Effect of Sharpness Angle and Feeding Speed on the Surface Roughness during Milling of Various Wood Species

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The article presents research on the effect of the sharpness angle on the quality of machined surface of native wood species (pine, beech, and black locust) and an exotic species called iroko. Four sharpness angle values were analyzed at 25, 40, 45, and 55°. The experiment was conducted on a bottom-spindle milling machine, with a constant spindle rotational speed (6000 min^{-1}) and four feeding speeds of 3.2, 8.3, 12.5, and 16.7 m/min. The influence of sharpness angle, feeding speed, and wood species on the quality of machined surface of wood was determined. The optimum ranges of the sharpness angle were established with respect to wood surface quality. The surface roughness of the samples decreased with decreasing in the sharpness angle in range of 55° to 40°. The optimal value of the angle was 40°, and the roughness increased with increasing feeding speed. It was found that an increase in wood density decreased surface roughness.

Keywords: Plane milling; Tool angle; Surface quality; Beech; Black locust; Scots pine; Iroko

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INTRODUCTION

The effects of machining of wood and wood-based materials are important factors concerning aesthetic and costs of final products. In mechanical wood processing, the quality of the surface is determined by numerous factors connected with the machined materials, properties, and parameters of machining process.

Surface roughness is a fundamental factor in determining the quality of the machined surface. Roughness parameters are also important data in tool wear analysis (Aguilera *et al.* 2016), reducing the amount of waste (Ugulino and Hernández 2017), coating application (Salca *et al.* 2017), and gluing and analyzing the durability of adhesive joints (Dilik and Hiziroglu 2012; Sogutlu 2017).

Roughness parameters are important indicators of surface quality of wood, and they are analyzed for different machining techniques. Research on the surface roughness of wood materials has been conducted for sawing (Kilic *et al*. 2006; Kılıç 2015; Kminiak and Gaff 2015), milling (Škaljić *et al*. 2009), sanding (Salca and Hiziroglu 2012; Hazir *et al*. 2017; Salca *et al*. 2017), cutting by water (Li *et al*. 2015), plasma treatment (Demirkir *et al*. 2014), and wood densification, including thermal treatment (Bekhta *et al*. 2014; Gáborík *et al*. 2016).

Sanding before the final finishing of surface produces good results (Kilic *et al*. 2006; Salca and Hiziroglu 2012). Mathematical models have been developed to find optimal machining parameters, among others using artificial neutral networks (Tiryaki *et al*. 2014; Hazir *et al*. 2017; Stanojevic *et al.* 2017).

Research to decrease surface roughness of wood and to eliminate the sanding process by selecting the optimal machining parameters, such as feeding speed, cutting speed, rake angle, clearance angle, and depth of cut, has been conducted for wood milling (Kilic *et al*. 2006). This type of research applies also to thermally modified wood (Budakçı *et al.* 2013; Kvietková *et al*. 2015a,b; Pinkowski *et al*. 2016). Sofuoğlu and Kurtoğlu (2015) noted that the surface is comparable with the surface after sanding.

Obtaining low surface roughness of wood is possible by using the appropriate selection of angular parameters of tools, such as rake angle, sharpness angle, and clearance angle. Hernández *et al*. (2001) studied the effect of rake angles on the surface roughness of wood, showing that white spruce (*Picea glauca*) had considerable machining defects after milling using a high feeding speed in the range of tested rake angles. Malkoçoğlu (2007) analyzed the effect of the rake angle and machining parameters on the surface roughness for five wood species; the lowest roughness was observed at an angle of 15°. Vančo *et al.* (2017) confirmed that the lowest roughness of thermally modified pine wood was obtained for a rake angle of 15°. Azemović *et al*. (2014) investigated the effect of three values of rake angle, which amounted to 42°, 35°, and 25°, on the surface roughness of fir wood. The best results were found for the lowest tested values of rake angles. Thus, experimental data on the effect of rake angles on the surface roughness of machined wood clearly confirms the rationality of using low angle values.

In terms of tool edge geometry, the sharpness angle correlating with the clearance angle is an important factor for providing acceptable conditions of the machined surface of wood. Research on impact of sharpness angle on machining effects has been carried out primarily with regard to tool wear. Keturakis and Lisauskas (2010) studied the effect of the sharpness angle of the tools made of high-speed steel HSS on the tool wear described by rounding radius and cutting power. Three values of sharpness angle were studied, which amounted to 40°, 45°, and 50°. The results showed varied wear, primarily depending on feeding per cutter. The lowest wear was observed for the highest tested sharpness angle. Keturakis and Juodeikienė (2007) studied tool wear during the birch wood milling, reporting a decrease in the surface roughness when the rounding radius of the edge and the feeding speed decreased. Kowaluk *et al.* (2009) tested the effect of the sharpness angles with values 25°, 40°, 45°, and 55°, on the wear of tools made of HSS, Cr, and HW during MDF milling, and the lowest wear was observed in the highest value of sharpness angle.

The effect of the sharpness angle on the surface roughness of wood is not clearly understood. Therefore, the aim of this study was to establish the dependency between the value of sharpness angles and quality of machined surfaces of various native and exotic wood species. Data was collected for optimal sharpness angle selection in the milling processes of solid wood.

EXPERIMENTAL

Knives with four values of sharpness angle β were used (Fig. 1). For the β angle name, the sharpness angle was used instead of the cutting angle of the wedge, which is the name appearing in ISO 3002-1 (1982).

The change of sharpness angle β caused a change in the clearance angle α because the rake angle and cutting angle were held constant at 25° and 65°, respectively. Tests included sets of sharpness and clearance angles of 25°/40°, 40°/25°, 45°/20°, and 55°/10°.

The knife dimensions were 50 mm × 30 × mm × 3 mm. All knives consisted of high-speed steel HSS18 (Gopol, Jarocin, Poland). Knives were fixed in a four-blade cutterhead by a clamping system with a wedge strip and tangential directed screws. In the milling processes, one properly and repetitively set knife was used in each operation. The cutterhead was balanced, and the cutting circle diameter D_s was 108 mm.

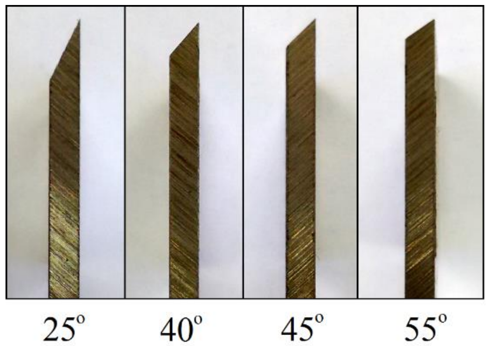

Fig. 1. Knives used in research (view from side perpendicular to main cutting edge)

The milling processes were completed with a Felder F 900 bottom-spindle milling machine (Hall in Tirol, Austria) with an engine power *N* of 5.5 kW and Felder F-38 feed equipment. The milling process is shown in Fig. 2. The spindle rotational speed *n* was 6000 min^{-1}. The four variants of the feeding speed were 3.2, 8.3, 12.5, and 16.7 m/min. The depth of cut was 1 mm.

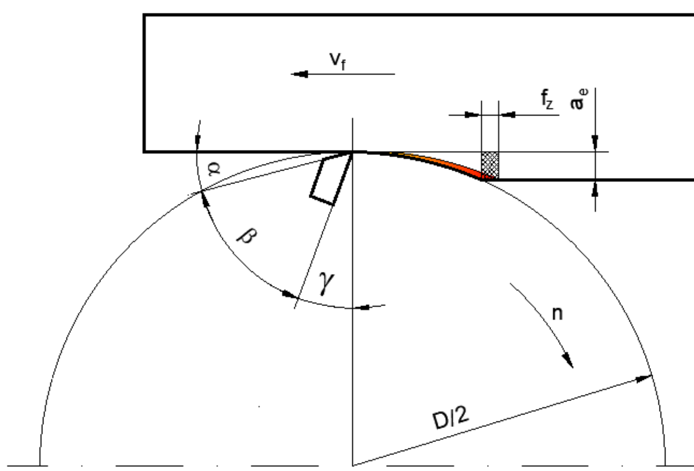

Fig. 2. A scheme of plane milling with conventional cutting. *D* – tool diameter, f_z – feed per tooth (edge), a_e – depth of cut (working engagement), v_f – feed speed, *n* – rotational speed, α – clearance angle, β – sharpness angle (cutting angle od wedge), γ – rake angle

Four wood species were tested, including the native species beech (*Fagus sylvatica* L.), black locust (*Robinia pseudoacacia* L.), and pine (*Pinus sylvestris* L.), and the exotic species iroko (*Milicia excelsa* (Welw.) C.C. Berg). The milling process was completed using samples with dimensions of 1000 mm × 200 mm × 19 mm with a moisture content of 6.5% to 6.9%. The density of samples was measured in accordance with ISO13061-2

(2014).

Surface roughness of the samples was determined using the contact method (Škaljić *et al.* 2009; Kılıç 2015; Thoma *et al.* 2015) and a profilometer ME10 (Carl Zeiss, Jena, Germany) that was equipped with a measuring gauge with a tip radius of 10 µm and apex angle of 90°. The cut-off length was 2.5 mm. Five measurements for each sample were completed in a temperature of 20 ± 2 °C, with a relative air humidity of 65 ± 3%, on samples of 120 mm × 20 mm × 19 mm. Altogether, 320 measurements were completed for all of the experiment variants of the wood species, sharpness angles, and feeding speeds. The surface roughness of the samples was characterized based on the two most frequently used parameters: the arithmetic mean surface roughness (R_a) and the surface roughness depth (R_z). These parameters were measured in accordance with ISO 4287 (1997).

In order to establish dependency between the analyzed factors, an analysis of variance was conducted at a significance level of α = 0.05. Homogeneous groups were identified using the Duncan's test. Statistical analysis was performed in STATISTICA 13.1 software (Statsoft Inc., Tulsa, OK, USA).

RESULTS AND DISCUSSION

Table 1 contains data displaying the density of tested samples. The minimum, maximum, mean values, and standard deviation are presented. The lowest average value of density was observed for pine samples fallowed by iroko, beech, and black locust.

Table 1. Statistical Analysis of Density Values of Samples Used in Tests

Species	Density (kg/m^3)			
	Minimum	Maximum	Arithmetic Mean	Standard Deviation
Pine	439	448	443	3.8
Iroko	496	514	503	7.2
Beech	675	717	697	18.7
Black locust	794	815	805	9.0

Table 2 contains results of the ANOVA tests for surface roughness parameters, including all factors that occurred in this experiment. This analysis showed that at an assumed significance level of α = 0.05, there were statistically significant differences between test samples, depending on the feeding speed, sharpness angle, wood species, and also the interactions between them.

The surface roughness parameters depended on the sharpness angle, as shown in Table 3. The Duncan's test confirmed significant differences between groups. The lowest values of both of the analyzed parameters were observed for the sharpness angle of 40°. For this angle, the average value of R_a was statistically different than for the rest of the knives. In the case of the R_z parameter, the lowest value was observed also for the sharpness angle of 40°, but the obtained values for the knives with a sharpness angle of 40° and 45° were not statistically different. These results are shown in Fig. 3. For increased readability of the data in Fig. 3, the scale range of the R_a parameter was reduced to a quarter of the size of the R_z parameter scale.

Table 2. Analysis of Variance (ANOVA) for Surface Roughness of the Samples

R_a Parameter					
Factor	Degrees of Freedom	Sum of Squares	Mean Squares	Fisher's F-Test	P-value
Intercept	1	4326.189	4326.189	10044.72	0.000000
Feed Speed (a)	3	231.149	77.050	178.90	0.000000
Sharpness Angle (b)	3	100.069	33.356	77.45	0.000000
Wood Species (c)	3	89.713	29.904	69.43	0.000000
a × b	9	10.248	1.139	2.64	0.006065
a × c	9	36.747	4.083	9.48	0.000000
b × c	9	65.029	7.225	16.78	0.000000
a × b × c	27	120.928	4.479	10.40	0.000000
Error	256	110.257	0.431		
Total	319	764.140			
R_z Parameter					
Factor	Degrees of Freedom	Sum of Squares	Mean Squares	Fisher's F-Test	P-value
Intercept	1	182339.1	182339.1	8004.932	0.000000
Feed Speed (a)	3	8205.4	2735.1	120.076	0.000000
Sharpness Angle (b)	3	3744.8	1248.3	54.801	0.000000
Wood Species (c)	3	3921.1	1307.0	57.380	0.000000
a × b	9	594.1	66.0	2.898	0.002784
a × c	9	1510.1	167.8	7.366	0.000000
b × c	9	2055.0	228.3	10.024	0.000000
a × b × c	27	4621.3	171.2	7.514	0.000000
Error	256	5831.3	22.8		
Total	319	30483.1			

Table 3. Average Values of R_a and R_z Parameters of All Tested Species Depending on Sharpness Angle

Sharpness Angle (°)	R_a (μm)	R_z (μm)
25	4.60 ^{c}	29.55 ^{c}
40	3.11 ^{a}	20.59 ^{a}
45	3.40 ^{b}	22.01 ^{ab}
55	3.59 ^{b}	23.34 ^{b}

Note: The letters a, b, and c beside average values indicate homogeneous groups. Different letters indicate statistically significant differences between groups.

The decrease of the sharpness angle from 55° to 40° caused a reduction in the surface roughness of the samples. However, a decrease in the sharpness angle to 25° caused an increase in roughness. Blades with as low value of sharpness angle caused effective grain cutting, but it became less stiff and may have caused vibrations. This may be the reason for higher roughness of the samples.

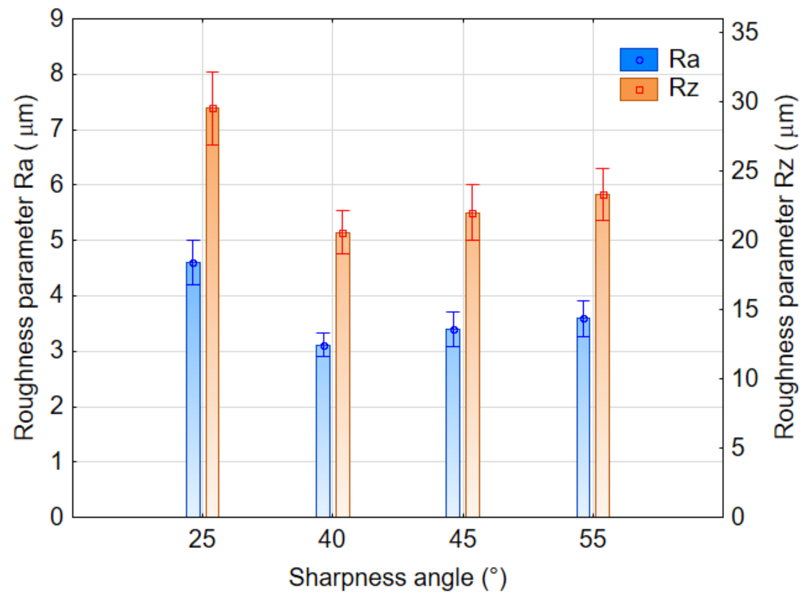

Fig. 3. Influence of sharpness angle on surface roughness parameters of all tested wood species

The surface roughness of each wood species is presented in Table 4. For both roughness parameters R_a and R_z, the lowest values were observed for black locust, which had the highest density of wood. Slightly higher roughness was obtained for beech, while the highest roughness was observed for the lowest density species, thus iroko and pine. While the values of the roughness parameters were significantly different for species characterized by the highest density (beech and black locust), for pine and iroko there were no statistically significant differences. The dependency between surface roughness of the samples and wood density is shown in Fig. 4. The designated trend lines were characterized by high coefficients of determination ($R^2 > 0.93$), which confirmed previous reports that roughness depends considerably on wood density (Csanády *et al*. 2015; Kminiak and Gaff 2015; Keturakis *et al.* 2017). Significant differences between species are caused by wood density and anatomical structure (Magoss and Sitkei 1999).

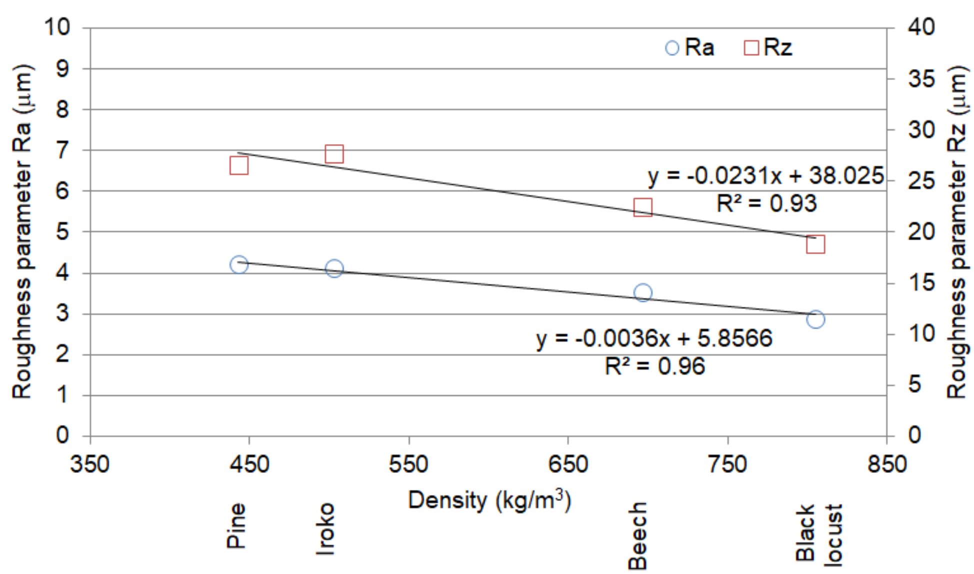

Fig. 4. Influence of wood species and density on surface roughness parameters

Table 4. Average Values of R_a and R_z Depending on Wood Species and Density

Wood species	Density (kg/m³)	R_a (μm)	R_z (μm)
Black locust	805	2.87 [a]	18.84 [a]
Beech	696	3.53 [b]	22.42 [b]
Iroko	503	4.10 [c]	27.65 [c]
Pine	442	4.20 [c]	26.58 [c]

Note: The letters a, b, and c beside average values indicate homogeneous groups. Different letters indicate statistically significant differences between groups.

Table 5 shows the average values of roughness parameters depending on the feeding speed. Duncan's test confirmed statistical differences between all of the analyzed variants of feeding speed for both R_a and R_z parameters. The data shows that with an increase in feeding speed, the surface roughness of the samples increased. This dependence has been confirmed previously (Škaljić *et al.* 2009; Azemović *et al.* 2014), and it has been caused by increased in load per knife, what may cause less effective grain cutting and more distortion on anatomical elements.

Table 5. Average Values of R_a and R_z Parameters of All Tested Species Depending on Feeding Speed

Feeding Speed (m/min)	R_a (μm)	R_z (μm)
3.2	2.58 [a]	17.10 [a]
8.3	3.22 [b]	21.73 [b]
12.5	4.08 [c]	25.83 [c]
16.7	4.83 [d]	30.82 [d]

Note: The letters a, b, and c beside average values indicate homogeneous groups. Different letters indicate statistically significant differences between groups.

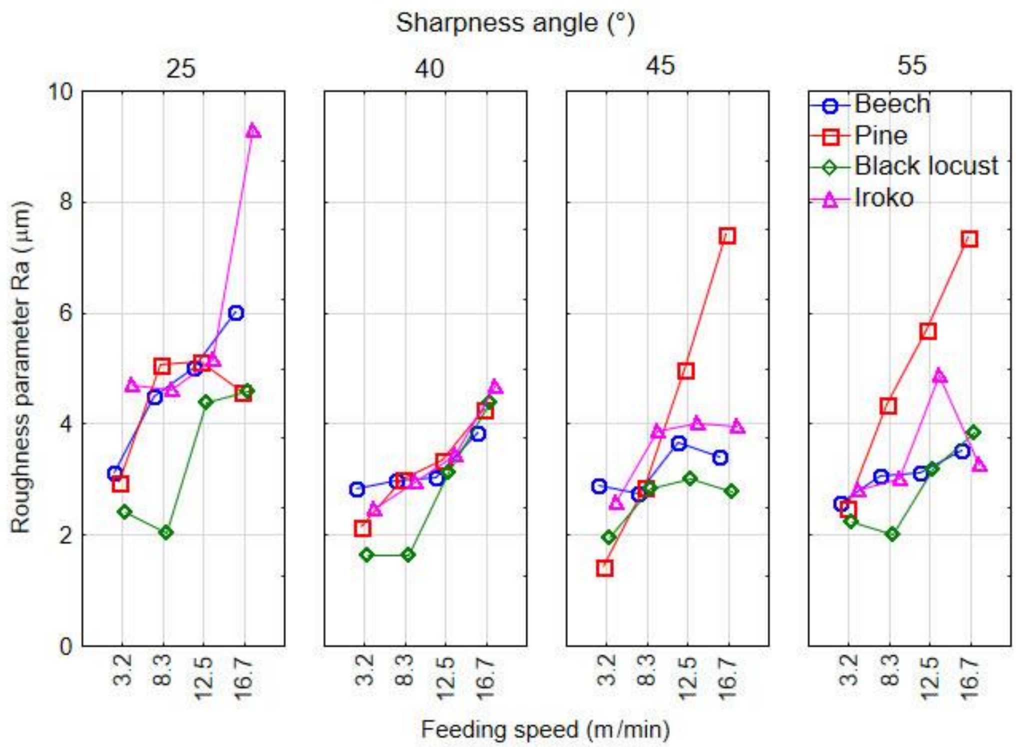

Fig. 5. Dependency between sharpness angle, wood species, feeding speed, and roughness R_a

The interactions of all analyzed factors for the R_a parameter are presented in Fig. 5. Generally, there was an upward trend of the R_a parameter when the feeding speed increased for all analyzed variants of the sharpness angle and wood species. The lowest dispersion of results was observed for the sharpness angle of 40°, while the highest dispersion occurred for an angle of 25°.

The values of the R_z parameter, as shown in Fig. 6, indicated an upward trend with an increase in the feeding speed. The lowest dispersion and the lowest results were observed for sharpness angle of 40°. The observed upward trend of surface roughness parameters varied depending on the wood species and sharpness angle. It may be caused by the heterogenous structure of wood within the species and differential anatomical structure between examined species.

The lowest values of both roughness parameters were observed for black locust, which was characterized by the highest density, while the highest roughness of samples and the lowest density were observed for pine.

The reason for the decrease in the surface quality of wood during the increase in the feeding speed can be explain by the increase in the chip thickness and greater stratification of grains during machining. Other authors confirm this in their research (Barcík *et al.* 2009). The results of the experiment show that surface roughness of wood depends significantly on the feeding speed, wood species, and the sharpness angle. Roughness of the samples increased when increasing feeding speed, while an increase in wood density decreased surface roughness.

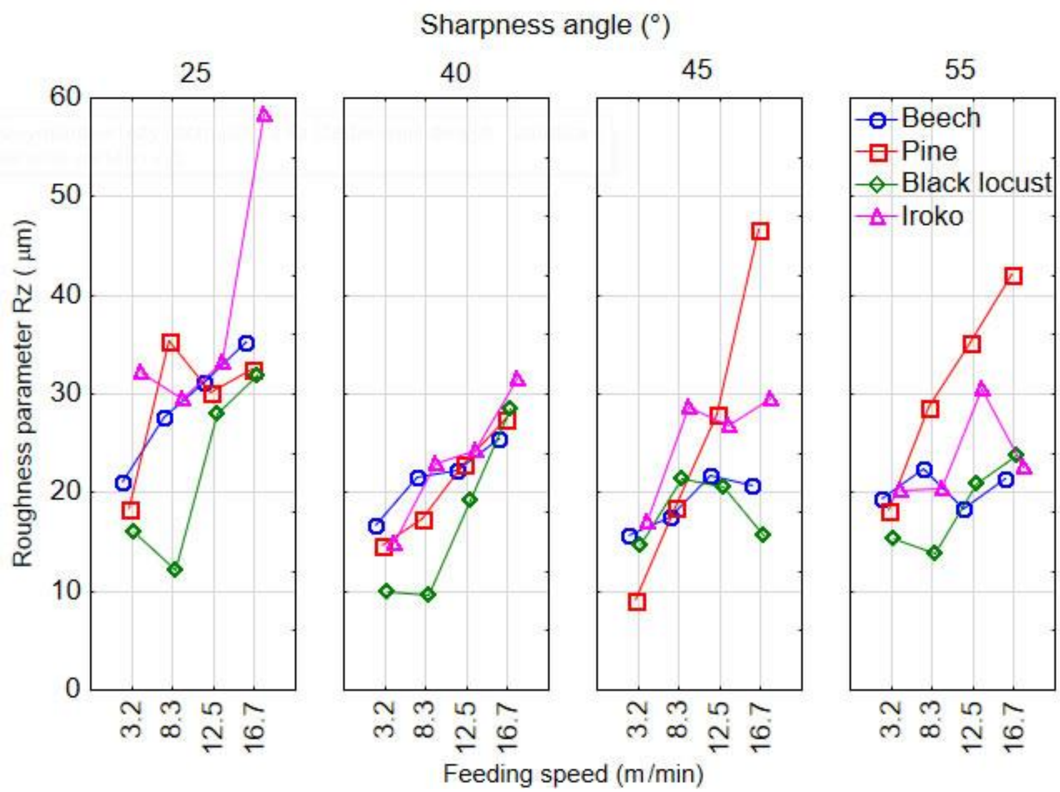

Fig. 6. Dependency between sharpness angle, wood species, feeding speed, and R_z parameter

CONCLUSIONS

1. The sharpness angle, wood species, and feeding speed had significant effects on the surface roughness of wood after milling.
2. Values of roughness parameters decrease with the decrease in the sharpness angle in range of 55° to 40°. For the sharpness angle of 25°, a significant increase in the surface roughness parameters was found.
3. Based on the range and results of experiment, the sharpness angle of 40° should be assumed to be the optimum value in terms of the surface quality of wood.
4. A large differentiation of surface roughness of the samples was stated between the tested species. An increase in the density of each wood species caused a linear decrease in the surface roughness of the samples.
5. The linear upward trend of analyzed parameters occurred with an increase in feeding speed. This trend depended on the wood species and sharpness angle, which may have been caused by the heterogenous structure of wood.
6. The great difference in surface roughness of the samples between the sharpness angles of 25° and 40° show a need to continue research with the angle narrowed to this range.

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