Medium-density Fiberboard (MDF) and Edge-glued Panels (EGP) after Edge Milling – Surface Roughness after Machining with Different Parameters

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The mean arithmetic deviation of the roughness profile was investigated during cylindrical milling of the board edges. The machined materials were a medium-density fiberboard, medium-density fiberboard with single-sided lamination, and edge-glued spruce panel. Contactless and contact profilometers were used to measure the roughness. Both methods were evaluated and compared. Tungsten carbide blades with three different compositions and treatments were used. The effect of the cutting speed (20 m/s, 30 m/s, 40 m/s, and 60 m/s) and feed rate (4 m/min, 8 m/min, and 11 m/min) on the surface roughness was also monitored. The results of this study compared two different methods for determining the surface roughness. The measurements were more accurate with a contactless profilometer, but the price is higher than that of the contact method. The operation was also more complicated, and the measurement itself took longer with a contactless profilometer. The evaluation of individual surface quality variables was faster with a contact device. The best results in terms of the surface quality were achieved by lowering the feed rate and increasing the cutting speed.

Keywords: Roughness; Feed rate; Cutting speed; Edge milling; Medium-density fiberboard; Edge-glued panel

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INTRODUCTION

Wood is a readily available natural material that has been used by people throughout history. This raw material has become a part of everyday life without people realizing its immense significance and benefits. Wood is a renewable source of energy, and is used in various forms in everyday activities (Bekhtam *et al.* 2014; Gaff *et al.* 2016; Gottlöber *et al.* 2016). Processing wood into a usable material is a very complex technological process that has a long history (Kminiak and Gaff 2015; Kubš *et al.* 2016).

Wood processing primarily involves the homogenization of the mechanical and structural properties of the wood so that it is a technically defined material, and the transformation of sawmill waste into a material intended for further processing (Afanasiev 1962). Wood utilization is diverse, and its processing methods are equally so. Milling is currently coming to the forefront of processing. Milling is a chip-forming method in which a layer of the material is removed from the workpiece in the form of small individual chips by use of a multi-blade rotary tool, which is called a milling cutter (Kvietková 2015; Kvietková *et al.* 2015b; Kvietková *et al.* 2015c; Lahtela and Kärki 2016; Metsä-Kortelainen and Viitanen 2017).

During milling, the milling cutter rotates around its axis (main motion of the process) and its teeth gradually cut through the workpiece, which simultaneously moves against the tool (secondary motion of the process) (Prokeš 1982). Each blade of the milling cutter gradually removes short chips from the machined material, so that the cutting process is not interrupted (Lisičan 1996).

The aim of milling is to create a workpiece with the required dimensions, shape, and surface quality (Welzbacher *et al.* 2011; Kvietková *et al.* 2015a). By using various types of milling tools, it is possible to machine external and internal surfaces that are primarily flat, but also surfaces that are shaped, irregular, slanted, have grooves, half grooves, rotary surfaces, *etc*. (Mikolášik 1981). The possibility of precision production and its wide application have given milling an important place in production. Milling is used to machine an increasing number of materials, not only wood, but also wood-based materials, such as agglomerated materials, and new materials.

A summary of all of the factors that affect the milling process can be defined as the cutting conditions (Bekéš *et al.* 1999; Welzbacher and Brischke 2008). For optimal milling, *i.e.* a process that is productive and economically-viable, it is necessary to understand the individual milling conditions and their interconnection (Kotěšovec 1981). The basic cutting conditions are the feed rate, cutting speed, and cutting depth. However, the milling process is also largely affected by other factors, such as the machined material, dimensions and shape of the cross section of the chip, overall stiffness of the machining system, and tool geometry (Sova 2001). The optimal conditions in the milling process are affected by different cutting conditions, as well as other factors, such as the machine tool and requirements given by the technical documentation. It is therefore very important to adhere to the parameters recommended by the manufacturers.

The roughness (R_a) of a milled surface is of technological, technical, and kinematic origin. Roughness results from the cutting of cells and annual rings, moisture content, and regularity of the wood grain (Sedlecký and Sarvašová Kvietková 2017; Söğütlü 2017). Even though the quality of the surface is much smoother than that of cut surfaces in most cases, they are still not perfectly smooth and will always have a certain degree of R_a. The technical causes of R_a lie in the precision of the knife setting in the shaper cutter head (or the precision of the milling cutter grinding), degree of blade dullness, and vibration and chatter of the milling cutter. These causes manifest themselves by the pulling of wood fibers by dull blades and irregularity of the width of waves on the milled surface (Lisičan 1996; Očkajová *et al.* 2016; Mračková *et al.* 2016).

The kinematic factor that affects R_a is the cycloid shape of the relative motion of the blade in the wood, and as a result it is impossible to theoretically achieve a perfectly flat surface with a rotary tool, even if there were no technological or technical causes. This is simply because each tool cutter creates a cutting surface that is curved. The advantages of milling are a relatively high performance and good surface quality. The workpieces exhibit some surface R_a after milling, which is manifested by microscopic (R_a) or macroscopic changes (waviness, depressions, ridges, and partially pulled fibers). The overall possibilities for evaluating the surface are given in the standard ČSN EN ISO 4287 (1999). All of the parameters defined in the standard can be applied to the primary, roughness, and waviness profiles. The quality of the surface of products created by the woodworking industry is most often evaluated by its mean arithmetic deviation of the profile (P_a, R_a, W_a). The aim of this article was to monitor variations in the surface quality, which was evaluated based on the mean arithmetic deviation of the roughness profile (R_a).

EXPERIMENTAL

Materials

The following three materials were machined: a medium-density fiberboard (MDF), medium-density fiberboard with single-sided lamination (MDF-L), and edge-glued panel (SEGP) from Norway spruce (*Picea abies* L.). The boards were used to make 500 mm x 500 mm x 18 mm samples. All of the samples were stored under standard conditions in a climatized room (relative humidity = 65% ± 3% and temperature = 20 °C ± 2 °C) for two weeks to achieve a moisture content of 12%. The density was determined according to ČSN EN 323 (1994) and is given in Table 1.

Table 1. Properties of the Construction Materials

Marking	Construction Material	Density (kg/m^3)	Producer
MDF	Medium-density fiberboard	750	DDL - Dřevozpracující družstvo (Lukavec, Czech Republic)
MDF-L	Medium-density fiberboard with single-sided lamination	730	DDL - Dřevozpracující družstvo
SEGP	Edge-glued panel from spruce wood	432	Holzindustrie Schweighofer s. r. o., (Tábor, Czech Republic)

Methods

Edge milling was performed with a one-spindle edge milling machine (FVS) with a STEFF 2034 feeding system (Maggi Technology, Certaldo, Italy). The milling cutters were mounted on a two-blade milling cutter head (Felder, Hall in Tirol, Austria). Both blades were always engaged, and the material removal thickness was 1 mm. The side of the board was milled three times along its length. The variable parameters of the edge milling and tool geometry are listed in Table 2.

Table 2. Cutting Parameters of the Edge Milling and Cutter Geometry

One-spindle Cutter FVS		Cutter Head (Ø 125 mm)	
Input power (kW)	3.8	Clearance angle (α)	10°
RPM	3000, 4500, 6000, and 9000	Cutting angle of wedge (β)	60°
Cutting speed (m/s)	20, 30, 40, and 60	Rake angle (γ)	20°
Feed rate (m/min)	4, 8, and 11	Cutting angle (δ)	70°

Three types of milling cutters were selected for the milling process, which were HW1, HW2, and HW1 CrTiN. The milling cutters were manufactured by Leitz GmbH & Co. KG (Oberkochen, Germany). The HW1 milling cutter is primarily designed for machining solid wood, HW2 is designed for agglomerated materials, and the HW1 CrTiN milling cutter is designed for hard agglomerated materials. The last milling cutter is made of the same material as the HW1 milling cutter and has a CrTiN coating. The coating was applied by a physical vapor deposition method by SHM, s.r.o. (Šumperk, Czech Republic). The basic properties of the milling blades are listed in Table 3.

Table 3. Properties of the Milling Blades

Milling Cutter	Cutting Material	Blade Type	Dimensions (mm)	Micro-hardness HV_m (GPa)
HW1	Tungsten carbide HW-05	5086	50 × 12 × 1.5	17
HW2	Tungsten carbide HW-03F	6906	50 × 12 × 1.5	22
HW1 CrTiN	Tungsten carbide HW-05 + CrTiN	5086	50 × 12 × 1.5	30

Based on the combination of the milling parameters (cutting speed and feed rate), tools (material and treatment of blades), and materials (MDF, MDF-L, and SEGP), 108 samples were created for edge milling.

An optical profilometer (LEXT 3D, Olympus, Praha, Czech Republic) with a measuring laser microscope (OLS4100, Olympus, Praha, Czech Republic) (contactless measurement) and profilometer (Form Talysurf 50 Intra, Taylor Hobson, Leicester, UK) (contact measurement) were used for taking measurements. The R_a was measured according to ČSN EN ISO 4287 (1999).

When measuring the surface quality with the contactless profilometer, optics predefined for measuring surface quality were used (MPlanApoN, 50x/0.95 LEXT, ∞/0/FN18). The light beam radius (R) was 0.2 µm. Additionally, a λc profile filter was used.

A standard arm with a conical tip R of 2 µm was used for measuring with the contact method. Additionally, a λc profile filter was used.

Table 4. Basic Lengths for Measuring the R_a

Periodic Profile	Measurement Parameter (ČSN EN ISO 4287 1999)			
R_{Sm} (mm)	$\lambda_c = l_c$ (mm)	l_n (mm)	l_t (mm)	r_{tip} (µm)
$0.013 < R_{Sm} \leq 0.04$	0.08	0.4	0.48	2
$0.04 < R_{Sm} \leq 0.13$	0.25	1.25	1.5	2
$0.13 < R_{Sm} \leq 0.4$	0.8	4	4.8	2 or 5
$0.4 < R_{Sm} \leq 1.3$	2.5	12.5	15	5
$1.3 < R_{Sm} \leq 4$	8	40	48	10

Settings used for both profilometers are colored in blue
l_n - evaluated length (length in X direction used for assessment of the evaluated profile
R_{Sm} - average width of roughness elements (arithmetic mean diameter X_s of profile elements in the range l_c
l_c - base length ($l_n = 5 \times l_c$); λ_c - cut-off value; λ_c = c
l_t - total measured length (ln increased by start and stop)
r_{tip}- arm radius

The R_a values were evaluated with STATISTICA 13 software (Statsoft Inc., Tulsa, USA) using an analysis of variance. The analysis used a 95% confidence interval, which represented a significance level of 0.05 ($P < 0.05$).

RESULTS AND DISCUSSION

Based on the level of significance, it was clear that each of the monitored factors and their interaction had a significant effect on the R_a after edge milling for both of the measuring methods (Tables 5 and 6).

Table 5. Effect of the Factors and their Interaction on the R_a - Contactless Method

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F-test	Significance P-level
Intercept	425041.9	1	425041.9	50622.1	0.000
1) Cutting speed	340.2	3	113.4	13.5	0.000
2) Feed rate	120.2	2	60.1	7.1	0.001
3) Cutter type	1515.5	2	757.8	90.2	0.000
4) Material type	88349.6	2	44174.8	5261.1	0.000
1; 2; 3; 4	2119.1	24	88.3	10.5	0.000
Error	8161.3	972	8.4		

Table 6. Effect of the Factors and their Interaction on the R_a - Contact Method

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F-test	Significance P-level
Intercept	302561.2	1	302561.2	145531.5	0.000
1) Cutting speed	331.6	3	110.5	53.2	0.000
2) Feed rate	147.9	2	73.9	35.6	0.000
3) Cutter type	685.9	2	342.9	165.0	0.000
4) Material type	63539.6	2	31769.8	15281.2	0.000
1; 2; 3; 4	414.4	24	17.3	8.3	0.000
Error	2020.8	972	2.1		

When comparing the two methods of measuring the R_a, a significant difference was found between all of the monitored cutting speeds (Fig. 1). The closest R_a values were measured at a cutting speed of 30 m/s. The average R_a values measured by the contactless method were 13.5% higher than those from the contact method. The greatest differences were measured at a cutting speed of 20 m/s. The average R_a values from the contactless method were 26.39% higher than those from the contact method. The contactless method exhibited higher R_a values.

After the effect of the cutting speed on the surface R_a was evaluated, it was concluded that increasing the cutting speed improved the surface quality. A similar finding was confirmed by the research by Yasir *et al.* (2016).

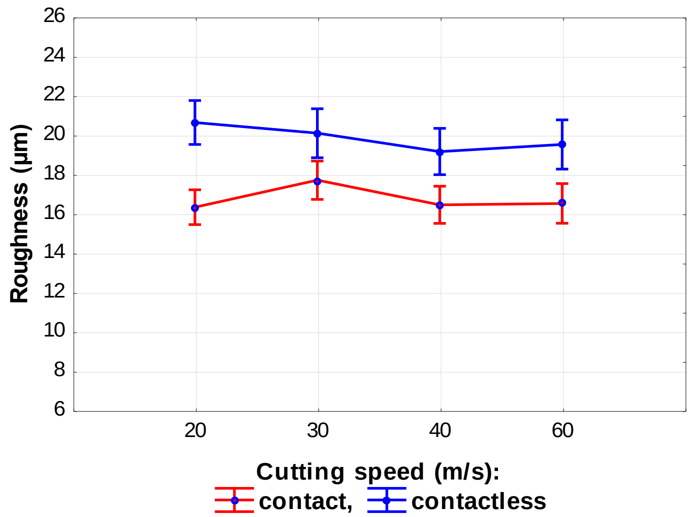

Fig. 1. Effect of the cutting speed on the R_a

When comparing the contact and contactless methods for assessing the effect of the feed rate on the surface R_a, a significant difference was found at all of the feed rates. Figure 2 shows that the individual curves were almost the same as each other at similar intervals. The average R_a values for the contactless method at a feed rate of 4 m/min were 19.7% higher than those for the contact method. At a feed rate of 8 m/min, the average R_a values for the contactless method were 18.8% higher, and at the highest monitored feed rate, they were 17.1% higher. Based on the results obtained in the evaluation of the feed rate, it was found that higher R_a values were exhibited by the contactless method.

According to Maher (2008), the surface R_a increased with the feed rate, which was also confirmed by this research when comparing the feed rates of 4 m/min with 8 m/min, and 4 m/min with 11 m/min. The research by Wilkowski *et al.* (2015) clearly showed that decreasing the feed rate improved the quality of the machined surface, but machining itself naturally took longer.

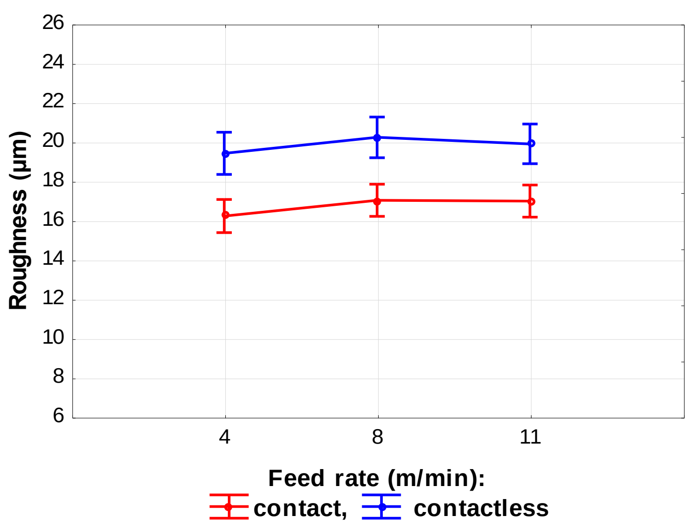

Fig. 2. Effect of the feed rate on the R_a

Figure 3 shows the effect of the cutter type on the resulting R_a of the milled surface. The largest range of values was found when using the HW1 CrTiN blade, where the average R_a values measured by the contactless method were 27.0% higher than those from the contact method. With the HW1 blade, the average R_a values measured by the contactless method were 15.2% higher than those measured by the contact method. The smallest difference was found with the HW2 blade, where the average R_a values measured by the contactless method were 13.6% higher than those measured by the contact method. The results recorded during the evaluation of the cutter type showed that the contactless method exhibited higher R_a values. For both surface R_a measurement methods, the HW1 milling cutter was the most suitable. Laina *et al.* (2017) found that the machining process and wood species greatly affects the resulting surface R_a.

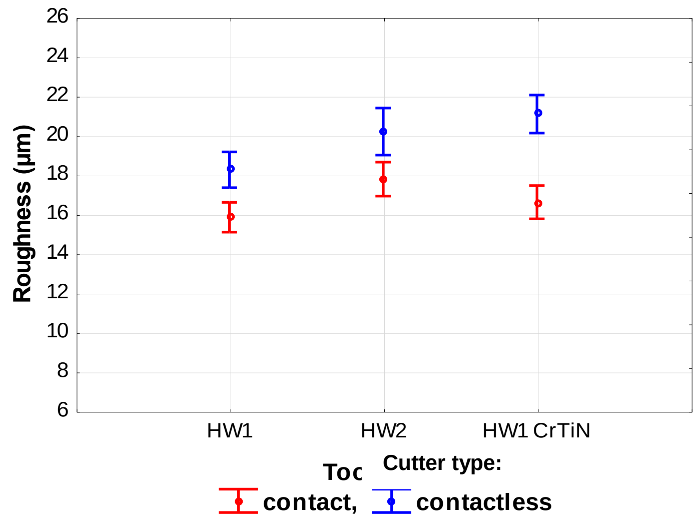

Fig. 3. Effect of the cutter type on the R_a

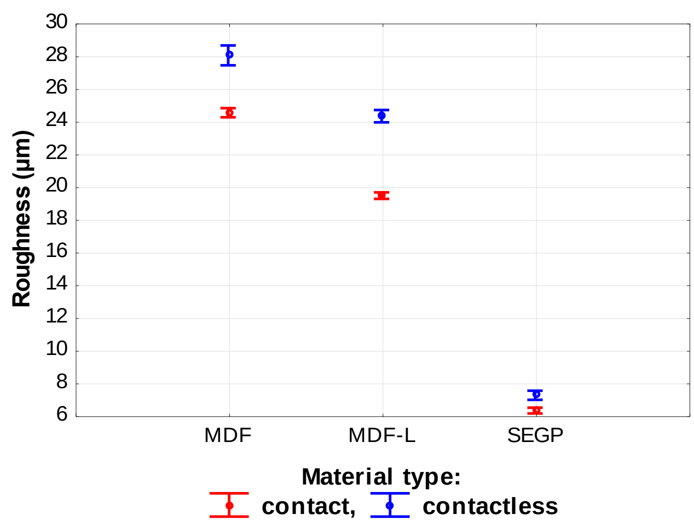

Fig. 4. Effect of the material type on the R_a

Even for the last criterion (material type), a significant difference was found between the contact and contactless methods of measuring the surface R_a. The average R_a values of the SEGP measured by the contactless method were 14.9% higher than the average R_a values measured by the contact method. In the case of the MDF, there was an increase of 14.3%. The greatest percentage increase in the average R_a values was recorded for the MDF-L (25.01%). As with the other monitored factors, the contactless method also exhibited higher R_a values for the different material types (Fig. 4).

It was confirmed that the material density has a great effect on the machinability characteristics (Lin *et al.* 2006). Based on the results measured by the contact and contactless methods, it was concluded that the highest R_a values were observed in the MDF, which had the highest density, and the lowest R_a values were observed in the SEGP, which had the lowest density. The type of material was proven to have a very significant effect on the R_a of the machined surface.

Table 7. Percentage Differences between the Contact and Contactless Methods for Measuring the R_a

	R_a (µm)		ΔR_a (%)
	Contact	Contactless	
v_c = 20 m/s	16.316	20.621	20.877
v_c = 30 m/s	17.69	20.079	11.898
v_c = 40 m/s	16.438	19.146	14.144
v_c = 60 m/s	16.507	19.507	15.379
v_f = 4 m/min	16.215	19.407	16.448
v_f = 8 m/min	17.019	20.22	15.831
v_f = 11 m/min	16.979	19.888	14.627
HW1	15.838	18.244	13.188
HW2	17.776	20.189	11.952
HW1 CrTiN	16.599	21.082	21.265
MDF	24.494	28.002	12.528
MDF-L	19.426	24.284	20.005
SEGP	6.292	7.2287	12.958
			15.469

v_c – cutting speed; v_f – feed rate; ΔR_a – percentage difference between the measured R_a values

Table 7 shows the percentage differences between the methods used for determining the R_a. The results indicated that higher R_a values were measured by the contactless method with the same settings for both of the profilometers in all of the cases. The total difference in the average R_a values was 15.5%. These differences were mainly because of the different *R* values of the arm or optical beam (2 µm/0.2 µm). Hendarto *et al.* (2006) determined the effect of various methods of the surface R_a evaluation and the changes in values between methods depending on the filtration used and partial difference of certain methods. The conclusions of the research by Budakçı *et al.* (2013) indicated that the laser method is more suitable for determining the surface quality than the contact method.

Table 8 shows an evaluation of the effect of factors on the surface R_a measured by the contactless method using Duncan's test. The R_a values measured by the contactless method indicated that there was a statistically significant difference between the cutting speeds of 20 m/s and 30 m/s. There was no statistically significant difference in the R_a values between the cutting speeds of 40 m/s and 60 m/s. This can be seen in Fig. 4, where it was clear that the differences in the R_a were not large after increasing the cutting speed from 40 m/s to 60 m/s. No statistically significant difference in the R_a values was confirmed between the feed rates of 8 m/min and 11 m/min. As with the contact method for measuring the R_a, the effects of the tool and material types were confirmed to be significant with a significance level of 0.000 for the contactless method.

Table 8. Comparison of the Effects of the Factors on the R_a using Duncan's Test – Contactless Method

No.	Cutting Speed (m/s)	(1) 20.621	(2) 20.079	(3) 19.146	(4) 19.507
1	20		0.030	0.000	0.000
2	30	0.030		0.000	0.022
3	40	0.000	0.000		0.147
4	60	0.000	0.022	0.147	

No.	Cutter Type	(1) 18.244	(2) 20.189	(3) 21.082
1	HW1		0.000	0.000
2	HW2	0.000		0.000
3	HW1 CrTiN	0.000	0.000	

No.	Material Type	(1) 28.002	(2) 24.284	(3) 7.2287
1	MDF		0.000	0.000
2	MDF-L	0.000		0.000
3	SEGP	0.000	0.000	

No.	Feed Rate (m/min)	(1) 19.407	(2) 20.220	(3) 19.888
1	4		0.000	0.026
2	8	0.000		0.125
3	11	0.026	0.125	

Table 9 shows an evaluation of the effect of factors on the surface R_a measured by the contact method using Duncan's test. A statistically significant difference was observed between the R_a values at the cutting speeds of 20 m/s and 30 m/s. At a cutting speed of 30 m/s, a significant difference was confirmed in comparison with all of the cutting speeds. The tool and material types were proven to be factors that very significantly affected the resulting surface R_a. For the feed rate, there was an insignificant difference between the feed rates of 8 m/min and 11 m/min.

Table 9. Comparison of the Effects of the Factors on the R_a Value Using Duncan's Test – Contact Method

No.	**Cutting Speed** (m/s)	**(1) 16.316**	**(2) 17.690**	**(3) 16.438**	**(4) 16.507**
1	20		0.000	0.328	0.148
2	30	0.000		0.000	0.000
3	40	0.328	0.000		0.578
4	60	0.148	0.000	0.578	

No.	**Cutter Type**	**(1) 15.838**	**(2) 17.776**	**(3) 16.599**
1	HW1		0.000	0.000
2	HW2	0.000		0.000
3	HW1 CrTiN	0.000	0.000	

No.	**Material Type**	**(1) 24.494**	**(2) 19.426**	**(3) 6.292**
1	MDF		0.000	0.000
2	MDF-L	0.000		0.000
3	SEGP	0.000	0.000	

No.	**Feed Rate** (m/min)	**(1) 16.215**	**(2) 17.019**	**(3) 16.979**
1	4		0.000	0.000
2	8	0.000		0.705
3	11	0.000	0.705	

Figures 7, 8, and 9 show the synergistic effect of all of the monitored factors on the R_a values.

After using the contactless method for measuring the R_a of the MDF, it was discovered that the values ranged from 24 µm to 37 µm. The lowest R_a values were measured with the HW1 milling cutter at a feed rate of 4 m/min and cutting speed of 60 m/s. In contrast, the highest values were recorded with the HW1 CrTiN milling cutter at a feed rate of 4 m/min and cutting speed of 30 m/s.

The value range when evaluating the R_a with the contact method was 21 µm to 29 µm. The lowest values were found using the HW1 milling cutter at a feed rate of 4 m/min and cutting speeds of 20 m/s, 30 m/s, and 60 m/s.

The measured R_a values showed that most of the best R_a results were achieved using the HW1 blade, even though the lowest values were not achieved with all of the factor combinations. The effect of the other blades seemed ambiguous.

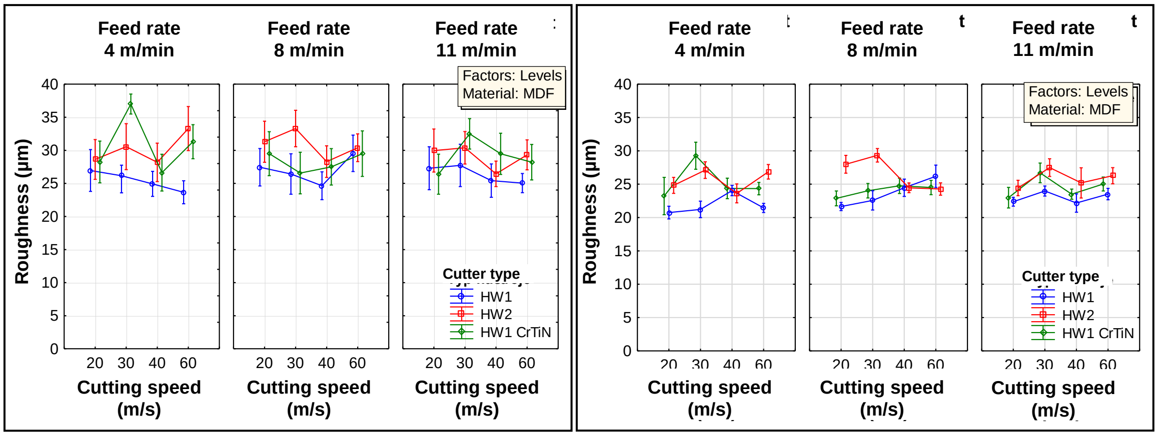

Fig. 5. Effect of the cutting speed, feed rate, and cutter type on the R_a of the MDF – contactless method on the left, contact method on the right

With the contact method for measuring the surface R_a of the MDF-L, the R_a values ranged from 19 µm to 27 µm (Table 9). The minimum values were found with the HW1 cutter at a feed rate of 4 m/min and cutting speed of 40 m/s, and with a feed rate of 11 m/min and cutting speed of 30 m/s. The highest R_a values were recorded with the HW2 and HW1 CrTiN cutters.

When measuring the R_a of the MDF-L with the contact profilometer, the R_a values ranged from 17 µm to 22 µm. The minimum mean R_a values were achieved with a feed rate of 4 m/min and cutting speeds of 40 m/s and 60 m/s for the HW1 milling cutter, and a feed rate of 4 m/min and cutting speed of 20 m/s for the HW1 CrTiN milling cutter.

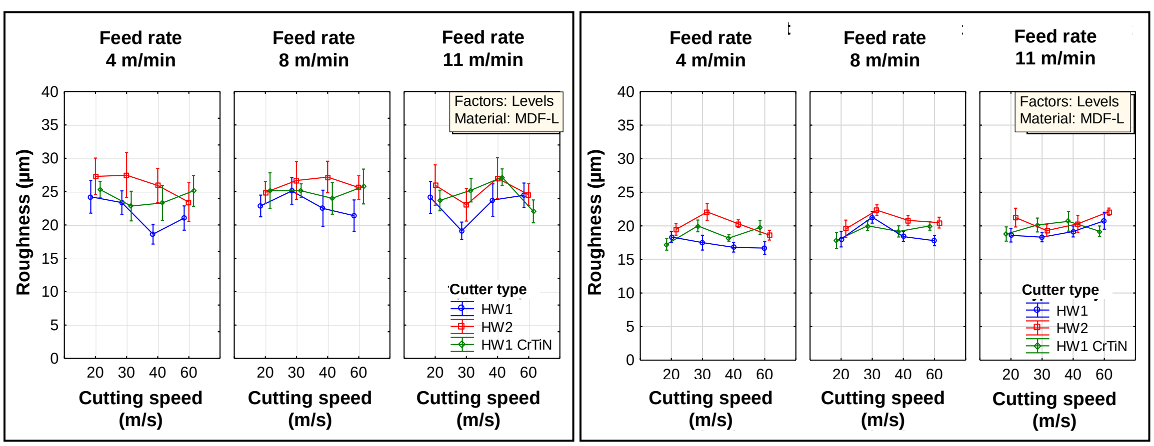

Fig. 6. Effect of the cutting speed, feed rate, and cutter type on the R_a of the MDF-L – contactless method on the left, contact method on the right

The R_a values of the SEGP when measured by the contactless method were in the range of 2 µm to 13 µm. The lowest R_a value was measured with the HW2 milling cutter at a feed rate of 4 m/min and cutting speed of 60 m/s. In contrast, the highest R_a values were recorded with the HW1 CrTiN milling cutter at a feed rate of 4 m/min and cutting speed of 20 m/s.

Table 10. Average R_a Values - Contactless Method

Cutting Speed (m/s)	Feed Rate (m/min)	Material Type	Cutter Type	R_a (µm)	Cutter Type	R_a (µm)	Cutter Type	R_a (µm)
20	4	MDF	HW1	27 (16.4)	HW2	29 (14.7)	HW1 CrTiN	28 (15.6)
30	4		HW1	6 (13.4)	HW2	31 (15.9)	HW1 CrTiN	37 (5.7)
40	4		HW1	25 (10.6)	HW2	28 (14.4)	HW1 CrTiN	27 (14.6)
60	4		HW1	24 (10.3)	HW2	33 (14.0)	HW1 CrTiN	31 (11.5)
20	8		HW1	27 (14.4)	HW2	31 (13.9)	HW1 CrTiN	29 (15.7)
30	8		HW1	26 (16.2)	HW2	33 (11.6)	HW1 CrTiN	27 (16.5)
40	8		HW1	25 (11.9)	HW2	28 (11.8)	HW1 CrTiN	28 (14.0)
60	8		HW1	30 (13.0)	HW2	30 (9.6)	HW1 CrTiN	29 (16.3)
20	11		HW1	27 (16.6)	HW2	30 (15.2)	HW1 CrTiN	26 (16.1)
30	11		HW1	28 (16.1)	HW2	30 (11.3)	HW1 CrTiN	32 (9.9)
40	11		HW1	25 (13.8)	HW2	26 (10.2)	HW1 CrTiN	29 (14.8)
60	11		HW1	25 (8.1)	HW2	29 (10.8)	HW1 CrTiN	28 (13.3)
20	4	MDF-L	HW1	24 (14.1)	HW2	27 (14.1)	HW1 CrTiN	25 (6.8)
30	4		HW1	23 (10.6)	HW2	27 (17.2)	HW1 CrTiN	23 (13.6)
40	4		HW1	19 (11.1)	HW2	26 (13.9)	HW1 CrTiN	23 (15.6)
60	4		HW1	21 (12.1)	HW2	23 (17.5)	HW1 CrTiN	25 (12.8)
20	8		HW1	23 (10.0)	HW2	25 (9.3)	HW1 CrTiN	25 (14.8)
30	8		HW1	25 (11.2)	HW2	27 (14.8)	HW1 CrTiN	25 (5.8)
40	8		HW1	22 (16.9)	HW2	27 (12.2)	HW1 CrTiN	24 (13.9)
60	8		HW1	21 (15.5)	HW2	26 (9.7)	HW1 CrTiN	26 (14.2)
20	11		HW1	24 (13.9)	HW2	26 (16.4)	HW1 CrTiN	24 (9.2)
30	11		HW1	19 (9.6)	HW2	23 (14.8)	HW1 CrTiN	25 (9.8)
40	11		HW1	24 (14.3)	HW2	27 (16.0)	HW1 CrTiN	27 (6.4)
60	11		HW1	24 (10.4)	HW2	25 (9.3)	HW1 CrTiN	22 (10.9)
20	4	SEGP	HW1	7 (15.8)	HW2	7 (15.5)	HW1 CrTiN	13 (8.3)
30	4		HW1	8 (15.0)	HW2	5 (8.5)	HW1 CrTiN	10 (9.2)
40	4		HW1	6 (15.0)	HW2	5 (15.5)	HW1 CrTiN	7 (13.0)
60	4		HW1	8 (6.8)	HW2	2 (11.1)	HW1 CrTiN	8 (11.8)
20	8		HW1	9 (12.9)	HW2	5 (13.6)	HW1 CrTiN	12 (10.6)
30	8		HW1	7 (8.8)	HW2	4 (15.0)	HW1 CrTiN	11 (13.9)
40	8		HW1	7 (9.5)	HW2	5 (6.8)	HW1 CrTiN	8 (11.6)
60	8		HW1	7 (5.9)	HW2	4 (8.0)	HW1 CrTiN	7 (9.8)
20	11		HW1	8 (14.1)	HW2	7 (12.4)	HW1 CrTiN	10 (9.1)
30	11		HW1	11 (16.5)	HW2	6 (16.9)	HW1 CrTiN	12 (9.9)
40	11		HW1	9 (14.9)	HW2	4 (12.0)	HW1 CrTiN	6 (12.7)
60	11		HW1	6 (9.9)	HW2	4 (13.6)	HW1 CrTiN	7 (13.3)

Values in parentheses are the coefficients of variation (CV) in %

Table 11. Average R_a Values - Contact Method

Cutting Speed (m/s)	Feed Rate (m/min)	Material Type	Cutter Type	R_a (µm)	Cutter Type	R_a (µm)	Cutter Type	R_a (µm)
20	4	MDF	HW1	21 (6.4)	HW2	25 (6.8)	HW1 CrTiN	23 (16.9)
30	4		HW1	21 (8.1)	HW2	27 (6.4)	HW1 CrTiN	29 (9.7)
40	4		HW1	24 (4.5)	HW2	24 (8.4)	HW1 CrTiN	24 (8.8)
60	4		HW1	21 (4.5)	HW2	27 (5.7)	HW1 CrTiN	24 (5.3)
20	8		HW1	22 (3.9)	HW2	28 (6.6)	HW1 CrTiN	23 (6.8)
30	8		HW1	23 (8.9)	HW2	29 (4.8)	HW1 CrTiN	24 (6.3)
40	8		HW1	24 (7.4)	HW2	24 (4.2)	HW1 CrTiN	25 (6.5)
60	8		HW1	26 (8.9)	HW2	24 (5.3)	HW1 CrTiN	25 (6.1)
20	11		HW1	22 (4.1)	HW2	24 (6.6)	HW1 CrTiN	23 (9.4)
30	11		HW1	24 (4.4)	HW2	27 (6.7)	HW1 CrTiN	27 (7.7)
40	11		HW1	22 (8.7)	HW2	25 (12.6)	HW1 CrTiN	24 (4.5)
60	11		HW1	24 (5.1)	HW2	25 (6.8)	HW1 CrTiN	25 (5.8)
20	4	MDF-L	HW1	18 (6.2)	HW2	19 (6.2)	HW1 CrTiN	17 (7.0)
30	4		HW1	18 (8.8)	HW2	22 (8.0)	HW1 CrTiN	20 (6.1)
40	4		HW1	17 (5.9)	HW2	20 (4.1)	HW1 CrTiN	18 (3.8)
60	4		HW1	17 (8.2)	HW2	19 (5.5)	HW1 CrTiN	20 (7.4)
20	8		HW1	18 (9.0)	HW2	20 (9.3)	HW1 CrTiN	18 (9.5)
30	8		HW1	21 (5.7)	HW2	22 (5.0)	HW1 CrTiN	20 (5.1)
40	8		HW1	18 (5.7)	HW2	21 (4.9)	HW1 CrTiN	19 (6.1)
60	8		HW1	18 (5.9)	HW2	20 (5.5)	HW1 CrTiN	20 (4.5)
20	11		HW1	19 (7.5)	HW2	21 (9.2)	HW1 CrTiN	19 (7.9)
30	11		HW1	18 (5.2)	HW2	19 (6.6)	HW1 CrTiN	20 (7.2)
40	11		HW1	19 (5.9)	HW2	20 (8.7)	HW1 CrTiN	21 (9.8)
60	11		HW1	21 (8.5)	HW2	19 (6.2)	HW1 CrTiN	19 (5.7)
20	4	SEGP	HW1	5 (11.4)	HW2	7 (11.5)	HW1 CrTiN	8 (14.4)
30	4		HW1	6 (7.1)	HW2	6 (15.0)	HW1 CrTiN	5 (16.8)
40	4		HW1	6 (19.3)	HW2	7 (19.9)	HW1 CrTiN	4 (21.0)
60	4		HW1	5 (17.4)	HW2	5 (16.9)	HW1 CrTiN	3 (33.0)
20	8		HW1	6 (8.2)	HW2	7 (7.8)	HW1 CrTiN	8 (16.1)
30	8		HW1	8 (14.0)	HW2	7 (18.4)	HW1 CrTiN	7 (15.1)
40	8		HW1	5 (11.0)	HW2	8 (10.1)	HW1 CrTiN	5 (11.2)
60	8		HW1	5 (12.6)	HW2	7 (18.9)	HW1 CrTiN	6 (14.5)
20	11		HW1	7 (7.3)	HW2	6 (13.1)	HW1 CrTiN	6 (8.6)
30	11		HW1	9 (5.7)	HW2	9 (13.7)	HW1 CrTiN	8 (7.3)
40	11		HW1	6 (11.8)	HW2	7 (11.7)	HW1 CrTiN	4 (12.3)
60	11		HW1	5 (14.7)	HW2	7 (11.5)	HW1 CrTiN	6 (16.8)

Values in parentheses are the CV in %

Škaljić *et al.* (2009), who dealt with the dependence of the surface quality on the feed rate in the machining of spruce wood, confirmed similar dependencies, *i.e.* the R_a decreased as the cutting speed increased.

The R_a values of the SEGP were generally lower than for the other materials. The R_a ranged from 3 µm to 9 µm. The minimum R_a value was measured with the HW1 CrTiN milling cutter at a feed rate of 4 m/min and cutting speed of 60 m/s.

It was not possible to unequivocally determine which instrument was the most suitable from the results, mostly because of the heterogeneous structure of the SEGP in its cross section.

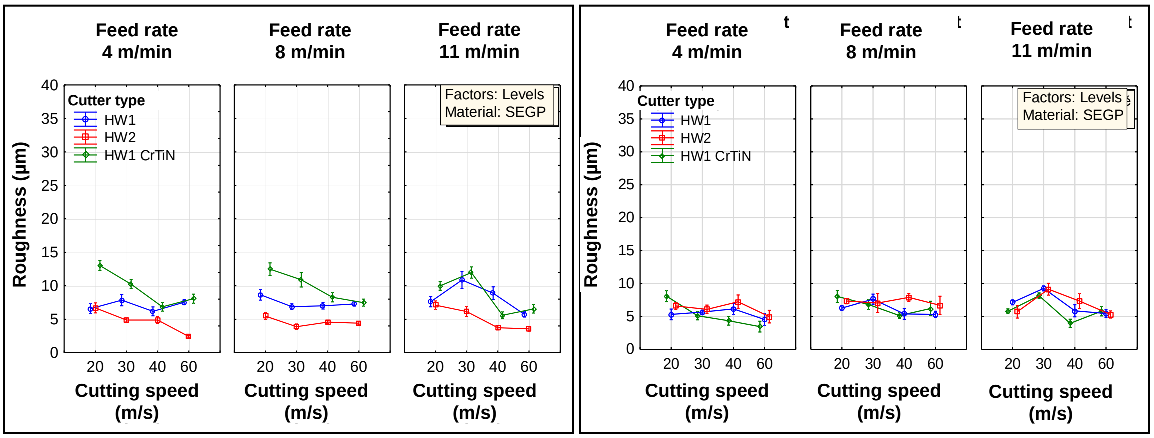

Fig. 7. Effect of the cutting speed, feed rate, and cutter type on the R_a of the SEGP – contactless method on the left, contact method on the right

Tables 10 and 11 show the average R_a values measured for each set of test specimens, as well as their coefficients of variation.

From the overall results, it was concluded that the optical contactless method was more accurate than the contact method. As was mentioned, the differences in the R_a values were caused by the different arm/beam R values. The contact method was limited by its own mechanical filter, which corresponded to the R of the arm (Fig. 8.).

For the machining parameter settings, the feed rates should be lower at higher cutting speeds to achieve the best results.

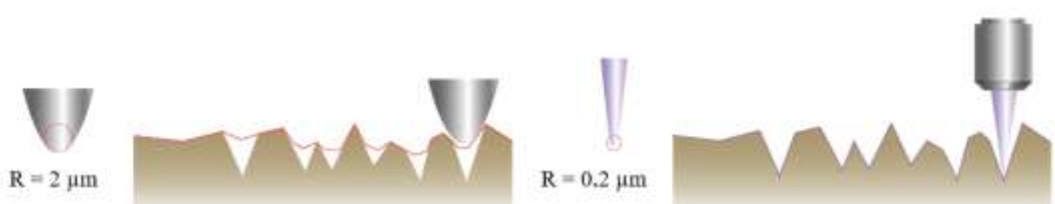

Fig. 8. Influence of radius on the measurement accuracy (left – contact method; right – contactless method)

CONCLUSIONS

1. With the contactless method, a standard dependence between the cutting speeds of 20 m/s, 30 m/s, and 40 m/s was demonstrated, *i.e.* the surface R_a decreased as the cutting

speed increased. With a further increase to 60 m/s, the surface quality slightly increased compared with the cutting speed of 40 m/s. These increased values were likely because of increased shaft vibrations. The differences in the R_a values were relatively insignificant for both methods.

2. A clear dependence between the feed rate and surface quality was demonstrated. As the feed rate increased, the resulting quality declined. Both methods used to measure the R_a had an almost identical effect.
3. When evaluating the individual types of milling cutters, it was found that the most suitable tool for machining the given materials was the HW1 milling cutter. With the contact method, the HW1 CrTiN milling cutter was shown to be more suitable than the HW2 milling cutter. In contrast, the HW2 milling cutter proved to be more suitable than the HW1 CrTiN milling cutter for the contactless method.
4. The machined material significantly affected the milling process. The R_a values during the machining of the MDF and MDF-L were 3.5 times higher than during the milling of the SEGP for both methods.
5. It was clear from the comparison of the contactless and contact methods for measuring the R_a that more accurate results were obtained by the contactless method. The R_a measured by the contactless method was 15.5% higher than those from the contact method. Therefore, it is better to use an optical profilometer to evaluate the R_a. The disadvantages of the optical profilometer are its higher purchase price, expensive maintenance, and complicated operation.

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