

Effect of Chip Thickness and Tool Wear on Surface Roughness and Cutting Power during Up-Milling Wood of Different Density

Grzegorz Pinkowski,* Magdalena Piernik, Marcin Wołpiuk, and Andrzej Krauss

The aim of this study was to determine the effect of average chip thickness and blade wear on the cutting power consumption and surface quality obtained in up-milling wood of different densities. The surface roughness was investigated using the contact method, recording the roughness parameters R_a and R_z , and the cutting power was determined using a wattmeter. The research was conducted for two variants of blade wear, *i.e.*, sharp and blunt, and three variants of chip thickness (0.10, 0.06, and 0.02 mm). Four wood species with very different densities were tested, *i.e.*, balsa (*Ochroma pyramidale* (Cav. ex Lam.) Urb.), obeche (*Triplochiton scleroxylon* K. Schum.), alder (*Alnus glutinosa* L. Gaertn.) and beech (*Fagus sylvatica* L.) For the lowest density woods, a better surface quality was found when cutting with a blunt knife compared to a sharp knife, while for the higher density woods (alder and beech) an inverse relationship was observed, *i.e.*, a blunt knife resulted in increased surface roughness. For obeche wood, the surface roughness was dependent on the chip thickness. In addition, for low-density woods (balsa and obeche), no differences in cutting power were shown as a function of blade condition. It was shown that both an increase in wood density and chip thickness resulted in an increase in cutting power.

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INTRODUCTION

In the woodworking industry, milling is the most common machining method. Using this machining method on numerically controlled machine tools, it is possible to produce any shape in a highly repeatable manner. This method is most often considered in terms of cutting performance, quality of the machined surface, tool wear, safety and ambient noise (Koleda *et al.* 2019). Many of these aspects are related to the cost of milling. One factor that significantly affects the cost is the energy consumed during cutting. This energy can be determined indirectly by determining cutting forces and power. Many authors have conducted research in this area, both for solid wood (Aguilera and Martin 2001; Ispas *et al.* 2016; Krauss *et al.* 2016; Hacibektasoglu *et al.* 2017; Kamboj *et al.* 2020; Guo *et al.* 2021; Yu *et al.* 2023) and wood materials (Guo *et al.* 2015; Wang *et al.* 2015).

In general, it can be concluded that an increase in the energy required for machining, for example, is related to an increase in the cutting depth (Krauss *et al.* 2016; Yu *et al.* 2023), the cutting speed (Kamboj *et al.* 2020) the chip thickness (Piernik *et al.* 2023), the feed rate (Ispas *et al.* 2016; Garrido *et al.* 2024), or the density of the cut materials (Aguilera and Martin 2001). However, not all studies confirm similar relationships, especially if the tool blades are made of new, *e.g.*, ceramic materials (Guo *et al.* 2021).

From the point of view of the quality of the machined surface, it is important to select machining parameters so as to achieve high machining efficiency while ensuring satisfactory surface quality. The most common determinant of machining quality is surface roughness (Hernández and Cool 2008; Gurau *et al.* 2017; Stefanowski *et al.* 2020), which can have a very wide range. Surface roughness depends on many factors related to the material being machined, such as the anatomical structure of the wood, density, and wood species, as well as on cutting-dependent factors such as machining parameters, blade type, blade wear, and machine tool accuracy.

Tool wear is an important parameter that significantly affects both machining quality and cutting energy requirements. This issue has been studied in relation to solid wood (Gilewicz *et al.* 2010; Pinkowski *et al.* 2010; Aguilera *et al.* 2016a; Bendikiene and Keturakis 2016, 2017; Keturakis *et al.* 2017; Koleda *et al.* 2019), as well as wood materials (Pinkowski *et al.* 2015). The main aspect analyzed in these studies, besides wear itself, is its effect on surface roughness. In general, surface roughness increases with tool wear, but such a relationship has not always been shown (Bendikiene and Keturakis 2016). In addition, some studies indicate that surface roughness increases, but only up to a certain wear of the blade, further blade wear may result in a decrease in surface roughness (Pinkowski *et al.* 2010; Aguilera *et al.* 2016b).

The influence of wood species, and the associated density, has a major impact on both energy consumption during machining and the quality of the resulting surface. Many authors have undertaken studies determining the influence of wood species on the energy demand and the quality of the obtained surface (Aguilera and Martin 2001; Malkoçoğlu 2007; Budakçı *et al.* 2013). In general, an increase in wood density increases cutting power and reduces surface roughness (Budakçı *et al.* 2013; Tosun and Sofuoğlu 2023). However, this relationship has not been confirmed in some studies. Malkoçoğlu (2007) among others, investigated the effect of five wood species with different densities on the formation of surface roughness. Differences were shown, but no strong correlation was obtained between species (densities). A similar study was performed by Thoma *et al.* (2015) and showed differences in surface roughness between species, but the correlation of this relationship was also low. Aguilera and Martin (2001) showed that there was no effect of density on roughness under different counter-milling conditions. Most research in this area has been conducted on medium- and high-density wood species. Only a few studies have been conducted for low-density woods such as obeche in solid form (Czarniak *et al.* 2019) and in modified form (Castro and Zanuttini 2004). Other low-density woods such as poplar are being investigated as post-densification materials, where it is found that an increase in material density improves surface quality after treatment (Tosun and Sofuoğlu 2023).

Due to the lack of data in the low density range, this study examined a wide range of wood densities and demonstrated the relationship between cutting power and surface roughness and tool wear in two states: sharp and blunted, using three chip thicknesses.

EXPERIMENTAL

Materials

Tests were carried out on four wood species with very different densities. A summary of these species is given in Table 1. The tests were carried out on rectangular-shaped specimens measuring 19 mm × 70 mm × 250 mm. Specimens were made oriented anatomically with respect to the wood fibres, so that the radial surfaces could be machined. The thickness of the sample, and at the same time the cutting width a_p in all cases, was 19 mm. The specimens were seasoned, and their moisture content during the tests was between 9% and 12%, depending on the species.

Table 1. Wood Species Used in Research

Wood species	Density (kg/m ³)
Balsa, <i>Ochroma pyramidale</i> (Cav. ex Lam.) Urb.	90
Obeche, <i>Triplochiton scleroxylon</i> K. Schum.	300
Alder, <i>Alnus glutinosa</i> L. Gaertn.	505
Beech, <i>Fagus sylvatica</i> L.	740

Wood Milling

Machining operations were performed using a computerized numerical control milling router CNC 6090 (KMA-MASZYNY, Gorzów Wielkopolski, Poland). A water-cooled spindle motor GDZ100-3 (Lunye Industrial Automation Equipment, Zhengzhou, Henan Province, China) was used, controlled by the inverter. The spindle allows for a rotation speed of up to 24000 min⁻¹, has a power of 3 kW, with a frequency control of up to 400 Hz. 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 was calculated as follows,

$$a_{av} = \frac{v_f}{nz} \sqrt{\frac{a_e}{D}} \quad (1)$$

where v_f is feed speed (m/min), n is rotational speed (min⁻¹), z is number of teeth on tool, a_e is cutting depth (m), and D is cutting diameter (m).

In the study, up-milling was used, of the radial surfaces of the samples, for each of the three average chip thicknesses analyzed. The average chip thicknesses and corresponding feed rates are given in Table 2. The other constant parameters were as follows: number of blades $z = 1$, cutting diameter $D = 16$ mm, cutting depth $a_e = 2.06$ mm, rotational speed $n = 18000$ min⁻¹, and cutting speed $v_c = 15$ m/s.

Table 2. Chip Thicknesses and Corresponding Feed Speeds

Chip thickness a_{av} (mm)	Feed speed v_f (m/min)
0.10	5.0
0.06	3.0
0.02	1.0

Tools Wear

Two states of blade wear were used in the study: sharp and blunt. A new blade was assumed to be sharp if its a radius of rounding of the cutting edge was approximately 6 μm, while a blunt blade had a radius of rounding of the cutting edge of approximately 26 μm

or larger. In order to determine the intensity of blade wear, a wear profile was determined perpendicular to the main cutting edge. Blade wear was measured using a Carl Zeiss ME10 contact profilometer (Carl Zeiss, Jena, Germany) with specialist measuring sensors. The profiles of the sharp and blunt blade were recorded using a conical stylus with an apex angle of 20° and a tip radius of $25\text{ }\mu\text{m}$ and are shown in Fig. 1.

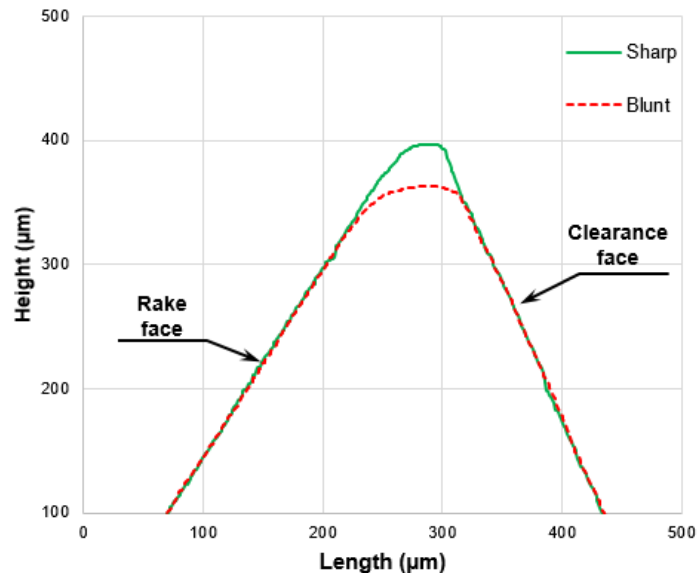


Fig. 1. Profiles perpendicular to the cutting edge of the blade for sharp and blunted states

Surface Roughness

Stylus profilometry 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. 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). This tester enables roughness parameters to be determined in accordance with the standard ISO 4287 (1997). The following parameters were applied in the course of measurements: measuring force – 0.75 mN , feed speed of the stylus – $500\text{ }\mu\text{m/s}$, radius of stylus curvature – $2\text{ }\mu\text{m}$, apex angle of the stylus – 60° , cut-off – 2.5 mm , and length of measured section – 12.5 mm .

Cutting Power

Cutting power was measured for each milling case in five replications with using a Rohde & Schwarz HMC8015 gauge (Rohde & Schwarz, Munich, Germany). 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 wattmeter was connected to the inverter to enable measurement of the spindle power only.

Statistical Analysis

Statistical analyses included a factorial ANOVA, followed by Duncan's test at $\alpha = 0.05$. All the statistical analyses were performed using the TIBCO Software Inc. Statistica version 13.3 (Palo Alto, CA, USA).

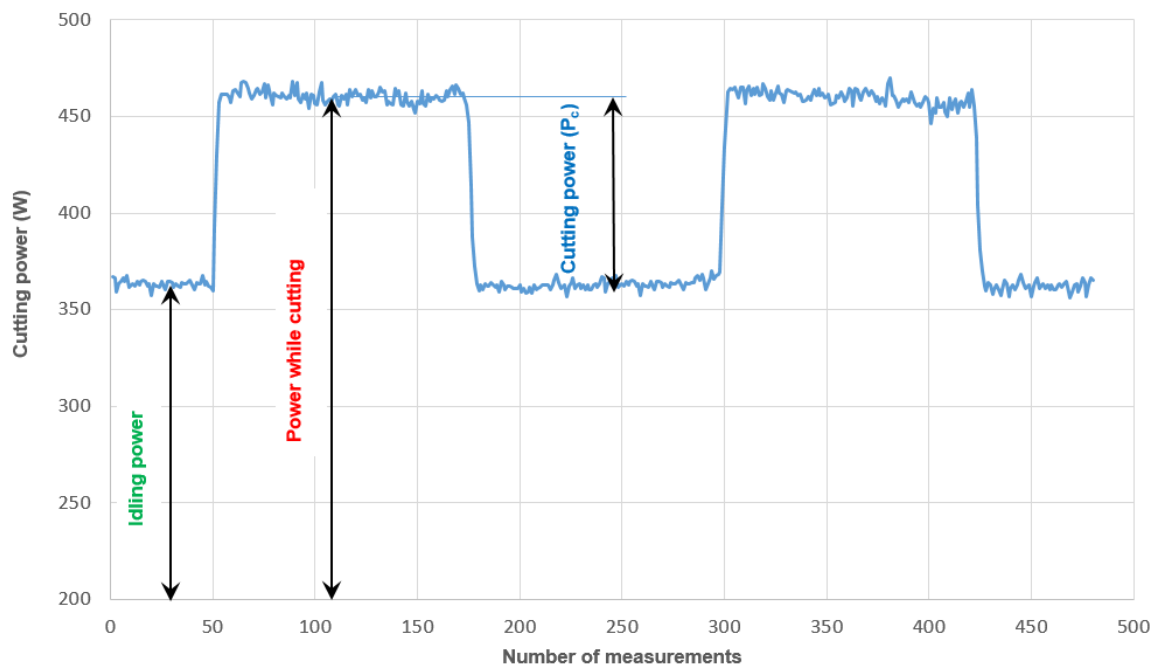


Fig. 2. An example graph of cutting power

RESULTS AND DISCUSSION

Roughness and Cutting Power

Table 3 shows the results of the ANOVA analysis of variance of the surface roughness parameters and cutting power for the factors in the experiment. The results of this analysis make it possible to conclude that, at the assumed level of significance ($\alpha = 0.05$), there were statistically significant differences between the obtained roughness parameters and cutting power depending on wood density, blade wear and average chip thickness ($P < 0.05$). These differences were found for all cases with one exception, namely for the triple interaction ($a \times b \times c$), for the parameter R_z , where $P=0.201$ was obtained.

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
Density (a)	529.7	0.000	4056.6	0.000	131278.4	0.000
Wear of cutting edge (b)	4.6	0.036	38.9	0.000	19229.6	0.000
Chip thickness (c)	816.2	0.000	4.7	0.034	5530.0	0.000
$a \times b$	182.5	0.000	35.2	0.000	3858.0	0.000
$a \times c$	61.3	0.000	7.5	0.000	2549.0	0.000
$b \times c$	21.018	0.000	2.854	0.019	238.7	0.000
$a \times b \times c$	32.927	0.000	1.658	0.201 ^{ns}	16.5	0.000

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

The results of the surface roughness parameters R_a and R_z , as well as the cutting power, as a function of the main factors, *i.e.*, density, tool wear and average chip thickness,

are summarized in Table 4. For surface roughness and cutting power as a function of wood density, there were differences between all values. The lowest surface roughness was obtained for the wood with the highest density, *i.e.*, beech ($R_a = 3.45 \mu\text{m}$, $R_z = 22.04 \mu\text{m}$) and the highest for the wood with the lowest density, *i.e.*, balsa ($R_a = 5.39 \mu\text{m}$, $R_z = 34.67 \mu\text{m}$). Such a relationship is in line with literature data (Magoss and Sitkei 1999; Budakçı *et al.* 2013; Pinkowski *et al.* 2019).

The cutting power showed an inverse relationship, *i.e.*, as the density of the wood increased, the cutting power increased. Such a relationship is consistent with other studies (Aguilera and Martin 2001). The highest value was obtained for the highest density ($P_c = 341.73 \text{ W}$), and the lowest for the lowest density ($P_c = 30.46 \text{ W}$).

Table 4. Results of 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)
Density(kg/m^3)	90	5.39 a	34.67 a	30.46 a
	300	4.47 b	28.59 b	116.91 b
	505	4.01 c	25.16 c	205.33 c
	740	3.45 d	22.04 d	341.73 d
Wear of cutting edge	sharp	4.29 a	26.67 a	137.98 a
	blunt	4.37 b	28.56 b	209.24 b
Chip thickness a_{av} (mm)	0.02	3.54 a	23.82 a	117.74 a
	0.06	4.17 b	26.50 b	183.76 b
	0.1	5.28 c	32.52 c	219.33 c

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

To better illustrate the relationships analyzed, the results for density are additionally shown in Fig. 3. Trend lines were determined for which equations and coefficients of determination are given. The density-dependent cutting power was characterized by an approximately linear relationship, although a better fit to the results obtained was provided by the power equation. The same was true for the surface roughness parameters. In this case, the logarithmic equations best described the relationships obtained. Figure 3 shows that the lower the density of the wood, the more progressive the increase in roughness.

The effect of blade wear was also significant and for this main factor, for a worn blade, the surface roughness was higher than for a sharp blade. This increase was for R_a about 1% and for R_z about 7%. The cutting power was also higher for the blunted blade than for the sharp blade by about 51.6%. The increase in roughness with increasing tool wear was confirmed by data in the literature (Pinkowski *et al.* 2010; Aguilera *et al.* 2016b).

Similar relationships were obtained for the average chip thickness, for which surface roughness and cutting power increase with increasing thickness. Such a relationship has been confirmed in the literature for beech (Han *et al.* 2004; Piernik *et al.* 2023), blackwood (*Acacia melanoxylon* R. Br.) (Aguilera and Zamora 2009), poplar (*Populus tremula* L.) (Barcık *et al.* 2009) and MDF (Davim *et al.* 2009; Sütçü and Karagöz 2012). For the parameter R_a , the increase was about 49% between the extremes of chip thickness, while an increase of about 36% was obtained for R_z . An increase in average chip thickness from 0.02 to 0.1 mm resulted in an increase in cutting power of approximately 86%.

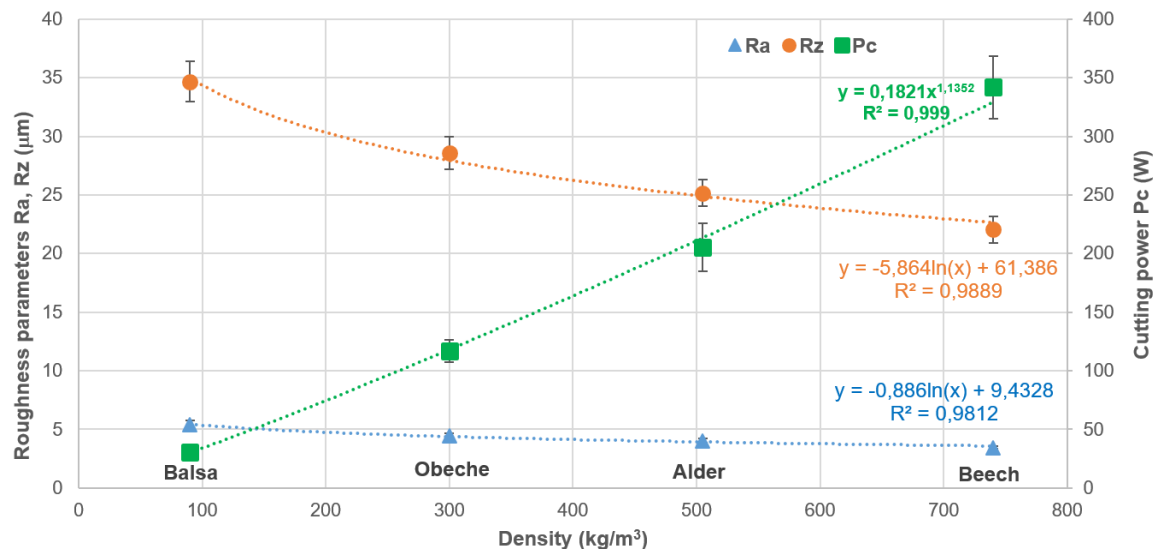


Fig. 3. Changes in surface roughness and cutting force as a function of density

Double Interactions

Table 5 shows the results for surface roughness and cutting power as a double interaction between density and blade wear. In general, a density-dependent effect of wear occurred for surface roughness for all densities except obeche wood for the parameter R_a . For balsa wood, a higher roughness was obtained for a sharp blade than for a worn blade, while for higher densities (above 300 kg/m³) the opposite relationship was obtained, *i.e.*, a worn blade resulted in a worse surface quality than a sharp blade, which is confirmed in the literature (Aguilera *et al.* 2016b).

Cutting power was higher for the worn blade than for the sharp blade, but only for densities of 505 kg/m³ and higher. Similar relationships were obtained in other studies (Bendikiene and Keturakis 2017). In contrast, for the densities of obeche wood and balsa, the cutting powers did not differ between the two states of blade wear.

Table 5. Results of R_a , R_z , and P_c as a Function of the Double Interaction between Density and Wear of Cutting Edge

Density (kg/m ³)	Wear of Cutting Edge	R_a (µm)	R_z (µm)	P_c (W)
90	sharp	6.02 a	36.94 a	32.14 a
	blunt	4.76 b	32.39 b	28.78 a
300	sharp	4.47 c	27.86 ef	118.71 b
	blunt	4.48 c	29.32 cd	115.11 b
505	sharp	3.68 d	23.10 d	159.11 c
	blunt	4.35 c	27.21 ef	251.55 d
740	sharp	3.01 e	18.78 b	241.94 e
	blunt	3.89 f	25.31 df	441.52 f

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

Table 6 shows the results of roughness and cutting power as a function of density and chip thickness. Within a given density, there was an increase in surface roughness as the average chip thickness increased, which is consistent with the results obtained in

previous studies (Piernik *et al.* 2023). For the parameter R_a , there was such a relationship for all cases and all averages differed from each other. Between the extremes of chip thickness, for densities of 90, 300, 505, 740 kg/m³ an increase in R_a values of 72%, 53%, 37% and 20% respectively was obtained. Therefore, it can be seen that the increase in R_a was greatest for the lowest density and decreases with increasing wood density. For the parameter R_z , there was also an increase in the value of this parameter with increasing chip thickness, but most cases these values were not statistically different from each other.

The cutting power for a given wood species increased with increasing chip thickness. Such a relationship has also been shown in other studies (Guo *et al.* 2015; Piernik *et al.* 2023). Between the extreme values of chip thickness, the increase was 530%, 150%, 139% and 39% for densities of 90, 300, 505, 740 kg/m³, respectively. It can be seen that the denser the wood, the smaller the increase in chip thickness causes the smaller increase in cutting power.

Table 6. Results of R_a , R_z , and P_c as a Function of the Double Interaction between Density and Chip Thickness

Density (kg/m ³)	Chip Thickness (mm)	R_a (μm)	R_z (μm)	P_c (W)
90	0.02	4.03 c	28.59 cde	7.48 b
	0.06	5.20 g	32.94 ef	36.71 c
	0.1	6.94 i	42.46 g	47.18 d
300	0.02	3.62 a	24.16 abc	62.60 e
	0.06	4.25 e	26.74 bcd	131.63 g
	0.1	5.54 h	34.88 f	156.50 h
505	0.02	3.38 b	21.47 a	118.02 f
	0.06	3.79 a	24.70 abcd	216.56 i
	0.1	4.87 f	29.31 de	281.41 a
740	0.02	3.14 c	21.07 a	282.86 a
	0.06	3.44 b	21.62 a	350.13 j
	0.1	3.77 a	23.43 ab	392.20 k

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

Table 7 shows the results of roughness and cutting power as a function of chip thickness and blade wear condition. For chip thicknesses of 0.02 mm and 0.06 mm, a worn blade resulted in a worse surface quality, *i.e.*, an increase in the R_a parameter of 5% and 7%, respectively.

Table 7. Results of R_a , R_z , and P_c as a Function of the Double Interaction between Chip Thickness and Wear of Cutting Edge

Chip thickness (mm)	Wear of Cutting Edge	R_a (μm)	R_z (μm)	P_c (W)
0.02	sharp	3.45 a	22.28 ab	82.38 b
	blunt	3.63 b	25.37 ab	153.09 a
0.06	sharp	4.03 c	25.04 ab	151.35 a
	blunt	4.31 d	27.96 b	216.16 d
0.1	sharp	5.40 f	32.69 c	180.19 c
	blunt	5.16 e	32.35 c	258.46 e

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

For a chip thickness of 0.1 mm, the opposite relationship was observed, with a decrease in the R_a parameter of about 5%. This was an exception among the effects obtained, resulting from large scatterings, *i.e.*, differences in the R_a parameter between wood species, which were not considered in the double interaction analysis. For the R_z parameter, no differences were recorded for different blade wear within the same chip thickness. For cutting power, an increase in value was obtained at each chip thickness for the blunted blade and was 86%, 43%, and 43% for chip thicknesses of 0.02, 0.06, and 0.1 mm, respectively.

All Factors

Table 8 shows the results of roughness and cutting power as a function of all the factors analyzed, namely density, chip thickness and blade wear condition. Differences only occurred for the parameter R_a of the surface roughness and for the cutting power. Furthermore, to better illustrate the relationships, the results are also shown in Figs. 4 and 5. When analyzing the effect of blade wear on surface roughness for a given density and chip thickness, it can be seen that there were differences in the average values for all but one case, namely for a density of 300 kg/m³ and a chip thickness of 0.06 mm. For wood densities of 505 kg/m³ and 740 kg/m³, a blunted blade resulted in poorer surface quality, with the R_a increases at 505 kg/m³ being 10.6%, 27.6% and 17.4% for chip thicknesses of 0.02, 0.06, and 0.1 mm, respectively. For a density of 740 kg/m³, the increase in R_a was 21.9%, 22.7% and 42.4% for chip thicknesses of 0.02, 0.06, and 0.1 mm, respectively. The increase in surface roughness with blade wear was confirmed by other authors (Aguilera *et al.* 2016b; Pinkowski *et al.* 2010). However, the authors showed that once a certain wear is reached, there is a reduction in surface roughness.

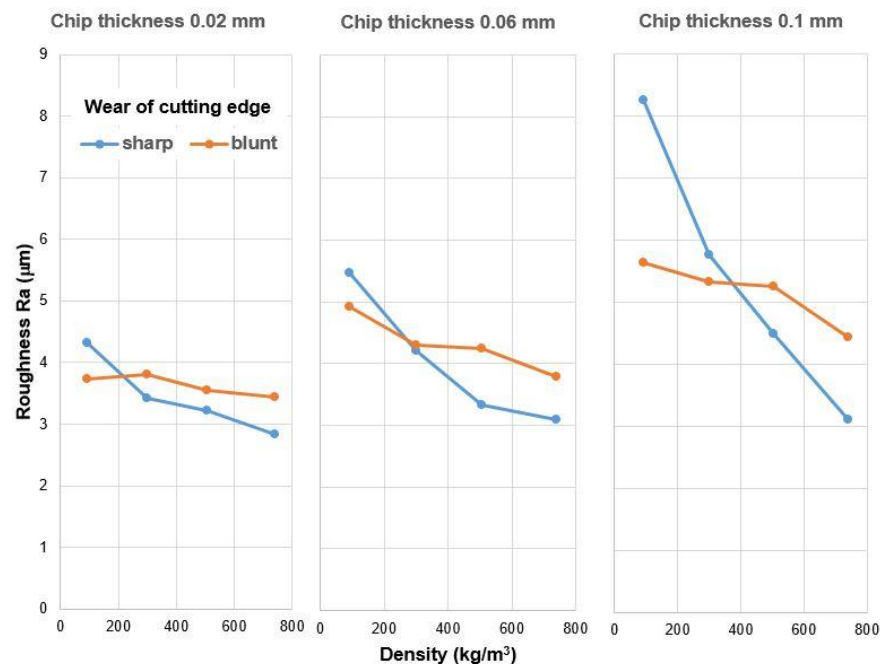
For a density of 300 kg/m³, the effect of blade wear is dependent on the chip thickness. For the smallest chip thickness of 0.02 mm, a blunted blade resulted in an increase in R_a of about 11.7 %, for a chip thickness of 0.06 mm there was no difference and for the largest chip thickness of 0.1 mm a sharp blade resulted in a deterioration in surface roughness of about 17.3%

For the lowest density of 90 kg/m³, the effect of tool wear was the opposite of that for alder and beech wood, *i.e.*, a higher surface roughness was obtained for the surface machined with a sharp blade. This is most evident for a chip thickness of 0.1 mm, at which an increase in R_a values of approximately 68% was obtained between the blunted and sharp knife. This relationship could be considered illogical, *i.e.* different than for other types of wood. This particular case of relationship could perhaps be explained by the relatively high strength of balsa wood in relation to its low density or by the thermal effect of a blunt blade on the wood surface. There is a lack of studies in the literature in such a range of wood densities. However, it is possible to find one in which better surface roughness was obtained after treatment with a blunted knife (Koleda *et al.* 2019). Those authors hypothesized that such changes could be caused by a change in the chemical composition of the wood due to the heat generated during the machining process. Lignin, as the building block of wood, is melted and the intercellular spaces are filled and the surface is plasticized, but at the same time they pointed out that this phenomenon has not been thoroughly investigated and requires further extended research.

Table 8. Results of R_a and P_c as a Function of the Triple Interaction between Density, Wear of Cutting Edge, and Chip Thickness

Density (kg/m ³)	Wear of Cutting Edge	Chip Thickness (mm)	R_a (μm)	P_c (W)
90	sharp	0.02	4.33 f	8.35 a
		0.06	5.47 hi	37.81 bc
		0.1	8.26 k	50.26 d
	blunt	0.02	3.73 e	6.62 a
		0.06	4.93 g	35.61 b
		0.1	5.63 ij	44.11 cd
300	sharp	0.02	3.42 cd	61.51 e
		0.06	4.21 f	138.21 h
		0.1	5.77 j	156.42 i
	blunt	0.02	3.82 e	63.69 e
		0.06	4.30 f	125.04 g
		0.1	5.32 hi	156.59 i
505	sharp	0.02	3.21 bc	93.92 f
		0.06	3.33 bcd	173.42 k
		0.1	4.48 f	210.00 l
	blunt	0.02	3.55 de	142.11 h
		0.06	4.25 f	259.70 m
		0.1	5.26 hi	352.83 o
740	sharp	0.02	2.83 a	165.75 j
		0.06	3.09 b	255.96 m
		0.1	3.11 b	304.10 n
	blunt	0.02	3.45 cd	399.96 p
		0.06	3.79 e	444.31 q
		0.1	4.43 f	480.30 r

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

**Fig. 4.** Changes in the R_a parameter depending on all factors, i.e., density, cutting edge wear and chip thickness

Factors Affecting Cutting Power

When analyzing the effect of blade wear on cutting power for a given density and chip thickness, it can be seen that at low densities (90 and 300 kg/m³) there were no differences in cutting power for all chip thicknesses. As the density increased, the cutting power values showed greater differences. For a density of 505 kg/m³, the increase was 51.3%, 49.7%, and 68% for chip thicknesses of 0.02, 0.06, and 0.1 mm, respectively. In contrast, for the highest density of 740 kg/m³, the increases were 41.3%, 73.6%, and 57.9% for chip thicknesses of 0.02, 0.06, and 0.1 mm, respectively. A similar relationship was confirmed in other studies (Curti *et al.* 2021).

When analyzing the effect of chip thickness and wood density on cutting power, an increase in cutting power can be observed with both an increase in density and an increase in chip thickness. Similar relationships can be found in the literature (Guo *et al.* 2015; Atanasov and Kovatchev 2019; Piernik *et al.* 2023).

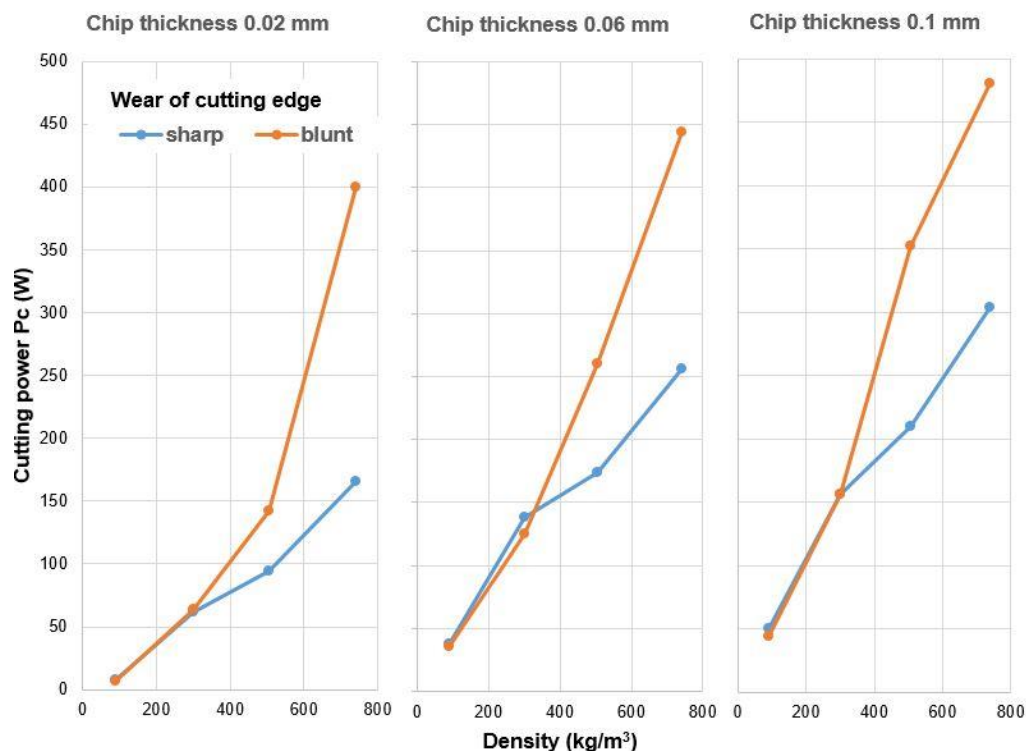


Fig. 5. Changes in the cutting power P_c depending on all factors, *i.e.*, density, cutting edge wear and chip thickness

CONCLUSIONS

1. Wood density, chip thickness, and tool wear had significant effects on both the surface roughness obtained after milling and the cutting power consumed during machining.
2. With increasing wood density, the values of roughness parameters R_a and R_z decreased. The lower the wood density, the more progressive the increase in surface roughness was, which was especially visible for wood with the lowest density. The cutting power increased progressively with increasing wood density.

3. Blade wear and chip thickness, considered as main factors, showed a negative effect on both surface roughness and cutting power, *i.e.*, an increase in the value of the main factor resulted in an increase in the values of the measured parameters R_a , R_z , and P_c .
4. Considering the interactions between all the factors studied, it was shown that for the lowest-density wood (balsa), better surface quality (lower roughness) was observed when cutting with a blunt blade compared to a sharp blade, while for higher-density woods (alder and beech), an inverse relationship was observed, *i.e.*, a blunt blade caused an increase in surface roughness. The relationship obtained for balsa wood requires further research to explain this illogical case. For obeche wood, the surface roughness was dependent on the chip thickness. For the smallest chip thickness, better surface quality for this species was obtained for the sharp blade, for a chip thickness of 0.06 mm no difference was observed and for the largest chip thickness, better surface quality was obtained for the blunt blade.
5. Cutting power considered in interactions between all analyzed factors showed differences depending on the blade wear only for densities of 505 and 740 kg/m³. For low-density wood (balsa and obeche), no differences in cutting power were shown depending on the blade condition. However, the effect of average chip thickness and wood density on cutting power was noted. It was shown that both an increase in wood density and chip thickness resulted in an increase in cutting power.

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