

## **MEDIUM-DENSITY FIBERBOARD AND EDGE-GLUED PANEL AFTER EDGE MILLING - SURFACE WAVINESS AFTER MACHINING WITH DIFFERENT PARAMETERS MEASURED BY CONTACT AND CONTACTLESS METHOD**

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### **ABSTRACT**

This article deals with the quality of the milled surface of board edges. The quality is evaluated using the  $W_a$  (mean arithmetic deviation of the surface waviness). The  $W_a$  was measured by two methods (contact and contactless). Form Talysurf 50 Intra was used for the contact method, and the LEXT 3D measuring laser microscope OLS4100 was used for the contactless method.

The variable factors whose effect on the resulting waviness was determined were the machined material, milling cutters, cutting speed and feed rate. The boards used were medium-density fiberboard, medium-density fiberboard with single-sided lamination and spruce edge-glued panel. Three different cutters were used for the milling, all of which were made of sintered carbide, and one of them was coated (CrTiN). The cutting speeds were 20, 30, 40 and 60 m·s<sup>-1</sup>, and the feed rates were 4, 8 and 11 m·min<sup>-1</sup>.

All the above-mentioned factors as well as their mutual interaction had an effect on the waviness. There was no significant difference between the two methods for determining the waviness. In terms of waviness, both methods are interchangeable.

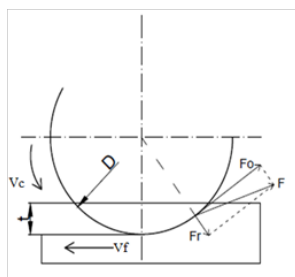
**KEYWORDS:** Roughness, feed rate, cutting speed, edge milling, medium-density fiberboard, edge-glued panel.

## INTRODUCTION

Wood as a material of widespread use, a natural origin, interesting appearance and specific properties, has interested mankind since the very beginning (Simanov 1993). In addition to solid wood in the form of logs and timber, wood-based materials are also widely used. Due to increasing technical progress, the possibilities for processing wood and wood materials and the production of technologically superior materials are increasing. To a certain extent, wood-based materials preserve the good properties of wood and exceed its unfavorable properties (Kvietkova et al. 2015a, b, c, Gaff et al. 2016, Sedlecký and Sarvašová Kvietková 2017).

These materials have gained their place and have become a dynamically developing sector in various industries. Today, they represent a wide range of flat and shaped products that are used in the furniture industry, construction, and other industries. The production of wood materials increases the efficient utilization of wood, to which today's technology also contributes (Štefka 2007). Classic machining methods are used to process wood-based materials. The machining process involves the removal of material, either by conventional methods or by unconventional methods. Each machining method is characterized by its own kinematics, cutting conditions, etc., which is the cause of different surface layers obtained by different machining methods (Kocman 2011, Kminiak and Gaff 2015, Kubš et al. 2016).

The rapidly changing market and product requirements, as well as quality requirements, forces design engineers to work on new projects that they can adapt to these requirements in the shortest time possible. Today, there are plenty of technologies on the market that respond flexibly to the constant movement (Aguilera et al. 2013). These technologies also include the milling process. Milling is classified as a chip-forming machining operation. Milling is a mechanical machining process in which the main cutting motion is the rotary motion of the milling cutter, and the workpiece is fed into the cutter (Fig. 1).



$F_o$  - circumferential component of the cutting force,  $F_r$  - radial component of the cutting force,  $D$  - tool diameter,  $v_c$  - cutting speed, and  $v_f$  - feed rate

*Fig. 1: Milling process.*

The chip thickness changes from zero to a certain maximum value. A chip thickness that is too small reduces the yield of the milling cutter and results in early wear of the blade (Mračková et al. 2016, Očková et al. 2016). The maximum chip thickness is given by the protrusion of the cutting blade from the cutter head. In practice, wood milling is a very widespread method of machining wood and wood-based materials. The workpiece can be machined to the desired shape and dimensions through the milling process. The basic feature of milling is the uneven but wavy appearance of the milled surface, resulting from the cycloid shape of the chips indicated by

the motion of the cutting edge on the workpiece. As a result, it is not possible to achieve an ideal smooth surface of the workpiece even with milling, and it is appropriate to deal with the quality of the machined surface. Over time and as wood consumption increases, the requirements for its use as well as the quality of the machined surface have also increased (Liptáková et al. 1995).

The quality of the machined surface is determined according to the machining method, appearance and depth of the marks made by the tool (Davim 2009). It is what the surface looks like, how it's curved, the direction of the grooves, how deep they are, etc. The appearance of the surface varies with each machining method, and it depends primarily on the kinematics of the machining method as well as the tool geometry (Aytin and Korkut 2016). The resulting profile of the workpiece also depends on the cutting conditions such as the cutting speed, feed rate and the depth of material removal. Surface roughness is caused by surface irregularities with relatively small spacing, including irregularities resulting from the machining method used or other influences involved in the machining process (Fujiwara et al. 2004, Sandak et al. 2011). These irregularities are believed to remain within defined boundaries, e.g. within the boundaries of the base length. As a shape deviation, waviness is placed between the roughness and shape deviation. In terms of the quality of the machined surface, in planar milling we evaluate the  $W_a$  (mean arithmetic deviation of the waviness profile, i.e. the surface waviness).

## MATERIALS AND METHODS

### Materials

A large-area material with a thickness of 18 mm was used for the machining. Three types of materials were milled: MDF = medium-density fiberboard, MDF-L = medium-density fiberboard with single-sided lamination and SEGP = edge-glued panel (Norway spruce, *Picea abies* L). The dimensions of the samples for milling were 500x500x18 mm. All samples were then conditioned for 2 weeks in a conditioning room ( $\phi=(65\pm3)\%$  and  $t=(20\pm2)^\circ\text{C}$ ) to achieve 12% equilibrium moisture content (EMC). The density of individual materials is shown in Tab. 1, and it was determined according to EN 323 (1993).

Tab. 1: Properties of construction materials.

Marking	Construction material	Density ( $\text{kg}\cdot\text{m}^{-3}$ )	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)

### Methods

The milling parameters and tool geometry are listed in Tab. 2. The edges of the samples were machined with all combinations of the individual factors on a one-spindle edge milling machine (FVS) with feeding system STEFF 2034 (Maggi Technology, Certaldo, Italy). The blades were mounted on two-blade milling cutter heads (Felder, Hall in Tirol, Austria) (Fig. 2.). Each sample was milled three times with a material removal of 1 mm.



Fig. 2: Cutter head.



Fig. 3: Blade types for edge milling.

Tab. 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 $\alpha$	10°
RPM	3000, 4500, 6000 and 9000	Cutting angle of wedge $\beta$	60°
Cutting speed	20, 30, 40 and 60 m·s <sup>-1</sup>	Rake angle $\gamma$	20°
Feed rate	4, 8, and 11 m·min <sup>-1</sup>	Cutting angle $\delta$	70°

Three types of milling cutters were used for the machining. All blades were manufactured by Leitz GmbH & Co. KG, (Oberkochen, Germany) (Fig. 3). The properties of the milling cutters are shown in Tab. 3. The HW1 and HW2 milling cutters were made of Tungsten carbide. The core of milling cutter HW1 CrTiN was made of the same material as milling cutter HW1, with the addition of CrTiN coating. The coating was applied at SHM, s.r.o. (Šumperk, Czech Republic).

Tab. 3: Properties of milling blades.

Marking	Cutting material	Blade type	Dimensions (mm)	Microhardness HV <sub>m</sub> (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 a combination of milling parameters (cutting speed, feed rate), tool (material and treatment of blades) and materials (MDF, MDF-L, SEGP), 108 samples for edge milling were created. Each sample was measured 10x, amounting to 1,080 waviness measurements.

Methods

The LEXT 3D optical profilometer, the OLS4100 measuring laser microscope (contactless measurement) and the Form Talysurf 50 Intra profilometer (contact measurement) were used for the measuring. OLS4100 is the laser microscope, for measuring was used optic MPLAPON50XLEXT (marked: MPlanApoN, 50x/0,95 LEXT, ∞/0/FN18), which is define for roughness. Accuracy of the laser microscope measurement is ± 2 %. Same measurement accuracy has Form Talysurf 50 Intra. The Wa was measured according to ČSN EN ISO 4287 (1999) and evaluated after applying the Gaussian filter. Measuring conditions for waviness are in Tab. 4.

Tab. 4: Measuring conditions for waviness.

Periodical profiles	Measuring conditions according to ČSN EN ISO 4287 (1999)			
$RS_m$ (mm)	$\lambda_c$ (mm)	$l_n$ (mm)	$l_t$ (mm)	$rtip$ ( $\mu m$ )
$0.013 < RS_m \leq 0.04$	0.08	0.4	0.48	2
$0.04 < RS_m \leq 0.13$	0.25	1.25	1.5	2
$0.13 < RS_m \leq 0.4$	0.8	4	4,8	2 or 5
$0.4 < RS_m \leq 1.3$	2.5	12.5	15	5
$1.3 < RS_m \leq 4$	8	40	48	10

Note:  $RS_m$  is the mean distance of roughness elements grooves,  $\lambda_c$  is the cutoff wavelength,  $l_n$  is the measuring length,  $l_t$  is the total length,  $rtip$  is the radius of measuring tip.

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

## RESULTS AND DISCUSSION

Tabs. 5 and 6 show the effect of each variable factor and their mutual interaction on the surface waviness. The level of significance “P” for all the monitored factors is less than 0.05; we can therefore conclude that all the factors and their mutual interaction have a statistically significant effect on the monitored waviness.

Tab. 5: The effect of individual factors and their interaction on the waviness –contactless method.

Monitored factor	Sum of squares	Degree of freedom	Variance	Fisher's F - Test	Significance Level “P”
Intercept	620162.2	1	620162.2	56558.08	0.000
1) Cutting speed	2042.5	3	680.8	62.09	0.000
2) Feed rate	364.3	2	182.1	16.61	0.000
3) Tool type	321.9	2	160.9	14.68	0.000
4) Material type	19266.1	2	9633.0	878.52	0.000
1; 2; 3; 4	5920.2	24	246.7	22.50	0.000
Error	10658.0	972	11.0		

Tab. 6: The effect of individual factors and their interaction on the waviness – contact method.

Monitored factor	Sum of squares	Degree of freedom	Variance	Fisher's F - Test	Significance Level “P”
Intercept	628866.4	1	628866.4	11780.2	0.000
1) Cutting speed	2575.663	3	858.554	16.083	0.000
2) Feed rate	794.482	2	397.241	7.441	0.001
3) Tool type	3187.782	2	1593.891	29.858	0.000
4) Material type	12919.6	2	6459.839	121.009	0.000
1; 2; 3; 4	7245.892	24	301.912	5.656	0.000
Error	51888.2	972	53.383		

It is clear from the waviness values measured by the contact and contactless method that as the cutting speed increases, the waviness values decrease (Fig. 4). Research by Gaff et al. (2015) had the same results. We could say that in terms of waviness, a higher cutting speed that ensures the smoothest surface of the machined workpiece is the most suitable. No significant differences were found in the comparison of the methods for measuring the waviness.

Keturakis and Juodeikienė (2007) showed the relationship between the surface quality and cutting speed. As the cutting speed increased, the quality of the surface also increased.

However, the curve shows that the values were reversed at cutting speeds of 30 and 40 m·s<sup>-1</sup>. Therefore, the Wa is higher at a cutting speed of 30 m·s<sup>-1</sup> than at a speed of 40 m·s<sup>-1</sup> for the contact method, and on the contrary, the Wa values are higher at m·s<sup>-1</sup> for the contactless method.

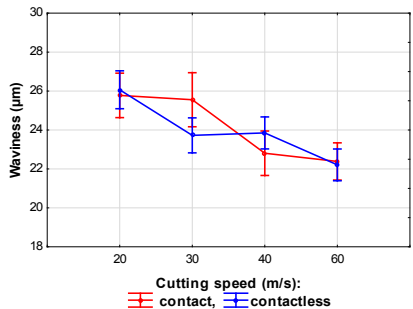


Fig. 4: The effect of the cutting speed on the waviness.

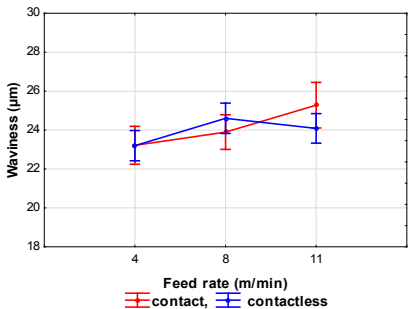


Fig. 5: The effect of the feed rate on the waviness.

The surface waviness, whether its mean arithmetic deviation profile or highest profile, increases as the feed rate increases, which means that the surface quality deteriorates. This fact is captured in Fig. 5. The causes of this decrease are the surface quality (waviness and roughness) of the real cutting edge, plastic deformations of the cut surface and vibration. If vibration is generated, there may be a greater increase in quality indicators in small shifts in comparison to greater shifts. Similar results were reported by Rousek et al. (2012).

For the feed rate, there was no significant difference between the contact and contactless methods. Fig. 5 clearly shows that at a feed rate of 4 m·min<sup>-1</sup> the values are almost identical; when comparing feed rates of 8 and 11 m·min<sup>-1</sup>, the values for the contactless method show a declining tendency, although the decline is not significant, and with the contact method they show a rising tendency.

The effect of the tool material on the surface quality during milling was confirmed by Siklienka and Adamcová (2012) in their research.

From a comparison of the methods for measuring waviness (Fig. 6), we can conclude that the HW2 tool showed a significant difference. The average waviness values when measuring with the contact method are 14.5% higher for the HW2 tool than the average values measured by the contactless method. No significant difference was demonstrated for the other types of tools. Budakci et al. (2013) found that the laser method is more suitable than the contact method for a more accurate assessment of the surface quality.

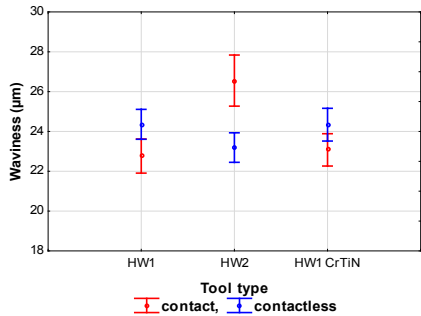


Fig. 6: The effect of the tool type on the waviness.

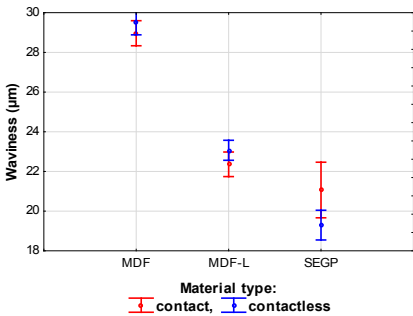


Fig. 7: The effect of the material type on the waviness.

In both cases, the highest waviness values were found in MDF (Fig. 7). Uneven waves are formed on the surface during milling, depending on the number of blades, the tool speed and the feed rate. The number of waves per unit of length (cm) is a decisive factor in the quality of the machined workpiece. When machining solid wood, 6 waves per 1 cm are acceptable. When machining MDF, due to the finer structure of the material, it is necessary to achieve at least 8 waves per 1 cm for a high-quality surface (Hrázský and Král 2004, 2007). On the contrary, the surface quality of spruce battenboard in terms of the waviness was the best of all the materials used, and it was the opposite of MDF and MDF-L when comparing the methods for determining the  $W_a$ .

Tab. 7 shows the percentage differences of individual mean values for all the variable factors. It is evident that the greatest difference was found in the HW2 blade, where the difference was 14.5%, and higher waviness values were found with the contact method.

Tab. 7: Percentage differences between the contact and contactless methods for measuring the  $W_a$ .

	Waviness		$\Delta W_a$ (%)
	Contact	Contactless	
$vc = 20 \text{ (m}\cdot\text{s}^{-1}\text{)}$	25.777	26.066	1.109
$vc = 30 \text{ (m}\cdot\text{s}^{-1}\text{)}$	25.555	23.724	-7.718
$vc = 40 \text{ (m}\cdot\text{s}^{-1}\text{)}$	22.806	23.852	4.385
$vc = 60 \text{ (m}\cdot\text{s}^{-1}\text{)}$	22.385	22.21	-0.788
$vf = 4 \text{ (m}\cdot\text{min}^{-1}\text{)}$	23.217	23.198	-0.082
$vf = 8 \text{ (m}\cdot\text{min}^{-1}\text{)}$	23.897	24.605	2.877
$vf = 11 \text{ (m}\cdot\text{min}^{-1}\text{)}$	25.278	24.086	-4.949
HW1	22.763	24.358	6.548
HW2	26.554	23.191	-14.501
HW1 CrTiN	23.075	24.34	5.197
MDF	28.965	29.525	1.897
MDF-L	22.36	23.067	3.065
SEGP	21.067	19.297	-9.172
			-0.933

The average percentage difference between the contactless and contact method was less than one percent (0.933 %), namely the average values found for the contactless method were 0.933% lower than those found for the contact method.

Research by Ohlídal (2010) indicates that optical methods of determining surface texture are not so common in practice, but they could very well supplement the methods of contact profilometry.

When evaluating the waviness results with Duncan's test (Tab. 8) measured by the contactless method, a statistically significant difference with a value of  $P = 0.000$  was found for the cutting speed in all monitored parameters, with the exception of values measured between cutting speeds of 30 and 40  $\text{m}\cdot\text{s}^{-1}$ . The effect of the feed rate was statistically very significant for all the determined parameters. As with the contact method, the tool type was proven to have a significant effect with a significance level of  $P = 0.000$  for the HW2 milling cutter in comparison with other tools. There was no statistically significant difference between the HW1 and HW1 CrTiN tool. As with the contact method, the effect of the material type was shown to have a significant effect in all the monitored cases.

Tab. 8: Comparison of the effect of individual factors on waviness using Duncan's test – contactless method.

N	Cutting speed ( $\text{m}\cdot\text{s}^{-1}$ )	(1) 26.066	(2) 23.724	(3) 23.852	(4) 22.210
1	20		0.000	0.000	0.000
2	30	0.000		0.653	0.000
3	40	0.000	0.653		0.000
4	60	0.000	0.000	0.000	

N	Feed rate ( $\text{m}\cdot\text{min}^{-1}$ )	(1) 23.198	(2) 24.605	(3) 24.086
1	4		0.000	0.000
2	8	0.000		0.036
3	11	0.000	0.036	

N	Tool type	(1) 24.358	(2) 23.191	(3) 24.340
1	HW1		0.000	0.942
2	HW2	0.000		0.000
3	HW1 CrTiN	0.942	0.000	

N	Material type	(1) 29.525	(2) 23.067	(3) 19.297
1	MDF		0.000	0.000
2	MDF-L	0.000		0.000
3	SEGP	0.000	0.000	

Tab. 9 shows the effect of each parameter on the waviness using Duncan's test and the contact method. A statistically significant difference between values measured at cutting speeds of 20 and 40  $\text{m}\cdot\text{s}^{-1}$  was found, as well as between the values found at cutting speeds of 20 and 60  $\text{m}\cdot\text{s}^{-1}$ . A comparison of the cutting speed of 30  $\text{m}\cdot\text{s}^{-1}$  with other values also showed a statistically

significant difference compared to the values measured at cutting speeds of 40 and 60 m·s<sup>-1</sup>. A statistically significant difference was found for virtually all the combinations of feed rates, but no difference was found between feed rates of 4 and 8 m·min<sup>-1</sup>. We can see that between feed rates of 8 and 11 m·min<sup>-1</sup> the level of significance was  $P = 0.011$ , i.e. the difference between these feed rates is statistically significant, but the difference is not as significant as for the other feed rates. An evaluation of the effect of the type of blade on the waviness did not show a statistically significant difference between the HW1 and HW1 CrTiN blade, but a statistically significant difference was demonstrated in all other blade type combinations. The last evaluated factor was the type of milled material. Here a statistically significant difference was found for all individual combinations of all types of material.

*Tab. 9: Comparison of the effect of individual factors on waviness using Duncan's test – contact method.*

N	Cutting speed (m·s <sup>-1</sup> )	(1) 25.777	(2) 25.555	(3) 22.806	(4) 22.385
1	20		0.724	0.000	0.000
2	30	0.724		0.000	0.000
3	40	0.000	0.000		0.504
4	60	0.000	0.000	0.504	

N	Feed rate (m·min <sup>-1</sup> )	(1) 23.217	(2) 23.897	(3) 25.278
1	4		0.212	0.000
2	8	0.212		0.011
3	11	0.000	0.011	

N	Tool type	(1) 22.763	(2) 26.554	(3) 23.075
1	HW1		0.000	0.566
2	HW2	0.000		0.000
3	HW1 CrTiN	0.566	0.000	

N	Material type	(1) 28.965	(2) 22.360	(3) 21.067
1	MDF		0.000	0.000
2	MDF-L	0.000		0.018
3	SEGP	0.000	0.018	

With the contactless method for measuring waviness, the average values found in MDF ranged from 19 µm to 39 µm (Tab. 10). The lowest waviness values were achieved with the HW1 tool, a cutting speed of 60 m·s<sup>-1</sup> and a feed rate of 4 m·min<sup>-1</sup>. The highest waviness value was measured with the tool with CrTiN coating at a cutting speed of 20 m·s<sup>-1</sup> and a feed rate of 4 m·min<sup>-1</sup>.

For the contact method, the average waviness values during the machining of MDF ranged from 22 to 37 µm (Tab. 11). The best quality was achieved using the HW1 blade at a cutting speed of 40 m·s<sup>-1</sup> and a feed rate of 11 m·min<sup>-1</sup>. The highest value was measured using the HW1 blade again at the highest feed rate and the lowest cutting speed.

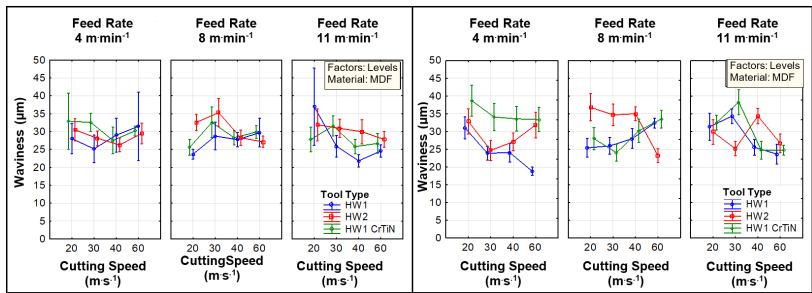


Fig. 8: The effect of cutting speed, feed rate and tool type on the waviness of MDF (contact method on the left, contactless method on the right).

The average waviness values determined by the contactless method for MDF-L ranged from 17 µm to 34 µm (Tab. 10). As with the contact method of measuring waviness, with the contactless method the highest average Wa value was also recorded with the HW1 CrTiN tool at a cutting speed of 30 m·s<sup>-1</sup> and a feed rate of 8 m·min<sup>-1</sup> (34 µm). The lowest average values (17 µm) were recorded with the following combination: HW1 milling cutter, cutting speed of 40 m·s<sup>-1</sup> and feed rate of 4 m·min<sup>-1</sup>.

With the contact method, the lowest values were measured with the HW1 blade at a feed rate of 4 m·min<sup>-1</sup> and a cutting speed of 40 m·s<sup>-1</sup>, and at a feed rate of 11 m·min<sup>-1</sup> and a cutting speed of 30 m·s<sup>-1</sup>. The average value interval with the contact method was 18 – 31 µm.

The most suitable milling cutter in terms of the resulting waviness of the machined surface is the HW1 milling cutter.

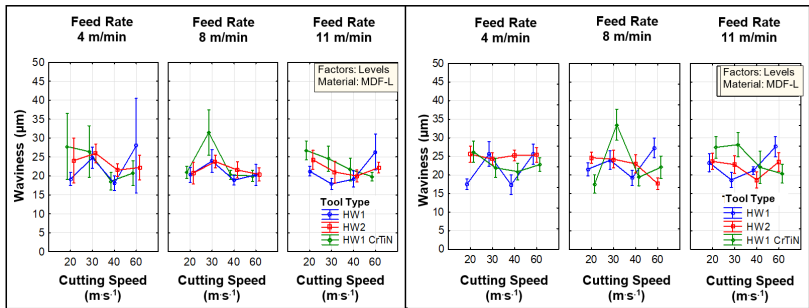
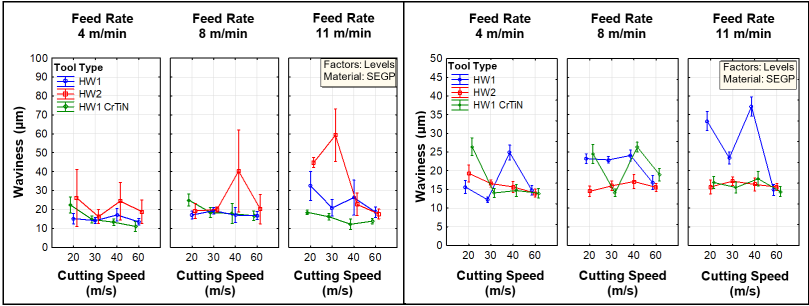


Fig. 9: The effect of cutting speed, feed rate and tool type on the waviness of MDF –L (contact method on the left, contactless method on the right).

The waviness values after SEGP machining when measured with the contactless method ranged from 12 µm to 37 µm. The lowest Wa value was recorded with the HW1 milling cutter at a cutting speed of 30 m·s<sup>-1</sup> and a feed rate of 4 m·min<sup>-1</sup>. The highest values were also recorded with the HW1 milling cutter at a set cutting speed of 60 m·s<sup>-1</sup> and a feed rate of 8.

When evaluating the contact method for SEGP machining, the average waviness values ranged between 11 and 59 µm. This large range of values was due to the heterogeneous structure of SEGP, namely solid spruce wood. A value of 59 µm was measured with the HW2 milling cutter, a feed rate of 11 m·min<sup>-1</sup> and a cutting speed of 30 m·s<sup>-1</sup>. The lowest Wa value was found at the highest cutting speed and the lowest feed rate with the HW1 CrTiN milling cutter.



Note: A different axis for the waviness was chosen for each method due to the high values measured with the contact method.

Fig. 10: The effect of cutting speed, feed rate and tool type on the waviness of SEGP (contact method on the left, contactless method on the right).

Tabs. 10 and 11 show the average Ra values measured in each set of test specimens, as well as their coefficients of variation.

Tab. 10: Average values of waviness – contactless method.

Cutting speed (m·s <sup>-1</sup> )	Feed rate (m·min <sup>-1</sup> )	Material type	Tool type	Wa (μm)	Tool type	Wa (μm)	Tool type	Wa (μm)
20	4	MDF	HW1	31 (13.8)	HW2	33 (15.1)	HW1 CrTiN	39 (15.7)
30	4		HW1	24 (11.6)	HW2	25 (16.0)	HW1 CrTiN	34 (15.5)
40	4		HW1	24 (15.2)	HW2	27 (12.9)	HW1 CrTiN	34 (14.3)
60	4		HW1	19 (8.7)	HW2	32 (15.7)	HW1 CrTiN	33 (14.3)
20	8		HW1	25 (14.6)	HW2	37 (14.5)	HW1 CrTiN	28 (15.4)
30	8		HW1	26 (12.6)	HW2	35 (12.2)	HW1 CrTiN	24 (13.9)
40	8		HW1	28 (13.9)	HW2	35 (7.7)	HW1 CrTiN	30 (15.2)
60	8		HW1	32 (5.8)	HW2	23 (12.0)	HW1 CrTiN	34 (10.5)
20	11		HW1	31 (17.0)	HW2	30 (16.4)	HW1 CrTiN	32 (8.7)
30	11		HW1	34 (8.5)	HW2	25 (11.1)	HW1 CrTiN	38 (12.8)
40	11		HW1	26 (12.1)	HW2	34 (8.6)	HW1 CrTiN	25 (14.4)
60	11		HW1	24 (16.3)	HW2	27 (13.7)	HW1 CrTiN	25 (7.6)
20	4	MDF- L	HW1	18 (11.6)	HW2	26 (11.9)	HW1 CrTiN	26 (15.1)
30	4		HW1	26 (18.0)	HW2	24 (9.4)	HW1 CrTiN	22 (16.4)
40	4		HW1	17 (21.2)	HW2	25 (8.1)	HW1 CrTiN	21 (14.9)
60	4		HW1	26 (14.8)	HW2	25 (10.9)	HW1 CrTiN	23 (11.5)
20	8		HW1	22 (11.4)	HW2	25 (8.5)	HW1 CrTiN	18 (19.6)
30	8		HW1	24 (14.7)	HW2	24 (13.6)	HW1 CrTiN	34 (17.5)
40	8		HW1	19 (15.0)	HW2	23 (14.7)	HW1 CrTiN	19 (16.8)
60	8		HW1	27 (13.7)	HW2	18 (12.7)	HW1 CrTiN	22 (19.1)
20	11		HW1	23 (14.6)	HW2	24 (12.8)	HW1 CrTiN	27 (14.9)
30	11		HW1	19 (15.0)	HW2	23 (14.5)	HW1 CrTiN	28 (16.0)
40	11		HW1	21 (7.0)	HW2	19 (16.5)	HW1 CrTiN	22 (27.8)
60	11		HW1	28 (13.9)	HW2	24 (14.8)	HW1 CrTiN	20 (17.4)

20	4	SEGP	HW1	16 (14.4)	HW2	19 (16.4)	HW1 CrTiN	26 (12.3)
30	4		HW1	12 (8.4)	HW2	17 (8.3)	HW1 CrTiN	14 (11.5)
40	4		HW1	25 (11.0)	HW2	16 (13.4)	HW1 CrTiN	15 (15.0)
60	4		HW1	15 (12.5)	HW2	14 (10.6)	HW1 CrTiN	14 (13.1)
20	8		HW1	23 (4.1)	HW2	14 (13.2)	HW1 CrTiN	25 (14.5)
30	8		HW1	23 (5.2)	HW2	16 (11.3)	HW1 CrTiN	14 (10.5)
40	8		HW1	24 (8.5)	HW2	17 (15.4)	HW1 CrTiN	26 (7.1)
60	8		HW1	17 (15.6)	HW2	16 (9.4)	HW1 CrTiN	19 (12.4)
20	11		HW1	33 (10.8)	HW2	16 (16.5)	HW1 CrTiN	17 (12.8)
30	11		HW1	23 (9.5)	HW2	17 (9.4)	HW1 CrTiN	16 (13.4)
40	11		HW1	37 (9.7)	HW2	16 (15.2)	HW1 CrTiN	18 (14.9)
60	11		HW1	15 (14.3)	HW2	16 (8.4)	HW1 CrTiN	14 (13.4)

The values in parentheses are the coefficients of variation (CV) in %.

Tab. 11: Average values of waviness – contact method.

Cutting speed (m·s <sup>-1</sup> )	Feed rate (m·min <sup>-1</sup> )	Material type	Tool type	Wa (μm)	Tool type	Wa (μm)	Tool type	Wa (μm)
20	4	MDF	HW1	28 (11.0)	HW2	30 (14.4)	HW1 CrTiN	33 (13.5)
30	4		HW1	25 (11.3)	HW2	28 (10.3)	HW1 CrTiN	33 (10.7)
40	4		HW1	29 (12.7)	HW2	26 (10.1)	HW1 CrTiN	28 (19.2)
60	4		HW1	31 (12.3)	HW2	29 (13.7)	HW1 CrTiN	30 (6.3)
20	8		HW1	24 (8.1)	HW2	33 (9.8)	HW1 CrTiN	26 (12.0)
30	8		HW1	29 (19.0)	HW2	35 (15.5)	HW1 CrTiN	33 (18.4)
40	8		HW1	28 (10.0)	HW2	28 (10.5)	HW1 CrTiN	28 (9.8)
60	8		HW1	30 (18.9)	HW2	27 (8.1)	HW1 CrTiN	30 (8.3)
20	11		HW1	37 (10.7)	HW2	32 (19.6)	HW1 CrTiN	28 (17.3)
30	11		HW1	26 (16.1)	HW2	31 (11.7)	HW1 CrTiN	32 (12.5)
40	11		HW1	22 (11.2)	HW2	30 (15.8)	HW1 CrTiN	26 (10.6)
60	11		HW1	25 (9.6)	HW2	28 (10.8)	HW1 CrTiN	27 (14.3)
20	4	MDF- L	HW1	19 (12.3)	HW2	24 (14.4)	HW1 CrTiN	28 (14.0)
30	4		HW1	25 (15.9)	HW2	26 (13.4)	HW1 CrTiN	26 (15.9)
40	4		HW1	18 (15.2)	HW2	22 (10.9)	HW1 CrTiN	19 (17.2)
60	4		HW1	28 (12.4)	HW2	22 (10.7)	HW1 CrTiN	21 (11.8)
20	8		HW1	20 (13.6)	HW2	21 (19.5)	HW1 CrTiN	21 (10.9)
30	8		HW1	24 (17.7)	HW2	24 (10.0)	HW1 CrTiN	31 (16.4)
40	8		HW1	19 (9.4)	HW2	22 (13.9)	HW1 CrTiN	20 (8.6)
60	8		HW1	20 (19.0)	HW2	20 (12.1)	HW1 CrTiN	20 (10.6)
20	11		HW1	21 (8.3)	HW2	24 (14.4)	HW1 CrTiN	27 (13.1)
30	11		HW1	18 (11.3)	HW2	21 (19.1)	HW1 CrTiN	25 (19.2)
40	11		HW1	19 (15.4)	HW2	20 (11.0)	HW1 CrTiN	22 (19.4)
60	11		HW1	26 (15.1)	HW2	22 (8.9)	HW1 CrTiN	20 (8.1)
20	4	SEGP	HW1	15 (15.3)	HW2	26 (10.2)	HW1 CrTiN	22 (6.6)
30	4		HW1	14 (16.2)	HW2	16 (12.1)	HW1 CrTiN	15 (17.6)
40	4		HW1	29 (17.7)	HW2	24 (16.7)	HW1 CrTiN	13 (19.1)
60	4		HW1	14 (17.8)	HW2	19 (15.6)	HW1 CrTiN	11 (12.9)
20	8		HW1	26 (16.7)	HW2	19 (19.2)	HW1 CrTiN	25 (17.8)
30	8		HW1	20 (10.7)	HW2	20 (9.8)	HW1 CrTiN	18 (10.9)

40	8		HW1	21 (10.9)	HW2	40 (15.4)	HW1 CrTiN	18 (11.3)
60	8		HW1	17 (18.5)	HW2	20 (13.9)	HW1 CrTiN	17 (11.2)
20	11		HW1	32 (12.7)	HW2	45 (8.3)	HW1 CrTiN	19 (8.2)
30	11		HW1	21 (19.4)	HW2	59 (16.5)	HW1 CrTiN	16 (15.8)
40	11		HW1	26 (19.2)	HW2	23 (16.6)	HW1 CrTiN	12 (11.9)
60	11		HW1	19 (11.2)	HW2	18 (20.4)	HW1 CrTiN	14 (14.4)

The values in parentheses are the coefficients of variation (CV) in %.

It is clear from a comparison of both methods for measuring the waviness that both devices showed similar results with the same settings. It's not possible to clearly determine which device is more accurate. If we evaluate the effect of the individual factors, the best quality in terms of waviness is achieved at low feed rates and high cutting speeds. The machined material and tool type are factors that significantly affect the final quality of the machined surface.

## CONCLUSIONS

1. When evaluating the cutting speed and its effect on waviness, it can generally be stated that higher quality is achieved at higher cutting speeds. However, when the cutting speed increases, the vibration of the machine also increases, which may increase the waviness values.
2. When the feed rate was increased, the surface waviness also increased. This is due to the fact that there is less time to mill the same amount of material. The workpiece therefore passes through the milling cutter faster, and the waviness as such is ideally determined by a combination of feed rate and cutting speed.
3. There was no clear indication of which blade is the most suitable type of tool. The HW1 and HW1 CrTiN blades have proven to be suitable for machining in terms of waviness. With the contact method, the HW2 milling cutter has proven to be the least suitable, but with the contactless method it was shown to be the most appropriate.
4. In terms of the machined material, the best quality evaluated through the waviness ( $W_a$ ) was found in SEGP. A comparison of both MDFs, namely raw MDF and MDF with single sided lamination, showed MDF-L to be more suitable. The machined material has a significant effect on the resulting waviness. In terms of the machined material, the best quality evaluated through the waviness ( $W_a$ ) was found in SEGP. A comparison of both MDFs, namely raw MDF and MDF with single sided lamination, showed MDF-L to be more suitable. The machined material has a significant effect on the resulting waviness.
5. No significant effect on the surface waviness ( $W_a$ ) was found between the evaluated methods. In general, we can say that both methods represented by the given devices can be used to measure the waviness. Both methods are therefore interchangeable, and we cannot say which one resulted in more accurate values.
6. The advantage of the contactless device is the possibility of repeated measurements, because the sample cannot be damaged by the optical beam, but the purchase price and subsequent costs are 10x higher for this device. Operating the contactless device is also more complicated. The contact device is more suitable in practice, and the contactless device is more suitable for a scientific evaluation of the waviness.

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