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COMPARISON OF THE ROUGHNESS OF THE CNC MILLED SURFACE OF SELECTED WOOD SPECIES

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ABSTRACT

This paper aims to quantify the surface roughness after the CNC milling of selected wood species. Optimization of the essential milling parameters, rotational speed, and feed speed is desirable for reducing surface roughness. Both technological parameters significantly contribute to the amount of feed per tooth, affecting surface roughness. In the experiment, three economically important wood species were compared – beech, oak, and spruce wood. In addition, the zones of sapwood, mature wood, and false heartwood were evaluated in beech wood. The surface roughness after milling was assessed using the Keyence VHX-7000 digital microscope. The main result of the experiment is represented by the determination of the combination of the parameters mentioned above that produces the lowest roughness. In addition, roughness measurements were supplemented by microscopic analysis to explain roughness changes occurring on the surface.

Keywords: surface roughness; CNC milling; Keyence VHX microscope; hardwood; softwood.

INTRODUCTION

CNC wood milling is currently a discussed issue in wood science (Atanasov *et al.,* 2023; Lungu *et al.,*2023). Increasing the availability of this machining technology also results in an increase in the number of CNC machines in individual woodworking companies. An indisputable advantage of CNC machine tools is the ability to vary their technological parameters and tools. It makes it possible to use this machine to process wood and wood materials precisely. Therefore, their use raises several questions that need to be addressed in research. The high number of technological parameters and the possibility of changing them brings the need to deal with their optimization. Optimization can be carried out regarding energy consumption in CNC woodworking (Bal *et al.*, 2022), but especially regarding the quality of the created, most often milled surface (Aras and Sofuoğlu 2024; Demir *et al.*, 2022). According to research by (Hanincová *et al.*, 2024), optimizing the right tool selection and an appropriate set of machining parameters reduces cutting forces. It helps to minimise tool wear, reduces energy consumption, and improves surface quality. Properties that can be optimized and have a significant impact on surface quality include feed speed (Bendikiene and Keturakis 2016; Smajic and Jovanovic 2021), cutting speed (Sedlecký *et al.,* 2018), rotational speed (Çakiroğlu *et al.,* 2019) and feed per tooth (Loc and Hung 2021). However, parameters that cannot be optimized but are crucial in woodworking processes also contribute to the creation of the final quality. These include, for example, wear on the cutting edge (Djurković *et al.*, 2019; Koleda *et al.*, 2019) or the properties of wood, such as hardness (Bembenek *et al.*, 2021; Laina *et al.*, 2017) or wood moisture content (Benkreif *et al.*, 2021; Fu *et al.*, 2021; Rezaei *et al.*, 2022). According to (Singer and Özşahin 2022), the feed speed and rotational speed have the most significant impact on the quality of the created surface (evaluated by the roughness and waviness). Research shows that with an increase in feed speed, there is also an increase in surface roughness (Gochev 2018; Yang *et al.*, 2023). Increasing feed speed directly correlates with an increase in feed per tooth, leading to more severe conditions beneath the cutting edge and a higher likelihood of crack formation. This, in turn, significantly impacts the surface roughness parameters *Ra* and *Rz* (Pinkowski *et al.*, 2018). The value of rotational speed, a crucial milling parameter, significantly influences surface quality. As rotational speed increases, feed per tooth decreases, resulting in smoother surfaces (Pelit *et al.*,2021). Therefore, it is essential to look for a way to determine the optimal value of important technological parameters (Cakmak *et al.*,2023; Jiang *et al.*, 2022; Wei *et al.*, 2021). Correct and quick determination of the most optimal parameters is crucial, especially for those woodworking companies that produce different wood species. Regarding solid wood processing, the most used materials are spruce, beech, and oak solid panels or boards, especially for beech wood. Differences in milled quality between false heartwood, mature wood, or sapwood as its internal parts are demonstrated. The priority of research in the field of quality management of CNC milling should, therefore, be the effort to determine the combinations of those technological parameters that produce satisfactory quality.

The term "quality of the created surface" is the accepted size of the actual surface deviations (irregularities) from the ideally smooth surface. However, from a kinematic point of view as well as from the point of view of the wood structure, the surface smoothness cannot be achieved. In the practice of machining, therefore, there is an effort to achieve such a degree of surface unevenness that is acceptable from the point of view of related technologies – gluing or application of paints. Surface irregularities, defined as the waviness and roughness on the actual surface, must be understood in a broader context. The roughness of the wood surface, in the form of microscopic hills (peaks) of the surface (wood fuzziness, unseparated protruding fibres) and the form of surface dales (torn fibres or cut deep anatomical pores) is one of the ideal properties that can be used to optimize the CNC milling process. The purpose of the optimal setting of the technological parameters of the CNC machining center is to reduce the presence of torn fibres, surface fuzziness or marks of the cutter's passage. These machining errors are time-consuming to eliminate in the subsequent sanding process. Significant damage to the surface can also put the workpiece out of further production (economic loss). Therefore, the priority of research on the roughness of wood after CNC milling is not to determine the microscopic height of irregularities but to try to achieve the most optimal surface condition for subsequent sanding.

The aim of this paper is to quantify the roughness of the milled surface of selected wood species under changing technological parameters – feed speed and rotational speed of a CNC 5-axis machining center. The contribution of the presented paper is the research of the two most important technological parameters for the development of surface roughness acting simultaneously. The combination of technological parameters that creates the lowest roughness in the milling process will be determined from the measured data.

MATERIALS AND METHODS

Sample preparation before CNC milling

A total of 40 samples from quality class I boards with semi-radial (T/R) surface and with dimensions of 20 mm × 70 mm × 400 mm (thickness × width × length) were prepared from spruce wood (*Picea abies* L.), oak wood (*Quercus petraea* (Matt.) Liebl.) and beech wood (*Fagus sylvatica* L.). The dimensions of the samples were determined as optimal dimensions regarding the design of the CNC 5-axis machining center and the design of the mechanical clamps. These wood species were chosen as primary representatives of coniferous, ring-porous, and diffuse-porous wood species. Individual groups of wood species have their anatomical specifics (eg: coniferous wood species have tracheids, ring-porous wood species have earlywood vessels…) which significantly influence the surface morphology. Samples from beech wood were separately manipulated from a part of false heartwood, mature wood, and sapwood. The false heartwood was selected on the boards by visual assessment since the false heartwood has a significantly darker color (Dzurenda and Dudiak 2023). The sapwood part was manipulated 1 cm from the edge of the board. Part of the mature wood was visually assessed on the boards in a wet state when color differences were present between the mature wood and the sapwood. The moisture content of the samples ranged from 8 to 10 %, corresponding to the interior conditions. After sawing from the boards, all samples were processed on a planing and thicknessing milling machine to a nominal thickness.

CNC Sample Milling

A 5-axis CNC machining center SCM Tech Z5 (SCM Group S.p.A., Rimini, Italy) was then used to mill the samples. Two mechanical clamps were used to clamp each sample. The samples were milled using a Klein T143 spiral milling cutter (Sistemi S.r.l., Pesaro, Italy) with a diameter of 20 mm, and 3 cutting edges were used to mill the samples. The tool was clamped in a GM 300 HSK 63F hydro clamp (Gühring KG, Albstadt, Germany) with a high concentricity. Each sample was milled with two tool passes, with one pass of the cutter removing a layer a_e = 1 mm. The reason for the low material removal is to simulate the conditions of the finishing milling operation, which is defined by the higher quality of the created surface. Milling was carried out under the following conditions: feed speed of 10 $m \cdot min^{-1}$ and 14 $m \cdot min^{-1}$ and rotational speed of 12,000 rpm and 18,000 rpm. Higher rotational speed and feed speed values have been selected as the optimum set by the manufacturer. The lowest values were chosen as the technological minimum.

Surface Roughness Measurement

Surface roughness was assessed using a Keyence VHX-7000 digital microscope. The milled edge of the samples was scanned by five evenly distributed scans. The reason for scanning multiple locations on the milled edge is to quantify the surface roughness along the milling cutter's trajectory. All scans were taken at 100× zoom using the VH-Z100R lens. The measurement of surface roughness parameters was carried out in accordance with ISO 25178-2 standards (EN ISO 25178-2:2022). The following conditions were selected for filtration: S-filter = 25 μm, L-filter = 2.5 mm. The Keyence VHX-7000 digital microscope calculates 1 parameter value from 1 evaluated area. In the case of amplitude parameters, such as *Sz*, this means – the highest and lowest point on the evaluated area (similar principle as in the measurement of *Rz*). Thus, the parameter can be significantly distorted due to, for example, protruding (raised) fibres. To prevent distortion of parameter values, 5 square-shaped evaluation surfaces with a size of 2.5 × 2.5 mm were digitally put within one scan (the length of the page is identical to the size of the L-filter according to the recommendations of the technical standard). The microscope then calculated 1 parameter value as the arithmetic mean of 5 data (from 5 square-shaped evaluation surfaces), similar to the line roughness parameters (*Rz*, *Rp*, *Rv*...) measurements. The methodology of adding a larger number of evaluated areas thus brings more reliable results than the methodology for evaluating the total surface based on only 1 evaluated area. The following parameters of wood roughness were used according to (EN ISO 25178-2: 2022): *Sa* (arithmetic mean height), *Sz* (maximum height), *Sp* (maximum peak height), *Sv* (maximum pit depth), *Ssk* (skewness). *Sa* is the mean of the absolute value, the difference in height (ordinate values) of each point compared to the arithmetical mean of the surface (S-L surface in this case). The advantage of this parameter is its relative stability. The disadvantage is that it does not define the heights of individual irregularities, but only the average deviation from the surface. The second disadvantage is that several different uneven surfaces can have the same *Sa* value. *Sz* is defined as the sum of the largest peak height value and the largest pit depth value within the defined area. In general, *Sz* is the sum of *Sp* and *Sv*. All these height (amplitude) parameters are sensitive to local elevations (peaks) or depressions (pits) of the profile. Their advantage is that they provide an idea of the heights of individual irregularities on the defined area. *Ssk* parameter of skewness can also be very essential. The value of the parameter Ssk defines whether the surface is dominated by hills or dales of the profile. The disadvantage is that this parameter is very sensitive during measurement.

RESULTS AND DISCUSSION

Influence of feed speed and rotational speed as independent factors on surface roughness parameters

The basic set of 400 measurements was statistically evaluated by the statistical software STATISTICA 14 (TIBCO Software Inc., Palo Alto, California). Before evaluation, the outliers were removed from the measured set, and the measurement was then repeated. Two-way ANOVA assessed the impact of various factors on surface roughness. To ensure the validity of the ANOVA results, several assumptions must be met:

1. Normality: The distribution of the random variable values (areal surface texture parameters) within each group should be approximately normal. The Shapiro-Wilk test confirmed that this assumption holds for all groups.
2. Equality of variance: The variances of the random variable within each group should be equal. Levene's test indicated that this assumption may not be strictly met, potentially due to the inherent variability of wood structure.
3. Independence of measurements: The observations within each group should be independent of one another. This assumption was ensured by the experimental design and evaluated by a logical assessment.

The ANOVA method is a robust technique. This means that assumptions can be violated to some extent, but the method can still be applied. The results of the two-factor ANOVA show that both investigated factors (technological parameters) – feed speed and rotational speed have a statistically significant influence, separately and in mutual interaction ($p = 0.000$). The effect of another condition is the impact of one factor. A three-factor ANOVA was also used to optimise the milling process, where the investigated factors – feed speed, rotational speed, and wood species- have a statistically significant influence ($p = 0.000$). However, the single-dimensional results for each dependent variable showed that statistically significant effects were not observed for some of the investigated roughness parameters (Tab. 1).

Tab. 1 Single-dimensional results of p-values for individual areal surface texture parameters according to selected factors.

Factor	*Sa*	*Sz*	*Ssk*	*Sp*	*Sv*
Wood Species	0.000	0.000	0.000	0.000	0.000
Feed Speed	0.032	0.001	0.000	0.000	0.116
Rotational speed	0.000	0.000	0.455	0.004	0.000
Wood Species*Feed Speed	0.059	0.000	0.000	0.000	0.058
Wood Species*Rotational speed	0.000	0.002	0.232	0.000	0.013
Feed Speed*Rotational speed	0.202	0.000	0.200	0.001	0.000
Wood Species*Feed Speed*Rotational speed	0.612	0.012	0.026	0.000	0.201

Note: Sa (arithmetic mean height); *Sz* (maximum height); *Ssk* (skewness); *Sp* (maximum peak height); *Sv* (maximum pit depth).

In Tab. 2, it is possible to see the average values of roughness parameters for individual wood species, as well as the influence of feed speed and rotational speed on their development. After determining the values in Tab. 2, the individual surfaces were then scanned with a digital microscope (Fig. 1).

Tab. 2 Average values of individual areal surface texture parameters (values in brackets represent standard deviations).

Wood Species	Feed Speed [$m \cdot min^{-1}$]	Rotational speed [rpm]	*Sa*	*Sz*	*Ssk*	*Sp*	*Sv*
Beech (Sapwood)	10	12 000	8.06 (0.94)	162.52 (41.48)	-0.35 (0.24)	57.24 (7.66)	105.27 (37.20)
Beech (Sapwood)	10	18 000	9.22 (0.70)	169.70 (29.63)	-0.50 (0.16)	65.87 (9.66)	103.83 (27.36)
Beech (Sapwood)	14	12 000	8.75 (1.14)	168.82 (40.96)	-0.57 (0.40)	59.31 (7.45)	109.51 (36.88)
Beech (Sapwood)	14	18 000	10.27 (1.26)	233.55 (59.63)	-0.32 (0.32)	78.97 (13.02)	154.59 (49.69)
Beech (False Heartwood)	10	12 000	8.13 (1.28)	199.31 (70.83)	-0.80 (0.76)	62.04 (11.46)	137.27 (62.34)
Beech (False Heartwood)	10	18 000	8.64 (1.71)	214.30 (74.53)	-0.57 (0.58)	68.74 (15.24)	145.56 (66.61)
Beech (False Heartwood)	14	12 000	8.11 (1.04)	162.01 (42.52)	-0.46 (0.50)	56.54 (6.96)	105.46 (39.37)
Beech (False Heartwood)	14	18 000	9.79 (1.90)	249.34 (76.30)	-0.35 (0.30)	74.43 (16.76)	174.91 (62.07)
Beech (Mature Wood)	10	12 000	7.54 (0.82)	154.49 (46.75)	-0.37 (0.70)	58.67 (6.70)	95.81 (44.32)
Beech (Mature Wood)	10	18 000	7.87 (0.83)	154.16 (25.08)	-0.05 (0.19)	62.12 (9.82)	92.04 (20.54)
Beech (Mature Wood)	14	12 000	8.01 (0.67)	155.41 (21.35)	-0.35 (0.19)	59.25 (7.61)	96.16 (17.78)
Beech (Mature Wood)	14	18 000	8.48 (0.69)	164.12 (27.32)	0.03 (0.19)	64.62 (14.00)	99.50 (18.96)

Oak	10	12 000	11.36 (2.41)	286.80 (63.78)	-3.74 (0.48)	74.32 (37.39)	212.48 (35.41)
Oak	10	18 000	11.03 (3.17)	259.56 (44.79)	-3.81 (0.58)	58.75 (15.53)	200.80 (41.16)
Oak	14	12 000	12.57 (3.06)	260.64 (46.84)	-3.33 (0.79)	70.93 (36.99)	189.70 (30.95)
Oak	14	18 000	11.80 (2.37)	265.74 (46.41)	-3.91 (1.18)	56.51 (9.95)	209.24 (45.82)
Spruce	10	12 000	11.74 (3.45)	148.15 (53.54)	0.64 (1.02)	102.76 (57.75)	45.40 (8.51)
Spruce	10	18 000	14.32 (1.51)	137.41 (65.78)	0.07 (0.33)	89.26 (62.97)	48.16 (5.23)
Spruce	14	12 000	10.29 (3,12)	160.16 (68.73)	1.43 (2.08)	117.23 (65.10)	42.92 (11.31)
Spruce	14	18 000	14.27 (3.79)	302.55 (201.12)	2.21 (2.68)	236.65 (172.38)	65.90 (34.89)

Note: n, number of samples; *Sa* (arithmetic mean height); *Sz* (maximum height); *Ssk* (skewness); *Sp* (maximum peak height); *Sv* (maximum pit depth).

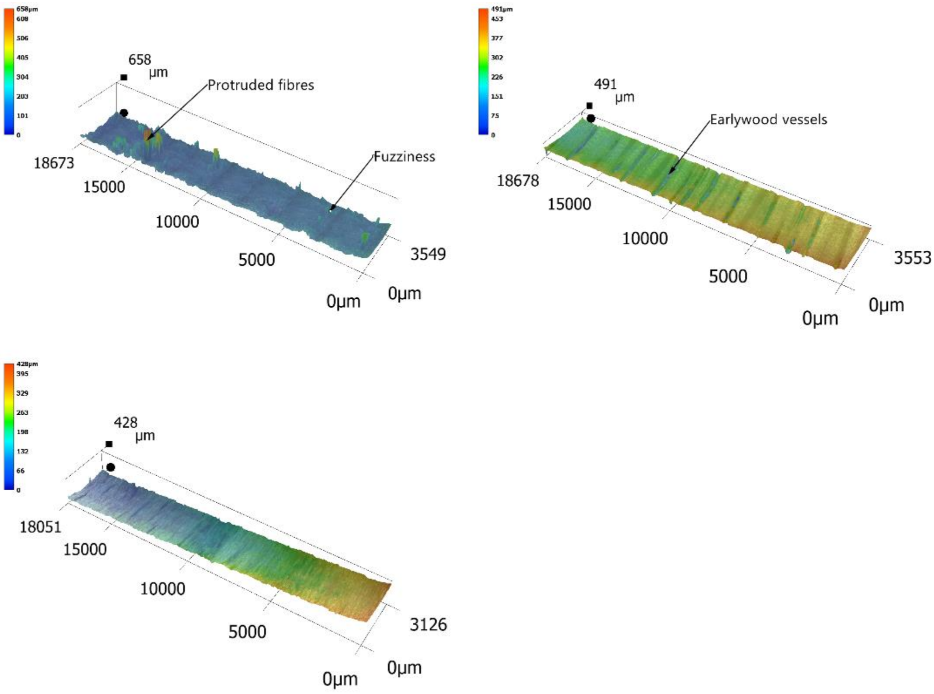

Fig. 1 Scans and topography of surfaces after CNC milling (clockwise – spruce, oak, and beech wood). Lens zoom 200×.

Based on Tab. 2, it can be stated that spruce wood achieves the highest roughness value after milling (according to *Sa*). This is explained by the low density of spruce wood and the resulting protruding fibres formed on the surface after CNC milling. A larger group of protruding fibres that have not been completely separated in the milling process creates fuzziness on the surface (Carll and Wiedenhoeft 2023). This is also the cause of the increase of spruce wood roughness. A greater tendency to form fuzziness on the surface is, especially, with wood species with a lower density according to (Landry *et al.*, 2013). With increasing density, there is a decrease in the fuzziness of the surface (Evans *et al.*, 2017). The authors' claims are also confirmed by the microscopic analysis in Fig. 1. On the scan of the spruce wood surface, several protruding fibres can be observed, which protrude significantly above the surface level. This, in turn, also caused an increase in surface roughness parameters in measurements. At the same time, from the topography of the spruce wood surface, it is possible to see sharp transitions between latewood, less milled wood, and more milled earlywood. At the same time, fuzziness tends to occur in the zone of earlywood, i.e., less dense, and softer wood (Fig. 2). This also proves the claims of the authors. From Tab. 2, it is also possible to see that in spruce wood compared to other wood species, *Ssk* and *Sp* values have risen sharply. Positive values of *Ssk* as a parameter indicate the prevalence of protrusions (hills and peaks) compared to surface dales (Gurau and Petru 2018). *Sp* also suggests that the overall surface roughness is made up of protrusions in the form of protruded fibres.

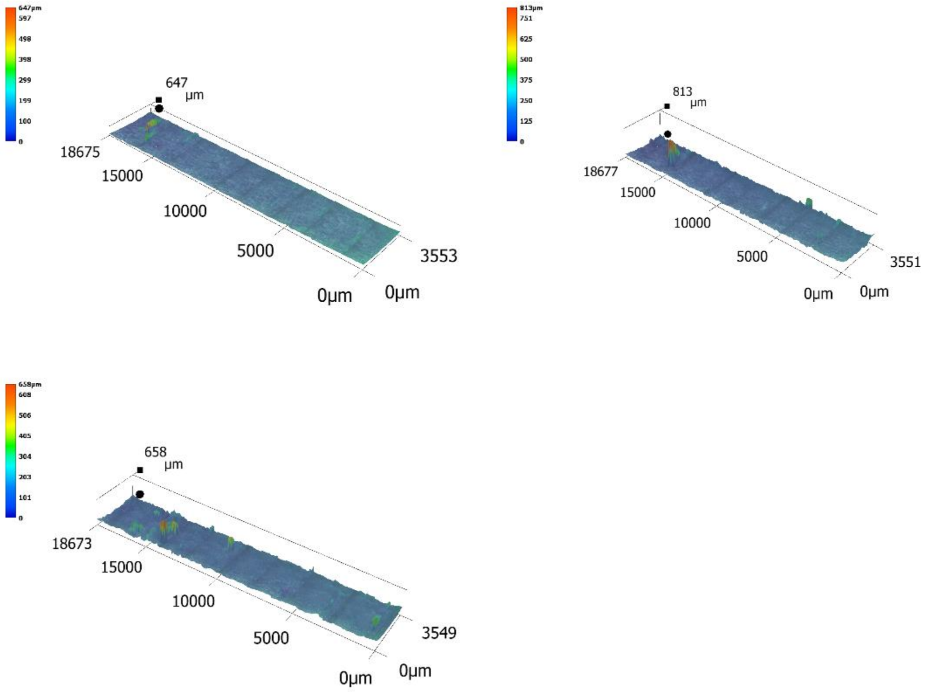

Fig. 2 Spruce wood surfaces with protruding fibres after CNC milling. Lens zoom 200×.

The second wood species with the greatest surface roughness is oak (according to *Sa*), based on Tab. 2. However, the opposite situation occurred as with spruce wood. The lowest, negative *Ssk* values and high *Sv* values mean that the surface is made up of significant dales. Also, research by (Gurau *et al.*, 2019; Lungu *et al.*, 2023) shows that the increase in the negative value of skewness (evaluated by the parameter *Rsk*) can be explained by anatomical cavities and the prevalence of surface depressions (pits and dales). From the surface microscopy in Fig. 1, it can be noted that roughness occurs mainly due to the presence of deep vessels of earlywood. This also confirms the claims found by other authors. In the case of beech wood, it is also possible to observe surface depressions due to the cell structure in Fig. 1. However, compared to oak wood, they do not cause such a significant increase in roughness. Beech wood therefore has the lowest measured roughness after CNC milling. At the same time, research on individual parts of beech wood showed that the lowest roughness after milling is in the zone of mature wood. On the other hand, the highest in the sapwood zone, which again may be due to a lower density compared to false heartwood and mature wood (Dzurenda *et al.*, 2023). On the other hand, the denser zones of beech wood had a lower roughness after milling. The relationship between higher density and lower roughness after milling is also in line with the work of the authors (Kang *et al.*, 2023).

Tab. 2 shows that the roughness of the wood surface increases as the feed speed increases. The same results are presented in the thesis of (Ibrišević *et al.,* 2023; Smajic and Jovanovic 2020). This confirms the machining theory of the deterioration of conditions below the cutting edge. By (Wei *et al.,* 2021) with a higher feed speed, the cutting edge cuts off a larger amount of material and increases the average milling depth. This will result in a higher load on the milling edge and a higher vibration amplitude on the edge. This also leads to a higher irregularity of the machined surface. When increasing the rotational speed, the roughness of the wood was supposed to be reduced according to the (Kúdela *et al.,* 2018; Li *et al.,* 2014). (Pelit *et al.,* 2021) stated that rotational speed increases from 12 000 rpm to 18 000 rpm should reduce the roughness by 8 to 12 %. However, Tab. 2 shows an increase, which may probably be due to higher vibrations of the tool. This does not contradict the findings of other authors, that the reduction of feed per tooth and the associated reduced load on the cutting edge should reduce vibrations. When investigating the feed speed as one factor and the wood species as the other factor, statistically significant changes occurred, especially for wood species with lower density. The sapwood zone of beech wood and spruce wood had a statistically significantly higher roughness expressed by the parameter *Sz* at a higher feed speed. This is evidenced by the significant growth of the *Sv* parameter, which is calculated from the dales of the surface. In the case of spruce wood, there was a sharp increase in the parameter *Sp* with increasing feed speed, which indicates the prevalence of surface protrusions. Together with the *Ssk* parameter, they prove that with increasing feed speed, the fuzziness of the surface and the proportion of protruding fibres increases. Of all the measured wood species, the lowest roughness was measured in the zone of mature wood in beech wood. The highest roughness, on the other hand, was measured in spruce and oak wood. As already mentioned, the cause of the roughness of spruce wood was the fuzziness of the surface. In the case of oak wood, the cause is deep vessels of earlywood, visible even to the naked eye. By (Lungu *et al.,* 2023), the *Rsk* parameter (similarly the *Ssk* parameter) for oak wood reaches negative values mainly due to the deep pores of the earlywood vessels.

According to Tab. 2 the effect of wood species and rotational speed changes on surface roughness parameters. As with the change in feed speed, there have been statistically significant differences in wood species with lower density. In the case of sapwood, the fibres were torn out of the surface and in the case of spruce, the fuzziness of the surface increased. Also, in the case of a false heartwood of the beech wood, it was found that the depressions of the surface increased. These findings contradict the theory of machining and the findings of other authors. As the rotational speed of the tool increases (if there is no change in the number of cutting edges), the feed per tooth is reduced. The lower the feed per tooth, the lower the roughness (Pinkowski *et al.,* 2018). The explanation for this experiment may be the increase in vibration when the rotational speed of the CNC machine increase (Hortobágyi *et al.,* 2023). Also from the book of the authors (Csanády *et al.,* 2015) it follows that as the increasing vibrations, the surface roughness increases.

Influence of the interaction of feed speed and rotational speed on surface roughness parameters for different wood species

Tab. 1 shows that the interaction of three factors (wood species, feed speed, and rotational speed) statistically affects the amplitude parameter *Sz*. This finding is consistent with the work of (Kúdela *et al.,* 2018). This three-factor analysis of variances brings a demanding interpretation of the measured data. However, its results closely simulate the conditions of actual production practice, in which it is necessary to set the following for the CNC machine tool: feed speed, rotational speed, thickness of the removed layer, machining strategy, and tool. Feed and rotational speeds are among the most essential technological parameters in roughness formation (Singer and Özşahin 2022). That is why the authors dealt with their mutual interactions (Pinkowski *et al.*, 2018). They found that the worst quality when using a tilting spindle moulder occurs at high feed speeds and low rotational speeds. Rapidly deteriorating conditions occurred at feed speeds above 25 m×min-1 and rotational speeds below 10 000 rpm.

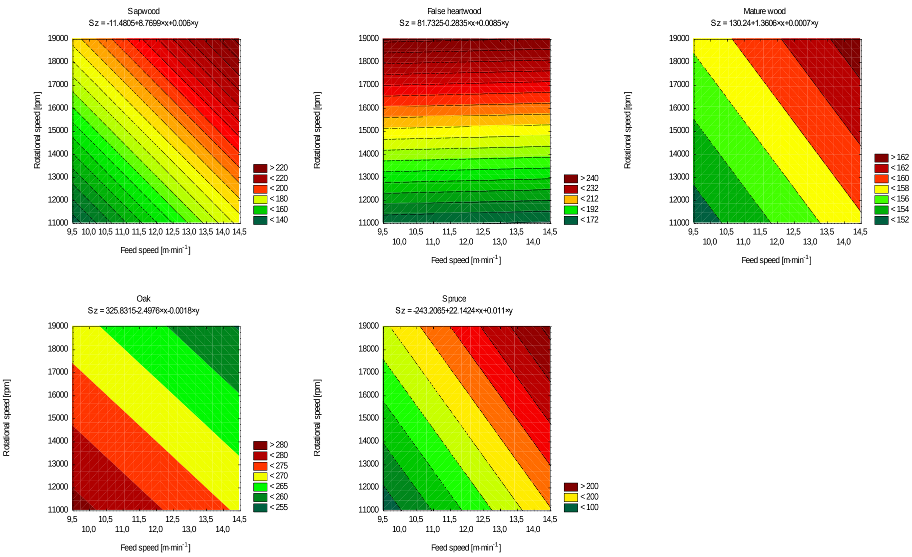

Fig. 3 Development of the areal surface texture parameter *Sz* depending on the selected rotational speed and feed speed for individual wood species.

Fig. 3 shows the results of the mutual interaction of feed speed and rotational speed on the parameter *Sz*. For all selected wood species, it is about creating a prediction model based on which it is possible to determine the expected value of surface roughness (defined by the *Sz* parameter). In most cases, it was confirmed that the worst quality (the highest surface roughness) was produced at the highest rotational speed and highest feed speed and vice versa. This also confirms previous findings. The measured results show that the same trend was measured for most wood species. The opposite situation occurred with oak wood, where the highest roughness arose at the lowest rotational speed and lowest feed speed. This contradictory finding will be explored in more detail in future experiments.

Subsequently, the milled surfaces with the highest and lowest roughness (boundary variants) were subjected to microscopic analysis (Fig. 4). The variant with the highest roughness was for spruce and beech wood at a feed speed of 14 $m \cdot min^{-1}$ and rotational speed of 18 000 rpm. The variant with the lowest roughness was at feed speeds of 10 $m \cdot min^{-1}$ and rotational speed of 12 000 rpm. With oak wood, the situation was the opposite. For samples of spruce wood with the highest surface roughness, it is possible to observe a distinctive fuzziness, i.e., a group of fibres. From the image it can be identified that this fuzziness has formed mainly in earlywood, which has a lower density. After adjusting the technological parameters, a surface condition with lower roughness was achieved. For spruce wood, it was mainly about removing the characteristic fuzziness of the surface, i.e., better separation of protruding fibres. This is essential especially for subsequent sanding processes. In the most optimal variant, the roughness (evaluated through the *Sz* parameter) was reduced by more than half. It should be borne in mind that roughness in conditions of woodworking cannot be eliminated due to the anatomical structure of the wood (Luo *et al.*, 2020; Magoss *et al.*, 2022) and the kinematic movement of the tool (Kopecký *et al.*, 2019). In Fig. 3 it can also be observed that in the variant with the lowest roughness, the surface of spruce wood shows roughness due to differently milled parts of earlywood and latewood. This creates the so-called anatomical earlywood-latewood waviness (Gurău *et al.*, 2022). This is also the reason why the waviness (and the roughness) is greater in the case of spruce wood compared to other wood species. These results were also confirmed by (Kúdela *et al.*, 2018). In the work of (Kúdela *et al.*, 2016), it was investigated that the milling process cannot remove the waviness between earlywood and latewood. In the case of oak wood, it was possible to microscopically observe the reduction of the characteristic waves (marks) after passing the cutter. Tool marks could also be observed with the naked eye in the variant of the highest roughness. On the other hand, in the variant of the lowest roughness, they could only be observed at the microscopic level. The removal of waves as marks of the passage of the tool is a desirable condition, especially for follow-up wood sanding processes. In the case of beech wood, the roughness of the wood has also been reduced. Fig. 3 shows that the lowest surface roughness is achieved at low feed speeds and low rotational speed. However, in the microscopic analysis, no significant differences were observed at 200× objective magnification (for this reason, beech wood was not shown in Fig. 4). A likely explanation is the overall more homogeneous structure of beech wood. In the future, therefore, the change in the roughness of sapwood, mature wood and false heartwood could be microscopically expressed using SEM analysis.

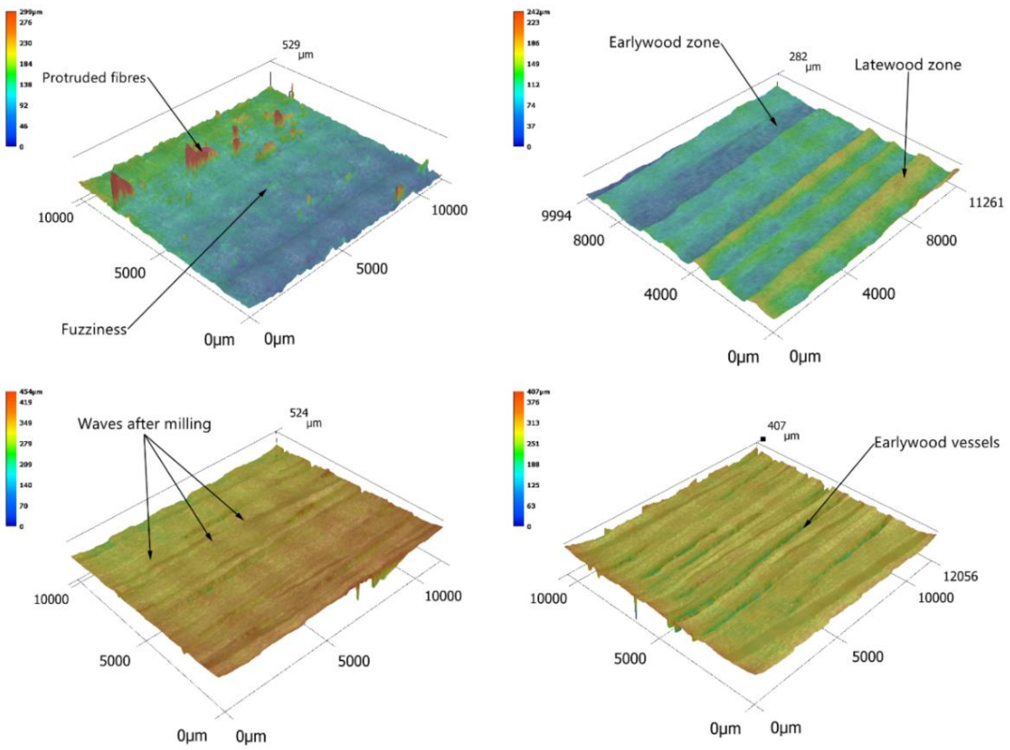

Fig. 4 Scans and topography of surfaces with the highest (left) and lowest roughness achieved (right) based on Fig. 3. In the upper part – spruce wood, in the lower part – oak wood. Lens zoom 200×.

CONCLUSION

In the presented paper, the surface roughness of beech, oak, and spruce wood after CNC milling was quantified. From beech wood, the matrix of the experiment was expanded to include its parts – sapwood, mature wood, and false heartwood. The following conclusions can be drawn from the results:

1. The highest roughness after CNC milling occurs in spruce wood due to protruding fibres (fuzziness). The second highest roughness was measured in oak wood, mainly due to the deep vessels of earlywood. On the other hand, the lowest roughness was measured for beech wood, specifically for the zone of mature wood.
2. The roughness increased with increasing feed speed. At the same time, it was found that the roughness increased with increasing rotational speed. A possible explanation was the increasing tool vibrations.
3. When the feed speed and rotational speed are investigated together, the lowest surface roughness is precisely at a feed speed of 10 m·min-1 and a rotational speed of 12 000 rpm (for spruce wood and individual parts of beech wood) and at a feed speed of 14 m·min-1 and a rotational speed of 18 000 rpm (for oak wood).
4. Optimization of technological parameters reduced waves as tool marks and the fuzziness of the surface, improving the quality of the finished CNC-milled surface.
5. The optimal way to optimize technological parameters regarding surface irregularities is to use the *Sz* areal surface texture parameter, which was also confirmed by microscopic analysis.
6. For each wood species, the models based on which it is possible to predict the development of roughness at selected parameters of feed speed and rotational speed were calculated.

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