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Use of Spinning Roller in Cylindrical Densification; Spring back in Black Poplar, Larch and Cedar of Lebanon after Densification

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Abstract: Wood materials have been the solution to many needs throughout history due to their unique positive properties. By improving the properties of wood materials, their areas of use can be expanded and ensured that they are preferred. The densification process is one of the studies carried out to improve wood material properties. With densification, the physical and mechanical properties of the wood material can be improved. There are many different methods used for densifying wood materials. While the densification process brings many positive properties to the wood material, an undesirable situation such as spring-back after the process is the negative side of the densification process. In this study, black poplar (*Populus nigra* L.), larch (*Pinus nigra* Arnold) and cedar of Lebanon (*Cedrus libani* A.Rich.) trees were shaped into cylinders on a lathe. After that, densification processes were carried out on the lathe machine using the spinning roller designed and manufactured for this purpose. Densification processes were carried out at 0.081, 0.121, and 0.202 mm/rev feed, at 200 and 400 rev/min, and 0.5 and 1 mm densification depths. The spring-back rates after densification in three different types of cylindrical wood materials were investigated. Theoretical and experimental spring-back amounts of test specimens whose surfaces were densified under different densification conditions were interpreted. When evaluated in general, the highest densification rate was obtained in black poplar wood species, 0.081 mm/rotate feed, 200 rpm spindle speed and 1 mm depth of densification. The lowest spring-back ratio was obtained in larch wood species, 0.121 mm/rotate feed, 400 rpm spindle speed and 1 mm depth of densification. The highest densification percentage was obtained in black poplar wood species, and the lowest in larch wood species. The lowest percentage of spring-back was obtained in the larch wood species and the highest in the black poplar wood species.

Keywords: Cedar, densification, larch, poplar, spinning roller, spring back

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1. INTRODUCTION

Wood material has been used in many areas throughout history to meet human needs. Today, with the rapid increase in population, wood material, which is one of the natural resources, has started to be insufficient. This situation reveals the need to use the resources available more efficiently.

Numerous studies aim to use wood material efficiently, minimise its negative aspects, and further develop its positive properties. Densification, which is one of the processes for these purposes, is generally applied to low-density wood species. Densification using temperature and pressure in an open system known as Thermo-Mechanical (TM) and densification using temperature, pressure and steam in a closed system called Thermo-Hygro-Mechanical (THM). In addition, there is densification made by temperature and pressure after pre-softening with steam, called Viscoelastic-Thermal-Compression (VTC) (Senol and Budakci, 2019; Kaya and Sofuoglu, 2023). And there are also methods, such as densification using temperature, pressure and vibration, called Thermo-Vibro-Mechanical (TVM) By densification, dimensional stability, hygroscopicity, durability and mechanical properties improve

(Welzbacher et al., 2008). On the other hand, it is stated that the densified wood material has a more homogeneous structure depending on the densification ratio (applied pressure) (Blomberg, et al., 2005).

Since the densification of wood material increases its mechanical properties and hardness, many attempts have been made to develop a suitable process in this regard. In the process of densification with compression of the wood material, the cell wall of the material collapses and the void volume is reduced (Kutnar et al., 2009; Pelit, 2014; Pelit and Sonmez, 2015, Sofuoglu, 2022; Sofuoglu et al., 2023; Tosun and Sofuoglu, 2021; Tosun and Sofuoglu, 2023a; Tosun and Sofuoglu, 2023b). Using wood material by increasing density can be an option compared to other materials (Blomberg and Persson, 2004; Pelit et al., 2014).

The density of wood material is mechanical (Rautkari, 2012) and machining (Lin et al., 2006; Malkocoglu, 2007; Malkocoglu and Ozdemir, 2006; Pinkowski et al., 2018; Sofuoglu et al., 2023; Zhong et al., 2013) significantly affect its properties. When examined in general, hardness, mechanical and physical properties increase, surface roughness and wettability decrease and occurrence of spring back as a negative situation may be seen, contingent on the increase in density in compressed densified wood species. In addition, another disadvantage caused by the densification process in the wood material is that deformations such as cracking, fracture, and breaking can occur in the cell wall of the densified wood material under normal atmospheric conditions (Rautkari et al., 2010).

The biggest problem encountered in densified wood materials is that they tend to return to their initial dimensions due to the spring-back feature that occurs immediately after densification. This situation occurs more when the wood material is used in places where it may be exposed to moisture or contact with water (Pelit, 2014). There are many studies to eliminate or minimize the spring-back, which is one of the negative aspects of the surface densification process. In some of these studies, the effect of additional methods applied before and after densification on spring-back was investigated. One of these methods is heat treatment (Skyba et al., 2009; Tenorio et al. 2021; Li et al., 2013; Fu et al., 2016; Laine et al., 2016; Esteves et al., 2017). It is known that the spring-back is also eliminated by the effect of temperature and steam (Kunar and Sernek, 2007; Pelit, 2014; Rautkari et al., 2010; Li et al., 2017). Heat treatment applied after the densification is more effective in reducing spring-back recovery than before (Esteves et al., 2017). Heat treatment reduces spring-back and improves wood stability and durability (Esteves and Pereira, 2009). However, most had less success in reducing spring-back in the densified wood. Previous work dealing with the combined-hydro-thermo-mechanical treatment showed great reduction in the densified poplar wood spring-back (Hajihassani et.al., 2018).

In other studies, wood veneers under the effect of heat, steam and pressure after recovery (Cloutier et al., 2008; Fang et al., 2012)**,** effect of ionic liquid or organic superbase pre-treatment on the elastic spring-back and Brinell hardness of surface-densified wood (Neyses et al., 2020), Examined that reducing the spring-back of surface densified solid Scots pine wood by hydrothermal post-treatment (Laine et al., 2013). When wood is re-moisture, the spring-back is one of the main problems of compressed wood. These authors proposed three mechanisms to avoid spring-back. Prevent the wood from being re-softened by changing the hygroscopicity of the cell, form covalent crosslinks between the wood components in the deformed state or release the elastic stresses and strains created during compression (Esteves et al., 2017). The spring-back effect, which is one of the main problems associated with the densification process, can be eliminated by steaming or heating, which can induce permanent fixation of the compressive deformation (Kutnar and Sernek, 2007). As the densification temperature and heat treatment temperature increase, the spring-back decreases. The densification time has little or no effect on the spring-back (Li et al., 2013). Another study examined densified wood impregnated with phenol resin for reduced spring-back (Schwarzkopf, 2021).

Some studies on the subject have shown that due to their dimensional stability and high density, densified wood veneers treated by the oil-heat treatment process show good potential for appearance products (Fang et al., 2011). The spring-back of densified samples was further significantly decreased following surface polymerization with glycerol and maleic anhydride (68% lower than the non-polymerized ones) (Yahyaee et al., 2022). Impregnation with phenol resin can significantly reduce the spring-back of compressed deformation. According to the results of the study with the Continuous Surface Densification of Wood method; spring-back of the densified cells occurred after the soaking-drying cycles but was considerably lower than in the other densification studies performed under static conditions. It was suggested that the lowered spring-back was a consequence of the specific process conditions, i.e., a combination of pre-wetting by spraying water onto the surface and a long pre-heating period before the compressive force was applied.

After densification, it is possible to talk about two types of spring-back. The first of these is sudden spring-back, which is triggered by the release of internal stresses that occur in the material when the press table is opened. The other is the air-dry spring-back that occurs when the material reaches a constant weight at 20ºC and 65% relative humidity.

The literature shows that; The spring-back effect in densified wood materials and coatings was investigated and evaluated in press-compressed materials. Studies have been carried out to reduce this effect. However, no case determination was found regarding the spring-back effect in the densification processes applied to cylindrical materials.

This study, it is aimed to expand the usage area of wood material in the woodworking and furniture industry. Densification processes contribute to this situation. However, with the method used in the study, the spring-back effect is not known in cylindrical densified materials.

With this study, the densification process was performed using a new method. It is planned to determine the spring-back condition, which can be seen as a measure of the success of the densification of cylindrical materials. With the determination of this situation, the ground will be prepared for the studies that can be done to prevent the spring-back condition.

2. MATERIAL AND METHOD

In the present experiments, black poplar (*Populus nigra* L.), larch (*Pinus nigra* Arnold) and cedar of Lebanon (*Cedrus libani* A.Rich.) wood species were used. Wood species commonly used and grown in Turkey. Conditioning of samples was carried out at temperatures of 20 ± 2 °C and 65 ± 5 °C, with relative humidity to moisture content (MC) of about 12%. The density of wood species at 12% humidity was specified as poplar 340 kg/m^3, larch 650 kg/m^3, cedar of Lebanon 500 kg/m^3 (ISO 13061 2014; ISO 13061-2 2014).

The test specimens were first cut in 2x2x30 cm dimensions. After this process, the test specimens were cylindrical on the lathe machine until their average diameter was 1.9 cm. By using a grooving insert, 5 sections of equal length were formed on the test specimens with an average diameter of 1.9 cm. 3 of these sections are used for the implementation of the experimental parameters and 2 are the control sections (Figure 1).

The prepared test specimens were kept in an air-conditioned cabinet at 20 ± 2°C and 65 ± 5% relative humidity until their weight was stable. The aim here is to ensure that the moisture content reaches 12 ± 2% before densification (Figure 2). The densification parameters and levels used in the experiments were determined as in Table 1 and experiments were conducted.

The experimental application of the study (Schematic representation for surface densification process) is given in Figure 3. Figure 4 shows the measurement of specimens with a caliper before and after densification.

Table 1. Assignment of levels to factors (parameters used in the densification of black poplar, larch, and cedar of Lebanon

Parameters	**Level 1**	**Level 2**	**Level 3**
Wood species	Black poplar	Larch	Cedar of Lebanon
Feed (mm/rotate)	0.081	0.121	0.202
Spindle speed (rpm)	200	400	
Depth of dens. (mm)	0.5	1	

Figure 1. Test specimens before densification

Figure 2. The position of the experimental specimens in the air-conditioned cabinet

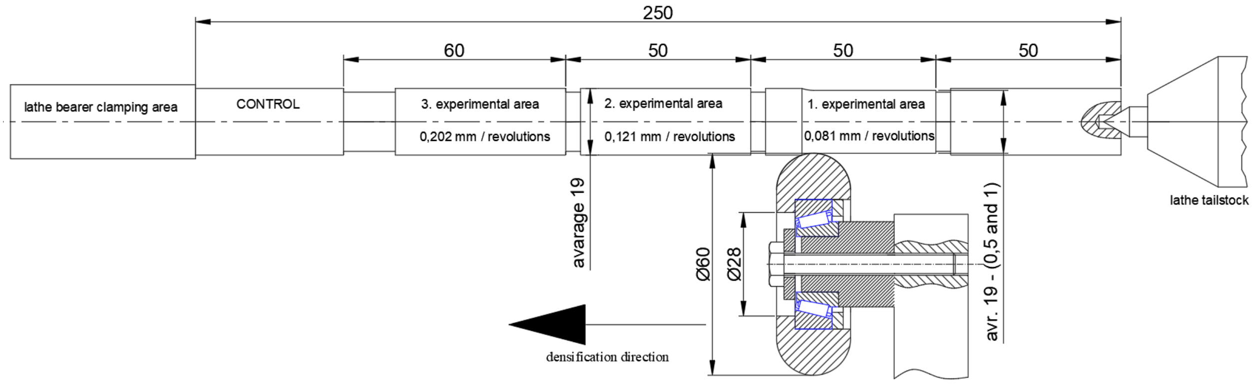

Figure 3. Schematic representation for surface densification process

Figure 4. Measurement of test specimens' diameters with the caliper.

The spinning roller, designed and manufactured for the densification process, is formed by bringing together seven pieces. The material of the main roller element, which performs the press function from these parts, is steel in DIN EN AISI 1.0402 C22 – 1020 standard. After this part is brought to its final shape by a turning machine, it was hardened by heat treatment. This part is supported by a tapered roller bearing perpendicular to the turning axis of the wood material to be densified and capable of meeting the forces that will occur in the direction of the densification axis. The standard number of this bearing is 302/30202-A. The other parts in the assembly set and the prismatic part connected to the tool post of the lathe was produced by using non-hardened steel materials in DIN EN AISI 1.0402 C22-1020 standard. The M6 bolt that connects the parts is supplied as standard. This assembled set was used for densification operations by connecting to the tool post on the lathe (Figure 5).

Figure 5. Densification of cylindrical parts with a spinning roller.

Densification processes were carried out on the TOS GALANTA SUIL 40A lathe seen in Figure 6. This lathe is in Kütahya Dumlupinar University, Simav Technology Faculty, Mechanical Engineering Department Laboratories.

Figure 6. TOS GALANTA SUIL 40A lathe.

Determining Compression Ratio

The density of wood materials is important because it directly affects their mechanical properties. The material densities obtained after the densification process are directly proportional to the compression ratio. The main item examined in this study is the detection of instantaneous spring-back due to densification processes.

First of all, the necessary environmental conditions were created for all test samples to be at 12% humidity before and during the densification process. For this, the test specimens, which were kept in the climatized cabinet until they reached a constant weight at 20 ºC and 65% relative humidity, were subjected to the densification process as soon as they were received from the climatized cabinet. Just before starting the densification process, the initial diameters (*tk*) of cylindrical wood materials were measured from 4 different points using a digital caliper with ±0.01 mm precision, and the arithmetic average of the measured diameters was taken. After the densification process, the diameters of the densified sections (*tilk*) were measured from 4 different points using the same digital caliper and the arithmetic average of these diameters was taken. While densifying the cylindrical wood material, two different diameter reductions, 0.5 mm, and 1 mm were aimed as test parameters. To observe the achievability of these aims, the theoretical % compression ratios were calculated for 0.5 mm in equation 1 ($Teo.SO_{0.5}$ (%)), and for 1 mm diameter reduction in equation 2 (($Teo.SO_1$ (%)). In Equation 3, experimental % compression ratios were calculated depending on the diameter changes before and after densification. The difference between the theoretical and experimental % compression ratios is the % spring-back amount calculated using equation 4.

$$Teo.SO_{0.5}\ (\%) = \frac{(tk - (tk - 0.5))}{(tk - 0.5)} x100 \tag{1}$$

$$Teo.SO_{1}\ (\%) = \frac{(tk - (tk - 1))}{(tk - 1)} x100 \tag{2}$$

$$Exp.SO\ (\%) = \frac{(tk - tilk)}{tilk} x100 \tag{3}$$

$$\begin{gathered} \mathrm{Spring-back}_{0.5}\ (\%) = Exp.SO\ (\%) - Teo.SO_{0.5}\ (\%) \\ \mathrm{Spring-back}_{1}\ (\%) = Exp.SO\ (\%) - Teo.SO_{1}\ (\%) \end{gathered} \tag{4}$$

$Teo.SO_{0.5}$ (%); theoretical % compression ratios for 0.5 mm, *tk;* initial diameter of test specimen, *0.5* mm and *1* mm; test parameters, $Teo.SO_1$ (%); theoretical % compression ratios for 1 mm, $Exp.SO$ (%); experimental % compression ratios in every test condition, $tilk$; diameters obtained as a result of experiments, $\mathrm{Spring-back}_{0.5}$ (%) and $\mathrm{Spring-back}_{1}$ (%); Spring-back percentages for 0.5 mm and 0.1 mm.

3. RESULTS AND DISCUSSION

Theoretical (targeted) densification under densification conditions, densification, and spring-back percentages obtained at the end of the test results are given in Table 2.

Table 2. Theoretical densification, experimental densification and spring-back percentages obtained according to densification conditions.

Material	Process N.	Feed (mm/rotate)	Feed (mm/min)	Spindle speed (rpm)	Dept. of dens. (mm)	Theoretical compression ratio (%)	Experimental compression ratio (%)	Spring-back (%)
Black poplar	1	0.081	16.2	200	0.5	2.85	1.75	-1.10
	2	0.081	16.2	200	1	5.63	2.79	-2.84
	3	0.081	32.4	400	0.5	2.78	0.84	-1.94
	4	0.081	32.4	400	1	5.57	2.67	-2.90
	5	0.121	24.2	200	0.5	2.85	1.63	-1.22
	6	0.121	24.2	200	1	5.63	2.29	-3.34
	7	0.121	48.4	400	0.5	2.78	0.67	-2.11
	8	0.121	48.4	400	1	5.57	2.30	-3.27
	9	0.202	40.4	200	0.5	2.85	1.92	-0.93
	10	0.202	40.4	200	1	5.63	2.27	-3.36
	11	0.202	80.8	400	0.5	2.78	0.84	-1.94
	12	0.202	80.8	400	1	5.57	2.62	-2.96
Larch	1	0.081	16.2	200	0.5	2.88	0.81	-2.07
	2	0.081	16.2	200	1	5.75	1.66	-4.09
	3	0.081	32.4	400	0.5	2.86	0.24	-2.62
	4	0.081	32.4	400	1	5.99	1.01	-4.98
	5	0.121	24.2	200	0.5	2.88	0.88	-1.99
	6	0.121	24.2	200	1	5.75	1.57	-4.19
	7	0.121	48.4	400	0.5	2.86	0.20	-2.66

	8	0.121	48.4	400	1	5.99	0.89	-5.10
	9	0.202	40.4	200	0.5	2.88	1.02	-1.86
	10	0.202	40.4	200	1	5.75	1.68	-4.07
	11	0.202	80.8	400	0.5	2.86	0.86	-2.00
	12	0.202	80.8	400	1	5.98	1.00	-4.98
Cedar of Lebanon	1	0.081	16.2	200	0.5	2.71	1.43	-1.28
	2	0.081	16.2	200	1	6.38	1.65	-4.74
	3	0.081	32.4	400	0.5	2.73	1.18	-1.55
	4	0.081	32.4	400	1	5.61	2.65	-2.96
	5	0.121	24.2	200	0.5	2.71	1.16	-1.55
	6	0.121	24.2	200	1	6.38	1.21	-5.17
	7	0.121	48.4	400	0.5	2.73	0.89	-1.84
	8	0.121	48.4	400	1	5.61	1.67	-3.94
	9	0.202	40.4	200	0.5	2.71	1.14	-1.57
	10	0.202	40.4	200	1	6.38	1.21	-5.17
	11	0.202	80.8	400	0.5	2.73	0.98	-1.75
	12	0.202	80.8	400	1	5.61	1.58	-4.03

Experimental and theoretical % compression ratios according to the densification processes for Figure 7 poplar wood type, Figure 8 larch wood type, and Figure 9 cedar wood type are given graphically.

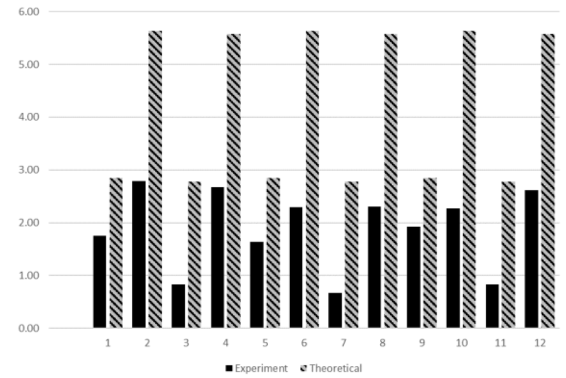

Figure 7. Experimental and theoretical % compression ratios according to the densification processes of the poplar wood.

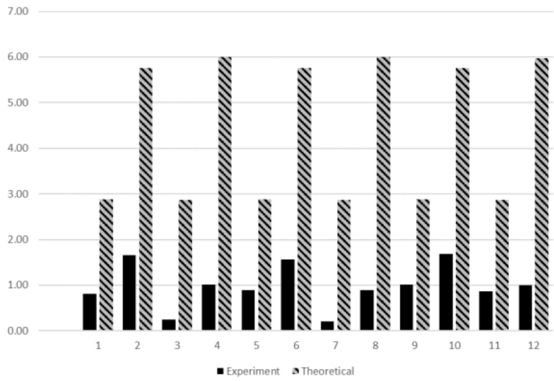

Figure 8. Experimental and theoretical % compression ratios according to the densification processes of the larch wood.

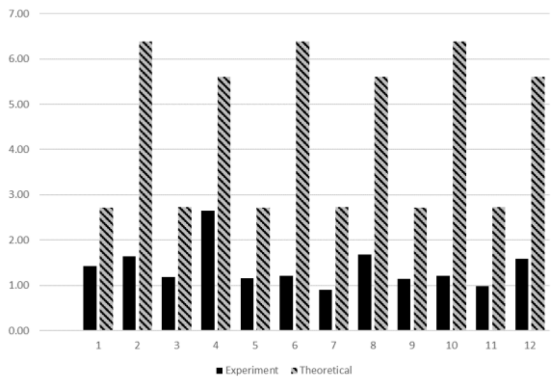

Figure 9. Experimental and theoretical % compression ratios according to the densification processes of the cedar wood.

As can be seen from the graphics, spring-back effect occurs after densification. It has been determined by experimental studies in the literature that the spring-back effect is a condition seen after densification (Pelit et. al., 2014; Tenario et. al., 2021; Laine et. al., 2016; Kariz et. al., 2017). It has been stated that the density increase obtained by compressing the wood material depends on the characteristics of the wood species, the spring-back effect, and the level of compression by the applied densification method (Rautkari, 2012; Pelit et al. 2015). The results of the variance analysis are given for densification in Table 3 and for spring-back in Table 4.

Table 3. Analysis of variance for densification

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Wood species	2	4.8445	2.4223	16.24	0.000
Feed (mm/rotate)	2	0.4598	0.2299	1.54	0.231
Spindle speed (rpm)	1	0.6889	0.6889	4.62	0.040
Depth of dens. (mm)	1	5.6644	5.6644	37.98	0.000
Error	29	4.3253	0.1491		
Total	35	15.9830			

According to the results of analysis of variance for densification, the effects of wood species (P=0.000<0.05) and spindle speed (P=0.040<0.05) and depth of densification (P=0.000<0.05) were found significant at 95% confidence level. Feed (P=0.231>0.05) has no statistical effect (Table 3).

Table 4. Analysis of variance for spring-back

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Wood species	2	6.8129	3.4064	11.26	0.000
Feed (mm/rotate)	2	0.4571	0.2286	0.76	0.479
Spindle speed (rpm)	1	0.2483	0.2483	0.82	0.372
Depth of dens. (mm)	1	44.6892	44.6892	147.71	0.000
Error	29	8.7737	0.3025		
Total	35	60.9813			

According to the results of analysis of variance for spring-back, the effect of wood species (P=0.000<0.05) and depth of densification (P=0.000<0.05) were found significant at 95% confidence level. Feed (P=0.479<0.05) and spindle speed (P=0.372<0.05) have no statistically significant effect (Table 4).

The main effect graph for the densification percentage is given in Figure 10. The highest densification percentage was obtained in black poplar wood species, and the lowest densification percentage was obtained in larch wood species.

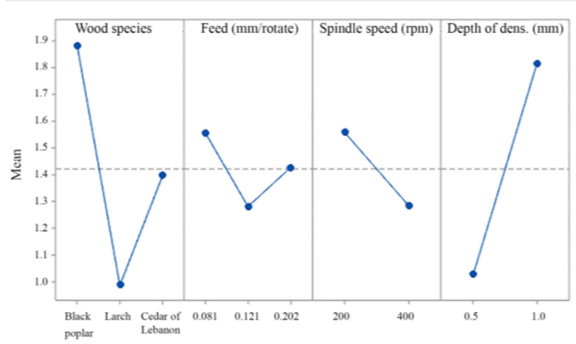

Figure 10. Main effect plot for densification

While the highest densification percentage was obtained at 0.081 mm/rotate feed, a decrease occurred at 0.121 mm/rotate with an increase in the feed value. And it rose again at the highest feed value of 0.202 mm/rotate. However, this value is around an average densification value. The highest densification value was obtained at 200 rpm spindle speed and 1 mm depth of densification. When evaluated in general, the highest densification was obtained in Black poplar wood species, 0.081 mm/rotate feed, 200 rpm spindle speed, and 1 mm depth of densification. When the interaction plot for densification is examined in Figure 11, it is seen that the highest densification occurs at 1 mm depth of densification for all wood species.

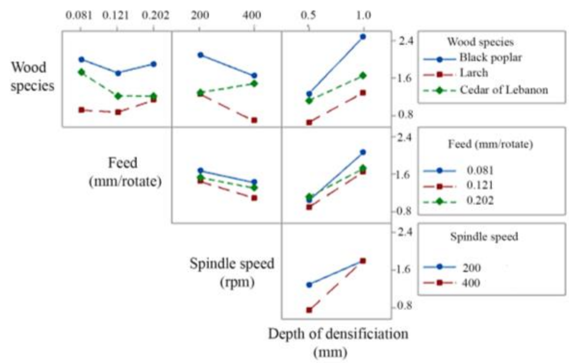

Figure 11. Interaction plot for densification

It is seen that the difference between 0.5 and 1 mm in terms of the densification percentage of poplar wood is high, while this difference is obtained close to each other in larch and cedar wood. The interaction of depth of densification in both feed and two spindle speed values occurred similarly in different wood species. Spindle speed showed similar interaction at different feed values. On the other hand, when the interaction between spindle speed and wood species was examined, the highest densification was obtained at 200 rpm in poplar and larch wood species. Although close to each other in Cedar, the highest value occurred at 400 rpm. The interaction between the feed and wood species is similar in all three wood types.

In Figure 12, the main effect graph for the spring-back percentage is given.

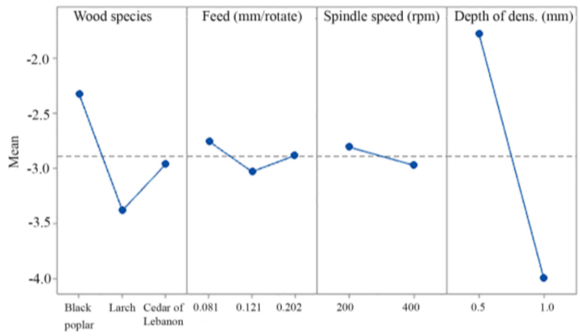

Figure 12. Main effect plot for spring-back

The highest spring-back percentage was obtained in the poplar wood species, and the lowest spring-back percentage was obtained in the larch wood species. The highest percentage of spring-back was obtained in 0.081 mm/rotate feed. With the increase of the feed value, a decrease of 0.121 mm/rotate occurred and increased again at the highest value of 0.202. However, this increase has not been too much. In fact, this change was not found to be significant at the 95% confidence level according to the result of the analysis of variance. The lowest percentage of spring-back was obtained at 400 rpm spindle speed and 1 mm depth of densification. When evaluated in general, the lowest percentage of spring-back was obtained in larch wood species, 0.121 mm/rotate feed, 400 rpm spindle speed, and 1 mm depth of densification.

When the interaction plot for spring-back is examined in Figure 13, it is seen that the lowest percentage of spring-back occurs at a 1 mm depth of densification for all wood species. The interaction of depth of densification in both feed and two spindle speed values occurred similarly in different wood species.

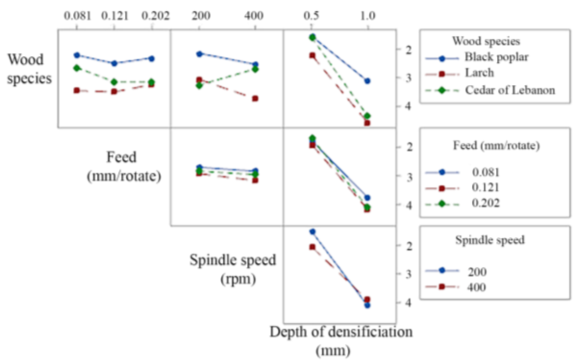

Figure 13. Interaction plot for spring-back

Spindle speed showed similar interaction in different feed values and the spring-back effect occurred close to each other in both feed values. However, when the interaction between spindle speed and wood species was examined, the lowest spring-back effect was obtained at 400 rpm in poplar and larch woods, while the lowest value occurred at 200 rpm in cedar woods, although they were close to each other. In terms of spring-back effect, the percentage of spring-back was very close to each other in larch and cedar woods at 200 rpm, and poplar and cedar woods at 400 rpm. The interaction between the feed and wood species is similar in all three wood types. With the increase in feed, there was a decrease in the spring-back percentage first, and then there was an increase again.

When the literature is examined, it has been tried to reduce the spring-back effect by steaming or heating, which can induce permanent fixation of the compressive deformation (Kutnar and Sernek, 2007).

4. CONCLUSIONS

In this study, black poplar (*Populus nigra* L.), larch (*Pinus nigra* Arnold), and cedar of Lebanon (*Cedrus libani* A.Rich.) wood species were selected as experimental materials. The surfaces of the cylindrical test specimens were densified by changing various densification parameters with the spinning roller on the lathe, and the densification and spring-back percentages were evaluated. The obtained results can be summarized as follows.

- The effects of wood species, spindle speed and depth of densification were significant for densification percentage. The effect of the feed is not significant.
- The effect of wood type and depth of densification was significant in terms of spring-back. The feed and spindle speed effect is not significant.
- When evaluated in general, the highest densification percentage was obtained in black poplar wood, 0.081 mm/rotate feed, 200 rpm spindle speed and 1 mm depth of densification.
- When evaluated in general, the lowest percentage of spring-back was obtained in larch wood species, 0.121 mm/rotate feed, 400 rpm spindle speed and 1 mm depth of densification.
- The highest densification percentage was obtained in the black poplar wood, and the lowest densification percentage was obtained in the larch wood.
- The lowest spring-back percentage was obtained in the larch wood species, and the highest spring-back percentage was obtained in the black poplar wood species.
- The highest percentage of densification and the lowest spring-back occurred at a 1 mm depth of densification for all wood species.

Ethics Committee Approval
N/A

Peer-review
Externally peer-reviewed.

Author Contributions
Conceptualization: Z.K., S.D.S.; Investigation: S.D.S.; Material and Methodology: Z.K., S.D.S.; Supervision: S.D.S.; Visualization: Z.K., S.D.S.; Writing-Original Draft: Z.K., S.D.S.; Writing-review & Editing: Z.K., S.D.S.

Conflict of Interest
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