

ANALYSIS OF THE INFLUENCE OF STEAMING TEMPERATURE ON THE SURFACE ROUGHNESS OF CNC-MILLED BEECH SAPWOOD AND FALSE HEARTWOOD

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ABSTRACT

A comparative analysis of the surface roughness of false heartwood and sapwood zones of beech wood (*Fagus sylvatica* L.) after thermal treatment by steaming, followed by CNC milling, is presented in the paper. The samples were treated in four steaming modes (95 °C, 115 °C, 125 °C, and 135 °C) simulating industrial conditions. The milled surfaces were evaluated using the roughness parameters R_a and R_z using a Keyence VHX-7000 digital microscope. The results show that thermal treatment reduces surface roughness in both zones, with the most significant improvement observed at medium temperatures (115–125 °C). The false heartwood zone consistently exhibited lower roughness values, indicating a denser, more stable structure during milling. Statistical analysis confirmed the significant influence of the treatment mode and wood zone on surface roughness. These findings provide guidance on optimizing heat-treated beech machining parameters, thereby increasing efficiency in furniture production.

Keywords: beech wood; thermal modification; CNC milling; surface roughness; sapwood; false heartwood.

INTRODUCTION

CNC wood milling is a key research topic in wood science (Atanasov 2021). With ongoing technological progress, their industrial applications continue to grow, leading to the wider use of CNC machines in woodworking enterprises (Červený *et al.*, 2022). However, to ensure high processing quality, an optimal process setup is essential. From a technological standpoint, it is important to optimize machining parameters to achieve the desired surface quality. Incorrect selection of these parameters not only leads to increased roughness or waviness, which prolongs subsequent sanding, but can also cause deep defects due to torn fibres. Such damage is often impossible to remove by conventional sanding and requires repair with filler or complete rejection of the workpiece from production. Therefore, several authors focus on determining the optimal parameter combination to achieve the target quality of the machined surfaces (Cota *et al.*, 2017; Gurău *et al.*, 2021; İşleyen and Karamanoğlu 2019; Pelit *et al.*, 2021).

The modernization of the wood industry has led to the use of new materials, including wood treated by steaming or hydrothermal processes. or thermal processes. Hydrothermal processes are carried out above 160 °C. Such modification changes several properties of wood – it improves dimensional stability (Damay *et al.*, 2024), reduces swelling, moisture

content, and surface hydrophobicity (Keržič *et al.*, 2021; Huang *et al.*, 2023), increases resistance to rot, and extends biological durability (Bi *et al.*, 2024; Anish *et al.*, 2023). At the same time, density and hardness are reduced, thereby affecting the surface quality after milling. Several studies confirm that appropriately selected heat treatment reduces the roughness of the milled surface (Korkut *et al.*, 2012; Shukla, 2019). In the case of steam-modified beech wood, it is necessary to investigate not only the effect of the heat treatment temperature on the surface roughness after milling, but also how the roughness changes in the sapwood and false heartwood areas. False heartwood is a common defect in beech wood and can occupy a significant part of the sawn timber. Therefore, from a process-optimization perspective, it is essential to determine the achievable surface roughness levels in two different parts of the wood.

In this work, the surface texture assessment was performed using the surface roughness parameter Ra, which is considered one of the most consistent and robust indicators of surface quality (Ružová and Haddadi 2025). In addition, the Rz parameter was evaluated as a complementary indicator because it provides information on the height of the most significant surface irregularities, thereby helping characterize surfaces where localized defects may occur. The primary objective of the research is to analyze the changes in surface topography after CNC milling under heat treatment conditions in the temperature range from 95 °C to 135 °C, and to compare the resulting differences between two structural zones of beech wood - the outer sapwood, which represents the peripheral part of the trunk, and the false heartwood, which forms its inner core area.

MATERIALS AND METHODS

Sample preparation:

Samples of European beech wood (*Fagus sylvatica* L.) with a tangential surface were prepared from boards that had previously undergone thermal modification by steaming under defined industrial regimes. From the boards, specimens with final dimensions of 20 mm in thickness, 70 mm in width, and 400 mm in length were made. In total, 20 specimens were prepared and subsequently divided into five groups of four pieces each. On every sample, 20 surface roughness measurements were performed.

The first group served as the untreated control and was prepared from non-steamed boards. The remaining four groups were derived from boards steamed under distinct industrial conditions. Material for the second group originated from boards steamed in mode I at a maximum temperature of 95 °C; material for the third group was obtained from boards steamed in mode II at 115 °C; group 4 samples originated from boards steamed in mode III at 125 °C; and the last group samples were prepared from boards steamed in mode IV at 135 °C.

All steaming processes were performed under industrial conditions at Sundermann s.r.o. in Banská Štiavnica, Slovakia, using saturated water steam in a pressure autoclave type APDZ 240 (Himmasch AD, Haskovo, Bulgaria), except for samples treated in mode I, saturated moist air at atmospheric pressure was used at 95 °C. The steaming regimes applied to the boards preceded the preparation of individual test specimens and represented the actual technological conditions employed in industrial practice.

The parameters t_{\min} and t_{\max} define the temperature range within which saturated water steam (or saturated moist air) is introduced into the autoclave during the steaming process. The value t_4 represents the temperature corresponding to the steam pressure level in the

autoclave, at which the internal pressure must be lowered to allow safe opening of the device after the steaming cycle has been completed.

Tab. 1 Modes of thermal modification of beech boards using saturated moisture content or saturated water steam.

Mode	Temperature of modification medium [°C]			Duration of technological operation [h]		
	t_{min}	t_{max}	t_4	$\tau_1 - phase I$	$\tau_2 - phase II$	Total time
Untreated control group	-	-	-	-	-	-
Mode I	92.5	97.5	90	6	1.5	7.5
Mode II	102.5	107.5	100			
Mode III	122.5	127.5	100			
Mode IV	132.5	137.5	100			

Note: The parameters t_{min} and t_{max} define the temperature range within which saturated water steam (or saturated moist air) is introduced into the autoclave during the steaming process. The value t_4 represents the temperature corresponding to the steam pressure level in the autoclave, at which the internal pressure must be lowered to allow safe opening of the device after the steaming cycle has been completed.

Before the steaming process, the initial moisture content of the boards ranged from 54.7% to 58.2%. Non-thermally treated and thermally modified boards were conditioned in a low-temperature drying mode, ensuring no impact on wood color change, achieving a final moisture content of $w = 12 \pm 0.5$ %, using a conventional hot-air kiln, Suzar KC 1/50 (SUZAR s.r.o., Považany, Slovakia).

CNC Sample Milling:

From the boards, test specimens with final dimensions of 20 mm × 70 mm × 400 mm (thickness × width × length) were produced using a circular table saw, a jointer, and a planer equipped with a helical cutterhead. For the purposes of this experiment, specimens were extracted both from the false heartwood zone and from the outer sapwood zone. Following the drying process, the samples were conditioned under indoor ambient conditions to stabilize their equilibrium moisture content within the range of 8 ± 2 %. After conditioning, the equilibrium moisture content was re-verified immediately before the surface roughness measurements using the gravimetric method. The milling was performed on a 5-axis CNC machining centre SCM Tech Z5 (SCM Group S.p.A., Rimini, Italy). Samples were clamped using a VCMC-S4 12-80 combined mechanical-vacuum system (Schmalz GmbH, Glatten, Germany), ensuring stable fixation. The milling tool used was a finishing positive spiral cutter T143 (Sistemi S.r.l., Pesaro, Italy) from WOOD-B (WOOD-B, Nové Zámky, Slovakia), with a diameter of 20 mm and 3 cutting edges. Milling was carried out under constant cutting conditions with spindle speed $n = 18,000 \text{ min}^{-1}$, depth of cut $a_e = 1 \text{ mm}$, and feed rate $v_f = 14 \text{ m} \cdot \text{min}^{-1}$. Each sample was milled in a single pass, corresponding to the finishing milling step. This shallow cut minimizes cutting forces, reduces fibre chipping and surface roughness.

Surface Roughness Measurement:

The roughness was evaluated with a Keyence VHX-7000 digital microscope (Keyence Corporation, Osaka, Japan). The milled edge of the samples was scanned by 20 evenly spaced scans measuring 3 mm × 18 mm. All scans were taken at 100× zoom using a VH-Z100R lens (Keyence Corporation, Osaka, Japan). Two profile traces were evaluated per image, resulting in 20 measurements for each parameter in both directions—perpendicular

to the board plane and parallel to the tool feed. The profile evaluation length was 12.5 mm. Roughness profiles were filtered according to STN EN ISO 21920 (2022) using an L-filter ($\lambda_c = 2.5$ mm) and an S-filter ($\lambda_s = 8$ μm). Surface roughness was assessed based on R_a and R_z parameters. R_a was chosen for its stability and common use in literature, enabling comparison with other studies. However, since surfaces with different topographies can share the same R_a (Musolff and Malburg 2021), R_z was also analyzed to capture differences between the highest and lowest surface points, reflecting total unevenness.

Statistical Evaluation:

The obtained dataset was evaluated using STATISTICA 14 software (TIBCO Software Inc., Palo Alto, California). In the first step, outliers were detected in the dataset. Then the measured data were subjected to analysis of variance (ANOVA) at the $\alpha = 0,05$ level of significance. Before applying the ANOVA method, three key statistical assumptions were tested to ensure the validity of the results. The Shapiro-Wilk test was performed on the distribution of the random variable values for all factor combinations (groups). The test confirmed that the values follow a Gaussian distribution. Levene's test was used to check the equality of variances across the individual factor levels. The results indicated that the null hypothesis of equal variances was not confirmed. This violation is likely attributable to the significant inherent heterogeneity of the wood structure being analyzed. The final and crucial assumption was the independence of the measured quantity's values (surface roughness). This assumption was deemed sufficient based on a logical assessment of the experimental procedure and data collection.

RESULTS AND DISSCUSION

The quality of the milled surface in the central false heartwood is lower compared to the peripheral sapwood zone, as might be seen in Tab. 2, where the roughness parameters are evaluated for unmodified (UM) samples as well. This difference reflects the natural anatomical variability of wood: sapwood generally has a lower density than false heartwood, leading to increased surface roughness even in unmodified, non-steamed wood (Adamčík *et al.*, 2024). At the same time, hardness and density tend to decrease towards the peripheral parts of wood, as reported by Dzurenda *et al.* (2023). As a result, the sapwood tends to exhibit a higher degree of fibre tearing under identical machining conditions. Furthermore, its lower density often results in protruding fibres on the surface after milling, creating a characteristic fuzzy texture (Landry *et al.*, 2013).

Tab. 2 Arithmetic averages of the parameters R_a and R_z for non-steamed and all steaming modes (n = 40; the values in parentheses represent the standard deviation).

Steaming mode	R_a (sapwood) [μm]	R_a (false heartwood) [μm]	R_z (sapwood) [μm]	R_z (false heartwood) [μm]
Untreated control group	8.21 (2.28)	7.20 (2.33)	37.0 (8.93)	30.3 (8.27)
Mode I	6.56 (1.64)	6.25 (1.36)	30.1 (7.48)	28.6 (5.34)
Mode II	7.09 (1.55)	6.22 (1.13)	32.8 (6.48)	27.8 (4.05)
Mode III	6.80 (1.57)	6.58 (1.60)	31.3 (6.91)	30.1 (6.41)
Mode IV	6.54 (1.92)	6.07 (1.52)	30.1 (9.12)	28.2 (7.39)

Based on the statistical analysis, it can be confirmed that thermal modification has a significant effect on the surface quality of milled beech boards, with both the treatment mode and the wood zone being key factors influencing surface roughness. The interaction between these factors was found to be not significant, as might be seen in Tab. 3. These findings emphasize the importance of thermal modification in enhancing the quality of beech wood intended for use in the furniture industry.

Tab. 3 Statistical significance of individual factors affecting surface roughness.

	<i>Ra</i> p-level	<i>Rz</i> p-level
MODE	0.000	0.001
ZONE	0.000	0.000
MODE * ZONE	0.519	0.519

The results, shown in Fig. 1, indicate an overall decrease in roughness with increasing steaming temperature, confirming the positive effect of the treatment on the quality of the milled surface (p-value < 0.000). The observed reduction in surface roughness with increasing steaming temperature can be linked to the physical–chemical processes occurring during thermal treatment. Steaming initiates partial hydrolysis of hemicelluloses, reducing their structural rigidity and contributing to a decrease in wood stiffness and density (Esteves and Pereira 2009).

At the same time, it was shown that the false heartwood shows lower *Ra* values than the sapwood, which is related to its higher density caused by lignification of the cell walls and a more homogeneous structure. Narrower confidence intervals at higher temperatures indicate more stable results and less variability of the measured samples, while larger deviations in untreated wood may be due to its natural inhomogeneity.

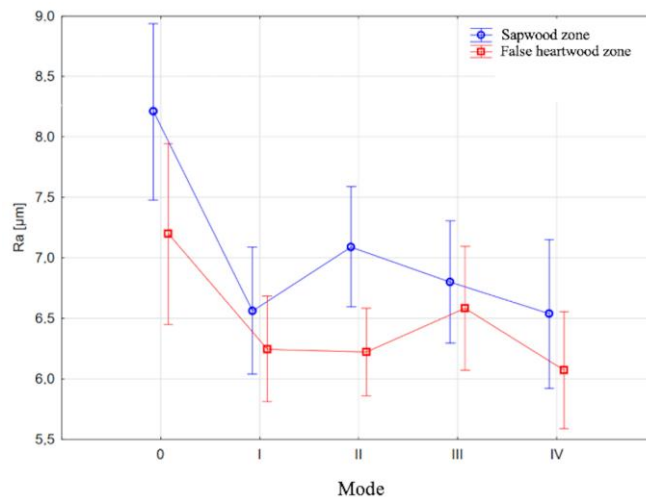


Fig. 1 Development of the *Ra* parameter depending on the change in steaming mode, with emphasis on the difference between the sapwood and false heartwood.

The statistical relevance of these variations confirms that the roughness of the machined surface may decrease even at comparatively moderate modification temperatures,

below 160 °C. Several researchers have likewise observed a statistically significant reduction in surface irregularity at elevated treatment temperatures above this limit (Corleto *et al.*, 2020; Kamboj *et al.*, 2020). According to the study by Vančo *et al.* (2017), who evaluated the surface quality of thermally treated pine wood, the surface roughness parameter Ra was lower at a modification temperature of 160 °C than in untreated pine wood; however, beyond this temperature, roughness began to increase again. Similar findings were reported by Korčok *et al.* (2019), who also observed a reduction in surface roughness of spruce wood up to 160 °C, followed by a subsequent rise at higher temperatures. Further investigations focused on beech wood milling under milder steaming conditions and also indicate that increasing the steaming temperature makes the surface smoother (Dzurenda and Dudiak 2025).

As in the previous graph, a consistent decrease in Rz values is observed when moving from mode 0 to IV, particularly in the sapwood zone. These results are shown in Fig. 2. This trend indicates that, with increasing steaming temperature, the maximum profile height of surface roughness decreases, resulting in a reduction in the highest surface peaks. The comparison between the sapwood and false heartwood zones shows that the false heartwood generally exhibits lower Rz values than the sapwood across most treatment modes.

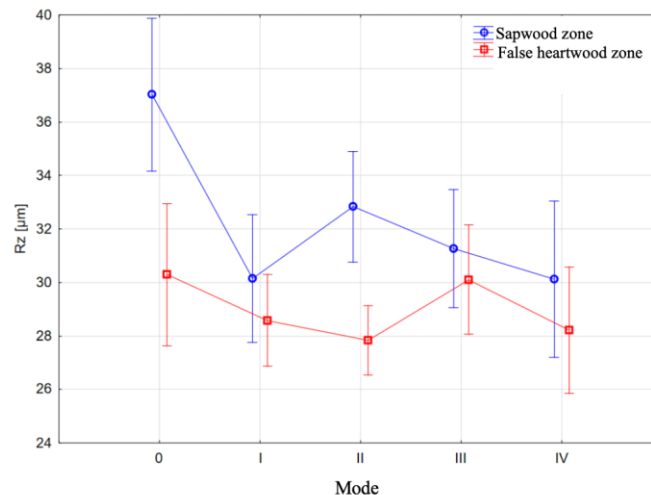


Fig. 2 Development of the Rz parameter depending on the change in mode, with emphasis on the difference between the sapwood and false heartwood.

Kučerka *et al.* (2022) reported comparable findings, noting that at a modification temperature of 160 °C, surface roughness decreased, but at higher temperatures between 160 °C and 200 °C, it gradually increased, showing a pronounced rise above 210 °C. Likewise, Kaplan *et al.* (2018b) addressed this phenomenon, stating that roughness values began to increase at 160 °C compared to untreated wood and continued to increase, thereby reducing surface quality within the 160-210 °C temperature interval. These measurements were obtained using a laser profilometer.

CONCLUSION

Initial differences in surface roughness between sapwood and false heartwood (untreated wood):

In untreated beech wood (UM), the natural variability between the peripheral sapwood zone and the central false heartwood was clearly reflected in the quality of the milled surface.

Sapwood exhibited higher Ra and Rz values, attributed to its inherently lower density and, consequently, lower hardness compared to false heartwood. As a result, even before thermal modification, false heartwood produced a smoother machined surface with fewer height irregularities.

Effect of steaming temperature on surface roughness:

The results indicate that thermal modification of beech wood by steaming improves milled surface quality. Compared to untreated material (UM), the average surface roughness Ra in sapwood decreased up to 20 %, and Rz up to 19 % in the optimal steaming modes. In false heartwood, the reduction was similar, with Ra decreasing by a maximum 16 % and Rz by 7 %. The most favorable results were achieved in the I. and IV. steaming modes, corresponding to temperatures of a maximum of 95 °C and 135 °C, where both Ra and Rz reached their lowest values. Statistical analysis confirmed that both the modification mode and wood zone significantly affect surface roughness ($p < 0.05$), with false heartwood consistently yielding lower Ra and Rz values than sapwood across all treatment modes. These findings support the conclusion that moderate steaming conditions, particularly those below 130 °C, yield smoother cutting and reduced surface irregularities. From a practical perspective, this paper demonstrates that mild thermal steaming can be an effective pre-treatment to improve the machinability of beech wood in CNC milling. The reduction in surface roughness achieved through steaming can lower post-processing requirements (sanding intensity, tool wear) and enhance the quality of final surfaces in industrial production, particularly in furniture and interior components where smoothness and uniformity are important.

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