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CROSS WARPING DURING VARIOUS DRYING PROCESSES OF BEECH WOOD (*FAGUS SYLVATICA* L.)

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ABSTRACT

Wood drying does not only consist of removing moisture; the quality of the dried product is the main requirement for the industrial process. Because wood shrinks during drying, deformations and stresses develop, leading to unusable products. When developing drying technologies and methods, the aim is to achieve the shortest possible drying time. The most common defects in wood after drying include cross warping (*cup*), which significantly affects the efficiency of processing the raw material into products. The research was focused on the impact of different drying conditions (*temperature, drying gradient)* on the size of the cross warping. The lower values were for the low-temperature drying at 1.4 %. The high-temperature drying process increased values to double from 2.3 to 2.8%. A reduction in the size of the cross warping defects can also be achieved by effectively loading the samples in combination with more precise control of the high-temperature drying process so that smaller values of the moisture gradients of the samples at the end of the drying process are achieved.

Keywords: cross warping; beech wood; high-temperature drying; low-temperature drying; drying gradient.

INTRODUCTION

Wood is a hygroscopic material due to the abundance of hydroxyl groups associated with the cell wall polymers, and the material exhibits dimensional changes with variations in moisture content (MC) and atmospheric relative humidity. The degree to which wood shrinks and swells with changing moisture content is an important property that determines its suitability for different applications. This property, known as dimensional stability, is often a target property for improvement in wood modification research. Its importance makes it a commonly quantified wood property (Sargent 2019). Drying shrinkage is common during wood processing and utilization induced by moisture loss (Fu *et al.*, 2022; Ormarsson 1999). The moisture content of a growing tree is high, and it is usually necessary to dry the timber before using it for construction purposes. It is essential to avoid excessive deformation of the sawn timber during wood drying. The deformation process is affected by differences in the moisture and temperature conditions. One may also optimize the conditions during the drying process to minimize unfavorable deformations, such as cup, twist, crook, and bow. A characteristic of wood is that its behavior is strongly orthotropic due to the internal structure of the material and is precisely dependent on moisture and temperature (Miyoshi *et al.*, 2018). In addition, the material is characterized by a substantial variation of the properties in the radial direction. Furthermore, the behavior of wood is strongly affected by variations in environmental conditions, especially when the trees are exposed to stress.

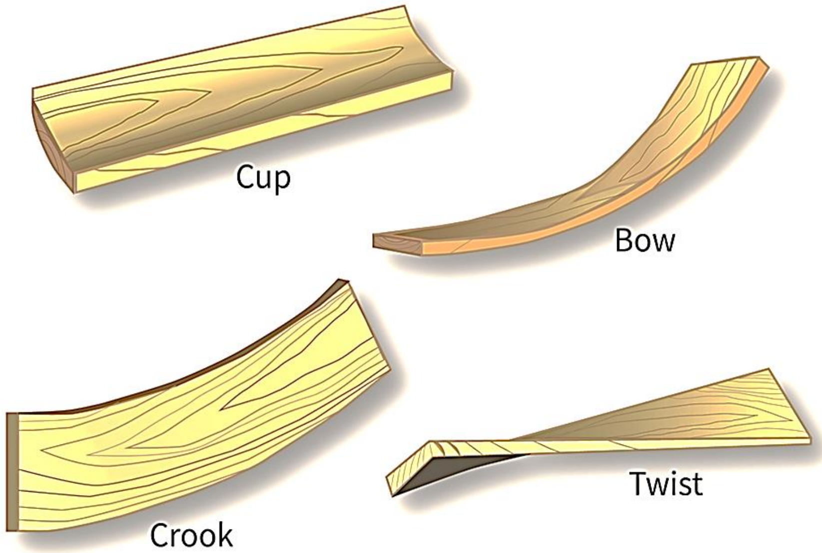

Fig. 1 Different forms of deformation of wood (Hill *et al.*, 2022)

This anisotropy affects many wood species characteristics such as strength, shrinkage, swelling, and thermal and electrical conductivity (Fig.1). As a representative example, wood exhibits different shrinkage levels among tangential, radial, and longitudinal directions. The tangential shrinkage is commonly the greatest, around 6–12%, followed by radial shrinkage at 3–6%, and longitudinal shrinkage is less than 0.1–0.2%. I shall refer to authors Glass and Zelinka 2021; Nocetti *et al.*, 2015. Based on the cited work (Barański *et al.*, 2021; Dudiak *et al.*, 2024), the cup deformation may occur in two directions, the xz- and the yz-plane, respectively. The average 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. The drying temperature was not considered statistically significant. The standard deviation values were lower for the thickness of 32 mm than for the thickness of 25 mm. It means that the thickness positively affects the size of the cross warping.

The loss of moisture leads to different drying shrinkage in various grain directions of wood; thus, shrinkage anisotropy of wood is one of the reasons for the drying stresses (Bond and Espinoza 2016). Additionally, due to the reliabilities of moisture content between the surface and core layers during the drying process of wood, as well as differences in material properties between heartwood and sapwood or earlywood and latewood, there will be irregular moisture content distribution. The irregular distribution of wood moisture will produce moisture gradient stress, which forms an additional source of drying stresses in wood. Therefore, shrinkage anisotropy stress and moisture gradient stress are the two principal catalysts for drying stresses in wood (Fu *et al.*, 2015; Dudiak and Dzurenda 2021). One type of deformation is a cup, defined as a board distortion in which there is a deviation from flatness across the width of the board (Simpson 1991, Vilkovský *et al.*, 2023).

The main objective of the present paper is to characterize and analyze one of the most common wood defects after drying, namely cross warping. This defect significantly affects the efficiency of the raw material being processed into products. Therefore, the article is designed to evaluate the effect of drying conditions on the cross warping size during high-temperature and low-temperature drying.

MATERIALS AND METHODS

The testing tree species was beech (*Fagus sylvatica* L.), the most economically important tree species in the forests of Slovakia. The logs were harvested in the University Forestry Enterprise's forests in the Hronská Breznica (altitude 268 m n. m.) location. Logs with a diameter at the thinner end of 50 to 56 cm and a length of 4 meters were used. The logs were sawn from the ground part of the tree. The logs were sawed by a cant log sawing pattern (Fig. 2) to produce the tangential lumber. Subsequently, the prisms were cut into 25 mm thick sawn timber. The dimensions of the samples were 25 × 120 × 1000 mm. Specimens were cut from the center of the lumber so that their net dimension was 1000 mm (marked grey color Fig. 2 a.)). Specimens with annual circles with a slope of 0 to 30° tangential sawn timber were selected for test specimens. At regular time intervals, the selected samples were weighed. Based on this moisture content, the drying process was controlled.

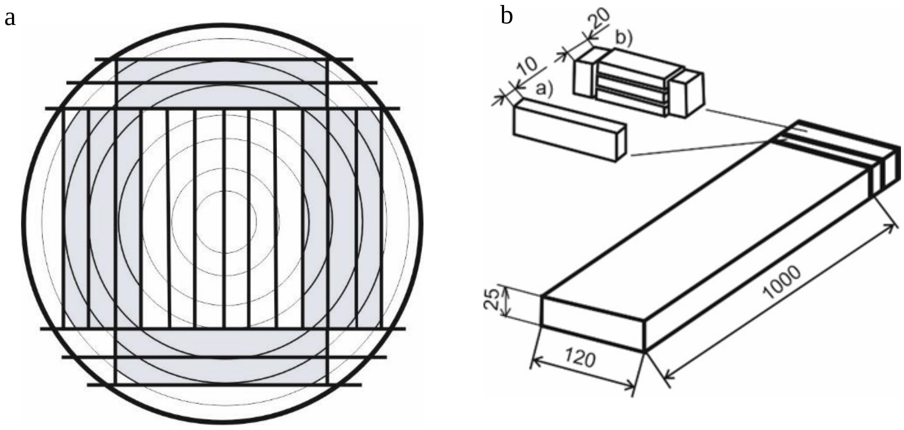

Fig. 2a.) Log–sawing pattern / Samples for determination (2b.) Moisture content sample a.) and moisture gradient b.)

Drying mode

Two drying modes were used. The samples were dried in the drying kiln in the drying laboratory at the Department of Wood Technology, Technical University in Zvolen, Slovakia, for high-temperature and low-temperature drying. A low-temperature drying mode with constant drying environment parameters was used for low-temperature drying (40°C). Two drying modes were used for high-temperature drying (*HT*), which differ in the maximum temperature used in the last mo stage (130 and 150 °C). The parameters of the drying modes are given in Table 1. The samples were dried to a final moisture content of 10 ± 1 %.

Tab. 1 Parameters of used drying modes.

Moisture content [%]		High-temperature drying process								Low-temperature drying process			
		t_s [°C]	Δt [°C]	U [-]		t_s [°C]	Δt [°C]	U [-]		t_s [°C]	Δt [°C]	U [-]	
above	60	100	4		5.82	100	4		5.82	40	5		5.82
60	40	100	4	5.82	3.88	100	4	5.82	3.88			4.8	3.2
40	30	100	6	4.44	3.33	100	6	4.44	3.33			3.2	2.4
30	25	100	6	3.33	2.78	100	6	3.33	2.78			2.4	2
25	20	115		5.68	4.55	115		5.68	4.55			2	1.6
20	15	130		10	7.5	130		10	7.5			1.6	1.2
15	10	130		7.5	5	150		21.43	14.29			1.2	0.8

Figure 3 shows a graphical representation of the average values of the drying gradients for the moisture stages and each drying mode. The drying gradient characterizes the drying intensity and is the ratio between the actual wood moisture content w and the equilibrium moisture content w_r. Moisture measurement was carried out using the oven dry method according to STN 49 0103.

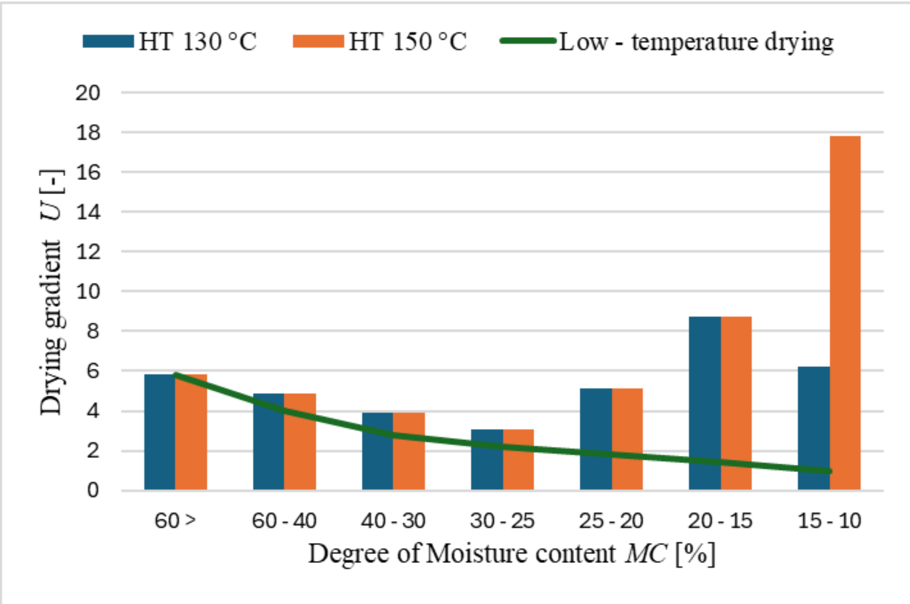

Fig. 3 Average values of drying gradient *U* in moisture levels and drying modes.

During drying, the drying samples were weighed at regular time intervals to determine the actual moisture content of the wood.

The moisture gradient characterizes the moisture distribution in the wood cross-section. The samples for the determination of the moisture gradient were processed, as shown in Figure 4. The moisture content of the individual layers was determined using the oven dry method. The level of the moisture gradient was calculated according to the equation:

$$\Delta w = w_c - w_p \ [\%] \tag{1}$$

Where: w_c – moisture content middle layer of wood [%], w_p – moisture content surface layer of wood [%].

Cross warping

The value of the cross warping level was evaluated using relative warping. Relative warping is the ratio of the maximum deflection *f* to the width of the sawn timber *b* (Fig. 4) and is expressed as a percentage.

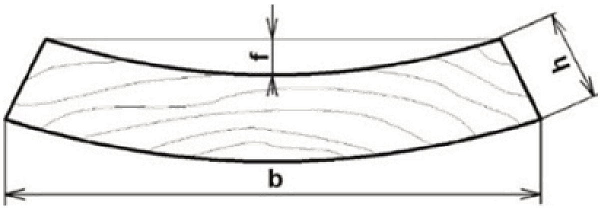

Fig. 4 Measurement of cross warping.

Due to the small volume of the dried samples in the dryer, their relative loading was small and did not affect the size of the measured cross warping. The values of cross warping *K* were calculated according to Eq. (2):

$$K = \frac{f}{b} \times 100 \ [\%] \tag{2}$$

Where: *f* – maximum deflection [mm], *b* - width of timber [mm].

Measurement of density in the absolutely dry state

Density in the absolutely dry state was determined for each sample. The measurement was performed under laboratory conditions. Density in the absolutely dry state was calculated by equation (3) according to the Slovak standards norm STN 490 103.

$$\rho_0 = \frac{m_0}{V_0} \ [\text{kg.m}^{-3}] \tag{3}$$

Where: m_0 is the weight of oven-dried moisture samples (kg) and V_0 is the volume of oven-dried moisture samples (m^{-3}).

RESULTS AND DISCUSSION

Table 2 shows the average values of the samples' moisture contents, drying times and rates, and densities at the dry state. Figure 5 graphically shows the samples' moisture loss as a function of time.

Tab. 2 Basic drying characteristics for individual modes.

Type of drying process	Maximal drying temperature [°C]	Moisture content [%]		Drying time [h]	Drying rate [%.h^{-1}]	Density [kg.m^{-3}]
		initial	final			
High-temperature drying (HT)	130	69.1	12.6	30.0	1.9	702.0
	150	69.0	10.0	30.0	2.0	717.0
Low-temperature drying	40	73.8	10.1	288.0	0.2	709.0

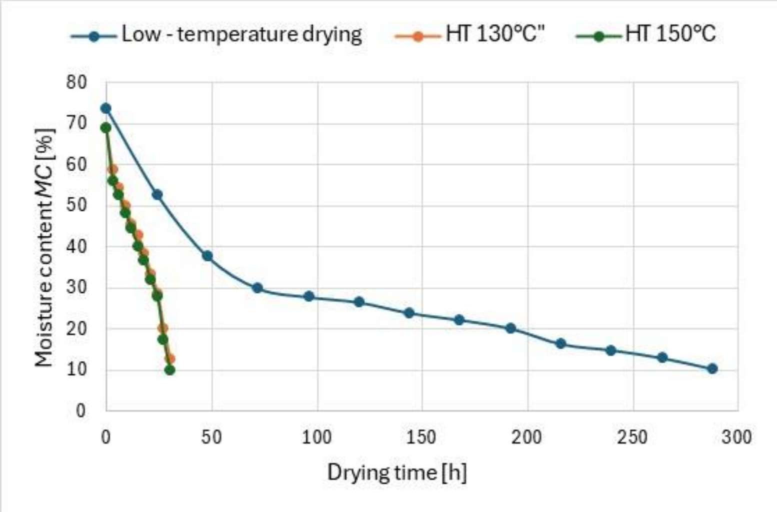

Fig. 5 Moisture content change of beech samples in high-temperature and low- temperature drying.

The initial moisture contents of the samples varied from 68 to 74.2 %, and the final moisture contents ranged from 9.4 to 12.8 %. With high-temperature drying and a drying temperature of 130 °C, the final moisture content was higher than initially planned, averaging 12 %. In the high-temperature drying, the curves were linear. This means that the moisture loss was proportional to the drying time. The average drying time was 30 hours, corresponding to the drying rate, which was slightly higher when a drying medium at a temperature of 150 °C was used.

The resulting drying times are very short compared with low-temperature drying of this wood due to the high drying intensity around the removal of bound water. In low-temperature drying mode, the drying time was 288 hours, and the drying rate was ten times shorter compared to high-temperature drying.

This corresponds to the drying gradient values for the drying modes used. All modes started with the same value (5.82), and the drying gradient gradually decreased.

For a high-temperature drying process with an average moisture content of 25 %, the drying gradient increased to 8.5. At the last moisture content stage, at a drying medium temperature of 150 °C, it reached almost 18. The drying gradient values decreased for low-temperature drying in the evaporation section of the water bound from the samples (below 25%). At the last moisture content stage, the drying gradient value was 1.

Moisture gradients were measured at three-hour intervals for both high-temperature drying modes. In the low-temperature drying process, the moisture gradient was measured at the beginning and the end. The calculated average values are shown in Figure 6.

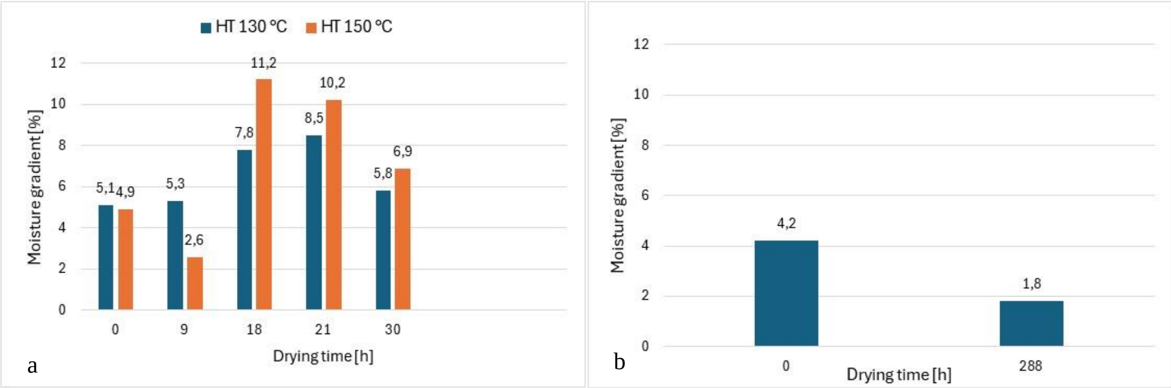

Fig. 6 Average values of moisture gradients of samples (a) High-temperature drying (b) Low-temperature drying.

After drying experiments, the absolute value of the cross warping (*f*) was measured at the center of the samples with a mechanical device and then converted according to equation (2) to the relative warping (*K*), considering the width of the samples. The converted mean values and their basic statistical characteristics are shown in Table 3.

Tab. 3 Mean values and basic statistical characteristics of the cross-sectional grading of the samples.

Type of drying process	Max drying temperature [°C]	Relative cross warping *K* [%]			variance standard [-]	deviation standard [-]	standard error [-]	coefficient of variation [-]	number of samples
		average	min.	max.					
High-temperature drying	130	2.8	1.5	4.0	0.789	0.888	0.256	32.3	30
	150	2.3	1.1	3.9	0.918	0.958	0.277	41.3	30
Low - temperature drying	40	1.4	0.6	1.5	0.245	0.495	0.143	28.1	30

The changes in the shape of the samples were small for both drying methods. The average values of relative cross-warping ranged from 1.4 to 2.8 % (Table 4). The lower values were for the low-temperature drying at 1.4 %. The high-temperature drying process increased values to double from 2.3 to 2.8%. Statistical analysis of the measured values showed that drying temperature or drying method was a moderately significant factor influencing the size of the cross warping. Besides the drying temperature, the drying gradient positively affected the size of the cross warping. The drying gradient in the low-temperature drying method decreased significantly from a critical wood moisture content of 40 %. In high-temperature drying, the value of the drying gradient was increasing (Fig. 3).

Assessing the effect of the drying method on the amount of cross warping based on the drying gradient is a more complex assessment, which also includes the impact of the relative humidity of the drying environment. Our findings are in concordance with authors Hill 2022; Sargent 2019). As also shown in the research of Xiang *et al.*, (2012) cross warping happens because the shrinkage parallel is more significant than that perpendicular to the growth rings. In other words, cupping results from tangential shrinkage of wood being more excellent than radial shrinkage, and the more significant the difference, the more severe the degree. Our observations are consistent with authors Konopka *et al.*, 2017 made comparable measurements of cross-warping where the drying process was carried out at 150 °C. The effect of the size of the cross warping was analysed for loaded and unloaded beech specimens ("lamellas") at an initial moisture content of approx. 40% and a final moisture content of approx. 10%. The values of *K* of the cross warping were 1-5.5%, and the slope of the annual rings was also determined. Higher values were for tangential samples. Our observations about reducing the size of the warping are also possible by efficient loading of the samples in combination with more precise control of the high-temperature drying process so that smaller values of the samples' moisture gradients at the end of the drying process are achieved are in accordance with other cited authors.

Between 130 and 150 °C drying temperatures, there was a statistically non-significant effect on cross-warping. High-temperature drying showed a positive impact of the high temperature on the amount of drying of the wood and, thus, on the size of the cross warping. When high temperatures are combined with the moisture content of the wood, partial plasticization occurs, which positively affects the formation of internal stresses in the wood and, ultimately, the size of the cross warping. Longitudinal warping was also observed in the samples, reflected by longitudinal bowing and twisting. Overall, it can be concluded that the values of cross-warping for both drying methods are positive, even because it was not possible for technical reasons to load the samples during drying, which eliminates the cross-warping further. Based on the cited work by Miyoshi (2014), it was revealed that the mechanical properties of wood in the lateral direction were significantly affected not only by the density but also by the structural features such as deformation of cell shapes, arrangement of rays or vessels, and the degree of the transition from the earlywood to the latewood.

CONCLUSION

When developing drying technology and methods, the aim is to achieve the shortest possible drying times; one way this can be achieved is by increasing the temperature of the drying environment. However, the dried wood must be protected. Cross-warping is one of the most common defects in the wood after drying, which considerably affects the efficiency with which the raw material can be processed into products. The following conclusions can be made from the measured results of the research:

- The high-temperature drying process is a very rapid drying method. Compared to the low-temperature drying method, the resulting drying times are, on average, 10 to 15%, corresponding to a drying rate approximately ten times higher.
- The drying curves for both modes of high-temperature drying were very rapid and linear. When a temperature of 150 °C was used in the last moisture level, the final moisture content of the samples was achieved more precisely.
- The values of moisture gradients at the end of the high-temperature drying process were large (5.8 - 6.9%), which had a negative effect on the size of the cross-warping of the samples.
- This indicates that a more optimal control of the drying process based on achieving the average required moisture content could be achieved. For low-temperature drying, the moisture gradient was 1.8 %.
- The average values of the cross warping were lower in the low-temperature drying process by 1.4 % compared to the high-temperature drying process, increasing values to double by 2.3 to 2.8%. The differences between the high-temperature drying modes (130

and 150°C) and the statistics were insignificant.
- Research into the effect of drying conditions on the size of wood warping is essential to increase the efficiency of processing raw materials into final products.

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