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Use of Spinning Rollers for Surface Densification of Wood

Uporaba rotirajućih valjaka za ugušćivanje površine drva

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ABSTRACT • *In this study, softwood cedar of Lebanon (Cedrus libani A.Rich.) and hardwood black poplar (Populus nigra L.), turned into cylinders by turning, were subjected to a surface densification process. Densification was carried out on the lathe using the spinning roller designed and manufactured for this purpose. Hardness, brightness and roughness (R_z) measurements were carried out on undensified and densified regions of the cylindrical solid wood materials. An increase in hardness and brightness and a decrease in roughness values occurred under all densification conditions. The highest surface hardness values occurred in cedar of Lebanon at 0.081 mm/rev feed, 200 rpm spindle speed, and 1 mm densification depth. On densified wood surfaces, as the feed from the densification parameters increases, the hardness decreases, and as the densification depth increases, the hardness increases-. The effect of surface densification parameters on the gloss and roughness results of the samples shows no linear effect in terms of experimental parameters. In both species, lower spring back was obtained at low depth of densification.*

KEYWORDS: *surface densification; spinning roller; roughness; glossiness; hardness*

SAŽETAK • *U ovom su istraživanju cilindrični uzorci drva libanonskog cedra (Cedrus libani A.Rich.) i srži drva crne topole (Populus nigra L.) bili podvrgnuti procesu ugušćivanja površine. Postupak je obavljen na tokarskom stroju uz pomoć posebno dizajniranoga i proizvedenoga rotirajućeg valjka. Mjerenja tvrdoće, svjetline i hrapavosti (R_z) površine provedena su na neugušćenim i ugušćenim dijelovima cilindričnih uzoraka drva. Povećanje vrijednosti tvrdoće i svjetline te smanjenje vrijednosti hrapavosti dogodilo se pri svim uvjetima ugušćivanja. Najveće vrijednosti površinske tvrdoće zabilježene su na uzorku drva libanonskog cedra pri posmičnoj brzini 0,081 mm/okr., frekvenciji vrtnje vretena 200 min^{-1} i dubini ugušćivanja 1 mm. Na ugušćenim se površinama drva s povećanjem posmične brzine tvrdoća smanjivala, a s povećanjem dubine ugušćivanja tvrdoća se povećavala. Utjecaj parametara ugušćivanja površine na sjaj i hrapavost uzoraka ne pokazuje linearni odnos u sklopu eksperimentalnih parametara. Za obje vrste drva dobiven je manji elastični povrat pri manjoj dubini ugušćivanja.*

KLJUČNE RIJEČI: *ugušćivanje površine; rotirajući valjak; hrapavost; sjaj; tvrdoća*

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1 INTRODUCTION
1. UVOD

It is known that properties such as durability, hardness, and strength are generally insufficient for wood, especially in wood materials with a low density. When these properties are demanded, the use of high-density wood material or densified wood can become an alternative to other materials (Sandberg *et al.*, 2021). Density is a factor affecting the mechanical properties of wood material (Blomberg and Persson, 2004). In recent years, when environmental awareness has increased, new environmentally friendly densification methods have started to be used (Senol and Budakci, 2016; Korkut and Kocaefe, 2009) such as densification using temperature and pressure in an open system known as thermo-mechanical (TM) (Sofuoglu, 2022; Sofuoglu *et al.*, 2022; Salca *et al.*, 2021; Tosun and Sofuoglu, 2021) and densification using temperature, pressure and steam in a closed system called thermo-hygro-mechanical (THM) (Parvis Navi, 2012). In addition to these, there is densification made by temperature and pressure after pre-softening with steam, which is called Viscoelastic-Thermal-Compression (VTC). There are also methods such as densification using temperature, pressure and vibration, called Thermo-Vibro-Mechanical (TVM) (Senol, 2018; Bekhta *et al.*, 2017; Senol and Budakci, 2016).

There are studies in the literature on density analysis and various mechanical properties in densified and heat-treated wood materials (Croitoru *et al.*, 2018; Burgos and Rolleri, 2012). Mechanical properties including the modulus of elasticity (MoE), modulus of rupture (MoR) (Wehsener *et al.*, 2023), hardness, and surface hardness (Gao *et al.*, 2019), and Janka hardness (Pertuzzatti *et al.*, 2018) increased with densification. Surface hardness increased with densification (Senol and Budakci, 2019; Laskowska, 2017). The hardness values in the radial and tangential directions of the densified samples increased depending on the compression rate in the cell walls (Budakci *et al.*, 2016). The surface wettability showed that surface-densified wood has good wetting protection (Rautkari *et al.*, 2010). Research has been done to determine and minimize the amount of spring back and set recovery (Scharf *et al.*, 2023; Neyses *et al.*, 2020; Kariz *et al.*, 2017). The following results were obtained in the study carried out to determine the surface properties of the surfaces obtained by applying top surface treatments. Surface roughness decreased, and surface brightness increased in densified samples. The surface brightness and hardness values increased with the increase of densification and densification ratio (Sofuoglu, 2022).

Turned wood materials are used for tool handles, wooden toys, stair railings, furniture pieces, etc. As the density increases in wood materials, porosity decreases, and smoother surfaces are obtained. Surface roughness is an important parameter in determining the economic value of wooden materials and has an important place in the success of upper surface quality. Especially when low-density wood materials are used, the mechanical properties can be improved by densification (Sogutlu, 2005). Smooth surfaces obtained by turning processes performed in accordance with the standard technique increase the success of varnishing and painting processes. Thus, more economical production can be made by using less materials and labor in surface treatments (Gurleyen, 1998). Although cylindrical wood materials have a wide area of use, scientific studies on surface densification have not been found in the literature as a result of research. It is believed that, when cylindrical, turned wood materials improve their properties by surface densification process, their areas of use increase and they can be used for a longer time without losing their surface properties. Thus, natural wood materials, which are depleted day by day, can be used more optimally.

In accordance with this purpose, in this study, surface densification was carried out using various densification parameters of cylindrical wood material. It is aimed to obtain the most suitable densification conditions in cylindrical materials by determining the high hardness and brightness and low roughness values, which are important for the use after densification.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

In the present study, cedar of Lebanon (*Cedrus libani* A.Rich.) (softwood) and black poplar (*Populus nigra* L.) (hardwood) were used (Table 1). These species are commonly grown and used in Turkey (Doğu *et al.*, 2001).

The density of wood species at 12 % moisture content was determined according to ISO 13061 (ISO 13061-2:2014) standards. They were conditioned at temperatures of ~ (20±2) °C and (65±5) % relative humidity (*RH*) to moisture content (*MC*) of about 12 % (ISO 13061-1:2014).

The experimental specimens were cut from the log prismatically with a size of 2 cm × 2 cm × 32 cm. The remaining 5 cm of the test sample on the lathe chuck side was left as a 2 cm × 2 cm square. It was connected to the four-legged lathe chuck from this square section. It was connected between the chuck and the tailstock on a universal lathe and machined until it reached an average diameter of 1.9 cm. After the turning process, channels with a depth and width of 4 mm were made using a grooving tool to create 5 cm long sections. 5 cylindrical sections were made on the experimental specimens. The

Table 1 Basic properties of the studied wood species
Tablica 1. Osnovna svojstva istraživanih vrsta drva

Wood species *Vrsta drva*	**Density, kg/m³** *Gustoća,* kg/m³	**Number of rings per cm** *Broj godova po* cm	**Moisture content** *Sadržaj vode*	**Age of trees** *Starost drva*	**Region** *Regija*
Black poplar *drvo crne topole*	340	0.78	12 %	12	Bahcekoy, Istanbul, Turkey
Cedar of Lebanon *drvo libanonskog cedra*	520	1.77	12 %	75	Simav/Kutahya Turkey

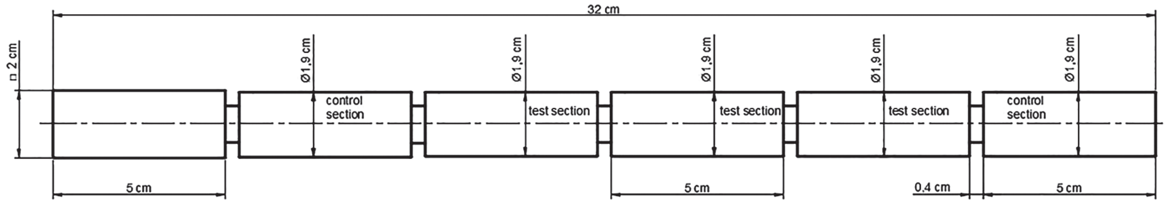

Figure 1 Technical drawing of test specimen
Slika 1. Tehnički crtež ispitnog uzorka

experimental parameters were applied to 3 of them, and the remaining 2 sections left at the end and at the tip of the sample were determined as control sections. A structure was obtained on the test specimen in which different test parameters would be created in each section. After all cylindrical turning and grooving operations, the surfaces were smoothed with 400-grit sandpaper. Each experiment parameter was performed 3 times in such a way that it was in a different part of another experiment specimen and their averages were taken. A total of 12 test specimens were used to complete the experiments (Figure 1).

The cylinder axis of the densification apparatus and the tall stock axis were aligned for the densification process. The apparatus was connected to the tool post section of the lathe. The measurement was reset when the densification cylinder started to rotate as soon as it contacted the test specimen. In order to keep bending to a minimum, low densification depths such as 0.5 mm and 1 mm, which are experimental parameters, were preferred. Experience obtained from other similar studies using the densification apparatus have also shown that the bending problem on the specimens in the experiments can be ignored for these densification depths.

2.1 Densification apparatus
2.1. Oprema za ugušćivanje

The assembly technical drawing of the spinning roller, which has been specially designed and manufactured for surface densification is shown in Figure 2. The surface densification process on a universal lathe, the shape of the specimen, the direction of densification and the details of the spinning roller set are presented in Figure 3. The densification parameters and levels are shown in Table 2. Among the process parameters, feed is the distance taken by the densification apparatus in mm for each revolution of the specimen. Spindle speed is the number of revolutions per minute of the test specimen. Experimental process of the study is presented in Figure 4.

Table 2 Process parameters used in turning of black poplar and cedar of Lebanon
Tablica 2. Parametri procesa tokarenja drva crne topole i libanonskog cedra

Parameter / *Parametar*	**Coded levels** *Oznake razina*		
	Level 1	Level 2	Level 3
Feed, mm/rev *posmična brzina,* mm/okr.	0.081	0.121	0.202
Spindle speed, rpm *brzina vretena,* okr./min	200	400	
Dept of densification, mm *dubina ugušćivanja,* mm	0.5	1	

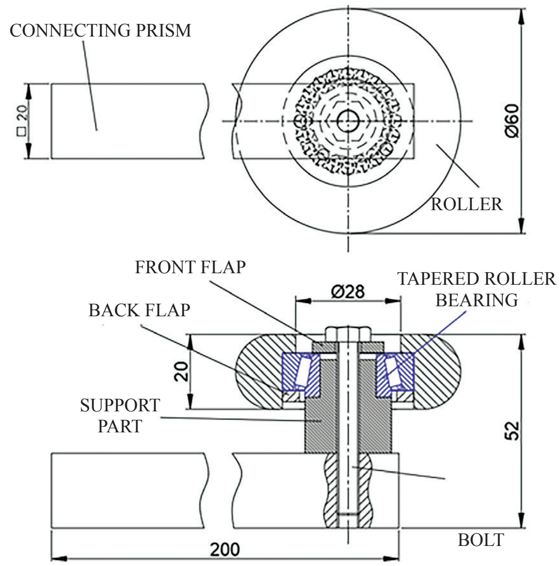

Figure 2 Technical drawing of spinning roller assembly
Slika 2. Tehnički crtež sklopa rotirajućeg valjka

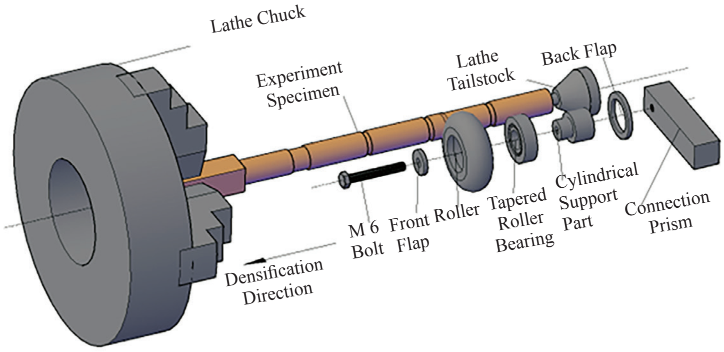

Figure 3 Densification system elements and details of assembly structure
Slika 3. Elementi sustava za ugušćivanje s detaljima

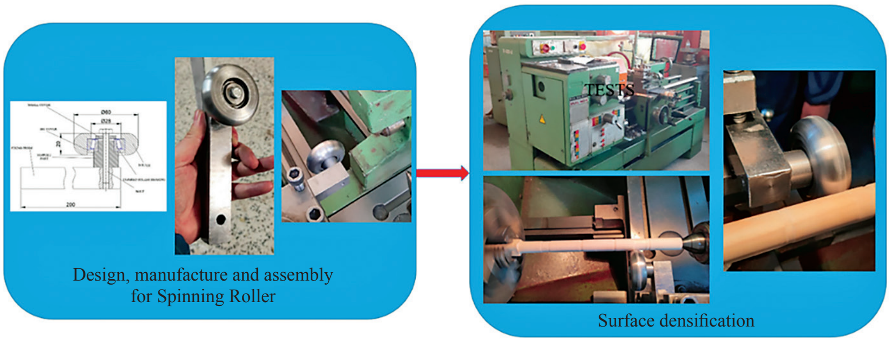

Figure 4 Schematic representation of experimental design
Slika 4. Shematski prikaz postavke eksperimenta

2.2 Determining surface glossiness, hardness and roughness
2.2. Određivanje sjaja, tvrdoće i hrapavosti površine

In the study, glossmeter (BYK Gardner brand Micro-TRI-gloss µ) was used for gloss measurements at 60°. Measurements were made according to the principles specified in EN ISO 2813:2014. The surface hardness was measured using a Shore D hardness tester (Tronic PD800). Surface roughness measurements were taken parallel to the grain at three separate points on each specimen according to ISO 468:2009 using a surface roughness tester (Time TR200, Time Group Inc., China). The measuring parameter (R_z) is described in ISO 468. The stylus probe speed was set to 10 mm/min, the diameter of the measurement needle was 4 µm, and the needle tip was 90°.

In the experimental specimen, 3 repeated hardness, roughness and brightness measurements were taken in the direction parallel to the fibers on the section where the experimental parameter was applied, and their averages were used. The same measurements were repeated for the control sections located at the tip and end of the experimental specimen, and were used for comparison with the sections where the test parameters were applied.

2.3 Determining compression ratio and spring-back
2.3. Određivanje stupnja ugušćenja i elastičnog povrata

In the study, the instantaneous compression ratio and instantaneous spring-back were evaluated depending on the densification parameters. The diameters of the test specimens were measured from 4 different points before the surface densification process and the average of the measurements was taken (D_{start}). The same measurement process was performed after the densification parameters were applied and the average diameters were determined by completing the process (D_{end}). Two surface densification depths of 0.5 mm and 1 mm were used in the study. Theoretical diameters are obtained when the densification depths are subtracted from the initial diameters of the test specimens ($D_{teor.}$). In addition to the surface densification depths, the average theoretical % compression ratio, the average experimental % compression ratio, and the average spring-back were found to depend on the feed and spindle speed. The theoretical % compression ratio (*Teo.C.R.*, %) was calculated with Eq. 1. Here x refers to the densification depths, and the results were obtained by taking 0.5 mm and 1 mm. Experimental % compression ratio (*Exp.C.R.*, %) was calculated using Eq. 2. In this equation, the average diameters before the experiment (D_{start}) and after the experiment (D_{end}) were used. In Eq. 3, the spring-back was calculated by taking the percentage of the difference between the average diameters after the experiment (D_{end}) and the theoretical diameters ($D_{teor.}$) were found.

$$Teo.C.R.(\%)=\frac{(D_{start}-(D_{start}-x))}{(D_{start}-x)}\cdot 100 \qquad (1)$$

$$Exp.C.R.(\%)=\frac{(D_{start}-D_{end})}{(D_{start})}\cdot 100 \qquad (2)$$

$$Spring-back\,(\%)=\frac{(D_{end}-D_{teor.})}{(D_{teor.})}\cdot 100 \qquad (3)$$

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Hardness, brightness, and roughness parameter values measured on densified surfaces are given in Tables 3, 4 and 5.

3.1 Evaluation of glossiness, hardness and surface roughness
3.1. Analiza sjaja, tvrdoće i hrapavosti površine

In both wood species, under all surface densification conditions, an increase in brightness values occurs as densification increases. Senol and Budakci (2016) and Sofuoglu (2022) showed that an increase in brightness values occurred after TVM and TM densification processes in solid wood materials. The highest brightness values are very close to each other in the black poplar, but they were formed under the 4th and 8th process number surface densification conditions, while in cedar of Lebanon the highest brightness value was obtained under the 5th process number surface densification conditions. When comparing the brightness values between the wood types in Table 3 and 4, it can be seen that higher brightness values were obtained in the black poplar after all the surface densification processes.

In both wood species, hardness values increased with densification in all surface densification conditions. Similar results were found in some other studies (Sofuoglu, 2022; Schwarzkopf, 2021; Laskowska, 2017; Budakci *et al*., 2016; Senol and Budakci, 2016; Rautkari *et al*., 2009). The highest hardness values are very close to each other in the black poplar, but they

Table 3 Hardness and glossiness values obtained according to surface densification conditions for black poplar
Tablica 3. Vrijednosti tvrdoće i sjaja za površinski ugušćeno drvo crne topole pri različitim uvjetima

Process number *Broj procesa*	**Feed, mm/rev** *Posmična brzina,* mm/okr.	**Spindle speed, rpm** *Frekvencija vrtnje vretena,* okr./min	**Densification depth, mm** *Dubina ugušćivanja,* mm	**Hardness, Shore D** *Tvrdoća,* Shore D		**Glossiness, GU** *Sjaj,* JS	
				Control *Kontrolni uzorak*	**Densified** *Ugušćeno*	**Control** *Kontrolni uzorak*	**Densified** *Ugušćeno*
1	0.081	200	0.5	39.50	41.25	2.97	3.33
2	0.081	200	1	44.50	51.75	2.50	2.70
3	0.081	400	0.5	40.40	45.40	2.70	2.93
4	0.081	400	1	40.90	48.40	2.83	3.63
5	0.121	200	0.5	39.50	43.25	2.97	3.43
6	0.121	200	1	44.50	51.50	2.73	2.93
7	0.121	400	0.5	40.40	43.80	2.70	3.00
8	0.121	400	1	40.90	41.86	2.83	3.67
9	0.202	200	0.5	39.50	40.75	2.97	3.27
10	0.202	200	1	44.50	48.75	2.73	3.13
11	0.202	400	0.5	40.40	43.20	2.70	2.80
12	0.202	400	1	40.90	41.00	2.83	3.33

Table 4 Hardness and glossiness values obtained according to surface densification conditions for cedar of Lebanon
Tablica 4. Vrijednosti tvrdoće i sjaja za površinski ugušćeno drvo libanonskog cedra pri različitim uvjetima

Process number *Broj procesa*	**Feed, mm/rev** *Posmična brzina,* mm/okr.	**Spindle speed, rpm** *Frekvencija vrtnje vretena,* okr./min	**Densification depth, mm** *Dubina ugušćivanja,* mm	**Hardness, Shore D** *Tvrdoća,* Shore D		**Glossiness, GU** *Sjaj,* JS	
				Control *Kontrolni uzorak*	**Densified** *Ugušćeno*	**Control** *Kontrolni uzorak*	**Densified** *Ugušćeno*
1	0.081	200	0.5	52.08	66.00	2.13	2.80
2	0.081	200	1	56.17	59.50	2.03	2.43
3	0.081	400	0.5	54.33	61.88	1.97	2.65
4	0.081	400	1	55.67	60.17	1.98	2.73
5	0.121	200	0.5	52.08	59.00	2.13	2.87
6	0.121	200	1	53.38	54.86	2.03	2.43
7	0.121	400	0.5	54.33	58.33	1.97	2.55
8	0.121	400	1	56.29	62.86	1.98	2.70
9	0.202	200	0.5	52.08	56.22	2.13	2.52
10	0.202	200	1	53.38	55.67	2.03	2.28
11	0.202	400	0.5	53.78	56.63	1.97	1.98
12	0.202	400	1	56.29	62.13	1.98	2.53

Table 5 Surface roughness values (R_z) obtained according to surface densification conditions for black poplar and cedar of Lebanon
Tablica 5. Vrijednosti hrapavosti površine (R_z) za površinski ugušćeno drvo crne topole i libanonskog cedra pri različitim uvjetima

Process number *Broj procesa*	**Feed, mm/rev** *Posmična brzina,* mm/okr.	**Spindle speed, rpm** *Brzina vretena,* okr./min	**Densification depth, mm** *Dubina ugušćivanja,* mm	**Black poplar surface roughness, µm** *Hrapavost površine drva crne topole,* µm		**Cedar of Lebanon surface roughness, µm** *Hrapavost površine drva libanonskog cedra,* µm	
				Control *Kontrolni uzorak*	**Densified** *Ugušćeno*	**Control** *Kontrolni uzorak*	**Densified** *Ugušćeno*
1	0.081	200	0.5	8.188	6.850	7.353	5.572
2	0.081	200	1	7.315	6.367	6.473	6.131
3	0.081	400	0.5	7.199	6.217	6.485	4.240
4	0.081	400	1	7.166	4.731	6.823	6.620
5	0.121	200	0.5	8.188	6.632	7.353	5.033
6	0.121	200	1	7.315	7.157	6.473	4.800
7	0.121	400	0.5	7.199	6.607	6.485	5.455
8	0.121	400	1	7.971	7.245	6.823	6.332
9	0.202	200	0.5	8.188	7.424	7.353	5.235
10	0.202	200	1	7.315	5.810	6.473	4.343
11	0.202	400	0.5	7.772	7.447	6.485	5.518
12	0.202	400	1	7.166	7.043	6.823	5.793

were formed under the 2nd and 6th process number surface densification conditions. And in the cedar of Lebanon, it was obtained under the 1st process number surface densification conditions.

When the hardness values for both wood types were compared after surface densification, the hardness values of cedar of Lebanon were higher than those of the black poplar wood under all surface densification conditions. Although the hardness value of the cedar of Lebanon was higher in the 6th process number surface densification condition, a value close to this was obtained in the black poplar. In both wood species, a decrease in roughness occurred with densification under all surface densification conditions. It was found in the literature that smoother surfaces are obtained in solid wood and wood-derived materials with increased density (Sofuoglu and Tosun 2023; Ayrilmis *et al*., 2019; Pinkowski *et al*., 2019; Zhong *et al*., 2013; Malkocoglu and Ozdemir, 2006). In general, wood species studied showed lower surface roughness values after densification (Bekhta *et al*., 2014). Pelit and Arısut (2022) and Sofuoglu *et al*. (2022) also found in their studies that a decrease in surface roughness values occurred in the densified wood materials (the data obtained in the study seem compatible with the literature). In Tables 6, 7 and 8, hardness, brightness and R_z values obtained in average roughness measurements show normal distribution at 95 % confidence level, since the P value is higher than 0.05 (P = 0.076 for hardness, P = 0.685 for brightness, P = 0.662 for R_z). According to the results of variance analysis, for hardness at 95 % confidence level, the feed (0.05<P = 0.127), spindle speed (0.05<P = 0.871), and depth of densification (0.05<P=0.204) did not make a statistically significant difference, while wood species (0.05>P=0,000) was found to make a statistically significant difference (Table 6).

Figure 5 shows the interaction of wood species, feed, spindle speed and depth of densification in terms of hardness in the main effect plot. Generally higher hardness values were obtained with the cedar of Lebanon. Although there is no significant difference between the groups, it is possible to say that, when the graph is examined in terms of the spindle speed, the values close to each other in terms of hardness were obtained at the spindle speed of 200 and 400 rpm. After

Table 6 Results of analysis of variance for hardness
Tablica 6. Rezultati analize varijance za tvrdoću

Source / *Izvor*	**DF**	**Adj SS**	**Adj MS**	***F* Value**	***P* Value**
Wood species (black poplar and cedar of Lebanon) *vrsta drva (crna topola i libanonski cedar)*	1	1237.54	1237.54	99.80	0.000
Feed, mm/rev / *posmična brzina,* mm/okr.	2	57.51	28.76	2.32	0.127
Spindle speed, rpm / *brzina vretena,* okr./min	1	0.34	0.34	0.03	0.871
Depth of densification, mm / *dubina ugušćivanja,* mm	1	21.55	21.55	1.74	0.204
Error / *pogreška*	18	223.20	12.40		
Total / *ukupno*	23	1540.13			

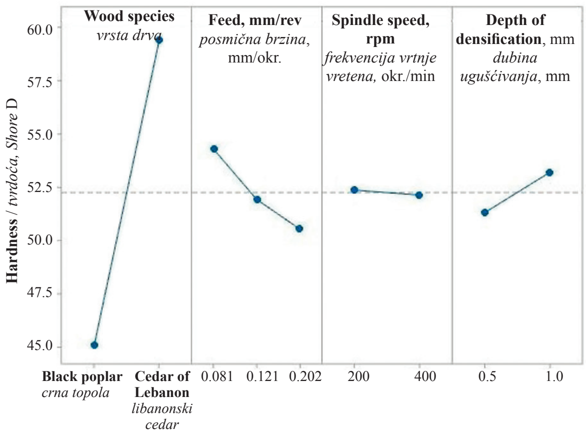

Figure 5 Main effects plot in terms of hardness of wood species, feed, spindle speed and depth of surface densification
Slika 5. Dijagram glavnih utjecaja tvrdoće drva, posmične brzine, frekvencije vrtnje vretena i dubine ugušćivanja površine na hrapavost

the surface densification process, the hardness on the wood surfaces decreases as the feed increases and increases as the densification depth increases. When evaluated in general, high surface hardness values occur in cedar of Lebanon at 0.081 feed, 200 spindle speed and 1 mm densification depth. The interaction graph in Figure 6 shows that the hardness decreases as the feed increases in the surface densification process for both wood species. As the spindle speed increases, hardness decreases in the black poplar, while an increase occurs in the cedar of Lebanon. While the depth of densification increased, the amount of hardness increased in the black poplar, but there was not much change in the cedar of Lebanon. The interactions of feed and spindle speed, feed and depth of densification, and spindle speed and depth of densification were close to each other in terms of hardness.

According to the results of the analysis of variance for brightness at a 95 % confidence level, feed (0.05<*P*=0.315), spindle speed (0.05<*P*=0.793), and depth of surface densification (0.05<*P*=0.804) did not make a statistically significant difference, while wood species (0.05>*P*=0.000) made a statistically significant difference (Table 7).

When evaluated in general, high surface brightness occurred in black poplar at 0.121 feed, 400 spindle speed, and 1 mm surface densification depth (Figure 7). The brightness value increases as the spindle speed and depth of surface densification are increased. The brightness value increases as the feed is increased, but when it is increased to 0.202 mm/rev, there is a decrease, with the lowest brightness value occurring in this feed. The interaction graphs in Figure 8 show that higher brightness is obtained in the black poplar wood. In cedar of Lebanon, the brightness did not change as the feed increased, but when it was increased to 0.202, the brightness also decreased. On the other hand, as the depth of surface densification increases, the brightness tends to decrease at 200 rpm, while it increases at 400 rpm.

According to the results of the analysis of variance for R_z at 95 % confidence level, feed (0.05<*P*=0.730), spindle speed (0.05<*P*=0.644), and depth of surface densification (0.05<*P*=0.972) did not

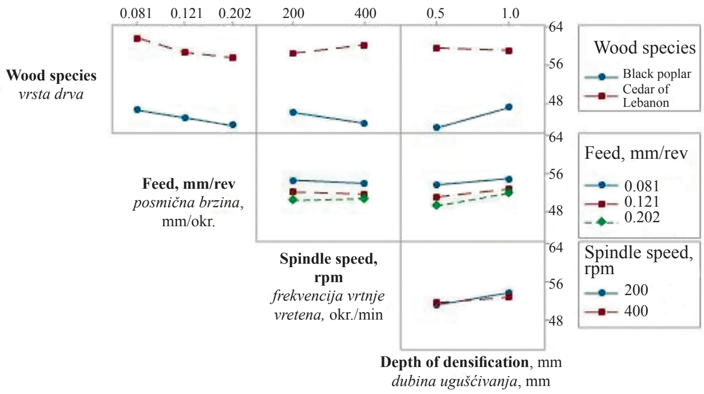

Figure 6 Interaction of wood species, feed, spindle speed and depth of surface densification in terms of hardness
Slika 6. Međusobno djelovanje vrste drva, posmične brzine, frekvencije vrtnje vretena i dubine ugušćivanja na tvrdoću

Table 7 Results of analysis of variance for glossiness
Tablica 7. Rezultati analize varijance za sjaj

Source / *Izvor*	DF	Adj SS	Adj MS	*F* Value	*P* Value
Wood species (black poplar and cedar of Lebanon) *vrsta drva (crna topola i libanonski cedar)*	1	2.45760	2.45760	28.94	0.000
Feed, mm/rev / *posmična brzina,* mm/okr.	2	0.20923	0.10462	1.23	0.315
Spindle speed, rpm / *frekvencija vrtnje vretena,* okr./min	1	0.00602	0.00602	0.07	0.793
Depth of densification, mm / *dubina ugušćivanja,* mm	1	0.00540	0.00540	0.06	0.804
Error / *pogreška*	18	1.52853	0.08492		
Total / *ukupno*	23	4.20678			

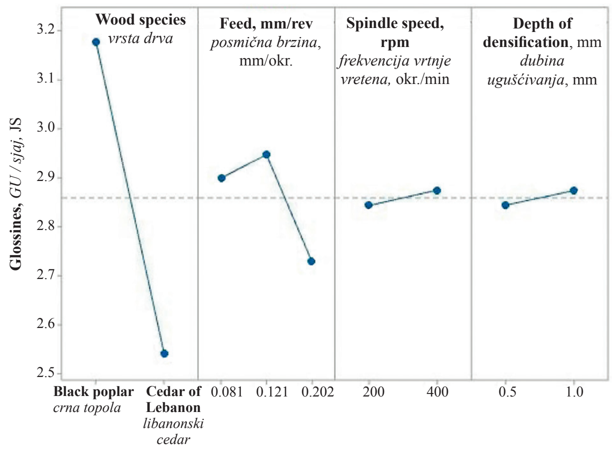

Figure 7 Main effects plot in terms of glossiness of wood species, feed, spindle speed and depth of surface densification
Slika 7. Dijagram glavnih utjecaja tvrdoće drva, posmične brzine, frekvencije vrtnje vretena i dubine ugušćivanja površine na sjaj

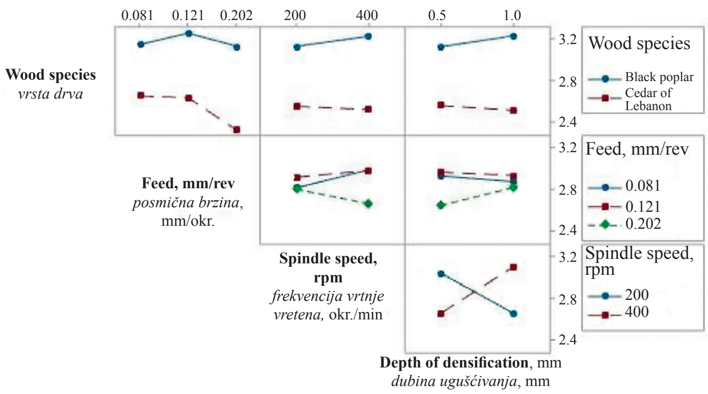

Figure 8 Interaction of wood species, feed, spindle speed and depth of surface densification in terms of brightness
Slika 8. Međusobno djelovanje vrste drva, posmične brzine, frekvencije vrtnje vretena i dubine ugušćivanja na sjaj

make a statistically significant difference, while wood species (0.05>P=0.002) made a statistically significant difference (Table 8).

When evaluated in general, according to the results of the main effect graph, low R_z value is obtained in cedar of Lebanon, 0.081 feed, 200 spindle speed and 0.5 mm surface densification depth. The brightness value increases as the spindle speed, and depth of surface densification are increased. However, with the increase in depth of surface densification, very low R_z values or close to each other have been obtained. In addition, as the feed is increased, the roughness value increases, and when it is increased to 0.202 mm/rev, a decrease occurs (Figure 9). Figure 10 shows that there is no difference between 0.081 and 0.121 feed in terms of R_z for cedar of Lebanon wood. When the feed value increased to 0.202, the roughness value decreased and the lowest R_z values were obtained at 0.202 feed for this wood species. In addition, a linear decrease occurred with increasing the feed value in cedar of Lebanon for R_z. Both wood species showed different responses in terms of spindle speed and depth of surface densification. In terms of R_z, with the increase in spindle speed and depth of surface densification, the R_z value decreased in Black poplar, while an increase occurred in cedar of Lebanon. The reason for this differ-

Table 8 Results of analysis of variance for R_z
Tablica 8. Rezultati analize varijance za parametar hrapavosti R_z

Source / *Izvor*	DF	Adj SS	Adj MS	***F* Value**	***P* Value**
Wood species (black poplar and cedar of Lebanon) *vrsta drva (crna topola i libanonski cedar)*	1	8.7097	8.70974	12.87	0.002
Feed, mm/rev / *posmična brzina,* mm/okr.	2	0.4329	0.21644	0.32	0.730
Spindle speed, rpm / *frekvencija vrtnje vretena,* okr./min	1	0.1495	0.14947	0.22	0.644
Depth of densification, mm / *dubina ugušćivanja,* mm	1	0.0008	0.00084	0.00	0.972
Error / *pogreška*	18	12.1794	0.67663		
Total / *ukupno*		21.4723			

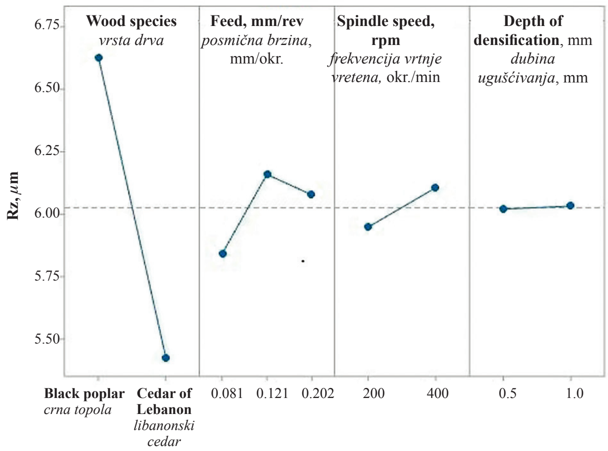

Figure 9 Main effects plot in terms of R_z of wood species, feed, spindle speed and depth of surface densification
Slika 9. Dijagram glavnih utjecaja tvrdoće drva, posmične brzine, frekvencije vrtnje vretena i dubine ugušćivanja površine na parametar hrapavosti R_z

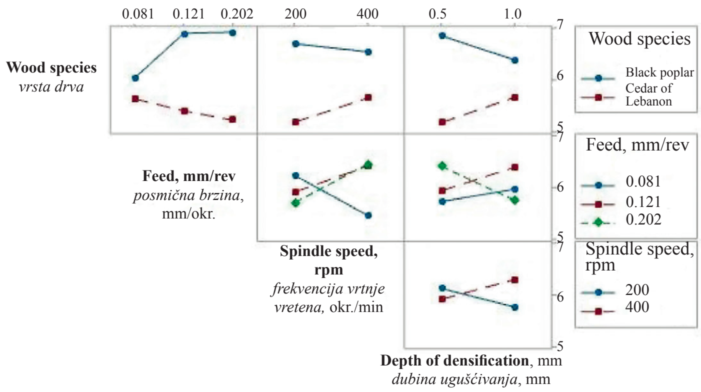

Figure 10 Interaction of wood species, feed, spindle speed and depth of surface densification in terms of R_z
Slika 10. Međusobno djelovanje vrste drva, posmične brzine, frekvencije vrtnje vretena i dubine ugušćivanja na parametar hrapavosti R_z

ence may be the fact that wood species have different anatomical structures. In the interaction between spindle speed and depth of surface densification, as the depth increases at 200 rpm, the roughness values (R_z) decrease, and this value increases at 400 rpm.

3.2 Evaluation of compression ratio and spring-back
3.2. Analiza stupnja ugušćenja i elastičnog povrata

The average % compression ratio and average % spring-back determined depending on the experimental parameters for the two wood species are given in Table 9.

Considering the feed parameter for both wood species, the most successful densification was obtained at the lowest feed (0.081 mm/rotate). Slow feed resulted in better densification of the porous wood. In terms of spindle speed, black poplar could be better densified at low rpm. Cedar of Lebanon could be better densified at high speed. Spindle speed is not seen as a direct determining factor in terms of densification among wood species. It is seen that more successful densification was obtained with high spindle speed for cedar of Lebanon. Dept of densification has been identified as the most drastic experimental parameter for densification success for both wood species. Surface densification increased with the increase of depth of densification from 0.5 mm to 1 mm for both wood species. In both species, lower spring back rate was obtained at low dept of densification.

4 CONCLUSIONS
4. ZAKLJUČAK

In this study, black poplar (*Populus nigra* L.) and cedar of Lebanon (*Cedrus libani* A. Rich.) were surface densified in their cylindrical shape. The results of the study show as follows:

- In both wood species, under all surface densification conditions, an increase in brightness and hardness values occurs with surface densification.
- After all the surface densification processes, higher gloss values were obtained in black poplar than in cedar of Lebanon.

Table 9 Average compression ratio and average spring-back for each experimental parameter
Tablica 9. Srednji stupanja ugušćenja i srednji elastični povrat za svaki parametar eksperimenta

Process parameter *Parametar procesa*		**Average diameter D_{start}, mm** *Srednji promjer D_{start}, mm*	**Theoretical diameter $D_{teor.}$, mm** *Teorijski promjer $D_{teor.}$, mm*	**Densified average diameter D_{end}, mm** *Srednji promjer nakon ugušćivanja $D_{teor.}$, mm*	**Average theoretical compression ratio, %** *Srednji teorijski stupanja ugušćenja, %*	**Average experimental compression ratio, %** *Srednji eksperimentalni stupanj ugušćenja, %*	**Average spring-back, %** *Srednji elastični povrat, %*
	Black poplar / *Drvo crne topole*						
Feed, mm/rev *posmična brzina,* mm/okr.	0.081	18.62	17.87	18.19	4.01	2.27	1.82
	0.121	18.59	17.84	18.25	4.01	1.83	2.28
	0.202	18.51	17.76	18.21	4.03	1.61	2.53
Spindle speed, rpm *frekvencija vrtnje vretena,* okr./min	200	18.46	17.71	18.02	4.03	2.37	1.74
	400	18.68	17.93	18.41	4.00	1.44	2.68
Densification depth, mm / *dubina ugušćivanja,* mm	0.5	18.26	17.76	18.04	2.74	1.21	1.57
	1	18.88	17.88	18.39	5.30	2.60	2.85
	Cedar of Lebanon / *Drvo libanonskog cedra*						
Feed, mm/rev *posmična brzina,* mm/okr.	0.081	18.29	17.54	18.00	4.16	1.61	2.68
	0.121	18.28	17.53	18.09	4.16	1.03	3.28
	0.202	18.24	17.49	18.09	4.17	0.83	3.50
Spindle speed, rpm *frekvencija vrtnje vretena,* okr./min	200	17.75	17.00	17.58	4.33	0.96	3.55
	400	18.79	18.04	18.54	3.99	1.35	2.76
Densification depth, mm / *dubina ugušćivanja,* mm	0.5	18.83	18.33	18.66	2.66	0.88	1.82
	1	17.71	16.71	17.45	5.67	1.44	4.49

- The hardness values of the cedar of Lebanon were higher than those of the black poplar in all surface densification conditions.
- In both wood species, a decrease in roughness values (Rz) occurs after surface densification under all surface densification conditions.
- When the two wood species were compared, smoother surfaces were obtained before and after surface densification due to the higher average density of the cedar of Lebanon wood material.
- The hardness of surface-densified wood surfaces decreased as the feed rate increased and increased as the surface densification depth increased.
- The most successful densification was obtained at the lowest feed.
- Spindle speed was not found to be a significant factor in terms of surface densification.

It is seen that the use of spinning rollers in the surface densification of cylindrical materials creates surface densification on the surfaces. The obtained results show that the properties of wood material are improved by surface densification. The results also show that this method is applicable to the surface densification of cylindrical wood materials.

Optimal parameters can be applied by evaluating the optimum points and results (hardness, brightness, and roughness) according to the data obtained in the surface densification of cylindrical solid wood material using a spinning roller.

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