0.94	0.22	5.69	0.94
11	No	21	No	0.050	64.22	8.07	73.89	4.76	0.66	0.10	5.11	0.33
12	No	21	No	0.405	59.22	3.19	72.56	7.09	0.91	0.18	5.52	0.33
13	No	33	Yes	0.050	57.33	6.60	67.78	9.02	0.81	0.03	2.10	0.30
14	No	33	Yes	0.405	57.67	5.92	71.22	9.00	0.94	0.03	2.67	0.28
15	No	33	No	0.050	61.22	5.07	69.33	4.44	0.97	0.13	4.25	0.51
16	No	33	No	0.405	56.44	3.78	67.89	6.03	1.00	0.02	4.63	0.54

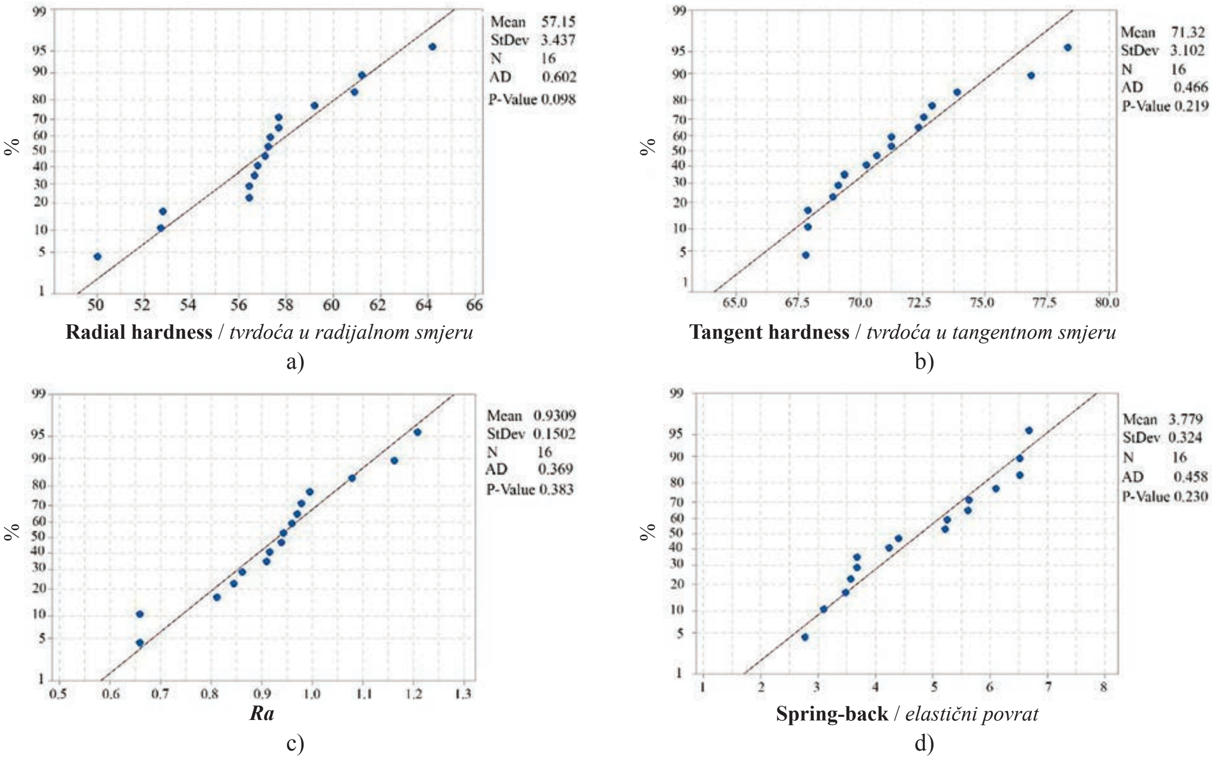


Figure 5 Normality graphs for radial hardness (a), tangent hardness (b), *Ra* (c), and spring-back (d)
Slika 5. Statistički grafovi za tvrdoću u radijalnom smjeru (a), tvrdoću u tangentnom smjeru (b), hrapavost *Ra* (c) i elastični povrat (d)

Since the *P* values is greater than 0.05 ($P = 0.098$ for radial hardness; 0.219 for tangent hardness; 0.383 for *Ra* and 0.230 for spring-back) in Figure 5, the values show a normal distribution at the 95 % confidence level.

After investigation the spring-back effect in densification processes in all conditions, it was established that the spring-back effect was lower at 0.05 mm /rev. The highest spring-back effect occurred at 0.405 mm/rev in small-diameter specimens without heat treatment and in specimens where heat was applied during densification (Figure 6).

When the control specimens are compared with the specimens after densification in various conditions, it is seen that *Ra* value decreased while radial and tangential hardness increased after densification in all conditions and in all specimens (Figure 7). When evaluating the large and small-diameter densified specimens with and without heat treatment considering the densification conditions, it can be seen that heat treatment increases the spring-back percentage and roughness, and decreases the radial and tangential hardness in large-diameter specimens in all densification conditions. In cases where heat was applied during densifi-

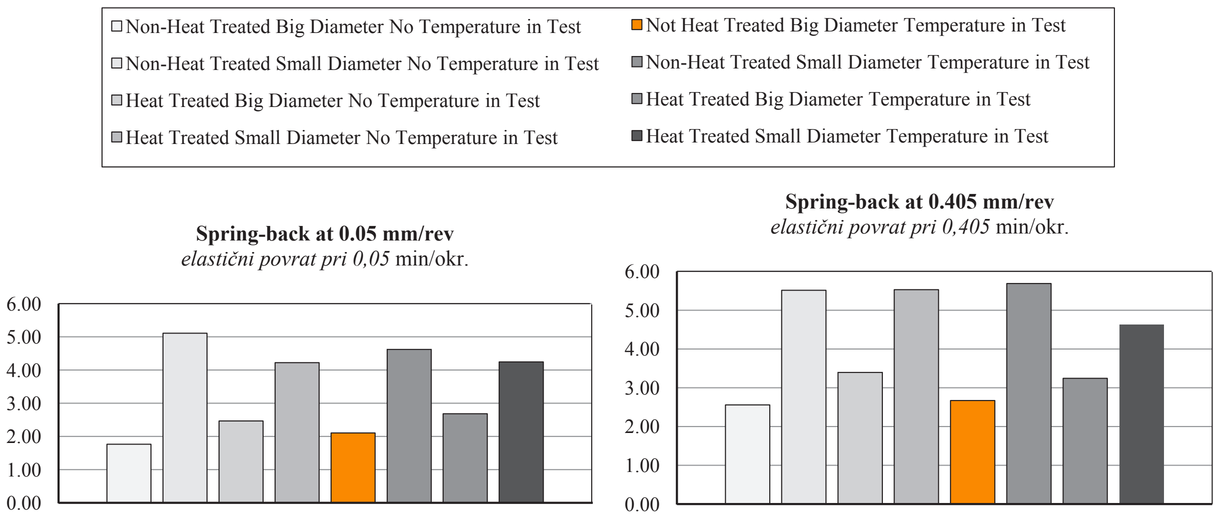


Figure 6 Effect of heat treatment and densification conditions on spring-back
Slika 6. Utjecaj toplinske obrade i ugušćivanja na elastični povrat

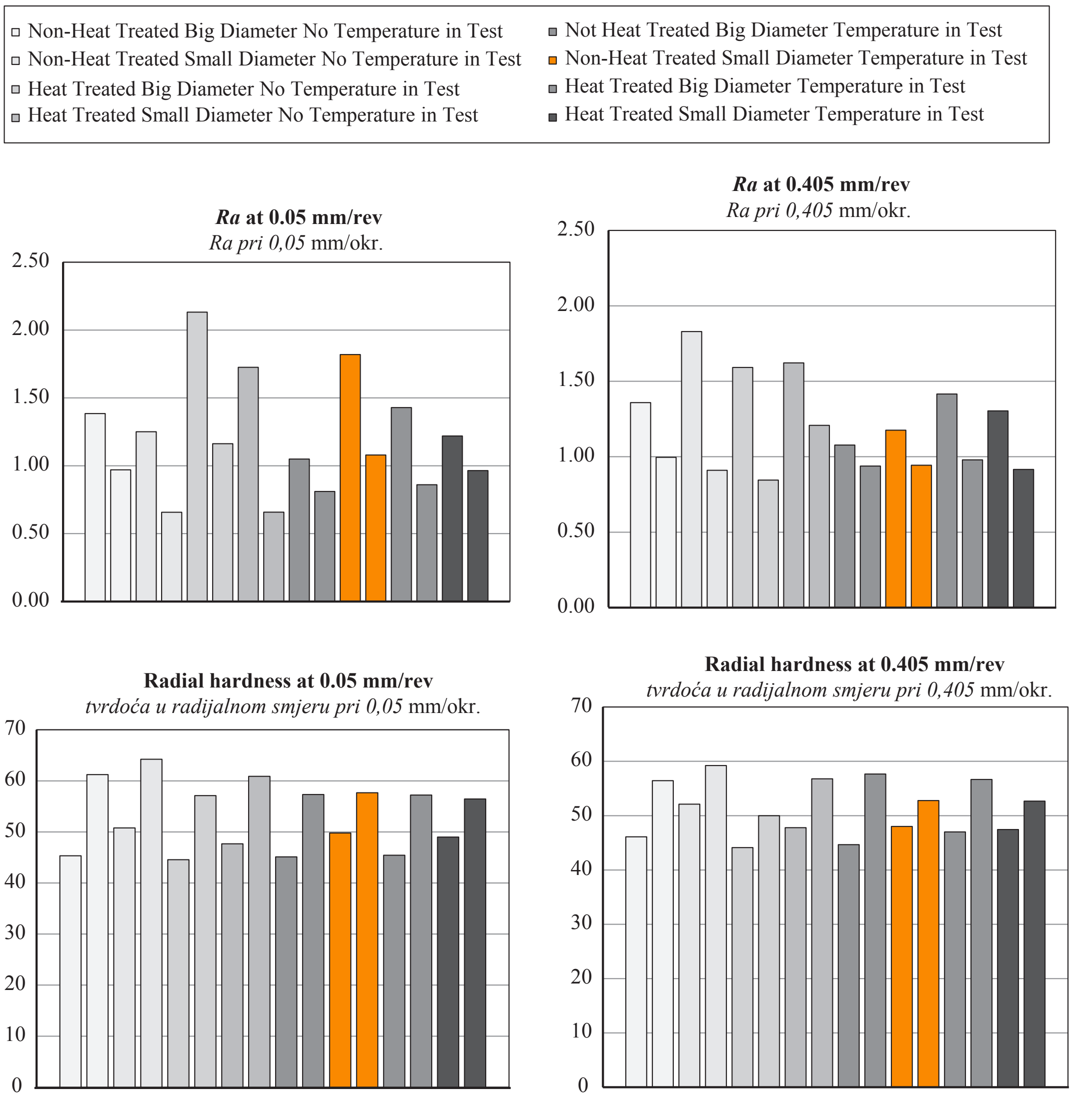


Figure 7 Comparison of differences in before and after test data of test specimens
Slika 7. Usporedba razlika u podatcima prije i nakon ispitivanja uzoraka

cation, close values were obtained in tangential hardness. When the densification process of small-diameter specimens was evaluated, it was observed that the spring-back percentage was lower in heat-treated specimens.

According to the results of variance analysis, at 95 % confidence level, the amount of progress in densification for radial hardness values (0.05 > P = 0.017) and densified diameter for percentage of spring-back (0.05 > P = 0.00) were found statistically significant. In addition, for radial hardness, tangential hardness, average surface roughness (*Ra*) and spring-back, heat treatment, diameter densified, heat application during densification and feed rate were found to be non-significant at 95 % confidence level (Table 3).

When the main effects plot of radial hardness is analyzed, it is found that the hardness is higher in conditions where no heat treatment is applied, lower diameter (21 mm), undertreatment is applied during surface densification, and the feed rate is lower (0.05) in surface densification (Figure 8). When the interaction graph (Figure 9) is evaluated in general, similar trends are generally observed in terms of tangential hardness in binary variables. However, the application of temperature during densification at different diameters (21 and 33 mm) significantly decreased the tangential hardness at low diameters, while it was slightly higher at high diameters. In unheat-treated specimens, the application of temperature decreased the radial hardness significantly, while in heat-treated specimens, although very close to each other, a very small decrease occurred. The increase in hardness is a natural result of the surface densification process. Since the densification process increases the hardness and mechanical properties of wood materials, there are many experiments and research in this field (Blomberg and Persson, 2004; Budakci *et al.*, 2022; Sofuoglu, 2022; Tosun and Sofuoglu, 2021; Sofuoglu *et al.*, 2022). This situation also shows similarities with the studies found in the literature (Rautkari *et al*., 2009; Budakci *et al*.,

Table 3 Results of analysis of variance (ANOVA)
Tablica 3. Rezultati analize varijance (ANOVA)

Radial hardness *Tvrdoća u radijalnom smjeru*	**DF**	**Adj SS**	**Adj MS**	***F*- Value**	***P* Value**
Heat treatment / *toplinska obrada*	1	22.038	22.038	3.14	0.104
Diameter / *promjer*	1	3.063	3.063	0.44	0.522
Heat / *zagrijavanje*	1	19.019	19.019	2.71	0.128
Feed rate, mm/rev / *posmična brzina,* mm/okr.	1	55.834	55.834	7.96	0.017
Error / *pogreška*	11	77.200	7.018		
Total / *ukupno*	15	177.154			
Tangent hardness *Tvrdoća u tangentnom smjeru*	**DF**	**Adj SS**	**Adj MS**	***F*- Value**	***P* Value**
Heat treatment / *toplinska obrada*	1	30.864	30.8642	4.54	0.057
Diameter / *promjer*	1	14.694	14.6944	2.16	0.170
Heat / *zagrijavanje*	1	23.901	23.9012	3.51	0.088
Feed rate, mm/rev / *posmična brzina,* mm/okr.	1	0.000	0.0000	0.00	1.000
Error / *pogreška*	11	74.833	6.8030		
Total / *ukupno*	15	144.293			
Average surface roughness (*Ra*) *Prosječna hrapavost površine (Ra)*	**DF**	**Adj SS**	**Adj MS**	***F*- Value**	***P* Value**
Heat treatment / *toplinska obrada*	1	0.005232	0.005232	0.19	0.675
Diameter / *promjer*	1	0.003173	0.003173	0.11	0.743
Heat / *zagrijavanje*	1	0.000434	0.000434	0.02	0.903
Feed rate, mm/rev / *posmična brzina,* mm/okr.	1	0.020497	0.020497	0.73	0.412
Error / *pogreška*	11	0.309437	0.028131		
Total / *ukupno*	15	0.338774			
Spring-back / *Elastični povrat*	**DF**	**Adj SS**	**Adj MS**	***F*- Value**	***P* Value**
Heat treatment / *toplinska obrada*	1	0.0090	0.0090	0.05	0.835
Diameter / *promjer*	1	21.8089	21.8089	109.98	0.000
Heat / *zagrijavanje*	1	0.0306	0.0306	0.15	0.702
Feed rate, mm/rev / *posmična brzina,* mm/okr.	1	2.2650	2.2650	11.42	0.006
Error / *pogreška*	11	2.1812	0.1983		
Total / *ukupno*	15	26.2948			

2016; Senol and Budakci, 2016; Laskowska, 2017; Schwarzkopf, 2021; Sofuoglu, 2022; Kaya and Sofuoglu, 2023b).

Based on the analysis of tangential hardness main effects graph (Figure 10), higher tangential hardness was observed when heat treatment was applied, with lower diameter (21 mm) and no heat applied during surface densification. However, approximately the same tangential hardness value occurred at both feed rates in surface densification. When the interaction graph is evaluated in general, similar trends are observed regarding tangential hardness in binary

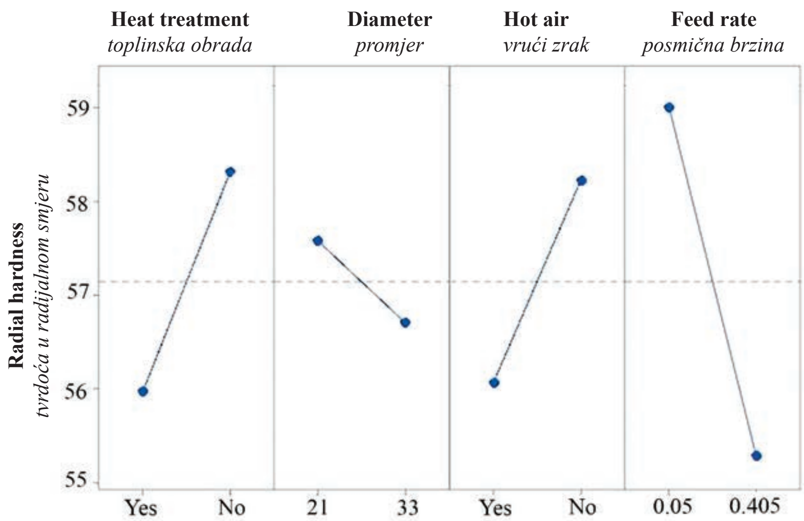


Figure 8 Main effects plot in terms of radial hardness
Slika 8. Dijagram glavnih utjecaja na tvrdoću u radijalnom smjeru

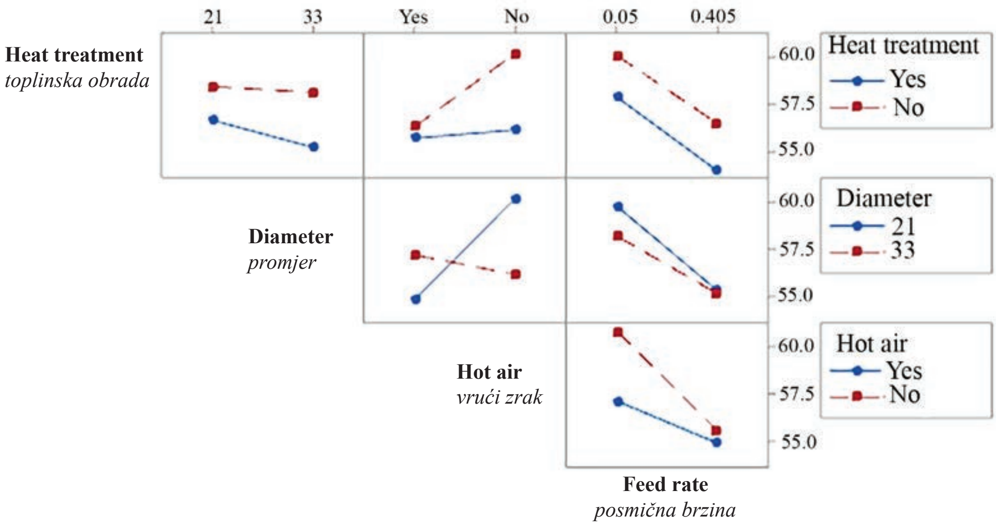


Figure 9 Interactions of heat treatment, diameter, hot air and feed rate of surface densification in terms of radial hardness
Slika 9. Djelovanje toplinske obrade, promjera, vrućeg zraka i posmične brzine na tvrdoću u radijalnom smjeru

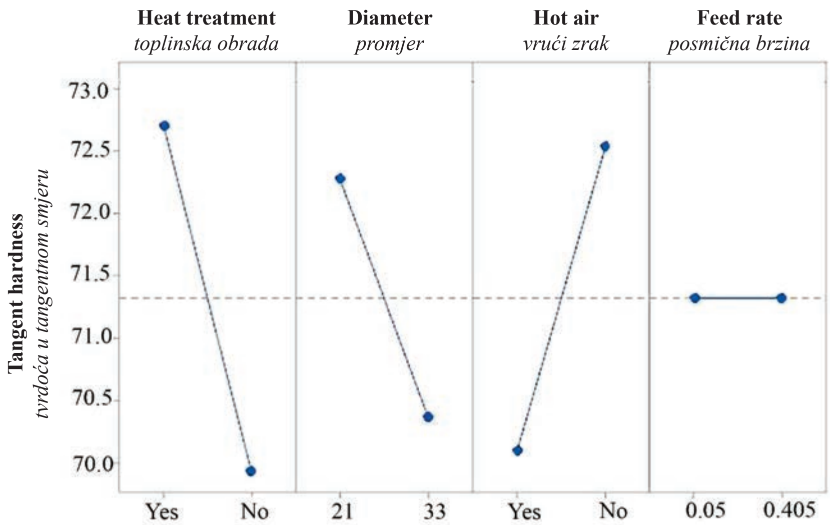


Figure 10 Main effects plot in terms of tangent hardness
Slika 10. Dijagram glavnih utjecaja na tvrdoću u tangentnom smjeru

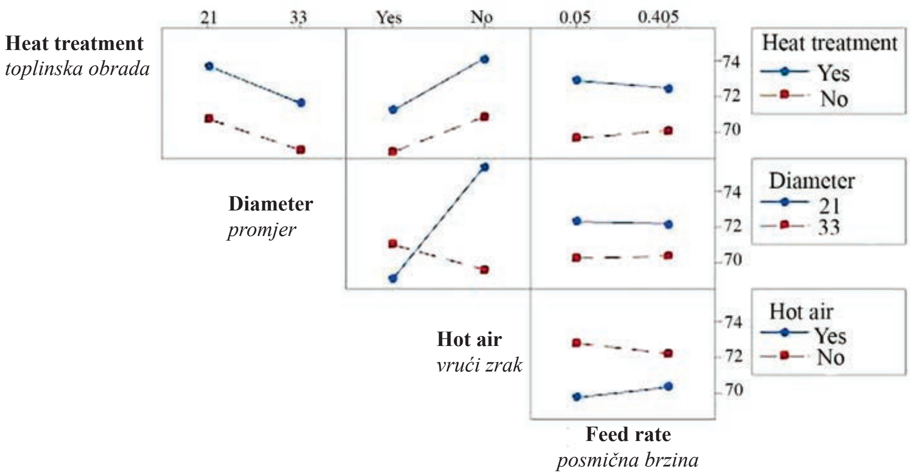


Figure 11 Interactions of heat treatment, diameter, hot air and feed rate of surface densification in terms of tangent hardness
Slika 11. Djelovanje toplinske obrade, promjera, vrućeg zraka i posmične brzine na tvrdoću u tangentnom smjeru

variables. However, applying heat during densification at different diameters (21 and 33 mm) significantly decreased the tangential hardness at low diameter, while it was slightly higher at high diameter (Figure 11). A similar result was observed for radial hardness.

When the main effects graph of roughness was analyzed, the *Ra* value was lower when no heat treatment was applied, the diameter was lower (21 mm), no heat was applied during surface densification, and the feed rate was lower (0.05) (Figure 12). When the interaction graphs for Ra were analyzed, close values were obtained for the specimens with or without heat treatment in densification conditions where heat was applied. However, applying hot air during densification decreased the roughness in the heat-treated samples. Applying hot air increases the roughness at low diameters and decreases the roughness at high diameters. *Ra* increased with the increase in the feed rate in low-diameter specimens, while *Ra* value decreased slightly in high-diameter specimens, although it did not change much. Other interactions between the variables can be seen in the plots (Figure 13).

Literature shows smoother surfaces in solid wood and wood-based materials with increased density (Malkocoglu and Ozdemir, 2006; Zhong *et al.*, 2013; Ayrilmis *et al.*, 2019; Pinkowski *et al.*, 2019; Sofuoglu and Tosun, 2023). Overall, densification is an application that allows the reduction of surface roughness (Bekhta *et al.*, 2014; Pelit and Arısut, 2022; Sofuoglu *et al.*, 2022). The data obtained in this study seem to be consistent with the literature. Uzun *et al.* (2024) reported that, due to the thermal treatment conditions, the average surface roughness (Ra) of the samples increased, and the highest Ra value was recorded in the specimens treated at 200 °C.

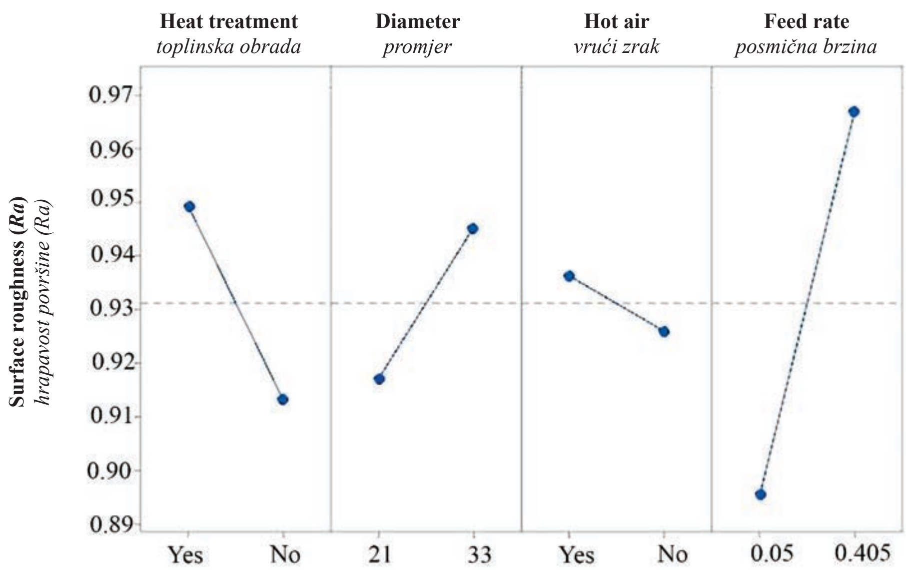


Figure 12 Main effects plot in terms of *Ra*
Slika 12. Dijagram glavnih utjecaja na hrapavost površine *Ra*

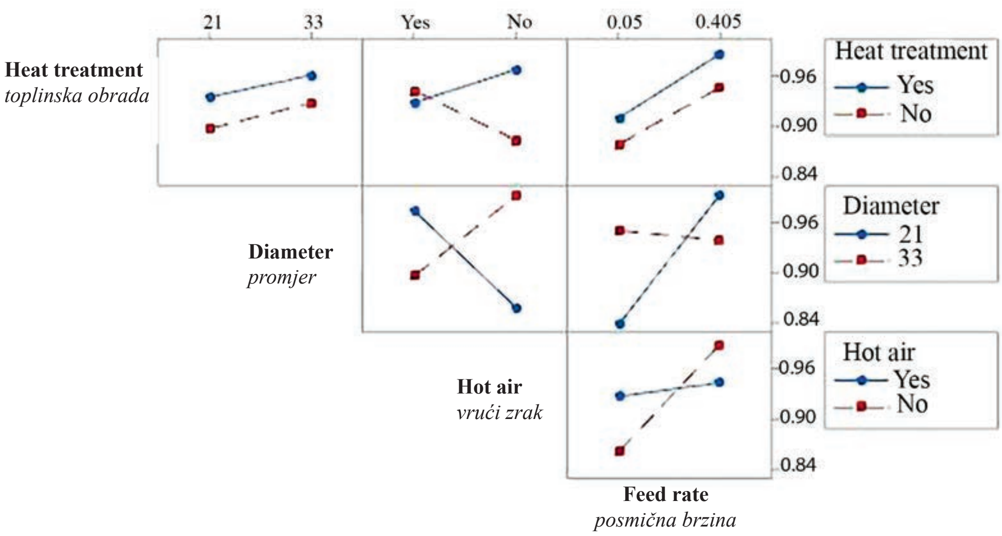


Figure 13 Interactions heat treatment, diameter, hot air and feed rate of surface densification in terms of *Ra*
Slika 13. Djelovanje toplinske obrade, promjera, vrućeg zraka i posmične brzine na hrapavost površine *Ra*

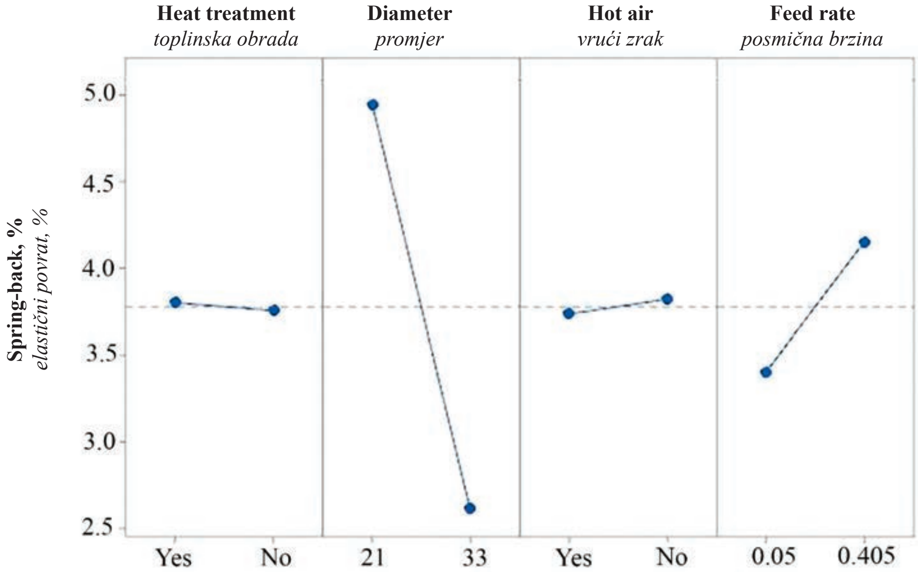


Figure 14 Main effects plot in terms of spring-back
Slika 14. Dijagram glavnih utjecaja na elastični povrat

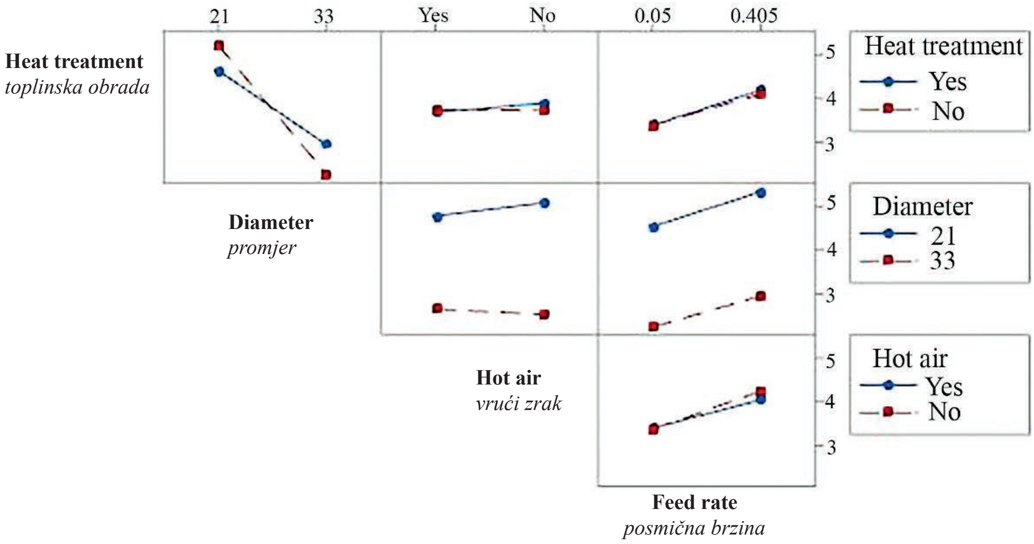


Figure 15 Interactions of heat treatment, diameter, hot air and feed rate of surface densification in terms of spring-back
Slika 15. Djelovanje toplinske obrade, promjera, vrućeg zraka i posmične brzine na elastični povrat

When the main effects graph of spring-back is analyzed (Figure 14), it is seen that the spring-back value is lower in the conditions where no heat treatment is applied, diameter is higher (33 mm), hot air is applied during surface densification, and the feed rate is lower (0.05 mm/rev).

When the interaction graphs related to spring-back are analyzed, it is seen that similar trends to the main effects graph are obtained in each variable group. While the temperature applied during densification did not have much effect on the spring-back in 33 mm diameter specimens, the application of temperature in 21 mm diameter specimens reduced the spring-back (Figure 15).

Temperature and steam are recognized methods for eliminating spring-back (Kunar and Sernek, 2007; Rautkari *et al.*, 2010; Pelit, 2014; Li *et al.*, 2017). The reduction of spring-back recovery is more effective when heat treatment is applied after densification rather than before (Esteves *et al.*, 2017). In addition to reducing spring-back, heat treatment increases the stability and durability of wood (Esteves and Pereira, 2009). The reduction in spring-back is influenced by higher densification and heat treatment temperatures, while the densification time has negligible or no effect (Li *et al.*, 2013). According to experimental studies in the literature, the spring-back effect is a phenomenon observed following densification (Pelit *et al.*, 2014; Kariz *et al.*, 2017; Tenario *et al.*, 2021). According to studies, the density increase resulting from compressing wood material is influenced by the wood species properties, the spring-back effect, and the level of compression applied during densification (Rautkari, 2012; Pelit *et al.*, 2015). Spring-back is significantly influenced by the wood type and densification depth, while feed and spindle speed have no notable effect (Kaya and Sofuoglu, 2023a).

4 CONCLUSIONS
4. ZAKLJUČAK

In this study, black pine *(Pinus nigra* Arnold.) was surface densified in its cylindrical shape. The results obtained from the study are as follows:

When the spring-back effect was examined in densification processes in all conditions, a lower spring-back effect was obtained at low revolutions (0.05 mm /rev).

The highest spring-back effect occurred at 0.405 mm/rev in small diameter samples without heat treatment and in samples where hot air was applied during production.

In both heat-treated and non-heat-treated specimens, a decrease in *Ra* value and increased radial and tangential hardness occurred after densification in all densification conditions.

The application of hot air decreased the roughness in the heat-treated specimens.

Applying hot air in densification increases the roughness at low diameters and decreases the roughness at high diameters.

When the main effects graph of spring-back was analyzed, the spring-back value was lower when no heat treatment was applied, diameter was higher (33 mm), hot air was applied during surface densification, and the feed rate was lower (0.05). The most successful densification was obtained at the lowest feed (0.05 mm/rev).

Spindle speed was not a significant factor in surface densification.

The use of spinning rollers allowed the surface densification of cylindrical wood. At the end of this densification process, it was observed that the properties of the wood material were improved. This method can be demonstrated to be effective for the surface densification of cylindrical wood materials.

The surface densification studies with a spinning roller will enable the application of optimal parameters based on the evaluation of hardness, spring back, and roughness results.

Surface densification process for cylindrical wood materials can be developed with mass production tools.

By making cost-benefit calculations, precision in production for fine workmanship can be provided with surface densification process.

Optimum production approaches will be obtained by trials with different wood species, heating and cooling processes, surface densification depths, feed and spindle speeds.

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