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The effect of the feed speed and rotation speed of plane milling on the surface roughness of beech wood

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Abstract: *The effect of the feed speed and rotation speed of plane milling on the surface roughness of beech wood.* The paper presents studies on the effect of feed speed and spindle rotation speed on the milled surface of beech wood worked on a milling machine. In this study eight feed speed variants and five spindle rotation speed variants were tested. The analyses focused on roughness characteristics of milled surface and detailed visual (organoleptic) analyses were conducted. A statistically significant effect of feed speed and spindle rotation speed was observed. Advantageous ranges of beech wood cutting parameters were determined for practical application in milling operations.

Key words: milling, surface roughness, feeding speed, rotation speed, beech wood

INTRODUCTION

Appropriate wood milling and attractive wood-based materials are produced by properly performed technological and manufacturing processes. At each stage of the production process connected with woodworking the effects of milling have to provide adequate surface quality, dimensional accuracy and shape precision of manufactured elements. By avoiding woodworking defects the number of defective products is reduced, the need for costly reworking is eliminated, which eventually is reflected in the reduction of manufacturing costs (energy, materials, disposal) and has a positive effect on environmental conditions.

Wood is an organic raw material. It is strongly anisotropic and heterogeneous. It exhibits marked variability in properties even within a single species (Kozakiewicz 2006).

Each observation concerning the effects of wood cutting primarily in relation to woodworking parameters provides significant information on technological processes and execution of woodworking tasks. Numerous studies have been conducted in this respect to investigate surface roughness in view of tool wear (Aguilera *et al.* 2016; Bendikiene, Keturakis 2016; Keturakis, Juodeikienė 2007), changes in tool geometry (Malkoçoğlu 2007), the effect of technological parameters (Hernández, Cool 2008; Sogutlu 2010) and the applied woodworking method (Kilic *et al.* 2006; Kminiak, Gaff 2015; Sofuoğlu, Kurtoğlu 2015).

Occasionally surface roughness changes significantly in the case of thermally modified wood, i.e. the type of wood material greatly increasing in popularity, mainly due to the attractive colour of modified wood resembling exotic species. Studies in this respect have been conducted for many wood species, e.g. beech (Aydin, Colakoglu 2005; Budakçı *et al.* 2013; Kvietková *et al.* 2015b), birch (Kvietková *et al.* 2015a) or pine (Budakçı et al. 2013; Gündüz *et al.* 2008; Pinkowski *et al.* 2016).

In recent years studies on surface roughness have also been conducted in relation to woodworking operations performed using modified tool blades. They were conducted on wood of Scots pine (Pinus sylvestris L.) (Gilewicz et al. 2010) or beech (*Fagus sylvatica* L.) (Pinkowski et al. 2011). In those studies advantageous relationships were observed for woodworking quality when using coated knives, thanks to the reduced wear of modified tool blades.

Studies concerning the effect of feed speed and rotation speed on woodworking quality are typically conducted within a limited range of values for these parameters. Thus it was decided in this study to supplement this aspect of the problem.

The aim of this study was to determine the effect of rotation speed and feed speed on quality of worked beech wood surface within a broad range of values available for woodworking machines. The study focused on practical applications. Experimental data will facilitate a proper selection of cutting parameters in joinery and furniture manufacturing processes.

RESEARCH METHODOLOGY

Tests were conducted on a Felder F 900 milling machine equipped with a Felder F-38 feeder. Effective removal of chips from the cutting zone was provided by a Felder type AF-22 dust collector. The power of the machine engine was 5.5 kW.

The experiments were conducted using HSS SW18 knives of 50x30x3 mm, blade angle of 45° and rake angle of 25°. The knives were mounted in a round four-knife pocket cutter. Only one effectively cutting knife was used in the tests, while the other knives were appropriately configured to guarantee cutter balancing. During the tests the machined layer was 1 mm in thickness, while cutting diameter was 120 mm.

Machined materials were beech (Fagus sylvatica L.) wood samples of 2500x100x19 mm, of grade 3 square-edged timber. Mean wood density was 670 $kg\cdot m^{-3}$ at a moisture content of 6.5%. Samples were milled along the grain at the radial cross-section. The surface geometric structure was analysed on a series of samples of 120x20x19 mm. Cutting operations were conducted using five spindle rotation speeds: 3500, 4500, 6000, 8000 and 10000 min^{-1} and eight feed speeds: 3.2, 6.3, 8.3, 12.5, 16.7, 25, 32 and 63.8 $m\cdot min^{-1}$.

Surface roughness was determined in accordance with the requirements of the ISO 4287 (1997) standard using a Mitutoyo SJ-201P tester. A measurement stylus was used with a tip radius of 2 μm, an angle of 60° and a small measurement pressure of 0.75mN. Cut-off length was 2.5 mm and sampling length was 12.5 mm. Roughness was measured on 3 samples for each cutting variant. Statistical analyses were conducted on a total of 120 samples.

Statistical inference, including analysis of multiple regression, was conducted at the significance level P=0.05. Statistical analyses were performed using the Statistica ver. 13 software package.

RESULTS AND DISCUSSION

In relation to surface roughness the most commonly used roughness parameters were determined, i.e. arithmetic mean surface roughness Ra and mean peak-to-valley height Rz. The average surface roughness values for the feed speed and rotation speed have been given in Table 1.

Table 1. Arithmetic means and standard deviations of the surface roughness parameters

Feed speed [m·min^{-1}]	Rotation speed [min^{-1}]	Ra parameter [μm]		Rz parameter [μm]	
		$\bar{X}$	s	$\bar{X}$	s
3.2	3500	2,13	0,12	12,88	1,70
	4500	2,29	0,21	14,19	1,95
	6000	2,08	0,37	13,49	3,98
	8000	3,45	0,32	20,09	2,51
	10000	2,10	0,38	12,83	2,51
6.3	3500	2,43	0,27	16,15	4,03
	4500	3,11	0,32	19,89	3,50
	6000	2,37	0,49	14,09	3,09
	8000	3,02	0,16	21,62	2,94
	10000	2,00	0,35	11,62	1,98
8.3	3500	3,09	0,45	17,85	4,16
	4500	3,72	0,19	28,26	1,42
	6000	2,69	0,37	15,31	2,61
	8000	2,97	0,60	18,69	1,97
	10000	2,58	0,31	20,57	0,18
12.5	3500	2,87	0,48	14,84	3,09
	4500	3,66	0,22	22,15	0,61
	6000	4,04	0,60	25,47	2,72
	8000	2,57	0,64	14,60	1,69
	10000	2,53	0,35	16,19	3,20
16.7	3500	3,38	0,17	17,52	1,08
	4500	3,39	0,19	19,67	1,40
	6000	3,30	0,30	18,45	2,12
	8000	2,82	0,46	19,76	2,12
	10000	3,35	0,83	22,71	5,59
25	3500	4,98	0,32	26,38	4,40
	4500	4,42	0,56	25,90	4,93
	6000	4,27	0,12	24,08	3,24
	8000	4,24	0,17	25,79	2,80
	10000	3,25	0,29	20,33	1,91
32	3500	7,21	0,23	35,41	5,27
	4500	4,75	0,52	28,39	3,35
	6000	3,96	0,09	21,65	2,29
	8000	5,17	0,71	23,77	1,60
	10000	3,60	0,43	20,04	1,08
63.8	3500	12,61	1,80	30,99	4,07
	4500	10,71	0,19	43,80	2,81
	6000	6,55	0,57	29,44	6,21
	8000	5,18	0,25	25,58	1,38
	10000	4,93	0,77	25,99	6,32

Data contained in Table 1 are also presented in a graphic form (Fig. 1). Based on these data differences were found in values of roughness parameters depending on the adopted ranges of technological parameters.

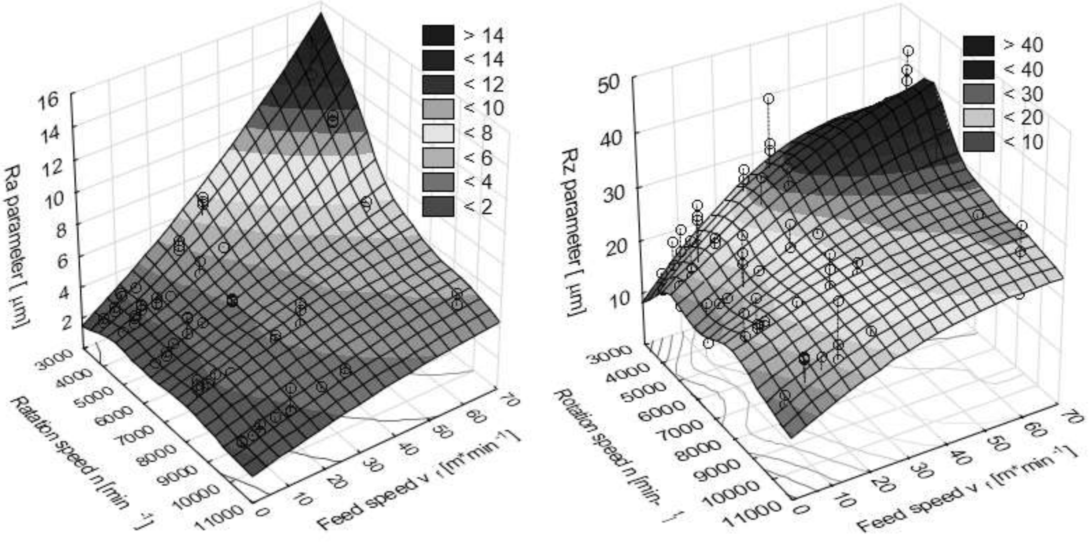

Figure 1. Values of roughness parameters Ra and Rz for milled beech wood surfaces depending on changes in feed speed and tool rotation speed

Based on obtained results of roughness, multiple regression models for Ra and Rz parameters were developed:

$Ra = 3,670 + 0,0924 * v_f - 0,00026 * n$ ($R^2 = 0.71$)

$Rz = 16,142 + 0,472 * v_f - 0,00317 * v_f^2 - 4,591e^{-008} * n^2$ ($R^2 = 0.53$)

where: v_f – feeding speed [m/min]; n – rotational speed [min^{-1}].

In order to verify the significance of differences between recorded results the analysis of multiple regression was performed, which results are presented in Table 2.

Table 2. Results of analysis of multiple regression for surface roughness depending on tested technological parameters

Roughness parameter	Factor	Sum of squares	Degrees of freedom	Mean squares	Fisher's F-Test	*P*- value
Arithmetic mean surface roughness (Ra)	Intercept	167,1530	1	167,1530	118,0098	0,000000
	Feeding speed	352,9459	1	352,9459	249,1794	0,000000
	Rotation speed	45,0042	1	45,0042	31,7729	0,000000
	Error	165,7227	117	1,4164		
Surface roughness depth (Rz)	Intercept	4039,557	1	4039,557	165,3720	0,000000
	Feeding speed	631,387	1	631,387	25,8478	0,000001
	Feeding speed^2	137,000	1	137,000	5,6085	0,019527
	Rotation speed^2	260,063	1	260,063	10,6465	0,001449
	Error	2833,543	116	24,427		

It results from data given in Table 2 that for both analysed roughness parameters statistical differences at the significance level of 0.05 are found between mean values of roughness parameters for the main effects, i.e. feeding speed and rotation speed.

Data presented in Table 1 show that values of both roughness parameters increase with an increase in feed speed and decreases with an increase in rotation speed. Similar dependencies have been reported by some authors (Sogutlu 2010) in relation to various wood species. This also applies to the thermally modified wood (Kvietková et al. 2015a, 2015b, Pinkowski et al. 2016).

Table 3. Evaluation of multiple regression analysis parameters for surface roughness depending on tested technological parameters

Ra parameter				
Effect	Param.	Standard error	t	p
Intercept	3,670418	0,337875	10,86323	0,000000
Feeding speed	0,092436	0,005856	15,78542	0,000000
Rotational speed	-0,000260	0,000046	-5,63674	0,000000
Rz parameter				
Intercept	16,14166	1,255212	12,85970	0,000000
Feeding speed	0,47163	0,092766	5,08407	0,000001
Feeding speed^2	-0,00317	0,001340	-2,36823	0,019527
Rotational speed^2	0,00000	0,000000	-3,26290	0,001449

Table 3 presented evaluation of multiple regression analysis parameters for surface roughness depending on tested technological parameters.

The effect of both analysed technological parameters, i.e. feeding speed and rotation speed, is connected with another woodworking parameter – feed per tooth fz. This parameter provides a significant criterion for the selection of cutting parameters adopted in catalogues of leading woodworking tool manufacturers worldwide, e.g. Leitz (2017). It is calculated from the following dependence:

$$f_z = \frac{v_f}{n \cdot z_c} \tag{1}$$

where: f_z is feed per tooth (mm), v_f is feed speed (mm·min^{-1}), n is rotation speed (min^{-1}), z_c – number of tooth.

Figure 2 presents a correlation between the value of feeding rate f_z for all conducted tests and roughness (parameters Ra and Rz) of the woodworked surface.

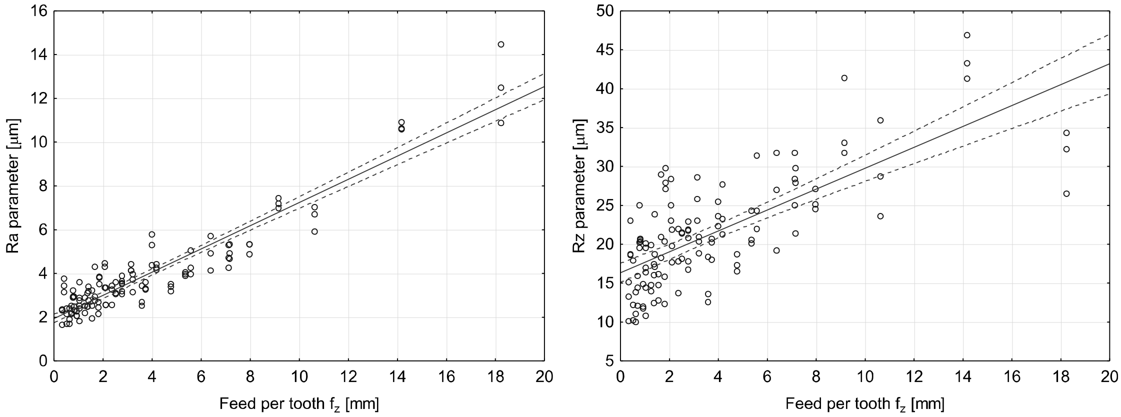

Figure 2. Correlation between feed per tooth fz and roughness parameters Ra and Rz for beech wood

In the case of Ra the correlation is much greater (r = 0.94) than in the case of the other analysed parameter, i.e. Rz (r = 0.72). It results from the method applied to determine Rz as the mean value of five maximum peak heights and valley depths in the measurement section, while parameter Ra is an averaged value of all points in the profile for the entire measurement point and it is not affected by single profile irregularities. Analyses showed that an increase in feed per tooth f_z results in an increased surface roughness.

The recorded data show that roughness of milled surfaces tends to decrease with an increase in spindle rotation speed at a constant number of blades over the entire testing range. This results from the fact that feed per tooth fz decreases with an increase in rotation speed. In turn, an increase in feed speed causes an opposite dependence, i.e. surface roughness increases with an increase in feed rate.

It was found in this study that the anatomical structure of wood and its defects (knots, cracks, non-parallel grain pattern) have a considerable effect on the quality of the milled surface depending on variable woodworking parameters. Visual analyses of the surfaces showed that at feed speeds exceeding 16.7 $m \cdot min^{-1}$ the non-parallel grain pattern in relation to the milled surface causes a rapid deterioration of quality of the milled surface, mainly chipped surface.

Figure 3 presents tested ranges of cutting parameters in terms of quality of the beech wood surface milled in a milling machine.

	Rotation speed n [min^{-1}]	Feed speed v_f [$m \cdot min^{-1}$]							
		3.2	6.3	8.3	12.5	16.7	25.0	32.0	63.8
f_z [mm]	3500	0.9	1.8	2.4	3.6	4.8	7.1	9.1	18.3
Ra [μm]		2.13	2.43	3.09	2.87	3.38	4.98	7.21	12.61
Rz [μm]		12.88	16.15	17.85	14.84	17.52	26.38	35.41	30.99
f_z [mm]	4500	0.7	1.4	1.8	2.8	3.7	5.6	7.1	14.2
Ra [μm]		2.29	3.11	3.72	3.66	3.39	4.42	4.75	10.71
Rz [μm]		14.19	19.89	28.26	22.15	19.67	25.90	28.39	43.80
f_z [mm]	6000	0.5	1.1	1.4	2.1	2.8	4.2	5.3	10.7
Ra [μm]		2.08	2.37	2.69	4.04	3.30	4.27	3.96	6.55
Rz [μm]		13.49	14.09	15.31	25.47	18.45	24.08	21.65	29.44
f_z [mm]	8000	0.4	0.8	1.0	1.6	2.1	3.1	4.0	8.0
Ra [μm]		3.45	3.02	2.97	2.57	2.82	4.24	5.17	5.18
Rz [μm]		20.09	21.62	18.69	14.60	19.76	25.79	23.77	25.58
f_z [mm]	10000	0.3	0.6	0.8	1.3	1.7	2.5	3.2	6.4
Ra [μm]		2.10	2.00	2.58	2.53	3.35	3.25	3.60	4.93
Rz [μm]		12.83	11.62	20.57	16.19	22.71	20.33	20.04	25.99

- recommended cutting parameters
- cutting parameters with limitations
- not recommended cutting parameters

Figure 3. Tested ranges of cutting parameters for beech wood milled on a milling machine in terms of surface roughness

The non-shaded table cells presented in Fig. 3 give recommended criteria for the selection of cutting parameters when milling beech wood on a milling machine in terms of milled surface quality. In the case of cells with light shading, containing acceptable roughness parameters, limitations are connected with reduced milling efficiency and potentially accelerated wear of the blade at low fz values. Cells with dark shading present undesirable selection criteria for woodworking parameters for beech wood milling, primarily due to the produced chipped surface and safety concerns in cutting operations.

CONCLUSIONS

As indicated by the research results, surface roughness in beech wood varies depending on the adopted woodworking parameters. Application of a greater feed speed causes an increase in roughness parameters, while an increase in tool rotation speed causes an opposite dependence, i.e. reduced values of roughness parameters.

It was found that both feed speed and rotation speed are statistically significant factors affecting surface roughness. A strong correlation is observed between feed rate and roughness parameters, with a stronger correlation found for Ra.

In terms of woodworking efficiency and thus also a reduction of manufacturing costs, it is recommended to strive to attain the greatest possible yield, whereas surface quality, analysed in this study, may prove to be a limitation here.

Proposed values of technological parameters need to be considered recommended values in view of surface quality. However, we should be aware of the potential development of surface defects during woodworking (e.g. chipped surface), which may appear at high feed speeds, particularly when cutting wood with an irregular grain direction.

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Streszczenie: *Wpływ prędkości posuwu i obrotowej podczas frezowania na chropowatość powierzchni drewna bukowego.* W pracy przedstawiono badania wpływu prędkości posuwu i prędkości obrotowej wrzeciona na stan obrobionej powierzchni drewna buka, na frezarce dolnowrzecionowej. W realizacji badań zastosowano osiem wariantów prędkości posuwu oraz pięć wariantów prędkości obrotowej wrzeciona. W ramach badań koncentrowano się na charakterystyce chropowatości obrobionej powierzchni oraz dokonywano szczegółowych analiz organoleptycznych. Stwierdzono zdecydowany wpływ prędkości posuwu i prędkości obrotowej wrzeciona, głównie w ujęciu posuwu na ostrze, na efekty obróbki drewna buka oraz ustalono korzystne zakresy parametrów skrawania drewna buka na frezarce dolnowrzecionowej.

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