Comparison of Sessile Oak (*Quercus petraea*) and Pedunculate Oak (*Quercus robur* L.) Wood Machinability

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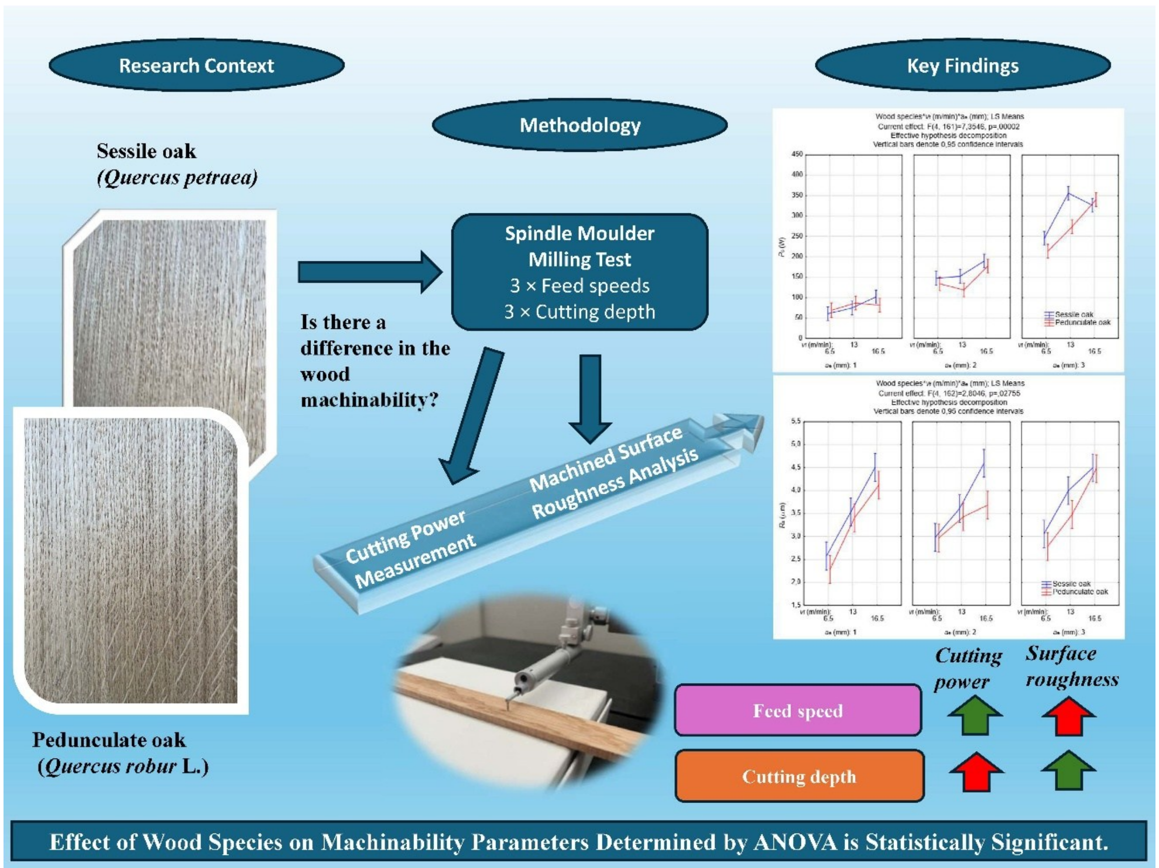
DOI: 10.15376/biores.21.3.7395-7411

GRAPHICAL ABSTRACT



Comparison of Sessile Oak (*Quercus petraea*) and Pedunculate Oak (*Quercus robur* L.) Wood Machinability

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It is usually stated that sessile oak wood has the same properties as pedunculate oak wood. However, in practice, sessile oak wood can be distinguished from pedunculate oak wood by appearance, quality, and machinability. The aim of the research was to compare cutting power and surface roughness, as machinability parameters, when milling sessile oak and pedunculate oak wood and to determine the effect of cutting depth and feed speed on the oak wood machinability. Radially sawn samples were milled in the longitudinal (90°-0°) cutting direction with three different cutting depths and at three feed speeds. During milling, the active electrical power and the machined surface profile were measured. The surface roughness parameters R_a, R_q, and R_z were determined according ISO 4287 (1997). The average cutting power and roughness parameters are higher when milling sessile oak than pedunculate oak wood. ANOVA showed that wood species, cutting depth, and feed speed had a statistically significant effect on cutting power and surface roughness parameters with exception of effect of cutting depth on the parameter R_z. The differences in machinability parameters between sessile and pedunculate oak wood when milling at the same feed speed and cutting depth were not sufficiently pronounced to be detected by post hoc analyses.

DOI: 10.15376/biores.21.3.7395-7411

Keywords: Machinability; Cutting power; Surface roughness; Pedunculate oak wood; Sessile oak wood

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INTRODUCTION

The two most known species of oak growing in Croatia are the pedunculate oak (*Quercus robur* L.) and the sessile oak (*Quercus petraea*). Pedunculate oak and sessile oak wood are processed in the same technological process without separation. In older literature sources it is stated that wood of the sessile oak and the pedunculate oak have very similar properties and equal machinability (Horvat and Krpan 1967; Despot 1985). In practice, experts emphasize the ability to differentiate these two species of oak according to the appearance and quality of the wood, as well as their machinability.

In order to evaluate the suitability of materials for processing by a certain machine, the concept of machinability is used. According to ASTM D 1666-87 (2004), machinability is defined as a property that describes the easiness to process and convert a certain wood species into a final product. Džinčić and Skakić (2012) state that machinability is the ability of a certain structural material to be machined by cutting or deforming using common, economical production techniques and technologies. According to Šavar (1990), better machinability means that a material that can be processed with a certain tool at higher cutting speeds, with less cutting force and lower energy consumption, longer tool life, better quality of the processed surface, a more favorable shape of the separated particle, and a lower operating temperature of the tool blade. Most often, the machinability of wood is expressed by measurement results of the cutting force (or cutting power) and the roughness of the machined surface. Some authors have proposed some other calculated machinability parameters, for example, the specific cutting energy, defined as ratio of cutting power and material removal rate, or specific cutting force, defined as ratio of cutting force and product of nominal chip thickness and cutting width (Šavar 1990; Goglia 1994; Astakhov 2014).

It is known that cutting forces, cutting power, and specific cutting force depend on wood density (Ettelt and Gittel 2004). McKenzie *et al*. (1999) found a very good linear correlation between wood density and cutting force. However, Eyma *et al*. (2004) pointed out that wood species of the same density may require very different cutting forces. Cutting force is also affected by the wood moisture content. All components of cutting force have been found to decrease when increasing the wood moisture content from about 12% to fibre saturation point (Beljo Lučić *et al.* 2004; Moradpour *et al.* 2013). The wood machinability is also significantly affected by the thermal modification of wood. Koleda *et al.* (2018) analyzed the power required for milling unmodified and thermally modified oak wood and determined a decrease in the required cutting power with increasing thermal modification temperature.

Specific cutting force, significantly depends on the material being processed (wood species, moisture content, wood temperature) and on the machine kinematics and wood cutting parameters (Orlowski and Ochrymiuk 2017; Koleda *et al.* 2018) such as the cutting direction, tool sharpness, chip thickness, cutting tool geometry and cutting speed (Džinčić and Skakić 2012; Porankiewicz and Goli 2014; Moradpoura *et al.* 2016).

Another parameter commonly used to determine the machinability of wood is the roughness of the machined surface, which is also used as a measure of the quality of the machined surface. The roughness of the machined wood surface depends on a number of factors related to the anatomical structure and properties of the wood, and the parameters of the machining tools and processing. The wood properties that affect surface roughness are density, moisture content, texture, and anatomical structure (Gurau *et al.* 2005; Magoss 2008; Laina *et al.* 2017). The most important factors of the machining process that affect roughness are the type of tool, the number of blades, the cutting angle, the tool radius, the feed speed and cutting speed, the cutting depth, and the speed and amplitude of the machine table vibrations (Usta *et al.* 2007; Škaljić *et al.* 2009; Csanády and Magoss 2013; Laina *et al.* 2017).

The standard procedure for measuring surface roughness relies on surface profile measurements using contact profilometers. That measurement cannot be used during the process of wood machining, but only on samples taken after processing, and the measurement process is relatively slow. In order to include the roughness of the machined surface as a parameter for on-line control of woodworking operations, non-contact methods for determining the surface roughness have to be used. Research into the implementation of non-contact surface roughness measurement methods and their application in industry has been ongoing for many years (Lemaster and Dornfeld 1982; Nasir and Cool 2019; Sandak *et al*. 2020), but in wood processing the application of non-contact methods in industrial in-line process control is still limited.

The results of many studies of the roughness of the oak wood machined surface have shown that the roughness parameters have higher values and greater dispersion compared to the roughness parameters of machined surface of other wood species. Such results are most often attributed to the anatomical structure of oak as a ring-porous wood species (Usta *et al*. 2007; Sofuoğlu and Kurtoğlu 2015; Thoma *et al*. 2015). Also, the size and distribution of pores can give the wood a very uneven texture, which explains the differences between the measurement results on multiple samples of the same wood species. Đukić *et al*. (2023) measured the average value of the R_a parameter of the anatomical profile of the pedunculate oak surface in a radial section and it was (2.1 ± 0.3) µm. Similar data were obtained by Gurau *et al*. (2005, 2007).

In research, the wood machinability is often described by functions. These are mathematical models that describe the dependence of the process output values on the input parameters and represent an approximation of the actual process function. In wood processing, the most often used basic functions involve forces (or the cutting power), the quality of the machined surface, and tool durability (Džinčić and Skakić 2012; Naylor *et al*. 2012; Orlowski and Ochrymiuk 2017; Loc and Hung 2021; Jiang *et al*. 2022; Yang *et al*. 2023).

One of the most important advantages of wood is its easy machinability, in contrast to metal and plastic products. However, its nonuniform characteristics within and between species plays a significant role on its efficient and effective machining. For this reason, it is important to correctly set the processing parameters and connect them with the properties of the wood being processed (Malkoçoğlu and Özdemir 2006).

The aim of this research was to compare the machinability of pedunculate oak and sessile oak wood when milling. Due to their similar physical and mechanical properties and common use in the same technological process, no research has been conducted to compare their machinability parameters. Also, the aim of research was to determine and compare the effect of feed speed and cutting depth on the cutting power and surface roughness when milling these two oak wood species.

EXPERIMENTAL

Materials

Selected machinability parameters of sessile oak and pedunculate oak wood were investigated on samples made from 4 m long planks remaining from logs after veneer cutting. The planks were cross-cut to obtain 1 m long wood samples. The conditioned samples were processed on a surface and thickness planer to a final thickness of 22.5 mm. The average density of sessile oak wood determined on 12 samples, was 0.732 (0.048) g/cm^3 and that of pedunculate oak wood was 0.596 (0.036) g/cm^3. The average moisture content in the samples was determined by the gravimetric method and was 9.2 % (0.3 %) for sessile oak wood samples and 11 % (1.1 %) for pedunculate oak wood samples. The standard deviation values of the data are given in brackets. The average ring width of sessile oak wood samples was 2.54 mm and that of pedunculate oak 2.30 mm. The samples had a texture of radial sawn timber (as shown in Fig. 1).

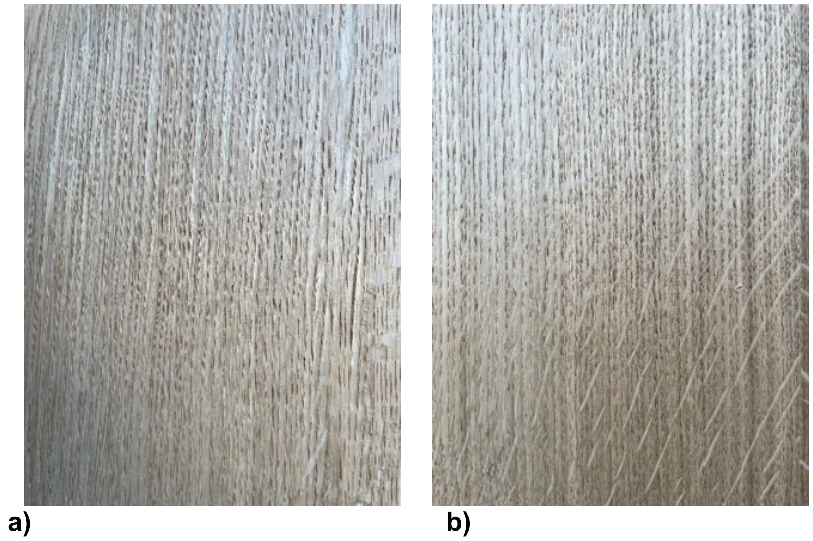

Fig. 1. Radial-sectional view of a) sessile oak and b) pedunculate oak wood

Milling Parameters

Machinability tests were performed during peripheral milling on a single-spindle moulder Rojek FSN300A Euro 7, with rated motor power of 5.5 kW and rotational frequency of 2865 min^{-1}. The tool was a standard turnblade rebating cutterhead without shear angle and with the cutterhead diameter D = 150 mm, produced by Leitz GmbH & Co. KG. Only one main tungsten carbide (HW) cutter with rake angle γ = 20° and clearance angle α = 15° in cutterhead was used for cutting (the other cutter was ground so it was not engaged in the cut) and the cutterhead was checked for unbalance. Before the experiment cutter edge profile was measured on the Zeiss Axio Zoom V16 microscope and analysed in Gwyddion software. The starting cutter edge radius was ρ_0 = 5 µm. The tool rotational frequency was n = 6000 min^{-1} and resulting cutting speed was v_c = 47 m/s. The samples were processed with three cutting depths a_e = (1, 2 and 3) mm and at three feed speeds v_f = (6.5; 13 and 16.5) m/min. Under these conditions, the effective feed rate was f_{zeff} = (1.1; 2.2, and 2.7) mm, which, according to the recommendations (Leitz 2011), should result in fine, medium, and coarse quality of the machined surface. The cutting direction corresponded to the longitudinal (90°-0°) cutting direction.

Methods

The active electrical power required during machine idling ($P_{el\text{-}0(pass)}$) and machining ($P_{el\text{-}tot(pass)}$) was measured using a three-phase energy and power quality analyzer Fluke 435-II (Netherlands). For each combination of input variables, 10 measurements of required active electrical power during wood samples machining ($P_{el\text{-}tot(pass)}$) were measured. Based on the measured values, using the approximate diagram of the three-phase asynchronous electric motor (Hamm 1970), the mechanical equivalents of the measured values were calculated and based on these values, the average cutting power ($P_{c(pass)}$) was calculated for each single milling pass according to the expression,

$$P_{c(\text{pass})} = P_{m-tot(\text{pass})} - P_{m-0(\text{pass})} \quad (1)$$

where $P_{m\text{-}tot(pass)}$ is average total mechanical power during single milling pass (W) and $P_{m\text{-}0(pass)}$ is average mechanical power during machine idling between each pass.

The roughness parameters R_a (the arithmetic mean deviation of the profile), R_q (the root mean square deviation of the profile) and R_z (the maximum height of the profile) were determined on the basis of the surface profile measured with a profilometer Mitutoyo SurfTest SJ-500 (Ser. No. B0007 1808) with a tip radius of 10 µm in accordance with ISO 4287 (1997). The measuring chain was calibrated with Mitutoyo Precision Reference Specimen, with mark 178-601 (s/n: 393041807). A Gaussian filter with a cut-off wavelength of 8 mm was applied, and the evaluation length was 40 mm. The profile of the machined surface was measured in the direction which coincides with the feed speed vector, that is, mainly in the direction of the fibers (Fig. 2). The roughness parameters R_a, R_q and R_z were selected for analysis because they are commonly used in researching the quality of the machined surface. However, their usefulness in determining the influence of tools and machines on the roughness of the machined wood surface, especially on ring-porous wood species, may be questionable due to the large influence of structural irregularities (pores) on the final wood roughness results (Csanady and Magoss 2013). Several samples of the machined surface were randomly cut out on the samples during milling and 10 measurements of roughness parameters were carried out on several samples for each combination of processing parameters.

Fig. 2. Surface profile measurements

The design of experiment consisted of 9 combinations of machining parameters for each wood species.

A three-factor analysis of variances (ANOVA) at 5% significance using Statistica software was performed to evaluate the effect of each factor on the cutting power and parameters of surface roughness. The post hoc Tukey HSD test has been used to determine the significance of pairwise differences between machinability parameters of sessile oak and pedunculate oak wood in the same milling conditions.

RESULTS AND DISCUSSION

Cutting Power

Table 1 presents the arithmetic mean values of the measured total electrical power, the calculated total mechanical power, and cutting power during milling of sessile oak and pedunculate oak wood samples under different machining conditions.

Table 1. The Arithmetic Mean Values of Cutting Power Measurements when Milling Samples of Sessile Oak and Pedunculate Oak Wood (*n*=10 series of milling passes)

Milling Parameters		Sessile Oak Wood			Pedunculate Oak Wood		
Feed Speed (m/min)	Cutting Depth (mm)	$P_{el\text{-}tot}$ (W)	$P_{m\text{-}tot}$ (W)	P_c (W)	$P_{el\text{-}tot}$ (W)	$P_{m\text{-}tot}$ (W)	P_c (W)
6.5	1	409 (10)*	308 (9)	61 (9)	418 (9)	317 (9)	70 (9)
	2	485 (14)	382 (14)	148 (14)	469 (6)	366 (6)	134 (6)
	3	593 (31)	487 (30)	245 (30)	566 (14)	461 (14)	214 (14)
13	1	421 (15)	320 (14)	75 (14)	430 (8)	328 (7)	87 (7)
	2	491 (23)	388 (22)	153 (22)	458 (23)	356 (22)	119 (22)
	3	713 (50)	604 (48)	356 (48)	628 (32)	521 (32)	274 (35)
16.5	1	448 (16)	346 (15)	102 (15)	423 (14)	322 (14)	82 (14)
	2	531 (27)	427 (27)	190 (27)	516 (39)	412 (38)	177 (38)
	3	675 (40)	567 (39)	326 (39)	692 (51)	584 (51)	340 (51)

$P_{el\text{-}tot}$ – arithmetic mean of total electrical power of 10 milling passes (W); $P_{m\text{-}tot}$ – arithmetic mean of total mechanical power of 10 milling passes (W); P_c – arithmetic mean of cutting power of 10 milling passes (W); * data are mean values and standard deviations are given in parentheses.

According to the results of the three-factor ANOVA analysis of the cutting power data (Table 2), at the significance level of $p < 0.05$, all three milling parameters (wood species, cutting depth and feed speed) had a statistically significant effect on the cutting power, which is in accordance with the current knowledge. Also, all interactions of the investigated parameters proved to be statistically significant, which indicates a different effect of changing the processing parameters on the cutting power during milling pedunculate oak wood and sessile oak wood (Fig. 3). The results of the study showed that variation of feed speed and cutting depth had a greater effect on cutting power than the difference of wood properties between sessile and pedunculate oak. Between selected input variables, cutting depth had the greatest effect on cutting power, which is obvious from the diagram in Fig. 3. The cutting power increased with the increase of cutting depth and feed speed. The results of the study of cutting force during longitudinal milling of oak wood conducted by Džinčić and Skakić (2012) showed that the average cutting force increases with increasing cutting depth and with increasing feed rate, with the cutting depth having a greater effect on cutting force, which is, taking into account that cutting power is proportional to cutting force, in line with the results obtained in this study. Research results of Jiang *et al*. (2022) also revealed significant effects of the cutting depth on the resultant cutting force.

The average cutting power measured during milling sessile oak wood, calculated as arithmetic mean of average values of cutting power in all combination of milling conditions, was 184 W, and the average cutting power during milling pedunculate oak wood was 166 W. According to research of Ettelt and Gittel (2004), the change in cutting force, which is proportional to cutting power, is linearly related to the change in wood density. So, a difference in cutting power could be expected, given that the density of sessile oak wood samples is about 23% greater than the density of pedunculate oak wood samples. Even from the research of Kivimaa (1950) it can be concluded that it is not the wood species, but its density, that has influence on cutting force. It also must be mentioned that wood species has the effect on cutting force, but through other properties related to specific wood species, its habitat, *etc.* One way of compensating the influence of wood density and the ratio of late to early wood on cutting force is to calculate and analyze the normalized value of cutting force as it is presented in research of Chuchala *et al*. (2021) and Huang *et al*. (2024).

The average value of cutting power during milling of sessile oak was greater than during milling pedunculate oak in six cases of milling parameters. Contrary to expectations, in three cases the situation was inverted, *i.e.* cutting power during milling of pedunculate oak wood was greater than during milling of sessile oak wood.

Analyses of pairwise differences between cutting power during milling of sessile and pedunculate oak wood samples across all parameter combinations using the post hoc Tukey HSD test revealed that there was no significant difference of cutting power in almost all cases of milling parameters (feed speed and cutting depth), as it is obvious from Fig. 3. Significant statistical difference of cutting power was noted only when milling wood samples at feed speed of 13 m/min and cutting depth of 3 mm. Although multifactorial ANOVA showed a statistically significant main effect of wood species, the Tukey HSD post hoc comparisons did not show statistically significant differences of cutting power between individual pairs of sessile and pedunculate oak wood samples after correcting for multiple testing. This result suggests that there is a general pattern of differences among wood species, but the differences of cutting power between samples of sessile and pedunculate oak wood when milling is performed with the same feed speed and cutting depth were not sufficiently pronounced to be detected in post hoc analyses. The obtained results could be explained by wood inhomogeneity and differences in density of wood samples of the same species (because they are cut from different logs) or by effect of measurement uncertainty on measuring lower values of cutting power.

Table 2. Results of ANOVA Analysis of the Influence of Processing Parameters on Cutting Power (n=10)

	Univariate Tests of Significance for Cutting Power P_c (W) Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of (Freedom)	MS	F	p
Intercept	5477715	1	5477715	7566.108	0.000000
Wood species	14008	1	14008	19.348	0.000020
v_f (m/min)	99470	2	49735	68.697	0.000000
a_e (mm)	1396337	2	698168	964.347	0.000000
Wood species * v_f (m/min)	6680	2	3340	4.614	0.011264
Wood species * a_e (mm)	8406	2	4203	5.805	0.003677
v_f [m/min]* a_e (mm)	56819	4	14205	19.620	0.000000
Wood species * v_f (m/min)* a_e (mm)	21298	4	5325	7.355	0.000018
Error	116561	161	724		
v_f – feed speed; a_e – cutting depth					

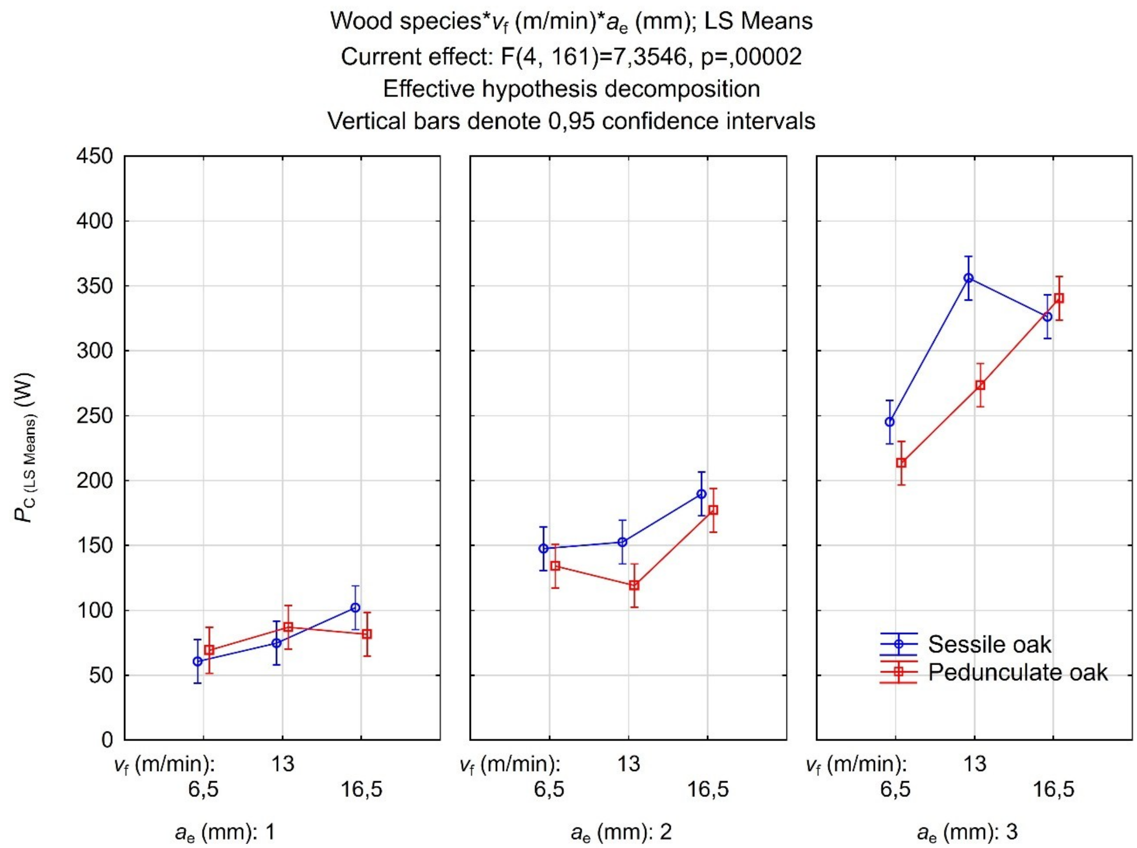

Fig. 3. ANOVA analysis of the effect of feed rate and cutting depth on cutting power during milling of sessile oak and pedunculate oak wood samples

From the experience and literature (Ettelt and Gittel 2004) it could be stated that measured values of cutting power for the same piece of solid wood can have fluctuations in the range of 20%. If the density and other influencing parameters are not closely monitored, this can lead to questionable conclusions. On the other hand, the reason for no significant differences of cutting power could lie in different effects of feed speed and cutting depth on cutting power when milling sessile and pedunculate oak.

Surface Roughness

Table 3 presents the surface roughness parameters obtained for samples of sessile oak and pedunculate oak wood processed by milling.

The mean values of all analysed roughness parameters were higher for sessile oak wood samples than for pedunculate oak wood samples. The average value of the roughness parameter R_a was 6% higher, the roughness parameter R_q was 5% higher, and the smallest difference was in the parameter R_z, which was 3%. In comparison to research results of other authors carried out on sessile oak and pedunculate oak wood samples (Usta *et al*. 2007; Sofuoglu *et al*. 2015; Thoma *et al*. 2015), in this study lower values of average surface roughness under similar milling conditions were obtained. The reason for the difference in these values may be in the choice of measurement points on the machined surface, especially if the measured surface profile includes fewer deep pores.

Table 3. Roughness Parameters of Milled Surfaces of Sessile Oak and Pedunculate Oak Wood Samples (*n*=10)

Processing Parameters		Sessile Oak Wood			Pedunculate Oak Wood		
Feed Speed (m/min)	Cutting Depth (mm)	R_a (µm)	R_q (µm)	R_z (µm)	R_a (µm)	R_q (µm)	R_z (µm)
6.5	1	2.58 (0.20)*	3.45 (0.34)	22.15 (3.74)	2.29 (0.20)	3.03 (0.31)	19.02 (2.33)
	2	2.98 (0.55)	3.76 (0.69)	21.41 (4.52)	2.97 (0.41)	3.93 (0.56)	22.87 (2.90)
	3	3.06 (0.47)	3.98 (0.62)	22.58 (3.02)	2.78 (0.54)	3.67 (0.73)	21.79 (4.59)
13	1	3.53 (0.41)	4.76 (0.59)	29.50 (4.20)	3.40 (0.47)	4.65 (0.73)	30.32 (4.62)
	2	3.61 (0.52)	4.74 (0.77)	27.80 (5.22)	3.43 (0.61)	4.49 (0.91)	27.36 (7.13)
	3	4.00 (0.90)	5.31 (1.32)	30.90 (8.45)	3.48 (0.42)	4.76 0.57)	29.63 (3.61)
16.5	1	4.51 (0.18)	5.77 (0.36)	32.88 (5.88)	4.12 (0.38)	5.18 (0.57)	28.85 (4.28)
	2	4.60 (0.54)	5.89 (0.79)	34.42 (6.62)	3.68 (0.44)	4.71 (0.61)	27.48 (4.52)
	3	4.50 (0.45)	5.95 (0.76)	34.41 (5.88)	4.48 (0.50)	5.87 (0.77)	34.41 (6.48)

R_a – the arithmetic mean deviation of the profile, R_q – the root mean square deviation of the profile; R_z – the maximum height of the profile. * Data present mean values of roughness parameters and standard deviations are given in parentheses.

Table 4 presents the results of the ANOVA analysis of the data obtained by measuring the surface roughness expressed as the parameter R_a. The wood species, feed speed, and cutting depth had a statistically significant effect on the roughness parameter R_a at the significance level $p < 0.05$.

However, the interaction of the wood species with feed speed or with the cutting depth did not show a statistically significant effect on the surface roughness, which indicates the similar effect of changing the processing parameters on the roughness parameter R_a for both wood species.

The feed speed had the most pronounced effect on the roughness of the machined surface. Usta *et al*. (2007) also showed in their research that the roughness parameter R_a is statistically significantly influenced by feed speed, cutting depth, wood properties and additionally the number of cutters in cutterhead.

The results of the ANOVA analysis of the influence of the processing parameters on the surface roughness expressed by the parameter R_q (Table 5) show a statistically significant influence of all investigated parameters, while the interactions of the parameters did not prove to be statistically significant. The analysis of the influence of the processing parameters on the surface roughness expressed by the parameter R_z (Table 6), which is significantly influenced by the anatomical structure of the wood, also showed that the influence of the wood species is statistically significant. The effect of the feed speed was also statistically significant, while the cutting depth did not have a significant effect on the roughness parameter R_z, nor did the interaction of the investigated parameters.

Based on the theoretical analysis of the cutter marks that are created by the passage of the tool during wood milling, it can be shown that for common values of cutting diameters the most influential technological parameter on the quality of machined surface is the effective feed per knife, which is directly proportional to feed speed. Given that the parameter R_a actually represents the mean absolute value of the measured (both filtered and averaged) signal of the machined surface roughness profile, and R_q its Root Mean Square (RMS) value, then it could be expected that these parameters increase with the increase of the theoretical cutting marks height. Of course, these values are also affected by the anatomical structure of the wood and machining roughness. The effect on surface roughness could have also involved the clearance in the fit between the tool and the spindle as well as inaccuracy in positioning the knives. For that reason, the present work used a head in which there was only one knife in order to exclude the influence of inaccuracy in the placement of the knives and their uneven engagement.

In the range of chosen input machining variables, calculated theoretical cutter mark heights were r_w = (2.4; 9.7 and 14.6) µm. Anatomical characteristics of ring porous wood species, which affect resulting surface profile, can have much higher variation. Considering the methodology for calculating the roughness parameter R_z, it can be expected that in such cases it is possible that this parameter is mostly influenced by anatomical properties of wood and not by machining parameters.

Figures 4 through 6 show the influence of feed speed and cutting depth on the roughness of the machined surface when milling samples of sessile oak and pedunculate oak wood, expressed by the parameters R_a, R_q and R_z. The figures clearly show that samples of pedunculate oak wood, on average, had a slightly better quality of the machined surface than samples of sessile oak wood. Differences in surface quality could be explained by the influence of density, texture, and anatomical structure of wood species. The influence of different wood density and wood structure in analyses of surface roughness parameters could be eliminated by normalization of analyzed surface parameters (Chuchala *et al*. 2023).

Table 4. Results of ANOVA Analysis of the Influence of Processing Parameters on Value R_a of Surface Roughness

	Univariate Tests of Significance for R_a (µm) Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	**SS**	**Degr. of (Freedom)**	**MS**	**F**	**p**
Intercept	2273.067	1	2273.067	9738.515	0.000000
Wood species	4.125	1	4.125	17.674	0.000043
v_f (m/min)	71.032	2	35.516	152.162	0.000000
a_e (mm)	2.899	2	1.450	6.210	0.002520
Wood species * v_f (m/min)	0.473	2	0.236	1.013	0.365337
Wood species * a_e (mm)	0.097	2	0.048	0.207	0.813033
v_f (m/min)* a_e (mm)	2.697	4	0.674	2.889	0.024086
Wood species * v_f (m/min)* a_e (mm)	2.619	4	0.655	2.805	0.027553
Error	37.812	162	0.233		
v_f – feed speed; a_e – cutting depth					

The pairwise comparisons across all parameter combinations by Tukey HSD post hoc test did not show statistically significant differences between roughness parameters of machined surfaces of sessile and pedunculate oak wood samples in almost all cases of milling parameters. Significant statistical difference of surface roughness parameters R_a and R_q was noted only when wood samples were machined at feed speed of 16.5 m/min and cutting depth of 2 mm.

ANOVA showed a statistically significant main effect of wood species on surface roughness parameters, but the differences between samples of sessile and pedunculate oak wood when milling was performed with the same feed speed and cutting depth were not sufficiently pronounced to be detected in Tukey HSD post hoc analyses. The reason for not observing significant differences could be in small number of measurements and large data deviation.

Table 5. Results of ANOVA Analysis of the Influence of Processing Parameters on Value R_q of Surface Roughness

Effect	Univariate Tests of Significance for R_q (μm) Sigma-restricted parameterization Effective hypothesis decomposition				
	SS	**Degr. of Freedom**	**MS**	**F**	**p**
Intercept	3909.181	1	3909.181	7905.437	0.000000
Wood species	6.205	1	6.205	12.548	0.000518
v_f (m/min)	112.681	2	56.341	113.936	0.000000
a_e (mm)	6.564	2	3.282	6.637	0.001696
Wood species * v_f (m/min)	1.478	2	0.739	1.495	0.227335
Wood species * a_e (mm)	0.088	2	0.044	0.089	0.914776
v_f (m/min)* a_e (mm)	4.050	4	1.012	2.047	0.090185
Wood species * v_f (m/min)*a_e (mm)	4.434	4	1.108	2.242	0.066817
Error	80.108	162	0.494		
v_f – feed speed; a_e – cutting depth					

Table 6. Results of ANOVA Analysis of the Influence of Processing Parameters on Value R_z of Surface Roughness

Effect	Univariate Tests of Significance for R_z (μm) Sigma-restricted parameterization Effective hypothesis decomposition				
	SS	**Degr. of Freedom**	**MS**	**F**	**p**
Intercept	137643.9	1	137643.9	5233.446	0.000000
Wood species	114.2	1	114.2	4.341	0.038770
v_f (m/min)	3499.6	2	1749.8	66.531	0.000000
a_e (mm)	153.4	2	76.7	2.916	0.057019
Wood species * v_f (m/min)	98.2	2	49.1	1.867	0.157917
Wood species * a_e (mm)	18.5	2	9.3	0.352	0.703467
v_f (m/min)* a_e (mm)	128.6	4	32.1	1.222	0.303493
Wood species * v_f (m/min)*a_e (mm)	166.9	4	41.7	1.587	0.180297
Error	4260.7	162	26.3		
v_f – feed speed; a_e – cutting depth					

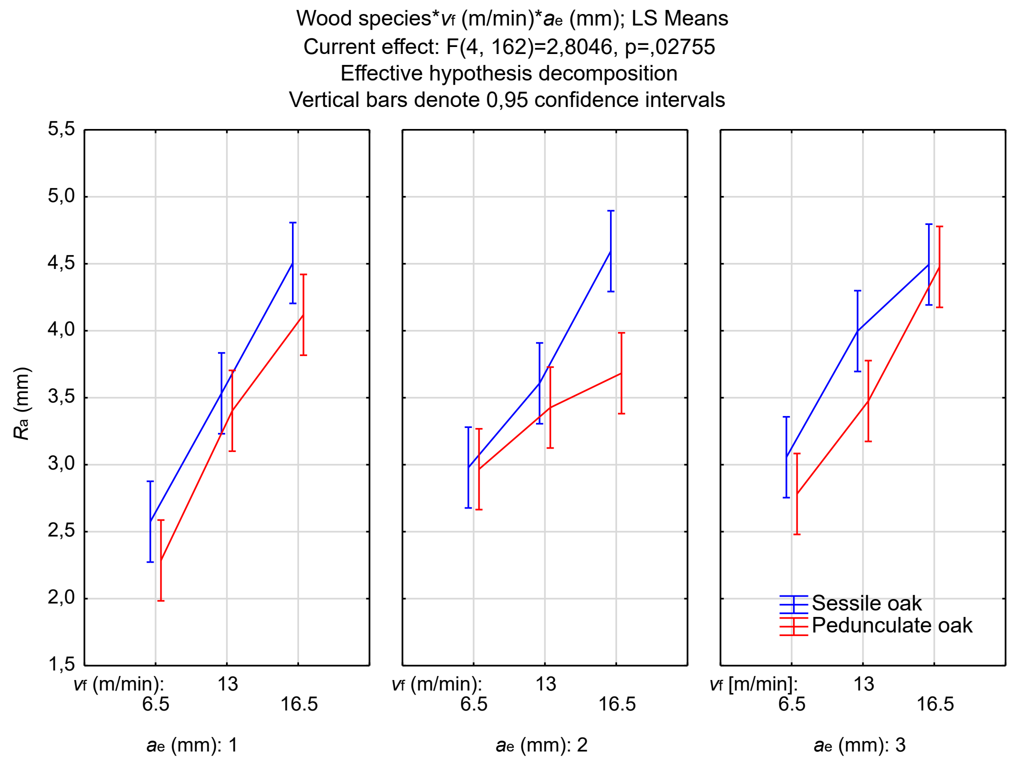

Fig. 4. ANOVA analysis of the effect of feed rate and cutting depth on the value of parameter R_a of surface roughness

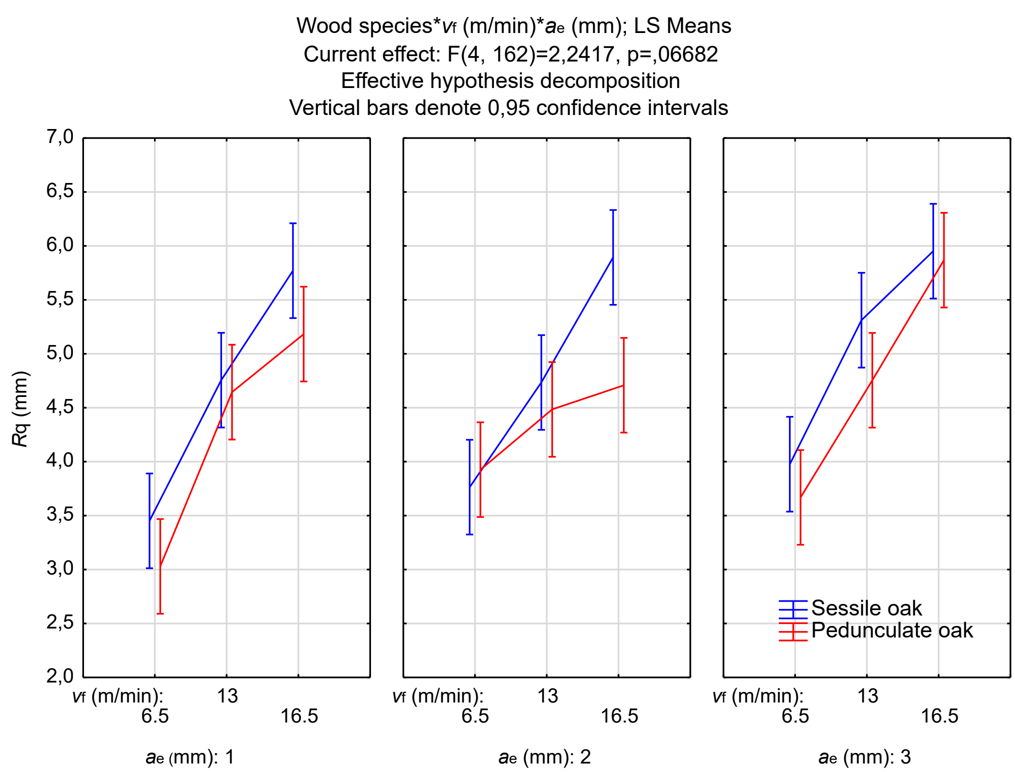

Fig. 5. ANOVA analysis of the effect of feed rate and cutting depth on the value of parameter R_q of surface roughness

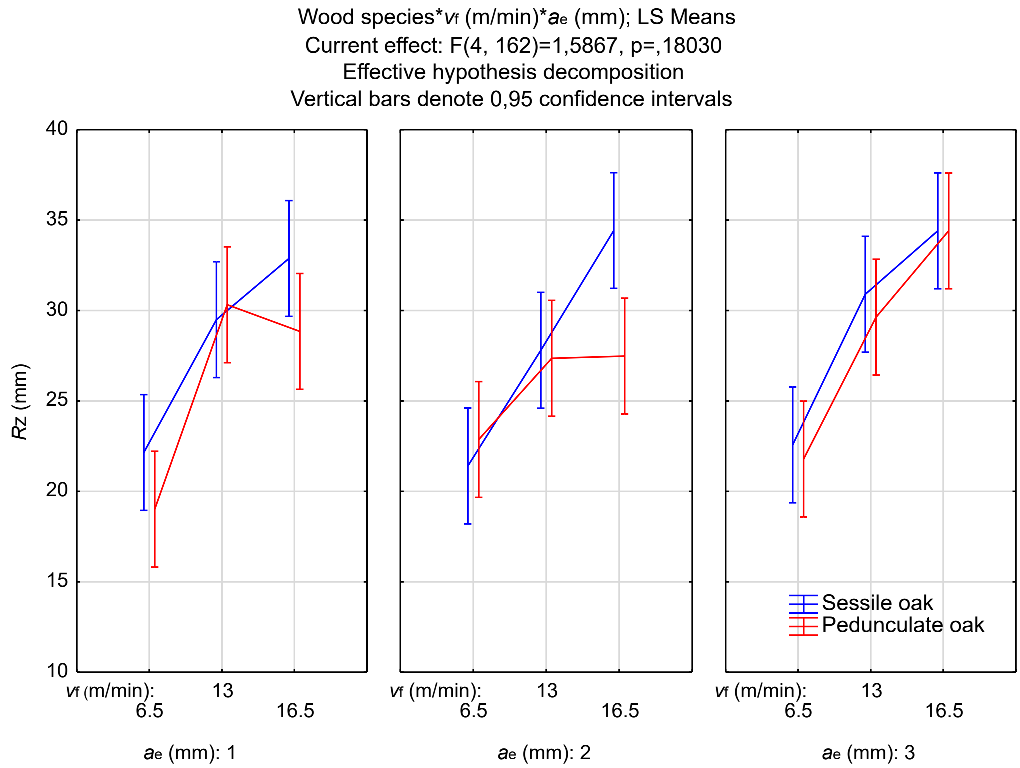

Fig. 6. ANOVA analysis of the effect of feed rate and cutting depth on the value of parameter R_z of surface roughness

According to Jiang *et al*. (2022), the cutting depth has significant effect on the surface roughness as well as the rake angle, while the cutting speed influence is insignificant. Research results obtained by Razaei *et al*. (2020) have shown that the increase in cutting speed and rake angle improved the surface quality, while increase in feed speed caused a deterioration in the surface quality, similarly as it has been shown in the present research. The same effects were obtained by Ajdinaj *et al*. (2023) in a study of the surface quality of silver fir wood planed at different feed rates after thermal modification. They concluded that the increase of feed rate affected the increase in the surface roughness of the wood, and the feed rate resulted as a more significant factor on the surface roughness than temperature of wood modification. Research results obtained by Thoma *et al*. (2015) have shown that the change of the planing parameters as rotational frequency, feed speed, and chip thickness did not significantly influence the surface roughness parameters. The probable reason for such results was relatively small range of rotational frequencies and feed speeds in their experiment. Thoma *et al*. (2015) stated that the differences between roughness parameters mainly can be explained by the influence of the wood texture and the texture uniformity. The size and distribution of the pores (particularly within the early wood), can give a very uneven wood texture. Wood species with small pores tend to be the most evenly textured compared to the wood species such as oak, which has very large and open pores.

In order to confirm the results obtained, research should be conducted on samples of sessile oak and pedunculate oak wood from different locations.

CONCLUSIONS

1. Although the average cutting power during milling sessile oak wood was greater than during milling pedunculate oak wood and three-factorial ANOVA has shown that global effect of wood species on cutting power is significant, the results of individual pairwise comparisons of cutting power during milling under the same conditions after correction by post hoc Tukey HSD did not reach statistical significance.
2. Similar to results of cutting power, higher values of roughness parameters R_a, R_q and R_z were measured on the machined surface of samples of sessile oak wood than pedunculate oak wood and three-factorial ANOVA has shown that wood species has significant effect on roughness parameters. However, the results of pairwise comparison by post hoc Tukey HSD test did not show significant differences of surface roughness parameters of sessile oak and pedunculate oak wood samples machined under the same milling conditions.
3. The research results showed that, of the milling parameters studied, the cutting depth had the most significant influence on the cutting power, and with the increase of cutting depth the cutting power increased too. On the other hand, the most significant influence on the surface roughness was the feed speed. Surface roughness parameters increased with the increase of feed speed.
4. Although a statistically significant effect of wood species on the machinability parameters of sessile oak and pedunculate oak wood was demonstrated by ANOVA, technological parameters were found to have a much greater effect on the machinability parameters than wood properties, which supports practical experience in considering them as materials with similar machinability.

ACKNOWLEDGMENTS

The authors are grateful for the support of the Bjelin Otok d.o.o., veneer production company.

Conflict of Interest

There is no personal interest or relationship that could potentially be affected by the publication of the manuscript.

REFERENCES CITED

Ajdinaj, D., Çota, H., Zejnullahu, F., Sejdiu, R., Bajraktari, A., and Mustafaraj, K. (2023). "Noise emission and quality of surface of thermally modified silver fir wood planed by horizontal milling machine," *Wood Research* 68(4), 718-731. https://doi.org/10.37763/wr.1336-4561/68.4.718731

Astakhov, V. P. (2014). "Machinability: Existing and advanced concepts," in: *Machinability of Advanced Materials*, John Wiley & Sons, Hoboken, NJ, USA, pp. 1-56. http://dx.doi.org/10.1002/9781118576854.ch1

ASTM D 1666-87 (2004). "Standard methods for conducting machining tests of wood and wood–base materials," West Conshohocken, PA, USA.

Beljo Lučić, R., Goglia, V., Pervan, S., Đukić, I., and Risović, 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.

Chuchala, D., Sandak, A., Orlowski, K. A., Sandak, J., Eggertsson, O., and Landowski, M. (2021). "Characterization of arctic driftwood as naturally modified material. Part 1: Machinability," *Coatings* 11(3), article 278. https://doi.org/10.3390/coatings11030278

Chuchala, D., Orlowski, K. A., Hiziroglu, S., Wilmanska, A., Pradlik, A., and Mietka, K. (2023). "Analysis of surface roughness of chemically impregnated Scots pine processed using frame-sawing machine," *Wood Material Science & Engineering* 18(5), 1809-1815. https://doi.org/10.1080/17480272.2023.2221655

Csanády, E., and Magoss, E. (2013). *Mechanics of Wood Machining*, Second Ed., Springer-Verlag, Berlin Heidelberg. https://doi.org/10.1007/978-3-642-29955-1

Despot, V. (1985). *Alati, mašine i uređaji u drvnoj industriji*, Svjetlost, Sarajevo.

Džinčić I., and Skakić, D. (2012). "Determining the parameters of wood machinability as a function of tangential cutting force during the process of machining wood by routing," *Wood Research* 57(1), 161-172.

Đukić, I., Jovanović, J., Župčić, I., and Jug, M. (2023). "Criterion for objective determination of threshold value in filtering surface roughness signal of solid wood after machining with fast Fourier transform (FFT) based filter," *Drvna Industrija* 74(3), 337-346. https://doi.org/10.5552/drvind.2023.0088

Ettelt, B., and Gittel, H. J. (2004). *Sägen, Fräsen, Hobeln, Bohren - Die Spanung von Holz und ihre Werkzeuge*, DRW-Verlag, Stuttgart.

Eyma, F., Meausoone, P. J., and Martin, P. (2004). "Study of the properties of thirteen tropical wood species to improve the prediction of cutting forces in mode B," *Annals of Forest Science* 61, 55-64.

Goglia, V. (1994). *Strojevi i alati za obradu drva - I dio* (in Croatian), Faculty of Forestry University of Zagreb, Zagreb.

Gurau, L., Mansfield-Williams, H., and Irle, M. (2005). "The influence of wood anatomy on evaluating the roughness of sanded solid wood," *Journal of the Institute of Wood Science* 17(2), 65-74. https://doi.org/10.1179/wsc.2005.17.2.65

Gurau, L., Mansfield-Williams, H., and Irle, M. (2007). "Separation of processing roughness from anatomical irregularities and fuzziness to evaluate the effect of grit size on sanded European oak," *Forest Products Journal* 57(1/2), 110.

Hamm, Đ. (1970). "Približni pojednostavljeni način određivania utroška električne energiie i predane mehaničke energije trofaznih asinhronih indukcionih elektromotora," (in Croatian), *Drvna industrija* 21 (7-8), 135-140.

Horvat, I., and Krpan, J. (1967). *Drvnoindustrijski Priručnik*, Tehnička knjiga, Zagreb, 527-530.

Huang, Y., Chuchala, D., Buck, D., Orlowski, K. A., Fredriksson, M., and Svensson, M. (2024). "Analysis of the relationship between cutting forces and local structural properties of Scots pine wood aided by computed tomography," *The International Journal of Advanced Manufacturing Technology* 135, 4975-4987. https://doi.org/10.1007/s00170-024-14797-w

ISO 4287 (1997). "Geometrical Product Specifications (GPS) - Surface texture: Profile method - Terms, definitions and surface texture parameters," International Organization for Standardization, Geneva, Switzerland.

Jiang, S., Buck, D., Tang, Q., Guan, J., Wu, Z., Guo, X., Zhu, Z., and Wang, X. (2022). "Cutting force and surface roughness during straight-tooth milling of walnut wood," *Forests* 13, article 2126. https://doi.org/10.3390/f13122126

Kivimaa, E. (1950). "Cutting force in wood working," Dissertation, University of Helsinki.

Koleda, P., Barcík, Š., and Nociarová, A. (2018). "Effect of technological parameters of machining on energy efficiency in face milling of heat-treated oak wood," *BioResources* 13(3), 6133-6146. https://doi.org/10.15376/biores.13.3.6133-6146

Laina, R., Sanz-Lobera, A., Villasante, A., López-Espí, P., Martínez-Rojas, J. A., Alpuente, J., Sánchez-Montero, R., and Vignote, S. (2017). "Effect of the anatomical structure, wood properties and machining conditions on surface roughness of wood," *Maderas. Ciencia y Tecnología* 19(2), 203-212. https://doi.org/10.4067/S0718-221X2017005000018

Leitz (2011). *Leitz-Lexicon*, Edition 6, Leitz GmbH and Co. KG, Oberkochen, Germany.

Lemaster, R. L., and Dornfeld, D. A. (1982). "Measurement of surface quality of sawn and planed surfaces with a laser," in: *Proceedings of the 7th International Wood Machining Seminar*, 54-62.

Loc, N. H., and Hung, T. Q. (2021). "Optimization of cutting parameters on surface roughness and productivity when milling wood materials," *Journal of Machine Engineering* 21(4), 72-89. https://doi.org/10.36897/jme/144426

Magoss, E. (2008). "General regularities of wood surface roughness," *Acta Silvatica et Lignaria Hungarica* 4, 81-93.

Malkoçoğlu A., and Özdemir, T. (2006). "The machining properties of some hardwoods and softwoods naturally grown in Eastern Black Sea region of Turkey," *Journal of Materials Processing Technology* 173, 315-320.

McKenzie, W. M., Ko, P., Cvitkovic, R., and Ringler, M. (1999). "Towards a model predicting cutting forces and surface quality in routing layered boards," in: *Proceedings of the 14th International Wood Machining Seminar*, 489-497.

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," *Eur. J. Wood Prod.* 71, 747-754. https://doi.org/10.1007/s00107-013-0734-z

Moradpour, P., Scholz, F., Doosthoseini, K., and Tarmian, A. (2016). "Measurement of wood cutting forces during bandsawing using piezoelectric dynamometer," *Drvna Industrija* 67(1), 79-84. https://doi.org/10.5552/drind.2016.1433

Nasir, V., and Cool, J. (2019). "Optimal power consumption and surface quality in the circular sawing process of Douglas-fir wood," *European Journal of Wood and Wood Products* 77(4), 609-617. https://doi.org/10.1007/s00107-019-01412-z

Naylor, A., Hackney, P., Perera, N., and Clahr, E. (2012). "A predictive model for the cutting force in wood machining developed using mechanical properties," *BioResources* 7(3), 2883-2894.

Orlowski, K., and Ochrymiuk, T. (2017). "A newly-developed model for predicting cutting power during wood sawing with circular saw blades," *Maderas. Ciencia y tecnología* 19(2), 149-162. https://doi.org/10.4067/S0718-221X2017005000013

Porankiewicz, B., and Goli, G. (2013). "Cutting forces by oak and Douglas fir machining," *Maderas. Ciencia y Tecnología* 16, 199-216. https://doi.org/10.4067/S0718-221X2014005000016

Razaei, F., Gaff, M., Kumar Sethy, A., Niemz, P., Kamboj, G., Ditommaso, G., Corleto, R., Das, S., and Gašparík, M. (2020). "Surface quality measurement by contact and laser methods on thermally modified spruce wood after plain milling," *The International Journal of Advanced Manufacturing Technology* 110, 1653-1663. https://doi.org/10.1007/s00170-020-05983-7

Sandak, J., Kazimierz, A. O., Sandak, A., Chuchala, D., and Taube, P. (2020). "On-line measurement of wood surface smoothness," *Drvna Industrija* 71(2), 193-200. https://doi.org/10.5552/drvind.2020.1970

Sofuoğlu, S. D., and Kurtoğlu, A. (2015). "Effects of machining conditions on surface roughness in planing and sanding of solid wood," *Drvna Industrija* 66(4), 265-272. https://doi.org/10.5552/drind.2015.1406

Šavar, Š. (1990): *Obrada metala odvajanjem čestica - I. dio - teorijske osnove*, (in Croatian), Školska knjiga, Zagreb, 117-123.

Škaljić, N., Beljo Lučić, R., Čavlović, A., and Obućina, M. (2009). "Effect of feed speed and wood species on roughness of machined surface," *Drvna Industrija* 60(4), 229-234.

Thoma, H., Peri, L., and Lato, E. (2015). "Evaluation of wood surface roughness depending on species characteristics," *Maderas. Ciencia y Tecnología* 17(2), 285-292. https://doi.org/10.4067/S0718-221X2015005000027

Usta, I., Demirci, S., and Kilic, Y. (2007). "Comparison of surface roughness of Locust acacia (*Robinia pseudoacacia* L.) and European oak (*Quercus petraea* (Mattu.) Lieble.) in terms of the preparative process by planning," *Building and Environment* 42, 2988-2992. https://doi.org/10.1016/j.buildenv.2006.07.026

Yang, C., Ma, Y., Liu, T., Ding, Y., and Qu, W. (2023). "Experimental study of surface roughness of pine wood by high-speed milling," *Forests* 14, article 1275. https://doi.org/10.3390/f14061275

Article submitted: March 24, 2026; Peer review completed: May 3, 2026; Revised version received: May 19, 2026; Accepted: June 11, 2026; Published: June 24, 2026.
DOI: 10.15376/biores.21.3.7395-7411