Effect of Chip Thickness, Wood Cross-sections, and Cutting Speed on Surface Roughness and Cutting Power during Up-Milling of Beech Wood

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The aim of the conducted experiments was to determine the effect of selected machining parameters on power consumption and surface quality obtained during the milling of beech wood using a computerized numerical control woodworking machine. Surface roughness was tested using the contact roughness measurement method, while roughness parameters R_a and R_z were recorded and cutting energy was determined. Tests were conducted for two variants of cutting speed (7.5 and 15 m·s^{-1}) as well as three variants of chip thickness (0.10, 0.06, and 0.02 mm); additionally, the tests examined different cross-sections of wood. It was found that greater chip thickness and feed speed caused an increase in surface roughness and cutting power. In turn, cutting speed had no effect on surface roughness, whereas its increase resulted in increased cutting power. Surface roughness at the radial and tangential cross-sections was comparable, while it was greater at the transverse cross-section. It was also found that cutting power was lowest at the radial cross-section, while it was greater at the tangential and the greatest at the transverse cross-section.

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INTRODUCTION

Woodworking is executed using a variety of cutting methods, *e.g.*, milling, sawing, drilling, turning, or sanding. Milling is one of the machining techniques most commonly applied for wood and wood-based materials. At present wood milling processes are frequently performed on computerized numerical control (CNC) woodworking machines. This provides high accuracy of machining parameter settings and ensures their maintenance at the assumed level. High rotational and feed speeds available in CNC machines facilitate advantageous efficiency of the process; however, machining quality also needs to be considered.

Surface roughness is one of the most commonly applied machining quality indicators, and as such it has been investigated in many studies concerning wood and engineered wood materials. Surface roughness is influenced by many variables, such as the condition of the cutting edge, feed speed, the manner of chip formation, or the type of machining and the resulting surface deformation. It is important to control surface roughness during production processes, *e.g.*, those involving bonding of wood elements, or appraising quality of final products (Kilic *et al.* 2006). This control in most cases is a technical requirement for machined products (Guo *et al.* 2015). Surface quality is a complex problem, dependent on many factors, including the heterogeneous wood structure and machining conditions (Malkoçoğlu 2007). Tests have been conducted on surface roughness of wood and wood-based materials, considering the effects of various factors such as cutting force (Aguilera and Martin 2001; Wang *et al.* 2015), thermal wood modification (Budakçı *et al.* 2013; Kvietková *et al.* 2015; Pinkowski *et al.* 2016), type of material (Davim *et al.* 2009; Candan *et al.* 2012; Bekhta *et al.* 2014; Guo *et al.* 2015; Stefanowski *et al.* 2020), machining parameters (Kilic *et al.* 2006; Malkoçoğlu 2007; Barcík *et al.* 2009; Pinkowski *et al.* 2018), tool wear (Gilewicz *et al.* 2010; Aguilera *et al.* 2016), species-specific characteristics (Thoma *et al.* 2015), analysis of acoustic signals (Aguilera and Barros 2012), among others.

Another important factor (also economically) is connected with power consumption (electrical energy demand) of machining. Cutting power is commonly used as the primary indicator for energy consumption of machining processes. This aspect has been investigated by numerous researchers (Aguilera and Martin 2001; Marthy and Cismaru 2009; Barcík *et al.* 2010; Kvietková 2015; Krauss *et al.* 2016; Ispas *et al.* 2016; Koleda *et al.* 2019; Chuchala *et al.* 2020).

The primary parameters of milling affecting both machining quality and energy consumption include machining diameter, cutting speed, feed speed, the number of cutters, feed per tooth, width a_e and cutting depth a_p. Changing the milling parameters causes different effects in terms of machining quality, efficiency, energy consumption, *etc.* Milling may be performed with the same mean chip thickness at different feed speeds and rotational speeds of the cutter tool obtaining different efficiencies, which is primarily determined by feed speed.

Many studies have already been conducted to determine dependencies between individual factors and their effect on machining quality and cutting power. The influence of feed speed on roughness (at a constant cutting speed) has been investigated by many researchers, who at an increasing feed speed found an increase in surface roughness of solid wood (Škaljić *et al.* 2009; Vanco *et al.* 2016) and wood-based materials (Davim *et al.* 2009; Guo *et al.* 2015; Wang *et al.* 2015), while some studies also showed a negligible effect of feed speed on roughness (Malkoçoğlu 2007).

The effect of cutting speed on surface roughness has also been investigated; however, in this case the dependencies were not consistent. Some authors indicated a positive effect of an increase in cutting speed on surface roughness of machined wood (Han *et al.* 2004; Kvietková *et al.* 2015; Ispas *et al.* 2016; Vanco *et al.* 2016) – although it was not always and with a slight increase only in some cases – as well as wood-based materials (Guo *et al.* 2015). Some analyses were conducted showing no effect of cutting speed on machining quality (Aguilera and Martin 2001; Aguilera *et al.* 2016; Rajko *et al.* 2021).

The influence of cross-section type was also partly investigated, with some authors reporting that “a tangential direction in the planing process produces a smoother surface compared to a radial direction” (Sogutlu 2010). An increase in the angle between feed direction and the orientation of wood fibers leads to increased roughness (Cyra and Tanaka 2000). However, these studies were conducted excluding the effect of cutting speed and feed.

Increasing the cutting speed leads to an increase in cutting power (Aguilera and Martin 2001; Barcík *et al.* 2010; Ispas *et al.* 2016; Koleda *et al.* 2019; Rajko *et al.* 2021). The same effect on cutting power also has been observed for feed speed (Marthy and

Cismaru 2009; Barcík *et al.* 2010; Kvietková 2015). Thus, the dependencies are evident; however, the cited studies were conducted without taking into consideration wood cross-sections, which is crucial, because during milling of curvilinear solid wood pieces on a CNC woodworking machine the cross-section is altered.

The research gap indicates the lack of data on the unambiguous shape of the relationship between individual machining parameters and their impact on surface roughness and cutting power. The aim of this study was to determine machining quality and cutting power at a constant chip thickness applying various variants of feed speed and cutting speed. Moreover, these dependencies were established in relation to individual wood cross-section variants.

EXPERIMENTAL

Materials

Tests were conducted on beech wood (*Fagus sylvatica* L.). It is a species producing hard wood, diffuse-porous surface, lacking sapwood, and characterized by no differentiation of annual rings into early and late wood. Beech is a species commonly used in furniture making. It is characterized by a relatively uniform, homogeneous anatomical structure, which is one of the reasons it is often used in research.

Tests were conducted on beam-shaped samples of 19 mm × 70 mm × 250 mm. Three sets of samples were produced, which were oriented anatomically in relation to wood fibers. Sample thickness and at the same time cutting width a_p in all the three cases was 19 mm. The diagrams of radial and transverse cross-sections are given in Fig. 1. Samples were produced from the same location in a log to ensure the smallest possible variability in terms of anatomical structure and density. Samples were seasoned. Their moisture content during the tests was 8 ± 1%, and density was on average 685 kg/m^3.

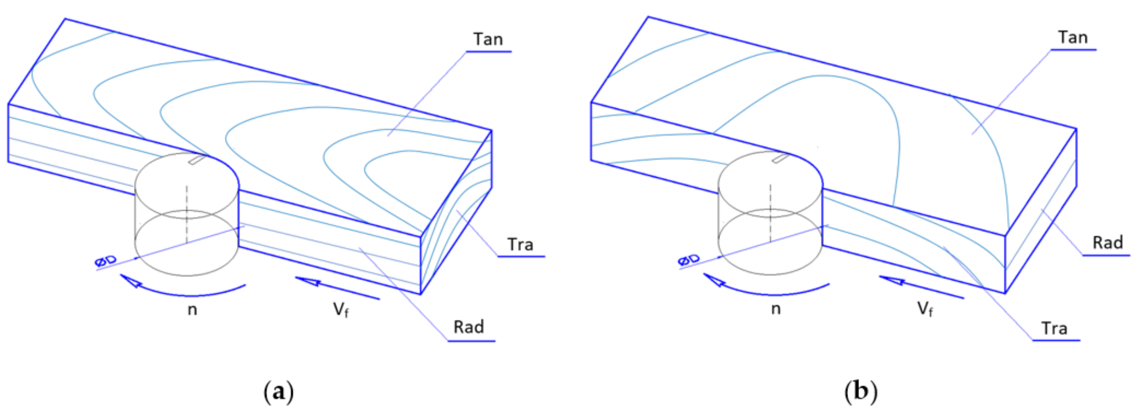

Fig. 1. Milling diagram with cross-section variants marked; milling operations at: (a) radial; (b) transverse cross-section; v_f – feed speed, n – rotational speed, cross-section: Rad - Radial, Tan - Tangential, Tra - Transverse

Methods

Wood milling

Machining operations were performed using a computerized numerical control FLA 16 CNC router (PIAP-OBRUSN, Toruń, Poland). An end radial cutter was the cutting tool used. Angle parameters for the HW cemented carbide cutter were: rake angle 20° and wedge angle 55°.

Average chip thickness (mm) was calculated according to the Eq. 1,

$$a_{av} = \frac{v_f}{nz}\sqrt{\frac{a_e}{D}} \tag{1}$$

where v_f is feed speed (mm/min), n is rotational speed (min^{-1}), z is number of teeth on tool, a_e is cutting depth (mm), and D is cutting diameter (mm).

It follows from this formula that the same mean chip thickness may be obtained using various combinations of parameters given in the formula, *i.e.*, feed speed, rotational speed, the number of cutter teeth, cutting depth, and tool diameter. To determine the effect of variable chip thickness on the measured parameters of surface roughness and cutting power during milling, appropriately selected values of feed speed and rotational speed were applied.

In these tests, two variants of up-milling were used for each of the three analyzed mean chip thickness levels. Values of the parameters for individual variants are given in Table 1. The radial, tangential, and transverse surfaces were milled. For each milling option one rotational speed of the tool and one cutting speed were adopted. The other constant parameters for all the variants were as follows: the number of cutters – 1, cutting diameter D – 16 mm, and cutting depth a_e – 2.06 mm.

Table 1. Milling Parameters

	Variant 1	**Variant 2**
Rotational speed n (min^{-1})	9000	18000
Cutting speed v_c (m·s^{-1})	7.5	15
Chip thickness a_{av} (mm)	Feed speed v_f (m·min^{-1})	
0.10	2.5	5.0
0.06	1.5	3.0
0.02	0.5	1.0

Determination of surface roughness parameters

Surface roughness parameters were determined using the profile method according to the ISO 4287 (1997) standard. It is the most common and objective method to determine surface roughness. It was applied to measure the most typical roughness parameters: R_a – mean roughness and R_z – mean peak-to-valley height or total roughness. Various authors often provide either parameter R_a (Škaljić *et al.* 2009; Budakçı *et al.* 2013; Sofuoğlu and Kurtoğlu 2015; Vanco *et al.* 2016; Koleda *et al.* 2019; Rajko *et al.* 2021) or R_z (Malkoçoğlu 2007; Aguilera *et al.* 2016), or both of them jointly as indicators of surface quality (Pinkowski *et al.* 2018). In some publications, to ensure a more extensive analysis of tested surface parameters, R_a and R_z are supplemented with parameter R_t (Davim *et al.* 2009; Sogutlu 2010; Pinkowski *et al.* 2016) as well as other additional parameters (Kilic *et al.* 2006; Ispas *et al.* 2016; Gurau *et al.* 2017; Hacibektasoglu *et al.* 2017). For each analyzed case a total of 5 roughness measurements were taken parallel to the direction of feed during machining. These measurements were obtained using a Mitutoyo Surftest SJ-210 surface roughness tester (Mitutoyo, Japan, Kawasaki) equipped with a diamond tip stylus. The following parameters were applied in the course of measurements: measuring force – 0.75 mN, feed speed of the stylus – 500 μm·s^{-1}, radius of stylus curvature – 2 μm, apex angle of the stylus – 60°, cut-off – 2.5 mm, length of measured section – 12.5 mm.

Cutting power

Cutting power was measured for each milling case in five replications. Cutting power was measured using a Rohde & Schwarz HMC8015 gauge (Rohde & Schwarz, Munich, Germany). Milling width a_p was 19 mm (sample thickness) and milling depth a_e was 2.06 mm. The analyses included only cutting power (P_c), which was the difference between cutting power generated during sample cutting (power while cutting) and power at idling (idling power), as presented in Fig. 2. The determined cutting power (P_c) was the average value from all collected measurement points during cutting for a particular process.

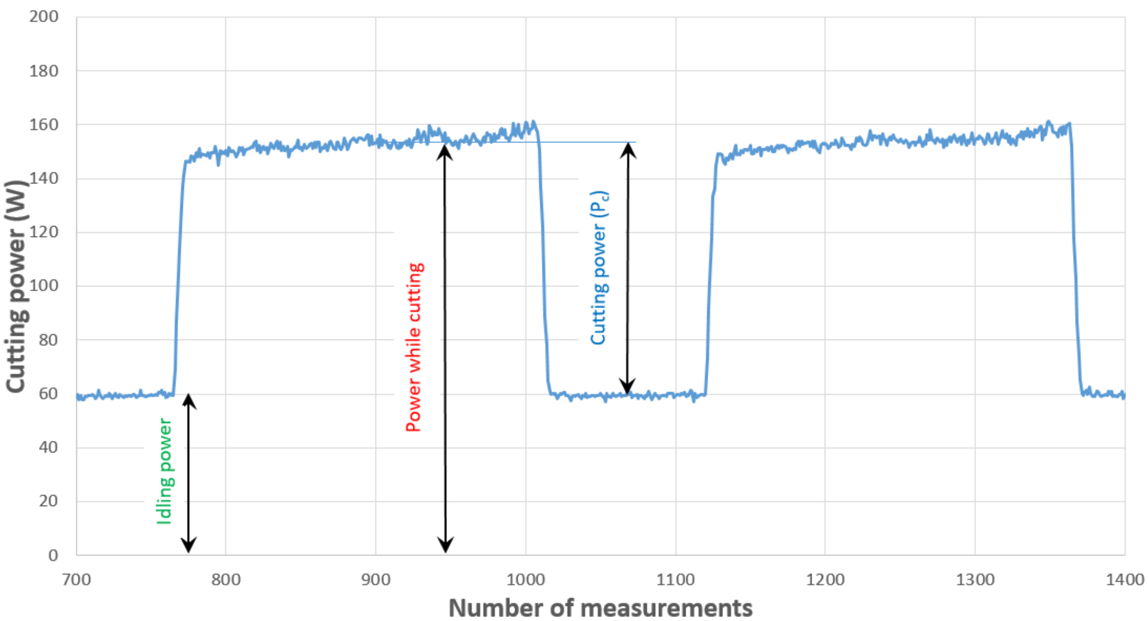

Fig. 2. An example graph of cutting power

Statistical analysis

Statistical analyses included a factorial analysis of variance (ANOVA), followed by Tukey's honest significant difference (HSD) test at $\alpha = 0.05$. All the statistical analyses were performed using the TIBCO Software Inc., Statistica version 13.3 (Palo Alto, CA, USA). The analysis of variance makes it possible to determine the existence of differences between the mean values, *i.e.* it allows determination of whether there are statistically significant differences between the obtained results.

RESULTS AND DISCUSSION

Table 2 presents averaged results of analyzed roughness parameters R_a and R_z, as well as cutting power P_c for all the milling cases along with their coefficient of variation. When investigating direct values, the lowest values R_a (2.1 µm) and R_z (13.86 µm) were recorded for the lowest mean chip thickness (0.02 mm) and variant 1 of cutting speed (7.5 m·s^{-1}) at the tangential cross-section. In turn, the highest values of R_a (10.25 µm) and R_z (80.72 µm) were obtained for the greatest chip thickness (0.1 mm) and variant 1 of cutting speed at the transverse cross-section. Differences observed between the minimum and maximum values need to be considered large, because they amounted to 8.15 µm and 66.86 µm, respectively, for R_a and R_z. The lowest value of cutting power P_c (36.56 W) was recorded for the smallest chip thickness (0.02 mm) and variant 1 of cutting speed for the radial cross-section, while it was greatest for the largest chip thickness (0.01 mm) and variant 2 of cutting speed (15 m·s^{-1}) for the transverse cross-section.

Table 2. Means of Roughness Parameters R_a and R_z and Cutting Power (P_c)

Chip Thickness (mm)	Cutting Speed (m·s^{-1})	Wood Cross-section	R_a (µm)	R_z (µm)	P_c (W)
0.02	7.5	Radial	2.68 (21.8%)	18.27 (28.9%)	36.56 (1.6%)
		Tangential	2.10 (10.5%)	13.86 (10.8%)	61.01 (1.2%)
		Transverse	3.57 (20.2%)	27.90 (23.2%)	94.14 (1.5%)
	15.1	Radial	2.29 (13.8%)	16.43 (19.4%)	77.01 (0.7%)
		Tangential	2.74 (7.8%)	19.10 (12.9%)	104.35 (1.8%)
		Transverse	2.90 (18.1%)	24.16 (23.8%)	132.35 (0.2%)
0.06	7.5	Radial	4.28 (21.0%)	31.25 (15.5%)	50.61 (1.0%)
		Tangential	2.93 (31.9%)	20.30 (36.9%)	94.31 (0.8%)
		Transverse	7.61 (23.3%)	60.11 (23.2%)	170.57 (0.4%)
	15.1	Radial	4.22 (14.7%)	26.33 (15.1%)	111.52 (0.6%)
		Tangential	5.56 (12.2%)	34.99 (8.7%)	140.15 (1.5%)
		Transverse	5.00 (28.9%)	40.79 (34.6%)	301.22 (0.2%)
0.1	7.5	Radial	4.79 (12.5%)	31.75 (4.3%)	65.18 (1.0%)
		Tangential	5.99 (16.2%)	38.47 (13.4%)	119.35 (1.9%)
		Transverse	10.25 (13.3%)	80.72 (11.5%)	303.01 (3.3%)
	15.1	Radial	4.73 (15.1%)	33.19 (10.6%)	119.46 (0.8%)
		Tangential	6.08 (12.5%)	36.58 (13.6%)	187.25 (2.9%)
		Transverse	9.10 (6.1%)	76.21 (8.1%)	388.43 (0.7%)

Note: Results in parentheses are the coefficients of variation

The analysis of the coefficient values indicates that variation in the analyzed roughness parameters in a vast majority of cases for R_a and R_z is small (up to 25%), or in some cases average (from 25% to 36.9%), while power cutting P_c exhibits minimal variation (from 0.2 to 3.3%).

The ANOVA (Table 3) was conducted for roughness parameters and for cutting power, with the effect of individual factors as well as interactions (double and triple) being verified.

Table 3. Summary of ANOVA in a Factorial Arrangement of Roughness Parameters and Cutting Power

Factor	R_a		R_z		P_c	
	F-Test	P-value	F-Test	P-value	F-Test	P-value
Chip thickness (*a*)	167.5	0.000	145.8	0.000	10802.0	0.000
Cutting speed (*b*)	0.9	0.336^{ns}	1.4	0.247^{ns}	10077.3	0.000
Wood cross-section (*c*)	75.8	0.000	138.6	0.000	21804.1	0.000
a × *b*	0.3	0.720^{ns}	0.4	0.677^{ns}	337.4	0.000
a × *c*	15.7	0.000	23.0	0.000	3119.6	0.000
b × *c*	16.7	0.000	9.6	0.000	300.5	0.000
a × *b* × *c*	4.5	0.003	4.2	0.004	173.8	0.000

Note: ns: non-significant (95% confidence level)

Based on this analysis, in most cases differences were found in terms of mean values. Exceptions in this respect included cutting speed for R_a and R_z, as well as the double interaction between chip thickness and cutting speed also for R_a and R_z. For cutting power significant differences were recorded for all the analyzed factors as well as interactions between them.

Table 4 presents results for R_a and R_z as well as cutting power P_c in the function of main factors, *i.e.*, chip thickness, cutting speed, and wood cross-section. Analysis of chip thickness as a main factor shows that all the analyzed chip thickness variants had a significant effect both on surface roughness (R_a and R_z) and cutting power P_c. This is indicated by various homogeneous groups identified by Tukey's test. The dependence between chip thickness and roughness and cutting power is presented in Fig. 3.

Table 4. Results for R_a, R_z, and P_c as a Function of Main Factors

Main Factor	Value	R_a (µm)	R_z (µm)	P_c (W)
Chip thickness a_{av} (mm)	0.02	2.72 [a]	19.95 [a]	84.24 [a]
	0.06	4.93 [b]	35.63 [b]	144.73 [b]
	0.1	6.82 [c]	49.49 [c]	197.11 [c]
Cutting speed v_c (m·s^{-1})	7.5	4.91 [a]	35.85 [a]	110.53 [a]
	15	4.74 [a]	34.20 [a]	173.53 [b]
Wood cross-section	Radial	3.83 [a]	26.21 [a]	76.72 [a]
	Tangential	4.24 [a]	27.22 [a]	117.74 [b]
	Transverse	6.40 [b]	51.65 [b]	231.62 [c]

Note: Means followed by the same letter in the column do not differ statistically in Tukey's test (P > 0.05)

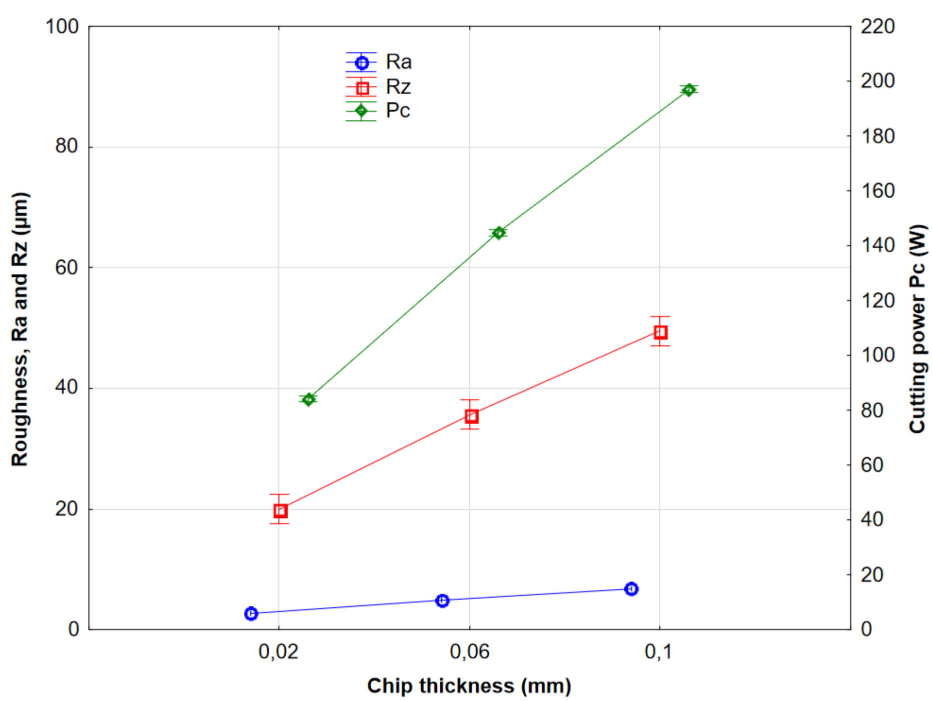

Fig. 3. Surface roughness and power cutting as a function of chip thickness. Vertical bars denote 95% confidence intervals for the mean

Along with an increase in chip thickness, there was also an increase in surface roughness as shown by R_a and R_z. This is consistent with testing results provided by the authors at machining of wood flour/polyvinyl chloride composite (Guo *et al.* 2015). An increase in chip thickness is consistent with an increase in feed speed. The greater the feed, the greater the resulting surface roughness. In tests on beech wood this was also confirmed by other authors (Han *et al.* 2004). The demand for energy consumed by milling grows also at an increased chip thickness (feed speed) (Ispas *et al.* 2016).

The effect of cutting speed as the main factor for R_a and R_z was not significant for surface roughness, as no difference was observed in mean values of R_a and R_z for cutting speeds of 7.5 and 15 $m \cdot s^{-1}$. In literature on the subject, this lack of any dependence has been confirmed in some studies. Aguilera *et al.* (2016) investigated two cutting speeds of 44 m/s and 56 m/s at machining of pine wood, and they found a difference in roughness as specified by parameter R_z. Another study by Aguilera and Martin (2001) tested beech wood while applying three cutting speeds and observed comparable roughness for all the conducted tests. Some reports have also been published where researchers stated an effect of cutting speed on surface roughness (Kvietková *et al.* 2015), whereas other authors confirmed this dependence only in some cases (Ispas *et al.* 2016; Vanco *et al.* 2016) or reported only a slight effect (Han *et al.* 2004). In turn, cutting speed significantly affects cutting power. This dependence is directly proportional, *i.e.*, cutting power grows with an increase in cutting speed. This dependence has been confirmed in other studies on beech wood (Barcík *et al.* 2010). In turn, while machining birch wood (Kvietková 2015) an increase in cutting power was recorded with an increase in cutting speed; however, no significant differences were found between all the applied values of cutting speed.

When analyzing the effect of wood cross-section on surface roughness parameters R_a and R_z, no differences were observed between the radial and tangential cross-sections, while a difference was recorded between the transverse cross-section and the other two cross-sections. For the effect of this factor on cutting power, a difference was found between all the three cross-sections. These dependencies are presented in Fig. 4.

Parameter R_a for the radial (3.83 µm) and tangential cross-sections (4.24 µm) was comparable, whereas the value obtained for the transverse cross-section (6.40 µm) was higher than R_a recorded for the radial and tangential cross-sections by 67% and 51%, respectively. An analogous situation was observed for the parameter R_z, with an increase for the transverse cross-section compared to the radial and tangential cross-sections, amounting to 97% and 90%, respectively. A lack of variability in roughness was also reported in studies on beech wood during planing (Kilic *et al.* 2006); however, this referred to the radial and tangential cross-sections only, as the transverse cross-section was not included in those investigations.

The effect of wood cross-section on cutting power Pc was significant for all the analyzed cross-sections. The lowest value of cutting power was obtained for the radial cross-section (76.7 W), while it was higher for the tangential cross-section (117.7 W) and the highest for the transverse cross-section (231.6 W). In the course of cutting operations along the grain, a chip was separated as a result of the disruption of adjacent fibers (which may be described as comparable to overcoming tensile strength across the grain). When performing transverse cutting operations it is necessary to overcome forces required to cut perpendicular fibers. Thus, machining along the grain is connected with the consumption of lesser power to separate the chip from the sample than is the case in transverse cutting.

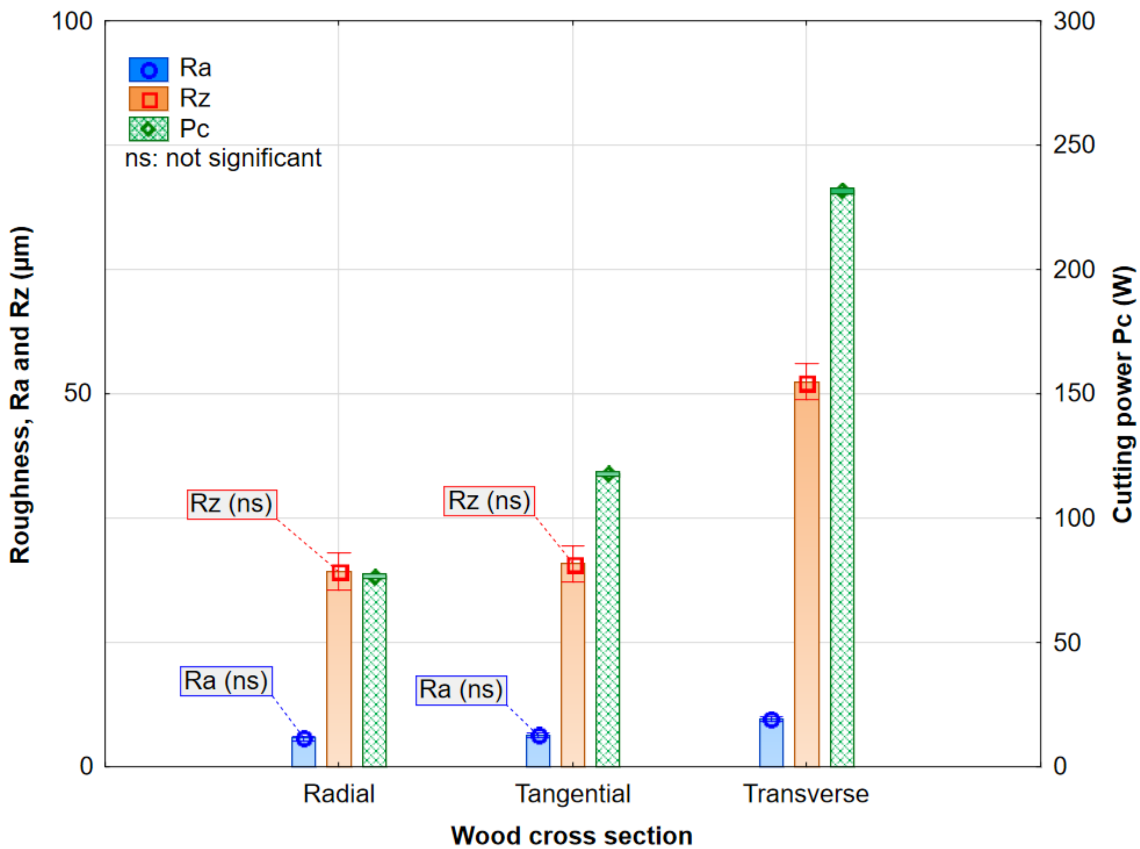

Fig. 4. Surface roughness and power cutting as a function of wood cross-section. Vertical bars denote 95% confidence intervals for the mean.

The obtained ANOVA results also indicate differences in interactions. For parameters R_a and R_z, interactions involving two factors differences were found for the pairs of chip thickness and wood cross-section, as well as cutting speed and wood cross-section. For cutting power, differences were recorded for all the pairs of factors. A list of obtained means in terms of homogeneous groups is given in Tables 5, 6, and 7.

Table 5. Results for R_a, R_z, and P_c as a Function of the Double Interaction between Chip Thickness and Cutting Speed

Chip Thickness (mm)	Cutting Speed ($m \cdot s^{-1}$)	R_a (µm)	R_z (µm)	P_c (W)
0.02	7.5	2.78 a	20.01 a	63.90 a
	15.1	2.65 a	19.90 a	104.57 b
0.06	7.5	4.94 b	37.22 b	105.16 b
	15.1	4.92 b	34.04 b	184.30 c
0.1	7.5	7.01 c	50.31 c	162.51 d
	15.1	6.64 c	48.66 c	231.72 e

Note: Means followed by the same letter in the column do not differ statistically in Tukey's test (P > 0.05)

Table 5 and data presented in Fig. 5 illustrate that parameters R_a and R_z showed no differences within the same chip thickness using different variants of cutting speed and feed. This is confirmed by tests conducted on beech wood (Aguilera and Martin 2001), although then it was recorded at different values of chip thickness and cutting speed. In contrast, there were differences between surface roughness recorded for different chip thicknesses. The lowest values were obtained for the smallest chip thickness (0.02 mm), while they were highest for the greatest chip thickness (0.1 mm). The dependence between chip thickness and feed speed was proportional, because when feed speed was increased, chip thickness also increased. Some authors have changed chip thickness by applying different feed speeds at a constant rotational speed. Thus, with an increase in feed speed surface roughness will increase. This dependence has been confirmed by many authors both for solid wood (Kvietková *et al.* 2015; Vanco *et al.* 2016) and for wood-based materials (Davim *et al.* 2009; Guo *et al.* 2015).

Table 6. Results for R_a, R_z, and P_c as a Function of the Double Interaction between Wood Cross-section and Cutting Speed

Wood Cross-section	Cutting Speed (m·s^{-1})	R_a (μm)	R_z (μm)	P_c (W)
Radial	7.5	3.92 a	27.09 a	50.78 a
	15.1	3.75 a	25.32 a	102.67 c
Tangential	7.5	3.68 a	24.21 a	91.55 b
	15.1	4.79 ab	30.22 a	143.92 d
Transverse	7.5	7.14 d	56.24 c	189.24 e
	15.1	5.67 c	47.05 b	274.00 f

Note: Means followed by the same letter in the column do not differ statistically in Tukey's test ($P > 0.05$)

Table 7. Results for R_a, R_z, and P_c as a Function of the Double Interaction between Chip Thickness and Wood Cross-section

Chip Thickness (mm)	Wood Cross-section	R_a (μm)	R_z (μm)	P_c (W)
0.02	Radial	2.49 a	17.35 a	56.79 a
	Tangential	2.42 a	16.48 a	82.68 b
	Transverse	3.24 a	26.03 a	113.25 c
0.06	Radial	4.25 b	28.79 a	81.07 b
	Tangential	4.25 b	27.64 a	117.23 c
	Transverse	6.30 c	50.45 b	235.90 f
0.1	Radial	4.76 d	32.47 a	92.32 d
	Tangential	6.04 c	37.53 a	153.30 e
	Transverse	9.68 f	78.47 c	345.72 g

Note: Means followed by the same letter in the column do not differ statistically in Tukey's test ($P > 0.05$)

For cutting power, an increase in this parameter was observed with an increase in chip thickness and cutting speed. The lowest values (63.9 W) were recorded for chip thickness of 0.02 mm and variant 1 of cutting speed, while they were highest (231.7 W) for chip thickness of 0.1 mm and variant 2 of cutting speed. These differences were significant, as confirmed by Tukey's test. Similar dependencies were shown by other authors, who investigated cutting power depending on cutting speed (Aguilera and Martin 2001; Barcík *et al.* 2010; Ispas *et al.* 2016) and feed speed (Barcík *et al.* 2010; Ispas *et al.* 2016).

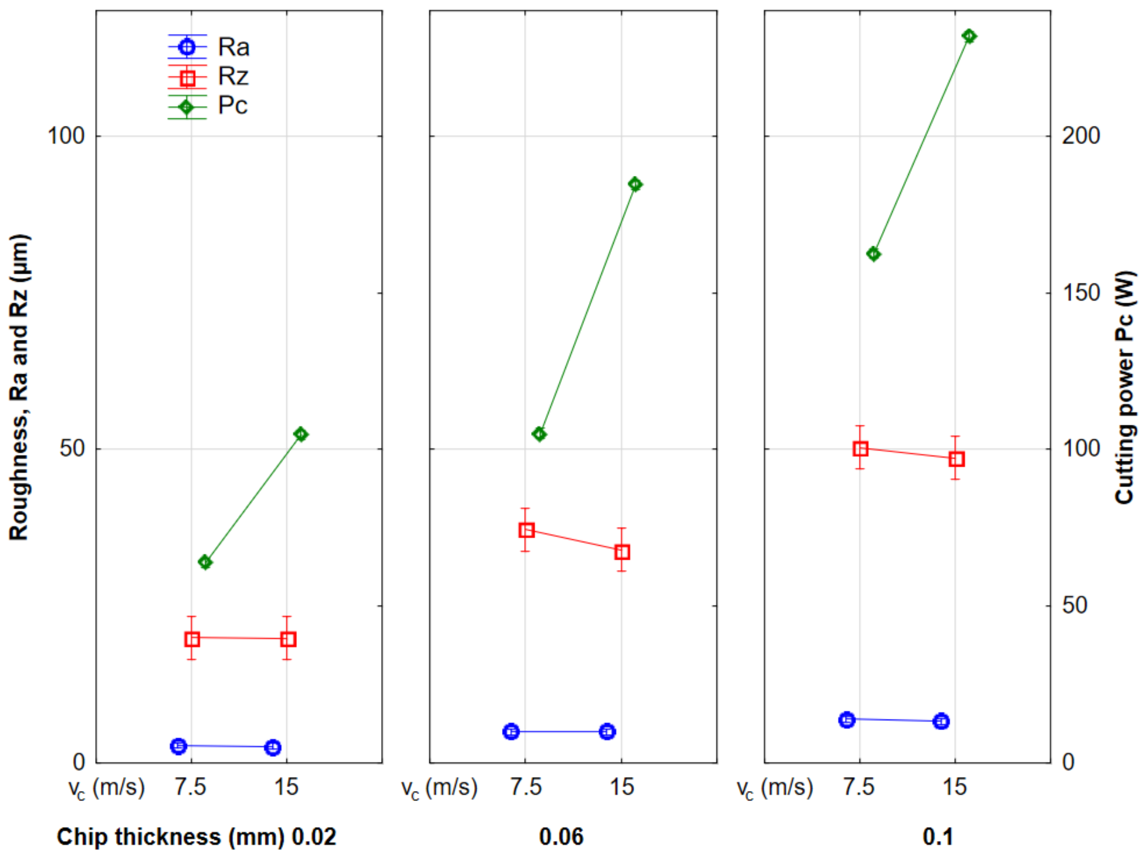

Fig. 5. Surface roughness and power cutting as a function of chip thickness and cutting speed. Vertical bars denote 95% confidence intervals for the mean

It follows from data presented in Table 6 that for the radial and tangential cross-sections no differences were found for surface roughness, whereas for the transverse cross-section R_a and R_z were markedly greater than analogous values recorded for the other two cross-sections. For the transverse cross-section a lower cutting speed resulted in greater values of R_a and R_z. It has been reported previously in literature that a lack of differences in surface roughness was confirmed for different cutting speeds (Aguilera and Martin 2001); however, those studies made no distinction between various anatomical profile cross-sections of wood. No differences were also observed when testing surface roughness at the radial and tangential cross-sections of beech wood at constant cutting conditions (Kilic *et al.* 2006). Other tests confirmed an increase in surface roughness along with an increase in the angle between feed direction and wood fibers (Cyra and Tanaka 2000). Those tests were conducted at a constant cutting speed (disregarding the effect of cutting speed). Some studies also confirmed a positive effect of increased cutting speed on surface roughness; however, this dependence was not consistent (it was not found in all the analyzed cases) (Vanco *et al.* 2016).

Cutting power P_c for each of the cross-sections showed values greater for variant 2, *i.e.* for greater cutting speed and feed values. For beech wood this was confirmed by earlier studies, although it was with no division into anatomical profile cross-sections (Aguilera and Martin 2001; Ispas *et al.* 2016).

Table 7 shows that for chip thickness of 0.02 mm the wood cross-section used had no effect on surface roughness, whereas it influenced cutting power, which was lowest for the radial cross-section (56.8 W) and highest for the transverse cross-section (113.2 W). For chip thickness of 0.06 mm cutting power values were analogous, whereas there was no difference in parameters R_a and R_z for the radial and tangential cross-sections. Beech wood is a diffuse porous wood with a uniform and homogeneous structure, with no division into early and late wood; thus, characteristics of surface at the radial and tangential cross-sections in terms of roughness may be similar. Roughness at the transverse cross-section had greater values in relation to the other two cross-sections. Variability in roughness between the radial cross-section and the other cross-sections may be caused by the anatomical structure of wood, and it results, among other things, both from the deeper penetration of the stylus tip into the lumen of wood cells at the transverse cross-section, as well as the deformation of wood fibers generated as a result of transverse cutting.

For the greatest chip thickness (0.1 mm), cutting power was changing analogously as it was at smaller chip thicknesses, whereas R_a values differed for all the cross-sections, while those of R_z differed only between the transverse cross-section and the other two cross-sections. Additionally, the greatest values of roughness R_a (9.68 µm) and R_z (78.47 µm) were observed for the transverse cross-section. The double interaction, *i.e.*, that between all the three analyzed factors, is presented in Table 8 and Figs. 6 and 7.

Table 8. Results for R_a, R_z, and P_c as a Function of the Triple Interaction between Chip Thickness, Cutting Speed, and Wood Cross-section

Chip Thickness (mm)	Wood Cross-section	Cutting Speed ($m \cdot s^{-1}$)	R_a (µm)		R_z (µm)		P_c (W)	
0.02	Radial	7.5	2.68	a	18.27	ab	36.56	a
		15.1	2.29	a	16.43	ab	77.01	d
	Tangential	7.5	2.10	a	13.86	a	61.01	c
		15.1	2.74	ab	19.10	ab	104.35	f
	Transverse	7.5	3.57	ab	27.90	ab	94.14	e
		15.1	2.90	ab	24.16	ab	132.35	i
0.06	Radial	7.5	4.28	bc	31.25	bc	50.61	b
		15.1	4.22	bc	26.33	ab	111.52	g
	Tangential	7.5	2.93	ab	20.30	ab	94.31	e
		15.1	5.56	bc	34.99	bc	140.15	j
	Transverse	7.5	7.61	d	60.11	e	170.57	k
		15.1	5.00	c	40.79	d	301.22	m
0.1	Radial	7.5	4.79	bc	31.75	bc	65.18	c
		15.1	4.73	bc	33.19	bc	119.46	h
	Tangential	7.5	5.99	c	38.47	bc	119.35	h
		15.1	6.08	c	36.58	bc	187.25	l
	Transverse	7.5	10.25	e	80.72	f	303.01	m
		15.1	9.10	e	76.21	f	388.43	n

Note: Means followed by the same letter in the column do not differ statistically in Tukey's test (P > 0.05).

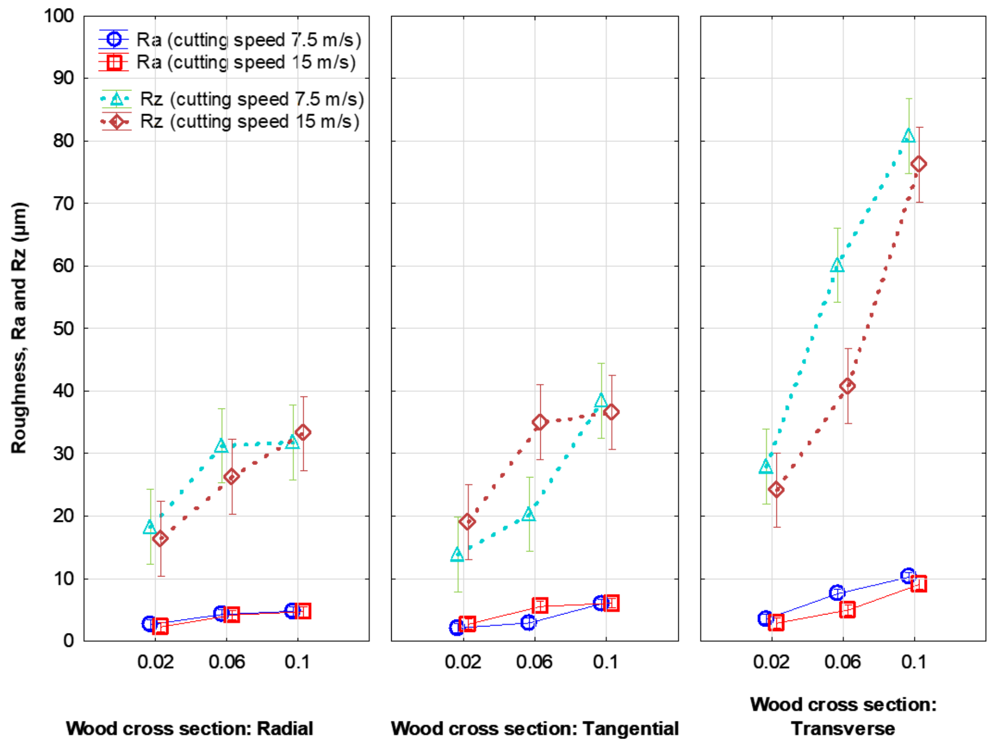

Fig. 6. Surface roughness R_a and R_z as a function of chip thickness, wood cross-section, and cutting speed. Vertical bars denote 95% confidence intervals for the mean.

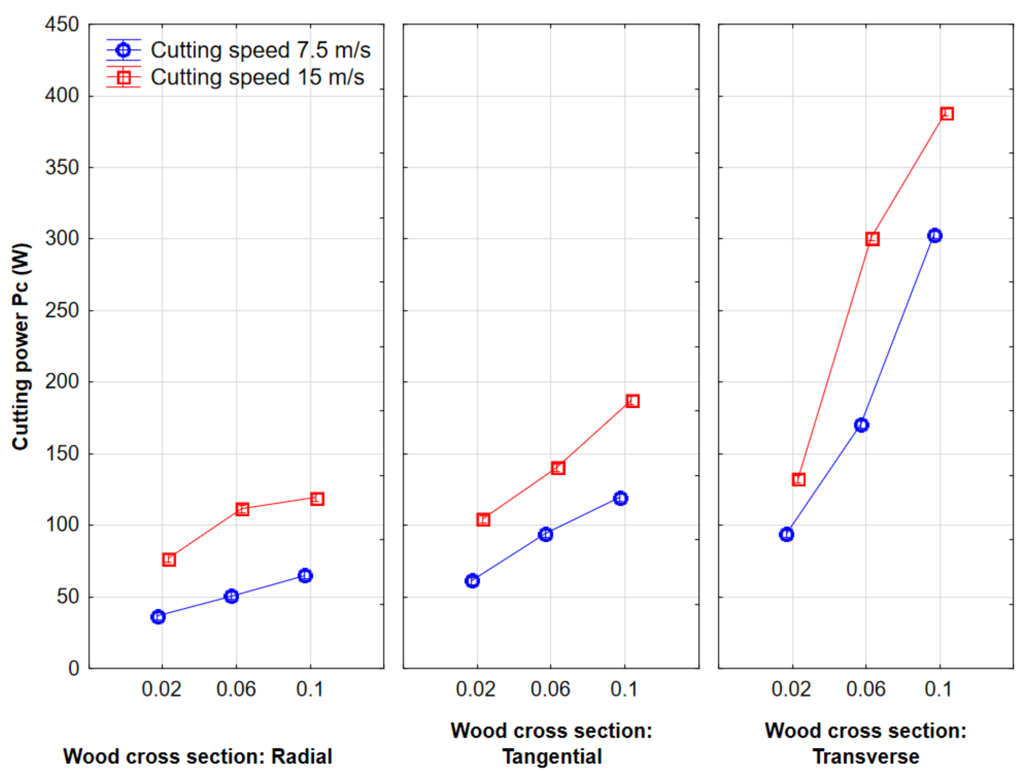

Fig. 7. Power cutting as a function of chip thickness, wood cross-section, and cutting speed. Vertical bars denote 95% confidence intervals for the mean.

Table 8 shows that for chip thickness of 0.02 mm, the surface roughness was the same (showed no differences between the means for individual cases). No effect of wood cross-section or cutting speed on roughness was observed. For chip thicknesses of 0.06 mm and 0.1 mm, the same dependence was found for the radial and tangential cross-sections; however, an increase in roughness was recorded for the transverse cross-section in relation to the other two cross-sections, which was confirmed in other studies (Cyra and Tanaka 2000). Roughness at the radial and tangential cross-sections did not differ, which is consistent with the reports from other publications (Kilic *et al.* 2006). For the transverse cross-section (at chip thickness of 0.06 mm), a significant effect of cutting speed on roughness was found, while a smaller cutting speed (variant 1) resulted in greater values of R_a and R_z. For the two other cross-sections no such dependencies were reported.

When analyzing the effect of chip thickness on surface roughness, it was observed that values of parameters R_a and R_z grew with an increase in chip thickness. Such a relationship was found for all the cross-sections; however, it was most evident for the transverse cross-section. At a small chip thickness the differences were statistically non-significant, whereas they tended to change into significant along with an increase in chip thickness.

The effect of the analyzed factors on cutting power was significant for a vast majority of cases. Cutting power was directly proportional in relation both to chip thickness and cutting speed. The effect of the anatomical profile cross-section was also statistically significant. The lowest values were found for the radial cross-section, they were higher for the tangential cross-section, and they were the highest for the transverse cross-section. This dependence is presented in Fig. 7. Such a dependence has also been confirmed by other authors for beech wood as well as other wood species; however, it was investigated with no consideration for anatomical profile directions (Barcík *et al.* 2010; Ispas *et al.* 2016; Koleda *et al.* 2019).

Because no significant effect of cutting speed was found on surface roughness, it may be stated that in view of milling efficiency it is recommended to apply variant 2 of cutting speed, *i.e.*, greater rotational speed and feed. However, an increase in efficiency is connected with an increased power demand, because cutting power significantly grows for cutting variant 2.

At a constant chip thickness a change of cutting speed from 7.5 to 15 $m \cdot s^{-1}$ resulted in an increase in efficiency by 100% (because feed speed also increases 2-fold), whereas power demand depending on the cross-section grew approximately by 102%, 57%, and 45%, respectively, for the radial, tangential, and transverse cross-sections. This occurs because it is better to apply a greater cutting speed, because at the radial cross-section the efficiency and power demand are balanced, whereas at the tangential and transverse cross-sections the increase in efficiency exceeds the increase in power demand.

CONCLUSIONS

Analyses were conducted on milling of beech wood while applying two variants of cutting speed and feed so as to obtain the same chip thickness. The variants were repeated for three chip thickness options, *i.e.*, 0.1, 0.06, and 0.02 mm, as well as three basic anatomical profile cross-sections. Surface roughness and power consumption were investigated during milling. The obtained results provided grounds for the following conclusions:

1. The effect of chip thickness on surface roughness proved to be significant. A directly proportional dependence was observed, *i.e.*, values of parameters R_a and R_z increased with an increase in chip thickness. An increase in chip thickness may be obtained by increasing feed speed and this dependence results in an increase in surface roughness.
2. At the constant cutting diameter, milling with the same chip thickness a_{av} at two different (2-fold greater) cutting speed v_c and feeds v_f showed a lack of significant differences in the recorded values of roughness parameters R_a and R_z.
3. The anatomical cross-section was investigated in the ANOVA as a main factor showing a significant effect on surface roughness. The smallest roughness was recorded at the radial cross-section, followed by the tangential cross-section and it was the greatest at the transverse cross-section. In the interactions between the main factors, a comparable surface quality was observed at the radial and tangential cross-sections, while it was greater at the transverse cross-section.
4. Cutting power was used as an indicator of power consumption during the milling process. It was observed that cutting power differed significantly during milling for all the analyzed factors and cutting variants. Cutting speed and chip thickness had a directly proportional effect on cutting power. For the effect of the anatomical profile cross-section the lowest power demand was recorded for the radial cross-section, while it was greater for the tangential cross-section and the greatest for the transverse cross-section (for the greatest chip thickness and cutting speed).
5. Because no deterioration of machining quality was observed with an increase in cutting speed within the analyzed range of values, it is recommended for industrial practice to perform cutting operations with a greater speed, *i.e.*, 15 $m \cdot s^{-1}$. It needs to be considered that power demand increases significantly in such a case; however, the increase is smaller than that for machining efficiency.

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