Analysis of the Effects of Drying Process of Red False Heartwood and Mature Wood on the Quality and Physical Properties of Beech Wood (*Fagus sylvatica* L.)

Ivan Klement* and Tatiana Vilkovská *

Red false heartwood is a defect that largely influences the quality of beech wood and is formed by air penetration into mature wood. The air in the mature zone accelerates the process of parenchyma dying and initiates the formation of red false heartwood substances and tyloses. For this study, the selections of suitable logs were made immediately after logging the trees on the same day. The first log was chosen without any type of red false heartwood, and the second log was chosen with healthy red false heartwood. The drying schedule was divided into two phases. After these measurements it was concluded that red false heartwood had a remarkably lower initial moisture content (MC) than the mature wood. The measured difference was almost 20%. The moisture gradient before drying was higher in the red false heartwood samples than in the mature wood samples. The red false heartwood had no effect on the intensity of casehardening. For both groups of samples, the drying quality was good without damaging the dried samples.

Keywords: Beech wood; Red false heartwood; Moisture gradients; Casehardening; Prong test; Drying curves

*Contact information: Technical University in Zvolen, Faculty of Wood Sciences and Technology, Department of Mechanical Wood Technology, Technical University in Zvolen, T. G. Masaryka 24, Zvolen, 96053 Slovakia; *Corresponding authors: klement@tuzvo.sk; tatiana.vilkovska@gmail.com*

INTRODUCTION

European beech (*Fagus sylvatica* L.) is an important tree species with a rather large distribution in western and central Europe (Furst *et al.* 2006). Beech wood is mainly used for furniture, packaging, plywood, and decorative veneer. Heartwood formation, in general, is associated with the breaking down of the water transport system and decreasing vitality of the parenchyma tissues (Nečesaný 1958; Kúdela and Čunderlík 2012; Barański *et al.* 2017). The theory of red false heartwood formation in beech wood is based on research by Nečesaný (1958). Red false heartwood formation is initiated when oxygenated air penetrates through dead branches, open knots, or other entrances into the stem core, where water content is low and the vitality of parenchyma cells is reduced. Additionally, the relatively vital parenchyma cells near the margin to the sapwood react by plugging vessels with tyloses (Nečesaný 1958; Kúdela and Čunderlík 2012). Because necrobiosis of parenchyma is slow, and heartwood substances polymerise rapidly, the substances are not deposited in the cell walls (Bozkurt and Erdin 2000). Consequently, the durability of red false heartwood is low compared to that of tree species with obligatory heartwood formation. The phenomenon of beech red false heartwood considerably affecting the quality of logs has been the object of professional and scientific interest for more than 100 years (Kudra *et al.* 2003). Moisture contents in mature wood are from 60% up to 80% and in red false heartwood are 35% up to 45% (Kúdela and Čunderlík 2012). Apart from the physical differences of red false heartwood, mature wood also has different drying characteristics (Marinescu *et al.* 2010). The drying rate has a close relationship with the two following parameters: the permeability coefficient and the diffusion coefficient. These two factors play a noticeable role in the drying behavior of wood within the free water and bound water domains (Klement and Huráková 2015). Red false heartwood also remarkably reduces the permeability of wood for liquid (Račko and Čunderlík 2010). The cited works of Barański *et al.* (2017) and Siau (1984) show that the relationship between drying different qualities of beech wood is remarkable in the free water domain. The structure of the red false heartwood noticeably affects the amount of tyloses in cells, which remarkably reduces the kinetics of water movement (Siau 1995). Marinescu *et al.* (2010) found that the content of tyloses in red false heartwood limits the kinetics of drying only above the fiber saturation point (FSP) and below the FSP the drying of both samples is balanced. Based on the cited work by Klement and Huráková (2015), it can be concluded that in high-temperature drying, the samples with the red false heartwood dried more slowly than the samples from the sapwood zone. For samples with red false heartwood, the average loss of moisture was $1.36\%\cdot h^{-1}$, and samples from the sapwood zone experienced a decrease of $2.42\%\cdot h^{-1}$. Moisture gradients and casehardening after drying were greater in the red false heartwood samples. European authors have investigated the influence of beech treatment in forests on red false heartwood formation (Knoke 2003; Kudra *et al.* 2003). This article considers the impact of the drying process of different zones of red false heartwood and mature wood on the final quality and physical characteristics of beech wood.

EXPERIMENTAL

Materials

Beech wood (*Fagus sylvatica* L.) was used for the experimental measurements. Samples were chosen from two beech logs with a diameter of 48 cm and length of 150 cm. Beech logs were selected from forests called Buršovo (Môťová) (475 m.a.s.l.) belonging to University Forest Enterprise of the Technical University in Zvolen, Slovakia. The selections of suitable logs were made immediately after the logging of trees and on the same day. The choice of the first log was qualified without any type of red false heartwood and the second log was qualified with healthy red false heartwood (Fig. 1).

Fig. 1. a) Log with healthy red false heartwood and b) log without any type of red false heartwood

The samples were selected from equal zones from both logs. Samples were marked mature wood (MW) and red false heartwood (FW). The test samples of mature wood and red false heartwood were selected with a thickness of approximately 3 cm, width of 10 cm, and length of 30 cm. Measurements were conducted on all the samples, both before and after the drying process. The process of high temperature drying was conducted in a laboratory kiln Memmert HCP 108 (Memmert GmbH + Co. KG, Schwabach, Germany) at the Department of Mechanical Wood Technology, Technical University in Zvolen, Slovakia.

Methods

The drying schedule was divided into different phases. The first part was heating, where the drying temperature was raised to 90 °C and the relative humidity was 94 ± 0.5%. The temperature of the dry bulb (t_d) was set to 90 °C and maintained in the first phase of the drying process until the moisture content in the samples did not decrease below the FSP approximately 30%. In turn, the relative humidity of surrounding air (φ) was set to 94%. After decreasing the moisture content below the fiber saturation point in both samples, the temperature of the dry bulb increased up to 120 °C and the relative humidity was without regulation. The last part of the drying schedule was cooling the samples to approximately 20 °C. The average final moisture content was 10% ± 1%. The oven-dry method was used for the moisture content determination. The weighing was performed with an accuracy of 0.01 g. The drying process to an absolute dry condition was performed in a laboratory kiln at 103 °C ± 2 °C. The moisture content was calculated using Eq. 1,

$$MC = \frac{m_w - m_0}{m_0} \cdot 100 \quad (1)$$

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

The fresh and oven-dried densities were determined for every sample with red false heartwood and mature wood content. The measurement was performed under laboratory conditions. The fresh density was calculated using Eq. 2, and the oven-dried density was calculated using Eq. 3,

$$\rho_w = \frac{m_w}{V_w} \ (\mathrm{kg \cdot m^{-3}}) \quad (2)$$

$$\rho_0 = \frac{m_0}{V_0} \ (\mathrm{kg \cdot m^{-3}}) \quad (3)$$

where m_w is the weight of fresh moisture samples (kg) and V_w is the volume of fresh moisture samples (m^{-3}); m_0 is the weight of oven-dried moisture samples (kg) and V_0 is the volume of oven-dried moisture samples (m^{-3}).

The intensity of water evaporation from the surface in cross section direction of samples was calculated using Eq. 4,

$$g = \frac{\Delta m}{2l(b+h) \cdot 3600 \cdot \tau} \ (\mathrm{kg \cdot m^{-2} \cdot s^{-1}}) \quad (4)$$

where Δm is the water loss from the wood during the drying (kg), l (*length*), b (*width*), and h (*thickness*) are the sizes of the dried sample (m), and τ is the drying time interval (h).

The temperature measurement was conducted using T-type thermocouples that were connected to the control panel (Comet MS6R; Comet system, Rožnov pod Radhoštem, Czech Republic). The temperatures were recorded in both groups of samples every 60 s. The locations of thermocouples for measuring the temperatures over the cross-section thickness are shown in Fig. 2.

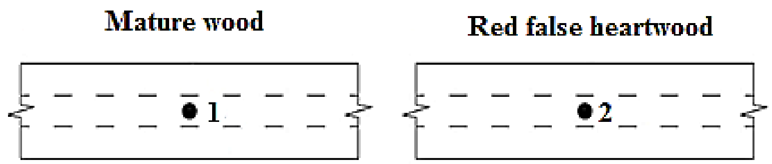

Fig. 2. The locations of thermocouples

All of the samples were measured before and after drying with moisture gradient. The samples were separated into three layers, in which the moisture content of each layer was determined by the oven-dry method. The moisture gradient was calculated using Eq. 5,

$$\Delta MC = w_m - \frac{\sum w_s}{2} \ (\%) \quad (5)$$

where ΔMC is the moisture gradient, w_m is the middle moisture content (%), and w_s is the surface moisture content (%).

Determining the internal stress (case hardening timber in tension or compression) of the wood) was made by prong tests STN EN 14298 (2017). The method of sawing and evaluating prongs is shown in Fig. 3. Subsequently, the prong samples were conditioned at 20 °C and a relative humidity of drying environment was 60% for 24 h. Prong deformation sizes were measured and evaluated according to Eq. 6:

$$K = \frac{(h-s)\cdot 100}{h\cdot b} \cdot 100 \ (\%) \quad (6)$$

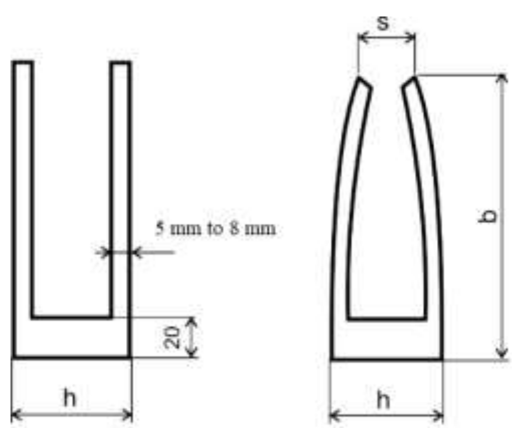

Fig. 3. Casehardening test prongs and measured parameters

RESULTS AND DISCUSSION

Table 1 shows the values of initial and final moisture contents, density, and drying times of red false heartwood samples and the comparative samples, which were prepared from the mature wood areas.

Table 1. MC, Density, and Drying Time of Red False Heartwood and Mature Wood Samples

Samples		Initial Moisture Content	Final Moisture Content	Density		Drying Time
		MC_i (%)	MC_f (%)	ρ_w (kg·m^{-3})	ρ_o (kg·m^{-3})	τ (h)
Mature wood (MW)	MW/1	70.46	9.38	934.42	625.99	160
	MW/2	70.83	9.36			
Red false heartwood (FW)	FW/1	51.35	9.76	785.89	624.24	158
	FW/2	51.07	9.59			

From the measured data, there was a noticeable difference in the initial moisture content of the compared groups of samples. In mature wood samples, the initial moisture content was nearly 20% higher than the red false heartwood samples. This also corresponded to the density at the given initial moisture (ρ_w). The mature wood samples had a higher density value. The densities measured at 0% MC (ρ_o) were almost the same for both groups of samples. Thus, the density of the red false heartwood did not differ from the density of mature wood. The present observations were consistent with those by Siau (1995) and Klement and Huráková (2015). The final moisture values of the compared groups of the samples can be considered as almost identical. The drying time of the samples from the red false heartwood was 2 h shorter than the mature wood samples, which was due to the lower initial moisture of these samples. The drying curves of the sample groups are shown in Fig. 4.

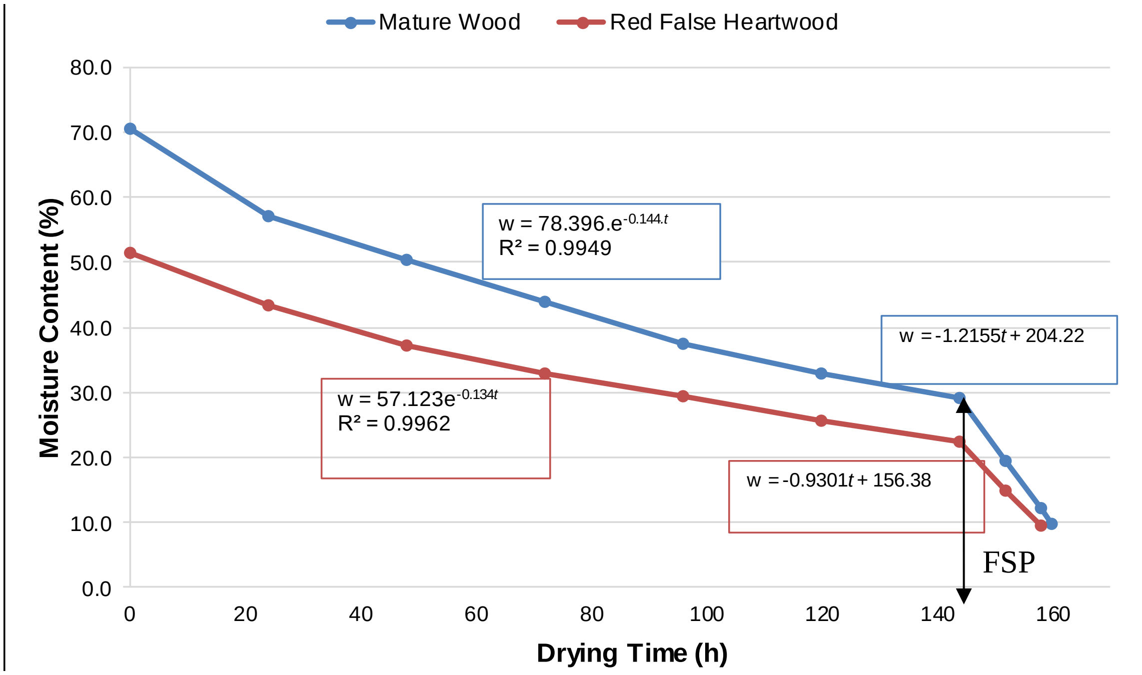

Fig. 4. Drying curves of mature wood and red false heartwood samples

The drying curves of both groups of samples had a similar shape. Their displacement was caused by different initial MC. From the initial MC to the fiber saturation point (FSP), the shapes of these curves were exponential. The drying curves were linear in the bound water domain when the drying temperature was increased up to 120 °C. The most noticeable approximation curves occurred in the first 24 h of drying, when the intensities of evaporation MC from the surface of the mature wood were noticeably higher than in the samples with red false heartwood. The values of MC and intensity of evaporation are shown in Table 2. Red false heartwood also remarkably reduces the permeability of wood for liquids (Pohler *et al.* 2006; Račko and Čunderlík 2010).

Table 2. Values of Moisture Content Evaporation Intensity from the Surface

Drying Time	Moisture Content		Moisture Loss		Evaporation of Moisture Intensity	
τ (h)	MC (%)		Δm (kg)		g (kg·m^{-2}·s^{-1})	
	MW	FW	MW	FW	MW	FW
0	70.46	51.35	-	-	-	-
24	57.08	43.30	76.82	43.74	1.14E-05	6.49E-06
48	50.40	37.13	38.37	33.52	5.69E-06	4.97E-06
72	43.83	32.92	37.76	22.87	5.60E-06	3.39E-06
96	37.59	29.44	35.79	18.92	5.31E-06	2.81E-06
120	32.93	25.62	26.78	20.74	3.97E-06	3.08E-06
144	29.18	22.44	21.53	17.26	3.19E-06	2.56E-06
152	19.46	15.00	55.80	40.40	2.48E-05	1.80E-05
158	12.17	9.42	41.89	30.34	2.49E-05	1.80E-05
160	9.74	-	13.95	-	2.48E-05	-

The calculated values of moisture content evaporation intensity from the wood surface in the different sections of drying showed that the samples of the red false heartwood dried more slowly compared to the mature wood samples.

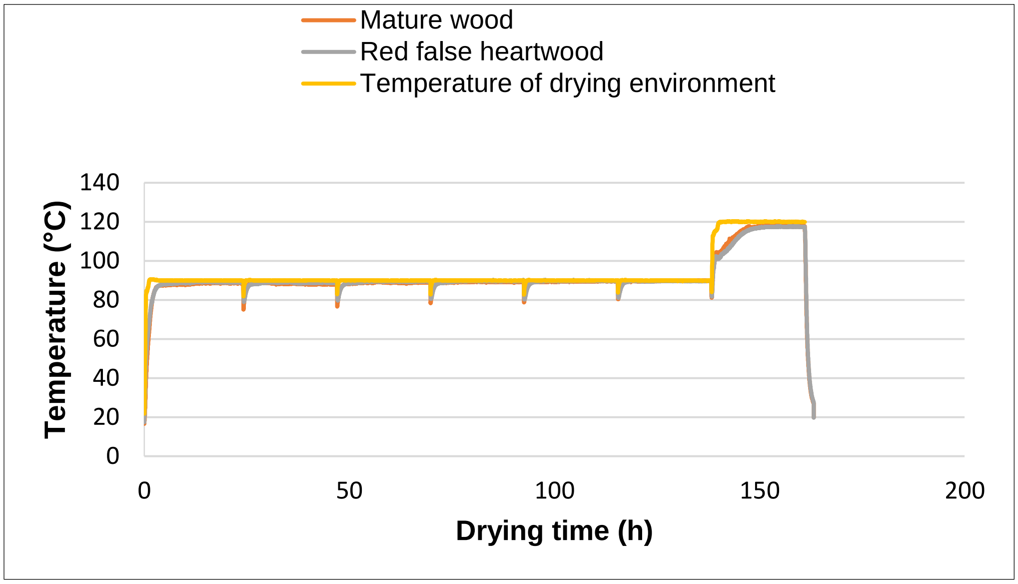

Fig. 5. Curves of temperature in samples and temperature of drying environment

However, the difference in moisture evaporation intensity was minimal as also shown by Klement and Huráková (2015). After the drying temperature was increased above 100 °C, the values increased in both groups, with a more pronounced increase in the mature wood samples. Figure 5 shows the temperature patterns measured in the middle of the samples in the drying process and the temperature of the surrounding air.

Based on the comparison of the temperature curves measured in the middle of the dried samples, there was no noticeable difference between the samples with red false heartwood and samples with mature wood. The paths of both curves were almost identical, and the difference between the sample temperatures and temperature of drying environment gradually decreased. The greatest differences were only in the first 60 h of drying. Afterwards, the average difference between the environment temperature and the samples was 1 °C. After the increase of the drying temperature to 120 °C, the temperature increase was more rapid in the mature wood than in the red false heartwood. The difference was possible to explain by the different MC during the temperature increase. The moisture contents were 29% and 22% of mature wood and red false heartwood samples, respectively. At the end of the drying process, the temperatures of the compared samples were equal and approximately 3 °C lower than the temperature of the drying environment. The present observations were consistent with those of Nečesaný (1958), Kúdela and Čunderlík (2012), and Barański *et al.* (2017). An evaluation of the quality was made on the basis of a comparison of the measured values of moisture gradients and the size of the casehardening that was assessed by prong tests. Graphic illustrations of the distribution of the moisture over the cross-section (thickness) of the samples (moisture distribution) before and after the drying process are shown in Fig. 6.

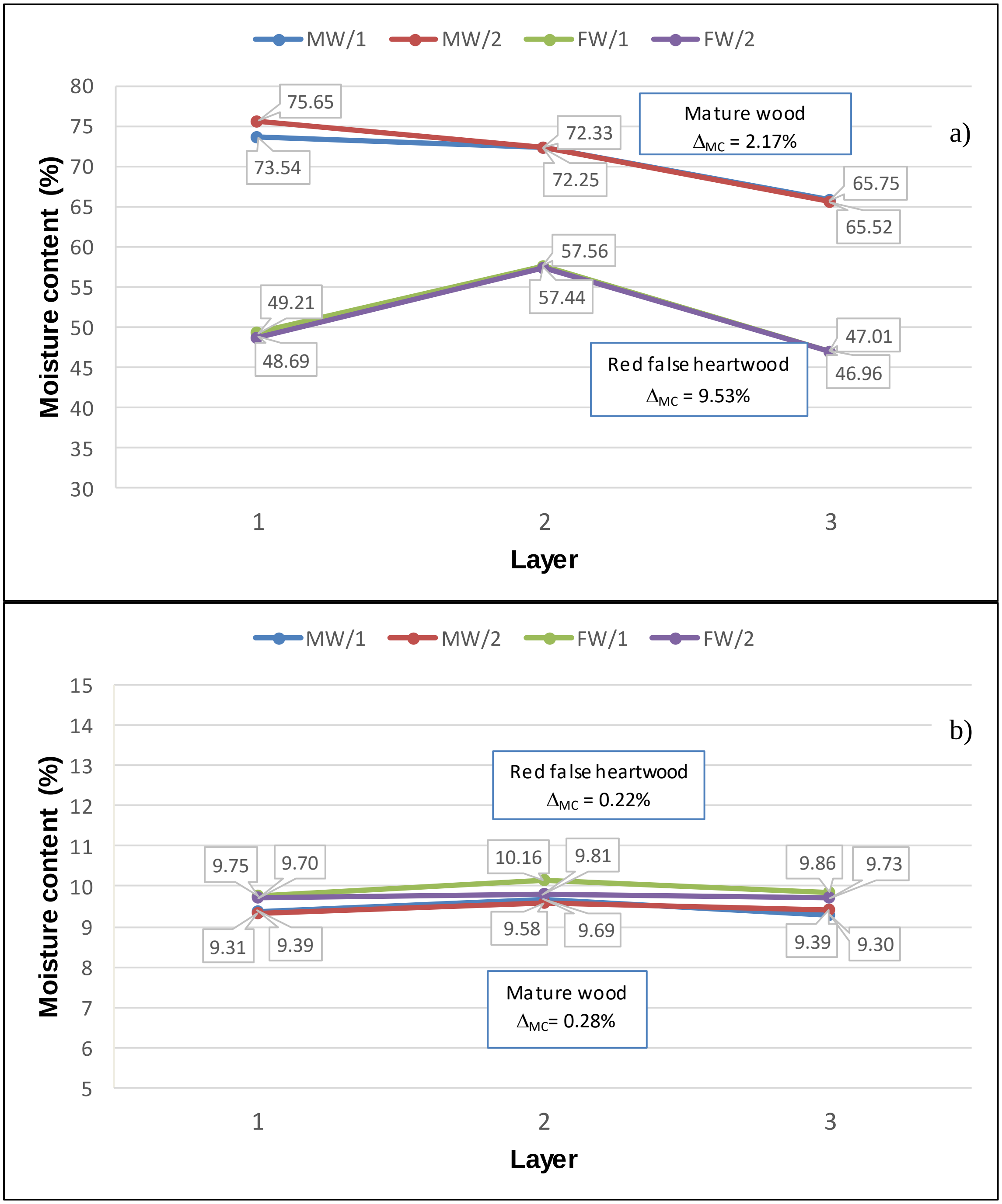

Fig. 6. Moisture distribution in cross-section: a) before drying and b) after drying

The samples of red false heartwood had higher values of moisture gradient, with a lower average MC, before drying. The noticeable differences were not caused by longer processing (storage) of the red false heartwood samples. Both of the sample groups were prepared at the same time and under the same conditions. The differences in MC distribution in the cross-section were minimal, and there was not any difference in measured values between the compared samples groups. These findings were in agreement with previously published results (Klement and Huráková 2015). Table 3 shows the calculated values of the moisture gradients and casehardening before and after drying. The prong deformation is shown in Fig. 7.

Table 3. Values of Moisture Gradients and Casehardening for Samples Before and After Drying

Samples		Before Drying Process		After Drying Process	
		Moisture Gradient	Casehardening	Moisture Gradient	Casehardening
		ΔMC (%)	*K* (%)	ΔMC (%)	*K* (%)
Mature wood (MW)	MW/1	2.68	1.69	0.34	29.81
	MW/2	1.66	1.55	0.23	21.40
Red false heartwood (FW)	FW/1	9.45	7.10	0.36	23.19
	FW/2	9.62	7.81	0.09	18.63

As previously mentioned, the higher values of moisture gradients were at the beginning of the drying process in the red false heartwood samples. This fact corresponded with higher values of casehardening. The values after the drying were equal between the compared groups and no noticeable differences were observed in the moisture gradient values nor in the casehardening. Approximately the same values of inner stress were created during the drying process. The red false heartwood had no effect on the casehardening intensity.

Fig. 7. Prong samples before and after drying

All of the samples were tangential because the orientation of red false heartwood in the log was near the pith. Therefore, it was not optimal for casehardening intensity evaluation. Figure 7 shows the one-sided deformation of prongs. The drying process had no effect on this deformation and it was caused by different shrinkage in the radial and tangential directions. Based on the measured values and also the visual evaluation, the quality of drying was higher without the defects in the dried wood STN EN 14298 (2017). The red false heartwood had no effect on decreasing the quality of the dried wood.

CONCLUSIONS

1. The red false heartwood had a remarkably lower initial moisture content (MC) than the mature wood. The average initial MC of mature wood was 70.6% and the false red false heartwod was 51.2%.
2. The density in the absolute dry state was equal between the red false heartwood and mature wood. Regarding the microscopic structure of beech wood, the cell wood structure of the samples from the red false heartwood (FW) was identical to the mature wood (MW). Initially, both groups of samples had approximately the same amount of bound water. The difference was in the amount of free water.
3. The red false heart wood samples dried in the whole process more slowly compared to the mature wood samples. The evaporation intensity was higher 1.14E-05 up to 3.19E-06 $kg \cdot m^{-2} \cdot s^{-1}$ in the mature wood samples in all of the drying process sections. The biggest difference was in the area of the free water domain, thus from an initial MC value to the fiber saturation point. The shorter drying time of the red false heartwood samples was caused by their lower initial MC approximately 51%. Based on measured values, there was no difference in the drying intensity between the mature wood and the red false heartwood samples. This indicates that a reduced permeability of the red false heartwood of the beech is caused by tyloses in cells.
4. The moisture gradient before drying was higher in the red false heartwood samples than in the mature wood samples. After the drying, the differences in moisture gradient were minimal and there was no difference in the measured values between the compared groups of samples. The average moisture gradients before drying were 9.53% for the red false heartwood and 2.17% for mature wood. Noticeable differences in FW decreased during the first 24 h of drying process to the value of samples from MW. The values of moisture gradients after drying were in the range 0.23% to 0.36%.
5. The measured casehardening values of the red false heard wood and the mature wood samples after drying were approximately equal. The red false heartwood had no effect on casehardening intensity. Higher values were measured in the red false heartwood before drying of 7.01% up to 7.81%, which was associated with higher values of moisture gradients before drying. However, this did not affect the final quality of the dried samples. After drying, the values of the compared groups were balanced. Red false heartwood did not affect the size of casehardening. For both groups of samples, the drying quality was higher without damaging the dried samples.
6. Under the operating conditions, it is recommended that timber/lumber with red false heartwood dry separately.

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