Kastamonu Uni., Orman Fakültesi Dergisi, 2024, 24(3): 248-259
Kastamonu Univ., Journal of Forestry Faculty
Doi:10.17475/kastorman.1599931

Research Article

Effects of Surface Densification Parameters on Hardness, Roughness and Springback of Cylindrical Black Poplar (*Populus nigra* L.)

Hüseyin YEŞİL[*1], Zafer KAYA[2], Sait Dündar SOFUOĞLU[3]

[1,2]Kütahya Dumlupınar University, Simav Vocational School, Simav, Kütahya, TÜRKİYE
[3]Kütahya Dumlupınar University, Faculty of Simav Technology, Simav, Kütahya, TÜRKİYE
*Corresponding Author: huseyin.yesil@dpu.edu.tr

Received Date: 19.03.2024 Accepted Date: 18.07.2024

Abstract

Aim of study: To determine the effect of densification process with heat and steam on hardness, roughness and spring-back in heat-treated and untreated wood to improve the properties of cylindrical wood material

Material and method: Turned black poplar (*Populus nigra* L.) wood specimens were used in the experiments. The densification process was carried out on an automatic lathe, using a specially designed and produced densification apparatus. During densification, 3 Bar hot steam and 600°C dry air were applied to the material.

Main results: In general, it has been found that the application of steam and heat in the cylindrical densification process of poplar material has the effect of increasing the roughness and springback values and reducing the surface hardness. It was evaluated that the heat treatment had a positive effect on roughness and springback values.

Research highlights: The percentage of spring back and roughness were lower in heat-treated cylindrical black poplar specimens.

Keywords: Poplar, Surface Densification, Hardness, Roughness, Spring-back, Heat Treatment

Silindirik Karakavakta (*Populus nigra* L.) Yüzey Yoğunlaştırma Parametrelerinin Sertlik, Pürüzlülük ve Geri Esneme Üzerine Etkileri

Öz

Çalışmanın amacı: Silindirik ağaç malzemenin özelliklerini iyileştirmek için ısıl işlem uygulanmış ve uygulanmamış ahşapta sıcaklık ve buharla birlikte yoğunlaştırma işlemi uygulamasının sertlik, pürüzlülük ve geri esnemeye etkisini belirlemektir.

Materyal ve yöntem: Deneylerde tornalanmış karakavak (*Populus nigra* L.) odunu örnekler kullanılmıştır. Yoğunlaştırma işlemi özel olarak tasarlanıp imal edilen yoğunlaştırma aparatı kullanılarak otomatik torna tezgahında yapılmıştır. Yoğunlaştırma sırasında malzemeye 3 Bar sıcak buhar ve 600°C kuru hava uygulanmıştır.

Temel sonuçlar: Genel olarak kavak malzemede silindirik yoğunlaştırma işleminde buhar ve sıcaklık uygulamasının pürüzlülük ve geri esneme değerlerini artırıcı, yüzey sertliğini düşürücü etkisi olduğu tespit edilmiştir. Isıl işlemin pürüzlülük ve geri esneme değerlerinde olumlu etkiye sahip olduğu değerlendirilmiştir.

Araştırma vurguları: Isıl işlem görmüş silindirik karakavak numunelerde geri esneme yüzdesi ve pürüzlülük daha düşük elde edilmiştir.

Anahtar kelimeler: Kavak, Yüzey Yoğunlaştırma Sertlik, Pürüzlülük, Geri Esneme, Isıl İşlem

Citation (Atıf): Yesil, H., Kaya, Z., & Sofuoglu, S. D. (2024). Effects of Surface Densification Parameters on Hardness, Roughness and Springback of Cylindrical Black Poplar (*Populus nigra* L.). *Kastamonu University Journal of Forestry Faculty*, 24 (3), 248-259.

Introduction

Low density woods are generally inadequate in 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). Density of wood material directly affects mechanical properties (Blomberg and Persson, 2004). Density can be increased by applying additional treatments to low-density wood. To increase the density, several environmentally friendly methods are used. One of them is the densification by means of temperature and pressure, known as Thermo-Mechanical (TM) (Tosun and Sofuoğlu, 2021; Salca et al., 2021; Sofuoğlu, 2022; Sofuoğlu et al., 2023) The other method is densification using temperature, pressure and steam in a closed system called Thermo-Hygro-Mechanical (THM) (Navi and Sandberg, 2012; Korkut and Kocaefe, 2009; Şenol and Budakçı, 2016). In addition to these, there is also densification made with heat and pressure after pre-softening with steam, called Viscoelastic-Thermal-Compression (VTC). There is another method called Thermo-Vibro-Mechanical (TVM), which uses temperature, pressure and vibration (Şenol and Budakçı, 2016; Bekhta et al., 2017; Şenol, 2018). There are also studies on densification of cylindrical materials in addition to these methods (Yesil et al., 2023, Kaya and Sofuoglu, 2023a; Kaya and Sofuoglu, 2023b; Kaya and Sofuoglu, 2024). Various mechanical properties of wood materials and density analyses have been investigated in studies using these methods. In general, mechanical properties such as young's modulus (MOE), modulus of rupture (MOR), hardness and surface hardness, Janka hardness were found to increase in densified wood (Gao et al., 2019; Laskowska, 2017; Şenol and Budakçı, 2019; Pertuzzatti et al., 2018; Wehsener et al., 2023). While radial and tangential hardness values in densified wood increased as a function of compression ratio, scanning electron microscopy analysis revealed that densification and heat treatment applications caused deformations in the cell walls (Budakci et al., 2016). FT-IR shows that no significant chemical changes occur during densification. It has been found that the surface densified wood has good wetting protection (Rautkari et al., 2010). The wettability analysis showed that the TM densified coating surfaces became more hydrophobic (Bekhta and Krystofiak, 2016). Research has also been carried out to determine and minimise the amount of spring-back in the densification process (Kariz et al., 2017; Neyses et al., 2020; Scharf et al., 2023). The effects of densification on surface treatments were also investigated. Surface roughness decreased and surface brightness increased in densified specimens (Pelit et al., 2015). Surface brightness and hardness values increased with increasing densification rate (Sofuoglu, 2022). It has been found that thermo-mechanical treatment has a significant effect on the change in color of beech and oak wood (Laskowska, 2020). It is also seen that the finite element method is used for densification analyses.

In recent years, heat treatment has become a preferred and widespread modification application to minimise wood materials' negative properties and improve their positive properties (İçel and Şimşek, 2017). Heat treatment was defined by Boonstra (2008) and Rowell et al. (2009) as a physical process resulting in permanent changes in the chemical content of cell wall components (cellulose, hemicellulose, lignin, etc.). Heat treatment improves the performance of the wood as it causes modification of its structure. Heat treatment provides many advantages, such as biological resistance against fungi and insects, low equilibrium moisture content, increased dimensional stability due to the reduction in the working of the wood, increased resistance to external weather conditions, decorative colour diversity and extended usage time (Wikberg, 2004; Jones and Enjily, 2006).

In cylindrical specimens, the steam and temperature applied during heat treatment and surface densification caused a decrease in the brightness values on the surfaces. The steam and temperature used to densify the surface caused the L and b values of the colour to decrease and the a value to increase (Yeşil et. al. 2023). With densification, hardness and gloss values increased and Rz (average peak-to-valley roughness) decreased (Kaya and Sofuoglu, 2023a). The lowest spring-back ratio was obtained with wood species, a feed rate of 0.121 mm per revolution, a spindle speed of 400 rpm and a densification depth of 1 mm (Kaya and Sofuoglu, 2023b). Turned wooden materials are used in many places, from furniture parts to tool handles, stair railings and wooden toys. Smooth surfaces obtained by turning processes carried out by the technique also increase the success of varnishing and painting processes. This enables economical production with lower material and labour costs (Gürleyen, 1998). An important parameter in determining the economic value of wood and wood-based materials is surface roughness (Demirci, 2013; Söğütlü, 2005). With the densification process, porosity in wooden materials is reduced and smoother surfaces can be obtained. 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 maintaining its lightness and other advantages. A higher surface quality can also be achieved on high-density wood materials with the surface densification process.

Cylindrical wood materials have a wide range of applications. However, there is a lack of scientific research into surface densification in this area. It is thought that by improving the properties of turned wood materials with surface densification process, their service life can be extended, and their usage areas will increase. In this way, natural wood materials, which are being depleted day by day, can be put to the best possible use.

For this purpose, cylindrical heat-treated and untreated black poplar wood materials were used as test specimens. Direct heat and hot steam were applied to the specimens during the densification process. Different densification parameters were used in the surface densification process. After the densification process, the aim was to obtain the most suitable densification conditions by determining the hardness, surface roughness and springback levels of the material.

Material and Methods

Material

Black poplar (*Populus nigra* L.) which is widely used in the woodworking and furniture industry and grows naturally in Turkey, was selected for the study. The test specimens were initially prepared with dimensions of 25 × 25 × 400 mm. The test specimens were processed on a universal lathe using different lathe cutters until they reached the average dimensions shown in Figure 1. A total of 12 test specimens were prepared in these sizes. The specimens were kept in the climate cabinet at 65 ± 5% relative humidity (RH), 20 ± 2°C, until their weight did not change, to reach 12% humidity (MC). The density of the test specimens at 12% moisture content was determined according to ISO 13061-1, (ISO 13061-1, 2014) and ISO 13061-2 (ISO 13061-2, 2014) standards.

Pre-heat treatment was applied to 6 of the test specimens. The experiments were carried out when all 12 test specimens reached relative humidity.

Figure 1. Specimens

Methods

Heat treatment

Half of the rough test specimens were heat treated at 160 °C under atmospheric pressure for 3 hours using an oven with a temperature sensitivity of ±1 °C (Figure 2). After the heat treatment, the specimens taken from the oven were reconditioned in the climate cabinet.

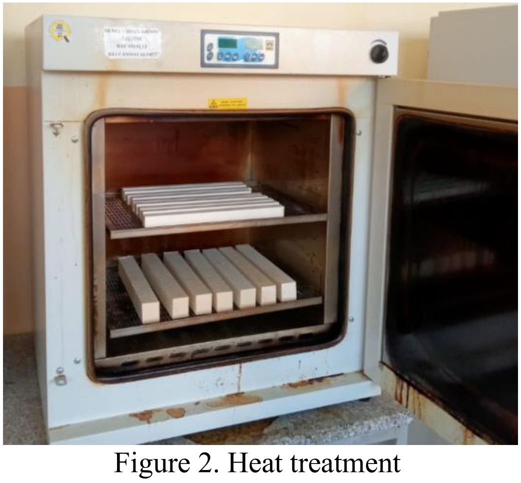

Figure 2. Heat treatment

Densification process

Three main components make up the experimental set for the surface densification process. The first is the densification apparatus which is specially designed and manufactured for densification process. This apparatus consists of a roller which rotates around its axis by pressing on the test specimen, a cylindrical support part, a prism for connection to the lathe pen, a standard tapered roller bearing and other components (front cover, cylindrical support piece, rear cover). The second element of the experimental set is heat regulated fan. This fan is fixed to the sports section of the lathe at a distance of approximately 50 mm from the test specimen. After stabilizing the temperature at 600 ºC, the experiment was started. The third element of the experiment set is the pressurized hot steam source. The steam device was positioned on the sports section of the lathe with approximately 10 mm between the steam output tip and the test specimen. In the device catalog, it is stated that a pressure of approximately 3 bar occurs in the chamber of the steam source. When the experiment starts, the densification apparatus, temperature source and steam source move simultaneously at the speed of the experiment parameters in the direction of densification. A schematic of the experimental set is shown in Figure 3. Each test parameter was planned to be in different sections of 3 different test specimens and applied with 3 repetitions.

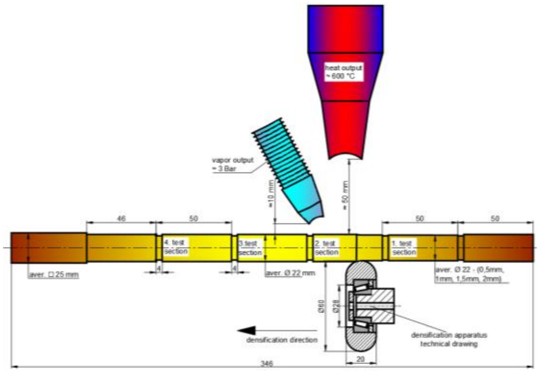

Figure 3. Schematic view of the densification process

A TOS GALANTA SUIL 40A lathe was used for the densification process. As experimental parameters, the spindle rotation speed was determined as 800 rpm and the depth of densification were 0.5 mm, 1.0 mm, 1.5 mm and 2.0 mm. Experiments were carried out with a feed rate of 0.02 mm at each revolution of the spindle. These parameters were chosen according to the authors' experience in their previous studies. (Kaya and Sofuoğlu, 2023a; Kaya and Sofuoğlu, 2023b).

Hardness measurement

A Tronic Shore D hardness tester (Figure 4) was used to measure the surface hardness of the specimens. It has been found that hardness measurements using a pendulum hardness tester and a durometer give approximate results, and these two methods can be recommended for use in measuring the hardness of wood materials. In this method, the relative hardness of the wood is determined by measuring the depth of the needle inserted into the wood sample with a certain force. The spring behind the needle is stretched according to the hardness of the material and the surface hardness can be determined depending on the tension of the spring (Sofuoglu and Yesil, 2016).

Figure 4. Hardness measurement

Roughness measurement

In each section of specimen, surface roughness measurements were taken at 3 different points parallel to the fibers. Surface roughness parameters (Ra and Rz) were determined according to ISO 468 (ISO 1982), ISO 3274 (ISO 1996) and TS EN ISO 21920 (2022). The measurements were performed by needle scanning method using Time TR200 (Time Group Inc., China) brand and model device (Figure 5). The sampling length was taken as 0.25 mm. Ra and Rz values were measured with a precision of ±0.01 µm. The probe speed was 10 mm/min, the diameter of the measuring needle was 4 µm and the needle tip was selected as 90°. Care was taken to ensure that the measurement environment was around 18-22°C and free of vibration. The device was calibrated before.

Figure 5. Surface measurement device

Springback measurement

The density of wooden materials affects their mechanical properties, and after the densification process, material densities are directly proportional to the compression ratio. This section focuses on the detection of instantaneous spring-back phenomenon caused by densification processes. Suitable environmental conditions were provided for before and during the densification process. The test specimens were kept in the air-conditioning cabinet at 20 ⁰C and 65% relative humidity until they reached a constant weight and then were subjected to the densification process. The diameters of specimens were measured before and after the densification process, and then the experimental procedure was completed by taking the average of these measurements. For the experiments, 4 different parameters were determined as surface densification depth. These are 0.5-1-1.5 and 2 mm. These four densification surface depth differences in the diameters of the test specimens between pre- and post-experiment were expected. This situation is shown schematically in Figure 6.

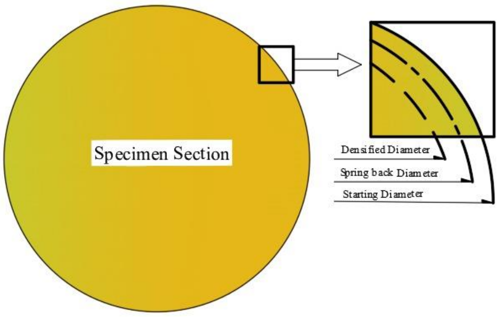

Figure 6. Spring back measurement

In order to evaluate the amount of this difference, the theoretical compression ratio (Teo. C. R.) was calculated as a percentage of the expected diameter change after densification (Equation 1). Here D_1; It refers to the initial diameter before the experiment. a; The values determined as experimental parameters are 0.5 mm, 1 mm, 1.5 mm and 2 mm.

$$\text{Teo. C. R.}\ (\%) = \frac{(D_1-(D_1-a))}{(D_1-a)} \times 100 \qquad (1)$$

Depending on the spring-back caused by the nature of the wood material, the theoretical compression ratio and experimental compression ratio are different from each other. After the experiments, the experimental compression ratio (Exp. C. R.) as a percentage of the diameter difference was calculated with equation 2. Here D_1; It is the specimen diameter measured before the experiment. D_2; It refers to the diameter of the test specimen after the parameters are applied.

$$\text{Exp. C. R.}\ (\%) = \frac{(D_1-D_2)}{(D_1)} \times 100 \qquad (2)$$

Spring-back percentage of the specimen as a result of the surface densification process was calculated using equation 3. D_2 used in the equation defines the diameter of the test specimen after the parameters are applied. D_3, defines the theoretical diameter, which expresses the difference after subtracting the surface densification amounts from the diameter of the test specimen before the experiment.

$$\text{Spring}-\text{back}\ (\%) = \frac{(D_2-D_3)}{(D_3)} \times 100 \qquad (3)$$

Results and Discussion

In Table 1, pre-heat treatment status (1/0), densification depth, steam-heat application status (1/0) are given. And the hardness, roughness and diameter values obtained as a result of the control measurements made before the experiment can be seen. The measurement results after densification are given in Table 2. Theoretical Compression Ratio (%) Experimental Compression Ratio (%) and Spring-back (%) depending on experimental parameters are given Table 3.

Table 1. Hardness (Tangential), hardness (Radial), roughness (Ra and Rz) and diameter values of the sections before the application of the experimental parameters (Control)

Densification depth (mm)	Heat treatment	Steam and Heat	Hardness (Tangential)	Hardness (Radial)	Roughness *Ra*	Roughness *Rz*	Diameter (mm)
0.5	Unheat T.	None S.H.	46.44	43.00	1.451	6.668	20.63
0.5	Unheat T.	S.H.	41.00	45.89	2.055	8.260	22.02
0.5	Heat.T.	None S.H.	47.67	47.33	1.353	6.330	21.88
0.5	Heat.T.	S.H.	44.78	42.44	1.781	7.077	21.83
1	Unheat T.	None S.H.	42.00	42.78	1.715	7.744	20.69
1	Unheat T.	S.H.	47.11	53.22	1.657	7.065	22.04
1	Heat.T.	None S.H.	44.78	45.56	2.212	9.037	21.90
1	Heat.T.	S.H.	44.89	42.33	1.597	6.129	21.88
1.5	Unheat T.	None S.H.	44.11	44.33	1.447	6.596	20.70
1.5	Unheat T.	S.H.	41.00	51.11	1.722	7.449	22.07
1.5	Heat.T.	None S.H.	42.22	43.56	1.352	5.560	21.97
1.5	Heat.T.	S.H.	41.78	42.44	1.874	7.331	21.88
2	Unheat T.	None S.H.	47.22	43.78	1.538	6.476	20.65
2	Unheat T.	S.H.	42.67	45.22	1.300	6.196	22.00
2	Heat.T.	None S.H.	48.11	42.00	1.694	8.256	21.98
2	Heat.T.	S.H.	45.33	44.33	1.257	5.483	21.82

Table 2. After applying the test parameters, hardness (Tangential), hardness (Radial), Roughness (Ra and Rz) and diameter values in the sections

Densification depth (mm)	Heat treatment	Steam and Heat	Hardness (Tangential)	Hardness (Radial)	Roughness *Ra*	Roughness *Rz*	Diameter (mm)
0.5	Unheat T.	None S.H.	51.56	46.00	0.999	5.053	20.42
0.5	Unheat T.	S.H.	46.00	50.22	1.492	6.170	21.85
0.5	Heat.T.	None S.H.	50.89	53.78	0.886	3.985	21.53
0.5	Heat.T.	S.H.	47.44	44.00	1.291	5.380	21.50
1	Unheat T.	None S.H.	48.78	50.22	0.947	4.718	20.12
1	Unheat T.	S.H.	51.56	57.78	1.367	5.210	21.63
1	Heat.T.	None S.H.	48.78	52.11	1.446	6.615	21.00
1	Heat.T.	S.H.	49.22	45.22	1.147	4.974	21.18
1.5	Unheat T.	None S.H.	52.67	53.44	1.442	6.776	19.88
1.5	Unheat T.	S.H.	48.89	58.67	1.358	5.717	21.45
1.5	Heat.T.	None S.H.	47.89	51.56	1.118	5.178	20.85
1.5	Heat.T.	S.H.	47.44	45.89	1.200	4.484	20.97
2	Unheat T.	None S.H.	63.00	55.78	1.028	4.852	19.47
2	Unheat T.	S.H.	51.89	53.22	1.400	4.982	21.02
2	Heat.T.	None S.H.	62.78	53.78	1.250	4.877	20.37
2	Heat.T.	S.H.	50.67	54.00	1.513	6.496	20.47

Table 3. Theoretical Compression Ratio (%) Experimental Compression Ratio (%) and Spring-back (%) depending on experimental parameters

Densification depth (mm)	Heat treatment	Steam and Heat	Theoretical Compression Ratio (%)	Experimental Compression Ratio (%)	Spring-back (%)
0.5	Unheat T.	None S.H.	2.48	1.05	1.41
0.5	Unheat T.	S.H.	2.32	0.79	1.52
0.5	Heat.T.	None S.H.	2.34	1.57	0.73
0.5	Heat.T.	S.H.	2.34	1.53	0.78
1	Unheat T.	None S.H.	5.08	2.77	2.17
1	Unheat T.	S.H.	4.75	1.85	2.82
1	Heat.T.	None S.H.	4.78	4.11	0.48
1	Heat.T.	S.H.	4.79	3.20	1.44
1.5	Unheat T.	None S.H.	7.81	3.95	3.56
1.5	Unheat T.	S.H.	7.29	2.82	4.26
1.5	Heat.T.	None S.H.	7.33	5.08	1.87
1.5	Heat.T.	S.H.	7.36	4.19	2.86
2	Unheat T.	None S.H.	10.72	5.73	4.38
2	Unheat T.	S.H.	10.00	4.47	5.08
2	Heat.T.	None S.H.	10.01	7.33	1.95
2	Heat.T.	S.H.	10.09	6.19	3.28

Table 4. ANOVA results of the data obtained after surface densification

Parameters	*DF*	*Adj SS*	*Adj MS*	*F*-Value	*P*-Value
Source (Hardness (Tangential))					
Densification depth (mm)	3	184.404	61.468	5.85	0.014
Heat treatment	1	5.316	5.316	0.51	0.493
Steam and heat	1	68.982	68.982	6.57	0.028
Error	10	105.039	10.504		
Total	15	363.740			
Source (Hardness (Radial))					
Densification depth (mm)	3	68.138	22.713	1.24	0.345
Heat treatment	1	39.062	39.062	2.14	0.174
Steam and heat	1	3.674	3.674	0.20	0.663
Error	10	182.434	18.243		
Total	15	293.308			
Source (Roughness *(Ra))*					
Densification depth (mm)	3	0.041431	0.013810	0.34	0.796
Heat treatment	1	0.002093	0.002093	0.05	0.825
Steam and heat	1	0.170500	0.170500	4.21	0.067
Error	10	0.404643	0.040464		
Total	15	0.618667			
Source (Roughness *(Rz)*)					
Densification depth (mm)	3	0.3193	0.1064	0.12	0.948
Heat treatment	1	0.1388	0.1388	0.15	0.704
Steam and heat	1	0.1154	0.1154	0.13	0.729
Error	10	9.0807	0.9081		
Total	15	9.6543			
Source (Spring-back (%))					
Densification depth (mm)	3	17.116	5.7053	34.30	0.000
Heat treatment	1	8.717	8.7173	52.41	0.000
Steam and heat	1	1.884	1.8838	11.32	0.007
Error	10	1.663	0.1663		
Total	15	29.380			

ANOVA was performed on the data obtained from these groups after the experiment. The results of the ANOVA are presented in Table 4.

According to the results of the analysis of variance in Tablo 4, the hardness in the tangential direction was found to be significant ($P<0.05$) at 95% confidence level in terms of densification depth and steam and temperature applied during surface densification. The effect of the heat treatment applied before densification was not statistically significant.

In terms of hardness and roughness (Ra and Rz) in radial direction, there is no statistical effect of densification depth, heat treatment applied before densification and steam and temperature applied during surface densification at 95% confidence level.

All factors (depth of densification, pre-densification heat treatment, steam, and temperature applied during surface densification) have a statistical effect at 95% confidence level in terms of spring-back.

Figure 7 presents the main effect graph for hardness in the tangential direction after surface densification. In general, higher hardness values were obtained in the tangential direction at a densification depth of 2.0 mm, in the specimens without heat treatment and in the processes where steam and temperature were not applied during densification.

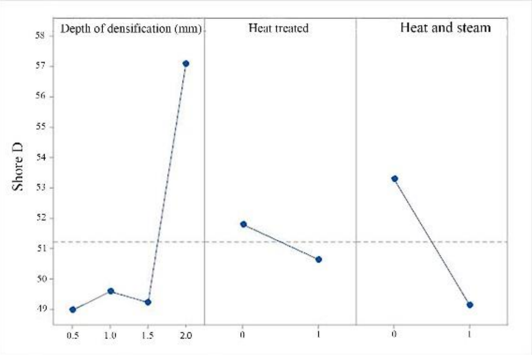

Figure 7. Main effect plot for hardness after surface densification in tangential direction

Figure 8 shows the main effect graph for hardness in radial direction after surface densification. In general, at a densification depth of 2.0 mm, higher hardness values were obtained in the radial direction as well as in the tangential direction in the specimens without heat treatment and in the processes where steam and heat were not applied during densification. As the densification depth increases, there was a linear increase in the hardness value in the radial direction.

When some literature on hardness changes in densified wood materials is examined; hardness is correlated with the densification rate, hardness increases after densification and as the densification rate increases (Rautkari et al., 2009; Budakci et al., 2016, Sofuoglu, 2022). The density of the heat-treated densified samples increased, but the complete dry density of the densified wood decreased as the temperature and time increased due to the mass loss (Düzkale Sözbir and Bektaş, 2019). Depending on the temperature and treatment time, the hardness of birch wood with densified surface was found to be 1.4 to 2.2 times higher than the hardness of non-densified wood (Laskowska, 2017). Similarly, in the production of composite plywood of poplar wood species, its density and mechanical properties increase with increasing press pressure and temperature (Demirkır et al., 2017). In terms of hardness, the results of the study are similar to the literature.

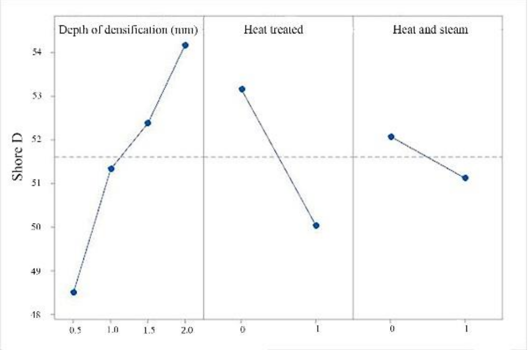

Figure 8. Main effect plot for hardness after surface densification in radial direction

Figure 9 shows the main effect plot for Ra after surface densification. In general, the highest Ra values were obtained at a densification depth of 2.0 mm, in the heat treated specimens and in the processes where steam and temperature were applied during densification. As the densification depth increased, the Ra value increased linearly.

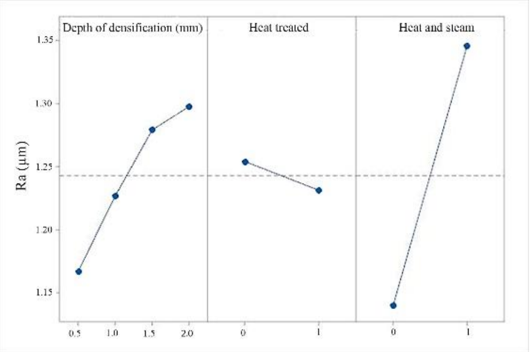

Figure 9. Main effect plot for Ra value after surface densification

Figure 10 shows the main effect graph for Rz after surface densification. In general, the highest Rz values were obtained at a densification depth of 1.5 mm, in specimens without heat treatment and in the processes where steam and temperature were applied during densification. As the densification depth increased, an increase in Rz value occurred, but at the highest densification depth of 2 mm, a decrease in Rz value occurred again.

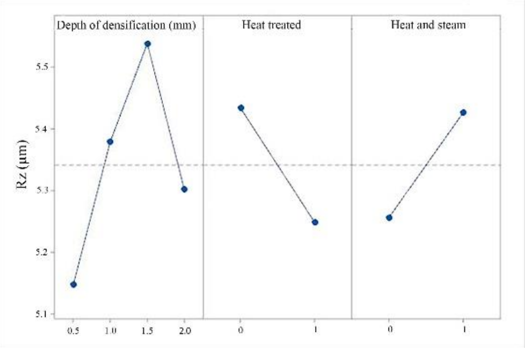

Figure 10. Main effect plot for Rz value after surface densification

In the literature, in the cylindrical densification of larch wood species, an increase in hardness values and a decrease in Rz value occurred with densification in all densification conditions (Kaya and Sofuoglu, 2023a).

Figure 11 shows the main effect graph for springback after surface densification. In general, the highest springback values were obtained at a densification depth of 2.0 mm, in specimens without heat treatment and when steam and temperature were applied during densification. As the densification depth increases, there is a linear increase in the springback values.

In previous similar studies, different results were obtained. The lowest spring-back percentage was obtained for the larch species and the highest spring-back percentage was obtained for the black poplar species (Kaya and Sofuoglu, 2023b). In the literature, attempts have been made to reduce the spring-back effect by steaming or heating (Kutnar and Sernek, 2007). In the densification of wood material by compression, densification is carried out by collapsing the cell wall of the material and reducing the void volume (Pelit, 2014; Kutnar et al., 2009). The increases in the strength values of the wood material after TM densification are due to the decrease in the void volume and the increase in the unit volume of cell wall material with load-bearing properties (Ulker et al., 2012). In the densification process, a significant decrease in the surface roughness of the wood material is observed as a result of the collapse of the cell walls and the cracks and cracks on the wood surface due to the effect of high temperature and pressure (Ozdemir S., 2020) Since the hardness value of denser wood materials increases depending on the density, the hardness properties of even wood materials with high density can be further improved by applying densification processes.

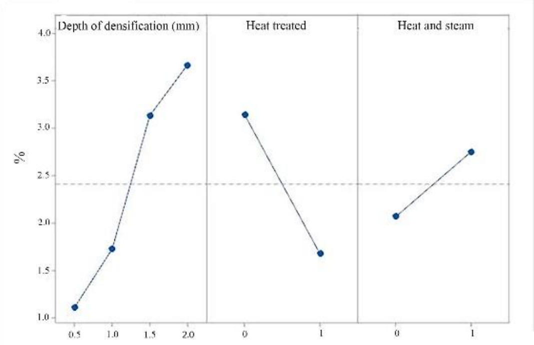

Figure 11. Main effect plot for spring-back value after surface densification

Conclusions

The general conclusions obtained from the findings can be summarized as follows:

- As the densification depth increased from 0.5 mm to 2.0 mm, the hardness values increased. Higher densification depths can be tried to harden the surface of poplar material of this diameter. A slight decrease in surface hardness values was recorded with steam and temperature application. The decrease in the radial direction was more limited.
- It was observed that the surface roughness values increased with densification. It was determined that steam and heat application increased the roughness values. It is thought that especially steam application may cause this situation. This effect was observed to be more limited in heat-treated samples. In this case, it can be concluded that heat treatment can be used to reduce the roughness values resulting from steaming densification.
- It has been determined that springback rates increase as depth increases. This situation should be taken into account for deeper densification. It has been determined that heat treatment has a decreasing effect on spring-back values.
- In general, it has been found that the application of steam and heat in the cylindrical densification process of poplar material has the effect of increasing the roughness and springback values and reducing the surface hardness. It was evaluated that the heat treatment positively affected roughness and springback values. Similar studies can be carried out on other wood materials to determine the effects of steam and temperature application.

Ethics Committee Approval

N/A

Peer-review

Externally peer-reviewed.

Author Contributions

Conceptualization: H.Y., Z.K., S.D.S.; Investigation: S.D.S., H.Y., Z.K.; Material and Methodology: H.Y.; Supervision: S.D.S.; Visualization: Z.K.; Writing-Original Draft: S.D.S., H.Y., Z.K.; Writing-review&Editing: S.D.S.; All authors have read and agreed to the published version of manuscript.

Conflict of Interest

The author has no conflicts of interest to declare.

Funding

The author declared that this study has received no financial support.

References

Bekhta, P. & Krystofiak, T. (2016). The influence of short-term thermo-mechanical densification on the surface wettability of wood veneers, *Maderas Cienc. y Tecnol.,* 18 (1), 79-90. DOI: 10.4067/S0718-221X2016005000008

Bekhta, P., Proszyk, S., Krystofiak, T., Sedliacik, J., Novak, I. & Mamonova, M. (2017). Effects of short-term thermomechanical densification on the structure and properties of wood veneers, *Wood Material Science and Engineering*, 12 (1), 40-54. DOI:10.1080/17480272.2015.1009488

Blomberg, J. & Persson, B. (2004). Plastic deformation in small clear pieces of Scots pine (Pinus sylvestris) during densification with the CaLignum process, *Journal of Wood Science*, 50, 307–314. DOI: 10.1007/s10086-003-0566-2

Budakçi, M., Pelit, H., Sönmez, A. & Korkmaz, M. (2016). The effects of densification and heat post-treatment on hardness and morphological properties of wood materials, *BioResources.*, 11(3), 7822-7838. DOI:10.15376/biores.11.3.7822-7838

Boonstra, M.J. (2008). A two-stage thermal modification of wood. Ph.D. dissertation, in cosupervision Ghent University and Université Henry Poincaré – Nancy, 1, 297, ISBN 978-90-5989-210-1.

Demirci, S. (2013). Effect of the Number of Knives, Feed Rate and Cutting Depth on Surface Roughness of Some Wood Species Processed with Planer, *Kastamonu University Journal of Forestry Faculty*, 13(1), 100-108.

Demirkır, C., Öztürk, H. & Çolakoğlu, G., (2017). Effects of press parameters on some technological properties of polystren composite plywood. *Kastamonu University Journal of Forestry Faculty*, 17(3), 517-522.

Düzkale Sözbir, G. & Bektaş, İ. (2019). Investigation of biological durability of heat treated and densified poplar wood against brown rot fungi. *Turkish Journal of Forestry*, 20(4): 421-426. DOI: 10.18182/tjf.636671

Gao, Z., Huang, R., Chang, J., Li, R. & Wu, Y. (2019). Effects of pressurized superheated-steam heat treatment on set recovery and mechanical properties of surface-compressed wood, *BioResources*, 14(1), 1718-1730. DOI:10.15376/biores.14.1.1718-1730

Gürleyen, L., (1998). Mobilyada kullanılan masif ağaç malzemelerde yüzey düzlüğünün karşılaştırılması, Gazi Üniversitesi Fen Bilimleri Enstitüsü, Yüksek lisans tezi, Ankara.

ISO 13061-1 (2014). Physical and mechanical properties of wood Test methods for small clear wood specimens Part 1: Determination of moisture content for physical and mechanical tests, International Organization for Standardization, Geneva, Switzerland

ISO 13061-2 (2014). Wood-determination of Density for Physical and Mechanical Tests, International Organization for Standardization, Geneva, Switzerland.

ISO 468 (1982). Surface roughness parameters, their values, and general rules for specifying requirements, International Organization for Standardization, Geneva, Switzerland.

ISO 3274 (1996). Geometrical Product Specifications (GPS) — Surface texture: Profile method — Nominal characteristics of contact (stylus) instruments, International Organization for Standardization, Geneva, Switzerland

İçel, B., & Şimşek, Y., (2017). Evaluations on microscopic images of heat treated spruce and ash wood, *Süleyman Demirel University Journal of Natural and Applied Sciences*, 21 (2), 414-420. DOI: 10.19113/sdufbed.17217

TS EN ISO 21920-2 (2022). Geometrical product specifications (GPS) - Surface texture: Profile - Part 2: Terms, definitions and surface texture parameters International Organization for Standardization, Geneva, Switzerland.

Jones, D. & Enjily, V. (2006). The potential for modified materials in the panel products industry – Properties and availability. In Proceedings of the COST Action E44-E49 Conference in Valensia on Wood Resources and Panel Properties, 23-30, Spain.

Kariz, M., Kuzman, M.K., Sernek, M., Hughes, M., Rautkari, L., Kamke, F.A. & Kutnar, A. (2017). Influence of temperature of thermal treatment on surface densification of spruce, *European Journal of Wood and Wood Products*, 75, 113-123. DOI:10.1007/s00107-016-1052-z

Kaya, Z. & Sofuoğlu, S. D. (2023a) Silindirik yoğunlaştırmada sıvama makarası kullanımı; masif ağaçta (Karaçam) yoğunlaştırılma sonrası sertlik, parlaklık ve yüzey pürüzlülüğü değişimi, *Mobilya ve Ahşap Malzeme Araştırmaları Dergisi*, 6(1), 14-25. DOI:10.33725/mamad.1260723

Kaya, Z. & Sofuoğlu, S. D. (2023b). Use of spinning roller in cylindrical densification; spring back in black poplar, larch and cedar of Lebanon after densification, *Bilge International Journal of Science and Technology Research*, 7(2), 117-127. DOI:10.30516/bilgesci.1278745

Kaya, Z. & Sofuoğlu, S. D., (2024). Use of spinning rollers for surface densification of wood, *Drvna industrija*, 75(2), 215-226. DOI: 10.5552/drvind.2024.0139

Korkut, S. & Kocaefe, S., (2009). Isıl İşlemin Odun Özellikleri Üzerine Etkisi, Düzce Üniversitesi, *Düzce Üniversitesi Orman Fakültesi Orman. Dergisi*, 5(2), 11-34.

Kutnar, A. & Šernek, M., (2007). Densification of wood. Zbornik gozdarstva in lesarstva, (82), 53-62.

Kutnar, A., Kamke, F.A. & M. Sernek, (2009). Density profile and morphology of viscoelastic thermal compressed wood. *Wood Science and Technology*, 43(1-2), 57.

Laskowska, L. (2017). The influence of process parameters on the density profile and hardness of surface-densified birch wood (Betula pendula Roth), *BioResources*, 12(3), 6011-6023. DOI:10.15376/biores.12.3.6011-6023

Laskowska, A., (2020). The influence of ultraviolet radiation on the colour of thermo-mechanically modified beech and oak wood, *Maderas Cienc. y Tecnol*. 22(1), 55-68. DOI:10.4067/S0718-21X2020005000106

Navi, P. & Sandberg, D., (2012). Thermo-hydro-mechanical wood processing. Crc Press.

Neyses, B., Karlsson, O. & Sandberg, D., (2020). The effect of ionic liquid and superbase pre-treatment on the spring-back, set-recovery and Brinell hardness of surface-densified Scots pine, Holzforschung, 74(3), 303-312. DOI:10.1515/hf-2019-0158

Ozdemir, S. (2020). Bükülmüş tabakalı kaplama kereste üretiminde Termo-mekanik yoğunlaştırma uygulanması ve mekanik özellikler üzerine etkisi, PhD thesis, Bartın University, Turkiye.

Pelit, H., (2014). Yoğunlaştırma ve ısıl işlemin doğu kayını ve sarıçamın bazı teknolojik özellikleriyle üstyüzey işlemlerine etkisi, PhD thesis, Gazi University, Ankara, Türkiye.

Pelit, H., Budakçı, M., Sönmez, A. & Burdurlu, E., (2015). Surface roughness and brightness of scots pine (Pinus sylvestris) applied with water-based varnish after densification and heat treatment, *Journal of Wood Science*, 61, 586-594. DOI:10.1007/s10086-015-1506-7

Pertuzzatti, A., Missio, A.L., de Cademartori, P.H.G., Santini, E.J., Haselein, C.R., Berger, C., Gatto, D.A., Tondi, G., (2018). Effect of process parameters in the thermomechanical densification of pinus elliottii and eucalyptus grandis fast-growing wood, *BioResources*. 13(1), 1576-1590. DOI:10.15376/biores.13.1.1576-1590

Rautkari, L., Properzi, M., Pichelin, F. & Hughes, M. (2010). Properties and set-recovery of surface densified Norway spruce and European beech, *Wood Science and Technology*, 44, 679–691. DOI:10.1007/s00226-009-0291-0

Rautkari, L., Properzi, M., Pichelin, F. & Hughes, M., (2009). Surface modification of wood using friction, *Wood Sci. Technol*., 43(3–4), 291-299. DOI: 10.1007/s00226-008-0227-0

Rowell, R., Ibach, E.E., McSweeny, J. & Nilsson, T., (2009). Understanding decay resistance, dimensional stability and strength changes in heat treated and acetylated wood. Proceedings of 4th European conference on wood modification, 27-29 April 2009, 489-502, Stockholm.

Salca, E., Brasov, U.T. & Bekhta, P., (2021). Effects of thermo-mechanical densification applied to veneers of fast-growing species to produce value-added plywood panels, *Cutting-edge Research in Agricultural Sciences*, 9, 161–177. DOI:10.9734/bpi/cras/v9/8628D

Sandberg, D., Kutnar, A., Karlsson, O. & Jones, D., (2021). Wood modification technologies : principles, sustainability, and the need for innovation, CRC Press, Taylor and Francis.

Scharf, A. & Lemoine, A., Neyses, B. & Sandberg, D., (2023). The effect of the growth ring orientation on spring-back and set-recovery in surface-densified, *Holzforschung*, 77(6), 394-406. DOI:10.1515/hf-2023-0004

Sofuoglu, S.D., (2022). Effect of thermo-mechanical densification on brightness and hardness in wood, *Turkish Journal of Engineering Research and Education,* 1(1), 15-19.

Sofuoglu, S.D., Tosun, M. & Atilgan, A., (2023). Determination of the machining characteristics of Uludağ fir (*Abies nordmanniana* Mattf.) densified by compressing, *Wood Material Science & Engineering*, 18(3), 841-851. DOI:10.1080/17480272.2022.2080586

Sofuoglu, S.D. & Yeşil, H., (2016). Ahşap sertlik değerlerinin farklı metotlar kullanılarak karşılaştırılması, in Proc. IMCOFE International Multidisciplinary Congress of Eurasia, Jul. 2016, 480-485.

Söğütlü, C., (2005). Bazı faktörlerin zımparalanmış ağaç malzeme yüzey pürüzlülüğüne etkisi, *Politeknik*, 8(4), 345-350.

Şenol, S., (2018). Determination of physical, mechanical and technological properties of some Thermo-Vibro-Mechanical (TVM) treated wood materials, PhD Thesis, Düzce University, Düzce, Turkey.

Şenol, S. & Budakci, M., (2016). Nechanical wood modificiation methods*, Mugla Journal of Science and Technology*, 2(2), 53-59. DOI:10.22531/muglajsci.283619

Şenol, S. & Budakci, M., (2019). Effect of Thermo-Vibro-Mechanic® densification process on the gloss and hardness values of some wood materials, *BioResources*, 14(4), 9611-9627. DOI:10.15376/biores.14.4.9611-9627

Tosun, M. & Sofuoğlu, S. D., (2021). Ağaç malzemenin sıkıştırılarak yoğunlaştırılması konusunda yapılan çalışmalar, *Mobilya ve Ahşap Malzeme Araştırmaları Dergisi*, 4(1), 91-102. DOI:10.33725/mamad.911947

Ülker, O., Imirzi, O. & Burdurlu, E., (2012). The effect of densification temperature on some physical and mechanical properties of Scots pine (*Pinus sylvestris* L.), *BioResources,* 7(4), 5581-5592.

Yeşil, H., Kaya, Z. & Sofuoğlu, S.D., (2023). Effect of heat and steam on color and brightness in cylindrical densification of black poplar (Populus nigra L.) wood, *MAMAD*, 6(2), 219-232, DOI: 10.33725/mamad.1403532

Wikberg, H., (2004). Advanced solid state NMR spectroscopic techniques in the study of thermally modified wood. Academic Dissertation, University of Helsinki, Department of Chemistry, Laboratory of Polymer Chemistry, Helsinki- Finland

Wehsener, J., Bremer, M., Haller, P. & Fischer, S., (2023). Bending tests of delignified and densified poplar, *Wood Material Science & Engineering*, 18(1), 42-50. DOI:10.1080/17480272.2022.2134049