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Article

The Effect of Steaming Beech, Birch and Maple Woods on Qualitative Indicators of the Surface

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Abstract: This work presents the effect of steaming beech, birch and maple woods on the resulting quality of the milled wood surface. The steaming process of the studied woods results in a targeted change in the color of the wood, which changes from the original light white-gray color to fine reddish-brown to dark brown color shades that are more or less saturated depending on the temperature of the saturated water steam. The color changes achieved during the modification process were identified using coordinates in the CIE L*a*b* color space. The achieved color changes were described through the total color difference of ΔE* and defined through classification grades using a color scale. The technological process of wood steaming with saturated water steam for the purpose of a targeted change in the color of the wood and experimental measurements of the roughness of the milled wood surface proved that the wood steaming process has a positive effect on the roughness of the wood surface of the investigated trees, depending on the steaming temperature. The reduction of roughness in the process of the modification of beech wood compared with native wood was at the temperature of the saturated water steam as follows: $t_{I} = 105 \pm 2.5$ °C by Ra = 12.3%, at $t_{II} = 125 \pm 2.5$ °C by R_a = 15.4%, at $t_{III} = 135 \pm 2.5$ °C by Ra = 16.9%. By modifying birch wood at $t_{III} = 135 \pm 2.5$ °C, the roughness decreased by Ra = 13.4%; the surface roughness decreased by Ra = 15.8% compared with native wood by modifying maple wood. The roughness of the milled surface of modified wood in individual treatment modes decreased compared with native wood, which means that the milled surface of modified wood is of a better quality, which is positive for its practical use.

Keywords: beech wood; birch wood; maple wood; wood steaming; wood color; CNC machining center; wood milling; wood surface roughness

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1. Introduction

The quality of the machined surface is an important factor that is influenced by both the technical and technological parameters of machines and tools used for cutting and machining [1–7] as well as the properties of the processed material (type of wood, wood moisture, macro-, micro- or sub-micro- structure) [8], thereby last but not least affecting the marketability of the product [9,10]. Authors from [11] define surface quality as a set of specific surface properties defined by ridges (peaks) and hollows. These features can also be named surface topography. The author from [1] characterizes the quality of the processed wood surface through the roughness and waviness of the surface as well as through possible damage to the wood surface by torn fibers and tool grooves, which are generally considered to comprise unevenness and to be the result of technological operations in which the integrity of the wood is violated due to processing. The standard from [12] evaluates the surface quality parameters of materials as the differences between surface unevenness, roughness (evaluated from the roughness profile) and waviness. According to the mentioned standard, we can define the real surface of the wood as the surface that borders the given body and separates it from the surrounding environment. In practice, to define the quality of the surface of the wood, the mean arithmetic deviation of the roughness, marked as Ra, is most often used. Interestingly, a study (i.e., [13]) presented an analysis of surface roughness by taking into account the density of the machined wood [14].

According to the works of the authors from [15–18], thermal or hydrothermal treatments of wood, such as steaming, drying or thermo-wood production technologies, also affect the quality of the treated wood surface. However, a study (i.e., [19]) showed that color changes occur only on surfaces with shallow depths.

The process of steaming wood with saturated moist air or saturated water steam temporarily changes the physical and mechanical properties of wood used in its division, shaping or densification. When heat is applied to wet wood in the wood steaming process, chemical reactions are initiated in it, including the extraction of water-soluble substances, the degradation of polysaccharides and the splitting of free radicals and phenolic hydroxyl groups in lignin, where they result in the formation of new chromophoric groups and structures that participate in the resulting change of the color of the wood. The steaming process and the above-mentioned chemical changes create permanent physical and mechanical changes in wood properties, such as a decrease in density, a weakening of most mechanical strengths and an increase in the fragility of the wood, affecting the machining process and the quality of the surface of the machined wood [8,16].

Recently, the attention of research in the field of wood steaming has been mainly focused on pressurized steaming with saturated water vapor in order to change the color of wood to different shades [20–26], which opens up space for designers and constructors to use the good mechanical and physical properties of steamed wood for utilizing various non-traditional colors.

The aim of this article is to analyze the effect of wood steaming modes of the deciduous trees of beech, birch and maple on the resulting quality of the created surface (roughness R_a) under specified cutting conditions, feed speed and material removal.

2. Material and Methods

2.1. Material

The wood of the selected deciduous trees of *Fagus sylvatica* L., *Betula pendula* and *Acer pseudoplatanus* used in the research was from Štiavnické vrchy (Slovakia). Radial cross-sections with the dimensions of h = 40 mm × width w = 80 mm × length l = 600 mm were used for this research. The wood was manipulated from the sapwood of the given trees after undergoing sawing one meter above the ground to produce a total number of 120 pieces, a process which was undertaken separately for each tree species. The blanks of each wood were divided into four groups that separately represented 30 pieces of blanks for each type of wood. The blanks of the 1st group were untreated (native wood). The blanks of the 2nd group were modified through the steaming process in mode I., the blanks of the 3rd group were modified through the steaming process in mode II. and blanks of the 4th group were modified by the steaming process in mode III.

2.2. Steaming and Drying of Blanks

The technological process of the wood steaming of individual wood species was carried out in pressure autoclave APDZ 240 (Himmasch AD, Haskovo, Bulgaria) at a higher pressure of saturated water steam than the atmospheric pressure. Temperatures of saturated water steam in individual treatment modes are shown in Table 1. Temperatures t_{max} and t_{min} represent the temperature range in which saturated water steam is supplied to the autoclave for the implementation of the technological process. Temperature t_4 is the temperature of the saturated water steam in the autoclave after reducing the pressure of the water steam in the autoclave to atmospheric pressure, thereby enabling the safe opening of the pressure device and the selection of samples after the specified modification time.

The saturated water steam of unsteamed as well as steamed wood was dried to the final moisture content of w = 12 ± 0.5%. The drying technology was realized through the low-temperature drying mode of [27], with an emphasis on preserving the obtained color in the steaming process.

Table 1. Modes of modification of blanks through saturated water steam.

Modes	Saturated Steam Temperature [°C]			Technological Operation Time [h]		
	t_{min}	t_{max}	t_4	τ_1-Phase	τ_2-Phase	Total Time
Mode I	102.5	107.5	100	1.5	7.5	9.0
Mode II	122.5	127.5	100			
Mode III	132.5	137.5	100			

2.3. Measuring the Color of Wood

Identification of the color of wood modified by steaming individual wood species as well as unsteamed wood in the CIE L*a*b* color space was determined using a color reader CR-10 colorimeter (Konica Minolta, Tokyo, Japan) using a D65 light source with an illuminated area of 8 mm. The measurement of the color of unsteamed and steamed wood was carried out on milled surfaces at a distance of 50 mm from the front of the blanks. The measured wood color values were evaluated based on changes in the CIE L*a*b* color space where the L* coordinate represents the lightness, the a* color coordinate represents the red color and the b* color coordinate represents the yellow color.

The value of the total color difference was calculated according to mathematical Equation (1):

$$\Delta E^* = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \quad (1)$$

where L^*_1, a^*_1 and b^*_1 values represent the coordinates of the color space of the surface of dry-milled native wood, L^*_2, a^*_2 and b^*_2 values represent the coordinates of the color space of the surface of dry-milled modified wood.

2.4. Milling of Blanks

Milling of unsteamed and steamed beech, birch and maple woods was carried out using a slotted spiral milling cutter type F193–16061 (IGM tools and machines, Tuchoměřice, Czech Republic) that was installed on a CNC 5-axis machining center SCM TECH Z5 from the manufacturer SCM Group, Rimini, Italy (Figure 1). Technical and technological parameters of CNC machining center are shown in Table 2. The orientation of the blanks during milling was always the same, with the length of the blank being on the x-axis, the width of the blank being in the direction of the y-axis and the thickness of the blank being on the z-axis. The feed rate was realized in the direction of the x-axis, and the material removal was in the direction of the y-axis.

Figure 1. CNC 5-axis machining center SCM Tech Z5.

Table 2. Technical and technological parameters of CNC machining center SCM Tech Z5 (ACM Group, 2017).

Technical Parameters of CNC Machining Center SCM Tech Z5	
Useful desktop (mm)	X = 3050, y = 1300, z = 3000
Speed x-axis (m.min^{-1})	0 ÷ 70
Speed y-axis (m.min^{-1})	0 ÷ 40
Speed z-axis (m.min^{-1})	0 ÷ 15
Vector rate (m.min^{-1})	0 ÷ 83
Technical parameters of the main electric spindle with HSK F63 connection	
Rotation axis C 640°	640°
Rotation axis B	320°
Revolutions (rpm)	600 ÷ 24 000
Power (kW)	11
Maximum tool dimensions (mm)	D = 160 L = 180

High-speed machining of wood by milling was carried out on the basis of the technological conditions listed in Table 3.

Table 3. Parameters of the wood milling process.

Parameter	Value
Feed per edge (f_z)	0.074 mm
Depth of cut (a_e)	3 mm
Tool rotates (n)	18 000 rpm

2.5. Measuring the Surface Roughness of Milled Wood

At the Department of Woodworking of the TU in Zvolen, in cooperation with the company KVANT s.r.o., the laser profilometer LPM-4 (KVANT s.r.o., Bratislava, Slovakia) was constructed on which the non-contact measurement of the surface roughness of milled, unsteamed and color-modified beech, birch and maple woods was performed. Figure 2 shows a roughness meter consisting of a solid aluminum structure that ensures stabilization during the measurement of the roughness of the wood surface. Height adjustment, head positioning or camera focus are realized using screws and grooves in the beam of the fixed structure. The principle of roughness measurement with this profilometer is based on triangulation laser profilometry measurement. The created profile along the cross-section of the measured object is photographed using a Marlin F131B digital camera (Allied Vision Technologies GmbH, Stadtroda, Germany) that captures the image using a laser line at a specified angle [28].

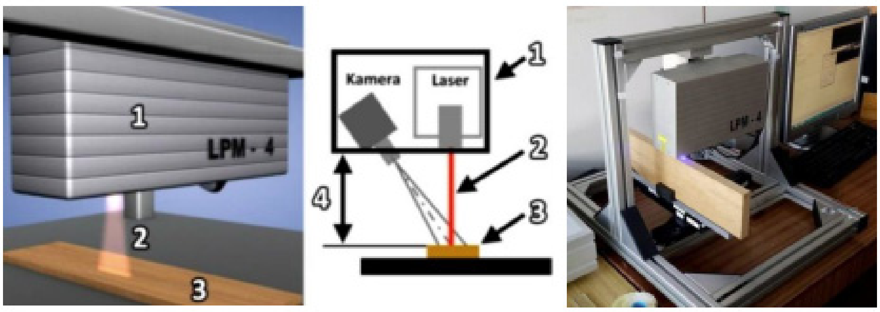

Figure 2. Operating principle of the LPM-4 as follows: 1—camera, 2—laser, 3—sample and 4—distance between the LPM–4 and the measured object.

2.6. Statistical Processing of Measured Data

From the measured data of the total color difference ΔE* of the wood of the studied trees and the roughness of the wood surface, the graphic dependences of ΔE* = f(t) and Ra = f(t) in the range of the temperatures were determined using the program STATISTICA 12 (Tibco, Palo Alto, CA, USA) where t = 105–135 °C and time τ = 9 h. Program processing of the measured results partially eliminated the influence of measurement errors caused by wood heterogeneity. The measured data were processed and the individual significance of the factors was evaluated using a multifactor analysis.

3. Results and Discussion

The process of steaming wood using the mentioned modes changes the color of the native wood from a light white-gray color with a yellowish tinge to the brown shades of the color achieved through mode I. and mode II. as well as to the dark brownish-gray color shades achieved through mode III. The saturation of wood coloring depends on the temperature of the saturated water steam in the technological process. The color of the wood in individual steaming modes is declared in Table 4, and the values on the coordinates of the CIE L*a*b color space are given in Table 5.

Table 4. The color of the wood of the studied trees in the process of steaming.

Wood	Native Wood	Wood Color Modification Modes		
		Mode I	Mode II	Mode III
Beech				
Birch				
Maple				

Table 4 lists the values on the coordinates of the CIE L*a*b* color space of unsteamed and steamed beech, birch and maple woods determined by steaming modes in a pressure autoclave.

From the measured values of the wood color of individual trees on the lightness coordinate of L* and the color coordinates of a* and b*, the total color difference of ΔE* of the wood color change in the steaming process was calculated using mathematical Equation (1). Graphical dependences of the total color difference of ΔE* on the temperature of the saturated water steam of individual modes are shown in Figure 3.

Table 5. Measured values of the wood color of the examined trees in the CIE L*a*b* color space.

Wood	Coordinates CIE L*a*b*	Native Wood	Wood Color Modification Modes		
			Mode I	Mode II	Mode III
Beech	L*	76.6 ± 2.3	66.7 ± 2.0	57.0 ± 2.1	52.5 ± 1.8
	a*	6.8 ± 1.8	10.1 ± 1.0	12.3 ± 0.9	12.7 ± 1.1
	b*	19.8 ± 1.7	20.6 ± 1.1	20.9 ± 1.1	20.3 ± 1.1
Birch	L*	83.7 ± 1.3	74.7 ± 0.8	64.3 ± 1.2	55.6 ± 0.9
	a*	6.8 ± 0.6	10.5 ± 0.7	12.5 ± 0.7	12.5 ± 0.3
	b*	19.8 ± 0.9	21.4 ± 0.6	18.5 ± 0.5	19.5 ± 0.6
Maple	L*	86.6 ± 1.2	77.4 ± 0.6	69.7 ± 0.8	61.8 ± 0.7
	a*	5.9 ± 0.5	10.6 ± 0.6	12.3 ± 0.5	11.6 ± 0.2
	b*	16.4 ± 0.5	18.3 ± 0.6	16.6 ± 0.5	17.3 ± 0.4

Figure 3. Graphical dependence of the total color difference ΔE* on the steaming mode.

The light white-gray color of native beech, birch and maple woods with a yellowish tinge was identified in the CIE L*a*b* color space with the values listed in Table 5. The measured values on the native wood color coordinates of the investigated trees are comparable to the values reported by the authors [20,23,29,30].

During the steaming process of wet wood, depending on the temperature and time, the formation of acetic acid and formic acid occurs as well as the degradation of polysaccharides in the form of the oxidation of carbohydrates and pectin and dehydration of pentoses turning into 2-furaldehyde; free radicals and phenolic hydroxyl groups also begin to form in lignin, resulting in the formation of new chromophoric groups that cause a change in wood color [31–34].

From the measured values of the lightness coordinate L*, it follows that the lightness (L_0*) of native wood has a decreasing tendency depending on the temperature of saturated water steam where at the temperature of saturated water steam t_{III} = 135 ± 2.5 °C, the lightness of beech wood decreased by ΔL_3* = 31.4%, birch wood by ΔL_3* = 33.6% and maple wood by ΔL_3* = 28.6%. The decrease in the lightness of the wood of the studied trees with the increase in the temperature of the saturated steam is not directly proportional. At higher temperatures of the steaming process, the decrease in lightness is higher and the darkening of the wood is more pronounced.

The decrease in the values of the lightness coordinate L* is in accordance with knowledge about the darkening of wood in thermal and hydrothermal technological processes such as the steaming of wood declared in the works of [19–21,35–37], drying using warm moist air or using superheated water steam [38,39].

Changes in the chromatic coordinate of red color a* have an increasing tendency. The value of the red color of native beech wood a_0* = 6.8 increases at the temperature of saturated water steam t_{III} = 135 ± 2.5 °C to the value of a_3* = 12.7. A similar increase in the red color coordinate of a* was also measured for birch and maple woods, as Table 5 declares. Significantly smaller magnitudes of changes were recorded for red color coordinate a* compared with the changes for lightness coordinate L*. The most pronounced red-brown color shade was recorded when wood was steamed at the temperature of saturated water steam t_{II} = 125 ± 2.5 °C, which is visible from the values of Δa*.

Changes in the chromatic coordinate of the yellow color b* are neither significant nor contradictory. In mode I., at the temperature of saturated water steam t_I = 105 ± 2.5 °C, a slight increase in values was recorded for all woody species, and a slight decrease or oscillation was subsequently recorded at higher temperatures. These changes indicate the formation of less stable compounds with the absorption of the spectrum of electromagnetic radiation with a yellow color wavelength of 560 nm. The said compounds react with water steam or extraction products to form other thermal decomposition products with lower or zero absorption of the yellow wavelength electromagnetic radiation spectrum.

Changes in the color of the wood of the studied trees during the steaming process, in addition to changes in the individual coordinates of the CIE L*a*b color space, were also analyzed through the overall color difference of ΔE*. The total color differences of wood color change ΔE*, which were caused by the technological process of steaming using saturated steam at a temperature in the interval between 105 °C and 135 °C, lie in the range of values of ΔE* = 8.9–28.8. Changes in the color difference are determined mainly by changes in the lightness coordinate of L* of steamed wood and, to a lesser extent, by changes in the chromatic coordinates of red color a* and yellow color b*.

From the course of changes in the color of the wood of the examined wood species in the steaming process and the total color difference of ΔE*, the following points can be made:

(a) A slight darkening and acquisition of a brown color shade of the wood in the interval of values ΔE* ≈ 8–10 occurs under the conditions of steaming beech, birch and maple woods at a temperature of saturated water steam of t_I = 105°C (Mode I);

(b) Beech, birch and maple woods at a temperature of saturated water steam t_{II} = 125 °C (Mode II) and also beech wood at a temperature of saturated water steam t_{III} = 135 °C (Mode III) acquire a significant darkening of the wood to a brown-red color in the interval of values ΔE* ≈ 16–21;

(c) Under the conditions of steaming birch and maple wood at a temperature of saturated water steam t_{III} = 135 °C (Mode III), the wood acquires a dark brown-red color. The total color difference has a value of ΔE* ≈ 23–29.

The achieved color changes in the process of steaming the wood of the studied trees were classified according to the achieved color shades and color changes according to the classified classification degrees of ΔE* given in the work of Dzurenda [40].

The process of steaming wood through saturated water steam changes the properties of the surface of the milled material (roughness) depending on the steaming temperature and the type of steamed wood, as declared in Figure 4.

Alongside the dependence of the average roughness of the milled surface of beech wood on the color change of the steamed wood, the roughness of the milled surface decreases as the value of the total color difference of ΔE* increases.

If the average roughness of the milled surface of unsteamed beech wood is Ra = 6.5 μm, then the roughness of the milled surface of red-brown beech wood acquired through steaming mode I. at the temperature of saturated water steam $t_I = 105 \pm 2.5$ °C is reduced. This reduction consists of the Ra = 12.3% roughness of the brown beech wood that was obtained through steaming mode II. at $t_{II} = 125 \pm 2.5$ °C. and decreases by Ra = 15.4%. Moreover, the roughness of steamed beech wood of a dark brownish-gray color acquired during steaming through mode III. with a temperature of $t_{III} = 135 \pm 2.5$ °C decreased by Ra = 16.9% compared with the roughness of native wood.

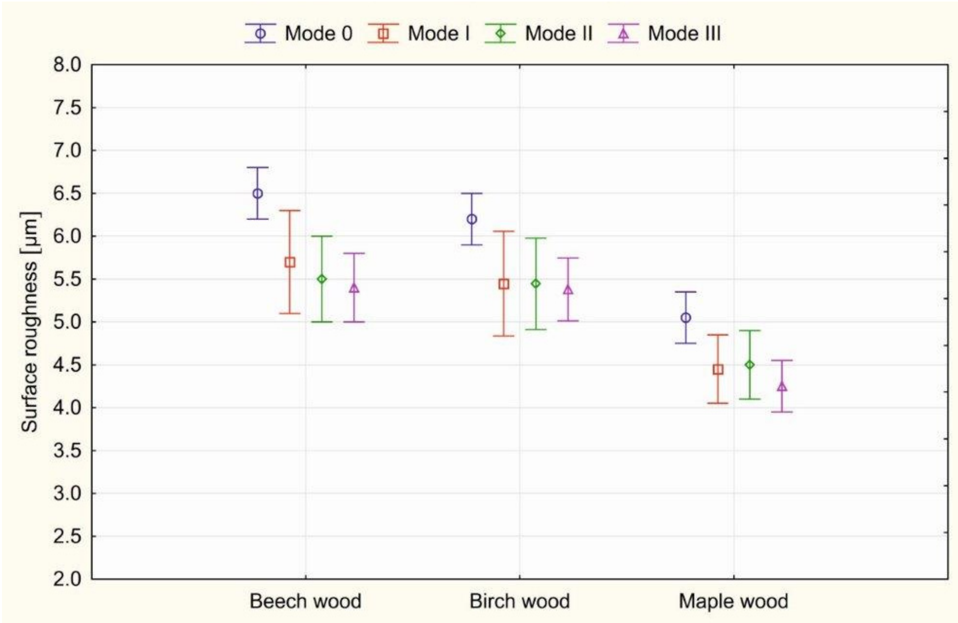

Figure 4. Graphical dependence of the average roughness of wood on the steaming mode.

Similarly, decreases in the surface roughness of steamed birch and maple woods are shown in Figure 4. When steaming birch wood, the roughness of the milled surface in individual modes decreased by $Ra_I = 12.9\%$, $Ra_{II} = 12.8\%$ and $Ra_{III} = 13.4\%$. The roughness of the milled surface of steamed maple wood represented a decrease in individual modes at the levels of $Ra_I \approx 11.9\%$, $Ra_{II} \approx 10.8\%$ and $Ra_{III} \approx 15.8\%$ compared with the roughness of the surface of native wood.

The decrease in the roughness of the steamed wood can be attributed to the increased brittleness of the wood due to the loss of amorphous polysaccharides [41]. The fragility of steamed wood causes the protrusions to break during the cycloidal movement of the tool in the machining process rather than because of the tearing off of the fibers. This fact results in the creation of a milled surface with less roughness. Authors of the study [42] state that the roughness of thermally treated wood, where an Ra value was employed, up to the thermal treatment temperature of t = 160 °C is lower than the roughness of native wood. From a thermal treatment temperature of above 160 °C, the roughness increases, and it is even higher than the roughness of native wood at a temperature of 210 °C.

From the comparison of the measured values of the roughness of beech, birch and maple woods in relation to the wood density of individual wood species, both for native and steamed wood, it follows that the roughness of the wood surface increases with increasing density. In our case, the average roughness of the surface of unsteamed beech wood with a value of Ra = 6.5 μm is 4.6% higher compared with the roughness of the surface of birch wood with an average value of Ra = 6.2 μm as well as compared with the roughness of the surface of maple wood with an average value of Ra = 5.0 μm, which is 23.1% higher.

Similar findings result from a comparison of the surface roughness of steamed beech, birch and maple woods to changes in density during the steaming process. The process of steaming wood using regime III. with saturated steam at a temperature of t = 135 ± 2.5 °C reduces the density of beech wood by 1.8%, birch wood by 4.4% and maple wood by 5.3% [25–27]. When the average value of the roughness of unsteamed beech wood is Ra = 6.5 μm, and the value of of steamed beech wood's saturated water steam is at the saturated temperature of t = 135 ± 2.5 °C and an average value of Ra = 5.4 μm, then the roughness of steamed wood is 16.9% lower, that of birch wood is 13.4% lower and that of maple wood is 15.8% lower. The stated findings are not in agreement with the work of the authors from [26] who state that surface roughness decreases with an increase in density. On the contrary, the authors from [43–45] state that the surface roughness is more affected by the technical–technological parameters of woodworking, such as removal, feed speed and revolutions of the cutting tool, than by the density of the wood.

The technological process of steaming wood through saturated water steam for the purpose of modifying the color of the wood of the studied trees was proven to have a positive effect on the milled surface, representing a higher quality milled surface. Meanwhile, the roughness of the milled surface of modified wood was lower compared with the milled surface of native wood.

4. Conclusions

The work presents the results of the color change of beech, birch and maple woods in the process of steaming wood through saturated water steam at temperatures of t_I = 105 ± 2.5 °C, t_{II} = 125 ± 2.5 °C and t_{III} = 135 ± 2.5 °C during τ = 9 h of steaming.

The technological process of wood modification by steaming the wood of the investigated woods causes a change in color from the original light white-gray color with a yellowish tinge to fine reddish-brown to dark brown color shades that are more or less saturated depending on the temperature of the modification. The color changes achieved during the modification process are identified using coordinates in the color space CIE L*a*b* and described through the total color difference of ΔE*. The changes in wood color achieved through the wood steaming process of the investigated wood species can be divided into three groups as follows: the first group consists of a slight darkening and acquisition of a brown color tone of the wood in mode I.; the second group consists of a significant darkening of the wood to a brown-red color achieved in mode II., and the third group consists of color changes to a dark brown-red color achieved in mode III.

The wood steaming process of the studied woods reduces the roughness of the wood surface depending on the steaming temperature, which means that the quality of the surface of the material increases. The reduction, compared with native wood, was found in the process of the modification of beech wood at the temperature of saturated water steam as follows: t_I = 105 ± 2.5 °C by Ra ≈ 12.3%, at t_{II} = 125 ± 2.5 °C by Ra ≈ 15.4%, at t_{III} = 135 ± 2.5 °C by Ra ≈ 16.9%. By modifying birch wood at t_{III} = 135 ± 2.5 °C, the roughness decreases by Ra ≈ 13.4% compared with native wood and by modifying maple wood, the surface roughness decreases by Ra ≈ 15.8% compared with native wood. The mechanical properties of steamed wood are affected by the loss of the amorphous parts of polysaccharides, on the basis of which we conclude that the surface roughness of the steamed wood has also been reduced. The roughness of the milled surface of the native and modified woods of the studied trees is negatively affected by the size of the material removal as well as the speed of the workpiece, which makes the milled surface of lower quality.

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