Deformation and Surface Color Changes of Beech and Oak Wood Lamellas Resulting from the Drying Process

Jacek Barański,[a] Aleksandra Konopka,[b] Tatiana Vilkovská,[c] Ivan Klement,[c] and Peter Vilkovský [c]

The drying process was examined relative to parameters' influence on the deformation and surface layer color changes of beech wood (*Fagus sylvatica* L.) and oak wood (*Quercus robur* L.). The goal was to analyze the impact of drying process conditions, wood and growth rings types, and load on the deformation and surface color changes of drying thin wooden elements. A further aim was to reduce the time of the lamella drying and minimize wood products defects. During each drying, 40 pieces of wood were dried, divided into two groups. For the first group, 30 pieces were dried under a uniformly distributed load of approximately 50 kg, while for the second group, 10 samples were dried without weight. The lamellas dried under load exhibited fewer cup, bow, and twist deformations than the lamellas dried without load. Cracks in the dried lamellas occurred comparably in those dried under and without load. Color changes in the specimens before and after drying were observed and measured. The differences in colorimetric parameters (*a*, *b*, and *L*) between wood without defects and with defects were less marked after drying than before drying. The color changes were only noticed in the surface layers of the specimens.

Keywords: Wood drying; High temperature wood drying; Wood deformation; Tension wood; Wood lamellas; Moisture content

*Contact information: a: Department of Energy and Industrial Apparatus, Faculty of Mechanical Engineering, Gdansk University of Technology, Gdansk, Poland; b: Department of Manufacturing Engineering and Automation, Faculty of Mechanical Engineering, Gdansk University of Technology, Gdansk, Poland; c: Department of Wood Technology, Faculty of Wood Sciences and Technology, Technical University in Zvolen, Zvolen, Slovakia; *Corresponding author: jbaransk@pg.edu.pl*

INTRODUCTION

The drying process of fresh timber is one of the most important processes when manufacturing wood products. The aim of drying is to ensure the dimensional stability of the timber before it is used in structures or manufactured items (Mills 1991; Gard and Riepen 2008; Baranski *et al.* 2014). The increasing customers' requirements and expectations puts pressure on wood products manufactures to reduce the time of the process and to achieve better optimization. Slow drying can maximize the stability, but it takes a long time and may be uneconomical. Therefore, most drying kiln practices dry timber as fast as possible without causing excessive defects (Walker 1993; Sedlar and Pervan 2010). The whole process affects the deformations, surface checking, and discoloration, and therefore the product quality and manufacturing costs. During this process, wood is subjected to complicated internal stresses. These arise when the outside of a piece of green wood dries below the fiber saturation point (FSP) and tries to shrink before the interior is ready for shrinkage. These stresses are greatly influenced by the temperature and relative humidity of the drying environment.

For the above reasons, a good drying process is very desirable with respect to the lumber and timber industries. A good drying process may prevent the lumber from developing outer and inner cracks, as well as several other defects, and it can increase the lumber strength. Initial drying conditions can be set up that will avoid surface and end checks, retain maximum dimensions, and minimize warping. Intermediate and final kiln conditions can be modified to speed drying without fear of internal defects. To relieve residual stresses at the end of drying process and thus avoiding distortion when material is re-sawed or machined to an asymmetric pattern, the final conditioning treatments must be used (Barański *et al*. 2017; Baranski 2018; Klement *et al*. 2019). On other hand, low quality of dried lumber not only affects the wood's monetary value, but also affects several of its workability properties, including those of planing, shaping, turning, boring, mortising, and sanding (Gu *et al*. 2004). Also for aesthetic reasons, wood color must also remain as uniform as possible (Keey 2005). The main factors that cause changes in wood properties such as color and drying defects include wood species characteristics such as density and chemical composition (Möttönen 2006), presence of extractives (Burtin *et al*. 1998; Luostarinen and Möttönen 2004; Keey 2005), tree age (Chowdhury *et al*. 2005), longitudinal position of the log in the standing tree (Ofori and Brentuo 2005), initial wood moisture content (Ofori and Brentuo 2005; Moya and Muñoz 2008), drying schedule (Simpson 1999; Gu *et al*. 2004), and presence of sapwood and heartwood (Yamamoto *et al*. 2003), as well as wetwood (Gu *et al*. 2004).

Lamellas are defined as the top layer of multilayer parquet elements or three-ply engineered floorboard (Kujawińska *et al.* 2020), Fig. 1. They are usually cut away from dry lumber. The thickness of this material is the most important dimensional property influencing drying time, because it affects the evaporation surface per volume (Güngör *et al.* 2010). As the thickness decreases, the evaporation surface of the material increases, and warping can occur.

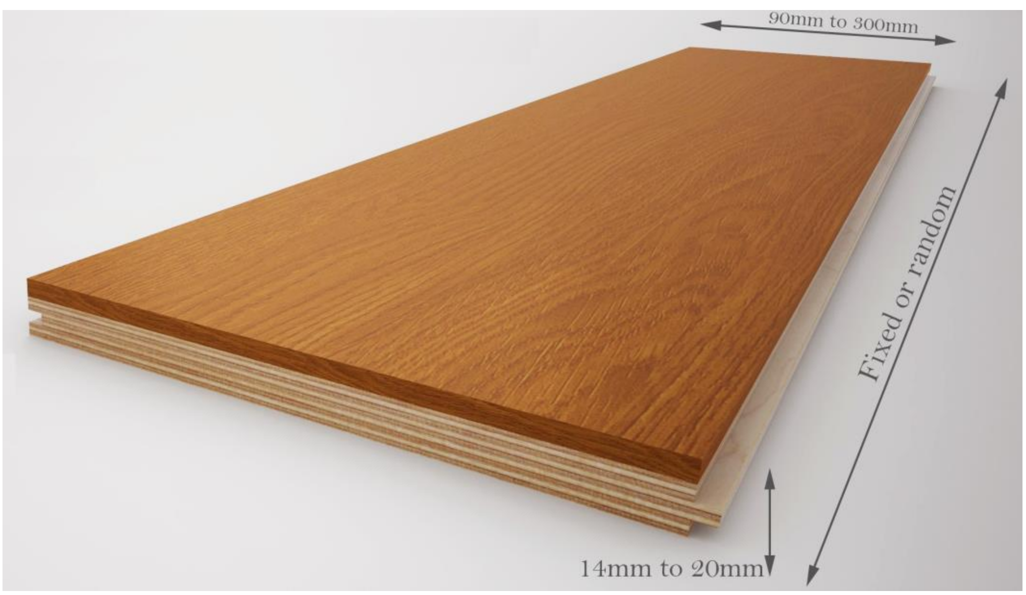

Fig. 1. View of lamella in the floor (Permission granted by Wood and Beyond; Sapir 2013)

Warping is caused by anisotropic shrinkage. Spiral grain, cross grain, reaction wood, and juvenile wood contribute to this deformation. Warping frequently causes serious problems in the wood construction industry. Wood can warp in several different ways, depending on the cause. The following types of deformation are distinguished: bow (lumber deviates from flatness lengthwise, but not across the face), twist (turning of four corners of any face of a board such that they are no longer in the same plane), cup (lumber deviates from a straight line across the width of the wood), crook (there is movement along one edge of the lumber), kink (lumber deviates edgewise from a straight line from end to end), and checking. The cup deformation may occur in two directions, the xz-plane and the yz-plane, and this is often termed cup and bow deformation (Gereke *et al*. 2011). The cup is towards the saw cut because the board surface is in compression, while the core is under tension. It will also press the saw during cutting. Furthermore, bow deformation may also occur when there is too much machining on one surface of the board. These deformations are not desirable; the boards should be free of such stresses and have stable dimensions after kiln drying (Walker 1993; Sehlstedt-Persson and Wamming 2010).

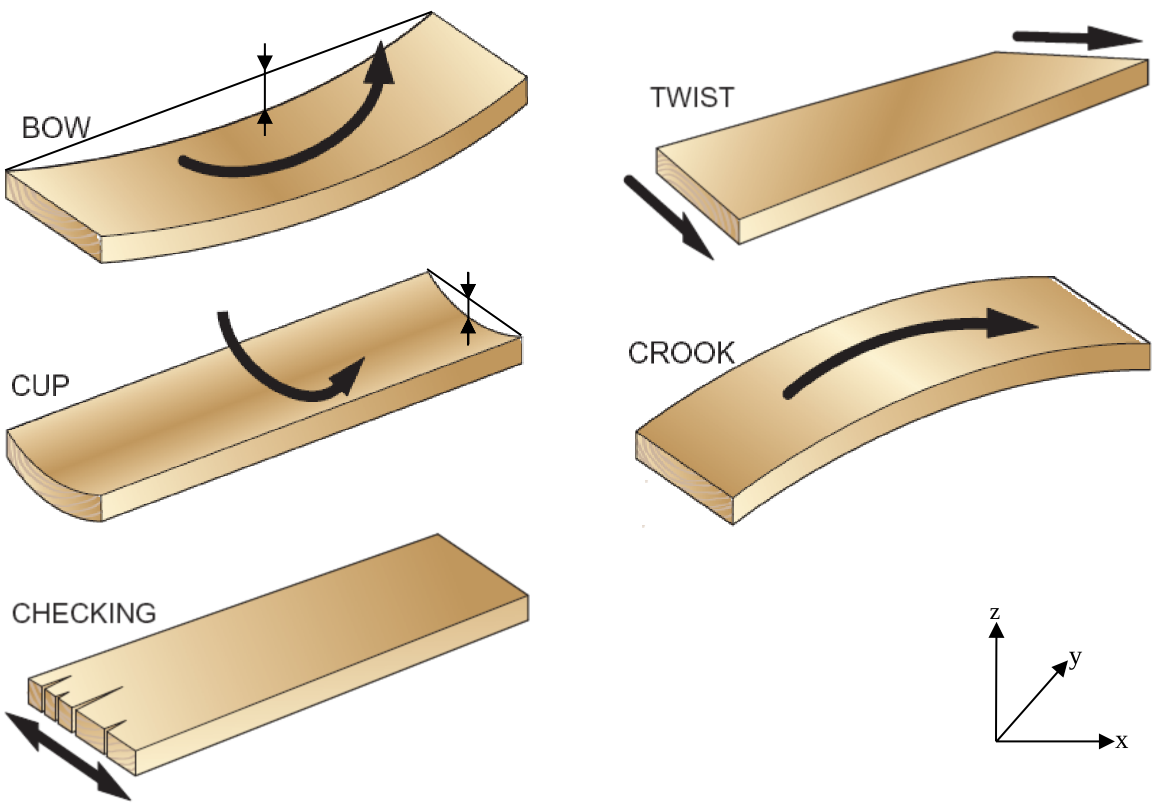

Fig. 2. Examples of wood deformations (Permission granted from Woodcraft magazine; Hurst-Wajszczuk 2008)

Twist usually causes the most severe problems, leading to wood downgrading and increasing the chance of substitution of wood with other engineering materials (Perstorper *et al*. 1995; Forsberg and Warensjö 2001). Checking means that the wood cracks at its ends; this occurs during drying when stresses exceed ultimate tension levels. It is a serious problem in timber drying and was noticed that it can reduce wood strength and quality (Kollman and Côté 1984).

Taking into consideration only cup warping, Trebula and Klement (2002) described the deformation effect of the cup type (cross warping) using the proposed parameter *K*. Warping defect can be minimized by restraint (Walker 1993). However, it may cause surface checking. Furthermore, Sharma *et al*. (1988) found that the incidence of warping and crooking could be reduced by the balanced tangential sawing technique (Sharma *et al*. 1988). The average of cross warping was in the range of 1.8% to 2.8%. Statistical analysis of the measured values showed that the thickness of the specimens is an essential factor affecting the size of the cross warping (Klement and Huráková 2016). The drying temperature level was not considered statistically significant. The values of standard deviation were lower for the thickness of 32 mm than for the thickness of 25 mm. This result indicates that the thickness has a positive effect on the size of the cross warping (Klement and Huráková 2016).

EXPERIMENTAL

The authors undertook research to reduce the time of the lamella drying in a semi-industrial convection drying kiln and to minimize wood defects. After experiments the impact of drying process conditions, wood and growth rings types, and load on the deformation and surface color changes of drying thin wooden elements was analyzed.

The drying processes were performed in a drying kiln with a 0.55 m^3 load capacity. The drying kiln is dedicated for all timber species of final moisture content to 6% in the high temperature of up to 150 °C. Superheated steam was using a steam generator, which maintained a constant temperature and relative humidity inside the drying kiln. Heat was supplied to the kiln, thanks to hot flue gas, with a heat exchanger located inside the drying kiln. The heat exchanger was supplied by exhaust gas generated in the external combustion chamber.

Steam circulation inside the drying chamber was forced with a fan. The speed of the drying medium could be increased up to 5.5 m/s. The temperature inside the drying kiln during experiments was set from 70 °C to 80 °C, while the relative humidity was set between 90% and 74%. The wood moisture content during the drying processes was measured inside the material at 8 positions of the drying kiln. It was possible to measure it at several characteristic points of the kiln's volume, *e.g*., at the middle and at the outer layers of the wood stack. The system that controlled the drying process was located outside the dryer. The thermocouples (four pieces) measured temperature inside the kiln and temperature inside the wood in 3 chosen locations in the dryer's volume. The drying medium parameters inside the kiln were measured using an E+E Elektronik EE31 humidity/temperature transmitter (E+E Elektronik Ges.m.b.H, Engerwitzdorf, Austria) with accuracies of 1.3% for humidity and 0.2 °C for temperature. The drying process was organized by the control system in two-stage process (Baranski 2018; Klement *et al*. 2019).

The moisture content of the dried wood was measured using the moisture content sensors based on resistance. Before and after the drying process, samples were taken to determine the absolute moisture content of the wood using the gravimetric method (Eq. 1) and a precision balance (PS 510.R1, Radwag, Radom, Poland) with a measurement accuracy of 0.005 g. Drying to an absolutely dry condition was performed in a laboratory kiln at 103 °C ± 2 °C. Moisture content (w) (%) was calculated using Eq. 1,

$$w = \frac{\mathrm{m_w} - \mathrm{m_0}}{\mathrm{m_0}} \cdot 100\% \tag{1}$$

where m_w is the weight of the wet specimen (g), and m_0 is the weight of absolutely dry specimen (g).

The experiments utilized 40 beech lamellas (*Fagus sylvatica* L.) and 40 oak lamellas (*Quercus robur* L.). The dimensions of the tested lamellas were 10 mm (thickness) × 205 mm (width) × 1425 mm (length), as shown in Fig. 3.

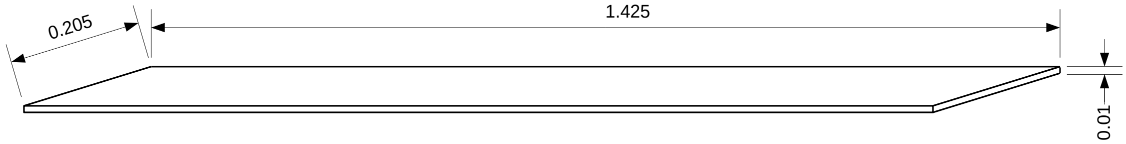

Fig. 3. The main dimensions (in m) of the wood lamellas prepared for the drying process

For the purpose of the experiment, similar samples were selected without visible defects. Other samples were used to fill the space of the dryer. Before the experiments, all samples were measured (main dimensions and color), and the densities and moisture contents of five selected samples were also measured.

The drying process was performed twice (for each species of tested wood) with the same drying schedule. During each test, 30 lamellas under a uniform distributed load of 50 kg and 10 pieces without weight were dried. In addition, wooden lamellas were selected with different angles of growth rings (15 radial and 15 tangential). In 10 lamellas, tension wood was marked. For detailed observation, detection of reaction beech wood in the lamellas was also provided by a chemical reagent that was developed at the Technical University in Zvolen (Zvolen, Slovakia). Figure 4 shows the drying kiln and an arrangement of lamellas before the drying process.

Fig. 4. View of the drying kiln and lamellas' stack before drying process

Color changes in the CIELAB color space (Fig. 5) were determined using an SP60 Portable Sphere Spectrophotometer (X-Rite, Inc., Grand Rapids, MI, USA).

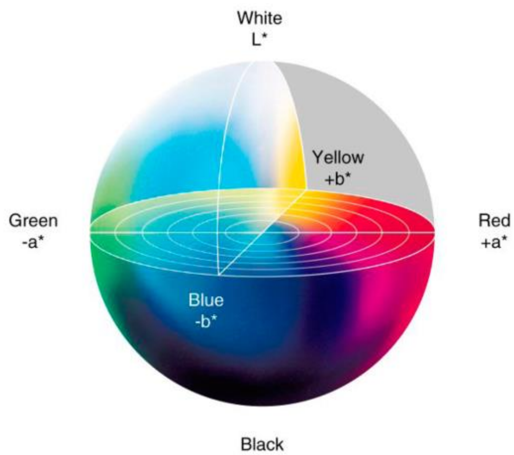

Fig. 5. CIELab color space; ISO 11664-4 (2008)

The color parameters were measured in the same places before and after drying (Fig. 5). The color changes were obtained as a comparison of the measured values with the parameters $L*$, $a*$, and $b*$ before drying, after the compressed steam treatment, and after drying ISO 11664-4 (2008). The color difference was calculated using Eq. 2,

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

where L_1^*, a_1^*, and b_1^* are the values of the color spectra before the drying process, and L_2^*, a_2^*, and b_2^* are the values of the color spectra after the drying process.

The parameters $L*$, $a*$, and $b*$ are coordinates of the colorimetric space (Allegretti *et al*. 2008). The results were evaluated using the following color criteria:

$\Delta E* < 0.2$: non-perceptible color change,
$2 > \Delta E* > 0.2$: slight change of color,
$3 > \Delta E* > 2$: color change perceptible in high filter,
$6 > \Delta E* > 3$: a color change perceptible with the average quality of the filter,
$12 > \Delta E* > 6$: high color change,
$\Delta E* > 12$: different color.

The color measurements were performed in 3 locations on 10 lamellas under load and 10 pieces without weight before and after drying process for each wood types shown in Fig. 6.

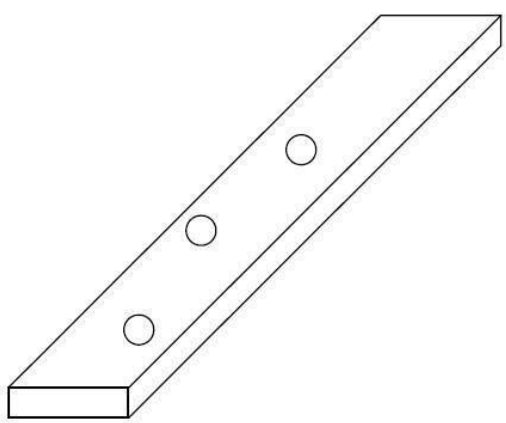

Fig. 6. Explanatory figure of the samples' locations used for measuring color changes

RESULTS AND DISCUSSION

During the same two identical drying processes, a total of 80 lamellas of beech and oak wood were dried. Figure 7 shows the changes in drying medium temperature, relative humidity, and wood moisture content during the drying process.

The drying time with a temperature of 80 °C was approximately 54 h, and the relative humidity of the drying medium was approximately 74% (in the third drying phase).

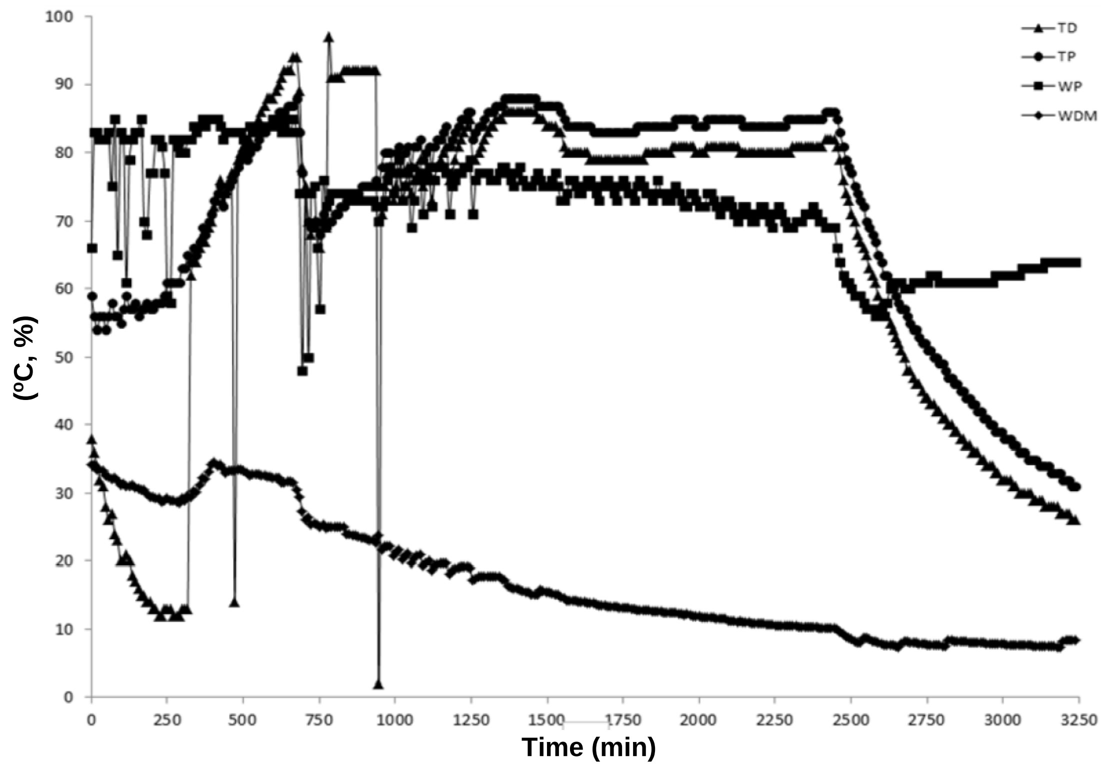

Fig. 7. The variable changes during the beech wood drying process: TD – wood temperature (°C); TP – drying medium temperature (°C); WP – drying medium humidity (%); and WDM – wood moisture content (%)

The first step in analyzing the lamellas' quality after drying was the gravimetric comparison of wood moisture contents before and after drying (Table 1). The moisture content values were averaged. In each case, 10 samples were taken (for a total of 40 samples). Comparable values of the lamellas' initial and final moisture contents were found.

Table 1. Averaged Values of Relative Moisture Content by Gravimetric Method

	Radial Oak Lamellas (%)	Tangential Oak Lamellas (%)	Radial Beech Lamellas (%)	Tangential Beech Lamellas (%)
Moisture content before drying	41.59	41.35	42.42	38.82
Moisture content after drying	10.48	10.16	10.25	9.78

Cross warping was evaluated through relative warping. The values were calculated using Equation 3 (Walker 1993),

$$K = \frac{f}{b} \cdot 100\% \quad (3)$$

where f is the distance marked in Fig. 8 (mm), and b is the width of the sample (mm).

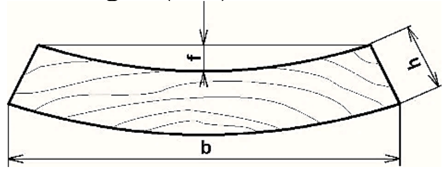

Fig. 8. Diagram of measured parameters for determining cross warping

The cup deformation was analyzed when the K parameter value (calculated using Eq. 3) exceeded 2%. The twist and bow types of wood deformation were assessed based on the direct observation.

Table 2. Averaged Values of the *K* Parameter after the Drying Process under a Load of 50 kg

	Radial Oak Wood Lamellas (%)	Tangential Oak Wood Lamellas (%)	Radial Beech Wood Lamellas (%)	Tangential Beech Wood Lamellas (%)
Lamellas not containing tension wood	0.27	0.26	1.00	1.70
Lamellas containing tension wood	0.87	0.37	5.20	1.51

After performing the drying process of the oak wood without tension (20 samples containing radial and tangential growth rings), the greatest K parameter value was 0.92%. It can be assumed that the entire batch could be further machined (K < 2%). Additionally, for 10 dried lamellas, coefficient K = 0%. For the drying process of 20 beech lamellas without tension (containing radial and tangential growth rings), the greatest K parameter value was 3.66%. Four dried lamellas were classified as unsuitable for further processing (machining) because of the high K value (K > 2%). Two lamellas had developed frontal cracks, while the rest of the dried batch did not show the deformation. Additionally, 10 oak lamellas and 10 beech lamellas with tension wood (with radial and tangential growth rings) were studied. Both species of lamella were dried under load and showed greater tendency for different types of deformation. For 4 beech wood lamellas, cup deformation was observed, and in 3 lamellas, bow deformation was observed, as cross warping. Only 3 beech lamellas were classified as suitable for further processing (machining). The oak wood lamellas showed less susceptibility to deformations caused by the presence of tension wood. In the batch of 10 lamellas, only 2 lamellas exhibited frontal cracks. Moreover, no other kind of deformation was found. The maximum value of the K parameter was 1.49%, and in 4 lamellas, K = 0%.

The oak wood lamellas (10 pieces) without load showed a tendency toward bow-type deformation, which occurred in the entire batch, disqualifying it from further processing (machining). Cross warping occurred in only 4 lamellas, and the K value ranged between 1.14% and 2.84%, with an average value of 1.79% (Table 3). The beech wood lamellas (10 pieces) without load presented all types of deformations, such as bow (8 pieces), cup (7 pieces), cracks (4 pieces), and twist (2 pieces).

Table 3. Averaged Values of the *K* Parameter after the Drying Process without Load

Lamellas without tension wood	Radial and Tangential Oak Wood Lamellas (%)	Radial and Tangential Beech Wood Lamellas (%)
	1.79	8.68

The oak and beech wood lamellas dried under a 50 kg load showed less tendency for twist, bow, and cup warping (Table 4). Frontal cracks were comparable to those in samples dried in the same drying schedule without load.

Table 4. Four Types of Deformation Occurring in Oak and Beech Wood Lamellas

	Lamellas Dried under Load of 50 kg		Lamellas Dried Without Load	
Type of Deformation	Percentage of Oak Wood Lamellas Containing Deformation after Drying	Percentage of Beech Wood Lamellas Containing Deformation after Drying	Percentage of Oak Wood Lamellas Containing Deformation after Drying	Percentage of Beech Wood Lamellas Containing Deformation after Drying
	[%]	[%]	[%]	[%]
Twist	16.7	6.7	30	20
Cracks	36.7	6.7	10	40
Bow	0	10	100	80
Cup	0	13.3	40	70

Figure 9 shows the comparison of the beech wood lamellas deformation under and without load.

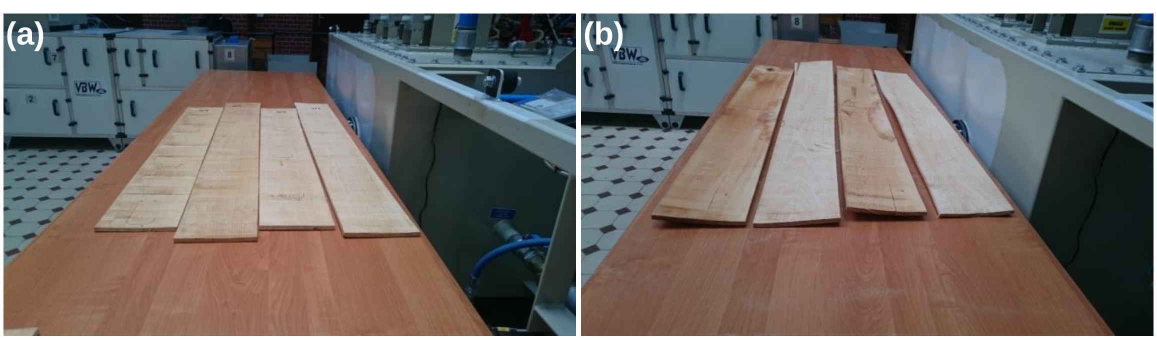

Fig. 9. Selected beech wood lamellas after drying process: (a) under load of 50 kg and (b) without load

Tables 5 to 8 show the color coordinates for specimens of different angles of the beech and oak wood. The beech wood samples exhibited more noticeable color changes than the oak wood samples, which were compared before and after drying. This result was because the oak wood is lighter than the beech wood, and thus the color change was weak after the high-temperature drying process.

The beech wood without defects showed smaller color difference parameter Δ*E** values 5.6 to 6.2 for radial cross section and 5.9 to 6.5 for tangential cross section than with defects 4.6 to 5.7 for radial cross section and 6.6 to 11.5 for tangential cross section respectively (Tables 5 and 6 and Fig. 10).

Table 5. Color Parameters and Differences (Δ*E**) of the Beech Wood Radial Cross Section Samples

	Without Defects			With Defects		
Position	Average Color Parameters L_1^* a_1^* b_1^* before Drying	Average Color Parameters L_2^* a_2^* b_2^* after Drying	Average Color Difference Δ*E**	Average Color Parameters L_1^* a_1^* b_1^* before Drying	Average Color Parameters L_2^* a_2^* b_2^* after Drying	Average Color Difference Δ*E**
1	68.31 10.78 30.68	65.87 11.04 28.46	5.867	68.70 10.27 30.24	67.99 9.88 27.19	5.080
2	67,22 11.62 32.20	66.08 10.80 28.51	5.563	67.14 10.99 29.57	66.45 10.70 26.92	4.608
3	67.80 11.45 32.02	65.52 11.20 29.30	6.190	65.46 10.75 27.98	65.27 10.85 26.30	5.682

Table 6. Color Parameters and Differences (Δ*E**) of the Beech Wood Tangential Cross Section Samples

	Without Defects			With Defects		
Position	Average Color Parameters L_1^* a_1^* b_1^* before Drying	Average Color Parameters L_2^* a_2^* b_2^* after Drying	Average Color Difference Δ*E**	Average Color Parameters L_1^* a_1^* b_1^* before Drying	Average Color Parameters L_2^* a_2^* b_2^* after Drying	Average Color Difference Δ*E**
1	67.43 11.91 31.10	67.49 9.96 27.53	6.219	70.84 10.03 27.22	69.25 8.75 25.92	6.577
2	68.83 10.72 31.51	70.00 9.11 26.18	6.460	57.12 14.03 29.28	64.76 9.83 24.20	11.489
3	67.68 11.84 31.45	68.16 9.46 26.89	5.907	61.23 11.25 27.84	68.20 8.71 23.09	9.664

Additionally wood radial cross section samples without defects have got higher range of color difference parameter than tangential cross section samples, respectively 5.6

to 6.2 and 5.9 to 6.5. In turn, tangential cross section samples with defects exhibited a higher range of color difference parameter than radial cross section samples, respectively 6.6 to 11.5 and 4.6 to 5.7.

Figures 10 and 11 show the average values and confidence intervals of the color difference parameters (ΔE^*) of the beech wood and oak wood samples, with defects and without defects.

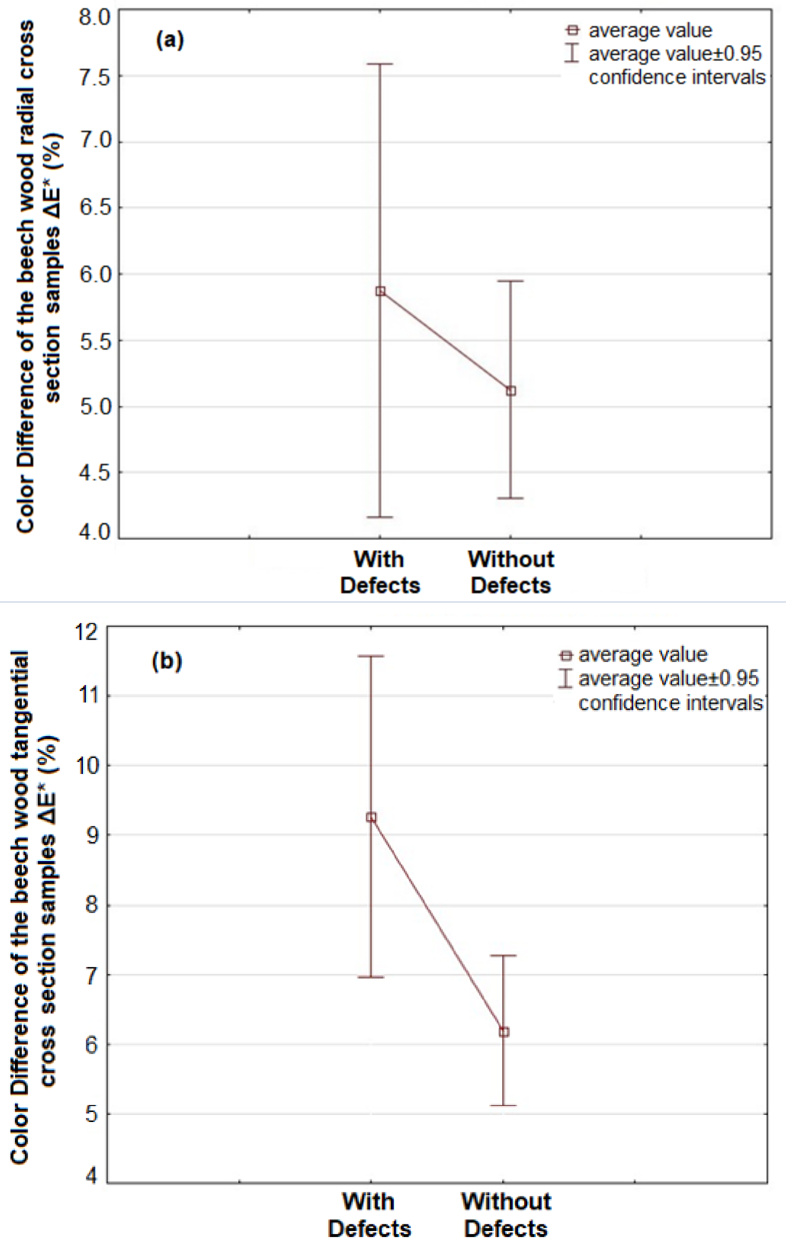

Fig. 10. Average values and confidence intervals of color difference parameters (ΔE^*) of the beech wood with defects and without defects: (a) radial cross section samples and (b) tangential cross section samples

While the oak wood without defects showed smaller color difference parameter ΔE^* values 5.1 to 5.5 for radial cross section and 4.4 to 6.2 for tangential cross section than with defects 5.1 to 7.0 for radial cross section and 4.6 to 7.3 for tangential cross section, respectively (Tables 7 and 8 and Fig. 11). The wood radial cross section samples without defects had a smaller range of color difference parameter than tangential cross section samples, respectively 5.1 to 5.5 and 4.4 to 6.2. In turn, tangential cross section samples with defects exhibited a slightly higher range of color difference parameter than radial cross section samples, respectively 4.6 to 7.3 and 5.1 to 7.0.

Table 7. Color Parameters and Differences (ΔE^*) of the Oak Wood Radial Cross Section Samples

	Without Defects			With Defects		
Position	Average Color Parameters L_1^* a_1^* b_1^* before Drying	Average Color Parameters L_2^* a_2^* b_2^* after Drying	Average Color Difference ΔE^*	Average Color Parameters L_1^* a_1^* b_1^* before Drying	Average Color Parameters L_2^* a_2^* b_2^* after Drying	Average Color Difference ΔE^*
1	63.72 6.17 20.78	63.48 7.01 21.92	5.535	59.25 7.84 21.50	66.02 6.91 21.36	7.016
2	61.34 6.78 20.58	63.55 7.17 22.13	5.130	58.75 7.11 20.46	65.13 7.17 22.12	6.914
3	62.75 6.27 20.89	63.59 7.60 23.04	5.424	59.66 7.01 20.74	63.59 7.60 22.90	5.149

Table 8. Color Parameters and Differences (ΔE^*) of the Oak Wood Tangential Cross Section Samples

	Without Defects			With Defects		
Position	Average Color Parameters L_1^* a_1^* b_1^* before Drying	Average Color Parameters L_2^* a_2^* b_2^* after Drying	Average Color Difference ΔE^*	Average Color Parameters L_1^* a_1^* b_1^* before Drying	Average Color Parameters L_2^* a_2^* b_2^* after Drying	Average Color Difference ΔE^*
1	65.99 5.86 19.71	65.52 7.50 22.86	5.400	65.32 6.19 20.28	63.91 7.15 21,87	4.602
2	64.04 6.55 20.84	63.79 7.69 22.85	4.356	63.43 5.88 19.14	63.98 6.79 21.10	6.579
3	70.02 5.34 19.38	65.69 7.77 22.88	6.243	62.58 6.08 19.81	64.43 7.07 22.08	7.347

It must be noted that those color changes are only visible on surface layers before machining. The machining process removed the surface layer and color difference became less noticeable.

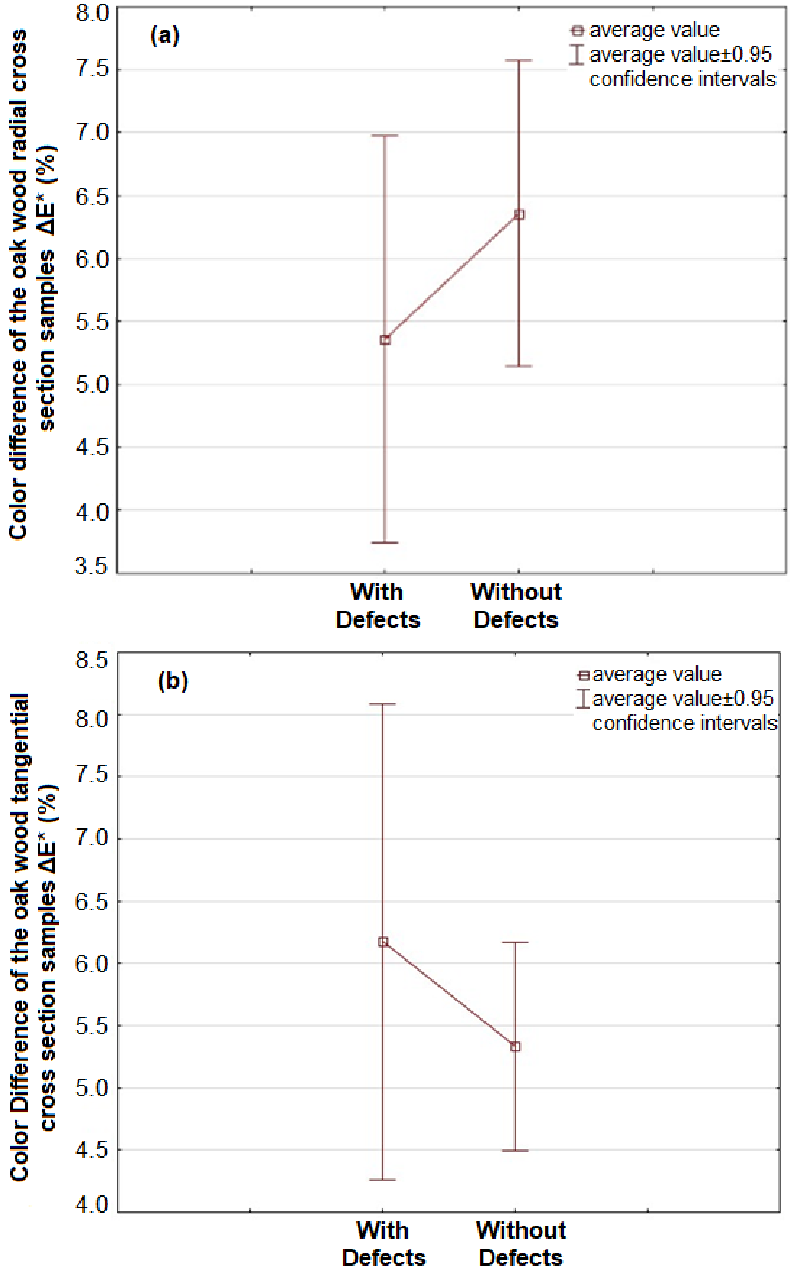

Fig. 11. Average values and confidence intervals of color difference parameters (Δ*E**) of the oak wood with defects and without defects: (a) radial cross section samples and (b) tangential cross section samples

CONCLUSIONS

The main objective of this study was the analysis of the impact of drying process conditions, wood and growth rings types, and load on the deformation and surface color changes of drying thin wooden elements. The shortening of the lamella drying process and reduction wood products defects were also studied. The results of experiment can be summarized as follows:

1. The oak wood lamellas without tension (containing radial and tangential growth rings) could be further machined (*e.g.* machining).
2. For the beech wood lamellas without tension (containing radial and tangential growth rings) 4 dried lamellas were classified as unsuitable for further processing (*e.g.* machining) and only 3 beech lamellas were classified as suitable for further processing (*e.g.* machining).
3. The oak lamellas and the beech lamellas with tension wood (with radial and tangential growth rings) dried under load showed greater tendency for different types of deformation.
4. The oak wood lamellas showed less susceptibility to deformations caused by the presence of tension wood.
5. The oak lamellas without load showed a tendency toward bow-type deformation, disqualifying it from further processing.
6. The beech lamellas without load presented all types of deformations.
7. The beech wood without defects show smaller color difference parameter ΔE^* values than with defects.
8. Wood radial cross section samples without defects exhibited a higher range of color difference parameter than tangential cross section samples.
9. Tangential cross section samples with defects showed a higher range of color difference parameter than radial cross section samples.
10. The oak wood without defects showed smaller color difference parameter ΔE^* values than with defects either.
11. Comparing to beech wood, oak wood radial cross section samples without defects had a smaller range of color difference parameter than tangential cross section samples.
12. Tangential cross section samples with defects had a slightly higher range of color difference parameter than radial cross section samples.

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