CHIP AND CHIPLESS WOODWORKING PROCESSES, 10(1): 101–114, 2016
Zvolen, Technical University in Zvolen, ISSN 1339-8350 (online), ISSN 2453-904X (print)

THE SUITABILITY OF REPEATED MACHINING IN NESTING MILLING ON CNC MACHINING CENTERS

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Abstract

The article deals with the suitability of repeated machining strategy in working by nesting milling on CNC machining center. Appropriateness of the strategy is assessed for MDF boards milling with thickness of 18 mm by router bits with one reversible razor blade and router bits with two reversible knives.
The article presents maximum feed rate based on both, subjective assessment of the operator, as well as on the basis of objective criteria, the quality of the surface represented by the arithmetic mean deviation of the roughness profile. The article simultaneously deals with the distribution of the arithmetical mean deviation of the roughness profile over the height of cut and how it is affected by multiple transition of woodworking machine. At the end of the article, there is analysis why repeated machining strategy is inefficient for this type of machining.

Key words: *nesting milling, machining strategy, the quality of the surface, feed rate, machining efficiency.*

1. INTRODUCTION

The application of CNC technology offers a variety of machining possibilities of the given material. In machining of agglomerated materials, so called nesting milling is becoming extremely popular. Nesting milling is process when workpiece is extracted from the input material by router bits milling while distribution of the individual workpiece within given material determinates optimization software and created surface is considered as final and therefore no further working with exception of grinding is necessary. Nesting milling can be done by different machining strategies, for example, repeated machining belongs in one of those basic ones whilst each strategy requires specific technological parameters.
As optimization criterion of choice of technological parameters has become a quality of the product, because determinants for success of the given product on the market, in other words in competitive environment, is quality and price.
For an objective indicator of the quality of the product, it is considered to be precision and the surface quality of the workpiece. Under the precision of workpiece we understand the degree of proximity of workpiece geometry to the values indicated on the drawings. We can take in consideration the shape and dimensional accuracy. The question of sufficient accuracy with CNC machining centers is solved by design of the machine and therefore more significant question is related to the quality of finished surface. Surface quality can be

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precisely defined by parameters of surface irregularities. Surface roughness has kinematic, technical and technological reasons.
Kinematic causes of inequality (causes of waviness) lie in the cycloid shape of relative movement of the cutting edge of the knife in the wood, which makes absolutely flat surface even theoretically unreachable by rotary tool.
Technological causes of inequality (causes of roughness) consist for example in vessels cuts, fibers, annual rings, moisture, milling along and against fiber and type of wood and etc.

Technical causes of inequality (causes of roughness and waviness) lie in the precision of setting of knives in the cutter head (or in precision of grinding disc cutters to equal diameter of all cutting edges) in the state of wear of the cutting edge of the blade and in vibration and shaking of milling tool. They are expressed both in uprooting fibers (cutting edge wear) and irregularities in the distance ripples on a milled surface.
This article sets as its objective to find the maximum feed rate for various machining strategies and then assess the suitability of the given machining strategy with regards to the efficiency of the process.

2. METHODOLOGY

Material

The characteristics of used material:

Raw medium hardboard (MDF) supplied by Bučina Ltd. Zvolen, Slovakia were used in the experiment. MDF boards had **thickness h = 18 mm** format and **width w = 2800, length l = 2070 mm**. Basic technical parameters provided by manufacturer are presented in Tab. 1.

Table 1 Technical parameters of raw medium-density fiberboard.

Property	Test method	Request
Thickness tolerance	STN EN 324-1	± 0,3 mm
Dimensions tolerance	STN EN 324-1	± 5,0 mm
Squareness tolerance	STN EN 324-2	± 2 $mm.m^{-1}$
Humidity	STN EN 322	4 ÷ 11 %
Formaldehyde release	STN EN 120	< 8 mg / 100 g a.s. samples
Thickness range		> 6 >9 >12 >19 >30 < 9 <12 <19 <30 <45 (mm)
Bending strength	STN EN 310	23 22 20 18 17 (MPa)
Tensile strength	STN EN 319	0,65 0,60 0,55 0,55 0,50 (MPa)
Swelling after 24 hours	STN EN 317	17 15 12 10 8 (%)
Modulus of elasticity	STN EN 310	2800 2500 2200 2150 1900 (MPa)

Characteristics of the machine:
The experiment was conducted at **5 axes CNC machining center SCM Tech Z5** (Figure 1) supplied by BOTO Ltd., Nové Zámky, Slovakia. Basic technical and technological parameters provided by the manufacturer are presented in Table 2.

Figure 1 CNC machining center SCM Tech Z5

Table 2 Technical and technological parameters of CNC machining center SCM Tech Z5

Technical parameters of CNC machining center SCM Tech Z5	
Useful desktop	x = 3050mm , y = 1300mm, z =300mm
Speed X axis	0 ÷ 70 m.min^{-1}
Speed Y axis	0 ÷ 40 m.min^{-1}
Speed Z axis	0 ÷ 15 m.min^{-1}
Vector rate	0 ÷ 83 m.min^{-1}
Technical parameters of the main spindle - electric spindle with HSK F63 connection	
Rotation axis C	640°
Rotation axis B	320°
Revolutions	600 ÷ 24 000 ot.min^{-1}
Power	11 kW 24 000 ot.min^{-1}
	7,5 kW 10 000 ot.min^{-1}
Maximum tool diameter	D = 160 mm
	L = 180 mm

Characteristics of tools:

For experiment, router bit with one reversible razor blade type designation **KARNED 4451** and router bit with two reversible knives type designation **KARNED 4551** were used, both by manufacturer Karned Tools Ltd., Prague, Czech Republic. Basic technical and technological parameters provided by the manufacturer are in Table 3. Router bits were equipped with reversible blades **HW 49.5 / 9 / 1.5** and **HW 50/12 / 1.5** from sintered carbide **T03SMG** (standard material used for the treatment of HDF, and MDF DTD), from BOTO Ltd., Nové Zámky, Slovakia. Basic technical parameters provided by the manufacturer of sintered carbide provide Table 4.

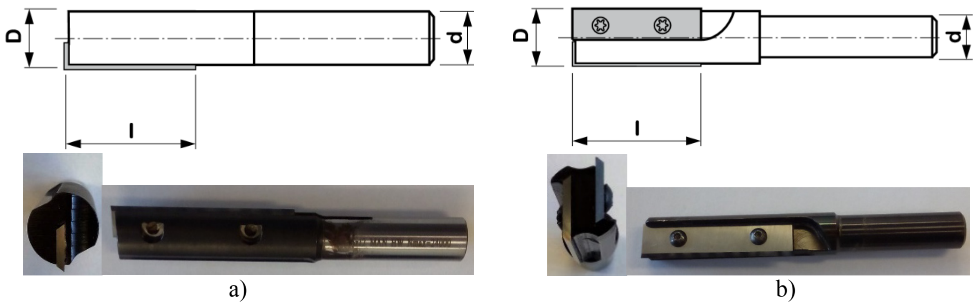


Figure 2 router bits used in the experiment a) with one replaceable knife b) with two interchangeable cutting knifes (D - diameter operation, I - working length, d - clamping diameter)

Table 3 Technical and technological parameters of router bits

Miller	Working diameter D [mm]	Working length l [mm]	Diameter of the chucking shank d [mm]	Dimensions of used razor blades L x š x h [mm]	Blades material
KARNED 4451	16	49,5	12	49,5 x 9 x 1,5	**T03SMG**
KARNED 4551	16	50	12	50 x 12 x 1,5	**T03SMG**

Table 4 Technical data of cemented carbide

Classes of TIGRA	ISO CODE	US CODE	Binder %	Hardness		Bending strength	
				HV10	HRA±0.2	N/mm^2	psi
T03SMG	K1	C4++	3.5	2100	94.6	2400	348.000

Method

The experiment was conducted in the following steps:

1. Router bit was fitted with the hydraulic clamp **SOBO. 302680291 GM 300 HSK 63F** from Gühring KG Albstadt company, Germany and then inserted into a CNC machine magazine.
2. The input format of MDF board (2750*1840 mm) was divided in half (2*2750*868 mm)
3. Half- formatted MDF board was placed in a CNC machining center so that the longer side was in the X-axis and the shorter side was in the Y-axis, attaching the MDF was provided by 12 evenly placed suction cups measuring 120 x 120 x 35 mm (vacuum set was 0.9 bar) (suction cups distance from the edge of the MDF board was not more than 50 mm) (see Figure 3). Since the MDF board format dwindled during the experiment, suction cups location was corrected till the distance from the edge of the MDF board was less than 20 mm.
4. The experiment was carried out in a way that a router bit was gripped by CNC machining center (KARNED 4451 or KARNED 4551) and by using the given strategy (per pass "I" **e=h**, the two transitions "II" **e = 1/2h** or three transitions "III", **e = 1/3h** see Figure 4) 5 mm thick strip of MDF board was cut off (ie. sample "L" as the left). Then CNC machine tool gripped circular saw with 250 mm diameter and separated another 5 mm thick strip of MDF boards (ie. Sample "P" as the right) from the format. After separation of required samples, the MDF board was released and pushed to the end stop and the process was repeated with a different combination of technological parameters. The process was carried out at constant operation speed of router bit **n = 20,000** $\mathbf{min^{-1}}$ and changing feeding speed from

$\mathbf{v_f = 1\ m.min^{-1}}$ to speed where $\mathbf{v_f} = \mathbf{v_{f\ /\ max\ /\ permissible}}$, based on a professional judgment of machine operator, machine did not produced surface of good quality or because of an excess tool load, milling process was accompanied by an enormous increase in the noise produced by CNC machine.

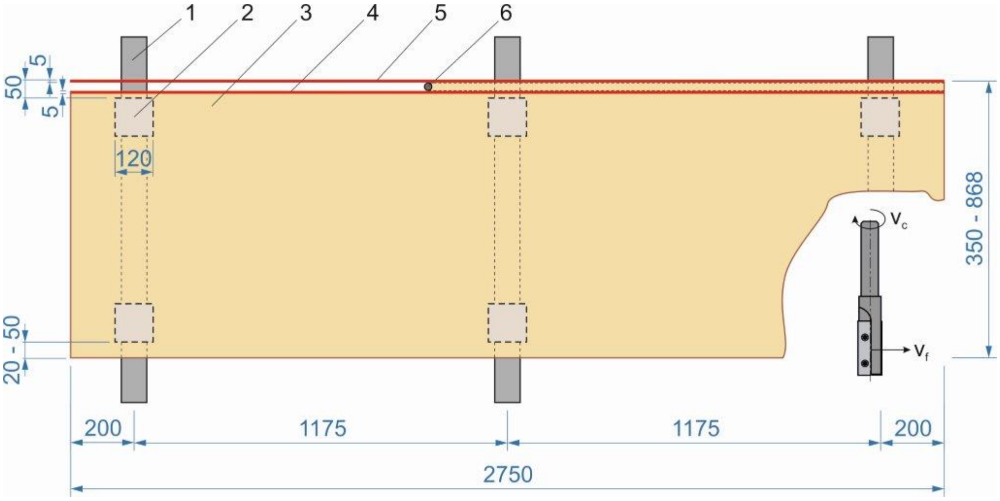
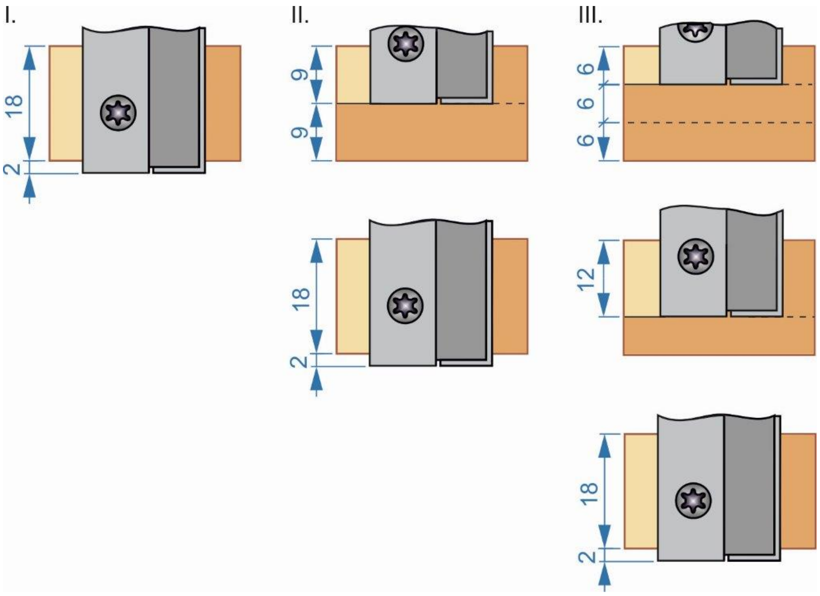


Figure 3 Scheme of samples preparation (1 - CNC machining center transverse beam , 2 - vacuum suction cup, 3 - MDF board, 4 - sample "P", 5 - sample "L", 6 - router bit, v_c - direction cutting speed, v_f - direction of sliding velocity)



a) b) c)

Figure 4 Machining strategy a) on the first transition, b) on two transitions, c) on three transitions

5. L sample was left for further evaluation, and there were extracted samples from P sample in order to determine surface roughness. Samples were extracted according to the methodology by Siklienka and Adamcova (2012) see the diagram on figure 5.

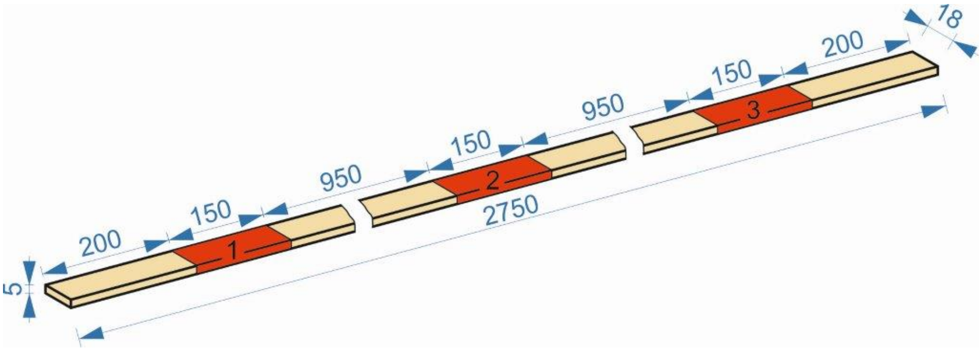


Figure 5 Exctracting method of test samples for the determination of surface roughness (Siklienka and Adamcova 2012)

3. MEASUREMENTS AND EVALUATION

Determination of surface roughness:
The inequality of the surface of the test piece was measured with a laser profilometer LPM-4 (Figure 6) from the Kvant Ltd. Slovak Republic. Profilometer uses triangulation principle of laser profilometry. The image of the laser line is scanned at an angle by digital camera. Then an object profile in cross-section is evaluated from scanned image. Obtained data are mathematically filtered and individual indicators of primary profile are set, profile of waviness and roughness profile (Kminiak, Gaff, 2015)
For measuring surface roughness, methodology by Siklenka and Adamcova (2012) was used reflecting the standard EN ISO 4287. On each test sample, measurements were performed on three tracks located in the middle of samples, evenly spaced across the width of the sample (4.5 / 7.5 / 10.5 / 13.5 from the edge of the sample), line length was 60 mm and the track being oriented in the direction of displacement of the spindle in a milling process (Figure 7). Surface roughness was evaluated using parameter of **arithmetic mean deviation of roughness profile R_a**.

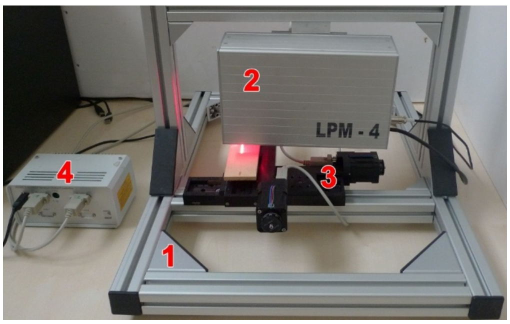


Figure 6 Laser Surface Profile LPM - 4 (1 - supporting structure allowing manual preset of working distance and mounting of profilometric head and trolley system, 2 - profilometric head, 3 - feed system of the XZ axis, 4 - control system of working desk shifts)

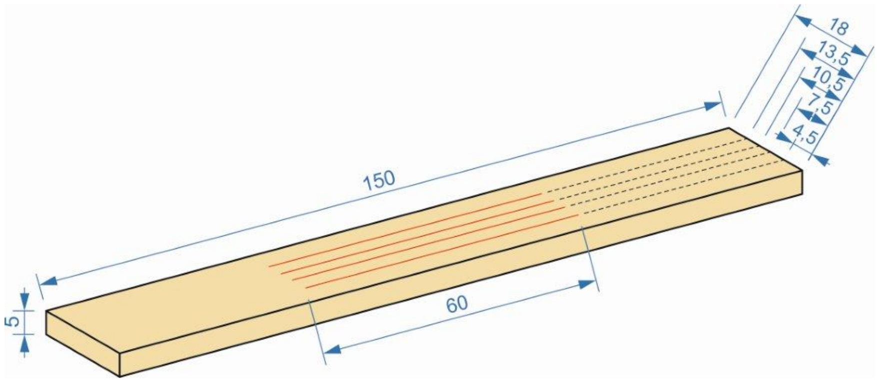


Figure 7 Placement of surface roughness measuring tracks across the width of the sample (Siklienka and Adamcova 2012)

4. RESULTS AND DISCUSSION

To verify the suitability of the repeated machining strategy of material (for one transition - material removal **e = h**, for two transitions - material removal **e = 1/2 h** and three transitions - material removal **e = 1/3 h**), by nesting milling of MDF board with thickness **h = 18 mm**, it was necessary, in the first step, to determine feeding speed ($\mathbf{v_{f\,/\,min}} \div \mathbf{v_{f\,/\,max}}$) for each combination of parameters

Choice of sliding speed $\mathbf{v_{f/real}}$ / real ($\mathbf{v_{f\,/\,real}} < \mathbf{v_{f\,/\,max}}$) is left to the CNC machine operator. Helpful utility for the operator in choosing speed are charts, where, based on the width of the cut B, it possible to determine the recommended level $\mathbf{v_f}$ (for our chosen instrument, a recommended sliding speed by the diagram is $\mathbf{v_{f/recommended}}$ = 5m.min^{-1}). In real life however, the operator selects a sliding rate based on his experience - their subjective assessment of the situation (usually $\mathbf{v_{f/real}} \leq \mathbf{v_{f/recommended}}$, therefore recommended sliding speed by diagram represents certain limit values of sliding speed). Operator manages the process by subjective perception of noise of the milling and the subjective assessment of the quality of the surface (for our chosen instrument operator usually chooses sliding speed $\mathbf{v_{f/real}} \approx$5 m.min-1.)

Since we wanted to determine the maximum allowable feeding speed only based on an assessment of the situation by the operator of CNC machining center without heaving others factors influence our experiment, we chose the following procedure.

We left experienced operator (it is the operator of CNC machine working in small series production with frequently changing production and the need for frequent adjustment of cutting conditions, with 8 years of experience in machining of agglomerated materials including MDF) to set the value of the permissible feeding speed on the basis of his experience (noise of milling process and the quality of the surface) without any real knowledge of the current feeding velocity (avoidance of diagram influence in setting of feeding speed limit values) and even with the risk of damaging the instrument.

During the experiment, there was no tool damage regardless of combination of the parameters. The average values of maximum sliding speeds $\mathbf{v_{f\,/\,max}}$ obtained by this experiment presents graph on Figure 8. As can be seen from values, results obtained this way are much higher than the results expected and as stated by the CNC machining operator himself, with real feedback of the actual speed of the slide, he would turn down sliding speeds.

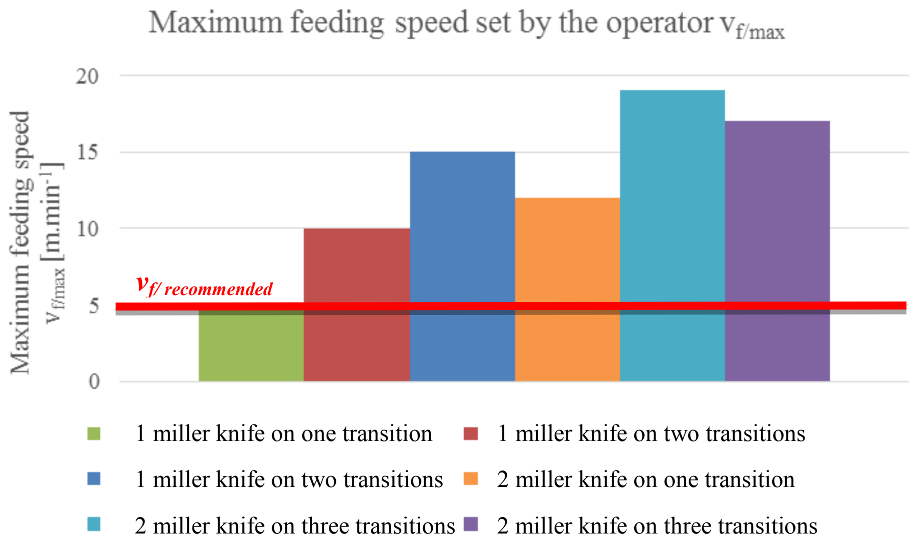


Figure 8. Maximum feeding speed set by the operator VF / max / permissible

Then we proceeded further and chose arithmetic mean deviation of the roughness profile $\mathbf{R_a}$ as optimization criteria. The first step was the analysis of values distribution of the arithmetical mean deviation of the roughness profile along the height of cut - material thickness, because in multiple transition of working tool, the tool is in contact with surface multiple times and that may affect the surface quality in the area of machining.

The statistical evaluation (Table 5) indicated that the arithmetic mean deviation of the roughness profile is dependent on the track in which it was measured, but it was not demonstrated on the machining strategy though - the number of transitions of working tool through the working zone.

Table 5 Results of multifactor analysis of diffusion for determination of the dependence of the arithmetical mean deviation of roughness profile on track measuring and machining strategy

	SS	Degr. of Freedom	MS	F	p
Intercept	0,071458	1	0,071458	5268,284	0,000000
Machining strategy	0,000054	2	0,000027	1,995	0,137865
Track of measuring	0,000618	3	0,000206	15,195	0,000000
Machining strategy/ Track of measuring	0,000031	6	0,000005	0,377	0,893549
Error	0,004056	299	0,000014		

The course of dependence of mean arithmetic deviation of the roughness profile from track measurement f (Figure 9) can be explained by density distribution profile of MDF boards (the edges of the MDF board are thicker compared to the center of the board).

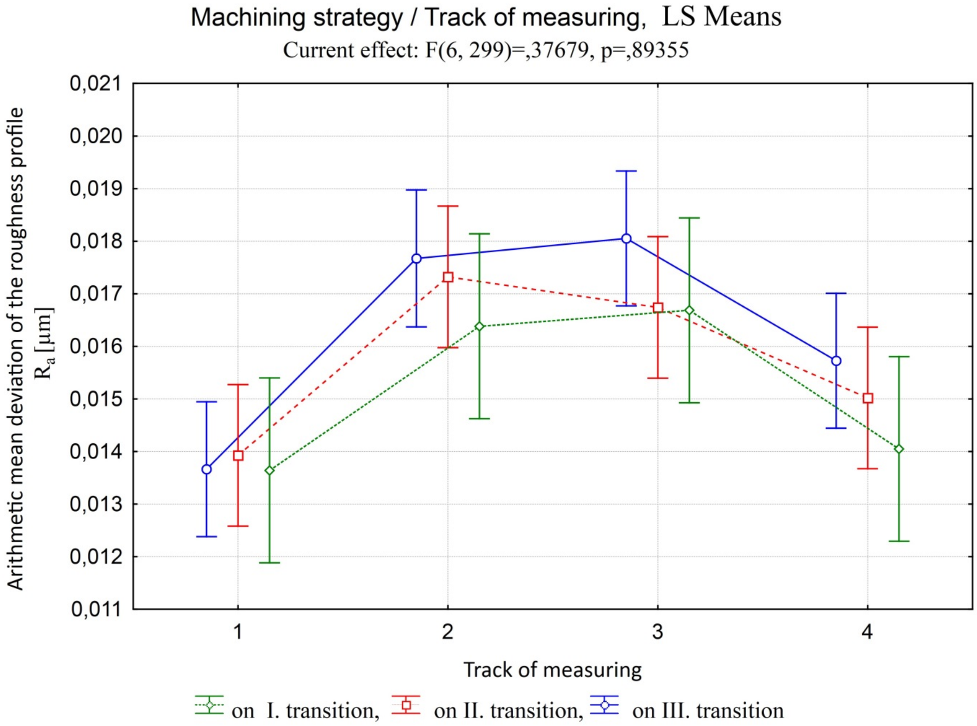


Figure 9 Dependences of the arithmetic mean deviation of roughness profile Ra on track of measuring for different machining strategies

Since it was not proved the effect of machining strategies on the distribution of the arithmetical mean deviation of the roughness profile along the height of the cut, in the further evaluation, we will not select its value by the number of passes through working zone, but we will evaluate it as a whole.

The overall course of average values of the arithmetical mean deviation of the roughness profile regarding to the sliding speed throughout the range of sliding speeds is shown on Figure 10.

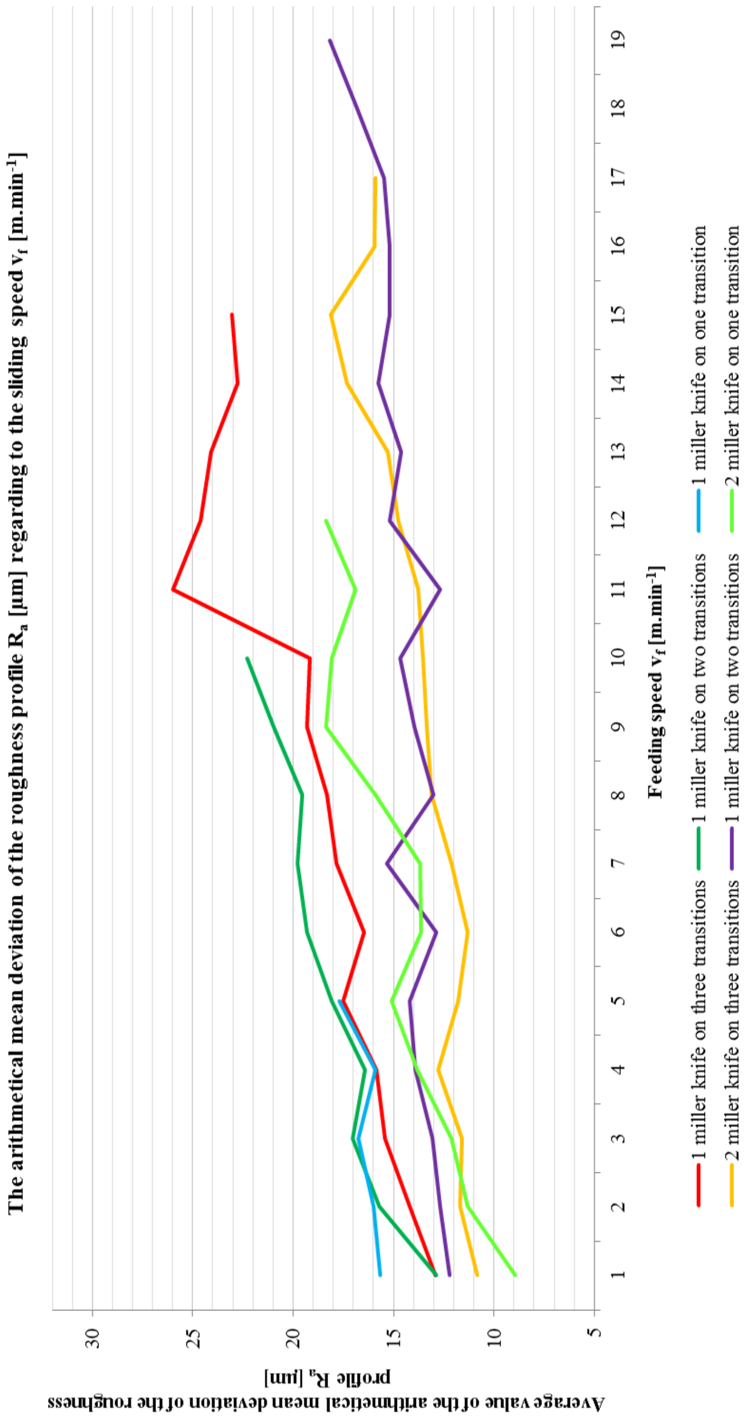


Figure 10 The dependence of the average value of the arithmetical mean deviation of the roughness profile R_a on the feeding speed v_f

Table 6 presents the values of the arithmetical mean deviation of the roughness profile at sliding speeds chose by the operator of CNC machining center based on his subjective assessment considered by operator as limit (further increases would not be appropriate).

Table 6 Maximum feeding speeds set by the operator VF / max / permissible and reached value of the arithmetical mean deviation of roughness profile Ra

Type of tool	Number of transitions	Feeding speed $v_{f/max}$ [m.min^{-1}]	Arithmetical mean deviation of the roughness profile			
			Ra [µm] Mean	Ra [µm] Std.Err.	Ra [µm] -95.00%	Ra [µm] +95.00%
1 Knife	I. transition	3	17,71375	0,999107	15,58420	19,84330
1 Knife	II. transitions	5	22,29300	1,114218	20,01746	24,56854
1 Knife	III. transitions	7	23,04200	1,517589	19,98542	26,09858
2 Knife	I. transition	8	18,36675	1,042864	16,25172	20,48178
2 Knife	II. transitions	18	18,15725	1,088102	15,97836	20,33614
2 Knife	III. transitions	17	15,88425	1,209409	13,45626	18,31224

As already mentioned, the method is highly subjective as it depends on the experience of the operator. If we want to set the maximum allowable feeding speed based on specific measurable indicator, for example quality value of the surface required by experience $\mathbf{R_a}$ **= 16 microns** (the value is not defined by norm, we set it on the basis of a survey among three MDF boards processors, who evaluated samples made by us and chose for them eligible ones based on the quality of the surface), our conclusion is that the satisfactory quality of the surface is achievable at feeding speeds lower than those established by the operator of CNC machining center. Image 11.

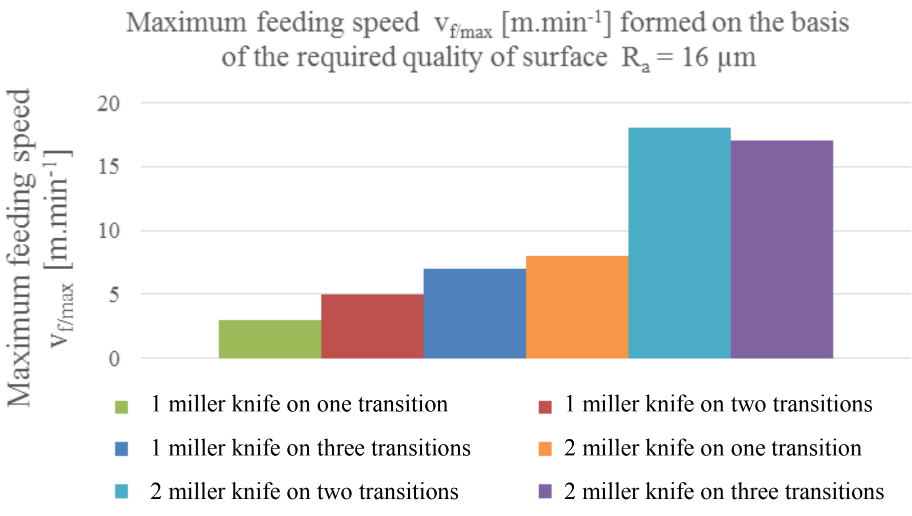


Figure 11 Maximum feeding speed $v_{f/max}$ formed on the basis of the required quality of surface R_a = 16 microns

We also subjected the dependence of the arithmetical mean deviation of the roughness profile on the type of mill, feeding speed and the machining strategy to statistical analysis

(Table 7) (analysis required limiting the range of the sliding speed to one constant **v_f = 1 ÷ 5 m.min^{-1}**).

Statistical analysis indicated that all three assessed factors have statistically significant effect on the value of the arithmetic mean deviation of the roughness profile and the order of significance is the type of cutter, sliding speed and finally, machining strategy. The interaction of machining strategies and feeding velocity has not been demonstrated. Graphical representation of statistical analysis displays Figure 12.

Table 7 Results of multi-factorial analysis of variance to determine the dependence of the arithmetical mean deviation of roughness profile on the type of cutter, the size of the sliding speed and machining strategy.

	SS	Degr. of Freedom	MS	F	p
Intercept	0,023969	1	0,023969	6446,335	0,000000
Machining strategy	0,000029	2	0,000015	3,921	0,023298
Feeding speed	0,000166	4	0,000041	11,148	0,000000
Miller type	0,000361	1	0,000361	96,990	0,000000
Machining strategy/ Feeding Speed	0,000006	8	0,000001	0,193	0,991340
Machining strategy/ Miller type	0,000009	2	0,000004	1,198	0,306439
Feeding Speed/ Miller type	0,000011	4	0,000003	0,712	0,585751
Machining strategy/ Feeding Speed/ Miller type	0,000048	8	0,000006	1,617	0,131056
Error	0,000335	90	0,000004		

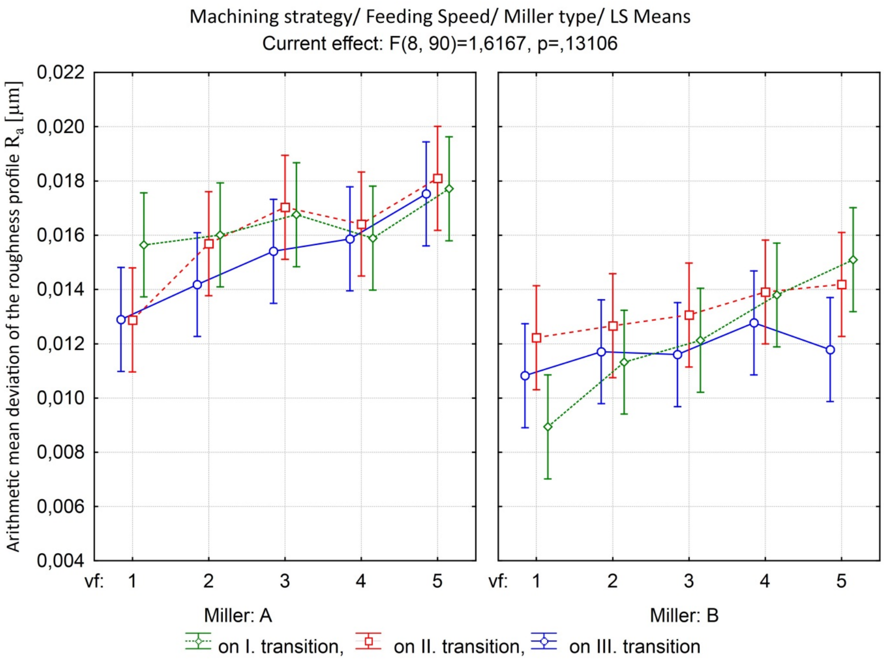


Figure 12 Dependencies of the arithmetical mean deviation of the roughness profile R_a from the type of cutters, feeding speed and machining strategy

As it is clear from obtained results, applying repeated machining strategy allows us to use higher feeding speeds.
In order to make given machining strategy successful, it is necessary to at least multiply feeding speed to the number of passes, but only in case of closed objects without the need of inter-transfer.
In the case of single-bladed cutter, this means that in double transition, feeding speed should be 6 $m.min^{-1}$ and in triple transition 9 $m.min^{-1}$. And thus from the standpoint of single-bladed cutter use, this strategy is inappropriate.
In a case of double-bladed cutter, this means that in double transition feeding speed should be 16 $m.min^{-1}$ and in triple transition 24 $m.min^{-1}$. And therefore, even from the standpoint of double-bladed cutter use, this strategy is inappropriate.

5. CONCLUSION

Based on the presented results we can make the following conclusions:
• Real feeding speed, when determined based on experience of the operator is higher than the feeding speed based on optimization criteria of the arithmetical mean deviation of the roughness profile.
• End users determine the value of the optimization criteria of the arithmetical mean deviation of the roughness profile R_a = 16 microns.
• The repeated machining strategy allows the use of higher feeding speeds. But increase of feeding velocity does not compensate for the extension of working time due to necessity of multiple transitions on the same path and therefore in terms of efficiency, repeated machining strategy is inappropriate.

AKNOWLEDGMETS
This work was supported by grants from VEGA no. 1/0725/16 „Prediction of the quality of the generated surface during milling solid wood by razor endmills using CNC milling machines.“

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