The effect of beech wood (*Fagus Sylvatica* L.) steaming process on the colour change versus depth of tested wood layer

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The results of experimental research on the colour changes of beech wood at different depths of the tested layer are presented. Beech wood (*Fagus Sylvatica* L.) dried in a conventional kiln was tested. Half of the wood samples were steamed prior to the drying process. Colour changes were measured at various depths after the face milling process was used to remove the material to expose to the deeper surface. The colour changes were measured based on the three-axis CIELAB system, recommended by CIE (Comission Internationale de l'Eclairage) and according to ISO 11664-2 and ISO 11664-4 standards. As a result of the analysis four parameters were determined: the colour changes (ΔE), the colour chroma (C_{ab}), the hue angle (h) and the colour saturation (S_{ab}).
The performed experimental research revealed that the surface of steamed wood is more susceptible to colour change. A significant colour change in both steamed and dried wood occurs only up to a depth of about 2 mm.

Keywords: beech wood, steaming process; colour change; kiln drying; depth changes

Introduction

Wood is a natural and renewable material and its use in modern architecture and civil construction is still increasing. The specific properties of wood and the development of technology for the production of wooden materials allow it to be used for building facades (Sekularac *et al.* 2012, Sekularac *et al.* 2016) and construction elements (Ahmed and Arocho 2021, Bukauskas *et al.* 2019, Miebach 2018, Sotayo *et al.* 2020). To increase the range of application of wooden materials, thermal modification of wood can be applied (Bekhta *et al.* 2017, Sandberg *et al.* 2013). Among many others, the steaming process is one of the main methods used (Colak *et al.* 2007, Peker *et al.* 2015, Yilgor *et al*. 2001). The main purpose of the thermal treatment of wood by steaming is to obtain higher plasticity of material (Šprdlík *et al.* 2016) and to form special shapes (Wright *et al.* 2013). These mechanical properties are obtained as a result of the material sterilisation and reduction of stresses occurring in it (Kudela 2009). It can be assumed that the changes in the chemical composition of wood occurring during the steaming process have a significant impact on its mechanical properties (Kacíková *et al.* 2020, Nemeth *et al.* 2016). Varga and van der Zee (2008) showed that the mechanical properties obtained as a result of the steaming process highly depend on the wood species. In the case of birch wood, Kminiak *et al.* (2020) did not see an effect of the steaming process on the chip granulation level during the frame sawing and peripheral milling processes. Timar *et al.* (2016) presented that the steaming process together with changes in chemical composition in treated wood, also causes a visible colour change. The colour change formation is a complicated process and depends on many degrading factors (McCurdy *et al.* 2005, Kudra *et al.* 2003, McDonald *et al.* 2010, Gonzalez de Cademartori *et al.* 2013). Beech wood often includes defects, such as red heartwood reaction wood (tension wood), that can significantly disturb the colour measurements. The previous studies analysed the effect of the steaming process on changes of the colour of wood on the external surface layer only. (Barcík *et al.* 2015, Klement *et al.* 2019b, Tolvaj *et al.* 2012, Geffert *et al.* 2017). Cividini *et al.* (2007) presented the results of the colour change distribution of the surface of thermally treated spruce and oak wood. Tolvaj *et al.* (2012) showed that an increase in the heat treatment temperature intensifies the surface colour change. The conducted experiments have shown that, apart from temperature, the processing time also plays a significant role in the intensity of the hue and lightness change of softwoods after the steaming process (Tolvaj *et al*. 2012, Varga and van der Zee 2008). Geffert *et al.* (2017) revealed significant changes in the lightness of beech wood after steaming. According to the studies discussed, one of the main factors influencing the change of wood colour is temperature. Igaz *et al.* (2019) showed that during the milling process of hardwood, temperatures in the vicinity of the cutting zone exceed 70° C. These are similar to the temperatures used during a conventional kiln drying process of beech wood (Bond and Espinoza 2016). Additionally, McCurdy *et al.* (2006) showed that drying temperatures of *Pinus radiata* above 60° C significantly affect the change in colour. Therefore, it is possible to conclude that the cutting process can also affect the colour of the wood machined layer. Colorimetric measurement is often used in wood quality control and in assessing the colour of final wood products subjected to drying and often machined (Klement *et al.* 2019a, Klement and Vilkovská 2019). An important parameter in assessing wood colour is its homogeneity, which determines the final appearance of the product (Abrahão 2005).

The steaming process for wood is used to achieve specific mechanical properties of the treated wood. However, we often also want to preserve the natural colour of the wood. Therefore, the goal of this study was to investigate how deep is the colour changes of beech wood after two different treatment processes: first - only conventional kiln drying process, second - carrying out the steaming process immediately before the conventional kiln drying process. This experiment will allow determining whether the wood after the steaming process and secondary machining will retain a similar colour to its natural colour.

Theoretical background

The colour changes for wood and other materials are measured based on the three-axis CIELAB system (Fig. 1) recommended by CIE (Comission Internationale de l'Eclairage) and accord to ISO 11664-2 and ISO 11664-4 standards. The system includes parameters located on individual axes, which are perpendicular to each other. The main vertical axes describes lightness (L), which is the relation between blackness and whiteness. Two horizontal axis are parameters a and b, which define the chroma (C_{ab}) and hue angle (h).

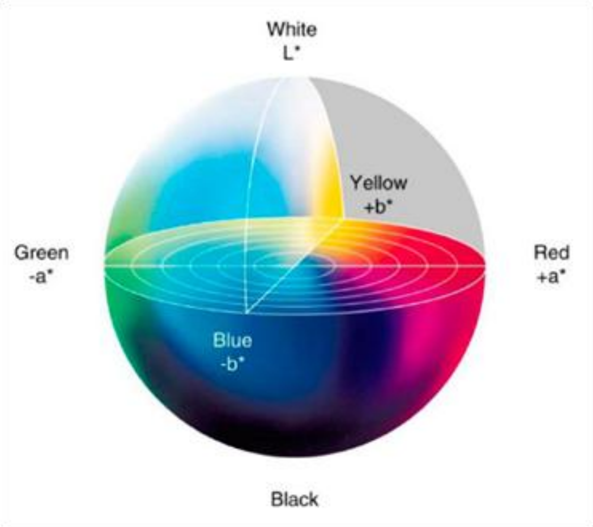


Figure 1. CIELAB colour space according ISO 11664-4 (2019), (Baranski *et al.* 2020)

The h parameter specifies the hue of the colour and is one of the main components of the colour analysis, which is defined as "the degree to which a stimulus can be described as similar to or different from the stimuli described as red, green, blue and yellow". Hue can also be represented quantitatively (Equation 1). The h parameter value often corresponds to the angular position around a central or neutral point or axis in the colour space coordinate system (Klement and Vilkovská 2019).

$$h = \tan^{-1}\frac{b}{a}\ [°] \tag{1}$$

where: h is the parameter defining the hue of wood [°], a is the chromaticity parameter defining relation between the red and green colour [-], b is the chromaticity parameter defining relation between the yellow and blue colour [-],

Colour chroma (C_{ab}) refers to the intensity of the colour. Technically, it is the term for the bandwidth of the light generated from the source, which can be described as follows:

$$C_{ab} = \sqrt{a^2 + b^2}\ [-] \tag{2}$$

Additionally, the important parameter for analysing colour is saturation (S_{ab}). The colour saturation is determined by the combination of light intensity and its distribution in the spectrum at different wavelengths, which can be described as follows:

$$S_{ab} = \frac{C_{ab}}{\sqrt{{C_{ab}}^2 + L^2}} \cdot 100\ \ [\%] \tag{3}$$

The most saturated colour is achieved using only one wavelength under high light intensity, such as laser light. As the light intensity decreases, the colour saturation also decreases. The colour changes can analyse based on the basis parameters from CIE space (L, a, b), but in this case the differences between the individual parameters need to be analysed. The overall colour difference can be determined by the parameter ΔE, as follows:

$$\Delta E = \sqrt{(L_2 - L_1)^2 + (a_2 - a_1)^2 + (b_2 - b_1)^2}\ \ [-] \tag{4}$$

where L_1, a_1, b_1 are the values of colour spectra prior to the treatment process, and L_2, a_2, b_2 are the values of colour spectra after the treatment process. The colour changes criteria according to the standard ISO 11664-4 (2019) are presented below:

$\Delta E < 0.2$: invisible colour change;

$2 > \Delta E > 0.2$: slight change of colour;

3 > *ΔE* > 2: colour change visible in high filter;

6 > *ΔE* >3: colour changes visible with the average quality of the filter;

12 > *ΔE* > 6: high colour change;

ΔE > 12: different colour.

Materials and Methods

Material and sample preparation process

The object of the study was beech wood (*Fagus sylvatica* L.) originated from Slovak forests belonging to the Technical University in Zvolen. One board of green wood randomly selected from sawmill was used to prepare samples. Twelve samples with dimensions W = 50 mm × H = 50 mm × L = 240 mm and radial sections were prepared in industrial conditions.

Half of the tested samples firstly were thermally treated by the steaming process. General parameters of the performed steaming process are summarised in Table 1. After the steaming process, the treated samples together with the remaining raw samples (6 steamed and 6 raw samples, 12 in total) were subjected to a conventional kiln drying process. Klement *et al.* (2019b) showed that the drying process of previously steamed wood does not significantly affect the colour changes of beech wood, either natural or tension wood. This process consisted of four stages: preheating, drying at 65° C until the wood moisture content (MC) reached the fibre saturation point (FSP), drying at 45° C when MC content was below FSP, and cooling down. The other specific parameters of the drying process are also shown in Table 1. The final MC values for dried samples were obtained at approximately 7.1%. All samples from both groups: only drying and steamed prior to the drying process, were stored in laboratory conditions in dark with limited ultraviolet (UV) light, ensuring a constant air temperature (T_a) of 20° C and relative humidity (*RH*) of 65%. After the drying process, all samples were conditioned in the dynamic climate change chamber MKF 115 E3.1 (BINDER GmbH – Headquarters, Tuttlingen, Germany) by four months in darkness at constant T_a = 20° C and *RH* = 65%, until final MC values about 12% were obtained. MC values were measured using the oven-drying method.

Table 1. The parameters of drying and initial steaming processes

Process	Temperature T [°C]	Pressure p [kPa]	Relative humidity RH [%]	Time t [h]	Moisture content MC [%]	
					before	after
Steaming	heating	200	100.0	3.5	64.4 ±12.4	55.4 ±3.5
	108.0	360	100.0	2.5		
	cooling down	200	100.0	1.0		
Drying	heating	101.3	65.0	1.0	58.9 ±4.6	7.1 ±0.6
	45.0	101.3	60.0	20		
	65.0	101.3	55.0	7.0		
	cooling down	101.3	-	1.0		

Process of removal the subsequent wood layers

The face milling process was used to remove consecutive layers of analysed wood samples. The milling process was carried out on the 5 axis milling centre AX320 Pinnacle located in the laboratory of the Gdańsk University of Technology (GUT) using the end milling cutter manufactured by ASPI company, Suwalki, Poland. This cutter has two soldered blades from cemented carbide. The main parameters of the milling process, such as cutting speed $v_c = 3.69$ m·s^{-1} (rotational speed n = 4405 min^{-1}) and average uncut chip thickness h_{av} = 0.18 mm (feed speed v_f = 2848 mm·min^{-1}), were selected–taking into account the results presented by Igaz *et al.* (2019). The milling process, with selected main parameters, should not generate a temperature above 50° C. This should significantly reduce the effect of the cutting process on the change of colour of the processed wood. All work movements of the cutting tool were performed by the machine tool in accordance with the CNC programme on the Heidenhain TNC640 control system. The samples to be machined were clamped in a vice with jaws of 100 mm long and were supported from below on the whole surface of the sample by a steel plate. The main cutter dimensions and milling process parameters are presented in Table 2.

Table 2. Main parameters of milling cutters and milling processes.

Milling cutter settings			
Name of parameter	**Symbol**	**Unit**	**Value**
Tool diameter,	D_c	mm	16
Shank diameter,	d_o	mm	12
Number of teeth,	z	–	2
Tool length],	L_t	mm	70
Working length of the tool	L_c	mm	35
Side rake angle	γ_f	°	3
Side clearance angle	α_f	°	25
Tool cutting edge angle	κ_r	°	90
Cutting edge inclination angle	λ_s	°	2
Material of edges	–	–	HM
Milling processes settings			
Name of parameter	**Symbol**	**Unit**	**Value**
Cutting speed	v_c	$m \cdot s^{-1}$	3.69
Spindle speed	n	min^{-1}	4405
Feed speed	v_f	$mm \cdot min^{-1}$	2848
Feed per tooth	f_z	mm	0.32
Average uncut chip thickness	h_{av}	mm	0.18
Cut depth	a_p	mm	2.5
Cut width	a_e	mm	5

Methodology of colour parameters measuring

The main colour parameters (L, a, b) for each sample were measured using Colour Reader CR-10 (Konica Minolta, Inc., Tokyo, Japan). The colour parameters for each sample were measured on 11 layers (0 - 10), where layer 0 was the raw surface of the sample after heat treatment, uncut. The subsequent layers (1, 2, 3, ...,10) represented the surfaces after the removal of successive layers of material with a depth of 2.5 mm (Figure 2). The measurements were taken at four points (Figure 2) on each layer. The last layer was located approximately at mid-depth of the sample. The measurements of colour parameters were made directly after the removal of each layer, without unclamping the specimen from the vice.

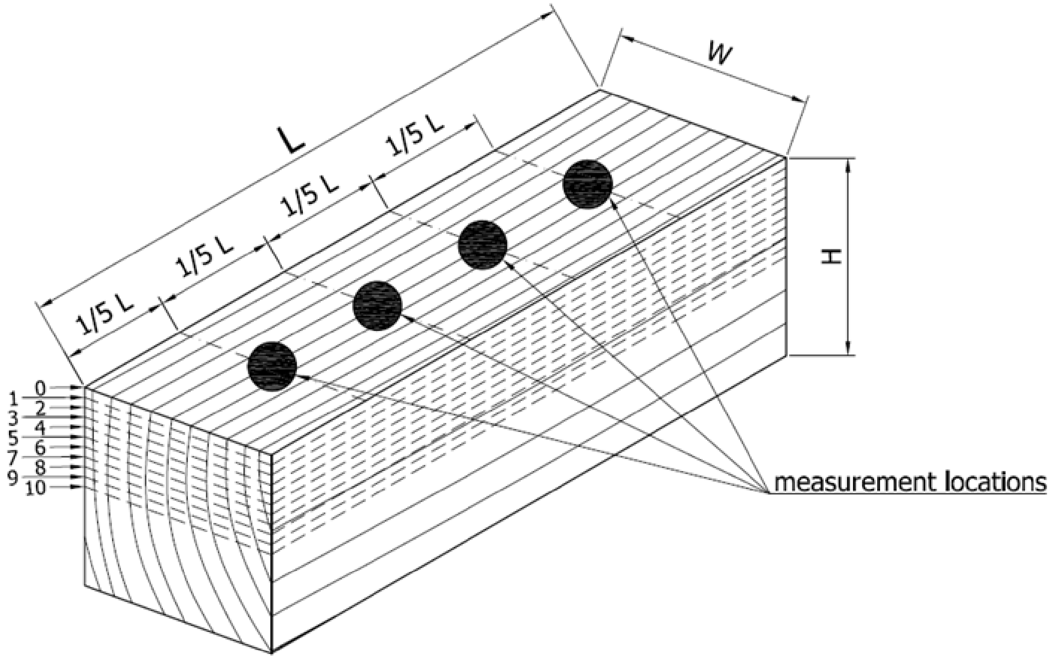


Figure 2. Sample and location on the sample of successive measurement layers.

Results and Discussion

The mean values and standard deviation of the measured parameters determining the surface colour of the tested samples are summarised in Table 3. Based on the results of the colour parameters (*L*, *a*, *b*) measurements on the surface of the tested samples, it was found that the steamed wood has a darker surface colour, which is indicated by the lower value of lightness (*L*). The determined values of the lightness parameter (*L*) and the other parameters (*a*, *b*) for the samples additionally subjected to the steaming process, are very similar to the values obtained in previous works discussing the steaming process of beech wood (Timar *et al.* 2016, Varga and van der Zee 2008).

Table 3. The mean values and standard deviation of the measured parameters (*L*, *a*, *b*) determining the surface colour of the beech wood, for both treatments: only drying and additionally steamed before drying.

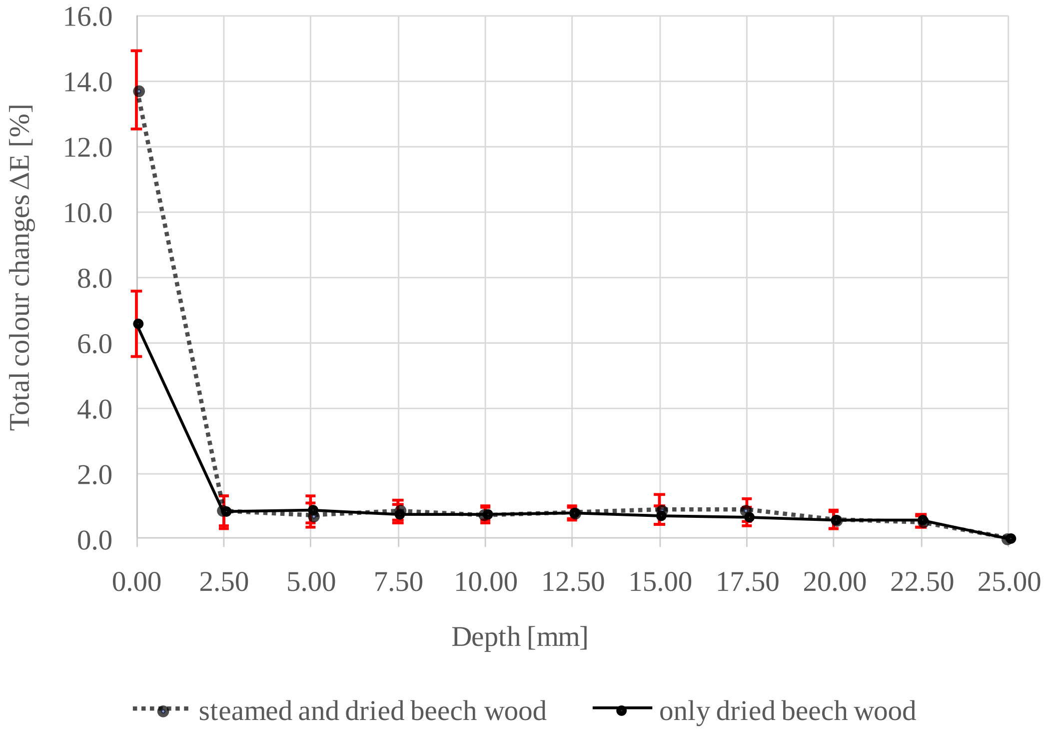
	Steaming before drying			**Only drying**		
	L	***a***	***b***	***L***	***a***	***b***
Average	56.15	14.33	20.43	61.25	10.98	20.45
Standard deviations	1.11	0.65	0.47	1.12	0.42	0.21

The values of basic parameters of colour changes ΔE between external layer (layer 0) and selected internal layers are presented in Table 4. A significant phenomenon is the occurrence of strongly noticeable differences between the external layer and the first internal layer (layer 1 depth = -2.5 mm). In contrast, the difference between the first internal layer and the centre of the sample (layer 10 depth = -25 mm) is negligibly small (Table 4).

Table 4. The average total colour change with standard deviations between the indicated layers.

Layers	Steaming before drying		Only drying	
	$\Delta E_{av.}$ [%]	**Description**	**$\Delta E_{av.}$ [%]**	**description**
0-10	13.73 ± 1.19	different colour	6.58 ± 1.01	high colour change
0-1	13.01 ± 1.19	different colour	6.36 ± 1.01	high colour change
1-10	0.78 ± 0.36	slight change of colour	0.81 ± 0.52	slight change of colour

These strongly noticeable differences in colour between the external layer and the first internal layer were observed for both analysed wood heat treatments methods: kiln drying and with additionally steaming prior to the drying process. Nevertheless, for steamed wood the values of the parameter describing the colour difference are double. The mean values of the ΔE parameter together with the standard deviations for the individual internal layers of material in relation to the layer at the centre of the sample (layer 10) are presented in Figure 3. In Figure 3 it is possible to observe the course of colour change~~s~~ between the raw external layer and the successive internal layers for both analysed treatment processes. This course of colour changes is more clearly illustrated by the condensed data in Table 4. Very noticeable for both processes are the significant differences in colour between the raw external layer and the first internal layer, the depth of which was 2.5 mm. The differences between the internal layers are not strongly noticeable. This means that both the kiln drying process and the process with additionally steaming before kiln drying change the colour of the wood on the external surface, but these changes are not significant in layers deeper than 2.5 mm.



material inner layers with reference to the layer located in the middle of sample.

Varga and van der Zee (2008) showed that changes in the colour of external surfaces as a result of the steaming process can be correlated with a decrease in wood hardness of up to 25%. The differences in values of parameter *ΔE* for the external surfaces of kiln-dried and additionally steamed wood before are significant, but already at a depth of 2.5 mm these values for both treatments are almost identical (Figure 3). The values of individual parameters describing colour determined for all the internal layers (from layer 1 to layer 10) for both treatments methods are presented in Table 5.

Table 5. The mean and standard deviations of the colour parameters for the middle layers of only dried and additionally steamed before drying beech wood samples.

	Steaming before drying			**Only drying**			**Colour Difference**
	L	***a***	***b***	***L***	***a***	***b***	**ΔE [%]**
Average	68.82	10.23	17.13	67.28	10.65	17.90	1.78
Standard deviations	0.30	0.16	0.12	0.80	0.33	0.39	0.84

The strongly noticeable differences in colour changes on the raw surfaces for the two analysed treatments were the cause for extended tests on steamed samples. The steamed samples were subjected to additional colour change measurement tests to verify the effect of the steaming process on the material colour in the depth range of 0 - 2.5 mm. Subsequent levels of colour measurement were carried out in 0.25 mm increments. The results of this additional test are shown in Figure 4.

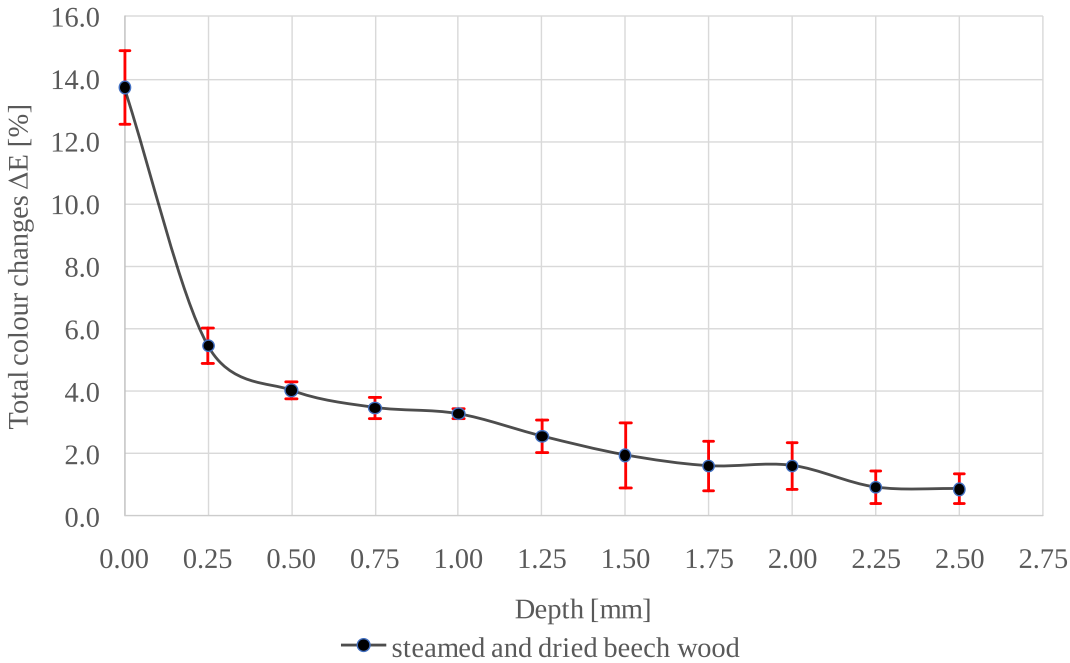


Figure 4. Total colour changes parameter ΔE_{av} with the standard deviations for the individual material inner layers with reference to the layer located in the middle of sample for additionally steamed before drying wood.

The results presented in Figure 4 show that beech wood samples subjected to the steaming process show strong colour changes on the wood surface. However, these changes already decrease to values below the changes caused by the drying process after removing a layer of material 0.25 mm thick. Based on the results obtained, it was found that the change in the colour of the wood occurs only in the surface layers, at the depth not exceeding 2 mm. This phenomenon allows assuming that both heat treatment processes (kiln drying and steaming before drying) change the colour of the wood surface. Significant colour changes due to the steaming process of beech wood were also demonstrated by Timar *et al.* (2016). However, significant colour changes were combined with only minor changes in FTIR spectra. Based on the results obtained for the depth of colour changes as a result of the steaming process of beech wood, it can also be assumed that the changes in wood hardness shown by Varga and van der Zee

(2008), as a result of the same process, can also only occur to a certain small depth of material. The applied Janka method, traditionally used to measure wood hardness, deforms the material to a depth of 5.642 mm. Thus, to verify the depth of change in wood hardness as a result of steaming, another method, requiring a much smaller depth of deformation, would have to be used, or a special methodology would have to be applied. However, if the production process still includes machining after the heat treatment processes, the layer of material with the changed colour might be removed and the colour of the machined surface will be similar to the colour of the material internal.

Statistical analysis of total colour changes (Figure 5) showed that the colour change between layer 1 (after the removal of 2.5 mm of material from the surface) and the layer in the centre of the sample (layer 10) for dried and steamed wood was within the range of $0 < \Delta E < 2$, which is interpreted as a slight change of colour. The obtained results proved that after removing 2.5 mm of material from the surface of beech wood (dried and additionally steamed before drying), the colour change in the cross-section is insignificant.

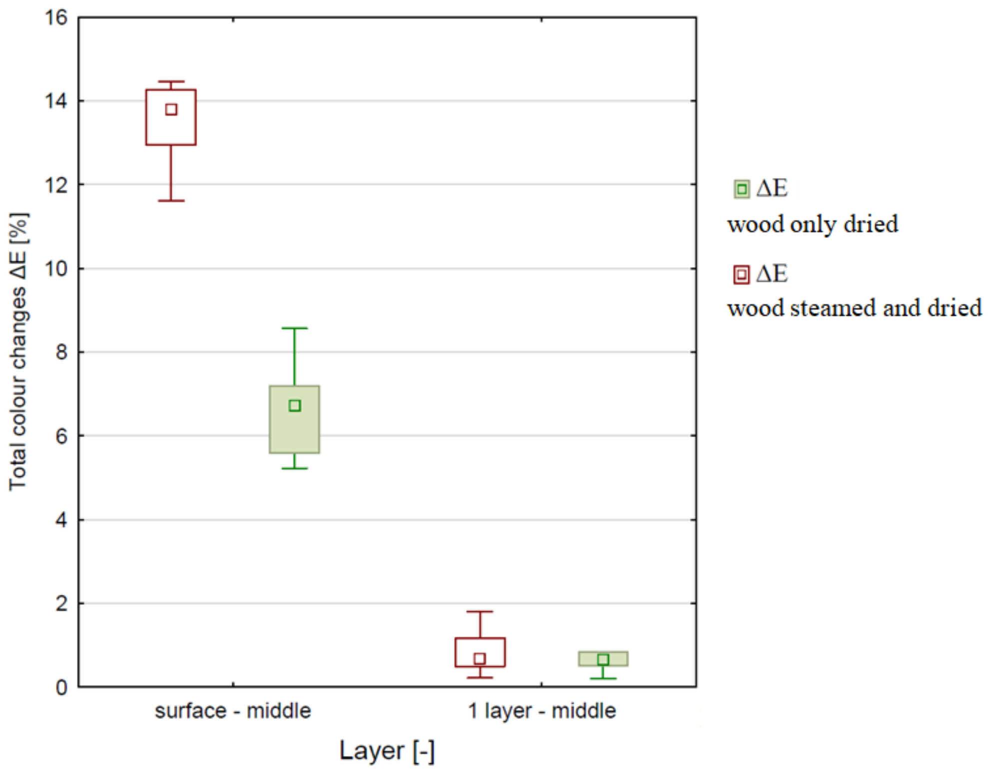


Figure 5. Total colour changes ΔE between layers: 0 – 10 (surface-middle) and 1 – 10 (first layer-middle) for both processes: only drying and steaming before drying process.

The obtained results of the colour chroma parameter are summarised in Figure 6. The graphs show the C_{ab} parameter for the surface layers (layer 0) and for the other layers (layers from 1 to 10). On the basis of the obtained results, slight differences were found in the values of the colour chroma parameter into only dried and additionally steamed before drying samples. For both cases, a decrease in the values of the chromaticity colour parameter inside the sample was observed. The range of the C_{ab} parameter in internal layers is comparable to the surface layer, which indicates its uniformity in the cross-section of the tested material, both after the drying and steaming processes.

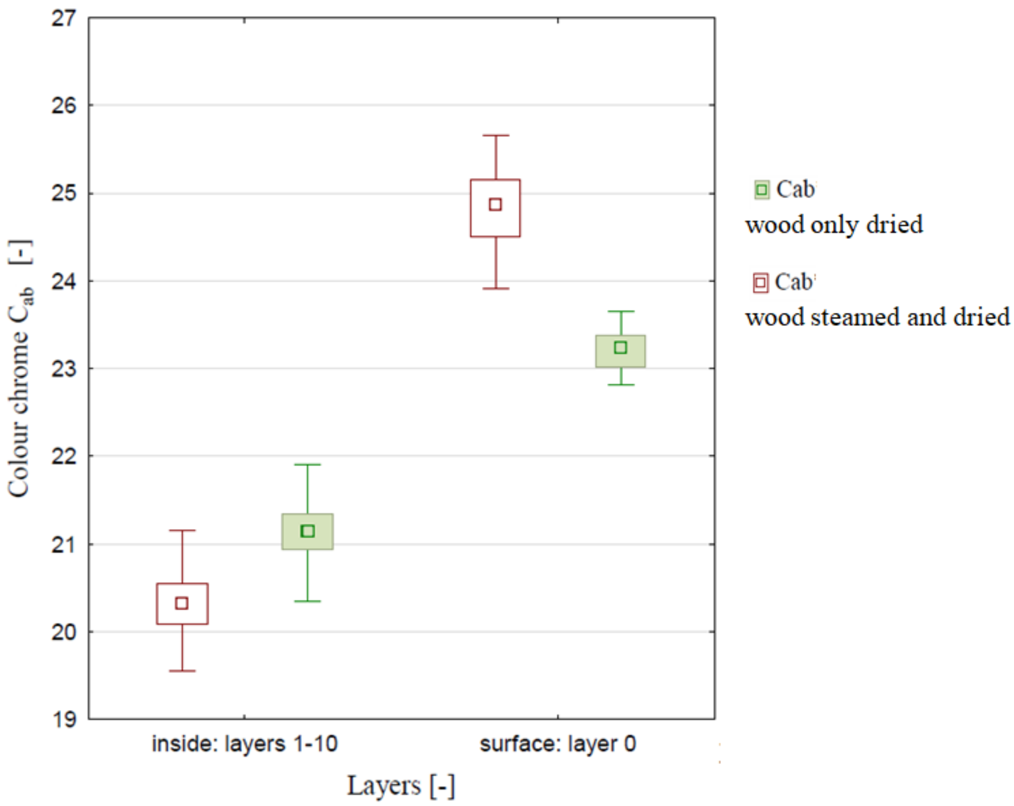


Figure 6. Colour chroma C_{ab} in the surface layer and in the cross-section of the wood for both processes: only drying and steaming before drying process.

On the basis of the obtained results (Figure 7), analogous tendencies of decrease in the value of the parameter determining colour saturation (S_{ab}) for the internal layers of dried and additionally steamed before drying wood were found. Inside the tested samples, the value of the S_{ab} parameter is stabilised (the range obtained for the inner layers is only 1.8% for dried wood and 3% for steamed wood). Dried wood can be characterised by a decrease in the value of the colour hue angle (h) parameter after removal of the first layer of material. In the case of steamed wood, an increase in values are observed in excess. In both cases (steamed and dried wood), the *h* parameter stabilises inside the tested samples, as indicated by a small range of the obtained *h* values (Figure 8).

The colour changes as a result of steaming only occur at the small depth of material. Therefore, if the material were subjected to additional machining that would remove the layer with the colour change, it would be possible to obtain wooden components with the natural colour of beech wood. However, the additional removal of the surface layer would generate more material waste, which would increase the cost of the manufacturing process, and would indeed have a negative impact on the sustainable use of sources of the natural material wood. Therefore, it is important to properly design the manufacturing process of wooden components in such way that the process of removing the layer with the colour changed as a result of the steaming process was connected with the necessary machining operations to obtain the expected dimensions and surface quality. This will not generate additional waste and will allow users to enjoy the natural colour of the wood.

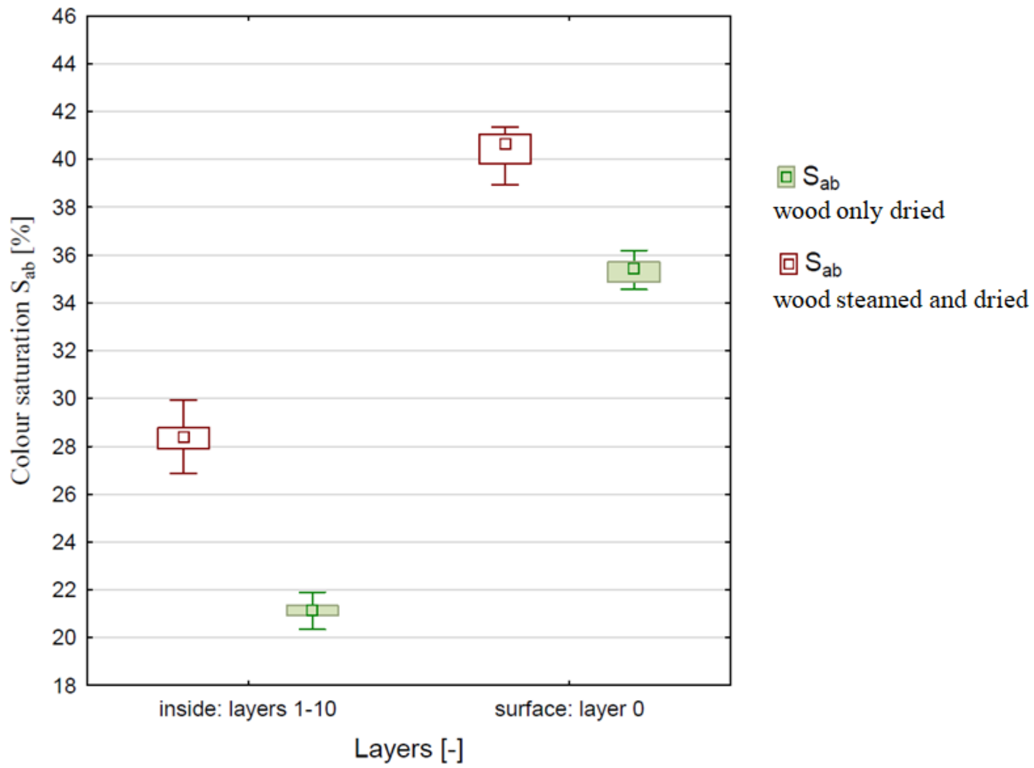


Figure 7. Colour saturation S_{ab} in the surface layer and in the wood cross-section for both processes: only drying and steaming before drying process.

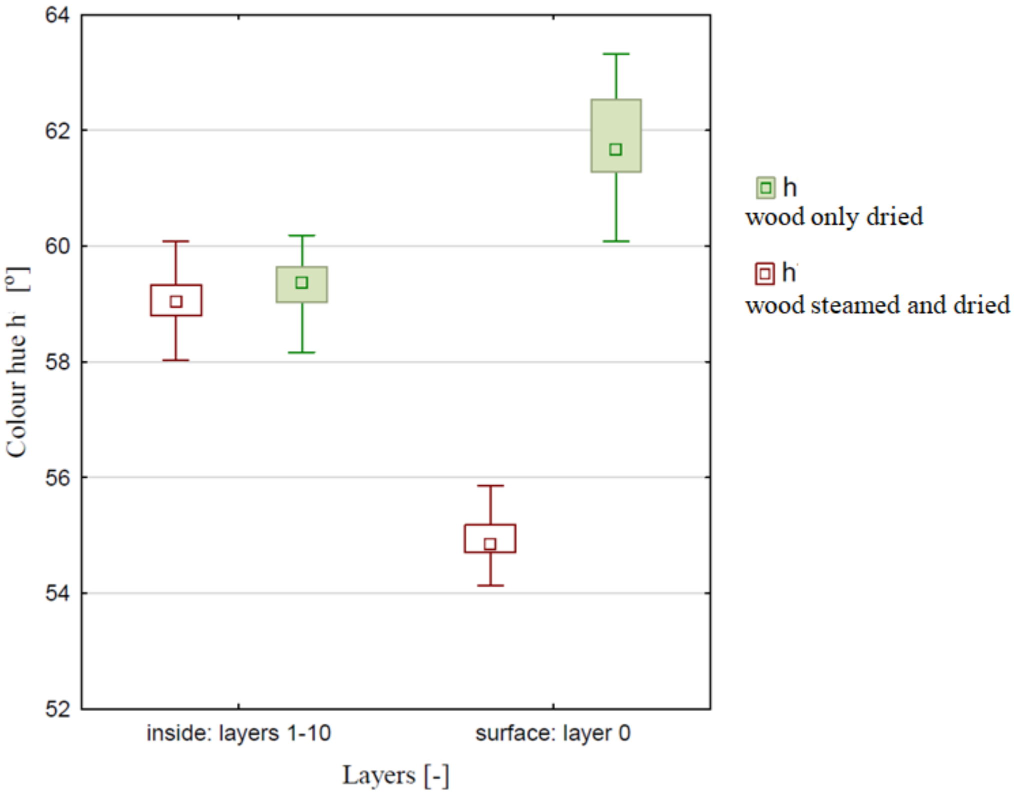


Figure 8. Colour hue angle *h* in the surface layer and in the wood cross-section for both processes: only drying and steaming before drying process.

Conclusions

On the basis of the carried out experimental tests and analysis of obtained results, it can be concluded that

- Both the kiln drying process and the process with steaming before drying change the colour of the outer surfaces of beech wood in relation to its inner layers.
- The steamed wood before drying has a darker surface colour than only conventionally dried wood, as evidenced by the lower lightness value (L).
- The steaming process of beech wood changes the colour of the external surface to a much greater extent than the drying process alone (double).
- Colour changes on the external surface of beech wood in both analysed processes occurred only at a small depth (up to about 2 mm).
- The tests showed slight differences in the colour of the internal layers between dried and steamed beech wood.
- On the basis of the obtained results, slight differences were found in the values of the colour chroma (C_{ab}) and colour saturation (S_{ab}) parameters in dried and

steamed samples. A decrease and stabilisation of parameters inside the sample was observed in both considered cases.

- Dried wood is characterised by a decrease in the value of the colour hue angle (*h*) parameter after the removal of the first layer of material. In the case of steamed wood, an increase in values was observed in excess. In both cases (only dried wood and wood steamed before drying), the parameter *h* stabilises inside the tested samples.

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