

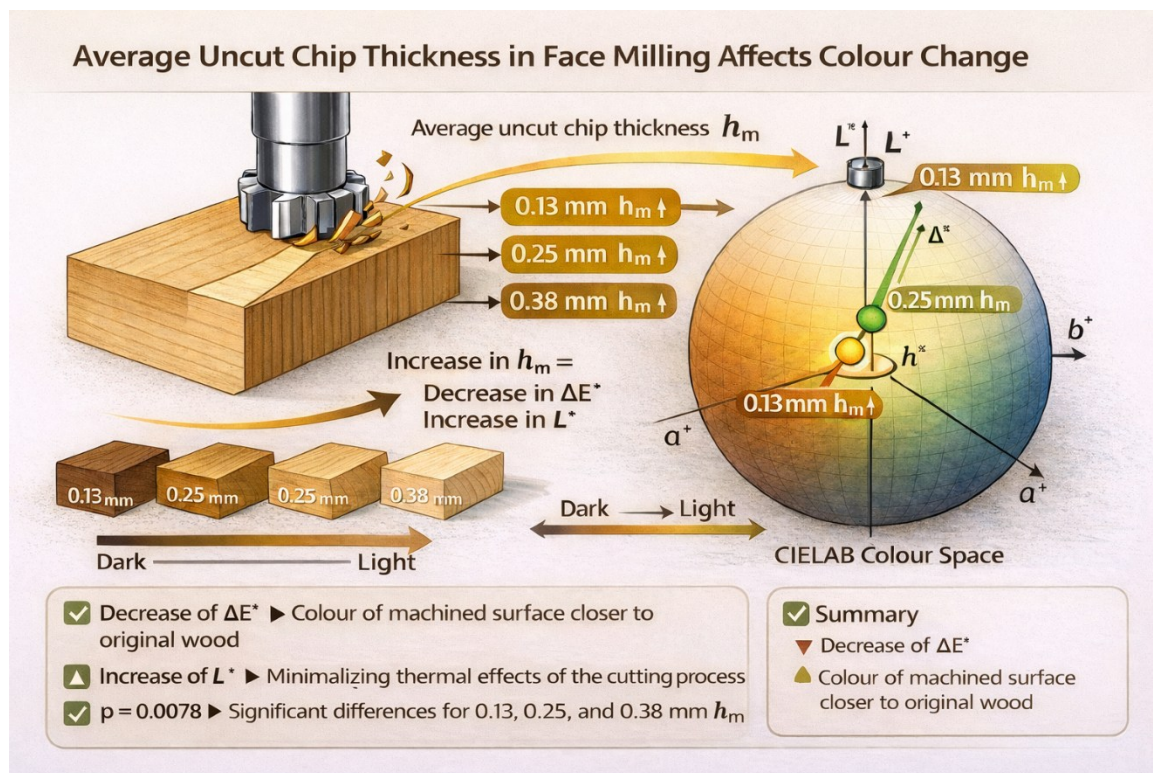
Effect of Average Uncut Chip Thickness on the Colour of Beech Wood (*Fagus sylvatica* L.) During the Face Milling Process

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GRAPHICAL ABSTRACT



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This study aimed to establish quantitative relationships between the average uncut chip thickness and the colour change of beech wood (*Fagus sylvatica* L.) during face milling. A comprehensive analysis of colour change was conducted based on measurements of chromaticity parameters, lightness, total colour difference, and hue angle variation. It was concluded that the average uncut chip thickness was a key factor in determining the surface's visual quality. It was found that an increase in average uncut chip thickness (0.13 to 0.38 mm) correlated with a decrease in total colour difference and an increase in lightness, bringing the machined surface's colour closer to the original wood. This effect was attributed to the minimisation of local thermal effects through optimizing the cutting process. This avoids thermally sensitive chemical reactions that cause colour changes. Results from various statistical analyses showed significant differences in total colour differences across average uncut chip thicknesses of 0.13, 0.25, and 0.38 mm.

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Keywords: Beech wood; Face milling; Average uncut chip thickness; Colour changes; CIELab system

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INTRODUCTION

Beech wood (*Fagus sylvatica* L.) is widely and continuously distributed from southern Scandinavia to the Mediterranean, and in parts of Western and Central Europe, it is the most common hardwood species (EUFORGEN n.d.; Caudullo *et al.* 2017). In addition to spruce and pine, beech wood is widely used in the furniture industry as solid wood and as plywood or veneer. Pramreiter and Grabner (2023) noted the potential use of beech wood for structural applications.

Beech wood is prone to moisture absorption (Ilek *et al.* 2019; Glass and Zelinka 2021). Moreover, it cracks rapidly (Oltean *et al.* 2007; Fu *et al.* 2023) and deforms during drying (Yin and Liu 2021). Steaming beech wood helps relieve internal stresses, which improves its bending properties and machinability (Dudiak *et al.* 2024).

Beech is classified as a species with false heartwood (facultative coloured heartwood), which is formed due to pathological processes such as air penetration and oxidative reactions in the stem. The false heartwood may take various shapes, including

round, star-shaped, tongue-shaped, and irregular forms. Its colour ranges from pale reddish to vivid reddish-brown, while the surrounding sapwood is typically pale yellow to pinkish (Knoke 2002). After steaming, the sapwood acquires a uniform reddish-brown colour, resulting in a more homogeneous appearance (Wernsdörfer *et al.* 2005). Growth rings are distinguishable to the naked eye on all cross-sections. The wood surface generally lacks gloss and has few distinctive textural features.

Colour is one of the key aesthetic qualities influencing consumer choice of wood products. The visual aspect plays a decisive role. Sedliačiková and Moresová (2022) noted that consumers prefer reddish-brown shades of beech wood when selecting furniture. Moderate use of wood in interior design positively affects visual attention and psychological perception (Li *et al.* 2021; Lipovac and Burnard 2021).

Various factors affect wood's colour changes (Mai and Militz 2023). Color deviations are also caused by certain special features (*e.g.*, knots, compression wood, red heart, foxiness). In softwoods, the color differences between clear wood and knots are usually greater than in hardwoods (Niemz *et al.* 2023). Therefore, detection in hardwoods is usually more difficult. For example, S. Sandoval-Torres *et al.* (2010) note that hot air thermal treatment leads to wood darkening. Esteves *et al.* (2008) established that the visual effect of autoclave treatment with saturated steam at 190 to 210 °C causes a reduction in wood lightness, which increases with the treatment's duration and temperature. In the study by Konopka *et al.* (2021), colour changes in steamed wood during drying were found to be greater than those in untreated wood. However, the depth of the affected colour layer was minor. Conversely, Tolvaj *et al.* (2009) demonstrated the possibility of homogenising beech wood with both white and red heartwood. It was also noted that the initial moisture content of the wood does not affect the colour change if it is above the fibre saturation point.

Wood is also subject to constant atmospheric exposure, which contributes to colour change. Kržišnik *et al.* (2018) conducted a comprehensive analysis of both biological and climatic factors influencing wood colour and observed its cyclical variation. Unlike ultraviolet ageing, artificial ageing caused by temperature changes occurs volumetrically, leading to varying degrees of colour change depending on the wood species. This is associated with the content of hemicellulose, lignin, and extractives, as concluded by Liu *et al.* (2017). Colour change under light irradiation is explained by lignin decomposition, with coniferous species exhibiting greater colour change than deciduous species, as confirmed by Mitsui (2004). Oltean *et al.* (2008) noted that softwood species discolour faster than hardwood species under simulated indoor sunlight exposure.

Another factor affecting wood colour change is the chemical reactions from exposure to salts and acids. The intensity of colour change strongly depends on the amount of extractives, the structure of lignin, and the type of diazonium salt used for staining (Ortlieb *et al.* 2025). Škëma *et al.* (2023) showed that the intensity of colour change correlates with the concentration of iron ions in the wood, and can be used as an indicator of the depth and intensity of hydrothermal processes.

Mechanical processing also plays a significant role in wood colour change. Colour transformation is caused by changes in surface roughness (Wood 2011; Davim *et al.* 2009), which alter the angle of light refraction and scattering (Liu *et al.* 2023). Cutting forces lead to surface heating, resulting in changes in the wood colour (Chuchala *et al.* 2022). The application of lubricants and cooling fluids causes substantial changes in the colour of the machined wood surface, which gradually diminish over time but remain even after 24 h (Chuchala *et al.* 2024). Moreover, colour change in wood can serve as an indirect indicator

of changes in its elastic and strength properties (Nguyen *et al.* 2019). Thus, wood colour can be considered an aesthetic attribute and a functional indicator.

The verification of wood colour depends on industrial and production requirements. For example, the use of the CIELab system in accordance with ISO 11664-2 (2022) and ISO 11664-4 (2019) standards allows colour changes to be determined for different processing types (Barański *et al.* 2020). For colour-based automated selection of beech wood, Wang *et al.* (2021) proposed a machine vision technology combined with an unsupervised learning technique that reduced data processing time and computational complexity. In turn, modelling approaches evaluate the influence of various external factors on wood colour. For instance, Schnabel *et al.* (2009) proposed a locally weighted regression method that visualized surface ageing kinetics and statistically justified comparisons of different technological treatments or operating conditions.

In addition to natural effects, the influence of anthropogenic factors has also been studied. Li *et al.* (2018) proposed using response surface methodology (RSM) to model and establish relationships between colour changes and the parameters of laser modification of wood. Due to the high variability of wood colour and other factors, artificial neural networks have been used. For example, Van Nguyen *et al.* (2018) used the support vector machine model with improved particle swarm optimization as studied by Li *et al.* (2023). Liang *et al.* (2025) used various models with optimisation techniques, such as the extreme learning algorithms with hybrid kernels (IZOA-DHKELM). Such approaches enable improved accuracy in predicting wood colour characteristics. The integration of intelligent systems into the research process accounts for nonlinear dependencies between technological parameters and colour, reduces the number of experimental studies required, and facilitates quality control.

Despite numerous studies addressing wood colour change under thermal, climatic, and chemical influences, the effect of machining parameters has remained insufficiently investigated. Average uncut chip thickness, h_m , is a cutting parameter describing feed movement and cross-section of the removed cutting layer. It is one of the main parameters that affects the cutting force values in machining processes and can be related to the progression of thermally sensitive chemical reactions in the wood's surface layers.

The available literature provides limited quantitative data regarding the average chip thickness and changes in the colour parameters of beech wood during face milling. Therefore, the present study aimed to establish quantitative relationships between the average uncut chip thickness (h_m) and changes in the colour parameters (lightness L^* , chromaticity parameters a^* and b^* , total colour difference ΔE^* , and hue angle variation h^*) of beech wood (*Fagus sylvatica* L.) during face milling.

EXPERIMENTAL

Materials

The materials used were beech wood (*Fagus sylvatica* L.) samples harvested from the Pomeranian region in Poland. The samples were selected from the sapwood zone without visible signs of false heartwood. Sample 6, in which false heartwood was identified during processing, was excluded from the colour change analysis. The specimens were sawn using a table-circular-sawing-machine into dimensions of 120 mm in length and a square cross-section of 50 mm × 50 mm. The samples were stored under laboratory conditions with a moisture content of $MC = 8 \pm 1.2\%$. The oven dry density of the samples

was $\rho = 690.9 \pm 30.1 \text{ kg}\cdot\text{m}^{-3}$, determined by the oven-dry method. Storage conditions prevented any sunlight from affecting the sample preparation materials. The samples were numbered from 1 to 10, and the wood annual rings orientation was determined. This allowed the appropriate number of surfaces (A, B, C), where the machining direction was either tangential to the fibres (denoted T) or radial (denoted R). Figure 1 shows the samples with the radial and tangential fibre directions relative to the milled surfaces.



Fig. 1. Sample designation indicating the orientation relatively to the fibres tangential T, or radial R direction of processing

Machine Tools, Cutting Tools, and Cutting Parameters

The experimental study was carried out on a 5-axis machining centre AX320 (Pinnacle Machine Tool Co., Ltd., Taiwan). The common experimentation method was conducted using OFAT (one-factor-at-a-time) experimentation (Astakhov 2012). The analysed face milling process was performed with three average uncut chip thicknesses (h_m): 0.13, 0.25, and 0.38 mm for surfaces A, B, and C. These values were determined based on the selected feed per tooth values f_z (0.2, 0.35, 0.5 mm) and other geometric parameters (Eq. 1, Fig. 2). The feed per tooth values in the analysis case were equal to the maximum uncut chip thickness values (Fig. 2), calculated as follows,

$$h_m = 114.6^\circ / \varphi_s \cdot f_z \cdot \sin(\kappa_r) \cdot (a_e / D) \quad (1)$$

where κ_r is the tool cutting edge angle (90°), a_e is the width of cut (50 mm), D is the cutting tool diameter (50 mm), and φ_s is the – wrap angle (180°).

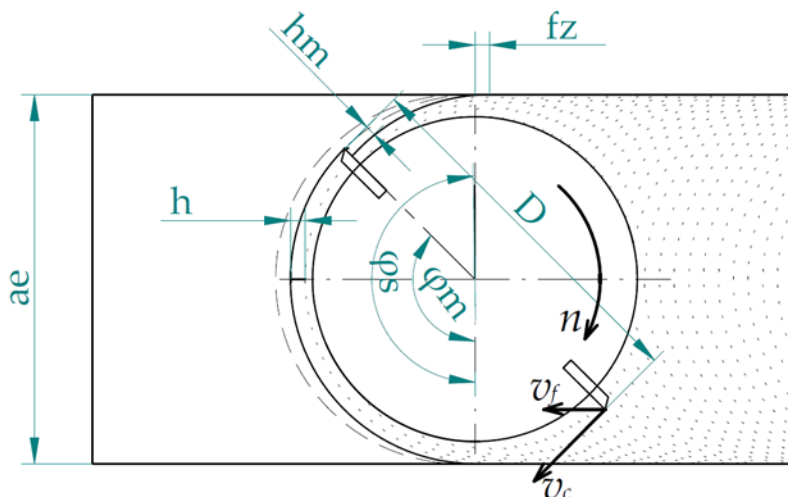


Fig. 2. Face milling process with basic cutting parameters, where v_c – cutting speed, v_f – feed speed, n – spindle speed, f_z – feed per tooth, h – maximum uncut chip thickness, h_m – average uncut chip thickness, D – tool diameter, ϕ_s – wrap angle, ϕ_m – angle of the average chip thickness position, a_e – width of cut

The cutting speed v_c was stable for each machining test at $25 \text{ m} \cdot \text{s}^{-1}$. The depth of cut a_p remained the same throughout the study at 1 mm.

Analysed Colour Parameters

One of the main problems of X, Y, and Z systems is that color differences are not perceptually equidistant. Hence, the CIE (International Commission on Illumination) developed a color system with equidistant color differences (Van Acker *et al.* 2023). To measure the colour parameters (L^* , a^* , b^*) used in the three-dimensional CIELab system recommended by the CIE (ISO 11664-4 2019; Barański *et al.* 2020; ISO 11664-2 2022), a handheld CR-10 spectrometer from Konica Minolta was employed. The parameters L^* , a^* , and b^* represent the coordinates of the three-dimensional colourimetric space. The L^* parameter corresponds to the lightness axis (0 – black, 100 – white), a^* to the red-green axis (positive values indicate red, negative values indicate green), and b^* to the blue-yellow axis (positive values indicate yellow, negative values indicate blue). These parameters were measured directly before and after machining the samples.

The total colour difference was determined using the ΔE^* parameter (Eq. 2) (Van Acker *et al.* 2023). The hue angle h^* was defined as the polar angle derived from the position of the colour point in the a^*/b^* plane.

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (2)$$

The hue angle change h^* was calculated as the difference between the hue before and after machining (Eq. 3).

$$h^* = \arctan(b^*/a^*) \quad (3)$$

Colour changes were evaluated according to the scale proposed by Cividini *et al.* (2007). Measurements were conducted at five points on each of the surfaces A, B, and C in the central part of the sample to avoid the influence of edge colour variations.

Statistical Analysis

The significance of the effect of the depth of cut on colour change was determined through the statistical analysis of the colour measurements data of beech wood samples before and after milling.

Normality of the data distribution for each depth level was assessed using the Shapiro–Wilk test (Ghasemi and Zahediasl 2012; Mishra *et al.* 2019). After confirming normality, potential outliers were identified using the Grubbs test (Grubbs 1969). To evaluate differences in mean values, a one-way analysis of variance (ANOVA) was performed. Additionally, the Wilcoxon test with Bonferroni correction (Wilcoxon 1945; Conover 1999) and the non-parametric Friedman test were performed (Hazra and Gogtay 2016).

RESULTS AND DISCUSSION

The machined surfaces of beech wood samples during face milling with three different feed per tooth are shown in Fig. 3. All analysed surfaces were noticeably darkened due to the phenomenon “burning” of wood. As the average uncut chip thickness increases, the “burning” effect decreases. In addition, there were darker areas around the edges of the samples and lighter central areas (Fig. 3). This was related to the variation in the average uncut chip thickness resulting from the kinematics of face milling (Fig. 2). On the cutting tool axis position in feed direction (centre of sample) was the maximum uncut chip thickness h value. These values decreased to almost zero as they approached the sample edge. It was observed that small values of uncut chip thickness result in a “burning” phenomenon presenting as very dark, sometimes almost black, surfaces.

In sample 8 (Fig. 3a), a brightened area of irregular shape was visible. This was caused by a hidden internal crack in the sample, which was not visible during sample preparation but caused the material to vibrate during milling. As a result of these vibrations, the cross-section of the cutting layer changed, and the phenomenon’s effects were visible. Additionally, false heartwood was identified in sample 6, which noticeably distorted the colour of the analysed surfaces. Both samples were excluded from the colour change analysis.

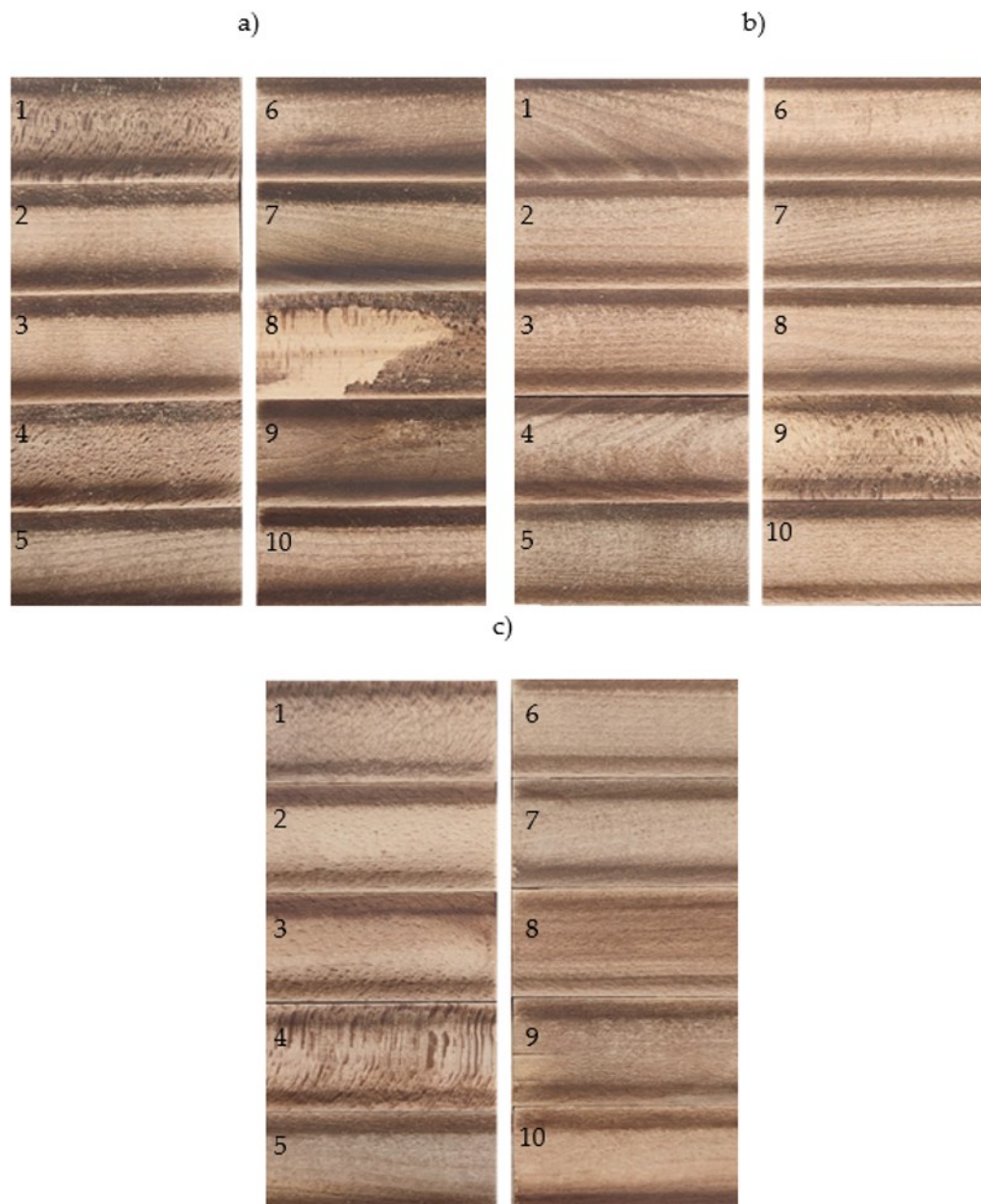


Fig. 3. Wood surface after face milling with different average uncut chip thicknesses: a) $h_{m1} = 0.13$ mm; b) $h_{m2} = 0.25$ mm; c) $h_{m3} = 0.38$ mm

Figure 4 presents the mean values with the standard error, reflecting the uncertainty of the mean estimate, for the colour parameters L^* , a^* , and b^* for wood before and after machining. Lightness increased during the milling of beech wood with increasing average uncut chip thicknesses. The minimum uncut chip thickness was 22% relative to the untreated surface, with the greatest decrease in the L^* parameter. This data indicated that increasing the h_m to 0.38 mm reduced the overall colour change relative to mechanically untreated wood.

Parameter a^* increased for all investigated depths of cut relative to the initial state. The increase was directed towards the red region, and an 18% maximum increase was

observed for the average uncut chip thicknesses of 0.25 mm. Parameter b^* showed a similar trend to a^* , increasing relative to the initial state.

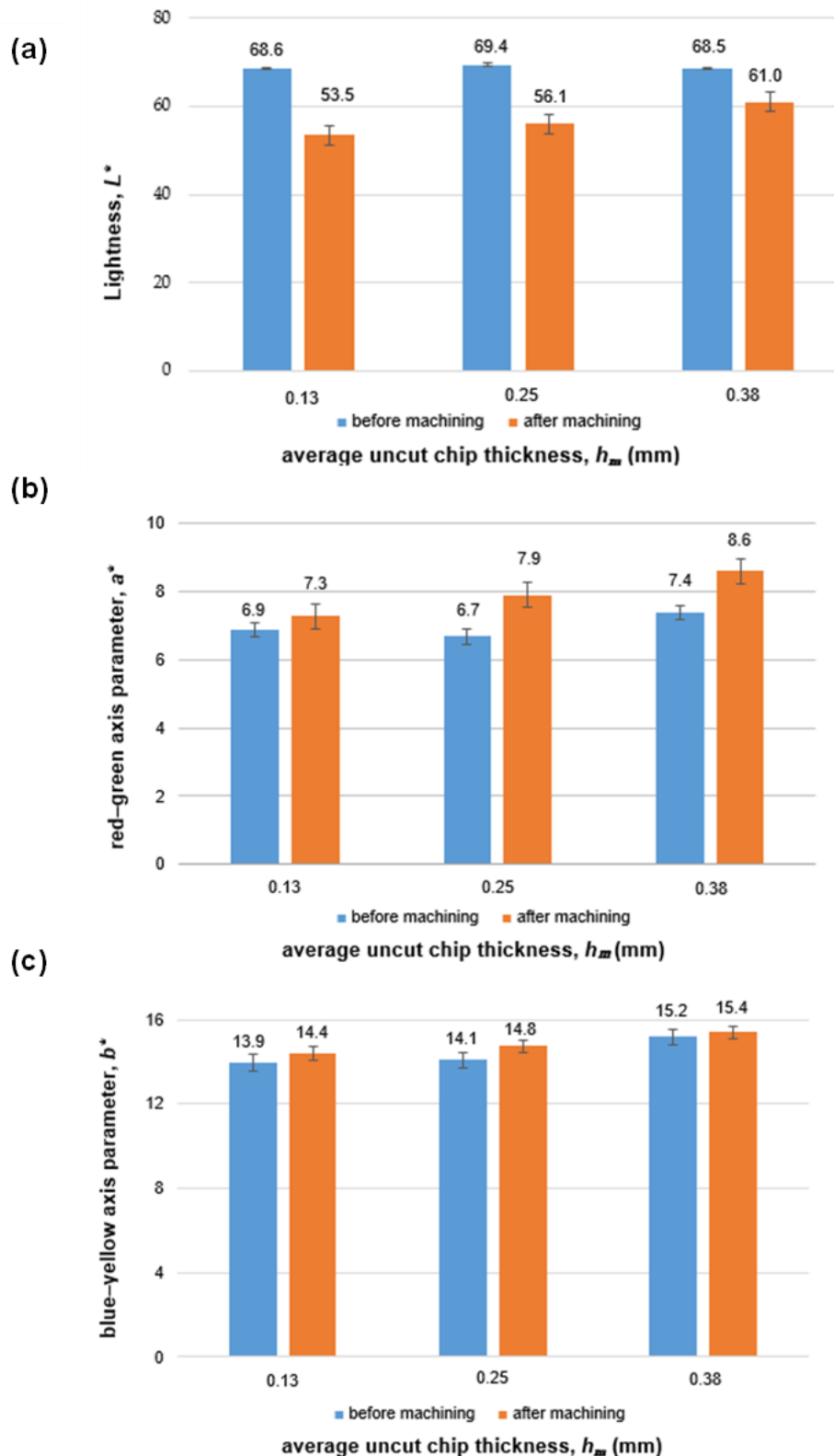


Fig. 4. Mean value of basic measured parameters of the CIELab system with standard errors before and after the face milling process of the analysed surfaces

However, changes in b^* were minor and reached a maximum of 4% at an average uncut chip thickness of 0.25 mm. The increase in b^* shifted the wood colour towards yellow. The overall colour change was shifted towards warm orange tones. This shift imparted an association with tropical species, thereby increasing the market value of beech blanks without the use of chemical colourants.

The mean values of the hue angle h^* as a function of the average uncut chip thickness for beech wood are presented in Fig. 5.

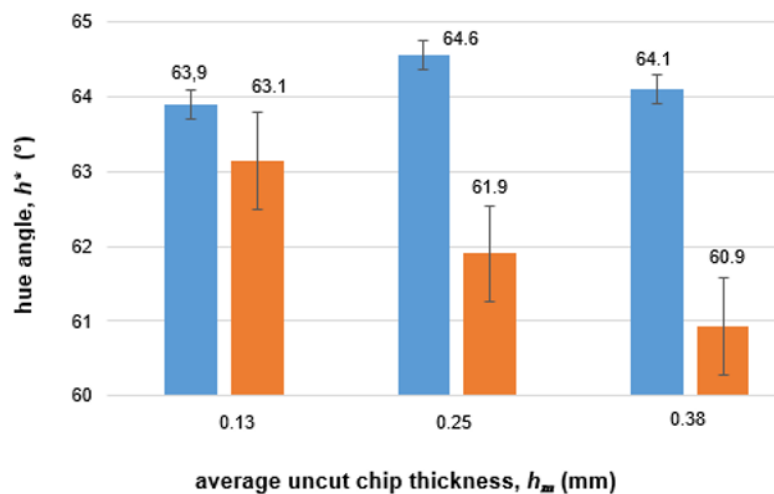


Fig. 5. Mean values of hue angle h^* with standard errors before and after the face milling process of the analysed surfaces

A decrease in the hue angle h^* was observed with increasing average uncut chip thickness. A reduction in the hue angle h^* of up to 5% was observed for the largest analysed average uncut chip thickness ($h_m = 0.38$ mm) compared to the value before milling. The reduction in the hue angle h^* indicated a shift towards reddish tones.

The mean values of the total colour difference ΔE^* as a function of the average uncut chip thickness h_m for beech wood are presented in Fig. 6. The total colour change was determined using the ΔE^* parameter. This parameter provided a quantitative assessment of the overall colour difference between wood before and after machining. As the average uncut chip thickness h_m increased, the colour change during machining decreased. This phenomenon may be because as the cross-section of the cut layer increased, the share of friction in the cutting process decreased, which reduced the amount of heat generated in the cutting zone. Similar observations in decreased temperature during the cutting process as the cross-sectional area of the cut layer increased were also reported by Igaz *et al.* (2019).

It should be noted that the cutting speed was kept constant at $25 \text{ m}\cdot\text{s}^{-1}$ throughout all experimental tests. This was intentional, as the present study followed the one factor at a time methodology, where the average uncut chip thickness h_m was the sole variable parameter. However, the cutting speed is expected to affect the colour change of wood during machining. An increase in cutting speed leads to higher temperatures in the contact zone between the tool and the machined surface (Ispas *et al.* 2016), which may intensify thermally induced chemical reactions responsible for wood darkening. Conversely, a reduction in cutting speed may increase the contact time between the tool and the workpiece, potentially enhancing the contribution of friction to heat generation. Therefore,

the investigation of the effect of cutting speed on the colour characteristics of machined wood surfaces represents a promising direction for future research.

The effect of the average uncut chip thickness h_m (0.13; 0.25; 0.38 mm) on the mean values of the total colour difference ΔE^* was assessed through one-way repeated-measures of ANOVA. Before the parametric analysis, the normality of the distribution of differences between factor levels was verified using the Shapiro–Wilk test. No deviations from normality were detected ($p > 0.05$). Potential outliers were assessed using Grubbs' test, and no statistically significant outliers were identified.

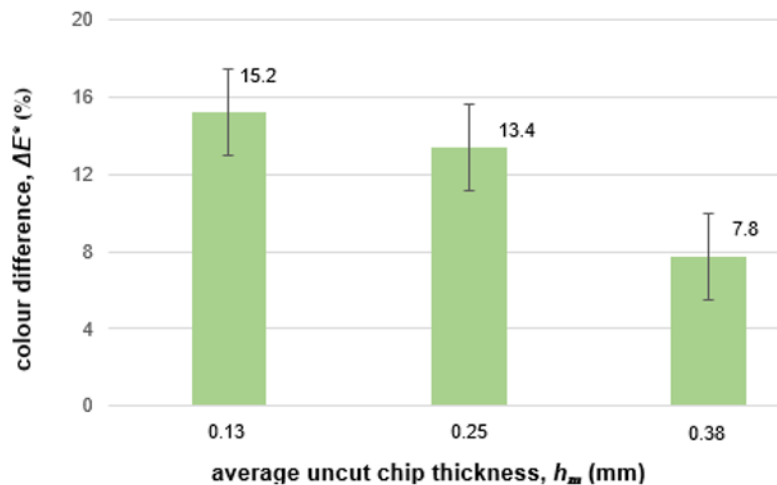


Fig. 6. Mean values of total colour changes ΔE^* with standard errors before and after the face milling process of the analysed surfaces

Post hoc analysis was performed, where ANOVA indicated statistical significance. The Wilcoxon test with Bonferroni correction was used for pairwise comparisons. The non-parametric Friedman test was conducted in addition to the parametric analysis to verify the robustness of the results against potential violations of normality. The results of the statistically significant tests are presented in Table 1.

Table 1. Parameters of Statistical Analyses

Test / Analysis	Compared Groups	P-Value	
ANOVA	0.13, 0.25, 0.38	0.0001	$F(2,14) = 19.148$
Friedman test	0.13, 0.25, 0.38	0.0015	$\chi^2 = 13.000$
Post-hoc Wilcoxon + Bonferroni	0.13 vs 0.25	0.3125	
	0.13 vs 0.38	0.0078	
	0.25 vs 0.38	0.0078	

The results of the repeated-measures analysis of variance confirmed the obtained data: $F(2,14) = 19.15$; $p < 0.001$. The non-parametric Friedman test revealed a statistically significant effect of the depth of cut on the investigated parameter ($\chi^2 = 13.000$; $p = 0.0015$). Post hoc analysis (Wilcoxon test with Bonferroni correction) demonstrated significant differences between $h_{m3} = 0.38$ mm, $h_{m1} = 0.13$ mm, and $h_{m2} = 0.25$ mm ($p = 0.0078$), whereas the differences between $h_{m1} = 0.13$ mm and $h_{m2} = 0.25$ mm were not statistically significant ($p = 0.3125$). Similar statistical relationships were established for differences in the lightness parameter L^* .

From the above analysis, it follows that the average uncut chip thickness had a statistically significant effect on the total colour change ΔE^* . Face milling at different h_m may be used as a machining operation and as a method of modifying the wood colour, making it more saturated at a milling with $h_{m1} = 0.13$ mm or preserving the original colour at a $h_{m3} = 0.38$ mm.

It was observed that the edges of the machined samples were darker than the central region. The width of the darkened edge was approximately 6 to 11 mm. This effect was discussed above and presented in Fig. 3. The "burning" phenomenon was caused by lower average uncut chip thickness values and a higher share of friction during the cutting process. Together with higher friction participation in the cutting process, the temperature in the cutting zone increased (Igaz *et al.* 2019). This effect was particularly noticeable along the longer edges of the samples (Fig. 3), where the colour differed from the wood's natural colour.

Additionally, the samples were divided into two groups to compare colour changes in the radial (R) and tangential (T) fibre directions (Fig. 1). Group 1 (1, 2, 3, 4) corresponded to the tangential fibre orientation relative to surface C (0.38 mm), and Group 2 (5, 7, 9, 10) to the radial fibre orientation relative to surface C. ANOVA analysis showed that the machining direction relative to the fibres did not have a statistically significant effect on colour change; for $h_{m2} = 0.25$ mm, $p = 0.08$.

CONCLUSIONS

1. During the face milling process of beech wood, one of the main factors affecting the colour change is the average uncut chip thickness.
2. The a^* parameter exhibited a direct correlation with increasing average uncut chip thickness. A difference of 18% was observed when machining at an average uncut chip thickness $h_{m2} = 0.25$ mm. This resulted in a shift of the wood colour towards warmer tones. The b^* parameter also showed a direct proportional correlation with increasing h_m , but to a lesser extent. The change in the b^* parameter reached a maximum of 4% relative to the initial wood colour. Milling of beech wood changed the colour parameters relative to the untreated surface. Increasing the average uncut chip thickness h_m caused an increase in the L^* parameter, while the a^* and b^* parameters increased towards red and yellow tones, respectively. The maximum increase reached 18% for a^* and 4% for b^* at $h_{m2} = 0.25$ mm. As a result, the wood colour shifted towards warmer orange tones.
3. Face milling of beech wood at different values of h_m is an effective tool for controlling and obtaining the expected visual quality of the machined surface. While a minimum average uncut chip thickness of 0.13 mm leads to thermal darkening (a decrease in L^* by 22%), increasing it to $h_{m3} = 0.38$ mm ensures stabilisation of the visual parameters and preservation of the original wood colour.
4. For the maximum analysed average uncut chip thickness $h_{m3} = 0.38$ mm, the total colour change ΔE^* reached 7.8%. These values increased as the average uncut chip thickness decreased. For the minimum analysed value of $h_{m1} = 0.13$ mm, ΔE^* reached 15.2%.

5. ANOVA statistical analysis showed that the wood fibre orientation on the surface did not have a statistically significant effect on colour change, simplifying the technological prediction of the visual quality of products. The p-values were 0.14, 0.08, and 0.6 (significance level 0.05) for average chip thickness h_m of 0.13, 0.25, and 0.38 mm.

ACKNOWLEDGMENTS

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Conflict of Interest

The authors declare no conflicts of interest.

Use of Generative AI

The GPT AI tool was used to generate the Python code for performing statistical analyses and to create some of the components used in the graphical abstract.

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