Surface Roughness of Medium-Density Fiberboard (MDF) and Edge-Glued Panel (EGP) After Edge Milling

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The mean arithmetic deviation of the roughness profile (R_a) was investigated for the edge surface after edge milling of medium-density fiberboard, medium-density fiberboard with single-sided lamination, and spruce edge-glued panel. Tungsten carbide blades with three different compositions and treatment (HW1, HW2, and HW1 + CrTiN coating) were used. During edge milling, the feed rate (4, 8, and 11 m/min) and cutting speed (20, 30, 40, and 60 m/s) were changed. The lowest roughness values were found in spruce timber, and the highest values were found in untreated MDF. The highest edge surface roughness was measured after using the HW2 tool. Slightly lower values were found using HW1 CrTiN, and the lowest values were found using HW1. Increasing the cutting speed led to a very slight increase in roughness. Increasing the feed rate had the same effect, but its effect was more significant. The article provides an understanding of the interaction of the most frequently occurring factors relative to the quality of the work surface of the large-area materials.

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

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INTRODUCTION

The quality of the machined wood surface is an important factor that affects the final appearance of the product or subsequent technological processes such as bonding (adhesion and cohesion), grinding, coating, and surface treatment (consumption of coating material, application method) (Lemaster and Dornfeld 1982; Candan *et al*. 2012; Očkajová *et al.* 2016).

Even the most carefully machined surface has a certain unevenness, most commonly defined by roughness and waviness. Surface roughness is manifested by microscopic and macroscopic recesses, ridges, elevations, or partially ripped bundles of wood fibers; their occurrence on the surface is mostly irregular (Söğütlü 2010). Waviness is caused by traces left by the tool, resulting from the kinematics of the tool or its disturbance, clamping inaccuracy, *etc*. In practice, roughness and waviness of the surface overlap, which is why it is sometimes recommended to merge them. However, sometimes it is necessary to distinguish waviness from roughness because they do not hold the same importance in the assessment of different types of workpieces. The roughness of the created surface depends on various factors and conditions (Davim *et al*. 2007; Thoma *et al*. 2015; Tiryaki *et al*. 2015), which can be broken down as follows:

- machining type (machining direction, geometry and positioning of tool) (Novák *et al*. 2011; Akgül *et al*. 2012),

- machining parameters (cutting speed, feed rate, etc.) (Gaitonde *et al*. 2008; Lu 2008; Škaljić *et al.* 2009; Barcík and Gašparík 2014),
- micro-geometry of tool (tool surface treatment, cutting edge wear),
- anatomy or composition as well as properties of machined material (wood species, material type, surface finishing) (Taylor *et al*. 1999; Gurau *et al*. 2005).

Even if the machining parameters are the same, each machining method leaves characteristic unevenness on the surface; for example, surfaces machined by a saw are different from milled surfaces (Costes and Larricq 2002; Kvietková *et al*. 2015a,c; Gaff *et al*. 2016; Kubš *et al*. 2016). Surface roughness is different based on the direction of the machining motion and the direction perpendicular to this motion.

Surface roughness requirements are specified according to the functional use of the future product (Aquilera and Martin 2001). In the past, surface roughness was mostly detected by visual and tactile inspections because these methods were fast and economical. However, these methods only provided subjective and qualitative estimates but did not ensure the appropriate quality of products or processes (Fujiwara *et al*. 2005). Due to requirements for accuracy, the sensory methods were replaced by numerical quantitative measurement. The surface roughness is determined by specifying a numeric value (maximum, minimum, nominal value, or range of values) of a parameter, or several parameters, and the baseline length value for which this parameter is determined. The current standardized system according to ČSN EN ISO 4287 (1999) evaluates individual components of the complex of unevenness, *i.e*., waviness and roughness separately. It defines the profile parameters for relevant profile characteristics (such as roughness profile R_p, R_a, R_z, *etc*.).

The quality of milled surfaces is significantly higher than that of sawed surfaces. However, not even milling guarantees an ideal smooth surface; there will always be a certain degree of roughness. The origin of unevenness on the milled surface depends on technological and technical causes, as well as the properties of the material (Kvietková *et al*. 2015b; Kminiak and Gaff 2015; Očkajová *et al.* 2014). Technological causes of unevenness during milling, such as chosen method, direction of milling, cutting speed, and feed speed, depend on the manufacturing process and determine the desired surface quality (Lavery *et al*. 1995; Mračková *et al.* 2016). Technical causes of surface unevenness are mainly due to machine parameters such as type of milling head, number and placement of blades, dulled cutting edge of the blades, blade setting accuracy, and tool vibration. Material properties are based on anatomical (wood species or material, grain direction, wood defects, *etc*.), physical (density, moisture content), and mechanical (hardness, strength, *etc*.) properties of the machined material (Novák *et al*. 2011). These properties, in interaction with technical and technological factors, create a range of surface roughness. Using inappropriate or blunt tools, poorly set milling parameters, or poor milling methods may result in mechanical damage to the surface (Steward 1984).

Milling wood-based materials is strictly dependent on their composition and density. Medium-density fiberboard (MDF) has a more homogeneous structure than solid wood. While solid wood has an anisotropic nature, MDF is composed of several isotropic layers (Zerizer *et al*. 2003; Boucher *et al.* 2007), where the highest density is at the edges and the lowest density is in the center. Unlike MDF, edge-glued panels (EGP) have properties almost identical to the solid wood of which they are composed (Sütçü 2013), although they usually have a slightly higher density (Sofuoglu 2017). EGP milling depends on the wood species, the mutual orientation of individual boards, their anatomical structure, and the occurrence of defects.

This research aimed to investigate edge surface roughness after edge milling of medium-density fiberboard (MDF), medium-density fiberboard with single-sided lamination (MDF-L), and spruce edge-glued panel (SEGP). The edge milling was carried out with 3 blades, each made of a different material or surface treatment. During edge milling, the basic parameters such as cutting speed (20, 30, 40, and 60 m/s) and feed rate (4, 8, and 11 m/min) were varied.

EXPERIMENTAL

Materials

Medium-density fiberboard (MDF), medium-density fiberboard with single-sided lamination (MDF-L), and edge-glued panel (SEGP) from Norway spruce (*Picea abies* L.) were used. Samples of 500 × 500 × 18 mm were prepared from these materials. All samples were conditioned for 2 weeks in a conditioning room (ϕ = (65 ± 3) % and t = (20 ± 2) °C) to achieve 12% equilibrium moisture content (EMC) ISO 13061-1 (2014). The density of the samples was determined according to ČSN EN 323 (1994), as shown in Table 1.

Table 1. Properties of 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 (Lukavec, Czech republic)
SEGP	Edge-glued panel from spruce wood	432	Holzindustrie Schweighofer s. r. o., (Tábor, Czech republic)

Fig. 1. Cutter head

Methods

Edge milling

The edge milling was carried out on a one-spindle edge milling machine (FVS) with a feeding system STEFF 2034 (Maggi Technology, Certaldo, Italy). The machining was performed with a two-blade milling cutter head (Felder, Hall in Tirol, Austria) (Fig. 1) with 3 blade types.

The removal thickness of 1 mm was constant during the edge milling. The edge of each sample was milled three times along its length. The edge milling parameters, as well as the tool geometry, are shown in Table 2.

Table 2. Cutting Parameters of Edge Milling and Cutter Geometry

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

Three types of milling blades produced by Leitz GmbH & Co. KG (Oberkochen, Germany) (Fig. 2) were chosen for the milling. Standard HW1 and HW2 blades from the manufacturer were used and not retrofitted. The HW1 + CrTiN blade was identical to the HW1 blade in terms of material, but its surface was additionally modified with a CrTiN coating. The coating was applied by the PVD (physical vapour deposition) method at SHM, s.r.o. (Šumperk, Czech Republic). This CrTiN coating applied by the PVD method is primarily designed for harder wood-based materials and is used to improve the dulling resistance and increase the durability of cutting tools.

Fig. 2. Blade types for edge milling

The dimensions and basic characteristics of the blades specified by the manufacturer are shown in Table 3. Based on a combination of milling parameters (cutting speed and feed rate), tool (material and treatment of blades) and materials (MDF, MDF-L, SEGP), 108 samples for edge milling were created.

Table 3. Properties of Milling Blades

Marking	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

Methods

The measurement was carried out using the roughness tester Form Talysurf Intra 2 (Taylor Hobson, Leicester, UK) on the lateral milled edge of the sample, on which the center was determined and one-centimeter sections were marked from the center, five sections to the left and five sections to the right.

Each section was divided into three equal parts (underneath each other) that were 6 mm wide. Each sample was measured 10 times, with one measurement per center of each of the one-centimeter sections. The roughness tester measured the roughness by inserting the arm with a tip radius of r_{tip}=2 µm. The Gaussian filter and λ_c were used to evaluate the roughness values.

The roughness was represented by the arithmetic mean deviation of the roughness profile (R_a) directly measured on edge surface. Mathematically, R_a is the arithmetic mean deviation of the profile from the midline within the range of the basic length l_r, calculated according to the principle shown in Fig. 3.

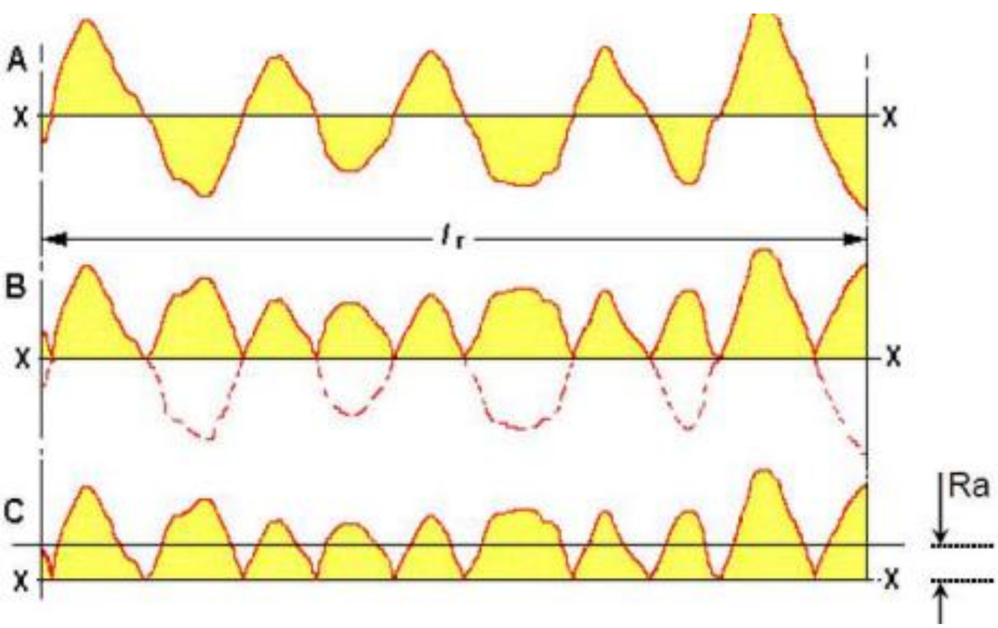

Fig. 3. Principle of roughness determination

The roughness values R_a were evaluated using STATISTICA 13 software (Statsoft Inc., Tulsa, OK, USA) and the MANOVA analysis. The analysis used a 95% confidence interval, which reflected a significance level of 0.05 ($P < 0.05$). The measuring conditions for roughness are given in Table 4.

Table 4. Measuring Conditions for Roughness

Periodical profiles	**Measuring conditions according to ČSN EN ISO 4287 (1999)**			
R_{Sm} (mm)	$\lambda_c = l_r$ (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

Note: R_{Sm} is the mean distance of roughness elements grooves, λ_c is the cutoff wavelength, l_r is the base length, l_n is the measuring length, l_t is the total length, r_{tip} is the radius of measuring tip, λ_f is the filter of long-wave parts on the surface. Highlighted conditions were used in this research.

RESULTS AND DISCUSSION

Based on the "P" significance levels, each of the monitored factors, as well as their four-factor interactions, had a statistically significant effect on the roughness after edge milling (Table 5). Figure 4 shows that the highest roughness values were achieved at a cutting speed of 30 m/s.

At the other monitored cuttings speeds, there was no statistically significant difference. In general, higher cutting speed results in improved surface quality and reduced cutting force (Costes and Larricq 2002). Similarly, according to Davim *et al*. (2009), surface roughness decreases as cutting speed increases.

Table 5. The Effect of the Factors and their Interaction with Roughness

Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F- Test**	**Significance Level *P***
Intercept	302561.2	1	302561.2	145531.5	0.000
1) Cutting speed	331.6	3	110.5	53.2	0.000
2) Tool type	685.9	2	342.9	165.0	0.000
3) Feed rate	147.9	2	73.9	35.6	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		

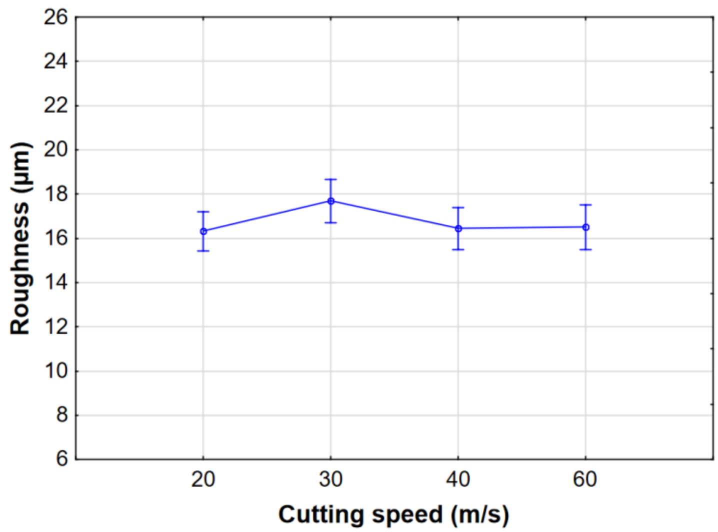

Fig. 4. The effect of the cutting speed on the roughness

In terms of surface quality, the type of tool used was highly significant (Fig. 5). The lowest roughness values were measured using the HW1 (15.8 µm) tool, and a statistically insignificant increase in roughness was found when using HW1 CrTiN (16.6 µm). The highest surface roughness values were achieved after milling with HW2 (17.8 µm). In this case, there was a statistically significant increase (12%) compared with the values measured using the HW1 tool. Generally, the tool type, namely tool material, rake angle, and tool wear, is a parameter that affects the surface roughness (Kminiak *et al.* 2016).

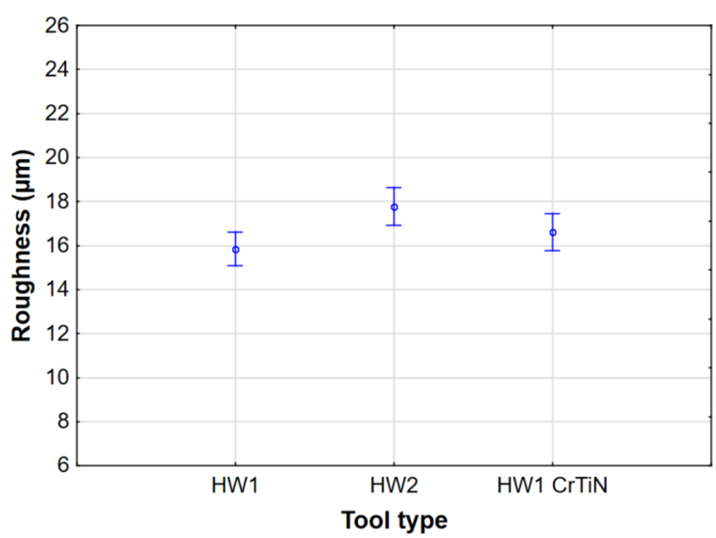

Fig. 5. The effect of the tool type on the roughness

The lowest roughness values were achieved at a feed rate of 4 m/min (16.21 µm) (Fig. 6). At feed rates of 8 and 11 m/min, the measured values were statistically significantly higher than at a feed rate of 4 m/min. No significant difference was found between roughness values measured at feed rates of 8 m/min and 11 m/min. In these cases, the difference was only 0.23 %, whereas the R_a value for a feed rate of 8 m/min was the highest. Davim *et al*. (2009) also found that the surface roughness increases as the feed rate increases.

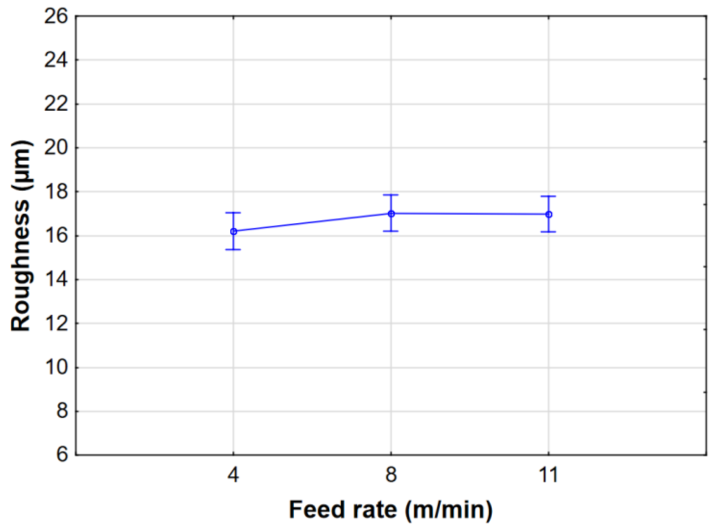

Fig. 6. The effect of the feed rate on the roughness

When machining fir wood, Škaljić *et al.* (2009) discovered a significant increase in R_a when the feed rate was increased from 6 m/min to 12 m/min. However, a further increase in the feed rate to 18 m/min made no significant difference.

In terms of the quality of the machined surface, the material is the factor with the most significant effect of all the monitored factors (Fig. 7). In SEGP, an average roughness value of 6.29 µm was found, while in MDF–L this value was 19.43 µm. In MDF materials, it was 24.49 µm. It is clear from the above that in the case of material, a statistically very significant difference was found between all the monitored sets of samples. The density of the material contributed to this fact the most, as confirmed by Lin *et al.* (2006), who found that the density of materials has a great effect on their machinability characteristics.

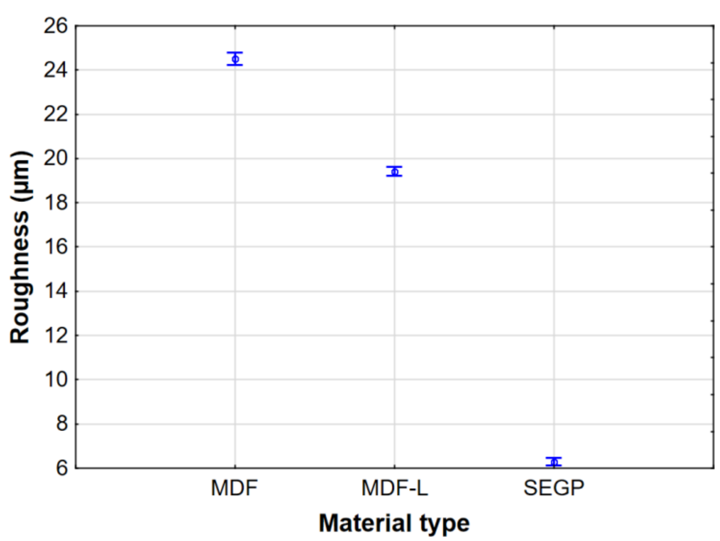

Fig. 7. The effect of the material type on the roughness

Table 6 shows the evaluation of the effect of factors on the roughness using Duncan's test. The results clearly show a statistically significant difference between the roughness values measured at cutting speeds of 20 and 30 m/s. There was no statistically significant difference in roughness values between cutting speeds of 20, 40, and 60 m/s.

Table 6. Comparison of the Effects of Factors on Roughness Using Duncan Test

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.	Tool type	(1) 16.599	(2) 15.838	(3) 17.776
1	HW1 CrTiN		0.000	0.000
2	HW1	0.000		0.000
3	HW2	0.000	0.000	

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

No.	Feeding 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	

The effect of the tool in all the observed cases was confirmed as a very significant factor with a significance level of P = 0.000. The effect of the feed rate corresponds with the results in Fig. 6, where it is apparent that the difference in roughness by changing the feed rate from 8 to 11 m/min was not great. The effect of the type of material was a very significant factor with a significance level of P = 0.000.

Figures 8 through 10 show the synergistic effect of all 4 monitored factors on roughness values. In all monitored interactions, the effect of the material significantly contributed to the change in the measured values. Another factor with a significant effect on the synergistic effect of the monitored factors is the tool type. MDF machining showed that the lowest R_a was achieved using a HW1 milling cutter, a feed rate of 4 m/min, and cutting speeds of 20, 30 and 60 m/s. The R_a value was identical in these cases, namely 21 µm. The lowest value was achieved at the lowest feed rate (feed per tooth) (Wilkowski *et al*. 2015). The highest value for the HW1 tool was 26 µm at a cutting speed of 60 m/s and a feed rate of 8 m/min. The maximum R_a in MDF was achieved using HW2 tools (cutting speed 30 m/s and feed rate 8 m/min) and HW1 CrTiN (cutting speed 30 m/s and feed rate 4 m/min), at a value of 29 µm. The interval for all R_a values was 21 to 29 µm (Table 7).

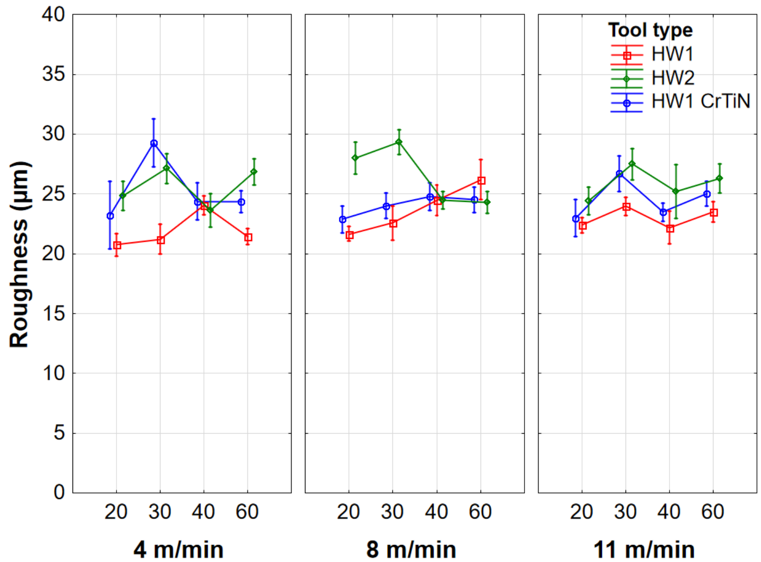

Fig. 8. The effect of cutting speed, feed rate, and tool type on the roughness of MDF

When machining single side laminated MDF, the R_a ranged from 17 µm to 22 µm. In comparison with MDF, these values are lower and have a smaller interval. The minimum value was achieved at a feed rate of 4 m/min using the HW1 tool at cutting speeds of 40 and 60 m/s, and for HW1 CrTiN at a cutting speed of 20 m/s. In contrast, the highest R_a values were achieved with the HW2 tool at a cutting speed of 30 m/s and feed rates of 4 and 8 m/min.

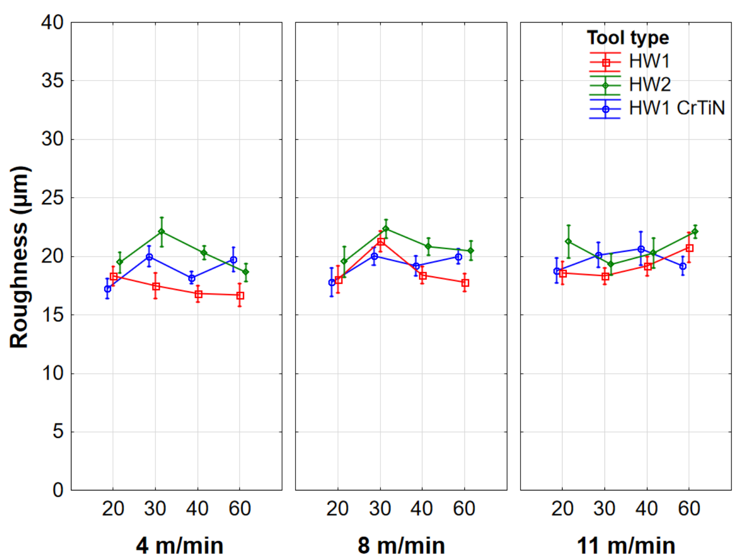

Fig. 9. The effect of cutting speed, feed rate, and tool type on the roughness of MDF-L

When determining the R_a after SEGP machining, the values were generally lower than those measured in the machining of MDF and MDF-L. The values ranged from 3 to 9 µm (Table 7), with the minimum value achieved in one case at a cutting speed of 60 m/s and a feed rate of 4 m/min using the HW1 CrTiN tool. The maximum of the value range was achieved using tools HW1 and HW2 at a cutting speed of 30 m/s and a feed rate of 11 m/min. Similar dependencies are shown in the research by Škaljić, *et al.* (2009), who dealt with the feed rate dependence in the machining of fir wood.

Table 7. Average Values of Roughness

Cutting speed (m/s)		**Feed rate** (m/min)	**Material type**	**Tool type**	R_a (µm)	**Tool type**	R_a (µm)	**Tool type**	R_a (µm)
20		4		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		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		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 coefficients of variation (CV) in %

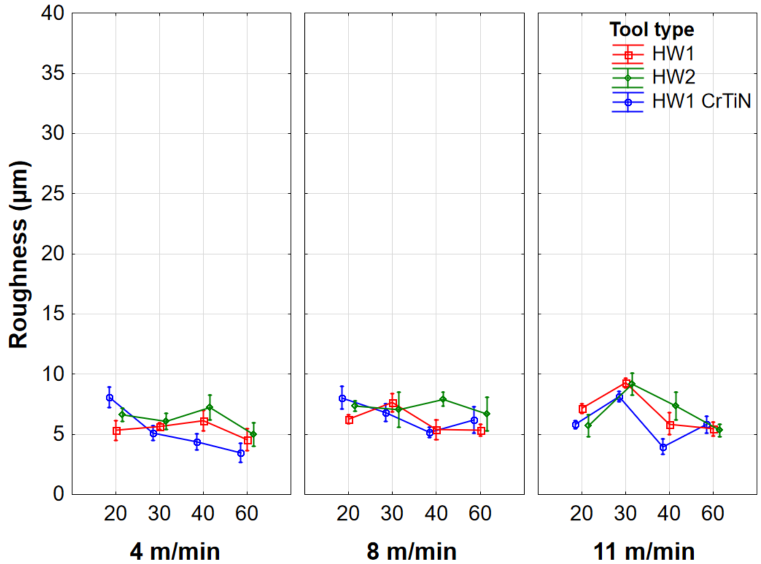

Fig. 10. The effect of cutting speed, feed rate, and tool type on the roughness of SEGP

In all of the evaluated machined materials, the maximum value was measured using the HW2 tool, although some of the maximum values were the same for other types of tools. Interestingly, all of the maximum values for all milled materials were achieved at a cutting speed of 30 m/s, while the minimum values did not have one common factor.

CONCLUSIONS

1. In general, the cutting speed had a statistically significant effect on the roughness values, but this effect was not clear. The differences in roughness achieved at individual speeds were not significant. The cutting speed of 30 m/s had the most pronounced effect, especially in MDF.
2. The effect of the feed rate was clear: an increase in the feed rate resulted in a direct proportional increase in roughness. However, the difference in roughness found at the highest and lowest feed rate was only 4.7%.
3. The highest edge surface roughness was measured after using the HW2 tool. Slightly lower values were found using HW1 CrTiN, and the lowest values were found using HW1.
4. The effect of the machined material was the most pronounced. The roughness found after MDF milling reached values that were 26.3% higher than values measured in MDF-L, and up to 289% higher than the roughness measured in SEGP.
5. The article provides an understanding of the interaction of the most frequently occurring factors with the quality of the work surface of medium-density fiberboard.

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