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DETERMINATION OF PROCESSING CHARACTERISTICS OF WOOD MATERIALS DENSIFIED BY COMPRESSING

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ABSTRACT

The main objective of this study is to determine optimum cutting parameters in order to specify the effect of densification by compressing on the processing properties of solid wood material and to achieve the best surface quality in materials densified at different rates. In line with this goal, the widely grown and low-density black poplar (*Populus nigra*) tree species were selected as the experimental material. Samples, which were compressed and densified by Thermo-Mechanical method at 0 %, 20 % and 40 % ratios, were processed at 1000 mm/min, 1500 mm/min and 2000 mm/min feed speeds and in 12000 rpm, 15000 rpm, 18000 rpm rotation speed on a computer numerical control machine by using two different cutters. Surface roughness values (*Ra* and *Rz*) were measured in order to evaluate surfaces obtained. Smoother surfaces were obtained in computer numerical control machining of densified samples. The lowest surface roughness values occurred in 40 % densified samples, which were the densest. The lowest surface roughness was obtained when 40 % densified samples were processed with cutter no.1 (two-flutes straight end mill), at 1000 mm/min feed speed and at 18000 rpm. *Ra* and *Rz* roughness values increased with the increase of the feed rate.

Keywords: Densification, machining, *Populus nigra*, roughness, thermo-mechanics, wood material.

INTRODUCTION

From past to present, different “Wood Modification Methods” have been developed as a result of all scientific studies and research to eliminate some of the negativities of massive wood material. Modification of wood is applied to change or improve negative properties of wood material (Senol 2018, Senol and Budakcı 2016).

Wood material is often considered too soft or too weak for use in structures requiring high strength, hardness and durability. However, wood material with increased density can be used as an alternative to other materials (Blomberg and Persson 2004, Homan *et al*. 2000, Kutnar and Šernek 2007, Pelit *et al*. 2014). Density of wood material significantly affects its mechanical (Blomberg and Persson 2004, Kamke 2006, Kutnar and Šernek 2007, Pelit *et al*. 2014, Rautkari 2012) and machining properties (Blomberg and Persson 2004, Kamke 2006, Kutnar and Šernek 2007, Pelit *et al*. 2014, Rautkari 2012).

A lot of research has been done to improve densification process since increasing density of wood material increases its mechanical properties and hardness (Blomberg and Persson 2004). Density of low-density wood materials can be increased by densification process and their commercial value can be increased. Tree species with high density can be increased in density even more, and their properties can be improved by making them more resistant (Blomberg *et al*. 2005, Kutnar and Sernek 2007, Pelit *et al*. 2014).

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Many types of densified wood materials have been produced around the world until today. Also, in recent years, there have been restrictions in the use of protective impregnate materials that is harmful to humans and the environment with the increase of environmental priority perspective, this has led the development of new environmentally compatible methods that protect wood material against biological degradation and increase its dimensional stability (Korkut and Kocaefe 2009, Senol and Budakci 2016). Deformations occur in cell wall of compressed wood material under normal atmospheric conditions.

In densified wood materials; There are studies in the literature on density analysis and various mechanical properties (Ábrahám *et al*. 2010, Ábrahám and Németh 2012, Arruda and Del Menezzi 2013, Fang *et al*. 2012, Gong *et al*. 2010, Hajihassani *et al*. 2018, Kamke 2006, Kariz *et al*. 2017, Laine *et al.* 2013, Laskowska 2017, Pelit 2014, Pelit and Sonmez 2015, Rautkari *et al*. 2009, Senol *et al*. 2017, Skyba *et al*. 2009, Ulker *et al*. 2012, Cruz *et al*. 2018, Gao *et al*. 2019, Laskowska 2020, Pertuzzatti *et al*. 2018), determination of changes in surface hardness (Laine *et al.* 2013, Laskowska 2017, Pelit *et al*. 2015b, Rautkari *et al.* 2009, Rautkari *et al.* 2013, Senol and Budakci 2019, Skyba *et al.* 2009, Ulker *et al.* 2012), microscopic analysis (Blomberg and Persson 2004, Budakci *et al*. 2016, Rautkari *et al*. 2010), wettability (Arruda and Del Menezzi 2013, Bekhta and Krystofiak 2016), determination of spring-back amounts (Kariz *et al*. 2017, Laine *et al*. 2013, Pelit and Sonmez 2015), determination of surface properties by applying upper surface processes to surfaces obtained (Pelit 2014, Pelit *et al*. 2015a), resistance to fungi and termites (Esteves *et al*. 2017, Wehsener *et al*. 2018), color or gloss changes (Ábrahám *et al*. 2010, Cruz *et al*. 2018, Laskowska 2020, Pelit *et al*. 2015a, Tenorio *et al*. 2021). In addition, analysis on densification was made using finite element method (Fleischhauer *et al*. 2019). Many of these studies are related to densified *Populus* tree species (Ábrahám *et al*. 2010, Ábrahám and Németh 2012, Ahmed *et al*. 2013, Budakci *et al*. 2016, Diouf *et al*. 2011, Fang *et al*. 2012, Gaff and Gašparík 2013, Gao *et al*. 2019, Gong *et al*. 2010, Hajihassani *et al*. 2018, Bami and Mohebby 2011, Lamason and Gong 2007, Lykidis *et al*. 2020, Mania *et al*. 2020, Ozdemir 2020, Pelit *et al*. 2018, Senol 2018, Senol *et al*. 2017, Wehsener *et al*. 2018). In general, physical and mechanical properties improve, surface roughness and wettability decrease, hardness increases, and spring-back may occur as a negative situation in wood species that are compressed and densified depending on density increase. However, there have been no studies on the change in the processing properties of massive wood materials whose structure and density are changed by increasing density with compressing and the optimum processing properties of obtained materials.

Before densified materials are turned into final product, they must be processed with machines used in machining of classical wood and wood-based materials, as well as with modern computer numerical control (CNC). In this context, with this work parameters will be determined to obtain lowest surface quality, productivity will increase and next processes such as sanding etc. will be reduced or unnecessary.

Black poplar (*Populus nigra*) that are produced and used frequently in the world by using CNC, with various machining parameters that will affect surface quality in different values. Therefore, the scopes of this study were organized as the following:

To determine the effect of densification on machining properties and to investigate optimum processing parameters to obtain the smoothest surface for black poplar, for the machined surface, stylus tracing surface roughness profilometer was used to measure surface roughness (*Ra* and *Rz*) values, and statistical software was used to analyze the results.

MATERIALS AND METHODS

Black poplar (*Populus nigra* L.), which is one of the broad-leaved tree species with a wide usage area, low density and widely grown, was chosen as the experimental material in the study. Samples were all randomly selected from Afyonkarahisar, Turkey. The test specimens were cut from the parts of air-dried (approximately 15 % MC) sapwood. They were conditioned at temperatures of 20 °C ± 2 °C and 65 °C ± 5 °C, with a relative humidity to moisture content (MC) of about 12 %. The density of poplar tree species at 12 % humidity was determined as 850 kg/m^3 according to ISO 3130 (1975) and ISO 13061 (2014) standards. Experimental process of the study is given in Figure 1.

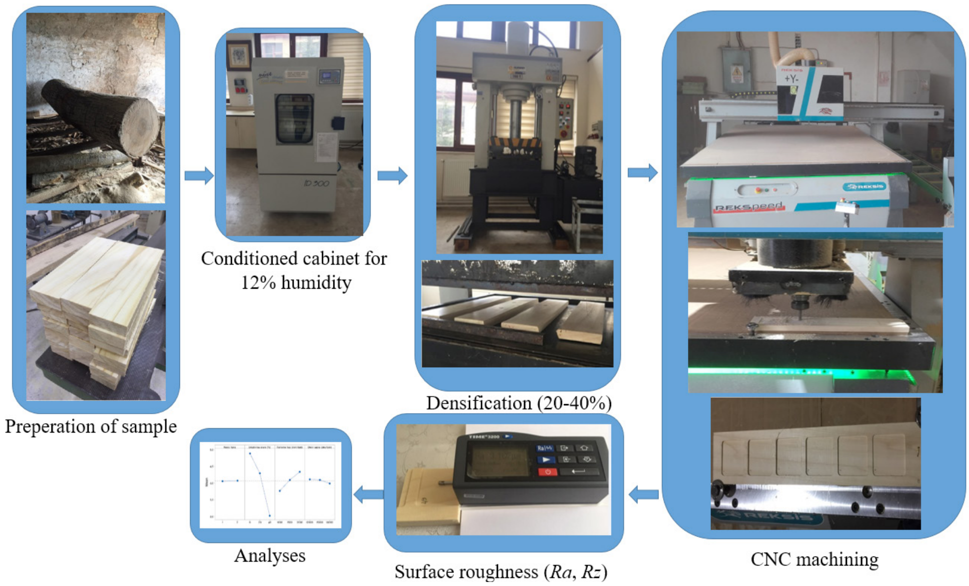


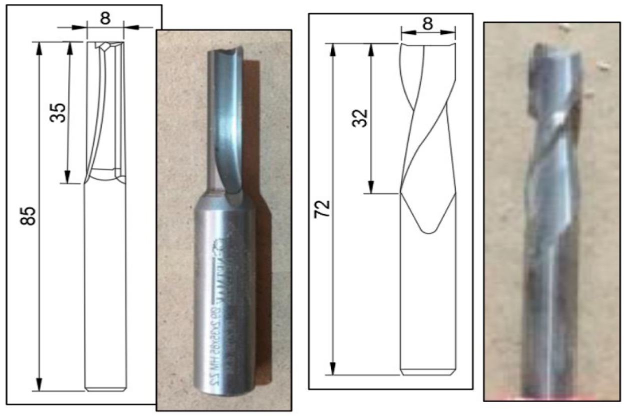
Figure 1: Schematic representation of experimental design.

Samples in the dimensions given in Table 1 were densified by compressing with thermo-mechanical (TM) method in open system (Total time = Heating time + 15 min). With a specially designed hydraulic press (Gazi University, Ankara/Turkey) with table dimensions of 60 cm x 60 cm, which can control temperature and pressure (100 t-250 atm), compression process in radial direction was carried out with automatic control at 60 mm/min loading speed. Densified test samples were kept under the press for 15 minutes and at the end of this period, samples were taken from the press, and they were allowed to cool down to room temperature under 5 kg/cm^2 pressure in order to minimize spring-back effect.

Table 1: Pre-compression dimensions of test samples.

Compression ratio	Lenght (longitudinal direction) (mm)	Width (tangential direction) (mm)	Thickness (radial direction) (mm)
Control	430	85	20
20 %	430	85	25
40 %	430	85	33,3

After that; experiments were carried out on a Reksis Rekspeed 2137 3 axis CNC milling machine (Cözüm ahsap¸ Afyonkarahisar, Turkey) with 9 kW spindle power, a maximum spindle speed of 24000 rpm and a maximum feed rate of 60 m/min. Experiments were carried out with two router cutters (Netmak, Double-edged straight end mill and Two-flutes helisel end mill that was 8 mm in diameter) (Figure 2). New and sharp cutters were used in each cutting test. Four parameters were used in the experiment and one of them had 2 levels, while others had three levels (Table 2).



(a) (b)

Figure 2: High speed stell end mills (mm) (a) Two-flutes straight end mill (Netmak), (b) Two-flutes helisel end mill (Knob).

Table 2: Assignment of levels to factors (parameters used in the face milling of black poplar).

Symbol	Parameter	Coded levels		
		Level 1	Level 2	Level 3
A	Cutter type	1	2	-
B	Compression ratio (%)	0	20	40
C	Feed rate (mm/min)	1000	1500	2000
D	Spindle speed (rpm)	12000	15000	18000

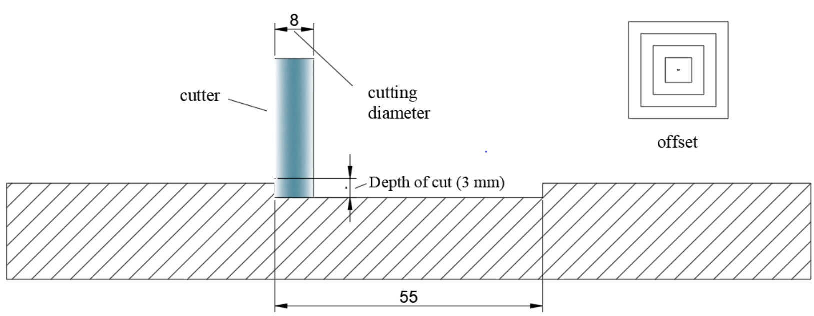


Figure 3: CNC process parameters.

A total of 54 pieces with dimensions of 55 x 55 mm^2 were grooved on wood materials by a CNC router (Figure 3). Surface roughness measurements were performed on a radial surface parallel to grain at 3 separate points on each specimen. Measuring parameters (*Ra* and *Rz*) are described in ISO 468 (1982). Measurement of surface roughness was conducted according to the protocols in ISO 468 (1982), ISO 3274 (2017), and ISO 4287 (2015). Surface Roughness Tester Time TR200 (Time Group Inc., China) type surface roughness measurement equipment was used for the determination of surface roughness values via a contact stylus trace method. Sampling length was taken as 0,8 mm (*Ra*: 0,32 µm - 2,50 µm). Surface roughness values were measured with an accuracy of ±0,01 µm. Stylus probe speed was chosen as 10 mm/min, diameter of measurement needle was 4 µm, and needle tip was 90°. Care was taken to have a measurement environment around 18 ºC - 22 °C, and without vibrations. Tool was calibrated prior to measurement, and calibration was checked at established intervals.

Analysis of variance (ANOVA) at a 95 % confidence level was applied using Minitab 19 software on the data obtained from the study. Data were evaluated by obtaining normality, main effect, and interaction graphs.

RESULTS AND DISCUSSION

Experiments were carried out by machining of surfaces with CNC in order to determine the effect of cutter type, compression ratio, feed rate and speed on roughness parameters (*Ra* and *Rz*) in the study. Roughness parameter values measured on machined surfaces are given in Table 3.

Table 3: Surface roughness values obtained according to machining conditions.

Process No	Cutter type	Compression ratio (%)	Feed rate (mm/min)	Spindle speed (rpm)	*Ra* (µm)	*Rz* (µm)
1	1	0	1000	12000	4,61	24,37
2	1	0	1000	15000	4,41	23,48
3	1	0	1000	18000	3,94	21,82
4	1	0	1500	12000	4,26	23,06
5	1	0	1500	15000	4,61	22,76
6	1	0	1500	18000	4,91	26,40
7	1	0	2000	12000	4,93	24,86
8	1	0	2000	15000	4,74	24,27
9	1	0	2000	18000	5,25	29,06
10	1	20	1000	12000	4,05	22,44
11	1	20	1000	15000	3,94	20,39
12	1	20	1000	18000	3,35	17,40
13	1	20	1500	12000	5,33	26,12
14	1	20	1500	15000	3,91	21,10
15	1	20	1500	18000	3,80	20,28
16	1	20	2000	12000	5,45	25,12
17	1	20	2000	15000	5,20	25,67
18	1	20	2000	18000	5,03	25,26
19	1	40	1000	12000	2,72	14,95
20	1	40	1000	15000	2,60	15,06
21	1	40	1000	18000	2,32	11,73
22	1	40	1500	12000	2,86	15,86
23	1	40	1500	15000	3,50	18,51
24	1	40	1500	18000	3,04	15,75
25	1	40	2000	12000	3,59	20,77
26	1	40	2000	15000	3,92	19,17
27	1	40	2000	18000	3,31	18,56
28	2	0	1000	12000	4,57	22,17
29	2	0	1000	15000	4,75	22,77
30	2	0	1000	18000	5,29	28,59
31	2	0	1500	12000	5,10	24,65
32	2	0	1500	15000	5,42	24,95
33	2	0	1500	18000	5,27	25,85
34	2	0	2000	12000	4,64	23,89
35	2	0	2000	15000	5,21	25,14
36	2	0	2000	18000	6,02	28,71
37	2	20	1000	12000	3,45	19,42
38	2	20	1000	15000	4,36	19,77
39	2	20	1000	18000	4,22	21,91
40	2	20	1500	12000	4,80	26,28
41	2	20	1500	15000	3,68	20,60
42	2	20	1500	18000	4,41	24,26
43	2	20	2000	12000	4,43	21,48
44	2	20	2000	15000	4,14	21,64
45	2	20	2000	18000	3,68	17,20
46	2	40	1000	12000	3,44	18,90
47	2	40	1000	15000	3,30	17,16
48	2	40	1000	18000	2,50	12,69
49	2	40	1500	12000	2,87	17,12
50	2	40	1500	15000	3,16	16,67
51	2	40	1500	18000	2,76	15,30
52	2	40	2000	12000	2,88	15,00
53	2	40	2000	15000	2,86	15,96
54	2	40	2000	18000	2,78	15,62

When Table 2 is examined, the lowest roughness values (*Ra* = 2,32 µm and *Rz* = 11,73 µm) were obtained in the cutter type no. 1 at 40 % compression ratio with 1000 mm/min feed speed and 18000 rpm. For *Ra*, the highest roughness value (*Ra* = 6,02 µm) was measured at 0 % compression ratio, 2000 mm/min feed rate and 18000 rpm speed for cutter type 2, and for *Rz* (*Rz* = 29,06 µm), it was obtained at 0 % compression ratio for cutter type 1 with 2000 mm/min feed rate and 18000 rpm.

Statistical analyses were performed by using MINITAB R19 software with a confidence level of 95 % (e.g., significance level of 0,05). The obtained data were subjected to normality test. As seen in Figure 4, average *Ra* and *Rz* values obtained in average roughness measurements show normal distribution at 95 % confidence level, since the *P* value is higher than 0,05 (P = 0,150 for *Ra*; P = 0,229 for *Rz*).

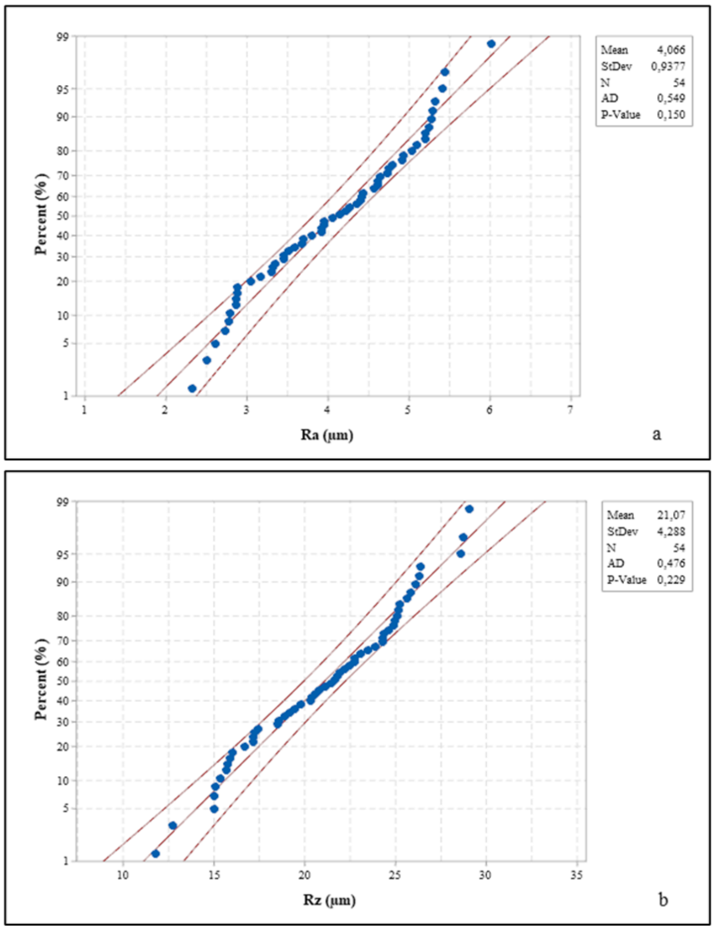


Figure 4: Normality graphs obtained from a) *Ra* (up) and b) *Rz* (down) values using the Anderson-Darling normality test (95 % confidence level).

According to variance analysis results, for *Ra* at a 95 % confidence level; it was seen that cutter type (0,05 < P = 0,911) and speed (0,05 < P = 0,738) did not make a statistically significant difference, and compression ratio (0,05 > P = 0,000) and feed speed (0,05 > P = 0,004) was found to be a statistically significant difference (Table 4).

Table 4: Results of one-way analysis of variance for *Ra*.

Source	DF	Adj SS	Adj MS	*F*- Value	*P* Value
Cutter type	1 2	0,0030	0,0030	0,01	0,911
Compression ratio (%)	2 2	32,5740	16,2870	68,44	0,000
Feed rate (mm/min)	2 2	2,9299	1,4649	6,16	0,004
Spindle speed (rpm)	2 2	0,1456	0,0728	0,31	0,738
Error	46	10,9462	0,2380	-	-
Total	53	46,5987	-	-	-

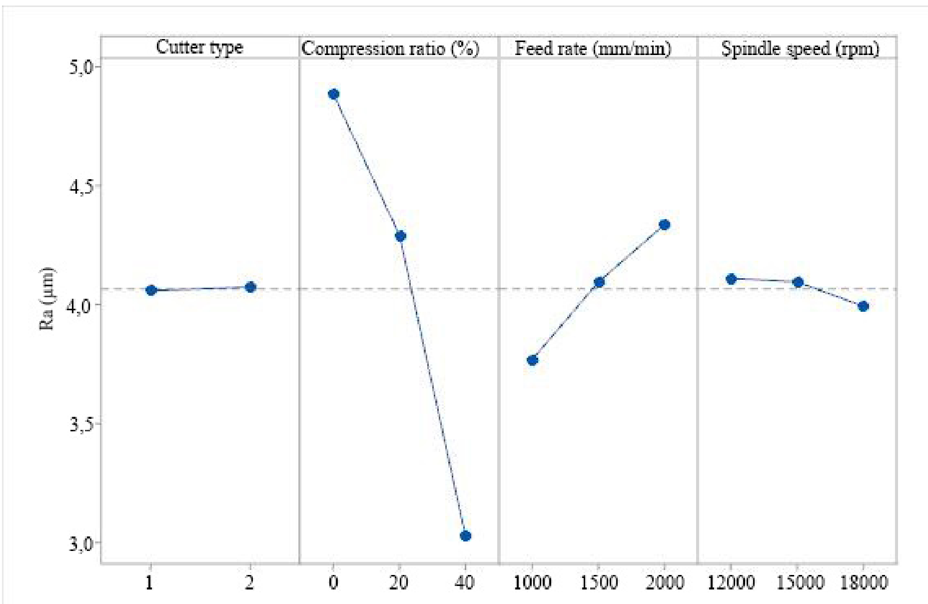


Figure 5: Main effects plot in terms of *Ra* of cutter type, compression ratio, feed rate and spindle speed.

In Figure 5, the interaction of cutter type, compression ratio, feed rate and speed in terms of R*a* is shown in the main effect plot. In terms of cutter type, it is seen that values close to each other in terms of *Ra* were obtained in machining with the cutter number 1 and 2. Although there is no significant difference between the groups, it is possible to say that generally lower R*a* values were obtained with the cutter number 1 and better results can be obtained. According to the results of the variance analysis, the factor with the highest effect in terms of *Ra* value (P = 0,00) is the compression ratio. It is seen that as the compression ratio increases, *Ra* value decreases linearly and it creates a statistically significant difference. It is also stated in the literature that smoother surfaces were obtained in massive wood and wood-based materials with high density (Hiziroglu 1996, Kilic *et al*. 2006, Lin *et al*. 2006, Malkocoglu 2007, Malkocoglu and Ozdemir 2006, Pinkowski *et al*. 2018, Zhong *et al*. 2013). Acoording to Kminiak and Gaff (2015), hardwoods induce better surface quality than softwoods (Kminiak and Gaff 2015) and Budakci *et al*. (2011), diffuse porous wood species within hardwoods are typically associated with lower surface roughness than ring porous wood species (Nasir and Cool 2020). The reason for the decrease in *Ra* value can be interpreted as the decrease in gaps in the anatomical structure of the wood material with the increase in density and accordingly, smoother surfaces can be obtained when machined. It is seen that *Ra* value increases as the feed rate increases and it creates a statistically significant difference (*P* = 0,004). In the literature, it was stated that roughness values increase as a general tendency as the feed rate increases in the processing of wood and wood-based materials (Aykac and Sofuoglu 2021, Bal 2018, Bal and Akçakaya 2018, Davim *et al*. 2009, Hazir *et al*. 2018, Ilter *et al*. 2002, Isleyen and Karamanoglu 2019, Karagoz 2010, Koc *et al*. 2017, Pinkowski *et al*. 2018, Sutcu and Karagoz 2012, Sofuoglu *et al*. 2022). It seems that the data obtained in the study are compatible with the literature. With the increase in the speed, it is seen that *Ra* value decreases although it is not considered as significant at 95 % confidence level (P = 0,738). While there was a slight decrease in the R*a* value with the increase of speed from 12000 rpm to 15000 rpm, the decrease was higher with the increase of the speed from 15000 rpm to 18000 rpm. With the increase in the speed in rotary cutting cutters, roughness values decrease and smoother surfaces can be obtained (Aykac and Sofuoglu 2021, Davim *et al*. 2009, Hazir *et al*. 2018, Isleyen and Karamanoglu 2019, Karagoz 2010, Koc *et al*. 2017, Sofuoglu 2015, Sutcu and Karagoz 2012, Sutcu and Karagoz 2013). It is seen that the data obtained in the study show similar trends with the literature. The higher the number of cutter marks per unit distance on the material surface of the cutters, the smoother surfaces can be obtained (Malkocoglu and Ozdemir 2006, Sofuoglu 2008, Sofuoglu and Kurtoglu 2014). Accordingly, the impact of spindle speed directly depends on the dynamic behavior of the cutter when cutting at different spindle speeds. Higher or lower spindle speed results in getting close to a blade's natural frequency and increasing the tool's vibration, then it will result in higher roughness or waviness (Nasir and Cool 2019, Nasir *et al*. 2020). However, if the speed exceeds a certain value, burning may occur on the material surface. In Figure 6, the interactions of cutter type, compression ratio, feed rate and speed in terms of R*a* are given graphically.

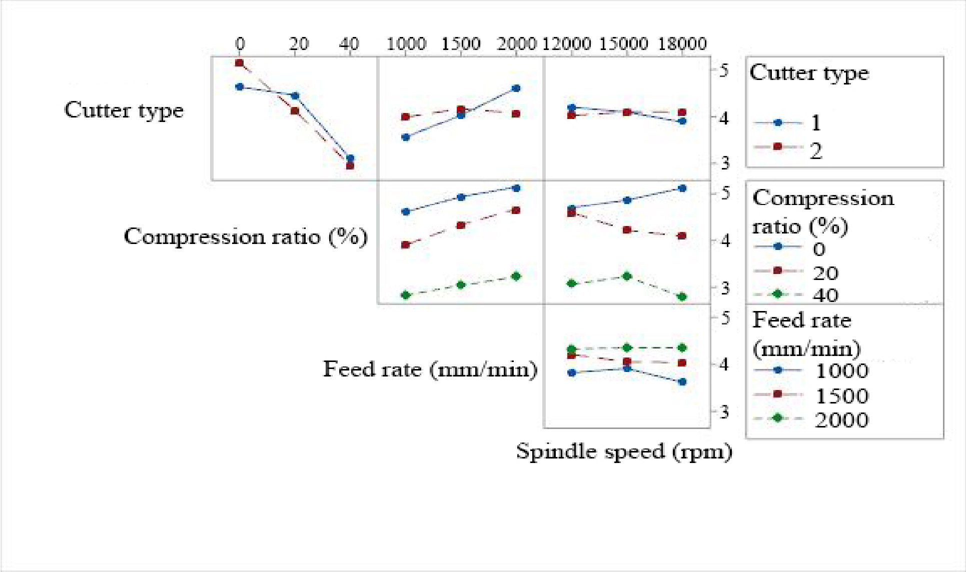


Figure 6: Interactions of cutter type, compression ratio, feed rate and l speed in terms of *Ra*.

According to the interaction graphics in terms of *Ra*; It is seen that the cutter number 2 results in lower roughness values by providing a linear relationship with the increase in density. Although lower *Ra* values were obtained on machined surfaces by cutter number 1 with the increase in density, this was not as linear and distinct as much as cutter number 2. There was an increase in the *Ra* value linearly in machined with cutter no. 1, with the increase in the feed rate. This was slightly different in cutter no. 2, with the increase in the feed rate from 1000 mm/min to 1500 mm/min, the *Ra* value slightly increased, but with the increase in the feed rate to 2000 mm/min, the *Ra* value was slightly decreased. Again, when looking at cutters in terms of the speed, different reactions occurred in terms of cutters even if difference was very small. While there was a tendency to decrease in *Ra* values with the increase in the speed in machined surfaces with cutter number 1, there was a tendency to increase for cutter number 2. Approximately close *Ra* values were obtained for both cutters at 15000 rpm.

As the density increased in terms of compression ratio and feed rate, lower *Ra* values were obtained. As the feed rate increases, a linear increase occurs in the *Ra* value for each density value. While *Ra* values was close to each other in non-densified and 20 % densified samples at at 12000 rpm, much lower *Ra* values were obtained at 40 % concentration. Considering compression and speed relationship, the most obvious difference occurred at 18000 rpm. Nearly *Ra* values were obtained at each speed at a feed rate of 2000 mm/min. While very close *Ra* values were obtained at feed speeds of 1500 mm/min and 2000 mm/min at 12000 rpm, similar *Ra* values were obtained at 1000 mm/min and 1500 mm/min at 15000 rpm. The differences in feed rates were more apparent at 18000 rpm.

When examining the variance analysis table for *Rz* in Table 5, although different *P* values were obtained according to *Ra* in terms of the significance of factors, it is seen that results are the same in terms of whether they are meaningful or not.

Table 5: Results of one-way analysis of variance for *Rz*.

Source	DF	Adj SS	Adj MS	*F*- Value	*P* Value
Cutter type	1	2,038	2,038	0,38	0,542
Compression ratio (%)	2	666,087	333,043	61,58	0,000
Feed rate (mm/min)	2	53,137	26,569	4,91	0,012
Spindle speed (rpm)	2	4,297	2,149	0,40	0,674
Error	46	248,767	5,408	-	-
Total	53	974,326	-	-	-

According to the variance analysis results, for *Rz* at the 95 % confidence level; cutter type (0,05 < P = 0,542) and speed (0,05 < P = 0,674) did not make a statistically significant difference, while it was observed that compression ratio (0,05 > P = 0,000) and feed speed (0,05 > P = 0,012) made a statistically significant difference (Table 5). The factor with the highest effect for *Ra* and *Rz* values was the compression ratio, the second effective factor was the feed rate.

In Figure 7, the interactions of cutter type, compression ratio, feed rate and speed in terms of *Rz* are shown in the main effect plot.

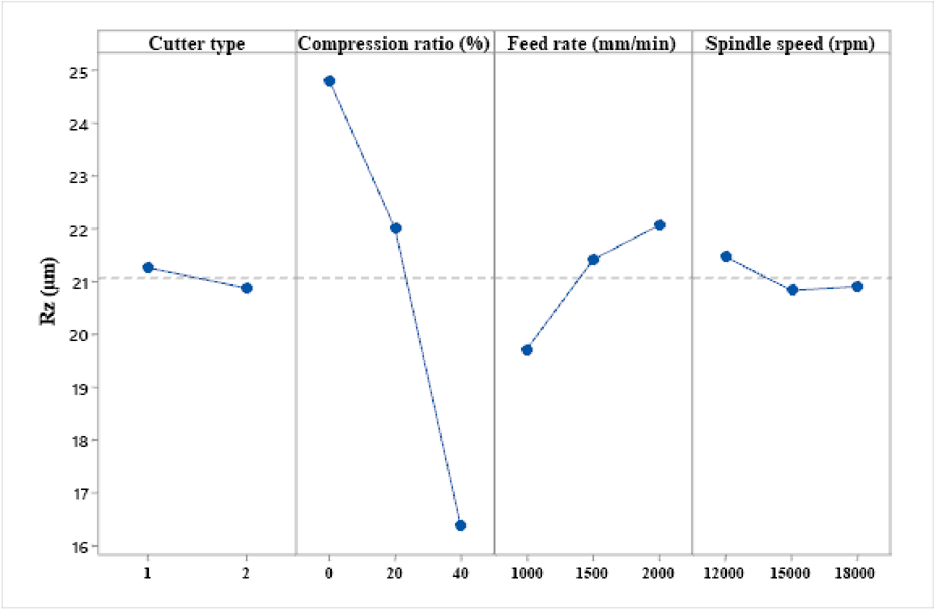


Figure 7: Main effect plot of cutter type, compression ratio, feed rate, and speed in terms of *Rz*.

When the graph is examined in terms of the cutter type, it is seen that values close to each other in terms of *Rz* were obtained in the cutter number 1 and 2. However, although there is no statistically significant difference, it is possible to say that, unlike the *Ra* value, lower *Rz* values were obtained with the cutter number 2 and better results can be obtained.

An evaluation similar to *Ra* can be made for compression ratio and speed in terms of *Rz*. However, while the *Rz* value decreased with increasing the speed from 12000 rpm to 15000 rpm, there was a slight increase in the *Rz* value with increasing the speed from 15000 rpm to 18000 rpm, unlike the *Ra* value. The results obtained for *Rz* were similar to *Ra* in terms of feed rate, speed and density as general tendency and gave similar values as tendency with the literature.

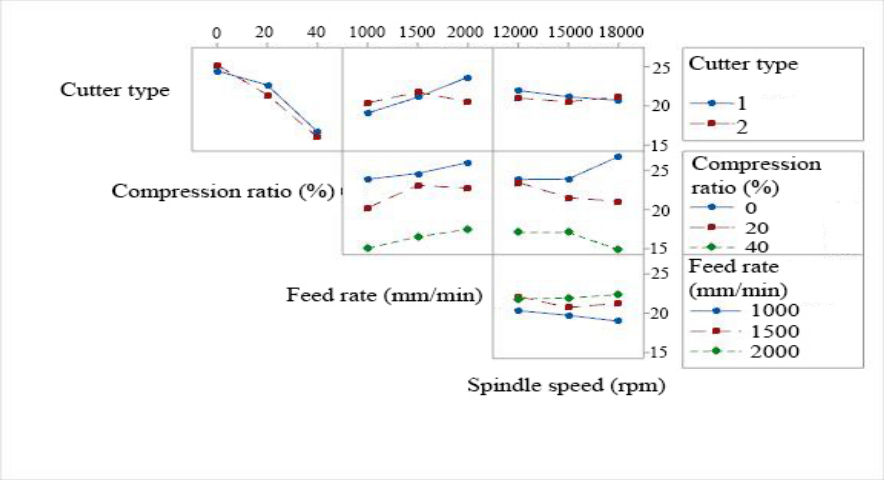


Figure 8: Interactions of cutter type, compression ratio, feed rate and speed in terms of *Rz*.

In general, similar relationships occurred in the interaction graphs in *Ra* and *Rz*. However, when the interaction graphs are evaluated in terms of *Rz*, while the cutter number 1 and 2 have close *Rz* values in non-densified samples and 40 % densified samples in terms of the compression ratio with the cutter, this difference is slightly more in 20 % densified samples. In the relation of 20 % compression ratio and feed rate, the graph did not show a linear relationship as in *Ra*. While the roughness value of *Rz* increased when the feed rate was increased from 1000 mm/min to 1500 mm/min, a slight decrease in the *Rz* value was observed when the feed rate was increased to 2000 mm/min. However, this drop remained at a value between 1000 mm/min and 1500 mm/min (Figure 8).

CONCLUSIONS

In this study, black poplar (*Populus nigra*) tree species, which is an intensively and rapidly growing tree species in our country, was preferred in order to determine the effect of thermo-mechanical densification on machining properties of massive wood material. Its low density and insufficient mechanical properties have limited the use of this material. With the thermo-mechanical densification method, it was aimed to improve properties of the test specimens, which were densified in various ratios, Machining was performed CNC machine in different parameters and the surface quality of the obtained areas was evaluated by considering surface roughness. When the obtained roughness values are examined:

The surface roughness, both R_a and R_z, increased with increasing feed rate, but decreased with increasing spindle speed. From the ANOVA, it can be seen that compression ratio was the most dominating factor for surface roughness.

Statistically, the difference of the cutters used in machining of massive wood materials did not affect the roughness of the machined surfaces.

With the increase in the compression ratio (from 0 % to 40 %), roughness values decreased. Denser materials give smoother surfaces in machining.

Ra and *Rz* roughness values increased with the increase of the feed rate.

With the increase in the speed, there was a decrease in surface roughness values in general.

Keeping cutter feed rate low affects the surface quality positively. However, this situation causes an increase in machining time. In this case, the intersection should be ensured at the optimum point by evaluating intersection time and feed rate.

Increasing speed over a certain value was not found to be statistically significant in surface roughness values. In order for the cutter to be used efficiently and for a long time, the cutter speed should be applied taking into account the values specified on the cutter.

The lowest roughness value for R*a* occurred in the cutter type number 1% at 40 % compression ratio, 1000 mm/min feed rate and 18000 rpm.

The highest roughness value for *Ra* occurred at 0 % compression ratio, 2000 mm/min feed rate, 18000 rpm speed in cutter number 2.

The lowest roughness value for *Rz* occurred in the cutter type number 1 % at 40 % compression ratio, 1000 mm/min feed rate and 18000 rpm.

The highest roughness value for *R*z occurred at 0 % compression ratio, 2000 mm/min feed rate and 18000 rpm in the cutter type number 1.

Further investigations should be conducted to identify optimum machining parameters for different wood machining methods and densified wood species.

AUTHORSHIP CONTRIBUTIONS

M. T.: Writing - original draft, Visualization, Writing - review & editing. S. D. S.: Supervision, Validation, Visualization, Writing - review & editing.

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REFERENCES

Ábrahám, J.; Németh, R.; Molnár, S. 2010. Thermo-mechanical densification of Pannónia Poplar. In Proceedings of the Quality Control for Wood and Wood Products. COST Action E53, 4-7 May 2010, Edinburgh, UK.

Ábrahám, J.; Németh, R. 2012. Physical and mechanical properties of thermo-mechanically densified poplar. In Proceedings of the International Scientific Conference on Sustainable Development and Ecological Foorprint. 26-27 March 2012, Sopron, Hungary. https://www.researchgate.net/profile/Robert-Nemeth-8/publication/266458563_Physical_and_Mechanical_Properties_of_Thermo-_mechanically_Densified_Poplar/links/566ae81f08ae1a797e3962fc/Physical-and-Mechanical-Properties-of-Thermo-mechanically-Densified-Poplar.pdf

Ahmed, S.A.; Morén, T.; Hagman, O.; Cloutier, A.; Fang, C.H.; Elustondo, D. 2013. Anatomical properties and process parameters affecting blister/blow formation in densified European aspen and downy birch sapwood boards by thermo-hygro-mechanical compression. *Journal of Materials Science* 48(24): 8571-8579. https://doi.org/10.1007/s10853-013-7679-9

Arruda, L.M.; Del Menezzi, C.H.S. 2013. Effect of thermomechanical treatment on physical properties of wood veneers. *International Wood Products Journal* 4(4): 217–224. https://doi.org/10.1179/2042645312Y.0000000022

Aykac, E.; Sofuoglu, S. D. 2021. Investigation of the effect of machining parameters on surface quality in Bamboo. *Tehnički vjesnik* 28(2): 684-688. https://doi.org/10.17559/TV-20200102202928.

Bal, B.C. 2018. The effects of some tool paths adjustments of CNC machines on surface roughness and processing time of fiberboards. *Furniture and Wooden Material Research Journal* 1(1): 21-30. https://doi.org/10.33725/mamad.427588

Bal, B.C.; Akçakaya, E. 2018. The effects of step over, feed rate and finish depth on the surface roughness of fiberboard processed with CNC machine. *Furniture and Wooden Material Research Journal* 1(2): 86-93. https://doi.org/10.33725/mamad.481278

Bami, L.K.; Mohebby, B. 2011. Bioresistance of poplar wood compressed by combined hydro-thermo-mechanical wood modification (CHTM): Soft rot and brown-rot. *International Biodeterioration & Biodegradation* 65(6): 866-870. https://doi.org/10.1016/j.ibiod.2011.03.011

Bekhta, P.; Krystofiak, T. 2016. The influence of short-term thermo-mechanical densification on the surface wettability of wood veneers. *Maderas. Ciencia y Tecnologia* 18(1): 79-90. https://doi.org/10.4067/S0718-221X2016005000008

Blomberg, J.; Persson, B.; Blomberg, A. 2005. Effects of semi-isostatic densification of wood on the variation in strength properties with density. *Wood Science and Technology* 39(5): 339-350. https://doi.org/10.1007/s00226-005-0290-8

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(4): 307-314. https://doi.org/10.1007/s10086-003-0566-2

Budakci, M.; Ilce, A.C.; Korkut, D.S.; Gurleyen, T. 2011. Evaluating the surface roughness of heat-treated wood cut with different circular saws. *BioResources* 6(4), 4247-4258. https://bioresources.cnr.ncsu.edu/resources/evaluating-the-surface-roughness-of-heat-treated-wood-cut-with-different-circular-saws/

Budakci, M.; Pelit, H.; Sonmez, 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. https://doi.org/10.15376/biores.11.3.7822-7838

Cruz, N.; Bustos, C.; Aguayo, M.G.; Cloutier, A.; Castillo, R. 2018. Impact of the chemical composition of pinus radiata wood on its physical and mechanical properties following thermo-hygromechanical densification. *BioResources* 13(2): 2268-2282. https://doi.org/10.15376/biores.13.2.2268-2282

Davim, J.P.; Clemente, V.C.; Silva, S. 2009. Surface roughness aspects in milling MDF (Medium Density Fibreboard). *The International Journal of Advanced Manufacturing Technology* 40(1-2): 49-55. https://doi.org/10.1007/s00170-007-1318-z

Diouf, P.N.; Stevanovic, T.; Cloutier, A.; Fang, C.H.; Blanchet, P.; Koubaa, A.; Mariotti, N. 2011. Effects of thermo-hygro-mechanical densification on the surface characteristics of trembling aspen and hybrid poplar wood veneers. *Applied Surface Science* 257(8): 3558-3564. https://doi.org/10.1016/j.apsusc.2010.11.074

Esteves, B.; Ribeiro, F.; Cruz-Lopes, L.; Ferreira, J.; Domingos, I.; Duarte, M.; Duarte, S.; Nunes, L. 2017. Densification and heat treatment of maritime pine wood. *Wood Research* 62(3): 373-388. http://www.woodresearch.sk/wr/201703/04.pdf

Fang, C.H.; Mariotti, N.; Cloutier, A.; Koubaa, A.; Blanchet, P. 2012. Densification of wood veneers by compression combined with heat and steam. *European Journal of Wood and Wood Products* 70(1-3): 155-163. https://doi.org/10.1007/s00107-011-0524-4

Fleischhauer, R.; Hartig, J.U.; Haller, P.; Kaliske, M. 2019. Moisture-dependent thermo-mechanical constitutive modeling of wood. *Engineering Computations* 36(1): 2-24. https://doi.org/10.1108/EC-09-2017-0368.

Gaff, M.; Gašparík, M. 2013. Shrinkage and stability of thermo-mechanically modified aspen wood. *BioResources* 8(1): 1136-1146. https://bioresources.cnr.ncsu.edu/resources/shrinkage-and-stability-of-thermo-mechanically-modified-aspen-wood/

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. https://bioresources.cnr.ncsu.edu/resources/effects-of-pressurized-superheated-steam-heat-treatment-on-set-recovery-and-mechanical-properties-of-surface-compressed-wood/

Gong, M.; Lamason, C.; Li, L. 2010. Interactive effect of surface densification and post-heat-treatment on aspen wood. *Journal of Materials Processing Technology* 210(2): 293-296. https://doi.org/10.1016/j.jmatprotec.2009.09.013

Hajihassani, R.; Mohebby, B.; Najafi, S.K.; Navi, P. 2018. Influence of combined hygro-thermomechanical treatment on technical characteristics of poplar wood. *Maderas. Ciencia y Tecnología* 20(1): 117-128. https://doi.org/10.4067/S0718-221X2018005011001

Hazir, E.; Erdinler, E.S.; Koc, K.H. 2018. Optimization of CNC cutting parameters using design of experiment (DOE) and desirability function. *Journal of Forestry Research* 29(5): 1423–1434. https://doi.org/10.1007/s11676-017-0555-8

Hiziroglu, S. 1996. Surface roughness analysis of wood composites: a stylus method. *Forest Products Journal* 46(7-8): 67-72. https://www.proquest.com/openview/2e7a7f7cd74116bf0667475543bf95d7/1?pq-origsite=gscholar&cbl=25222

Homan, W.; Tjeerdsma, B.; Beckers, E.; Jorissen, A. 2000. Structural and other properties of modified wood. In Proceedings of the World Conference on Timber Engineering. Whisthler Resort, B.C, Canada.

Ilter, E.; Camliyurt, C.; Balkiz, O.D. 2002. Researches on the determination of the surface roughness values of Bornmullerian fir *(Abies bornmülleriana* Mattf.*).* Technical Bulletin No: 283. Central Anatolia Forestry Research Institute: Ankara,Turkey.

ISO. 1975. Wood determination of moisture content for physical and mechanical tests. ISO 3130. ISO: Geneva, Switzerland.

ISO. 2014. Wood-determination of density for physical and mechanical tests. ISO 13061. ISO: Geneva, Switzerland.

ISO. 1982. Surface roughness- Parameters, their values and general rules for specifying requirements. ISO 468. ISO: Geneva, Switzerland.

ISO. 2017. Geometrical Product Specifications (GPS) - Surface texture: Profile method - Nominal characteristics of contact (stylus) instruments. ISO 3274. ISO: Geneva, Switzerland.

ISO. 2015. Geometrical Product Specifications (GPS)-Surface texture: Profile method- Terms, definitions and surface texture parameters. ISO 4287. ISO: Geneva, Switzerland.

Isleyen, U.K.; Karamanoglu, M. 2019. The influence of machining parameters on surface roughness of MDF in milling operation. *BioResources* 14(2): 3266-3277. https://bioresources.cnr.ncsu.edu/resources/the-influence-of-machining-parameters-on-surface-roughness-of-mdf-in-milling-operation/

Kamke, F.A. 2006. Densified radiata pine for structural composites. *Maderas. Ciencia y Tecnología* 8(2): 83-92. https://doi.org/10.4067/S0718-221X2006000200002

Karagoz, U. 2010. Investigation of machining parameters on the surface quality in CNC routing wood and wood-based materials. Master's thesis, Suleyman Demirel University, Graduate School of Natural and Applied Sciences, Isparta, Turkey. https://tez.yok.gov.tr/UlusalTezMerkezi/tezDetay.jsp?id=AWaLG6v1B2Wm2E0fJHwS3A&no=wINiJ-p6GWAWeaSvgWlfUQ

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(1): 113-123. https://doi.org/10.1007/s00107-016-1052-z

Kilic, M.; Hiziroglu, S.; Burdurlu, E. 2006. Effect of machining on surface roughness of wood. *Building and Environment* 41(8): 1074-1078. https://doi.org/10.1016/j.buildenv.2005.05.008

Kminiak, R.; Gaff, M. 2015. Roughness of surface created by transversal sawing of spruce, beech, and oak wood. *BioResources* 10(2): 2873-2887. https://bioresources.cnr.ncsu.edu/wp-content/uploads/2016/06/BioRes_10_2_2873_Kminiak_G_Surface_Unevenness_Created_Transversal_Sawing_6794.pdf

Koc, K.H.; Erdinler, E.S.; Hazir, E.; Oztürk, E. 2017. Effect of CNC application parameters on wooden surface quality. *Measurement* 107: 12-18. https://doi.org/10.1016/j.measurement.2017.05.001

Korkut, S.; Kocaefe, D. 2009. Effect of heat treatment on wood properties. *Düzce University Journal of Forestry* 5(2): 11-34. https://dergipark.org.tr/tr/pub/duzceod/issue/4827/291144

Kutnar, A.; Šernek, M. 2007. Densification of wood. *Zbornik gozdarstva in lesarstva* 82: 53-62. http://eprints.gozdis.si/198/1/zbgl-82-6.pdf

Laine, K.; Antikainen, T.; Rautkari, L.; Hughes, M. 2013. Analysing density profile characteristics of surface densified solid wood using computational approach. *International Wood Products Journal* 4(3): 144-149. https://doi.org/10.1179/2042645313Y.0000000031

Lamason, C.; Gong, M. 2007. Optimization of pressing parameters for mechanically surface-densified aspen. *Forest Products Journal* 57(10): 64-68. https://web.s.ebscohost.com/ehost/detail/detail?vid=0&sid=e1f5b87f-99d3-4ea0-a0c4-52129680710e%40redis&bdata=Jmxhbmc9ZXMmc2l0ZT1laG9zdC1saXZl#AN=27351845&db=bsu

Laskowska, A. 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. https://doi.org/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. Ciencia y Tecnologia* 22(1): 55-68. https://doi.org/10.4067/S0718-221X2020005000106

Lin, R.J.T.; Van Houts, J.; Bhattacharyya, D. 2006. Machinability investigation of medium-density fibreboard. *Holzforschung* 60(1): 71-77. https://doi.org/10.1515/HF.2006.013

Lykidis, C.; Moya, R.; Tenorio, C. 2020. The effect of melamine formaldehyde impregnation and hot-pressing parameters on the density profile of densified poplar wood. *European Journal of Wood and Wood Products* 78(3): 433-440. https://doi.org/10.1007/s00107-020-01515-y

Malkocoglu, A. 2007. Machining properties and surface roughness of various wood species planed in different conditions. *Building and Environment* 42(7): 2562-2567. https://doi.org/10.1016/j.buildenv.2006.08.028

Malkocoglu, A.; Ozdemir, T. 2006. The machining properties of some hardwoods and softwoods naturally grown in Eastern Black Sea Region of Turkey. *Journal of Materials Processing Technology* 173(3): 315-320. https://doi.org/10.1016/j.jmatprotec.2005.09.031

Mania, P.; Wróblewski, M.; Wójciak, A.; **Roszyk, E.; Moliński, W. 2020.** Hardness of densified wood in relation to changed chemical composition. *Forests* 11(5): 506. https://doi.org/10.3390/f11050506

Nasir, V.; Cool, J. 2019. Optimal power consumption and surface quality in the circular sawing process of Douglas-fir wood. *European Journal of Wood and Wood Products* 77: 609-617. https://doi.org/10.1007/s00107-019-01412-z

Nasir, V.; Cool, J. 2020. A review on wood machining: characterization, optimization, and monitoring of the sawing process. *Wood Material Science & Engineering* 15(1): 1-16. https://doi.org/10.1080/17480272.2018.1465465

Nasir, V.; Mohammadpanah, A.; Cool, J. 2020. The effect of rotation speed on the power consumption and cutting accuracy of guided circular saw: Experimental measurement and analysis of saw critical and flutter speeds. *Wood Material Science & Engineering* 15(3): 140-146. https://doi.org/10.1080/17480272.2018.1508167

Ozdemir, S. 2020. The application of thermo-mechanical densification in production of curved laminated veneer lumber and the effect on mechanical properties. Ph.D. Thesis, Bartın University, Graduate School of Natural and Applied Sciences, Bartin, Turkey. https://tez.yok.gov.tr/UlusalTezMerkezi/tezDetay.jsp?id=ZT-86GirGSYZCJ_4lrLvmQA&no=Q-IVEf1bBl7juR4DAtZnUA

Pelit, H. 2014. The effects of densification and heat treatment on finishing process with some technological properties of Eastern beech and scots pine. Ph.D. Thesis, Gazi University, Graduate School of Natural and Applied Sciences, Ankara, Turkey.

Pelit, H.; Budakci, M.; Sonmez, A. 2018. Density and some mechanical properties of densified and heat post-treated Uludağ fir, linden and black poplar woods. *European Journal of Wood and Wood Products* 76(1): 79-87. https://doi.org/10.1007/s00107-017-1182-y

Pelit, H.; Budakci, M.; Sonmez, A.; Baurdurlu, E. 2015a. Surface roughness and brightness of scots pine (*Pinus sylvestris*) applied with water-based varnish after densification and heat treatment. *Journal of Wood Science* 61(6): 586-594. https://doi.org/10.1007/s10086-015-1506-7

Pelit, H.; Sonmez, A.; Budakci, M. 2015b. Effects of thermomechanical densification and heat treatment on density and Brinell hardness of scots pine (*Pinus sylvestris* L.) and Eastern beech (*Fagus orientalis* L.). *BioResources* 10(2): 3097-3111. https://bioresources.cnr.ncsu.edu/resources/effects-of-thermomechanical-densification-and-heat-treatment-on-density-and-brinell-hardness-of-scots-pine-pinus-sylvestris-l-and-eastern-beech-fagus-orientalis-l/

Pelit, H.; Sonmez, A. 2015. The effect of thermo-mechanical densification and heat treatment on some physical properties of Eastern beech (*Fagus orientalis* L.) wood. *Duzce University Journal of Science and Technology* 3(1): 1-14. https://dergipark.org.tr/en/pub/dubited/issue/4809/66235

Pelit, H.; Sonmez, A.; Budakci, M. 2014. Effects of ThermoWood® process combined with thermo-mechanical densification on some physical properties of scots pine (*Pinus sylvestris* L.). *BioResources* 9(3): 4552-4567. https://bioresources.cnr.ncsu.edu/resources/effects-of-thermowood-process-combined-with-thermo-mechanical-densification-on-some-physical-properties-of-scots-pine-pinus-sylvestris-l/

Pertuzzatti, A.; Missio, A.L.; Cademartori, P.H.G.; Santini, E.J.; Haselein, C.R.; Berger, C.; Gatto, A.D.; 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. https://doi.org/10.15376/biores.13.1.1576-1590

Pinkowski, G.; Szymański, W.; Krauss, A.; Stefanowski, S. 2018. Effect of sharpness angle and feeding speed on the surface roughness during milling of various wood species. *BioResources* 13(3): 6952-6962. https://bioresources.cnr.ncsu.edu/resources/effect-of-sharpness-angle-and-feeding-speed-on-the-surface-roughness-during-milling-of-various-wood-species/

Rautkari, L. 2012. Surface modification of solid wood using different techniques. PhD Thesis, Aalto University, Department of Forest Products Technology, Finland. https://aaltodoc.aalto.fi/handle/123456789/5259

Rautkari, L.; Laine, K.; Kutnar, A.; Medved, S.; Hughes, M. 2013. Hardness and density profile of surface densified and thermally modified Scots pine in relation to degree of densification. *Journal of Materials Science* 48(6): 2370-2375. https://doi.org/10.1007/s10853-012-7019-5

Rautkari, L.; Properzi, M.; Pichelin, F.; Hughes, M. 2009. Surface modification of wood using friction. *Wood Science and Technology* 43(3-4): 291-299. https://doi.org/10.1007/s00226-008-0227-0.

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(4): 679-691. https://doi.org/10.1007/s00226-009-0291-0

Senol, S. 2018. Determination of physical, mechanical and technological properties of some wood materials treated with thermo-vibro-mechanical (TVM) process. PhD. Thesis, Duzce University, Graduate School of Natural and Applied Sciences, Duzce, Turkey. https://tez.yok.gov.tr/UlusalTezMerkezi/tezDetay.jsp?id=0F-SI2yI2Beia1NX4IETMTg&no=Asx4VFAeQLz3GCIEnmN-UA

Senol, S.; Budakci, M. 2016. Mechanical wood modification methods. *Mugla Journal of Science and Technology* 2(2): 53-53. https://doi.org/10.22531/muglajsci.283619.

Senol, 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. https://bioresources.cnr.ncsu.edu/resources/effect-of-thermo-vibro-mechanic-densification-process-on-the-gloss-and-hardness-values-of-some-wood-materials/

Senol, S.; Budakci, M.; Korkmaz, M. 2017. The effect of Thermo-Vibro-Mechanical (TVM) densification process on density and abrasion resistance of some wood materials. *Journal of Advanced Technology Sciences* 6(3): 263-275. https://dergipark.org.tr/tr/download/article-file/378796

Skyba, O.; Schwarze, F.W.M.R.; Niemz, P. 2009. Physical and mechanical properties of Thermo-hygromechanically (THM) - densified wood. *Wood Research* 54(2): 1-18. http://www.woodresearch.sk/wr/200902/01.pdf

Sofuoglu, S. D.; Kurtoglu, A. 2014. Some machining properties of 4 wood species grown in Turkey. *Turkish Journal of Agriculture and Forestry* 38(3): 420-427. https://doi.org/10.3906/tar-1304-124

Sofuoglu, S.D. 2008. Effects of wood machining properties of some native species on surface quality. Ph.D. Thesis, Istanbul University, Graduate School of Natural and Applied Sciences, Istanbul. Turkey. https://tez.yok.gov.tr/UlusalTezMerkezi/tezDetay.jsp?id=gUTanfZOv2ijZHLGLmuEdA&no=-OB6ZVFXmt2TD8wlH4e8vw

Sofuoglu, S.D. 2015. Using artificial neural networks to model the surface roughness of massive wooden edge-glued panels made of scotch pine (*Pinus sylvestris* L.) in a Machining Process with Computer Numerical Control. *BioResources* 10(4): 6797-6808. https://bioresources.cnr.ncsu.edu/resources/using-artificial-neural-networks-to-model-the-surface-roughness-of-massive-wooden-edge-glued-panels-made-of-scotch-pine-pinus-sylvestris-l-in-a-machining-process-with-computer-numerical-control/

Sofuoglu, S.D.; Tosun, M.; Atilgan, A. 2022. Determination of the machining characteristics of Uludağ fir (*Abies nordmanniana* Mattf.) densified by compressing. *Wood Material Science & Engineering* https://doi.org/10.1080/17480272.2022.2080586

Sutcu, A.; Karagoz, U. 2012. Effect of machining parameters on surface quality after face milling of MDF. *Wood Research* 57(2): 231-240. http://www.woodresearch.sk/wr/201202/05.pdf

Sutcu, A.; Karagoz, U. 2013. The influence of process parameters on the surface roughness in aesthetic machining of wooden edge-glued panels (EGPs). *BioResources* 8(4): 5435-5448. https://bioresources.cnr.ncsu.edu/resources/the-influence-of-process-parameters-on-the-surface-roughness-in-aesthetic-machining-of-wooden-edge-glued-panels-egps/

Tenorio, C.; Moya, R.; Navarro-Mora, A. 2021. Flooring characteristics of thermo-mechanical densified wood from three hardwood tropical species in Costa Rica. *Maderas. Ciencia y Tecnología* 23: 1-12. https://doi.org/10.4067/s0718-221x2021000100416

Ulker, O.; Imirzi, O.; Burdurlu, E. 2012. The effect of densificatoin temperature on some physical ans mechanical properties of scots pine (*Pinus sylvestris* L.). *BioResources* 7(4): 5581-5592. https://bioresources.cnr.ncsu.edu/resources/the-effect-of-densification-temperature-on-some-physical-and-mechanical-properties-of-scots-pine-pinus-sylvestris-l/

Wehsener, J.; Brischke, C.; Meyer-Veltrup, L.; Hartig, J.; Haller, P. 2018. Physical, mechanical and biological properties of thermo-mechanically densified and thermally modified timber using the Vacu3-process. *European Journal of Wood and Wood Products* 76(3): 809-821. https://doi.org/10.1007/s00107-017-1278-4

Zhong, Z.W.; Hiziroglu, S.; Chan, C.T.M. 2013. Measurement of the surface roughness of wood based materials used in furniture manufacture. *Measurement* 46(4): 1482-1487. https://doi.org/10.1016/j.measurement.2012.11.041