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EFFECTS OF CUTTING PARAMETERS AND GRAIN DIRECTION ON SURFACE QUALITY OF THREE WOOD SPECIES OBTAINED BY CNC MILLING

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Abstract: *Computer Numerical Control (CNC) machines are increasingly popular in the production of furniture and wood products, because they combine high processing quality with short production time. The effective use of CNC machines depends on the processing parameters, which also affects the quality of the processed surface. The aim of this study was to determine the effect of feed rate, cutting direction, and grain direction on the surface roughness of various types of wood. Three European wood species (oak, beech, fir) were cut with a spindle speed of 16,000 rpm and two different feed rates (5,000 and 10,000 mm/min) using end mill tools on the CNC machine. The milling was performed in two cutting directions (radial and tangential) and two grain orientations (0° and 90°). An analysis of variance (ANOVA) was performed to evaluate the impact of the cutting parameters. The surface roughness measurements were taken, and two surface roughness parameters (Ra and Rz) were measured to determine the surface quality of the wood. According to the results of this study, the lowest surface roughness values, milling with the same processing parameters, occurred for oak wood, while the highest values occurred for fir.*

Key words: *wood, CNC milling, surface roughness, radial, tangential, grain direction, feed rates.*

1. Introduction

Wood is one of the most important raw materials which has been used since ancient times for the manufacture of different products that people use every day and for the construction of various objects. Nowadays, wood is indispensable

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in the human environment due to its esthetic and technological properties and because it is a renewable raw material. To be incorporated into different products, wood must be processed by various forms of mechanical processing and brought to an appropriate state. Today, numerous furniture factories are most often oriented towards producing small series of designed furniture of the highest quality. This kind of furniture production requires top technology such as computer numerical control machines (CNC).

CNC machines combine high processing quality with short production time. The effective use of CNC machines depends on the processing parameters, which also affect the quality of the processed surface [15]. When milling wood, due to the interaction of tools and wood, different forms of roughness occur on the surface, but roughness should be reduced to a minimum in furniture. The surface quality of wood materials is an important criterion, especially for finishing and surface lamination applications and choosing the machining method in the furniture industry [10, 16]. For a customer buying a final product, surface quality can be considered one of the most important factors determining the willingness to pay for the product [9].

The roughness of the wooden surface depends on many factors and can be related both to the properties of the wood and to the processing conditions [5, 8]. Wood surface roughness is a crucial indicator of the quality of the CNC processing parameter [6], and it is affected by cutting speed, depth of cut, tool conditions, and work piece [1]. Feed speed has an important influence on the roughness of the processed surface [7]. Important properties of wood are the wood species, its density, moisture content, and anatomical structure [20]. In fact, the final surface quality is influenced by many “external” factors, such as the tool settings or machine settings, and by some “internal” factors of the wood [3]. Wood is an anisotropic material with three directions of different physical properties, radial, tangential, and longitudinal. If processing with the same machine parameters, different roughness will occur in different wood sections because of varying grain directions. Accordingly, the roughness of wood depends on the wood section and the measurement direction. In general, radial sections have higher roughness than tangential sections due to interlocked fibres in the wood [12].

Milling is the primary operation to be performed with CNC woodworking machines [2, 10]. For the milling of beech wood with CNC, it has been found that the cutting angle, feed rate, and fibre direction affect the surface roughness, but cutting width does not have any impact on the surface roughness [13]. It has been observed that the cutting depth and the cutting angle do not have impacts on surface roughness, but the spindle speed and the feed rate do [15]. The general research indicates that the roughness values would reduce when operating with lower feed rate and higher spindle speed [18].

The surface roughness of wood and engineered wood materials is usually determined by methods based on surface-measuring equipment, either by contact or non-contact [4]. Generally, average roughness (R_a), maximum height of profiles (R_t) and root mean square deviation (R_q) are the roughness parameters used for the evaluation of the processed surface quality [19].

The aim of this study was to determine the effect of feed rate, cutting direction, and grain direction on the R_a and R_z roughness values after the CNC milling of three European wood species: oak (*Quercus robur L.*), beech (*Fagus sylvatica L.*), and fir (*Abies alba*).

2. Materials and Methods

Three wood species, i.e. oak (*Quercus robur L.*), beech (*Fagus sylvatica L.*), and fir (*Abies alba*), were studied because they are widely used in woodwork and furniture industry in Europe. The dimension of the specimens in the sample was 400 x 100 x 15 mm. The moisture content of the samples was measured by the gravimetric method in accordance with the procedures described in ISO 13061-1 [11]. The mean values of the moisture content of the wood specimens were: oak 11.9%, beech 12.0%, and fir 13.2%. Milling operations were performed parallel to the grain direction, and perpendicular to the grain. Milling was carried out for the tangential and radial surfaces as illustrated in Figure 1. Two feed rates (5 m/min and 10 m/min) were chosen for CNC milling. The rotation speed of the spindle was 16,000 rpm. The CNC milling of the samples and the experimental specimens obtained after the process are shown in Figure 2. After milling, the samples were cut to the size of 100 x 40 x 15 mm (Figure 2). A total of 360 experimental elements were produced (15 samples x 3 wood species x 2 wood sections x 2 grain directions x 2 feed rates) and surface roughness was measured.

Before CNC milling, the samples were conditioned at 20 ± 2°C and 65 ± 5% relative humidity (*RH*).

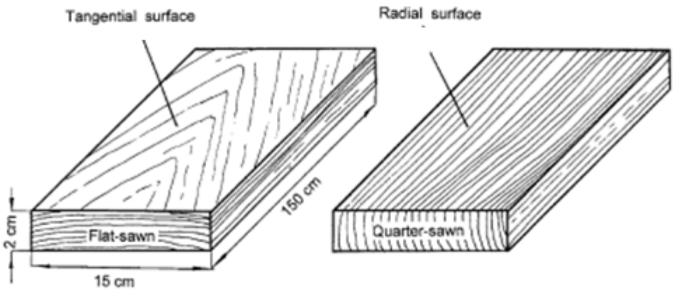


Fig. 1. *Schematic presentation of the specimens of tangential and radial section with flat-sawn and quarter-sawn direction and the dimension [14]*

Fig. 2. *Fir samples after processing, and final samples of oak, beech, and fir*

The samples were milled with a 4 axis CNC router (Figure 3) with Syntec 6MB control system, 8 kw spindle power, and a maximum spindle speed of 24,000 rpm, in the laboratory at the Faculty of Mechanical Engineering, University Sarajevo, Bosnia-Herzegovina. The VetricAspire program created the code files for the control of the CNC machines. The milling depth was 5 mm. A double-edged flat milling cutter with a diameter of 16 mm was used (Figure 3). The tool was mounted using the ISO30 ER32 tool holder. The milled elements were mounted on the table using the vacuum system.

Fig. 3. *CNC machine and cutting tool*

Surface quality measurements were performed using a Surftest SJ-201 instrument manufactured by Mitutoyo (Kawasaki, Japan), shown in Figure 4. The width of the measurement range of the instrument was 350 µm (-200 µm to +150 µm), equipped with an inductive pick-up diamond stylus tip. The measuring speed was 0.25 mm s^{-1} and the measuring length was 5 mm. Calibration of the instrument was performed before starting the measurements, with a reference sample. Two roughness variables, R_a (absolute arithmetic mean) and R_z (arithmetic mean deviation of the profile), were measured to evaluate the surface roughness of the sample.

Fig. 4. *Mitutoyo Surftest SJ-201, reference sample, and procedure of measurement*

Three different surfaces were formed on the milled material, as shown in Figure 2. On one surface we had climb cutting, on the opposite side conventional cutting, and face milling operating was applied on the bottom surface of the groove.

In this study, the surface roughness measurements were done on the bottom surface on the groove. Eight different measurements were taken on each sample, respectively two measurements on each of the four profiles.

Statistical analysis was performed using the JASP software. One-way analysis of variance (ANOVA) was done for the statistical evaluation of differences in the surface roughness parameters (R_a and R_z) depending on the feed rate, wood section (radial/tangential), and grain direction (parallel/perpendicular). An appropriate pairwise comparison Tukey's test was performed if the omnibus test proved statistical significance. Tukey's test was used to compare the mean values of the variance sources.

Descriptive statistics were also used to display the results. Graphic displays were made using column and line charts. The results were shown with a 95% family-wise confidence level.

3. Results and Discussion

The results of the surface roughness values of the CNC milled samples are presented in Tables 1 and 2.

Average roughness (R_a) of the different wood species Table 1

Wood species	Feed rate 5 m/min				Feed rate 10 m/min			
	Roughness R_a [µm]				Roughness R_a [µm]			
	perpendicular to the grain		parallel to the grain		perpendicular to the grain		parallel to the grain	
	on radial	on tangential	on radial	on tangential	on radial	on tangential	on radial	on tangential
Oak	3.92	5.47	1.60	2.11	5.83	6.09	2.82	3.55
Beech	5.09	5.01	2.12	1.92	6.30	6.28	3.36	2.72
Fir	6.52	5.86	3.00	3.85	7.54	6.51	4.20	4.83

Average roughness (R_z) of the different wood species Table 2

Wood species	Feed rate 5 m/min				Feed rate 10 m/min			
	Roughness R_z [µm]				Roughness R_z [µm]			
	perpendicular to the grain		parallel the grain		perpendicular to the grain		parallel the grain	
	on radial	on tangential	on radial	on tangential	on radial	on tangential	on radial	on tangential
Oak	24.46	35.42	10.68	12.98	37.38	37.36	17.55	19.84
Beech	31.36	32.28	13.45	12.77	37.38	37.80	21.04	17.09
Fir	44.89	34.64	17.15	23.67	44.86	40.23	24.66	27.89

The tables show the measured values of R_a and R_z depending on the cutting angle in relation to the position of the fibres (parallel and perpendicular), the wood section (radial and tangential), and the feed rate (5 and 10 m/min). It can be seen that when the feed rate increases, the values of R_a and R_z also increase, i.e. the surface roughness increases (Figure 5).

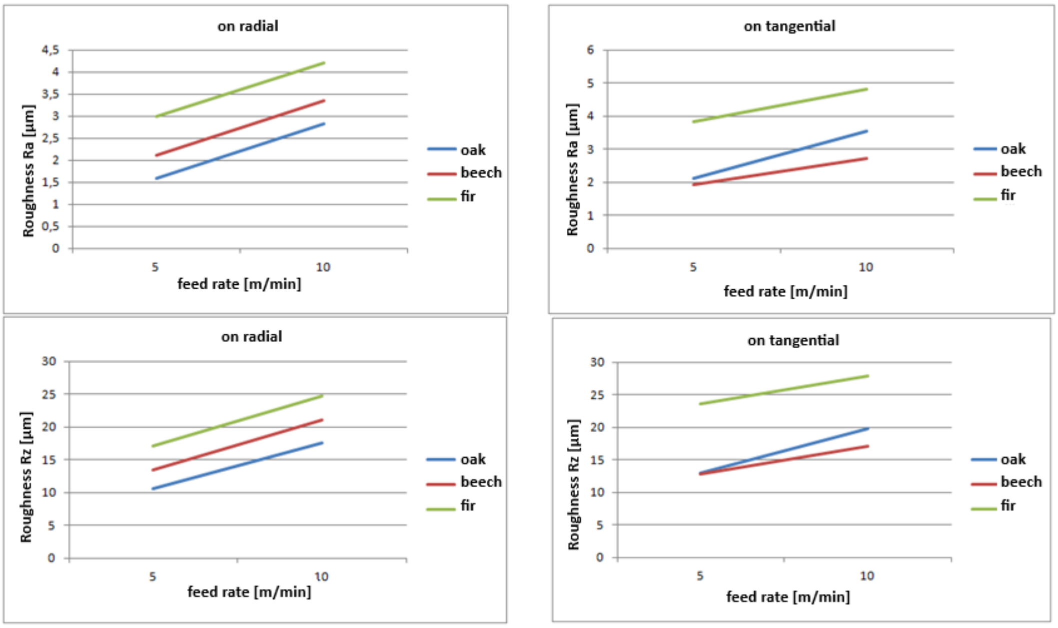


Fig. 5. *Surface roughness for oak, beech, and fir processed with different parameters parallel to the grain*

The lowest surface roughness in terms of the radial section for the wood milled at an angle of 0° (parallel to the grain) was obtained for oak wood, while the highest roughness values were obtained for fir wood. In the tangential section, the lowest roughness values were obtained for beech wood, while also in this case fir wood had the highest roughness values. For milling parallel to the grain in oak and fir wood, the R_a and R_z values were higher for the tangential section than for the radial section. In the case of beech wood, the opposite results occurred, i.e. the radial section had a higher roughness compared to the tangential section (Figure 6). The same results were obtained in an earlier study [13].

According to one-way ANOVA (Table 3), there was a significant difference in the surface roughness R_a obtained during milling parallel to the grain between the tangential and radial sections. Only in the case of beech wood milled with a feed rate of 5 m/min, there was no significant difference. The results of ANOVA and Tukey's test for oak, beech, and fir wood at different feed rates for milling parallel to the grain are shown in Figure 7 and Table 4. The obtained results were significantly different, except in two cases. The first one with results obtained for beech and oak wood in a tangential section milled parallel to the grain at a feed rate of 5 m/min, and the second with data obtained for beech and oak wood on a radial section, milled parallel to the grain at a feed rate of 10 m/min, did not differ significantly.

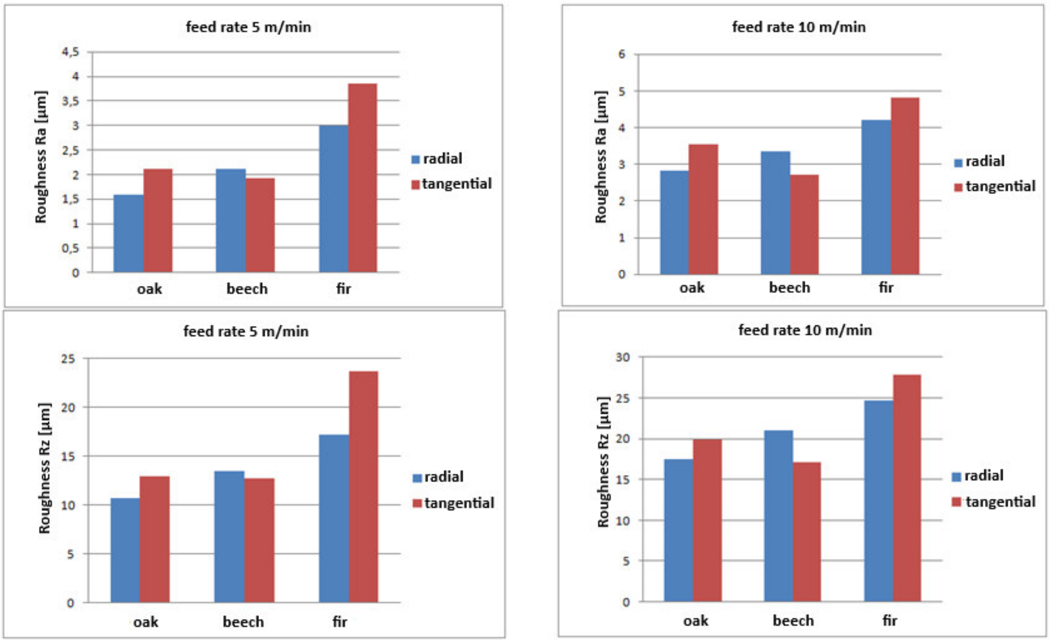
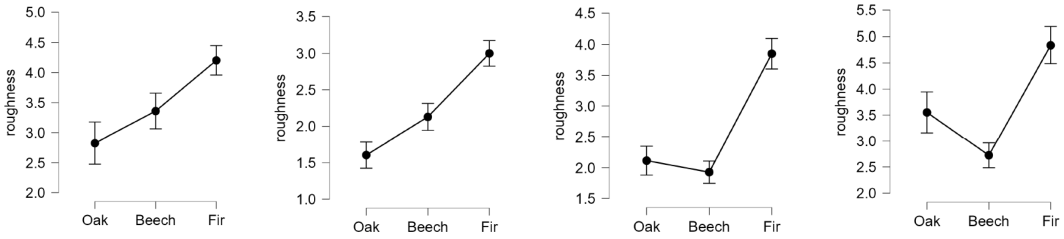


Fig. 6. *Surface roughness (R_a and R_z) for radial and tangential section for processing parallel to the grain*

Table 3

Results of ANOVA and Tukey's test on surface roughness R_a for radial and tangential section (parallel to the grain)

Wood	Surface roughness R_a [µm]									
	Feed rate 5m/min					Feed rate 10 m/min				
	Sum of Squares	df	Mean Square	F	p	Sum of Squares	df	Mean Square	F	p
Oak	4.92	1	4.92	12.29	< .001	9.89	1	9.89	7.84	0.007
Beech	0.87	1	0.87	2.46	0.12	7.98	1	7.98	10.58	0.002
Fir	25.08	1	25.08	31.69	< .001	13.54	1	13.54	8.98	0.003



a. b. c. d.

Fig. 7. *Box plots of surface roughness R_a parallel to the grain by wood section and feed rate: a. radial (5 m/min); b. radial (10 m/min); c. tangential (5 m/min); d. tangential (10 m/min)*

Table 4

Results of Tukey's test for beech, oak, and fir milled with different feed rates (parallel to the grain)

		Mean	Lower	Upper	SE	t	p
Radial section, feed speed 5 m/min							
Oak	Beech	-0.523	-0.869	-0.177	0.146	-3.582	0.001
	Fir	-1.394	-1.706	-1.083	0.132	-10.596	< .001
Beech	Fir	-0.871	-1.174	-0.569	0.128	-6.831	< .001
Tangential section, feed speed 5 m/min							
		Mean	Lower	Upper	SE	t	p
Oak	Beech	0.187	-0.259	0.634	0.188	0.995	0.581
	Fir	-1.735	-2.142	-1.329	0.172	-10.108	< .001
Beech	Fir	-1.923	-2.310	-1.535	0.164	-11.743	< .001
Radial section, feed speed 10 m/min							
		Mean	Lower	Upper	SE	t	p
Oak	Beech	-0.534	-1.077	0.009	0.229	-2.329	0.055
	Fir	-1.379	-1.869	-0.889	0.207	-6.656	< .001
Beech	Fir	-0.845	-1.313	-0.377	0.198	-4.274	< .001
Tangential section, feed speed 10 m/min							
		Mean	Lower	Upper	SE	t	p
Oak	Beech	0.827	0.164	1.490	0.280	2.956	0.010
	Fir	-1.283	-1.868	-0.698	0.247	-5.196	< .001
Beech	Fir	-2.110	-2.700	-1.520	0.249	-8.472	< .001

Previous studies indicated that the surface roughness increases with the increasing angle of milling [9]. The roughness values of R_a and R_z were higher for milling wood at an angle of 90° compared to milling at an angle of 0°.

Tables 1 and 2 show that processing wood perpendicular to the grain results in increased roughness values of R_a and R_z compared to processing wood parallel to the grain. Figure 8 shows that the roughness values of R_a and R_z increase with increasing feed rate for wood species in this investigation. Many researchers have concluded that feed rate is an effective factor in wood processing, and that the lowest roughness values are obtained at lower feed rates [7, 8, 10]. The highest values of surface roughness occurred for fir wood, while the lowest values were obtained for oak wood. During processing at an angle of 90°, the differences between the roughness of the wood in tangential and radial sections are smaller than when processing at an angle of 0° (Figure 9). During processing perpendicular to the grain, the wood fibres are cut at the same angle regardless of the section, so values of R_a are more uniform. When processing oak at an angle of 90° with the tangential section, higher values are obtained compared to the radial section, like the processing at an angle of 0°. In the case of beech wood, the roughness values for the radial section were higher than for the tangential section, similar to processing at an angle of 0°. In fir wood, the values of the R_a and R_z were higher on the radial section compared to the tangential section, and in this case the opposite results were obtained compared to processing wood parallel to the grain.

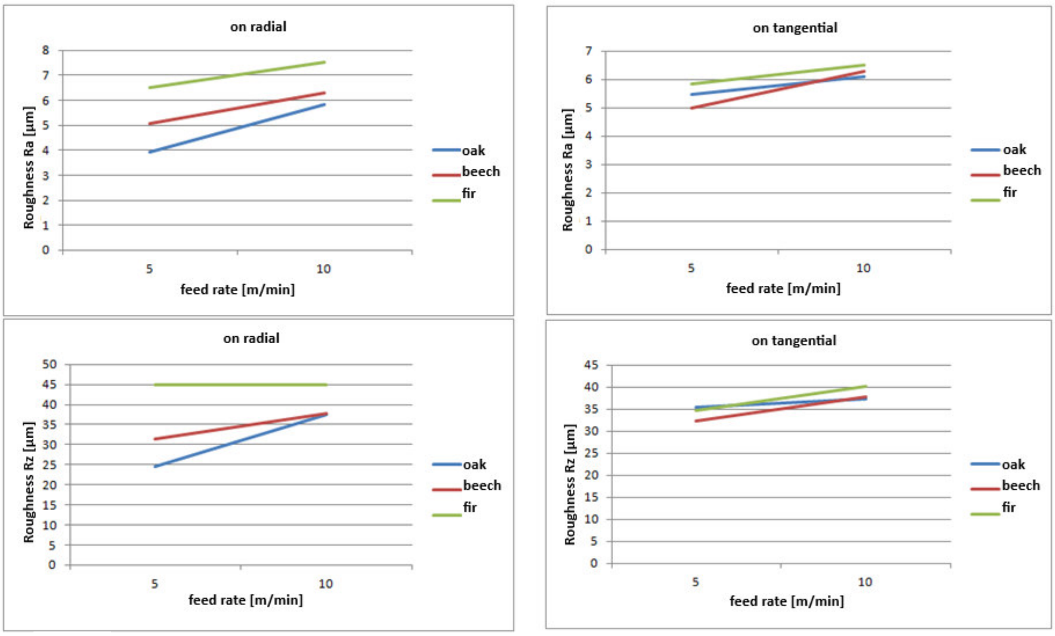


Fig. 8. *Surface roughness (R_a and R_z) for oak, beech, and fir processed with different parameters perpendicular to the grain*

One-way analysis of variance (ANOVA) and Tukey's test were performed for the statistical evaluation of the differences in the surface roughness (R_a) perpendicular to the grain (Table 5).

Table 5

Results of ANOVA and Tukey's test on surface roughness for radial and tangential section (perpendicular to the grain)

Wood	Surface roughness R_a [µm]									
	Feed rate 5m/min					Feed rate 10 m/min				
	Sum of Squares	df	Mean Square	F	p	Sum of Squares	df	Mean Square	F	p
Oak	26.948	1	26.948	12.551	< .001	0.815	1	0.815	0.227	0.601
Beech	0,0007	1	0,0007	0.0006	0.980	0.003	1	0.003	0.002	0.966
Fir	9.534	1	9.534	6.005	0.016	19.517	1	19.517	8.968	0.003

There was a significant difference in roughness parameters between the radial and tangential sections for oak and fir wood milled with a feed rate of 5 m/min, and fir wood milled with a feed rate of 10 m/min. In other cases, there were no significant differences between the radial and tangential section. Also, a previous investigation conducted by Kilica et al. [14] shows that there is no significant difference between the surface roughness characteristics of the tangential and radial machined surfaces of beech wood.

There was no significant difference in the surface roughness R_a in the tangential section between the wood species regardless of feed rate (Figure 10 and Table 6).

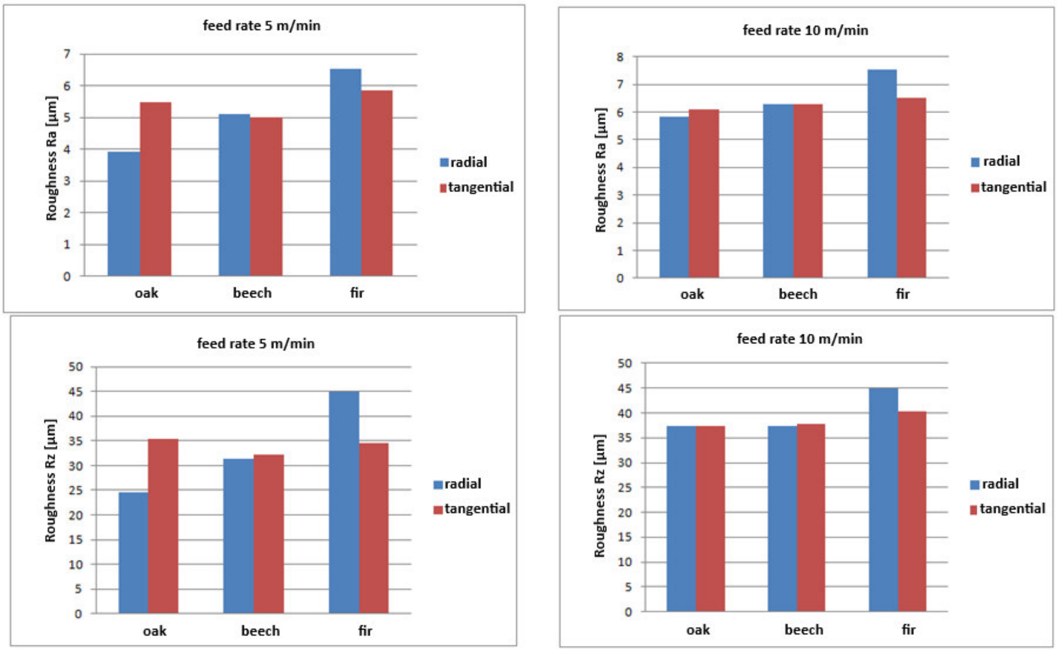


Fig. 9. *Surface roughness (R_a and R_z) for radial and tangential section for processing perpendicular to the grain*

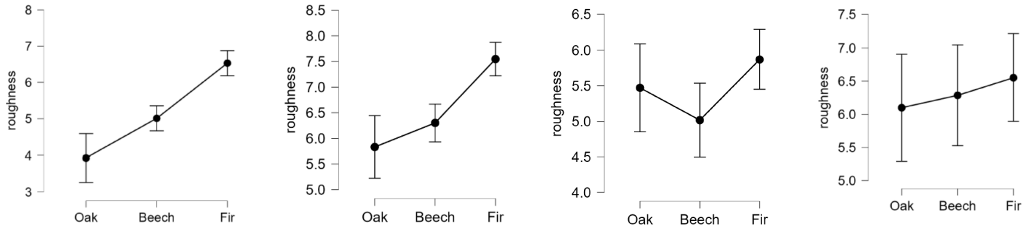


Fig. 10. *Box-plots of results of surface roughness perpendicular to the grain by wood section and feed rate: a. radial (5 m/min); b. radial (10 m/min); c. tangential (5 m/min); d. tangential (10 m/min)*

Table 6

Tukey's test for beech, oak, and fir milled with different feed rates (perpendicular to the grain)

		Mean	Lower	Upper	SE	t	p
Radial section, feed speed 5 m/min							
		Mean	Lower	Upper	SE	t	p
Oak	Beech	-1.086	-1.880	-0.291	0.334	-3.246	0.004
	Fir	-2.605	-3.355	-1.854	0.316	-8.248	< .001
Beech	Fir	-1.519	-2.147	-0.891	0.264	-5.746	< .001
Tangential section, feed speed 5 m/min							
		Mean	Lower	Upper	SE	t	p
Oak	Beech	0.455	-0.497	1.407	0.398	1.143	0.491
	Fir	-0.398	-1.201	0.406	0.336	-1.183	0.467
Beech	Fir	-0.853	-1.722	0.017	0.364	-2.345	0.056
Radial section, feed speed 10 m/min							
		Mean	Lower	Upper	SE	t	p
Oak	Beech	-0.469	-1.263	0.324	0.335	-1.402	0.343
	Fir	-1.714	-2.414	-1.014	0.296	-5.795	< .001
Beech	Fir	-1.245	-1.920	-0.569	0.285	-4.361	< .001
Tangential section, feed speed 10 m/min							
		Mean	Lower	Upper	SE	t	p
Oak	Beech	-0.187	-1.498	1.123	0.545	-0.343	0.937
	Fir	-0.452	-1.635	0.731	0.492	-0.919	0.630
Beech	Fir	-0.265	-1.448	0.918	0.492	-0.539	0.853

In the radial section there was a significant difference in surface roughness R_a in almost all cases between the compared wood species. Only in the case of a feed rate of 10 m/min, there was no significant difference in results between oak and beech wood.

4. Conclusion

In this work, the effect of various machining parameters of beech, oak, and fir wood on their surface roughness characteristics was investigated. Based on the results of this study, surface roughness values in wood processing depend on several factors. Wood species, feed rate, wood section, and grain direction are factors that are effective on the surface quality. Results showed that the surface quality decreases linearly as the feed speed rises.

The higher roughness values were obtained by milling softwood compared to hardwood.

By milling perpendicular to the grain, higher roughness values were obtained compared to milling parallel to the grain, and the increase in the radial section was about 45-60%. In the tangential section, surface values of R_a and R_z also increased by 25-65% when milling perpendicular to the grain.

The best results in terms of surface roughness were obtained by using oak wood with radial surface during milling parallel to the grain, and the more inferior results were obtained by using fir wood with tangential surface during milling perpendicular to the grain.

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