Comparative Analysis of Drying Processes: Moisture Content, Dimensional Stability, and Cutting Power in Beech Wood (*Fagus sylvatica* L.)

Jacek Baranski,[a,*] Aleksandra Suchta,[b] Tatiana Vilkovská,[c] Peter Vilkovský,[c,*] Daniel Chuchala,[b] Ivan Klement,[c] and Kazimierz Orlowski[b]

The effects of different drying modes on moisture distribution and cutting power was investigated for beech wood (*Fagus sylvatica* L.) from northern Poland. Samples (70 mm × 1000 mm) were subjected to air-drying (25 °C) and gas-steam drying (at 90 °C and 105 °C). Moisture content was measured across the cross-section, and cutting power was measured on a narrow-kerf frame sawing machine. The wood resistance was found to depend on moisture content and drying conditions, with higher resistance observed in normal (90 °C) and high-temperature (105 °C) gas-steam drying processes. Cutting power increased linearly with feed per tooth under all drying conditions, ranging from approximately 400 to 1100 W, with the strongest dependence observed for wood dried at 90 °C (r2=0.9364), while both feed per tooth and drying temperature significantly affected the sawing process. Boxplot analysis confirmed clear differences between drying regimes, showing the highest cutting resistance for air-dried samples, while thermally dried wood (90 °C and 105 °C) exhibited lower median cutting power values. Differences between 90 °C and 105 °C were minor. Although drying may influence thermal conductivity and dimensional stability, these effects were minimal at 105 °C due to conditioning, and both feed per tooth and drying temperature significantly affected the sawing process.

DOI: 10.15376/biores.21.3.7541-7557

Keywords: Gas-steam drying process; High-temperature drying process; Beech wood; Moisture content; Wood machining

*Contact information: a: Institute of Energy, Faculty of Mechanical Engineering and Ship Technology, Gdansk University of Technology, Gdansk, Poland; b: Institute of Manufacturing and Materials Technology, Faculty of Mechanical Engineering and Ship Technology, Gdansk University of Technology, Gdansk, Poland; c: Department of Wood Technology, Faculty of Wood Sciences and Technology, Technical University in Zvolen, Zvolen, Slovakia; *Corresponding authors: jbaransk@pg.edu.pl, xvilkovsky@tuzvo.sk*

INTRODUCTION

The moisture content (MC) of sawn timber must be reduced to an appropriate level through kiln drying before the material can be used in the production of furniture, flooring, or for structural purposes. This drying process is essential to ensure dimensional stability, improve mechanical performance, and reduce the risk of defects during further processing and service life (Majka and Sydor 2023). Drying above the fiber saturation point involves only the removal of free water and does not cause shrinkage of the wood. Shrinkage occurs only when the moisture content drops below the fiber saturation point (FSP), where bound water (BW) is removed from the cell walls and the development of internal stresses and deformation begins (Bajraktari *et al.* 2012).

Kiln drying is typically designed to operate at the highest possible intensity while maintaining low costs and acceptable product quality. This includes avoiding defects such as discoloration, deformation (twist, bow, crook, or cup), and drying-related damage caused by tensile wood, such as surface checking (Simpson and Tenwolde 1991; Denig *et al.* 2000; Keey *et al.* 2000; Perré and Passard 2007).

Surface checks are generally assumed to form in the early stages of kiln drying, when the moisture content is above the fiber saturation point. Moisture gradients generate tensile stresses in the surface layers, causing uneven shrinkage and resulting in surface cracking (Tiemann 1924; McMillen 1958; Schniewind 1960, 1963; Sandland and Gjerdrum 2007). The choice of drying method depends on factors such as wood species, thickness, required quality, cost, and initial moisture content. These parameters affect both the drying rate and the likelihood of defect formation during the process of drying (Korkua *et al.* 2025, Klement *et al.* 2025).

Wood density, which strongly influences most physical and mechanical properties of wood, is commonly considered to be a basic indicator of wood quality. The average density of beech wood at 12% moisture content is approximately 720 kg/m³ (Wagenführ 2000; Bectaş *et al.* 2002; Frühwald *et al.* 2003; Blass *et al.* 2005; Popović *et al.* 2006, Gryc *et al.* 2008). Whatever, beech wood density generally decreases from the stem centre toward the outer parts and with increasing height above the ground (Govorčin *et al.* 2003).

Majka and Sydor (2023) reported that beech wood is particularly susceptible to surface cracking, which can significantly affect the final quality of the material. This tendency is strongly influenced by the internal structure of beech wood, including the development of internal stresses during drying. Their study showed that cracking may occur even before reaching equilibrium moisture content under standard kiln drying conditions. Dry-bulb temperature (DBT) was identified as the main factor influencing tensile stress development and crack formation, with a notable interaction with wet-bulb depression (WBD). The results also indicated that higher drying temperatures (50 °C) can accelerate stress development and increase the risk of surface defects, while moisture content at failure represents a more relevant indicator of cracking susceptibility than equilibrium moisture content.

However, previous studies report differing findings regarding the relationship between wood moisture content and its machinability (Loehnertz and Cooz 1998; Zhu *et al.* 2019; Oliveira Guedes *et al.* 2020; Chuchała *et al.* 2020; Moradpour *et al.* 2013; Beljo-Lučić *et al.* 2004). Loehnertz and Cooz (1998) noted that this relationship depends on the wood species. However, according to Zhu *et al.* (2019), who studied pine (*Pinus sylvestris*), for example, increasing moisture content initially leads to a decrease in average cutting forces, followed by a stabilization at higher moisture levels. Cutting power is an important parameter in mechanical processing, as it reflects machine efficiency and helps prevent energy losses and overloads that may cause production interruptions. Energy consumption is influenced not only by processing parameters such as cutting speed and feed rate, but also by the internal structure of the wood. In particular, wood properties, especially density, have a direct effect on the cutting forces required (Eyma *et al.* 2004).

Chuchała *et al.* (2020) analyzed cutting power during band sawing of beech wood (*Fagus sylvatica* L.) dried under different conditions, including air drying at 20 to 25 °C, kiln drying at 60 °C, vacuum drying at 80 °C, and superheated steam drying at 100 °C. The study showed a clear dependence of cutting power on both moisture content and drying method, with values ranging from approximately 2.0 to 2.5 kW at higher moisture contents (≈18 to 20%) to 3.0 to 3.8 kW at lower moisture contents (≈8 to 10%), depending on the drying regime. Even at similar final moisture levels, cutting power differed between drying methods, indicating that drying-induced changes in wood structure play an important role. Furthermore, Oliveira Guedes *et al.* (2020) investigated the cutting energy required for machining dense hardwood species such as *Eucalyptus spp.* ($\rho \approx 600$ to 900 kg·m^{-3}) and *Corymbia citriodora* ($\rho \approx 900$ to 1100 kg·m^{-3}), whose density and mechanical properties are comparable to those of beech wood (*Fagus sylvatica* L., $\rho \approx 650$ to 750 kg·m^{-3}). The authors reported that cutting energy increased by approximately 30 to 60% as moisture content decreased from the green state to air-dried conditions, demonstrating a strong influence of drying stage on wood processing.

Moradpour *et al.* (2013), demonstrated that cutting forces during band sawing of oak and beech wood are strongly influenced by both moisture content and cutting direction. Beljo-Lučić *et al.* (2004) investigated circular rip sawing of oak and found that specific cutting forces and power requirements were lower in green wood (40 to 70% MC) than in kiln-dried wood (8 to 12% MC), with green wood requiring approximately 20 to 30% less power. These findings confirm that moisture content has a significant effect on sawing energy requirements.

Kopecký *et al.* (2014) investigated the cutting process of native beech wood (ρ = 691 kg·m^{-3}), and modified beech materials, namely hydrothermally treated and compressed beech (Bendywood: ρ = 739 kg·m^{-3}) and chemically impregnated compressed beech (Belmadur: ρ = 707 kg·m^{-3}). The samples having dimensions of 700 × 120 mm (length × width), were dried to approximately 8% moisture content, and machined to a uniform thickness of 21 mm. The study showed that the cutting force required for machining Bendywood was approximately 15% lower compared to native beech, despite its higher density. Similarly, Belmadur exhibited a reduction in cutting force of about 35% relative to native beech. The authors suggested that structural modifications caused by compression and treatment processes significantly influence the machinability of beech wood by reducing cutting resistance during processing. Blanchet *et al.* (2016) observed that birch wood dried under vacuum conditions exhibited improved mechanical performance, expressed by higher MOE and MOR values, compared to material dried in a kiln. In addition, Orłowski *et al.* (2019) reported that the temperature applied during wood drying can significantly influence the granulometric characteristics of sawdust generated in sawing operations.

Currently, a large number of studies (Blanchet *et al.* 2016; Zhu *et al.* 2019; Orłowski *et al.* 2019; Oliveira Guedes *et al.* 2020; Vilkovský *et al.* 2024) have focused on the influence of drying on moisture content, deformation, and cutting force, particularly in coniferous species (spruce, pine) and selected hardwood species (hornbeam, birch, eucalyptus). Therefore, attention should also be directed to beech wood from the perspective of optimizing machining processes in order to achieve higher-quality products.

This study was therefore focused on investigating the effect of different drying modes on the moisture content distribution and cutting power. Specifically, it examined how air-drying (25 °C) and gas-steam drying processes at elevated temperatures (90 and 105 °C) influence moisture distribution across the wood cross-section and the resulting cutting performance during machining.

EXPERIMENTAL

Material Used

The experimental material consisted of beech wood (*Fagus sylvatica* L.) obtained from the northern part of the Pomerania region in Poland. The logs had an average diameter of 100 cm. A total of 30 samples were prepared for the study. Test specimens with normal cross-sectional dimensions of 70 × 70 mm and lengths from 1050 to approximately 1500 mm were prepared from a log (3.2 m). Only sapwood samples were selected for the study. Samples containing heartwood, knots, checks, or other visible defects were excluded. Before the experiments, all specimens were measured and weighed. The initial and final moisture content (MC) and the density of the wood samples are presented in Table 1. The remaining wood material was used to fill the free volume of the drying kiln and ensure uniform drying conditions.

Measurement of Dimensional Stability

Dimensional stability was evaluated by measuring specimen width, thickness, and length before and after the drying process. Measurements were performed using a digital caliper with an accuracy of ±0.01 mm.

The relative differences in the main dimensions of the dried beech wood samples were calculated using the following formula (1):

$$\delta_i = \frac{d_{before\ drying} - d_{after\ drying}}{d_{before\ drying}} \cdot 100\% \tag{1}$$

The dimensional stability of the beech wood samples was evaluated by comparing the dimensions measured before and after drying.

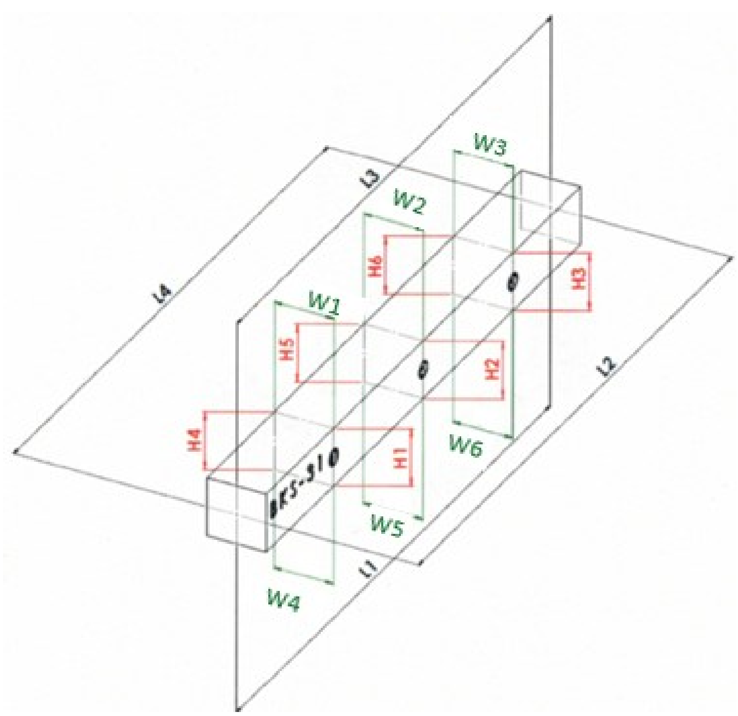

Fig. 1. Simplified view of the beech wood sample during dimensions' measurements (H – height/thickness, W – width, L – length)

Measurement of Moisture Content

The moisture content of each specimen was measured using a WRD-100 moisture meter (TANEL Co., Gliwice, Poland) that operates on the electrical resistance principle. The device has a measurement accuracy ±2% and a measurement range 4% to 100%. The moisture meter was calibrated for beech wood at a reference temperature of 25 °C according to the manufacturer's recommendations. Moisture measurements were carried out before (Measurement of moisture content at three locations before sawing), and after (Measurement of moisture content at nine locations on every piece of lumber) the drying process under semi-industrial conditions in accordance with established standards (EN 13183-1 2002, EN 13183-2 2002, EN 13183-3 2005). They were performed at nine locations (Fig. 2) along each specimen (near both ends and at the center). The average value was used for further analysis.

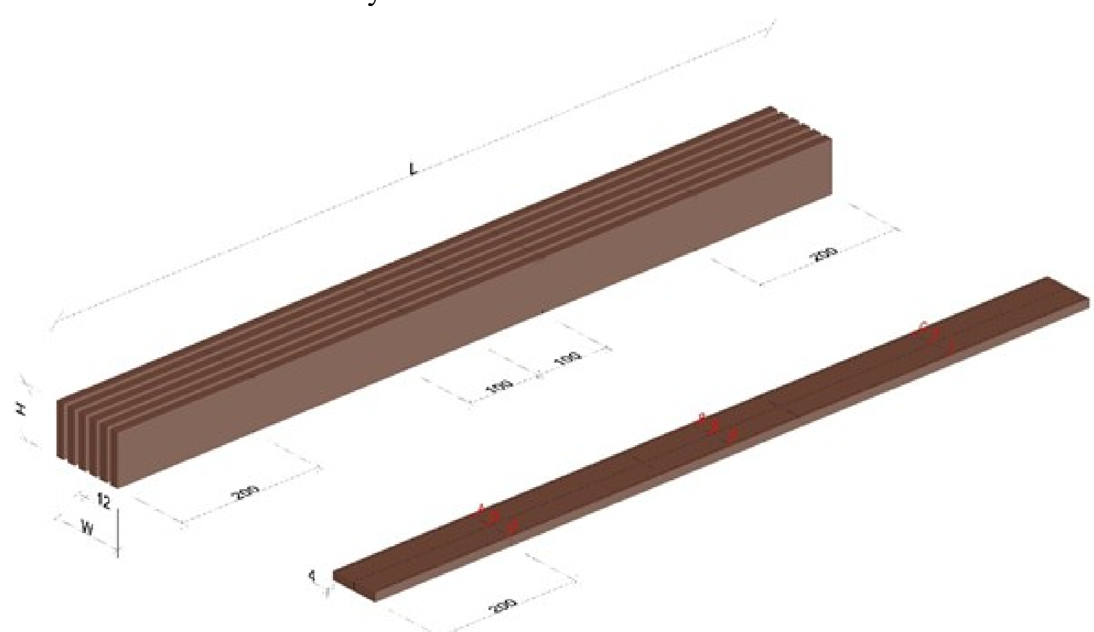

Fig. 2. The view of the sample with the locations of moisture measurement (from A to I)

All measurements were performed at 24-hour intervals in a laboratory maintained at a temperature of 25 °C and relative humidity φ of 29.5%. Under these conditions, the equilibrium moisture content (EMC) of the wood was approximately 6%.

The Drying Experiments

The drying experiments were carried out in an experimental semi-industrial kiln with a capacity of 0.55 m^3. The kiln was designed for high-temperature drying of wood to a final moisture content of approximately 6%, with operating temperatures up to 150 °C. Superheated steam generated by a steam generator was used to maintain the desired drying conditions, constant temperature, and relative humidity inside the kiln. Thermal energy was supplied through a heat exchanger installed within the drying kiln and fed with hot flue gases generated in an external combustion chamber.

During the experiments, the drying temperature was maintained within the range 90 to 105 °C, while the relative humidity was controlled between 80% and 90% or between 90% and 100%, depending on the drying process mode. The moisture content of the wood during the drying process was monitored at eight measurement locations distributed throughout the kiln. These locations represented characteristic regions of the kiln volume, including both the central and outer layers of the wood stack.

The drying process was controlled by a monitoring system located outside the kiln. Four thermocouples were used to measure the drying medium temperature inside the kiln and the temperature of the wood at three selected locations within the stack. The parameters of the drying medium were monitored using an EE31 humidity and temperature transmitter (E+E Elektronik Ges.m.b.H., Engerwitzdorf, Austria), with measurement accuracies of ±1.3% for relative humidity and ±0.2°C for temperature.

Measurement of Cutting Power

The cutting power measurements were performed during sawing tests conducted on a PRW15M sash gang saw. During the cutting process, three cutting edges of each tooth were simultaneously engaged in the work pieces. All sawing tests were carried out under narrow-kerf conditions.

The PRW15M frame saw operates with a kinematic system characterized by an elliptical tooth trajectory. Its drive system is dynamically balanced, which prevents contact between the saw teeth and the bottom of the kerf during operation (Table 1).

Table 1. Specifications of the Machine Tool

	Name	Unit	Symbol	Value
1.	Number of the saw strokes	rpm	n_F	685
2.	Stroke of the saw frame	mm	H_F	162
3.	Feed speed at 1st level	m/min	$v_{f\,I}$	0.2
4.	Feed speed at 2nd level	m/min	$v_{f\,II}$	1.3
5.	Number of saws in the gang	-	m	5
6.	Average cutting speed	m/s	v_c	3.69

The beech wood prisms with a high H_p of 70 mm were used in the sawing experiments. The process parameters described above constituted the input variables, whereas the average cutting power $\bar{P}_c$ was considered the output variable. The mean total power consumption $\bar{P}_{cT}$ and the idling power of the main drive system $\bar{P}_i$ were measured using a power transducer. The idling power $\bar{P}_i$ was determined immediately before each cutting test. The average cutting power was calculated as the difference between the mean total power consumption and the idling power of the drive system according to Eq. (2),

$$\bar{P}_c = \bar{P}_{cT} - \bar{P}_i \tag{2}$$

where $\bar{P}_c$ is the cutting power (W), $\bar{P}_{cT}$ is the total power consumption during sawing (W), and $\bar{P}_i$ is the idling power of the machine drive system (W).

RESULTS AND DISCUSSION

Moisture Content Measurement Before and After the Drying Process

Beech wood samples were dried using three different drying methods: air drying at 25 °C, conventional drying in an air–steam mixture at 90 °C, and high-temperature drying at 105 °C. The drying schedule consisted of successive drying stages designed to gradually reduce the moisture content while minimizing internal stresses and dimensional distortions. After the drying process, the samples were conditioned and subsequently evaluated in terms of moisture content, dimensional stability, density, and machining properties.

Table 2. Final Values of Moisture Content and Shrinkage of Beech Samples Before and After the Drying Process (Measurement of moisture content at three locations before sawing)

Drying regime	Sample	H - before drying (mm)	H - after drying (mm)	H - mean shrinkage (%)	W - before drying (mm)	W - after drying (mm)	W - mean shrinkage (%)
Air - drying (25°C)	1	68.2–69.5	62.1–65.8	7.6	69.4–71.1	65.0–67.8	6.7
	2	69.0–70.6	66.0–67.2	4.6	71.0–72.6	67.2–68.2	5.8
	3	69.9–72.9	68.4–69.3	3.9	67.4–71.3	62.6–66.0	4.5
	4	69.8–71.6	65.2–68.4	4.7	69.0–71.4	65.9–67.6	4.9
	5	71.6–73.8	66.7–68.2	7.2	70.2–71.0	68.0–69.2	2.1
Normal temperature drying (90°C)	1	69.3–70.5	62.9–62.6	10.3	69.6–71.0	66.3–68.0	3.2
	2	70.6–72.0	64.2–65.2	8.1	69.4–70.8	64.0–66.7	5.8
	3	72.0–72.4	66.7–68.3	6.5	67.2–70.7	58.8–64.1	10
	4	70.5–71.6	62.8–63.8	11.3	69.9–70.5	64.0–66.5	6.6
	5	71.9–73.1	64.0–65.3	10.7	71.3–72.8	67.6–69.2	4.1
High temperature drying (105°C)	1	68.7–70.5	62.0–64.4	8.3	70.8–71.7	66.6–68.3	4.8
	2	70.3–73.0	62.3–65.8	10.1	69.6–72.3	66.8–68.1	4
	3	70.4–72.0	66.4–68.1	5.2	68.8–71.8	61.8–67.3	6.1
	4	70.4–71.6	63.8–65.7	8.8	69.3–71.2	64.9–66.9	4.8
	5	71.6–72.3	64.4–66.3	7.7	69.8–72.0	66.0–68.8	4.1
Drying regime	**Sample**	**L - before drying (mm)**	**L - after drying (mm)**	**L - mean shrinkage (%)**	**Moisture Content before drying (%)**	**Moisture Content after drying (%)**	
Air - drying (25°C)	1	1330–1335	1315–1326	0.9	67.0–79.5	9.4–12.0	
	2	1340–1345	1337–1343	0.4	75.0–83.2	9.8–14.3	
	3	1323–1326	1319–1324	0.4	84.5–89.9	11.8–15.1	
	4	1352–1355	1347–1353	0.3	84.8–89.1	16.2–17.7	
	5	1328–1335	1326–1334	0.2	72.5–80.3	11.6–14.9	
Normal temperature drying (90°C)	1	1362–1367	1358–1364	0.2	70.2–71.0	6.0	
	2	1342–1348	1339–1345	0.3	71.0–81.3	6.0	
	3	1349–1356	1344–1349	0.4	85.5–88.5	6.0	
	4	1335–1340	1333–1337	0.2	83.0–84.7	6.0–7.8	
	5	1342–1345	1340–1344	0.2	76.0–83.5	6.0	
High temperature drying (105°C)	1	1336–1340	1330–1335	0.3	75.0–79.2	6.0–6.6	
	2	1344–1349	1340–1345	0.2	71.2–81.0	6.8–7.1	
	3	1348–1350	1341–1346	0.4	85.2–87.5	6.1–6.7	
	4	1340–1345	1335–1337	0.4	81.5–85.5	6.4–6.9	
	5	1342–1347	1335–1342	0.4	77.5–80.2	6.0–6.2	

The results (Table 2) clearly demonstrated the influence of the applied drying regimes on the final moisture content of the material. Air-drying at 25 °C led to the highest residual moisture content, ranging approximately from 9 to 17%, indicating a relatively mild and slow drying process. In contrast, both elevated-temperature regimes (90°C and 105 °C) resulted in significantly lower and more uniform final moisture contents, generally around 6 to 7%, with only minor differences between these two conditions. This suggests that increasing the drying temperature above the normal regime does not substantially reduce the equilibrium moisture content but mainly accelerates the drying process and improves consistency between samples. The differences between regimes were more pronounced in terms of moisture removal efficiency than in final moisture levels.

Each sample was sawn into lumber (cutting power measurement), and the moisture content of each sample was subsequently measured at nine locations. The results are presented in Table 3.

Table 3. Average Dimensions and Moisture Content of Beech Samples after Different Drying Conditions

Drying mode	Average moisture content (%)								
	A	B	C	D	E	F	G	H	I
air dried, 25°C	13.00	14.00	12.00	13.90	14.80	12.20	14.40	14.90	11.70
normal temp. dried, 90°C	5.50	5.00	6.10	5.20	5.00	6.00	5.00	5.20	6.50
high temp. dried, 105°C	6.40	6.70	6.30	6.40	6.60	6.60	6.70	6.50	6.50
Drying mode	Average dimension values (mm)								
	H	W	L						
air dried, 25°C	20	60	684						
normal temp. dried, 90°C	20	60	695						
high temp. dried, 105°C	20	60	668						

The study by Bajraktari *et al.* (2012), which evaluated beech wood defects due to different drying schemes, further confirmed that, in addition to moisture-related effects, the applied drying regime significantly influences the development of wood defects. Work by Bajraktari *et al.* (2012) and Klement *et al.* (2025) indicates that more intensive drying conditions tend to increase the risk of defect formation, such as surface and internal checking, warping, and collapse, particularly when moisture gradients within the material are high during the early stages of drying. In contrast, milder drying schemes generally reduce defect intensity but require longer drying times.

The results of the rubberwood drying study (Korkua *et al.* 2025) confirm a similar trend to the observations obtained for beech samples, where changes in the drying regime have a more pronounced effect on process kinetics and efficiency than on the final moisture content of the material. Increasing the air velocity from 1 to 3 m/s led to a reduction in drying time, while the final moisture content remained approximately the same in both cases, around 10%. Similar to temperature-increased drying regimes in beech wood, the more intensive conditions did not significantly reduce the equilibrium moisture content but primarily accelerated moisture removal and improved process uniformity. The differences between regimes were most evident in the initial drying phase, whereas in later stages the influence of operating conditions became less significant.

Measurement of Beech Wood Stability Before and After the Drying Process

The dimensional stability of the beech wood samples was evaluated by comparing the dimensions measured before and after drying. The results presented in Table 4 were combined to determine dimensional changes expressed both in millimetres and as a percentage of the initial dimensions.

Table 4. The Linear and The Relative Differences on the Main Dimensions of the Tested Elements (Beech Wood Samples) after Drying Processes

Drying mode	Measured Differences (mm / %)											
	Thickness – H (Average)						Width – W (Average)					
	1	2	3	4	5	6	1	2	3	4	5	6
Air dried	3.82/5.43	3.72/5.29	4.56/6.4	4.00/5.68	3.46/4.92	4.18/5.88	3.78/5.33	3.16/4.5	3.58/5.09	3.78/5.32	3.42/4.84	3.76/5.32
Norm. temp. dried	6.72/9.42	7.16/10	6.92/9.68	6.88/9.66	7.46/10.4	7.30/10.2	4.38/6.26	4.38/6.25	4.16/5.92	4.96/7.08	4.44/6.33	4.88/6.91
High temp. Dried	6.36/8.89	6.44/9	5.82/8.2	6.08/8.55	6.70/9.39	5.56/7.83	3.40/4.82	3.76/5.31	3.64/5.2	4.00/5.66	4.34/6.11	4.06/5.77

Drying mode	Length – L (Average)			
	1	2	3	4
Air dried	3.60/0.26	3.80/0.28	3.80/0.28	4.60/0.34
Norm. temp. Dried	3.60/0.26	3.60/0.26	3.80/0.28	3.60/0.26
High temp. Dried	4.40/0.35	4.80/0.46	6.20/0.5	6.80/0.41

In addition, the wood orientation (radial or tangential) should be specified for each sample because wood anisotropy strongly influences dimensional changes during drying.

The obtained results indicate that dimensional changes occurred in all drying variants, confirming the influence of moisture removal on wood shrinkage. As expected, tangentially oriented samples exhibited greater dimensional changes than radially oriented samples. Nevertheless, drying under controlled air–steam conditions resulted in satisfactory dimensional stability and limited deformation of the tested elements.

The dimensional stability results confirm that appropriate drying schedules can effectively reduce moisture content while maintaining acceptable geometric accuracy of the final product. This aspect is particularly important for subsequent machining operations and for ensuring the dimensional quality of finished wood products.

This observed pattern of dimensional changes can be explained by the mechanism of shrinkage and stress development during beech wood drying, as described in detail by Majka and Sydor (2023), Klement *et al.* (2025), and Popović *et al.* (2006). All of these authors state that the key factor is the formation of a moisture gradient between the surface and the core of the material, which leads to non-uniform shrinkage and the subsequent development of internal stresses. These stresses are most pronounced in the early stages of drying, when the moisture gradient is highest, and their intensity determines the material's susceptibility to deformation and defects. In the context of the present results, where only minor differences in overall dimensional stability were observed between the drying regimes, it can be assumed that the applied drying conditions did not generate substantially different moisture gradients and therefore did not lead to significantly different levels of internal stress development. At the same time, the slightly higher and more variable shrinkage values at the higher temperature of 90 °C may be associated with more intensive initial drying and a faster development of stresses, whereas at 105 °C, the critical moisture range may have passed more quickly, thereby reducing the duration of the most critical gradient conditions.

This interpretation is supported by Popović *et al.* (2006), who reported that increasing moisture content and temperature significantly reduce the strength and stiffness of beech wood due to softening of the lignin matrix. From the perspective of drying-induced dimensional stability, this means that wood has a reduced ability to resist internal stresses generated by moisture gradients, making it more susceptible to deformation, particularly in the early stages of drying when both moisture and temperature effects are most pronounced.

Measurement of Cutting Power after Drying

To evaluate the influence of the applied drying regimes on the machinability of beech wood, cutting power measurements were carried out during sawing tests using a PRW15M sash gang saw.

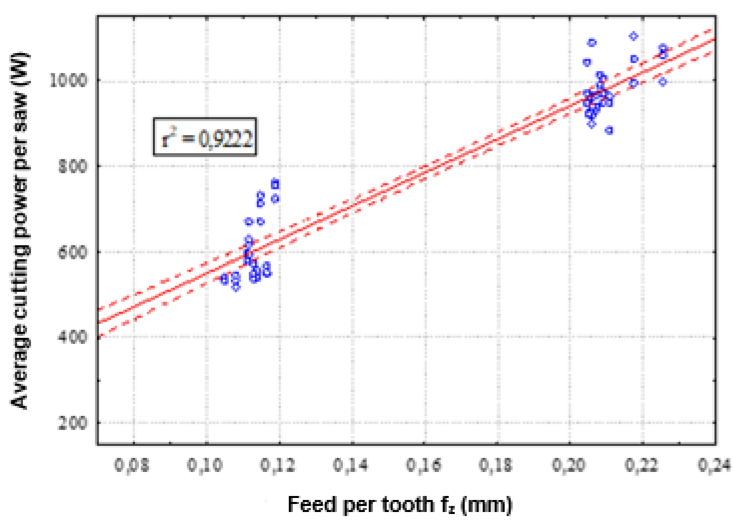

Fig. 3. Cutting power per saw in the feed per tooth function during cutting on sash gang saw PRW15M,a beech timber dried in air at 25 °C

The obtained results were processed and analysed separately for each drying regime. Two types of feed rates per tooth [mm] were used. For that reason, the analysis was carried out for both feed rates per tooth. Figure 3 shows the changes in cutting power per one saw when cutting beech wood dried in air at 25 °C.

For the air-dried beech wood samples (25 °C), the average cutting power per saw blade increased markedly with increasing feed per tooth (f_z). A strong linear relationship was observed between these parameters, as confirmed by the high coefficient of determination (R^2 = 0.9222), indicating that more than 92% of the variation in cutting power was explained by changes in feed per tooth. At lower feed values (approximately 0.10 to 0.12 mm), the average cutting power ranged between 500 and 700 W, whereas at higher feed values (approximately 0.20 to 0.22 mm), it increased to about 850 to 1050 W. This trend reflects the greater chip volume removed by each tooth and the resulting increase in cutting load. Although a certain degree of data scatter was observed, particularly at lower feed values, the overall variability remained relatively low, and the measured values closely followed the regression line. The results indicate that feed per tooth is a dominant factor affecting cutting power consumption during the sawing of air-dried beech wood.

Figure 4 shows the change in cutting power per saw while cutting beech wood dried in an experimental kiln using the gas-steam mixture at 90 °C.

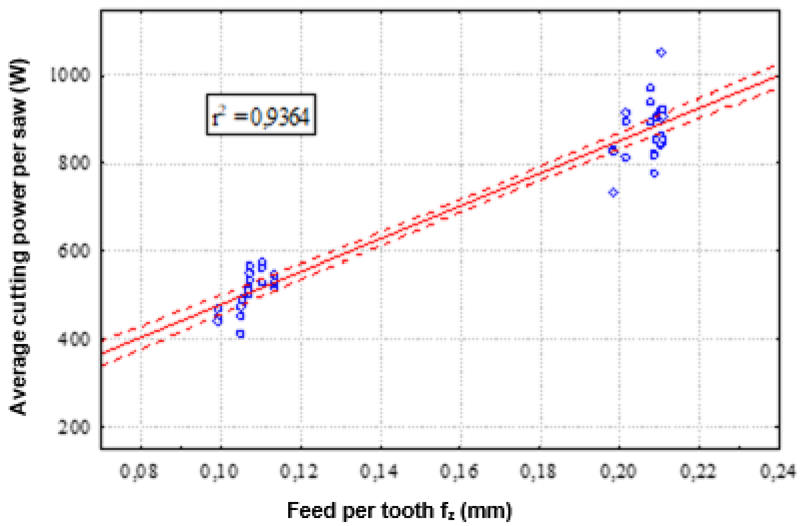

Fig. 4. Cutting power per saw in the feed per tooth function during cutting on sash gang saw PRW15M a beech timber dried under normal temperature at 90 °C

For the beech wood samples dried at 90 °C, the average cutting power per saw blade increased with increasing feed per tooth (f_z), exhibiting a strong linear relationship. The regression analysis yielded a coefficient of determination of $R^2 = 0.9364$, indicating that approximately 94% of the variability in cutting power was explained by changes in feed per tooth. At lower feed values (approximately 0.10 to 0.11 mm), the average cutting power ranged from about 450 to 550 W, whereas at higher feed values (approximately 0.20 to 0.21 mm), it increased to approximately 800 to 950 W.

Figure 5 shows changes in the cutting power per saw when cutting beech wood dried in an experimental kiln using a steam temperature of 105 °C. For beech wood dried at 105 °C, the relationship between feed per tooth and cutting power per saw blade also showed a clear positive trend, where increasing f_z led to higher average cutting power during sawing on the PRW15M frame saw. The experimental data, ranging from approximately 0.08 to 0.24 mm feed per tooth and 200 to 1100 W cutting power, were well described by a linear regression model, with a coefficient of determination $R^2 = 0.7950$, indicating that about 79.5% of the variability in cutting power was explained by changes in feed per tooth. Although some scatter of measured values around the regression line was observed, the overall trend remained consistent, confirming that higher feed per tooth results in increased cutting power under high-temperature drying conditions.

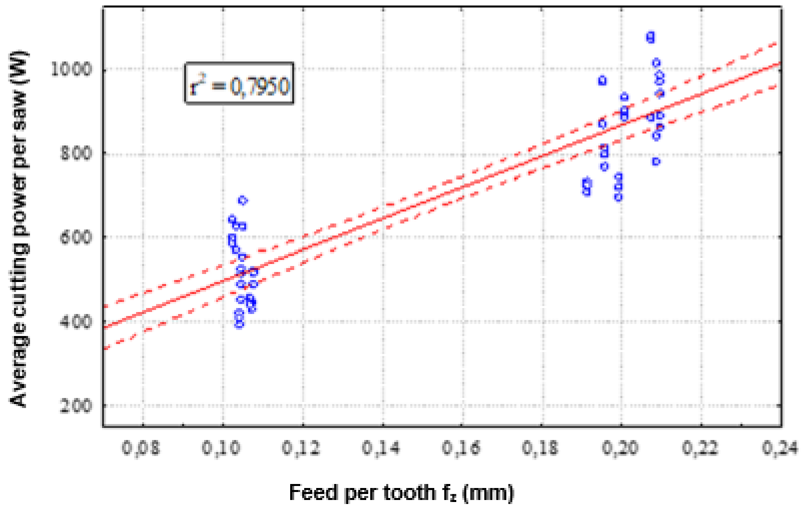

Fig. 5. Cutting power per saw in the feed per tooth function during cutting on sash gang saw PRW15M a beech timber dried under high temperature at 105 °C

Across all investigated drying regimes (25, 90, and 105 °C), cutting power increased with increasing feed per tooth, exhibiting an approximately linear relationship. This result indicates that feed per tooth is the dominant factor influencing cutting power, whereas the effect of the drying regime is mainly reflected in changes in the intensity (slope) of this dependence. Similar conclusions were reported by Kopecký *et al*. (2014) who demonstrated in their modelling of the energetic effects of wood sawing that cutting forces and power are directly dependent on the chip thickness generated by the tool tooth, which is closely related to the feed per tooth. An increase in uncut chip thickness, therefore, leads to higher energy demand during cutting.

These findings are also consistent with the study by Eyma *et al.* (2004), who investigated the machining of tropical wood species and found that cutting forces are significantly influenced by machining parameters and chip geometry. The authors showed that increasing chip thickness leads to higher cutting forces required for material separation, which consequently results in increased energy consumption of the process. In the study by Chuchala *et al.* (2020), the authors report that for beech wood, cutting power varies only slightly across drying methods, suggesting a generally weak influence of drying conditions on cutting power. At the same time, the authors indicate that drying-related changes in material properties may still contribute to variations in cutting power. However, this effect wasn't pronounced for beech wood in this study.

Figure 6 illustrates the effect of the drying regime (25, 90, and 105 °C) on the cutting power per saw blade (W). The measurements were divided into two groups according to feed per tooth (f_{z1} and f_{z2}). The results show that the f_{z2} parameter requires a significantly higher cutting power overall (approximately 700 to 1100 W) compared to f_{z1} (approximately 400 to 750 W). In both groups, a similar trend can be observed: the highest median cutting power was recorded at the reference temperature of 25 °C. An increase in drying temperature to 90 °C led to a decrease in cutting power in both cases. A further increase to 105 °C resulted in similar or only slightly lower median values compared to 90 °C. The analysis of variance confirmed the trends shown in the figure, demonstrating that the drying regime has a statistically highly significant effect on cutting power.

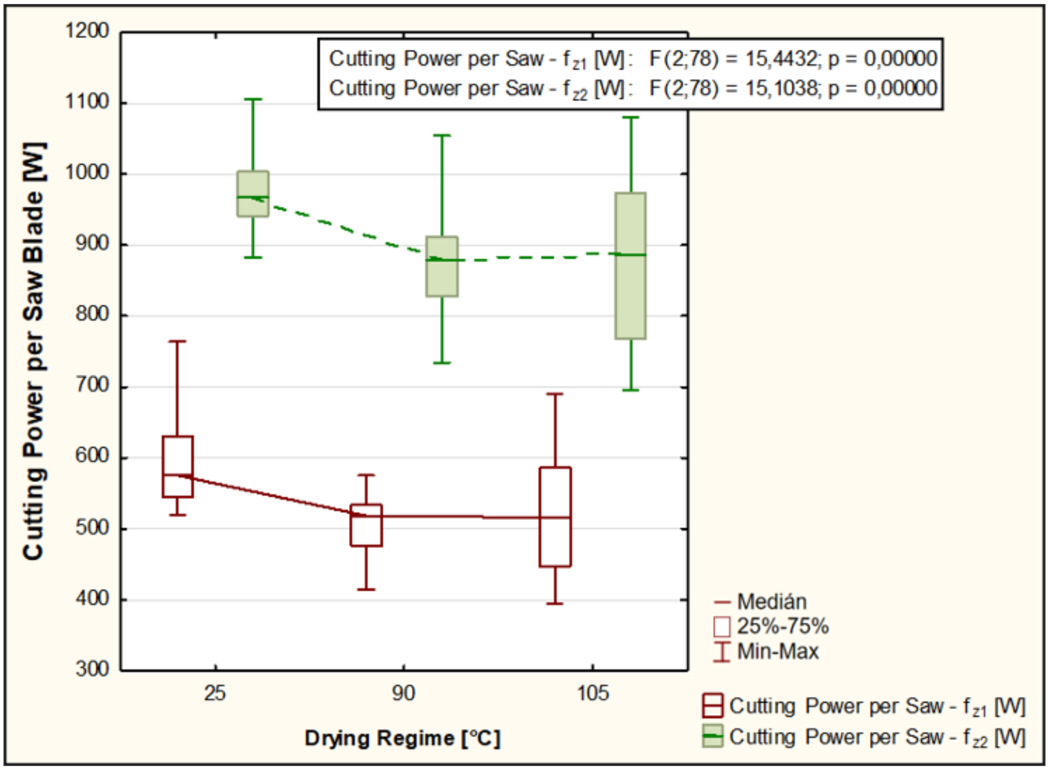

Fig. 6. Dependence of saw cutting power on the drying regime for the f_{z1} and f_{z2} parameters

The increase in cutting power of beech wood with decreasing moisture content observed in this study agrees with previously published findings. Oliveira Guedes *et al.* (2020) reported an increase of approximately 30 to 60% in cutting energy for dense hardwoods as the moisture content decreased from green to air-dried conditions. Similarly, Chuchała *et al.* (2020) observed that cutting power for beech wood increased from about 2.0 to 2.5 kW at higher moisture contents (18 to 20%) to approximately 3.0 to 3.8 kW at lower moisture contents (8 to 10%), with an additional influence of drying temperature. Moradpour *et al.* (2013) likewise found that reducing moisture content results in higher cutting resistance, reporting cutting forces for beech wood ranging from roughly 20 N/mm at 30% moisture content (radial direction) to about 44 N/mm at 12% moisture content (tangential direction). Collectively, these studies confirm that moisture-induced changes in wood density, stiffness, and internal structure significantly affect machinability, and support the use of cutting power as a sensitive indicator of drying-related effects.

CONCLUSIONS

1. The applied drying conditions significantly influenced the final moisture content of beech wood. Air-drying process at 25°C resulted in the highest moisture content (approximately 9% to 17%), whereas after drying processes at 90 and 105 °C lower and more uniform moisture contents were obtained, generally within the range of 6% to 7%.

2. Increasing the drying process temperature from 90 to 105 °C did not substantially reduce the final moisture content. The primary effect of elevated drying temperatures was an increase in drying efficiency and moisture content uniformity rather than a further reduction in equilibrium moisture content.
3. Dimensional changes occurred under all drying conditions. Tangentially oriented specimens exhibited greater shrinkage than radially oriented ones, confirming the anisotropic behaviour of beech wood during moisture removal.
4. The applied drying modes maintained satisfactory dimensional stability of the dried material. Only minor differences in shrinkage were observed among the drying regimes, suggesting that the investigated conditions did not impact substantially different levels of drying-induced internal stresses.
5. During machining, the cutting power increased linearly with feed per tooth for all drying schedules, indicating that feed per tooth was the primary factor governing energy consumption during sawing. The obtained coefficients of determination (R^2 = 0.795 to 0.936) confirmed a strong relationship between these variables.
6. The drying conditions significantly influenced the cutting power required during machining. Air-dried wood required the highest cutting power, whereas wood dried at 90 and 105 °C showed lower cutting power values. Only minor differences were observed between the two elevated-temperature drying modes.
7. The results indicate that high-temperature drying (90 and 105 °C) can improve drying efficiency while maintaining acceptable dimensional stability and favourable machining performance of beech wood. Under the investigated conditions, drying at temperatures above 90 °C provided limited additional benefits in terms of final moisture content and cutting power reduction.

ACKNOWLEDGEMENTS

This work was supported by the Slovak Research and Development Agency under contract no. APVV-21-0049. This work was supported by the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic and the Slovak Academy of Sciences project VEGA no. 1/0092/26.

The authors would like to express gratitude to Tomasz Muziński for the data used in this article.

REFERENCES CITED

Bajraktari, A., Sejdiu, R., Thaçi, B., Nunes, L., and Pereira, H. (2012). "Evaluation of beech wood defects due to different drying schemes," in: *WDC2012, 12th International IUFRO Wood Drying Conference - Challenges and Opportunities Related to Tropical Lumber Drying*, Belém, Para, Brazil.

Bektaş I., Güler C., and Baştürk M. A. (2002). "Principal mechanical properties of eastern beech wood (*Fagus orientalis* Lipsky) naturally grown in Andirin Northeastern Mediterranean Region of Turkey," *Turkish Journal of Agriculture and Forestry* 26(3), 147–154.

Beljo-Lučić, R., Goglia, V., Pervan, S., Đukić, I., and Risovic, S. (2004). "The influence of wood moisture content on the process of circular rip-sawing. Part I: Power requirements and specific cutting forces," *Wood Research* 49, 41-49.

Blanchet, P., Kaboorani, A., and Bustos, C. (2016). "Understanding effects of drying methods on wood mechanical properties at ultra and cellular levels," *Wood and Fiber Science* 48(2), 1-12.

Blass, H. J., Frese, M., Glos, P., Denzler, J. K., Linsenmann, P., and Steck, G. (2005). "Brettschichtholz in Buche: Untersuchungen zur Herstellung und Bemessung (Glulam made of beech: Investigations on production and design)," Universität Karlsruhe, Karlsruhe, Germany.

Chuchala, D., Ochrymiuk, T., Orlowski, K., Lackowski, M., and Taube, P. (2020). "Predicting cutting power for band sawing process of pine and beech wood dried with the use of four different methods," *BioResources* 15(1), 1844-1860. https://doi.org/10.15376/biores.15.1.1844-1860

Denig, J., Wengert E. M., and Simpson W. T. (2000). "Drying hardwood lumber. U.S. Department of Agriculture," Forest Service, Forest Products Laboratory, Madison

EN 13183-1 (2002). "Moisture content of a piece of sawn timber – Part 1: Determination by oven dry method," European Committee for Standardization (CEN), Brussels, Belgium.

EN 13183-2 (2002). "Moisture content of a piece of sawn timber – Part 2: Estimation by electrical resistance method," European Committee for Standardization (CEN), Brussels, Belgium.

EN 13183-3 (2005). "Moisture content of a piece of sawn timber – Part 3: Estimation by capacitance method," European Committee for Standardization (CEN), Brussels, Belgium.

Eyma, F., Méausoone, P.-J., Martin, P. (2004). "Study of the properties of thirteen tropical wood species to improve the prediction of cutting forces in mode B," *Ann. For. Sci.* 61, 55-64. https://doi.org/10.1051/forest:2003084

Frühwald, A., Ressel, J. B., and Bernasconi A. (2003). "Hochwertiges Brettschnichtholz aus Buchenholz, (High-quality laminated timber made from beech wood)," Institut für Holzphysik und mechanische Technologie des Holzes, Bundesforschungsanstalt für Forst- und Holzwirtschaft, Hamburg, Germany, BMBF Project No. 0339827, 198 pp.

Govorčin, S., Sinković, T., Trajković, J., and Despot, R. (2003). "Obična Bukva (*Fagus sylvatica* L.) u Hrvatskoj" (Common beech (*Fagus sylvatica* L.) in Croatia), Akademija šumarskih znanosti, Zagreb, pp. 652-669. ISBN 953-98571-1-2.

Gryc, V., Vavrčík, H., and Gomola, Š. (2008). "Selected properties of European beech (*Fagus sylvatica* L.)," *Journal of Forest Science* 54(9), 418-425. https://doi.org/10.17221/59/2008-JFS

Keey, R. B., Langrish, T. A. G., and Walker, J. C. F. (2000). *Kiln-drying of Lumber,* Springer, Berlin. https://doi.org/10.1007/978-3-642-59653-7

Klement, I., Vilkovská, T., Vilkovský, P., and Uhrín, M. (2025). "Comparison of pressure and atmospheric steaming processes and their effects on selected properties of beech wood (*Fagus sylvatica* L.)," *Appl. Sci*. 15, article 13066. https://doi.org/10.3390/app152413066

Kopecký, Z., Hlásková, L., and Orlowski, K. (2014). "An innovative approach to prediction energetic effects of wood cutting process with circular-saw blades," *Wood Research* 59(5), 827-834.

Korkua, K. S., Choosak, R., Siraporn, S., Dash, K. S., Chalearm, T., and Kamon, T. (2025). "Optimizing air velocity for energy-efficient and sustainable rubberwood drying kilns," *Results in Engineering* 27, 105840. https://doi.org/10.1016/j.rineng.2025.105840

Loehnertz, S. P., and Cooz, I. V. (1998). *Sawtooth Forces in Cutting Tropical Hardwoods Native to South America*, USDA, Forest Products Laboratory, pp. 16.

Majka, J., and Sydor, M. (2023). "Analysis of stress development during kiln drying of beech timber," *European Journal of Wood and Wood Products* 81, 1189–1200.

McMillen, J. M. (1958). *Stresses in Wood During Drying*, USDA, Forest Products Laboratory, Madison, WI, USA.

Moradpour, P., Doosthoseini, K., Scholz, F., and Tarmian, A. (2013). "Cutting forces in bandsaw processing of oak and beech wood as affected by wood moisture content and cutting directions," *European Journal of Wood and Wood Products* 71, 747-754. https://doi.org/10.1007/S00107-013-0734-Z

Oliveira Guedes, T., Silva, J., Gherardi Hein, P. R., and Ferreira, S. (2020). "Cutting energy required during the mechanical processing of wood species at different drying stages," *Maderas: Ciencia y Tecnología* 22(4). https://doi.org/10.4067/S0718-221X2020005000406

Orlowski, K. A., Chuchala, D., Muziński, T., Barański, J., Banski, A., and Rogoziński, T. (2019). "The effect of wood drying method on the granularity of sawdust obtained during the sawing process using the frame sawing machine," *Acta Facultatis Xylologiae Zvolen* 61(1), 83-92. https://doi.org/10.17423/afx.2019.61.1.08

Perré P., and Passard J. (2007). "Stress development," in: *Fundamentals of Wood Drying*, P. Perré (ed.), A.R. BO. LOR. Nancy, Paris, pp. 243-271.

Popović, Z., Šoškić, B., and Mirić, M. (2006). "Effect of moisture and temperature on some mechanical properties of beechwood," in: *Proceedings of the 5th International Symposium Wood Structure of Properties* '06. Zvolen, Arbora Publishers, pp. 349-354.

Sandland, K. M., and Gjerdrum, P. (2007). "Creep deformation in drying wood," in: *Fundamentals of Wood Drying*, P. Perré (ed.), A.R. BO. LOR. Nancy, Paris, pp. 85-104.

Schniewind, A. P. (1960). "On the nature of drying stresses in wood," *Holzforschung* 14, pp. 161-168. https://doi.org/10.1515/hfsg.1960.14.6.161

Schniewind, A. P. (1963). "Mechanism of check formation," *Forest Product Journal* 13, 475-480.

Simpson, W., and Tenwolde, A. (1999). "Physical properties and moisture relations of wood," in: *Wood Handbook – Wood as an Engineering Material*, General Technical Report FPLGTR- 113, Madison, WI. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 463.

Tiemann, H. D. (1924). "Causes of surface checks in wood in varnish-drying rooms," *SAE Transactions* 19, 565–593.

Vilkovský, P., Uličný, H. M., Klement, I., and Vilkovská, T. (2024). "The differences in shape stability for hornbeam (*Carpinus betulus* L.) lumber with and without spiral grain," *Applied Sciences* 14(12), article 5250. https://doi.org/10.3390/app14125250

Wagenführ, R. (2000). *Holzatlas*, Leipzig, Fachbuchverlag Lepzig: 707.
Zhu, Z., Buck, D., Ekevad, M., Marklund, B., Guo, X., Cao, P., and Zhu, N. (2019). "Cutting forces and chip formation revisited based on orthogonal cutting of Scots pine," *Holzforschung* 73(2), 131-138.

Article submitted: April 1, 2026; Peer review completed: May 25, 2026; Revised version received and accepted: June 12, 2026; Published: June 26, 2026.
DOI: 10.15376/biores.21.3.7541-7557