Effect of Cutting Conditions on Quality of Milled Surface of Medium-density Fibreboards

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The quality of milled surface medium-density fibreboards (MDF) and the effect of the wrong milling direction during the process of automatic milling in real conditions in practice (production machine, production tool, and material) are presented in the paper. Moreover, the effect of the double *vs.* single bladed milling cutter on the final surface quality with the simultaneous changes in individual parameters of feed rate, thickness of the removed layer, and cutting direction was investigated. The MDF was separated using the strategy "one per pass" with required cutting direction (climb or conventional) and the required thick strips cutting off (4 mm to 16+ mm) at a constant operation speed of the milling cutter (n = 20000 min^{-1}) and a changing feed rate from v_f = 1 m/min^{-1} to v_f = 5 m/min^{-1}. The use of a multi-bladed milling cutter resulted in the higher quality of the milled surface in all cases (change in feed rate, thickness of removed layer, and cutting direction). The effect of the wrong milling direction during automatic milling was observed only for a single-bladed milling cutter used. An increase in surface roughness (R_a) occurred; therefore, using the double-bladed milling cutter, which was not associated with an increase in surface roughness, is recommended.

Keywords: MDF milling; Machining strategy; Surface roughness; Replaceable blades

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INTRODUCTION

Wood has been an integral part of human life for ages. Wood, as the ultimate renewable material, is a competitive material due to its different chemical, biological, physical, and mechanical properties. Wood has an unquestionable impact on the sustainability of the future society (Mitterpach *et al*. 2016; May *et al*. 2017; Potkány *et al.* 2018; Tudor *et al*. 2018). Processing wood into a usable material is a complex technological process with an elaborate history. Milling is one of the wood processing methods. The aim of milling is to create a workpiece with the required dimensions, shape, and surface quality (Gaff *et al*. 2016). Milling is an optimal, productive, and an economically viable choice for wood machining; it is needed to understand all of the milling conditions. It affects economic viability, which is a key pillar of sustainable wood-processing industry (Hitka and Štípalová 2011; Lorincová *et al.* 2016; Kampf *et al*. 2016; Vlčková *et al*. 2017; Hitka *et al.* 2018). In terms of technology, milling is defined as the process of material machining with a rotary tool, either with a milling blade or milling head, and is characterized by chip production, where the chip thickness varies from minimum to maximum thickness and *vice versa* (Wyeth *et al*. 2009; Kubš and Kminiak 2017). The quality of milled surfaces is significantly higher than that of sawn surfaces (Rogozinski *et al*. 2015; Očkajová *et al*. 2016, 2018; Rogozinski *et al.* 2017; Kučerka and Očkajová 2018). However, not even milling guarantees an ideal smooth surface, there is always a certain degree of roughness (Sedlecký 2017). New machining technology makes it easier to obtain high-quality, finished products from materials otherwise difficult to machine. One of these processes is the computerized numerical control (CNC) method (Machado *et al.* 2009; Li *et al.* 2016; Liang *et al*. 2016).

The quality of a milled surface is affected by many factors (Engin *et al.* 2000). A summary of all the factors that affect the milling process can be defined as the cutting conditions (Békeš *et al*. 1999; Costes *et al*. 2004; Welzbacher *et al.* 2008; Marchal *et al.* 2009; Škaljič *et al*. 2009; Darmawan *et al*. 2011; Gejdoš *et al*. 2015; Mračková *et al*. 2016; Sedlecký and Kvietková 2017; Korčok *et al*. 2018a; Sedlecký *et al*. 2018). The surface quality is affected especially by the cutting tool used (Curti *et al*. 2017). In the case of wearing on the tool, an increase in temperature and vibration frequency can occur (Wang *et al.* 2016; Igaz *et al.* 2019). Subsequently, a decrease in the quality of milled surface is observed. Vibration can be reduced by using a lower feed rate; however, it changes the quality of machining as well. The tool rake angle was studied by Kuljich *et al*. (2013), Vančo *et al.* (2018), and Korčok *et al*. (2018b). The wear of the tool was studied by Ghosh *et al*. (2015), Lan *et al*. (2018), and Koleda *et al*. (2019). A wide range of collet quality, tool stiffness, offset, collet clamping quality, tooth overlapping, and moisture content of the milled material are other parameters that affect the quality of the milled surface. The effect of the type of milling cutter used (double *vs.* single-bladed), feed rate, thickness of the removed layer, and the direction of milling (climb *vs.* conventional) can be observed in the milling process. All mentioned parameters result in surface unevenness of the workpieces and roughness or waviness, ridges, or pulled fibres are manifested this way. The wavy structure obtained is called a cutter-mark and is inherent in the kinematic process of peripheral milling. Sanding and other time and money-consuming operations are examples of the simplest ways of how to reduce or remove the wavy structure (if necessary). Researchers Hynek *et al*. (2004), Robenack *et al.* (2013), Robenack *et al.* (2014), and Gottlöber *et al*. (2016) dealt with strategies on how to remove “cutter marks.” Quality is largely affected by feed per tooth (Felber and Lackner 2005), feed rate, cutting speed (Hernandez and Boulanger 1997; Bian *et al*. 2019; Wang *et al.* 2019), and the direction of cutting (Lisičan 2007; Barcík *et al*. 2014; Pinheiro 2014; Wilkowski *et al*. 2015; Koleda and Koleda 2016; Curti *et al*. 2018). Davim *et al.* (2009) investigated the influence of cutting speed and feed rate parameters through surface roughness in medium-density fibreboard (MDF) and observed that there is a decrease in the surface roughness when the spindle speed increases and an increase when the feed rate increases. Therefore, it is better to use a high feed rate. Machining depth and surface roughness change according to the workpiece and the machining parameters within the process and should be investigated in different operating parameters (Deus *et al.* 2018). Evaluating the surface roughness is important due to the technological properties of the surface: coating adhesion, surface adhesion, color stability *etc.* (Ozdemir *et al*. 2007, 2015; Gejdoš and Suchomel 2013; Reinprecht and Pánek 2015; Pánek *et al*. 2017; Kubovský *et al*. 2018; Šimůnková *et al*. 2019).

The effect on quality can be seen considering machined material as well. Material properties affecting the surface can be categorized as anatomical (wood species or material, grain direction, wood defects, *etc.*), physical (density, moisture content), and mechanical (hardness, strength, *etc.*) properties of the machined material (Eyma 2002; Eyma *et al.* 2004; Suchomel and Gejdos 2010; Novák *et al*. 2011; Suchomel *et al*. 2014; Kvasnová *et al*. 2016; Igaz *et al*. 2017; Marková *et al*. 2018; Klement *et al*. 2019; Očkajová *et al*. 2019, Tureková *et al*. 2019). However, Hernandez *et al.* (2014) showed that at temperatures higher than 0 °C, wood moisture content does not noticeably affect the mechanical properties inducing the chip fragmentation mechanism.

Modern technology has been adopted in the processing of wood and wood-based materials over the years. The use of CNC technology has become an everyday reality. CNC machining makes the production preparation process more complicated because the machining process must be planned in detail by designers. Subsequently, in the process of machining itself, there is only minimal chance to correct or optimize it. The process of machining is computerized using the CNC programs, so the role of a worker is only to control the functions, *i.e*., engineers and computer operators must be familiar with the process of milling, the effect of material, and technological parameters on the quality of milled material. These CNC programs can be prepared in various ways; the computer program can be handwritten (the computer operator must be skilled in using the programming language code), or in contrast, it can be prepared using more sophisticated parametric programming where the program is already created with automated integration of CAD (Computer-aided design) designs with assembly sequence planners. The production preparation process together with automatic programming introduces errors in the process of machining. However, there are some real-time error compensation techniques (Lenz and Merzenich 1988; Yuan and Ni 1998; Ramesh *et al*. 2000; Trejo-Hernandez *et al*. 2010; Lu and Yeh 2018; Wozniak and Jankowski 2018). Some of the errors are problematic to compensate in real time. One of them is incorrect tool path selection according to the error vectors, which is one of the most common errors. It can result in the change of milling direction (climb milling is changed into conventional milling). This error may be overlooked during the production preparation, and finding it in the production process is difficult. Therefore, whether the error vectors affect the quality of milled surfaces should be questioned, *i.e.*, whether the quality of all milled surfaces is satisfactory.

The aim of this paper is to investigate the effect of the milling cutter (double or single-bladed) on the final surface quality with simultaneous changes in individual parameters (feed rate, thickness of the removed layer, cutting direction), and the effect of the wrong milling direction during the process of automatic milling on the quality of the milled surface in real conditions (production machine, production tool, and material). The experiment, the research subject area, research tools, and specific values are according to the real conditions with the aim to meet the needs of real practice. Similar experiments have been conducted and results were published, however, only under laboratory conditions and standard tool conditions, *i.e*., climb milling was investigated. The standard way of milling was not studied in the current research (tool with the diameter of more than 100 mm and revolutions up to 8000 min^{-1}), but the milling process using the CNC machining center with a tool diameter of 16 mm and a revolution of 20000 min^{-1} was investigated. Moreover, correct and incorrect tool path milling were analyzed, *i.e*., potential errors of automatic milling were considered as well. Furthermore, the removed layers observed in the research were 4, 8, 12, 16, and 16+ (standard research deals with removed layers of 1 to 3 mm). Surface roughness was evaluated using the mean absolute deviation of the roughness profile (R_a).

EXPERIMENTAL

Materials

Raw MDF with a thickness (*h*) of 18 mm, width (*w*) of 2,800 mm, and length (*l*) of 2,070 mm were supplied by Bučina Ltd. (Zvolen, Slovakia) and were used in the experiment. Basic technical parameters provided by the manufacturer are presented in Table 1.

Table 1. Technical Parameters of Raw MDF

Property	Test Method	Request
Thickness tolerance (mm)	STN EN 324-1 (1999)	± 0.3
Dimensions tolerance (mm)	STN EN 324-1 (1999)	± 5.0
Squareness tolerance ($mm \cdot m^{-1}$)	STN EN 324-2 (1999)	± 2
Humidity (%)	STN EN 322 (1995)	4 to 11
Formaldehyde release	ISO 120 (2001)	< 8 mg/100 g
Thickness range (mm)		> 6 > 9 > 12 > 19 > 30
		< 9 < 12 < 19 < 30 < 45
Bending strength (MPa)	STN EN 310 (1998)	23; 22; 20; 18; 17
Tensile strength (MPa)	STN EN 319 (1995)	0.65; 0.60; 0.55; 0.55; 0.50
Swelling after 24 h (%)	STN EN 317 (1995)	17, 15, 12, 10, 8
Modulus of elasticity (MPa)	STN EN 310 (1998)	2,800; 2,500; 2,200; 2,150; 1,900

General characteristics of the machine were as follows: the experiment was conducted using a 5 axes CNC machining centre SCM Tech Z5 supplied (BOTO Ltd., Nové Zámky, Slovakia). Basic technical and technological parameters are presented in Table 2.

Table 2. Technical and Technological Parameters of CNC Machining Centre SCM Tech Z5

Technical Parameters of CNC Machining Centre SCM Tech Z5	
Useful desktop	X = 3,050 mm y = 1,300 mm z = 300 mm
Speed X axis	0 to 70 $m \cdot min^{-1}$
Speed Y axis	0 to 40 $m \cdot min^{-1}$
Speed Z axis	0 to 15 $m \cdot min^{-1}$
Vector rate	0 to 83 $m \cdot min^{-1}$
Technical Parameters of the Main Spindle – Electric Spindle with HSK F63 Connection	
Rotation axis C	640°
Rotation axis B	320°
Revolutions	600 to 24,000 rpm
Power	11 kW 24,000 rpm
Maximum tool diameter	D = 160 mm
	L = 180 mm

Characteristics of the tool

In the experiment, the milling cutters used were a single-bladed designation KARNED 4451 (Fig. 1a) and double-bladed designation KARNED 4551 (Fig. 1b) were used, both provided by Karned Tools Ltd. (Prague, Czech Republic). Basic technical and technological parameters provided by the manufacturer are mentioned in Tables 3 and 4. Milling cutters 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 high-density fiberboard (HDF), medium-density fibreboard (MDF), and chipboard), from BOTO Ltd. (Nové Zámky, Slovakia). A specific type of sintered carbide was selected following the previous research (Kminiak *et al*. 2016) evaluating the operational life of various types of sintered carbide. Low acquisition and operating costs are the main advantages of using the milling cutters with replaceable blades. Moreover, the blades can be changed due to the specific type of milled material. Basic technical parameters provided by the manufacturer of sintered carbide are shown in Table 5.

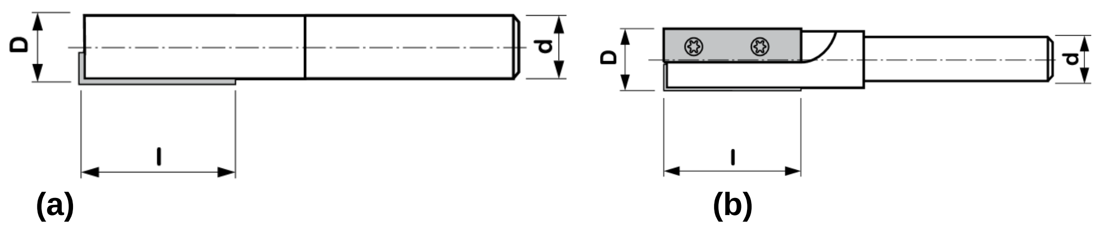

Fig. 1. Milling cutters used in the experiment: a) single-bladed and b) double-bladed (D - operation diameter, l - working length, d - clamping diameter)

Table 3. Technical and Technological Parameters of Milling Head

Technical and Technological Parameters of Milling Head	KARNED 4451	KARNED 4551
Total length of the tool	95 mm	
Cutter body diameter	16 mm	
Shank diameter	12 mm	
Height of the cutter body	49.5 mm	50 mm
Number of blades	1	2
Max. revolutions	24,000 min^{-1}	
Recommended max. feed speed	5 $m \cdot min^{-1}$	
α – Clearance angle	35°	
β – Cutting wedge angle	35°	
γ – Rake angle	20°	

Table 4. Technical and Technological Parameters of Milling Cutters

Miller	Working Diameter D (mm)	Working Length l (mm)	Diameter of the Chucking Shank d (mm)	Dimensions of Used Blades (mm)	Blade 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 5. Technical Parameters of Sintered 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	2,100	94.6	2,400	348,000

Methods

The experiment was performed according to the methodology of Kminiak *et al*. (2017). First, the milling cutter was fitted with a hydraulic clamp (SOBO 302680291 GM 300 HSK 63F; Gühring KG, Albstadt, Germany) and subsequently inserted into a CNC tool magazine. The original size of the MDF board (2,750 × 1,840 mm^2) was divided into two halves with the same dimensions (2 × 2,750 × 868 mm^3). A half sheet of MDF board was then placed in a CNC machining center with its longer side in the X-axis and its shorter one in the Y-axis. Then, MDF board was attached using 12 evenly placed suction cups at 120 × 120 × 35 mm^3 (vacuum pressure was 0.9 bar; the suction cups distance from the edge of the MDF board was no more than 50 mm). During the experiment, the milling cutter was gripped by the CNC machining center (KARNED 4451 or KARNED 4551) and material was separated using the strategy 'per one pass' with the required cutting direction (climb or conventional) and with the required thick strips of MDF board cutting of (4 mm, 8 mm, 12 mm, 16 mm, or 16+ mm). Subsequently, the CNC machine tool gripped the circular saw with the diameter of 250 mm and separated another 5-mm-thick strip of MDF board.

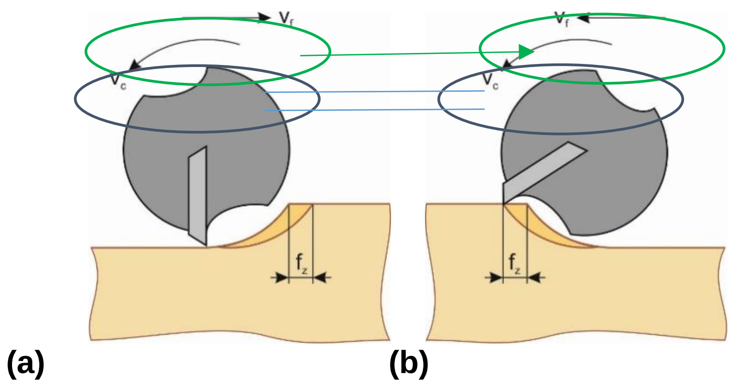

Fig. 2. Cutting direction: a) conventional and b) climb

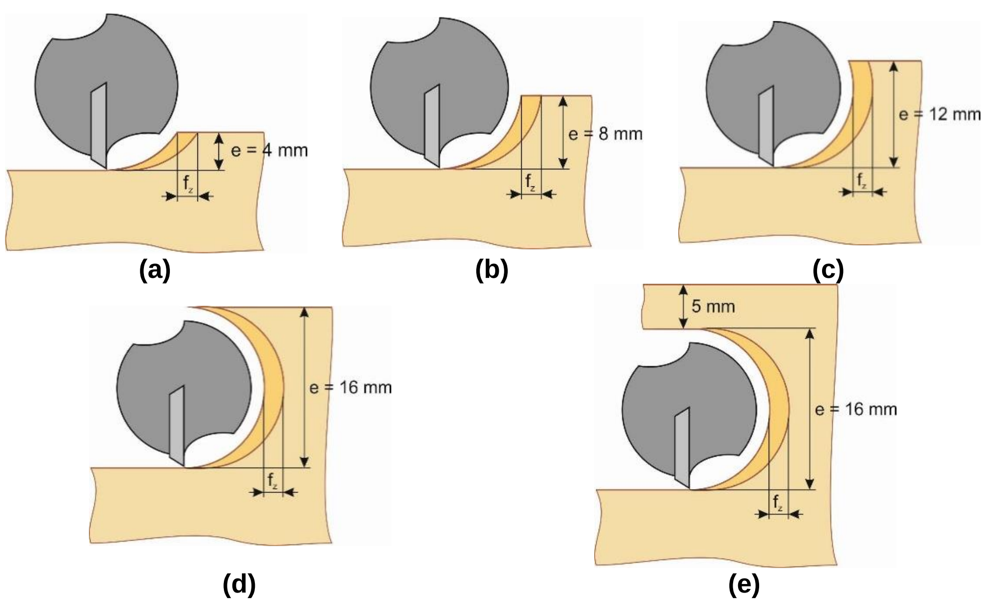

Fig. 3. Strategy of machining: a) thickness of the removed layer of 4 mm, b) thickness of the removed layer of 8 mm, c) thickness of the removed layer of 12 mm, d) thickness of the removed layer of 16 mm, and e) thickness of the removed layer of 16 mm plus any residual material

After the separation of required samples, the MDF board was released and pushed to the end-stop; the process was then repeated with a different combination of technological parameters. The process was conducted at a constant milling cutter operation speed (*n*) of 20,000 min^{-1} and a changing feed rate (v_f) from 1 $m \cdot min^{-1}$ to 5 $m \cdot min^{-1}$, representing a maximum feed rate of that recommended by the manufacturer. The effect of wrong cutting direction in the process of automatic milling was investigated following the changes in cutting direction. The change in climb milling due to the change of the vector of feed rate to parallel is shown in Fig. 2. The change is not caused by the change in tool rotation (blue circle) but is due to a change in the vector of speed rate (green circle). This is a specific feature of using the CNC machining centers, but for standard machines it does not occur.

The MDF strips with the width of 5 mm separated using the circular saw were extracted to determine the surface roughness. Samples were extracted according to the methodology of Kminiak *et al*. (2016), see Fig. 4.

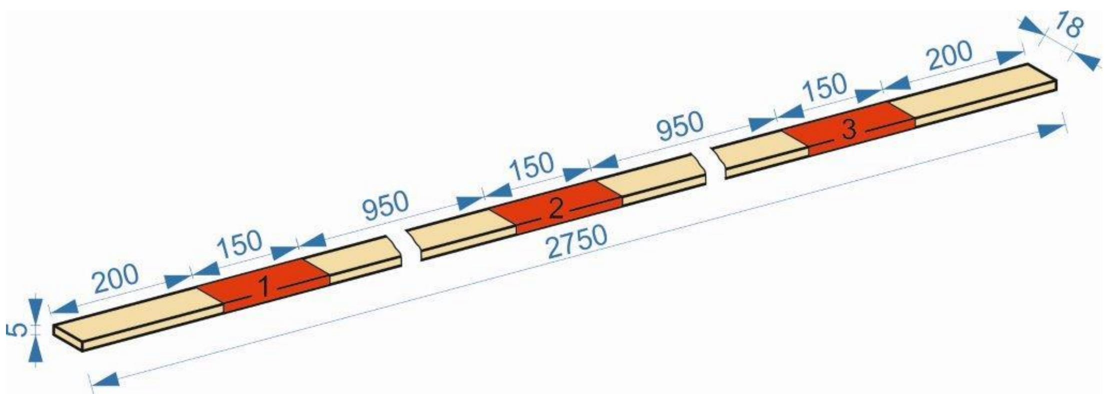

Fig. 4. Methods used to extract samples to determine the surface roughness; all units are expressed in mm

Determination of the surface roughness

Surface roughness of the samples was measured with a laser profilometer (Fig. 5) (LPM4; Kvant Ltd., Bratislava, Slovak Republic). A profilometer is based on the triangulation principle of laser profilometry.

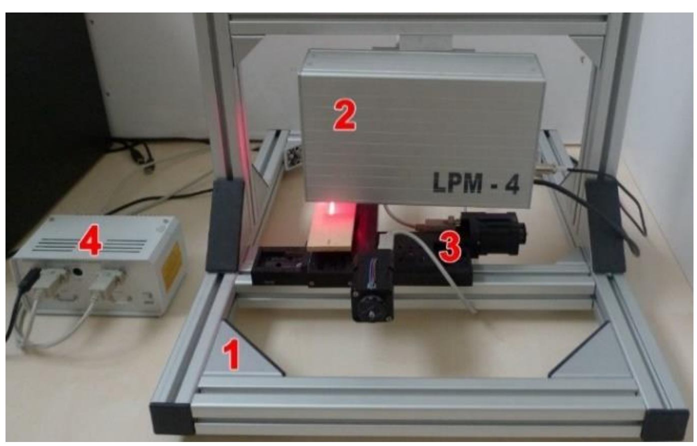

Fig. 5. Laser surface profilometer LPM4 (1 - supporting structure allowing manual preset of working distance and mounting of profilometric head and trolley system, 2 - profilometric head, 3 - feed system of the XZ axes, and 4 - control feed system of working desk)

The image of the laser line is scanned at an angle by a digital camera. Subsequently, an object profile in the cross-section is evaluated from the scanned image. Acquired data are mathematically filtered, and individual indicators of primary profile, as well as profiles of waviness, and roughness, are set (Gaff *et al*. 2015).

The methodology by Kminiak *et al.* (2017) considering the standard ISO 4287 (1997), was used to measure the surface roughness. Each sample was measured in three tracks located in the middle of the sample length, evenly spaced across the width of the sample (4.5, 7.5, 10.5, 13.5 mm from the edge of the sample). The line length was 60 mm and the track was oriented in the direction of displacement of the spindle in the milling process (Fig. 6). Surface roughness was evaluated using the mean absolute deviation of the roughness profile (R_a). This R_a was selected because it is a standard parameter used to determine the roughness of wood and wood-based materials. R_a is considered best suited to evaluate the effect of technology, as material abnormalities typical for wood are eliminated this way. The MDF is a specific wood-based panel that can also be evaluated using R_z, but due to the comparison of various materials defined using the R_a value, Ra was preferred in the research. R_z is the arithmetic mean value of the single roughness depths of consecutive sampling lengths, it means that R_z is the difference between the tallest "peak" and the deepest "valley" in the surface.

Measured values of the mean absolute deviation of roughness profile were evaluated using STATISTICA software (StatSoft, Inc., version 7, Tulsa, OK, USA).

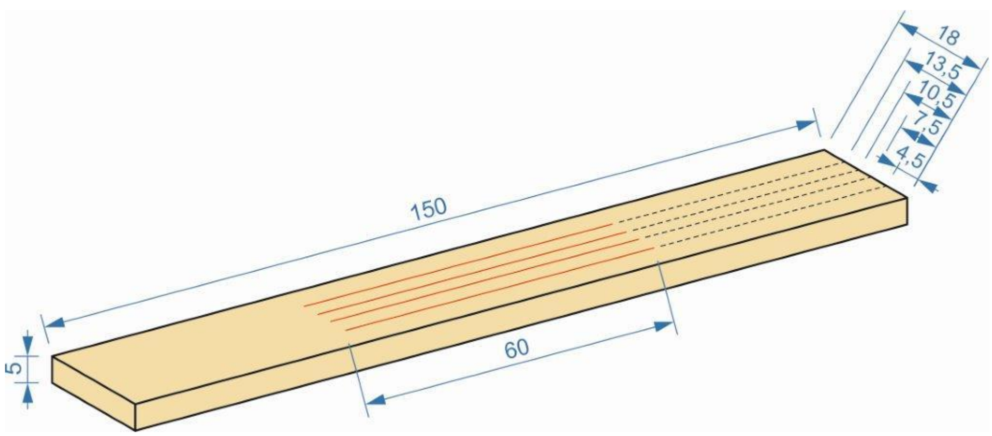

Fig. 6. Placement of tracks due to measuring the surface roughness across the width of the sample; all units are expressed in millimeters

Table 6. Summarized Data

Factors	Values
Type of milling cutter	Single blade / Double blade
Feed rate	V_f = 1/2/3/4/5 m·min^{-1}
Thickness of the removed layer	E = 4/8/12/16/(16+) mm
Cutting direction	Convential / Climb

RESULTS AND DISCUSSION

The factor analysis of variance (Table 7) showed that the effect of all examined factors was statistically significant. Following the analysis, examined factors were ordered in terms of the significance as follows: 1. Type of milling cutter, 2. Feed rate, 3. Thickness of the removed layer, and 4. Cutting direction.

Table 7. Factor Analysis of Variance for Dependence of Mean Absolute Deviation of Roughness Profile R_a on the Examined Factors

Factors	SS	df	MS	F	p-value
Intercept	83,343.15	1	83,343.15	13,011.00	0.0000
Thickness of the removed layer	688.10	4	172.03	26.86	0.0000
Feed rate	724.94	4	181.23	28.29	0.0000
Type of the milling cutter	2,875.41	1	2,875.41	448.89	0.0000
Cutting direction	144.93	1	144.93	22.63	0.0000
Thickness of the removed layer × feed rate	207.20	16	12.95	2.02	0.0107
Thickness of the removed layer × type of milling cutter	164.24	4	41.06	6.41	0.0000
Feed rate × type of milling cutter	236.73	4	59.18	9.24	0.0000
Thickness of the removed layer × cutting direction	28.65	4	7.16	1.12	0.3471
Feed rate × cutting direction	46.19	4	11.55	1.80	0.1270
Type of milling cutter × cutting direction	241.55	1	241.55	37.71	0.0000
Thickness of the removed layer × feed rate × type of milling cutter	162.70	16	10.17	1.59	0.0680
Thickness of the removed layer × feed rate × cutting direction	76.87	16	4.80	0.75	0.7422
Thickness of the removed layer × type of milling cutter	114.27	4	28.57	4.46	0.0015
Feed rate × type of milling cutter × cutting direction	72.50	4	18.12	2.83	0.0243
1 × 2 × 3 × 4	153.30	16	9.58	1.50	0.0965
Error	3004.22	469	6.41		

SS: Sum-of-squares; df: degrees of freedom; MS: Mean squares

The results of the gathered data are presented in the following section. Due to the specific conditions of the authors' experiment, the data gathered cannot be compared to the data of other authors. Comparison of the milling process when the dimensions of tools are completely different would be incorrect (direction of the vector of final cutting speed, *etc*.).

Following the factor analysis of variance (Table 7), the results showed that the surface roughness was most significantly affected by the type of milling cutter used. The value of the average surface roughness produced with the milling cutter (single-bladed) was 16.26 μm with a 95% confidence interval, and ranged from 15.78 to 16.75 μm. The value of the average surface roughness produced with the milling cutter (double-bladed) decreased to 11.33 μm with a 95% confidence interval and ranged from 11.08 to 11.60 μm Based on the results, the use of the double-bladed milling cutter resulted in a decrease in average surface roughness by 30.3%.

Statistical comparison of the average surface roughness produced with the milling cutter single and double-bladed with a 95% confidence interval is presented in Fig. 7.

Comparing the graphs, there was a significant narrowing of the 95% confidence interval by 45% when the milling cutter changed from single-bladed to double-bladed. The theoretical assumption that an increase in the number of cutting edges results in higher quality of the surface as a result of the lower feed per tooth with a subsequent chip-thinning effect was confirmed following the values gathered in the experiment.

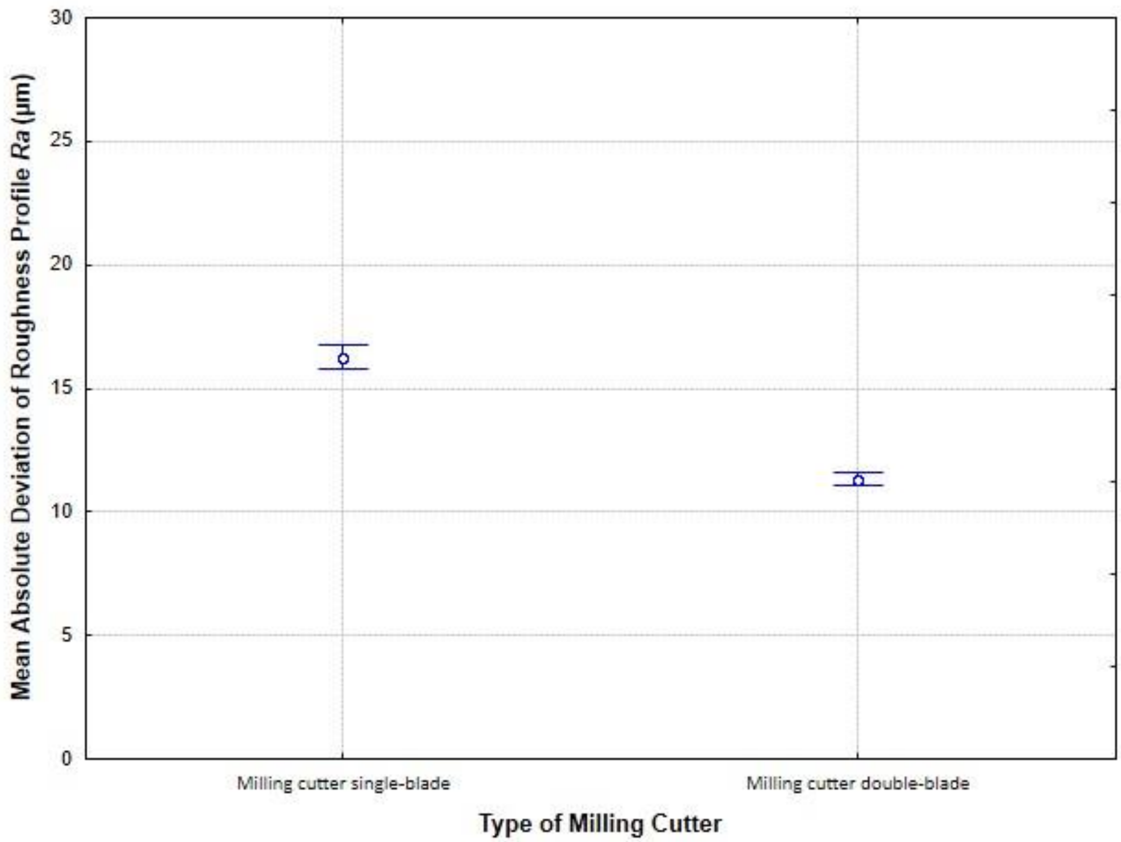

Fig. 7. Relation between mean absolute deviation of roughness profile (R_a) and the type of milling cutter used

The effect of the feed rate was another significant factor affecting the surface roughness. Following the analysis of the mean absolute deviation of the roughness profile shown in Fig. 8, an increase in surface roughness due to a higher feed rate was observed. The most significant and approximately linear increase in the surface roughness when the feed rate (V_f) ranged from 1 to 3 m·min^{-1} was observed with the single-bladed milling cutter. For the double-bladed milling cutter, the most significant increase in surface roughness was observed when the feed rate ranged from 2 to 4 m·min^{-1}. Following the graph in Fig. 10, differences in an increase in surface roughness depending upon feed rate are shown. For the single-bladed milling cutter, the increase in roughness was approximately twice as large as the double-bladed milling cutter (observed especially when the feed rate was $V_f \leq 3$ m·min^{-1}). This could have been due to higher feed per tooth (see Fig. 9). In scientific literature, various works dealing with the single-bladed milling cutter can be found. The same effect of the feed rate during the milling with the single-bladed milling cutter was also reported by Siklienka and Adamcova (2012). The exclusive use of the double-bladed milling cutter is presented in the work of (Kaplan *et al*. 2018).

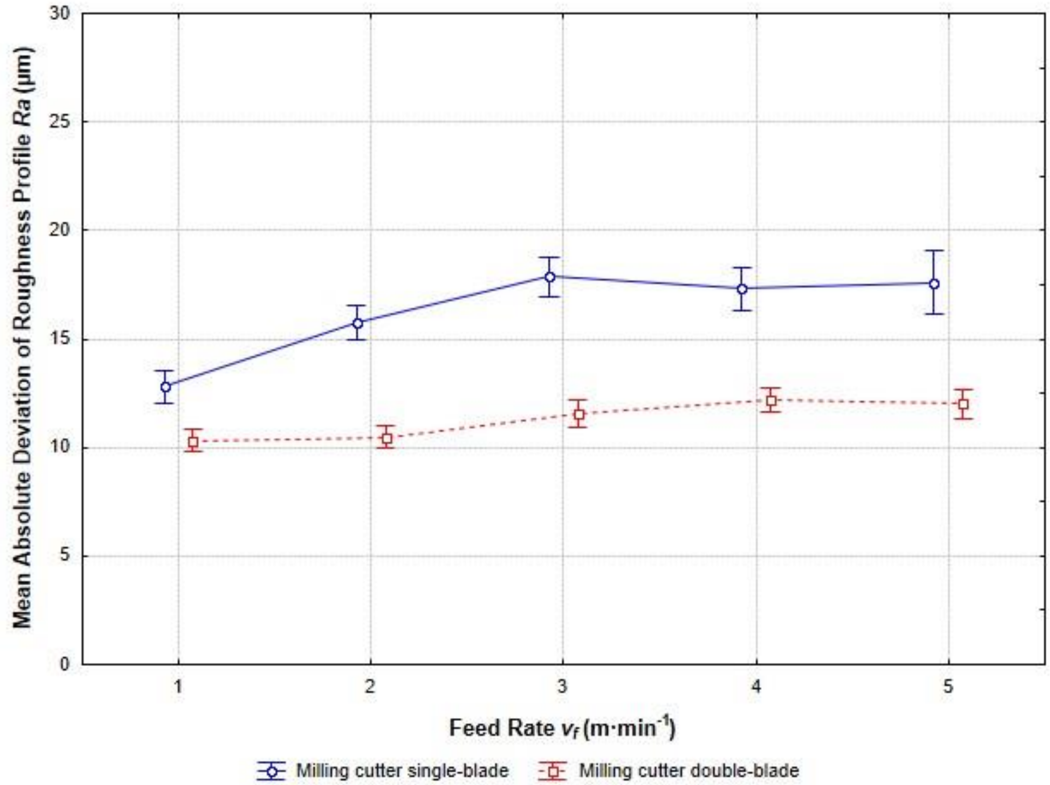

Fig. 8. Relation between mean absolute deviation of roughness profile and the feed rate

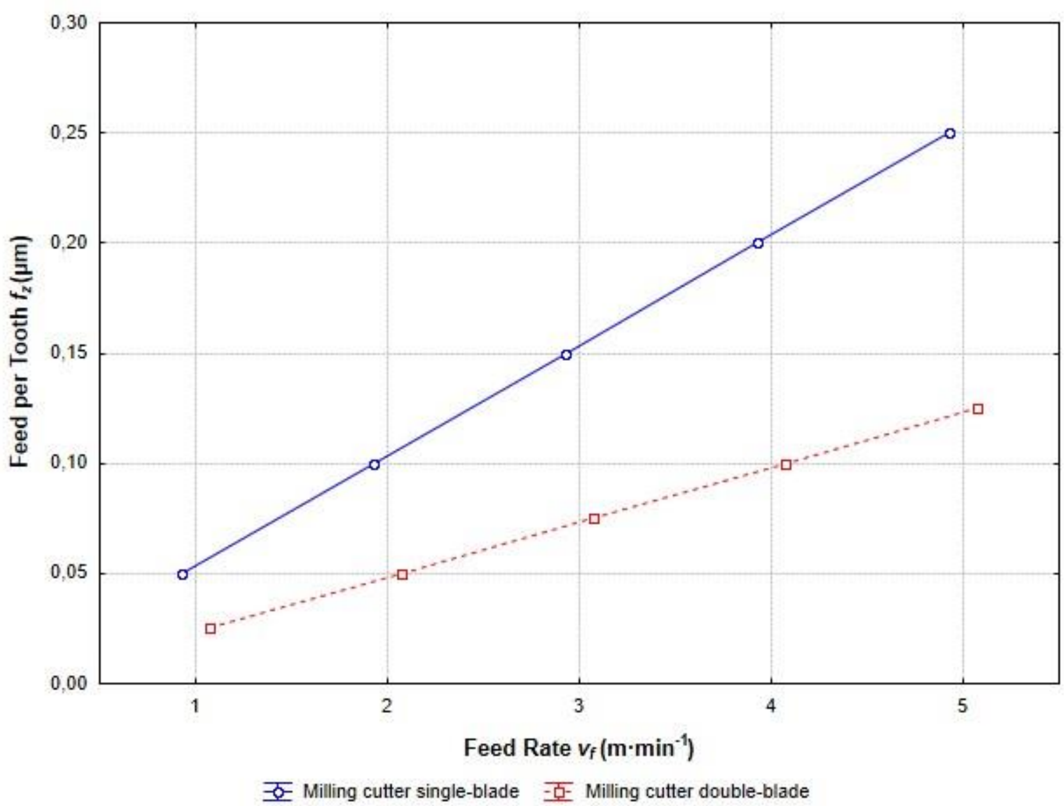

Fig. 9. Relation between feed per tooth and the feed rate

For the single-bladed milling cutter, the roughness of the surface produced was the smallest when the feed rate was V_f = 1 m·min^{-1}, with R_a =12.78 µm. A subsequent increase in the feed rate resulted in an increase in roughness with R_a = 17.85 µm when the feed rate was V_f = 3 m·min^{-1}; an increase of 40%. A further increase in the feed rate caused the increase in surface roughness to remain constant; thus the roughness oscillated around the value of R_a = 17.50 µm. When testing the double-bladed milling cutter, low roughness values were achieved at a feed rate of V_f = 1 m·min^{-1} with R_a = 10.31 µm. At the maximum feed rate (V_f) of 5 m·min^{-1}, the surface roughness increased to a value of 12.00 µm, *i.e.*, an increase of 16%. Following the calculated data, the observation that an increase in the surface roughness using the single-bladed milling cutter was twice as large as using the double-bladed milling cutter can be seen. This corresponded with an increase in the feed per tooth.

The thickness of the removed layer can be considered the third factor in terms of the significance of its effect on the surface roughness. In comparison to previous factors, the thickness of the removed layer did not affect the feed per tooth, but it caused a change in forming a chip, which was its cross-section. Following the gathered data of the single-bladed milling cutter, the increase in thickness of the removed layer resulted in the increase in surface roughness. However, with the double-bladed milling cutter, no statistically significant effect of the thickness of the removed layer on the change in surface roughness was proved when the thickness of the removed layer ranged from 4 to 16 mm. The assumption that the increased thickness of the removed layer increases the surface roughness as a result of increasing the internal tension in the cutting zone, which should result in cracks in the cutting zone, was rejected (Kminiak *et al*. 2017).

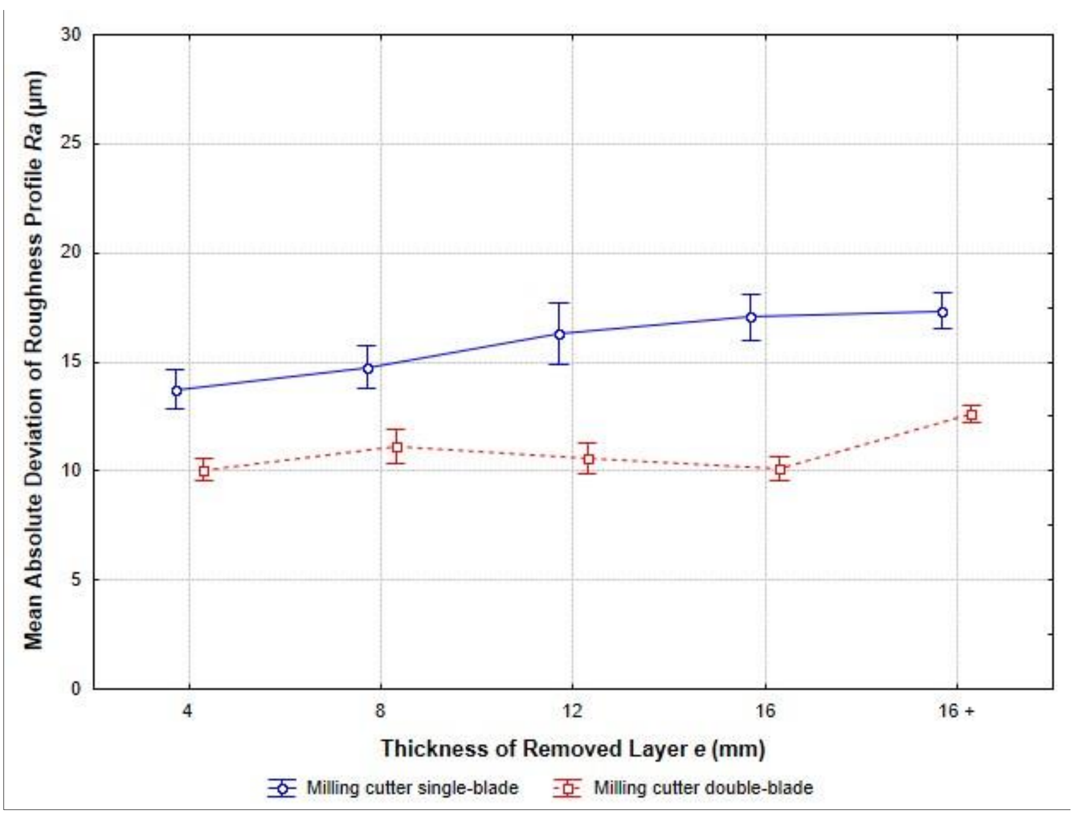

Fig. 10. Relation between mean absolute deviation of roughness profile and the thickness of the removed layer

A statistically significant difference was observed only for the thickness of the removed layer of 16+ mm, which was caused by vibration of non-gripped residual material. The relation between mean absolute deviation of roughness profile and the thickness of the removed layer is presented in Fig. 10.

Cutting direction was the last examined factor in terms of its effect on the surface roughness. Data analysis showed that, with the single-bladed milling cutter, the cutting direction affected the final roughness of the milled surface significantly. When climb milling was used, the average value of surface roughness was R_a = 14.9 µm, whereas when the conventional milling is used, the average surface roughness was R_a = 17.7 µm. The change in roughness depending upon the cutting direction with the single-bladed milling cutter was 18.8% for the use of climb milling. When using the double-bladed milling cutter, the effect of the cutting direction on the surface roughness was not identified. Statistical analysis of the mean absolute deviation of roughness profile and a 95% confidence interval is shown in Fig. 11. For the single-bladed milling cutter, the vector error of the tool path in the process of automatic milling may result in a lower quality of milled surface, *i.e.*, all milled surfaces may not be satisfactory. However, the results allow the statement that using the double-bladed milling cutter does not cause a change in the quality of the milled surface (not even in for changes in vectors of tool paths) to be true. This means that for the double-bladed milling cutter, this error cannot be considered significant.

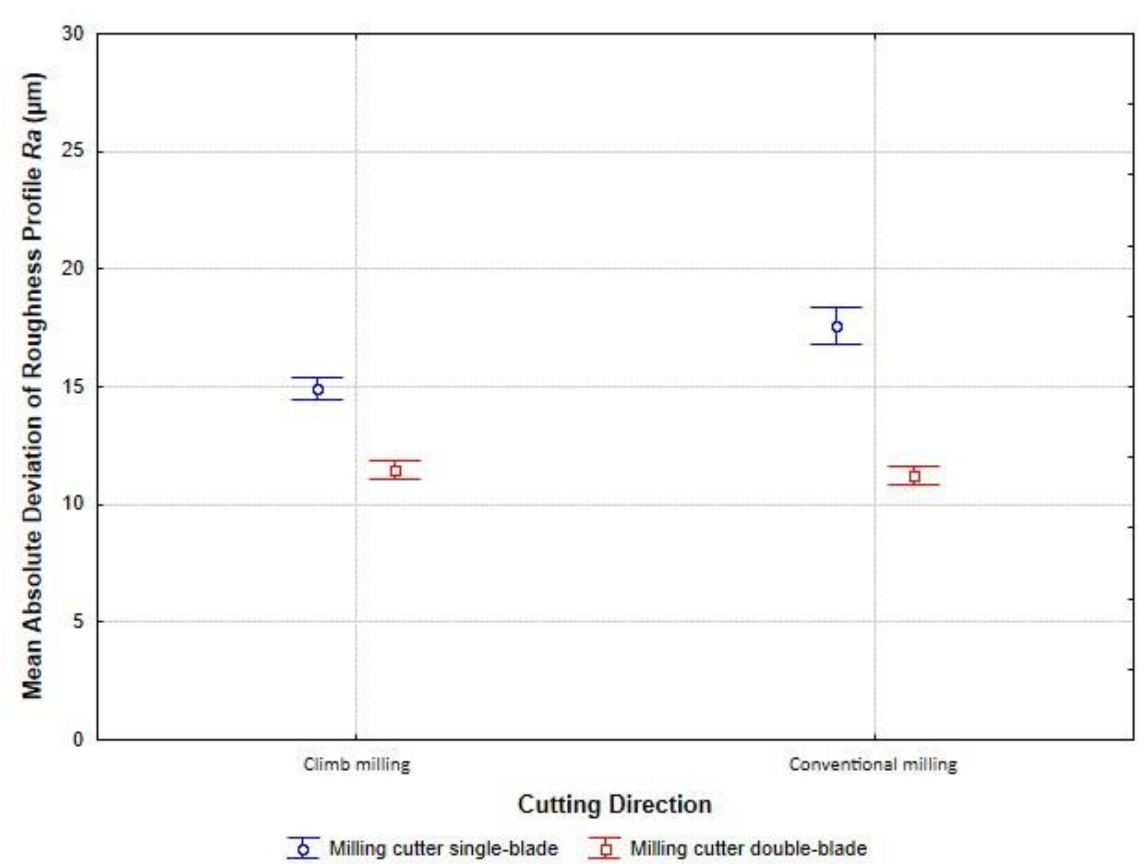

Fig. 11. Relation between mean absolute deviation of roughness profile and the cutting direction

CONCLUSIONS

1. In practice, the error caused by the wrong milling direction was observed as the most common error of automatic milling in the production process. In extreme situations, the error was presented acoustically and the tool could be damaged as well. In common situations in practice, the error may not be observed, which can result in the lower quality of milled surfaces, and, moreover, in the tool life.
2. Following the results of the research, the most significant factor affecting the roughness of the milled surface was the type of milling cutter used. Its effect was 17 times larger than the effect of other evaluated factors (feed rate, thickness of the removed layer, cutting direction). In terms of significance, other factors were comparable.
3. The difference in the final surface roughness for the double-bladed milling cutter and the single-bladed milling cutter was 30.3%. Furthermore, the variance of the roughness of the final surface was smaller when the double-bladed milling cutter was used. The increase in the number of cutting edges increased the surface quality as a result of a decrease in feed-per-tooth with a subsequent chip-thinning effect.
4. The increase in feed rate resulted in the increase in surface roughness, whereby the increase was more noticeable for the use of the single-bladed milling cutter than for the double-bladed milling cutter. When using the single-bladed milling cutter, the roughness increased with the feed rate ranging from 1 to 5 $m \cdot min^{-1}$, approximately 40%. When the double-bladed milling cutter was used, the roughness increased with the same feed rate approximately 16%, which was significantly lower in value. In both cases, the increase in roughness was due to the increase in feed per tooth.
5. The increase in the thickness of the removed layer caused, for the use of the single-bladed milling cutter, a gradual, almost linear increase in the surface roughness. Cumulating and subsequent vibration of residual material was considered the main reason. For the use of the double-bladed milling cutter, the significantly important increase in the surface roughness was observed only during milling with the thickness of the removed layer over 16 mm. When the values were lower than 16 mm, a statistically significant increase in the surface roughness was not shown. “Non-gripping” the residual material (and subsequent vibrations) due to more efficient removing when the double-bladed milling cutter was used (explained by its geometry), was considered the main reason. This theory was confirmed for the use of the four-bladed milling cutter. The increase in the thickness of the removed layer did not affect the surface roughness, seeing that the residual material was removed better in comparison to the double-bladed milling cutter. Following the theory, the increase in the thickness of the removed layer will not affect the surface roughness using the single-bladed milling cutter, but the residual material must be removed during the milling process, for example by the airflow (air blowing).
6. The effect of cutting direction was not statistically significant when the double-bladed milling cutter was used. When using the single-bladed milling cutter, the increase in surface roughness was statistically significant at the level of approximately 19% for the use of climb milling.

7. The use of the multi-bladed milling cutter resulted in a higher quality of the milled surface compared to the single-bladed milling cutter in terms of all examined factors. At the same time, using the "double-bladed milling cutter" did not result in a lower quality of the milled surface for the wrong vector of tool path in automatic milling.

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