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SURFACE WAVINESS OF MEDIUM-DENSITY FIBERBOARD AND EDGE-GLUED PANEL AFTER EDGE MILLING

Miroslav Sedlecký, Monika Sarvašová Kvietková
Czech University of Life Sciences, Faculty of Forestry and Wood Sciences
Department of Elementary Wood Processing
Prague, Czech Republic

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ABSTRACT

This article deal with investigation of mean arithmetic deviation of the waviness profile (Wa) on edge surface after edge milling of medium-density fiberboard, medium-density fiberboard with single-sided lamination and spruce edge-glued panel. Edge milling afftected feed rate 4, 8, and 11 $m \cdot min^{-1}$ and cutting speed 20, 30, 40 a 60 $m \cdot s^{-1}$. There were used for milling 3 types of tungsteen carbide blades with different composition and treatment (HW1, HW2 and HW1 + CrTiN coating). Working results show that the lowest values of waviness were found with a spruce glulam. Considering the machined surface quality the most suitable blade is HW1, then HW1 + CrTiN coating and the worst one is HW2. The lowest measured values of Wa were found with the feed rate of 4 $m \cdot min^{-1}$ and cutting speed of 60 $m \cdot s^{-1}$. The increase in cutting speed resulted in the drop in the values of average Wa, while the increase in feed rate had the opposite effect.

KEYWORDS: Waviness, feed rate, cutting speed, edge milling, medium-density fiberboard (MDF), edge-glued panel (EGP).

INTRODUCTION

Except for wood in the form of roundwood and timber the wood-based materials have broader use. Due to the growing technical progress the possibilities of wood processing and the production of technologically more perfect materials have been increasing (Hoadley 1990). Wood-based materials maintain advantageous and overcome unsuitable properties of wood to a certain extent. Due to the partial change of properties compared to wood their machining also go through partial change.

Division and machining of wood material is mostly carried out by some cutting tools (milling, drilling tools, saw tools, knives ...) and using cutting wedges the wood particles are broken up and divided from each other (Kvietková 2015). Each tool carries out cutting process which is a common denominator of dividing or machining (McKenzie 1960, Coelho et. al. 2008). One of the methods of material machining is also milling. The milling machines process wood and wood materials by the revolving movement of a tool (milling machine) which is clamped in the mechanism of main working movement (shaft, head, spindle) by three basic technological methods securing the smooth surface of material, required shape and dimension.

Uneveness which appear on the machined surface has in many cases certain characteristic arrangement which results from mutual geometric and kinematic relationships of a tool and workpiece accompanied with some physical phenomena (Ostman 1983, Kvietková et al. 2015a, b, Kminiak and Gaff 2015, Kubs et al. 2016).

We can assess the quality of the milled surface according to the kinematic unevenesses (i.e. according to the depth of waves and their distance given by feed) or according to tearing out a bundle of fibres (Fig. 1).

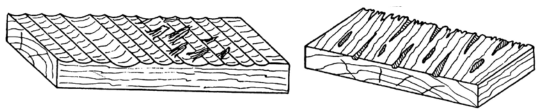

Fig. 1: Wood fibers torn out during milling.

After machining, the material surface is characterized by uneveness which manifests itself with more or less regular protrusion of particles from the machined surface (Sitkei and Magoss 2003). Weaviness and roughness are basic characteristics of the surface profile (Jackson et al. 2002). During milling, which is practically cyclic machining, the waviness is characteristic depending on cutting and feed rate. The waviness is caused by traces made by tools during work, when interrupted or inaccurately clamped (Mitchell and Lemaster 2002). Waviness is also affected by the tool blunting (Ohuchi and Murase 2005, 2006). In the past, the roughness and waviness of the surface was inspected by visual and touch control (Stumbo 1963). During touch control, it was necessary to collect a large quantity of samples to determine differences (Sandak and Negri 2005). Owing to the demands for accuracy the sensory checks were replaced with numeric quantitative measurement. Measurement represented only the values of roughness and waviness first (Fig. 2) and later, it was completed with more values of the profile roughness and waviness.

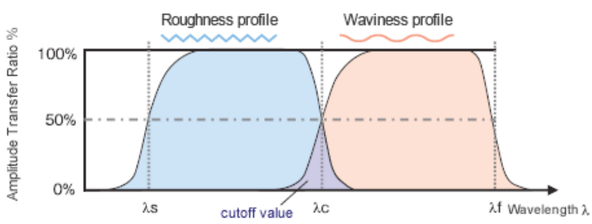

Fig. 2: Principle of waviness measurement according to ČSN EN ISO 4287 (1999).

This research was aimed at investigation of edge surface waviness after edge milling of medium-density fiberboard (MDF), medium-density fiberboard with single-sided lamination (MDF-L), and spruce edge-glued panel (SEGP). There were used three blades for edge milling which differed due to material or surface finish (HW-05, HW-03F and HW-05 CrTiN). The basic parameters of cutting speed (20, 30, 40, 60 m·s^{-1}) and feed rate (4, 8, 11 m·min^{-1}) were changing during milling.

MATERIALS AND METHODS

Materials

The research was aimed at 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 samples with dimensions of 500 × 500 × 18 mm, were cut from large-surface formats. According to the standard EN 323 (1993) there was found the density of individual materials which is given in the Tab. 1.

All samples were then conditioned for 2 weeks in a conditioning room (ϕ = 65 ± 3 % and t = 20 ± 2°C) to achieve 12% equilibrium moisture content (EMC).

Tab. 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)

Methods

Edge milling

Edge sides of samples of all three materials were milled on the one-spindle edge milling machine (FVS) with a feeding system STEFF 2034 (Maggi Technology, Certaldo, Italy). Two-blade milling cutter heads (Felder, Hall in Tirol, Austria) with three blade types were used for edge milling (Fig. 3). A milling depth of 1 mm was kept during edge milling. The edge side of each sample was milled 3 times along the entire length. Edge milling parameters and tool geometry are given in the Tab. 2.

Fig. 3: Cutter head.

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 α	10°
RPM	3000, 4500, 6000 and 9000	Cutting angle of wedge β	60°
Cutting speed	20, 30, 40 and 60 m·s^{-1}	Rake angle γ	20°
Feed rate	4, 8, and 11 m·min^{-1}	Cutting angle δ	70°

Each milling head was determined for one particular type of the blade which mutually differ by material or treatment. All blunts are made by the company Leitz GmbH & Co. KG, (Oberkochen, Germany) (Fig. 4). HW1 and HW2 blades were used without additional surface finish. HW1 + CrTiN blades are manufactured from the same material as HW1 and were treated with CrTiN coating. This coating was applied with the PVD method (physical vapour deposition) in the company SHM, s.r.o. (Šumperk, Czech Republic). CrTiN coating applied with the PVD method is designated for harder wood-based materials and is applied to cutting tools to improve their resistance to blunting and to prolong their service life (Navinšek et al. 1995, Su et al. 1996).

Fig. 4: Blade types for edge milling.

Dimensions and basic properties of blades given by the manufacturer are given in the Tab. 3.

Tab. 3: Properties of milling blades.

Marking	Cutting material	Blade type	Dimensions (mm)	Micro-hardness HVm (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.

The waviness was represented by the arithmetic mean deviation of the waviness profile (Wa) directly measured on edge surface.

Measurement took place on the side edge of the machine sample on which the centre was determined and from the centre centimetre sections were marked - five on the left and five on the right from the centre. Each of such sections was divided into three identical parts (under each other in the scope of thickness) of 6 mm in width.

The measurement was done by the roughness measuring machine Form Talysurf Intra 2 (Taylor Hobson, Leicester, UK) and was performed 10× on one sample, always once on each central part of centimetre section namely when the shoulder of the tip radius of rtip=2 μm was inserted. Gauss filter and λc were used during the assessment. Measuring conditions are listed in Tab. 4.

Tab. 4: Measuring conditions for waviness.

Periodical profiles	Measuring conditions according to ČSN EN ISO 4287 (1999)			
RSm (mm)	λc (mm)	ln (mm)	lt (mm)	rtip (μm)
0.013 < RSm ≤ 0.04	0.08	0.4	0.48	2
0.04 < RSm ≤ 0.13	025	1.25	1.5	2
0.13 < RSm ≤ 0.4	0.8	4	4,8	2 or 5
0.4 < RSm ≤ 1.3	2.5	12.5	15	5
1.3 < RSm ≤ 4	8	40	48	10

Note: RSm is the mean distance of roughness elements grooves, λc is the cutoff wavelength, ln is the measuring length, lt is the total length, rtip is the radius of measuring tip, λf is the filter of long-wave parts on the surface. Highlighted conditions were used in our research.

Waviness values were assessed by STATISTICA 13 software (Statsoft Inc., Tulsa, OK, USA) using the MANOVA analysis. The analysis used a 95% confidence interval, which reflected a significance level of 0.05 ($P < 0.05$).

RESULTS AND DISCUSSION

On the basis of the values of significance level "P" given in the Tab. 5 it is possible to state that the effect of all factors as well as mutual interactions of all factors is statistically significant. Statistical significance of factors is also confirmed by the Duncan test (Tab. 6).

Tab. 5: The effect of the factors and their interaction on the waviness.

Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F- Test**	**Significance Level P**
Intercept	628,866.4	1	628,866.4	11,780.2	0.000
1) Cutting speed	2,575.663	3	858.554	16.083	0.000
2) Tool type	3,187.782	2	1,593.891	29.858	0.000
3) Feed rate	794.482	2	397.241	7.441	0.001
4) Material type	12,919.6	2	6,459.839	121.009	0.000
1*2*3*4	7,245.892	24	301.912	5.656	0.000
Error	51,888.22	972	53.383		

Tab. 6: Comparison of the effects of factors on waviness using Duncan test.

No.	**Cutting speed ($m \cdot s^{-1}$)**	**(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	

No.	Feeding rate (m·min^{-1})	(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	

No.	Tool type	(1) 23.075	(2) 22.763	(3) 26.554
1	HW1 CrTiN		0.566	0.000
2	HW1	0.566		0.000
3	HW2	0.000	0.000	

No.	Material type	(1) 21.067	(2) 28.965	(3) 22.360
1	SEGP		0.000	0.018
2	MDF	0.000		0.000
3	MDF-L	0.018	0.000	

In the graphical assessment given in the Fig. 5, it is obvious the influence of the tool cutting speed on waviness. Waviness values decrease with increasing cutting speed (Gaff et al. 2015, 2016) came to the same conclusion. It could be stated in terms of waviness that the most suitable larger cutting speed is the one providing the minimum of waving surface of the surface being machined.

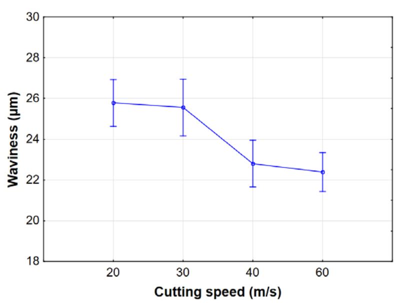

Fig. 5: The effect of the cutting speed on the waviness.

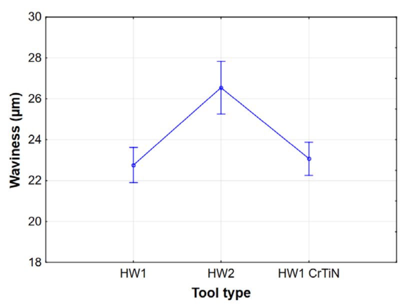

Fig. 6: The effect of the tool type on the waviness.

According to the fact that the cutting process is affected by several factors and all measured values of waviness comply with the standards we should consider also other factors when selecting the setting such as energetics and other quality properties of the surface.

The influence of the tool material on waviness is obvious in the graphical evaluation of the Fig. 6. In this case HW1 material appeared as the most suitable for dividing of individual materials with regard to the surface waviness after plane milling. The durability of the tool cutting wedge corresponds with the size of cutting wedge blunting. The largest waviness was noticed with the HW2 tool but also in this case the tool is suitable for dividing of materials because the measured values are within the standard. The influence of tool material on the surface quality during milling was also confirmed by Siklienka and Adamcová (2012).

The surface waviness, represented arithmetic deviation of profile, increases with the increase of feed rate i.e. surface quality gets worse (Fig. 7).

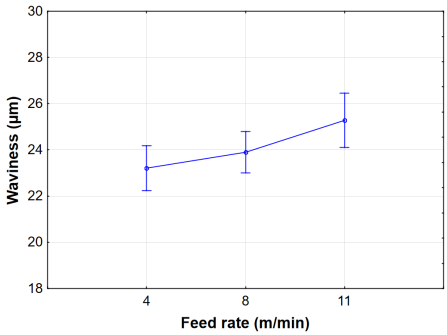

Fig. 7: The effect of the feed rate on the waviness.

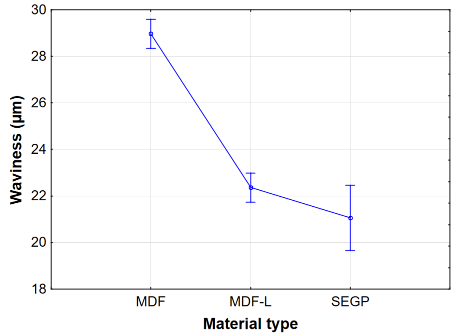

Fig. 8: The effect of the material type on the waviness.

The reasons are based on the surface quality of the real cutting edge, plastic deformations of cutting surface and vibration. In the area of small feeds, when vibration occurs, roughness might be larger than in case of large feeds. The reasons are based on the surface quality (waviness and roughness) of the real cutting edge, plastic deformations of cutting surface and vibrations. In the area of very small feeds, when vibration occurs, roughness can be larger than in case of larger feeds. Siklienka and Šustek (2007) as well as Rousek et al. (2010, 2012) confirmed our finding that the change in feed rate causes worsening of the machined surface quality.

The highest influence of machined material (Fig. 8) on waviness appears with the MDF. When milling, wavy uneveness occurs on the surface depending on the number of blades and tool revolutions on feed rate. A number of waves per the unit of length is a decisive factor of the quality of a machined part. When machining massive wood there are accepted 6 waves per 1 centimeter; when machining the MDF, according to the fine structure of material, it is necessary to achieve the minimum of 8 waves per 1 cm to obtain the quality good surface. With spruce glulam, the surface quality appeared as the best of used materials with regard to waviness.

During edge milling of the MDF, the best surface quality with respect to waviness was achieved with the HW1 tool at the cutting speed of 40 $m \cdot s^{-1}$ and feed rate of 11 $m \cdot min^{-1}$ (Fig. 9).

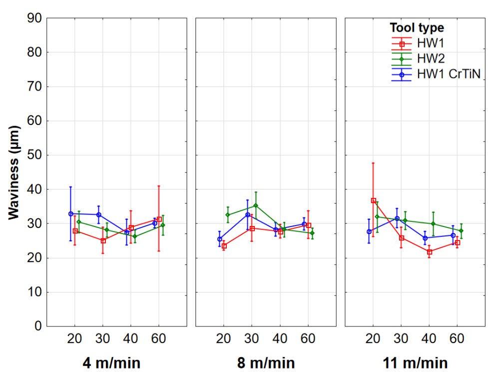

Fig. 9: The effect of cutting speed, feed rate and tool type on the waviness of MDF.

The tool with CrTiN coating achieved the lowest value at the identical setting of parameters. On the contrary, the highest values were achieved at lower cutting speeds, in case of the HW1 cutting speed was 20 m.s1 and in case of HW2 and HW1+CrTiN tools speed was 30 m·s^{-1}. All average values are within the interval of 22 to 37 µm.

When machining the MDF-L (Fig. 10) the average values fluctuate within the interval of 18 to 31 µm. The highest average value of 31 µm was measured at the cutting speed of 30 m·s^{1} and feed rate of 8 m·min^{-1} when using the HW1+CrTiN tool. The lowest values were measured at the cutting speed of 40 m·s^{1} and feed rate of 4 m·min^{-1}, namely with the HW1 and HW1+CrTiN tools. The HW2 tool achieved the best quality of the surface in two combinations of parameters namely at the cutting speed of 60 m·s^{1} and feed rate of 8 m·min^{-1} and further at 40 m·s^{1} and 11 m·min^{-1}.

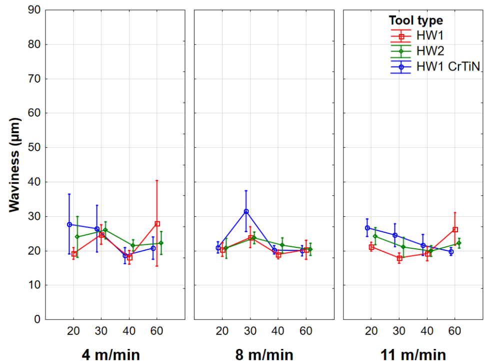

Fig. 10: The effect of cutting speed, feed rate and tool type on the waviness of MDF-L.

In case of the SEGP the interval of average values oscillates from 11 to 59 µm (Fig. 11). The lowest value of waviness was achieved with the HW1+CrTiN tool at the cutting speed of 60 m.s^{1} and feed rate of 4 m·min^{-1}. On the contrary the highest value (59 µm) was achieved with the HW2 tool at the feed rate of 11 m·min^{-1} and low cutting speed of 30 m·s^{1}. The values of waviness for all materials are given in the Tab. 7.

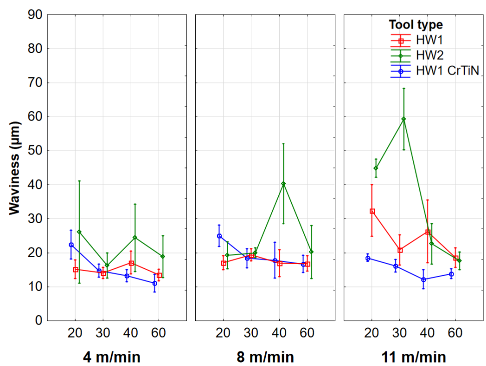

Fig. 11: The effect of cutting speed, feed rate and tool type on the waviness of SEGP.

Tab. 7: Average values of waviness.

Cutting speed (m·s⁻¹)	Feed rate (m·min⁻¹)	Material type	Tool type	Waviness (μm)	Tool type	Waviness (μm)	Tool type	Waviness (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 %.

The widest interval of average values was measured with the SEGP which is caused by the anisotropic structure of wood compared to the homogenous structure of the MDF in the central area where waviness was measured. The lowest and highest average value of waviness was achieved in milling of the SEGP. The MDF and MDF-L do not show such large fluctuation in average values. In case of the SEGP it is obvious that the best values were achieved at low feed rate. When machining the MDF and MDF-L the minimums were rather at the higher cutting speeds when all feed rates were occupied. Rousek et al. (2010) also found in their research that the wave height is given right by cutting speed and feed rate.

CONCLUSIONS

1. On the basis of statistical results it is possible to state that after machining individual materials the spruce glulam appeared the best with regard to waviness.
2. The HW-05 tool appeared as the most suitable tool in machining and used parameters combination with regard to the properties of wood-block tools used in milling and to the waviness.
3. The change in cutting speed of the plane milling process caused the reduction of waviness. Cutting speed affects the quality of the processed surface; if we want to achieve the higher quality of the machined surface, we have to select the higher cutting speed and in case of feed rate it is necessary to select the lowest values.
4. In the change of feed rate during the plane milling process the opposite change occurred - when increasing this parameter, waviness starts growing.

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Miroslav Sedlecký, Monika Sarvašová Kvietková
Czech University of Life Sciences
Faculty of Forestry and Wood Sciences
Department of Elementary Wood Processing
Kamýcká 1176
Cz-165 21 Prague 6 - Suchdol
Czech Republic
Corresponding author: mireksed@atlas.cz