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Influence of Tool Inclination and Effective Cutting Speed on Roughness Parameters of Machined Shaped Surfaces

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Abstract: Free-form surfaces in the automotive or aviation industry where the future shape of the product will contain complex surfaces raises the question of how to achieve the necessary shape of the required quality in the milling process. One of the methods of their production is the use of 5-axis milling, in which it is necessary to consider not only the input data of the process itself, but also the methodology for evaluating the desired results. Correctly answered questions can thus facilitate the choice of the inclination of the tool when machining parts of the surfaces defined in the experiment. The primary goal of the paper was to monitor the influence of tool inclination on the quality of the machined surface and effective cutting speed by evaluating surface roughness and surface topography. The experiment was designed to show the effect of different tool positions while the feed per tooth f_z for the finishing operation remained constant. The best result in terms of surface quality was achieved with a tool inclination of 15° in the cutting process. The most unfavorable result was obtained with a tool axis inclination of zero degrees due to unfavorable cutting conditions.

Keywords: 5-axis milling; effective cutting speed; tool axis inclination; roughness

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1. Introduction

The 5-axis milling is one of the most important production methods in current production technologies. In the production of complex, shaped surfaces by milling, not only the method of clamping the part and the choice of strategies and tools, but also the choice of the CNC machine itself plays an important role. The main advantage of using 5-axis milling strategies is changing the position of the axis of the milling tool with respect to the machined surface to ensure suitable cutting conditions [1]. The most used tools for finishing operations for 5-axis milling are copying tools. By using them, it is possible to achieve high surface quality, but only with consideration of the influence of some important parameters in the cutting process. These parameters include the cutting conditions, the angle of inclination of the tool axis to the surface normal, the accuracy of tool clamping, and, finally, the stability of the entire process.

When milling complex, shaped surfaces, when the contact of the tool with the workpiece changes, it is not possible to achieve cutting conditions with constant values. By changing the position of the tool axis, the effective diameter of the cutter is increased and, thus, the effective cutting speed is increased. For this reason, it is possible to perform more efficient milling with a simultaneous improvement in surface quality, change in force action, extension of tool life, and reduction of vibrations of the machine–tool–workpiece-fixture system [2,3]. The size of the effective diameter does not only depend on the diameter of the tool and the axial depth of the cut; another influencing factor is the angle of inclination of the tool axis. It is well known that one of the most important differences between 5-axis and 3-axis CNC milling is whether the tool axis vector is variable in the milling process [4]. Choosing a suitable angle of inclination is especially difficult for complex parts with different surface curvatures. On the one hand, a small angle of inclination is recommended to achieve a good surface roughness and a small height of irregularities. On the other hand, some areas on the machined surface may require a much larger minimum inclination angle to avoid high roughness values. Surface roughness is one of the process quality indicators, so it is important to identify the optimal conditions to achieve good results at low costs [5].

The advantage of applying 5-axis milling in the process of manufacturing complex-shaped surfaces is the use of the entire cutting edge of the copying tool, which rotates around its center by continuously changing the vector of the tool axis so that the cutting edge can be used evenly throughout the process [6].

The inclination of the tool to the milled surface during the entire cutting process significantly affects the basic characteristics of the surface, such as topography, roughness, and, finally, the dimensional and shape accuracy of the part. If we consider that the cutting speed of the center of the cutting edge is zero, when the axis of the cutting tool is perpendicular to the cutting plane, the produced milled surface can achieve a deteriorated surface quality in the form of measured parameters, e.g., roughness. The reason is the insufficient cross-section of the chip, which is removed from the milled surface. Antoniadis [7] tried to prove through research that the inclination angle of the tool axis during milling between the cutting tool and the workpiece can improve the quality of the milled surface. The author presented an analytical model that was developed in the object-oriented C++ language and described the geometry of the milling process with various copying tools. The author applied the program to "create" a surface roughness that matched the measurements of the milled samples.

Sadílek [8] analyzed the accuracy and roughness of the surface of machined experimental samples using 3-axis, 3 + 2-axis, and 5-axis milling, focusing mainly on the inclination angle of the tool axis. The following inclination angles were observed: βf = from 10° to 15° and βn = from 10° to 15°. The CAD model was compared with the prediction of errors in the CAM system, which allowed the determination of the size of the deviations of the calculated surfaces before the machining process, and also analyzed it with the real measured deviations using an Alicona optical microscope. The arithmetic mean of the inaccuracies in 5-axis machining was 18 μm and in 3 + 2-axis machining it was 47 μm. It was found that it is advisable to avoid the slope $\beta f = 0°$, where the surface roughness parameters Vmp, Sz, and Sp were the highest. At the same time, he recommends using the inclination angle of the tool axis in the interval βf = 15 to 20° and βn = 5 to 20°.

Reducing tool wear by controlling the angle of inclination of machining between the tool and the workpiece was investigated by Ko [9]. The simulation results showed that an angle of inclination of the tool axis of 15° was sufficient in terms of surface quality when machining hardened steels, and this value was verified by a cutting experiment using HSM milling. Schulz and Hock [10] investigated the effects of tool inclination in mould and die milling concerning tool life and workpiece quality. They found that downward milling with a tool inclination in the range of 10° to 20° represents the optimal machining strategy for low tool wear and better workpiece quality.

In 5-axis milling, it is necessary to position either the tool or the workpiece appropriately to avoid engaging the low-cutting-speed area. In addition, off-center milling is also used to study the effect of the contact area of the cutting edge when milling with copying tools [11]. Shan [12] investigated the influence of the tool inclination angle on the elastic deformation of thin-walled parts during multi-axis milling. The results showed that when the tool inclination angles are 15° or 45°, the cutting force and deformation of the test pieces are the smallest. In his experiments, Han [13] investigated tool orientation to achieve the desired surface quality and improve production efficiency. The goal was to evaluate the influence of the angle of inclination of the tool on the integrity of the surface, especially topography, roughness, and residual stress during high-speed milling of steel type P20. The results demonstrated the achievement of better values of the observed parameters at angles of 10° to 30° with the upward milling method because the cutting force slightly changed with the angle of inclination of the tool.

Kiswanto [14] presented a method and experimental results regarding the investigation of the effect of rake rate control on machined surface deviation, finding that increasing the rake rate resulted in higher surface roughness Ra. Pașca [15] investigated the change in surface roughness during milling with a copying tool when the tool axis was inclined in the positive feed direction. Secondly, using these experimental results, a mathematical model was designed to estimate the surface roughness for different values of the inclination of the tool axis. The best values of the surface roughness were achieved at values of the tool inclination angle in the intervals of 15 and 30 degrees. Good results were also obtained between 60 and 75 degrees, but milling using an angle of inclination of 45 degrees should be avoided because at this angle the worst surface roughness was achieved, while at small values of the angle of inclination, the influence of the spindle speed was negligible. Obtaining low surface roughness values does not have to be conditioned by excessive spindle speed or inclination of the tool.

Iqbal [16] investigated the effect of workpiece material (hardened steels), workpiece inclination angle, tool rotation speed, and radial depth of cut on tool life and workpiece surface roughness. For tool life, the most influential parameter of the workpiece material (chemical composition + hardness) was found, followed by tool rotation speed. The machinability of AISI D2 was found to be worse than that of X210 Cr12. High tool rotation speed values have been shown to be unfavorable for tool life, but favorable for surface treatment. The angle of inclination of the workpiece turned out to be the most influential parameter on the surface roughness. Its higher values provided a better surface finish because cutting in the center of the tool was avoided. It was found that the second influential parameter on the surface roughness was the radial depth of cut. Its higher settings had an adverse effect on the finish due to the formation of larger cusps at these values.

Izamshah [17] investigated the influence of machining parameters such as the change in speed, feed, and depth of cut on the roughness of the machined surface during the face milling process when milling polyether terketone materials intended for medical applications. A 15 mm thick thermoplastic polymer sheet manufactured by TECAPEEK (manufacturer Ensinger, Houston, USA) was used in the experiment. A flat carbide-end mill with two grooves with a diameter of 10 mm was used as the tool (a two-flutes flat carbide-end mill with a diameter of 10 mm and total length of 70 mm), while the experiment was carried out on a Deckel Maho 5-axis milling machine. As an evaluation method, he used the RSM (Response Surface Methodology) technique. He found that feed rate significantly affects surface roughness, followed by milling speed and depth of cut. Optical observation of the machined surface showed that the surface roughness mechanisms obtained in the machining of polymer-based composites differ from those obtained in the machining of metals. It turns out that some form of polymer softening occurs when the critical cutting speed is exceeded.

Kruth [18] focused his research on the differences obtained in 5-axis milling, where he used a constant tool orientation and compared it with a changing optimal tool orientation. Similar research was conducted by Kuruc et al. [19], where they evaluated the surface roughness parameters when using polycrystalline cubic nitride.

Further research in this area was carried out by Peng [20], who focused not only on the topography of the surface, but also created a model that made it possible to describe the trajectory of the tool, considering the angle of inclination of the tool axis, vibrations, cutting forces, and the plastic deformation of the material. By comparing the simulated microsurface with the experimental results, the theoretical model showed considerable reliability, which means that the 3D surface topography could be well controlled by the parameter recommended by the constructed model under certain conditions. Mathematical models in the area of surface topography assessment during 5-axis milling were also addressed by Xu [21], who created the equations of the positions of the cutting edge of the tool. It is an interpolation-based method that accurately calculates the cusp height of any point on the workpiece. It does not take into account the numerical iterations requiring a good starting point to reach the solution, but tries to eliminate the tolerance resulting from the discretization difference of the cutting edge and workpiece parameters in most methods.

A mathematical model for determining the topography and roughness of the milled surface when applying 5-axis milling using a copying tool was described in research by Layegh [22]. He mainly focused on the roughness parameters Sa and Sq with respect to cutting process parameters such as feed rate, radial depth of cut, and axial depth of cut. The selection of the evaluation method applied for obtaining information regarding the quality of the machined surface is also very important. We most often encounter the evaluation of the properties of machined surfaces in the form of shape dimensional accuracy and roughness. In practice, we encounter both contact and non-contact methods.

The evaluation of surface roughness (parameters Sa, Ssk, and S10z) using a non-contact method when milling a complex surface on a 3-axis milling center was dealt with in research by Varga [23], who evaluated these parameters regarding the selected milling strategy. He compared the milling strategies such as constant, spiral, and spiral circle milling, while evaluating the topography of the surface at three different heights with respect to the contact of the tool with the machined surface. Differences in tool paths were discernible, attributed to the influence of tool interaction with the machined surface. Better surface topography was achieved with the Constant Z strategy. In the Constant Z strategy, the toolpath was in line with the ideally machined surface and produced a uniform and periodic surface topography along the feed. The result was clearly visible toolpaths aligned along the contours. In the case of the spiral ring strategy, an increase in tool wear was visible, leading to an increase in the number of dimples. This led to an increase in friction between the tool and the workpiece, which resulted in instability in the cutting process and the formation of defects on the surface.

Varga [24] also used the contact method to evaluate the surface roughness of a complex, shaped surface containing concave and convex parts during 3-axis milling, where the Constant Z strategy achieved the best roughness values out of the milling strategies investigated. In his research, he compared the milling strategies of Linear, Linear 90°, Constant Z, Spiral, and Radial milling. As part of the evaluation of surface roughness, the values of the parameter Ra of 0.79 to 1.36 μm and Rz in the range of 3.60 to 6.33 μm were achieved. He also dealt with surface topography and production efficiency. The shortest free-form sample production time was achieved with the Linear 90° strategy, but the worst surface quality was achieved in terms of Ra and Rz roughness. An oriented tool path was achieved for each milling strategy. Comparison of the roughness led to the conclusion that in the case of producing a sample of the corresponding shape in the study, the Constant Z strategy would be effective due to the minimum proportion of finishing operations. Using the Linear 90° strategy would require a larger proportion of finishing work.

The influence of the angle of inclination of the tool axis on the roughness parameters was investigated Daymi [25], who focused on surface topography during the milling of Ti-6Al-4V titanium alloy. As a result, increasing the radial depth of the cut increased the surface roughness, but increasing the cutting speed decreased this parameter.

Uchikata [26] dealt with extending the tool life and at the same time reducing tool wear in the cutting process during 5-axis milling. In his research, he proposed a suitable position for the copying tool. In the proposed method, the vector of the tool axis with a swinging motion makes it possible to reduce tool wear by its dispersion over the entire surface of the tool. In his research, Morishige [27] proposed the use of a conical cutter for a 5-axis milling process. From the experiments carried out, a reduction in the length of the cut was found compared to milling with a copying tool, which indicates an improvement in the efficiency of the cutting process.

The analysis of tool wear and chip formation and the analysis of the machined surface during the multi-axis milling of a Ni-based superalloy using a toroidal tool was dealt with by Gdula [28]. The deviation of the tool in the process of the 5-axis milling of complex, shaped surfaces, which has a great influence on the dimensional and shape accuracy of the manufactured parts, was dealt with in research by Ma [29]. The aim of his research was to establish a methodology enabling the compensation of tool deflections during milling. Vavruška [30] dealt with the dynamic regulation of spindle revolutions and feed rate in order to extend the life of the tool when milling complex surfaces. He proposed an algorithm for calculating spindle speed and feed rate based on the implemented kinematic parameters of the actual spindle controller. In his further research, he focused on the influence of changing cutting conditions when milling shaped surfaces. He proposed an optimization method based on a newly derived relationship between the feed rate at the contact point and the feed rate at the tool reference point by calculating the actual motion pole of the tool reference point and the actual motion pole of the contact point [31].

Jun [32] developed a method that can be used to automate toolpath planning and generate high-performance 5-axis artistic surface milling. The author proposed a method of searching in the milling configuration space (C-space) to find the optimal tool orientation. He considered the global collision of tools during milling. Kobata's [33] study focused on the tool path generation method for 5-axis control milling concerning the interference of the tool with the workpiece. In his research, he emphasized the development of a CAM system designed for tool path generation. He developed the chosen tool path generation method with the maximum use of the configuration space concept, while the boundary of the configuration space was not formed by curvilinear interpolation from the point of view of long calculation time, but used linear interpolation.

Koizumi [34] dealt with toolpath generation for 5-axis control milling based on the area division method, where the interference region is divided into small areas. The effectiveness of the application of CAM systems in the field of 5-axis milling was addressed in research by Marciniak [35], who analyzed the possibility of reducing the milling time by adjusting the trajectory of the surface tool. The maximum width of the machined strip on the surface could be obtained if the tool moved on the surface approximately along the minimum curvature line. The complexity of simultaneous tool movement in five axes was investigated by Le [36], who proposed an error analysis method for 5-axis milling, which applied differential geometry techniques to evaluate the contact height between adjacent tool paths.

Senator et al. [37] studied the various free-form surface flank milling strategies. They focused on strategies for milling surfaces that are widely used in the production of turbocharger parts. The reason was to reduce the interference between the cutting tool and the machined surface to meet all the prescribed tolerances. He found that the linearity between the error and the radius of the cylindrical cutter allowed the determination of the appropriate mill cutter. However, it cannot be applied to a conical cutter. Monies et al. [38] dealt with in their study of the side milling of surfaces using a conical tool, where they tried to point out improved tool placements concerning the milling direction. As a result, when side milling using conventional CAM systems, the position of the cutter used was derived from a single contact point. But for surfaces that were significantly inclined, such as turbine blades, errors from this contact were unacceptable. The importance of the choice of milling strategy in the production of parts consisting of relief surfaces was described in research by Varga [39], who pointed out characteristic features after using a copying tool. He dealt with modeled and real surface quality, focusing on selected fragments of relief surfaces. The machined surface of the workpiece had a characteristic shape after using the copying tool. The locations and heights of the resulting cusps were changed according to the inclination of the tested fragment area.

The relationship between tool inclination and surface quality assessment including surface topography, dimensional accuracy, or roughness parameters in the cutting process can facilitate the choice of tool axis inclination when milling parts of surfaces defined in the experiment. The results of the experiment will make it possible to define which inclination of the tool axis is the most suitable for the given parts of the surfaces in terms of the considered parameters.

Different machining strategies for roughing, semi-finishing technologies with the creation of chips with defined (in this case) and undefined geometry of the cutting edges of the tools, have a significant impact on the final quality of the parts in terms of roughness and shape deviations. The mechanisms involved in milling free-form geometries with a copying tool are still not fully explored, as the process differs significantly from conventional milling. A review of the literature showed a large body of research related to the application of tool axis change in the cutting process concerning surface quality. However, there are few studies dealing with the evaluation of surface roughness concerning the change in tool inclination angle and effective cutting speed with application to two types of surfaces, convex and concave.

Surface roughness is associated with many problems that are closely related to its tribological performance. The measurement methodology and the ability to analyze data based on surface topography from the manufacturing process are justified because they become valuable in terms of accurate information regarding material contact. In some cases, this can be about the function of lubricants, seals, fatigue, friction, or wear resistance. The measurement process itself as well as data processing has a significant impact on the results achieved. During the evaluation, it is possible to encounter the fact that high-precision measuring devices may not provide a comprehensive evaluation of the properties of the surface topography. For this reason, in the methodology of the experiments, this contribution uses two evaluation methods, contact and non-contact methods, which have not yet been analyzed simultaneously. Likewise, the contribution offers a deeper analysis within the 3D morphology of the surface for all selected tool inclinations in the cutting process as well as for convex and concave surface types.

The results of the implemented experiment are important for the appropriate selection of parameters for real production. The deformation of the machined surface was caused by the perpendicular position of the tool, which was caused by the spiral trajectory of the tool transferred to the surface of the workpiece. The perpendicular position of the tool caused a negative change in the contact relationship between the tool and the workpiece. For this reason, the tool did not create enough space for the formation of chips, and the material was torn out of the surface layer of the machined material. Higher roughness values were observed compared to the other samples produced at the defined tool inclination. The results of the research point to the choice of the correct methodology for evaluating surface quality in the form of roughness parameters and surface morphology. This variable characteristic is different for different shapes and functional shaped surfaces, which require different approaches to their machining in terms of the inclination of the tool axis. The importance of the contact zone between the tool and the workpiece in the context of the effective diameter of the tool when milling shaped surfaces is critical for achieving the desired surface quality and minimizing errors. This contact zone should be designed with the curvature of the surface in mind to allow optimal contact and minimize deviations from the desired shape.

The aim of the research was to contribute to the expansion of knowledge about the influence of tool inclination and effective cutting speed on the roughness parameters of milled shaped surfaces. In the research, various aspects of the milling of shaped surfaces were analyzed, including the inclination of the tool and the three-dimensional shape of the surface, taking into account the convex and concave area of the produced samples. Another contribution can be found in the design of a methodology for evaluating the quality and importance of the contact zone between the tool and the workpiece at a defined inclination of the tool in the cutting process. It is important for understanding and optimizing the milling process of shaped surfaces. The result of the research is also the expansion of knowledge about the influence of the inclination of the tool in the cutting process on the roughness parameters, while two types of measurements were carried out—contact and non-contact measurement methods. Research has shown which tool inclinations are most beneficial in terms of reducing surface roughness. Evaluation of the quality of the curved surface obtained after milling brings many advantages to the development of research.

Determining the appropriate inclination of the tool when milling shaped surfaces enables the analysis of surface roughness, as well as the size and distribution of potential errors on a curved surface.

2. Materials and Methods

An aluminum alloy marked EN AW-6082 T651 with dimensions of 50 × 50 × 40 mm was chosen for the experiment. The original 3D model was created in the Autodesk Fusion 360 v.2.0.18719 CAD system. The selection of the sample as a CAD model (Figure 1) was conditioned by two types of surfaces—convex and concave. These are the most frequently occurring surfaces on parts with complex shapes. Four positions (inclinations) of the tool in the feed direction were analyzed in the experiment. A linear strategy was chosen as the finishing strategy for the sample production, with a pulled tool chosen as the tool feed method. The CAM system SolidCAM 2022 was chosen to generate tool paths allowing movement in 5 axes, and the DMG Mori DMU 60 eVo machine (manufacturer DMG MORI, Nagoya, Japan) was used for 5-axis continuous milling.

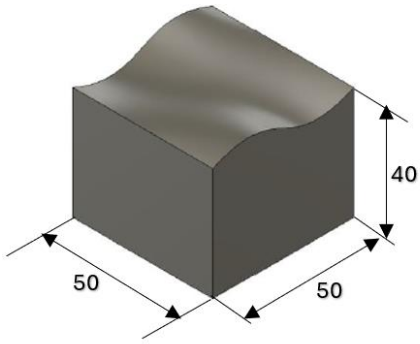


Figure 1. CAD model of sample.

Mechanical characteristics of the used material are given in Table 1. Chemical compositions are shown in Table 2 and the physical properties are shown in Table 3.

Table 1. Mechanical properties of used material.

Yield Stress $Rp_{0.2}$ [MPa]	Tensile Strength Rm [MPa]	Elongation [%]	Hardness HB
230	270	8	90

Table 2. Chemical composition of used material, wt. %.

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.70–1.30	0.5	0.1	0.4–1.00	0.6–1.2	0.25	0.20	0.10

Table 3. Physical properties of used material.

Density [kg/m^3]	Melting Range [°C]	Electrical Conductivity [MS/m]	Thermal Conductivity [W/m·K]	Co-Efficient of Thermal Expansion 10–6/K (20–100 °C)	Modulus of Elasticity [GPa]
2700	585–650	24–32	170–220	23.4	−70

The surface of the curve was created by joining two identical, mirror-turned surfaces. All side walls were perpendicular both to each other and to the bottom surface. The upper surface was formed by a 3D curve, mathematically described, as indicated by the following mathematical formula:

$$z = (25 - y)\frac{3.09}{43.09}\sin\left(\frac{2\pi}{50}x\right) + 40 \tag{1}$$

Basic operations such as roughing and semi-finish were the same for all samples. Production steps of the samples are shown in Figure 2, which describes the visual comparison of the operation used, and in Figure 3 visual comparison of the real production is shown. To finish the shaped sample, a copying tool made of sintered carbide was used with a length of 40 mm for the cutting part of the tool. The choice of cutting conditions corresponded to the tool manufacturer's recommendations. The type SCHUNK-20064359 TENDO EC SK40 was chosen for clamping the tools. The specification of the tools used for experiments is described in Table 4.

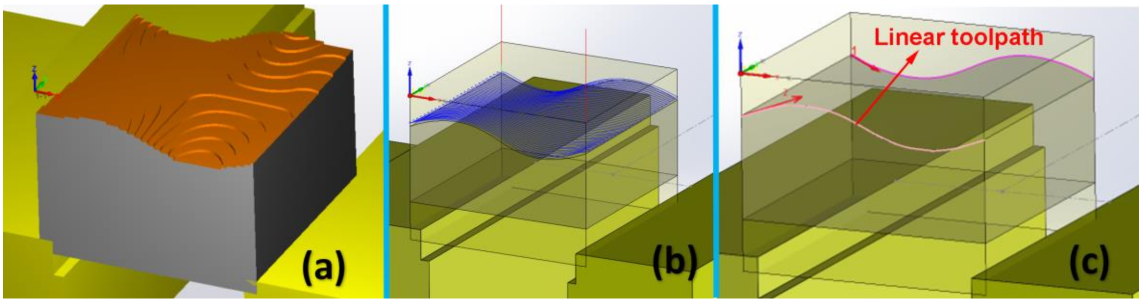


Figure 2. Visual comparison of the operation used (**a**) roughing (**b**) semi-finish, and (**c**) finish operation.

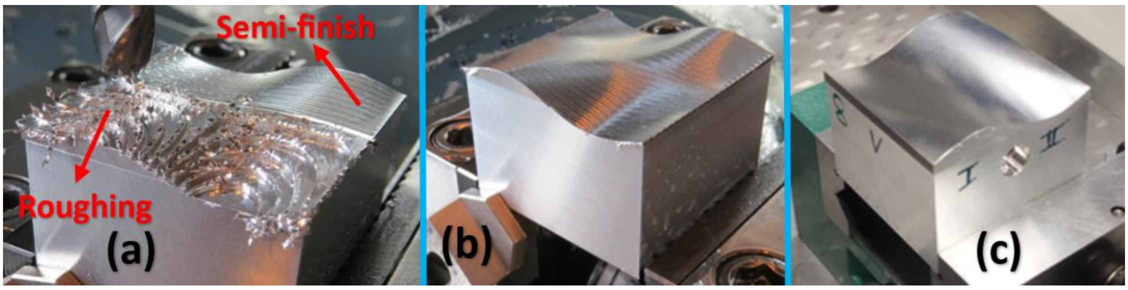


Figure 3. Visual comparison of the real production (**a**) roughing, (**b**) semi-finish, and (**c**) after finish.

The end mill tool D 40 mm was produced by Korloy, manufacturer KORLOY, Seoul, Republic of Korea (designation AMS2000S) with four interchangeable cutter plates marked APMT11-MM. The parameters of the tool used in the milling process are shown in Table 4. Table 5 clearly describes the cutting parameters used in the experiment.

Table 4. Parameters of the tool.

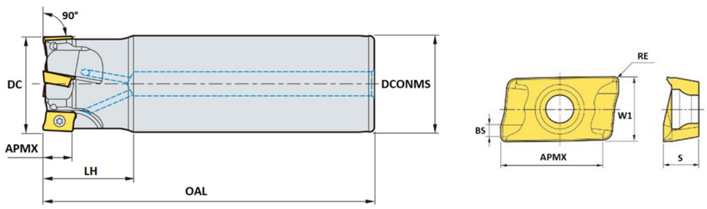
DC [mm]	CICT [mm]	APMX [mm]	OAL [mm]	LH [mm]	DCON-MS [mm]	RPMX [mm]	WT [mm]
40	5	11	130	42	32	1.98	0.813
Face milling—sketch of the tool							

Table 4. *Cont.*

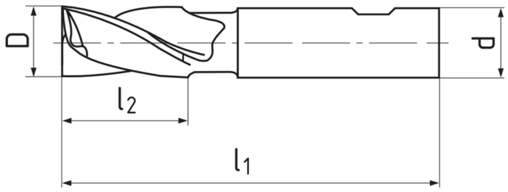
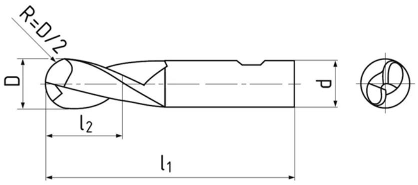
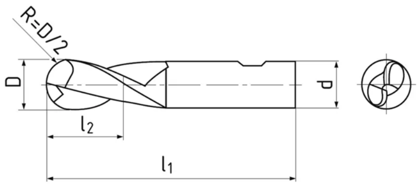
DC [mm]	CICT [mm]	APMX [mm]	OAL [mm]	LH [mm]	DCON-MS [mm]	RPMX [mm]	WT [mm]
D [mm]		d [mm]	L1 [mm]		L2 [mm]	z [-]	
6		6	92		40	2	
Roughing operation—sketch of the tool							
R [mm]	D [mm]	d [mm]	L1 [mm]	L2 [mm]	z [-]	λs [°]	γs [°]
6	12	12	73	16	2	25	10
Semi-finish operation—sketch of the tool							
R [mm]	D [mm]	d [mm]	L1 [mm]	L2 [mm]	z [-]	λs [°]	γs [°]
5	10	10	63	13	2	25	10
Finish operation—sketch of the tool							

Table 5. Cutting parameters used in experiment.

Tool Diameter [mm]	Cutting Speed [m·min^{-1}]	Feed per Tooth [mm]	Tooth Number	Tool Code	Operations
End Mill D 40	400	0.125	4	AMS2018S	Face milling
End Mill D6	370	0.05	2	273,618.060	Roughing
Ball End Mill D12	376	0.037	2	510,418.120	Semi-finish
Ball End Mill D10	150	0.04	2	207,125	Finish

The experiment included the following sequence:

- Roughing—end mill D6 mm, axial depth of cut a_p = 0.5 mm, radial depth of cut a_e = 0.6 mm, tool path tolerance T = 0.1 mm, and surface allowance P = 0.5 mm.
- Semi-finishing—ball end mill D12 mm, cutting material HSS Co8, milling strategy zig-zag, axial depth of cut a_p defined in accordance with the setting of the height of unevenness in the CAM system, where the value was 0.1 mm, radial depth of cut a_e = 1 mm, and surface allowance P = 0.3 mm.
- Finishing—ball end mill D10 mm, cutting material HSS Co8, milling strategy linear, radial depth of cut a_e = 0.3 mm, tolerance of tool path T = 0.01 mm, and scallop height SH = 0.002 mm.

To assess the influence of the change in the position of the tool axis relative to the milled surface, four tool inclination angles were chosen for the experiment (Table 6). Table 6 shows the values of the dependence of the effective tool diameter d_{ef} and the effective cutting speed v_{cef} during a specific change in the position of the tool axis in the cutting process. A constant cutting speed of v_c = 150 m·min^{-1} was chosen in the CAM system for each tool inclination angle, which represents spindle revolutions n = 4775 RPM. The axial depth of cut a_p and radial depth of cut a_e remained constant. A new tool was used for each sample milling process to ensure that the wear factor in the cutting process was minimized.

Table 6. Values of the dependence of the parameters d_{ef} and v_{cef} on a specific change in the position of the tool axis in the cutting process.

Tool Axis Inclination Angle β_f	Effective Tool Diameter d_{ef} [mm]	Effective Cutting Speed v_{cef} [m·min^{-1}]
0°	3.41	51.13
15°	5.73	85.91
30°	7.65	114.70
40°	8.66	129.84

The effective tool diameter d_{ef} in pulled tool milling was calculated according to the formula:

$$d_{ef} = d \cdot \sin\left[\arccos\left(\frac{d - 2a_p}{d}\right) + \beta_f\right] \text{ [mm]} \tag{2}$$

where a_p—axial depth of cut [mm];

β_f—tool axis inclination angle in the feed direction [°];

d—tool diameter [mm];

d_{ef}—effective tool diameter [mm] [40].

Based on the obtained values of the effective tool diameter d_{ef}, the effective cutting speed v_{cef} was calculated by the following equation:

$$v_{cef} = \frac{\pi\, n \cdot d_{ef}}{1000} \tag{3}$$

where a_p—axial depth of cut [mm]

d_{ef}—effective tool diameter [mm]

n—spindle speed [RPM]

v_{cef}—effective cutting speed [m·min^{-1}] [41]

Figure 4 shows the dependence of the effective tool diameter d_{ef} and the effective cutting speed v_{cef} on the position of the tool axis β_f when milling with a D10 mm copy cutter, at the axial depth of cut a_p = 0.3 mm and the spindle speed n = 4775 RPM.

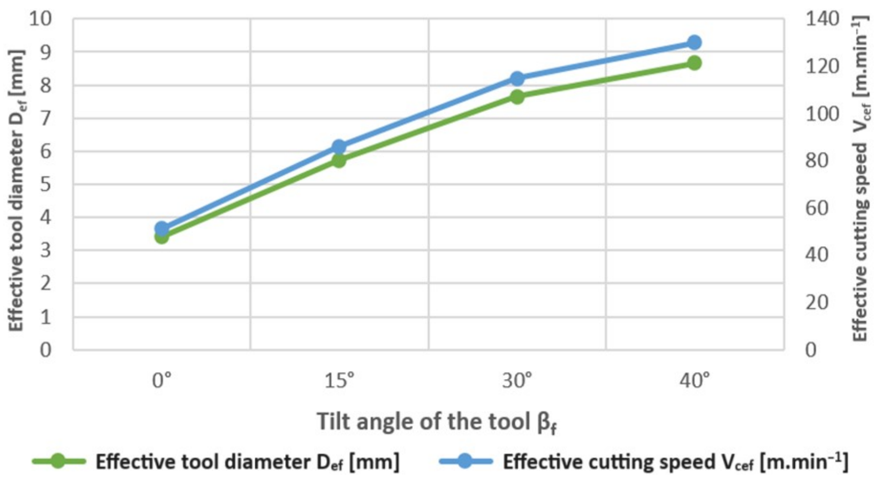


Figure 4. Dependence of the effective tool diameter d_{ef} and the effective cutting speed v_{cef} on the position of the tool axis β_f.

As can be seen in Figure 2, applying a change in the position of the tool axis relative to the milled surface leads to an increase in the effective cutter diameter d_{ef} and the effective cutting speed v_{cef}. The feed per tooth was constant during the experiment series, with the value f_z = 0.04 mm. For the experiment, the samples intended for production were divided into two groups:

- The first group of samples was made at a basic cutting speed v_c = 150 m·min^{-1} and revolutions n = 4775 RPM. The cutting speed was related to the nominal diameter of the cutting part of the tool. All samples for this group were made at a constant speed, while only the position of the tool axis β_f was changed.
- The second group of samples was made with a changing cutting speed adjusted so that the value of the cutting speed v_c = 150 m·min^{-1} was reached on the effective diameter, regardless of the position of the tool axis.

Speed values when changing the angle of inclination of the tool and maintaining a constant cutting speed are shown in Table 7.

Table 7. Speed values when changing the angle of inclination of the tool and maintaining a constant cutting speed.

Tool Axis Inclination Angle β_f	Effective Tool Diameter d_{ef} [mm]	Effective Cutting Speed v_{cef} [m·min^{-1}]	Spindle Speed [RPM]
0°	3.41	150	14 002
15°	5.73	150	8 333
30°	7.65	150	6 241
40°	8.66	150	5 513

Figure 5 shows the dependence of the effective tool diameter d_{ef} and the speed n on the position of the tool axis β_f.

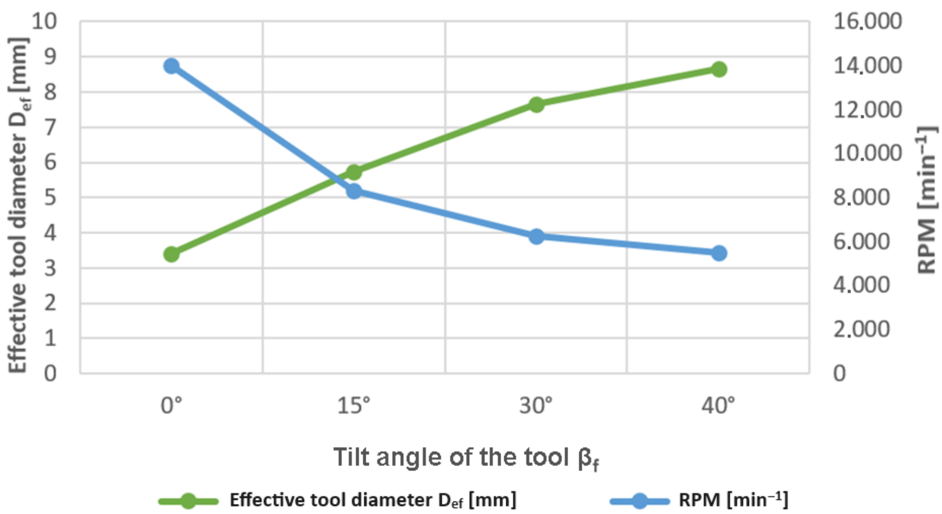


Figure 5. Dependence of the effective tool diameter d_{ef} and revolutions n on the position of the tool axis β_f.

For a comprehensive evaluation of the results of the experiment, the following procedures were chosen:

- Surface roughness measurement by contact measuring method: Mitutoyo ST-410.
- Measurement of surface roughness by non-contact measuring method: Zeiss Smartproof 5.
- Analysis of surface topography when changing the orientation of the tool axis: Zeiss Smartproof 5.

SURFTEST SJ-410 Series is a portable surface roughness tester. Its other features include:

- Measuring range:
  - X axis: 25 mm;
  - Z axis: 800 μm, 80 μm, and 8 μm.
- Detector:
  - Resolution: 0.01 μm (800 μm range)/0.001 μm (80 μm range)/0.0001 μm (8 μm range);
  - Stylus tip: 60°/2 μm;
  - Measuring force: 0.75 mN.

ZEISS is a widefield confocal microscope used for surface analysis in quality assurance and quality control. Its other features include:

- Lateral resolution (line–space pattern): 0.13 μm;
- Lateral measurement uncertainty: ±0.1 μm ±0.008 × L;
- Vertical measurement uncertainty: ±0.1 μm ±0.012 × L;
- Image data processing and measurements:
  - Two-dimensional: distance, height, angle, constructed elements, and profile roughness based on ISO/TR 23276 [42];
  - Three-dimensional: lateral distances, 3D distances, height, angle, constructed points, area, volume, and areal roughness according to ISO 25178-1 [43].

The roughness parameters were evaluated on the milled surfaces by the methods mentioned above. Contact and non-contact methods were chosen, within which the roughness parameters were evaluated separately. A comparison of the roughness parameters was carried out, concerning the convex and concave parts of the surface of the samples when changing the axis of the tool in the cutting process. Two-dimensional and three-dimensional roughness parameters were evaluated. While only the length of the profile was used to measure the 2D parameters, measurements in all directions were used to measure the 3D parameters. Before the measurement, calibration of the individual devices was carried out.

The primary goal was to monitor the effect of changing the tool axis on the quality of the milled surface by evaluating the roughness and topography of the milled surface. The experiment was proposed to show the effect of different tool positions. The feed per tooth f_z for the finishing operation remained constant. The result should be the determination of the most effective inclination of the tool axis, or the range of spatial angles of the position of the tool axis relative to the milled surface.

2.1. Methodology for Evaluating the Roughness of a Machined Surface by the Contact Measurement Method

Measurements of the roughness profile parameters Ra and Rz were carried out according to the ISO/TR 23276. The roughness was measured perpendicular to the feed direction in a length of 4.8 mm. One main measurement and two control measurements with an offset of ±0.1 mm were performed on the convex part of the surface of the samples. The same procedure was chosen for the measurement on the concave part of the surface of the samples. The roughness measurement was carried out on the convex and concave surface of each of the produced samples. It was measured in the center of individual areas, where the highest and lowest point of the measurement location was reached. During the measurement, there was always one main measurement and two control measurements with an offset of ±0.1 mm, while the measurement was carried out in a direction perpendicular to the direction of displacement in a length of 4.8 mm. A sample with marked places intended for surface roughness measurement is shown in Figure 6.

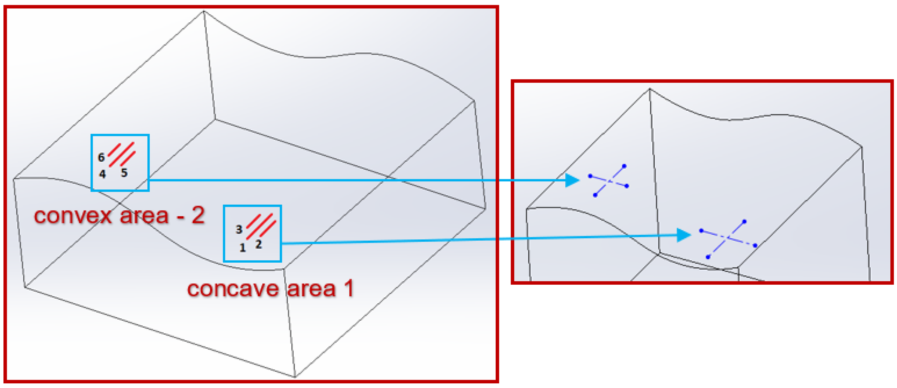


Figure 6. Marked measurement points on the convex and concave part of the sample surface for measuring the surface roughness.

2.2. Methodology for Evaluating the Roughness of a Machined Surface by the Non-Contact Measurement Method

Roughness profile parameters were evaluated. Selected profile (height and length) roughness parameters Ra, Rz, Rp, and Rv were selected. An L-filter with a size of 0.8 mm was used for the analysis of area parameters. The area of the measured surface was 1.50 × 1.50 mm. Since the overall assessment of the surface is quite difficult, the assessment of the section in the direction perpendicular to the milling direction was used. The surface profile was the intersection of the actual surface and the section plane. The same measurement areas were used for the non-contact method as for the contact measurement method.

3. Results

3.1. Evaluation of the Roughness of the Milled Surface by the Contact Measuring Method

3.1.1. Roughness Evaluation on the Convex Part of the Surface

Table 8 shows the values of the mean arithmetic deviation of the surface Ra for the convex part of the surface of the samples. From the average values, it is clear that a higher value of Ra was achieved for the milled surfaces made by maintaining the cutting speed by changing the revolutions. As the angle of inclination increases, the value of Ra increases at both values of the cutting speed. Graphical comparison of roughness parameters Ra for convex parts of surfaces are shown in Figure 7.

The values of the arithmetic average of the largest heights of the Rz profile for the convex part of the surface of the samples are presented in Table 9. The average values of Rz are higher for the surfaces made by maintaining the cutting speed by changing the revolutions. The exception is the surface made at a perpendicular position to the tool axis 0°. For samples made with this tool axis inclination, there is a noticeable increase in Rz values with an increasing angle of inclination, for both values of cutting speed. Figure 8 shows a graphical comparison of roughness parameters Rz for convex parts of surfaces.

Table 8. Measured roughness values Ra [μm] for the convex part of the surface using the contact method.

Roughness Ra [μm]	**0° n Constant**	**0° D_{ef} 3.41**	**15° n Constant**	**15° D_{ef} 5.73**	**30° n Constant**	**30° D_{ef} 7.65**	**40° n Constant**	**40° D_{ef} 8.66**
Position 1	0.616	0.611	0.496	0.610	0.611	0.627	0.623	0.632
Position 2	0.563	0.598	0.459	0.577	0.593	0.601	0.623	0.608
Position 3	0.654	0.641	0.519	0.593	0.617	0.623	0.700	0.652
Average	0.611	0.616	0.491	0.593	0.607	0.617	0.648	0.630

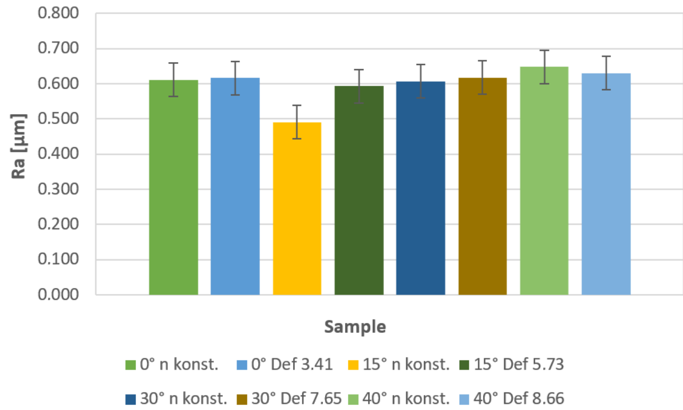


Figure 7. Comparison of roughness parameters Ra for convex parts of surfaces.

Table 9. Measured values of roughness Rz [µm] for the convex part of the surface by contact method.

Roughness Rz [µm]	0° n Constant	0° D_{ef} 3.41	15° n Constant	15° D_{ef} 5.73	30° n Constant	30° D_{ef} 7.65	40° n Constant	40° D_{ef} 8.66
Position 1	3.451	2.865	2.684	2.782	2.701	2.934	2.792	3.071
Position 2	3.632	2.585	2.791	2.657	2.748	2.853	2.874	2.852
Position 3	3.650	3.118	2.665	2.854	2.713	2.831	2.964	2.968
Average	3.578	2.856	2.713	2.764	2.721	2.873	2.877	2.964

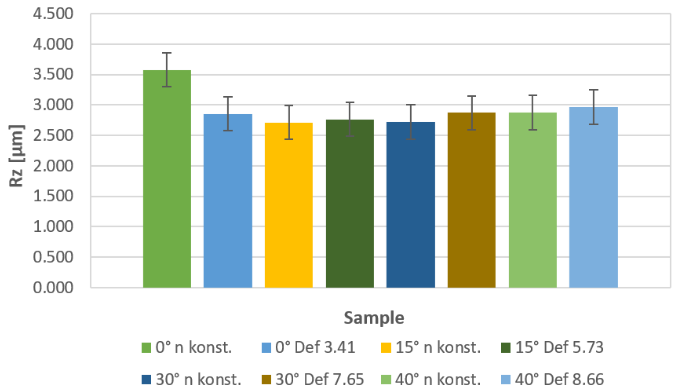


Figure 8. Comparison of roughness parameters Rz for convex parts of surfaces.

3.1.2. Roughness Evaluation on the Concave Part of the Surface

Table 10 shows the values of the mean arithmetic deviation of the surface Ra for the concave part of the surface of the samples. From the comparison of the average values, it can be concluded that a higher value of Ra was achieved for the surfaces of the samples produced by maintaining the cutting speed in the form of a change in revolutions. As the angle of inclination of the tool axis increases, the value of Ra increases at both values of the cutting speed. The exception is the surface where the tool acted perpendicular to the milled surface during the cutting process. A comparison of roughness parameters Ra for concave parts of surfaces is shown in Figure 9.

The values of the arithmetic average of the largest heights of the Rz profile for the concave part of the surface of the samples are shown in Table 11. Higher average values of Rz were measured for the surfaces made by maintaining the cutting speed by changing the revolutions. The exception is the surface made at a perpendicular position of the tool axis 0° to the milled surface, where the highest value of the Rz parameter was measured. For samples produced with a defined inclination of the tool axis, it was possible to see an increase in Rz values with an increasing inclination angle, for both cutting speed values. A comparison of Rz parameters for concave parts of surfaces is shown in Figure 10.

Table 10. Measured values of roughness Ra [μm] for the concave part of the surface by contact method.

Roughness Ra [μm]	0° n Constant	0° D_{ef} 3.41	15° n Constant	15° D_{ef} 5.73	30° n Constant	30° D_{ef} 7.65	40° n Constant	40° D_{ef} 8.66
Position 4	0.603	0.572	0.501	0.612	0.648	0.589	0.602	0.612
Position 5	0.706	0.573	0.549	0.598	0.633	0.624	0.629	0.609
Position 6	0.716	0.619	0.497	0.587	0.581	0.661	0.607	0.627
Average	0.675	0.588	0.515	0.599	0.620	0.624	0.612	0.616

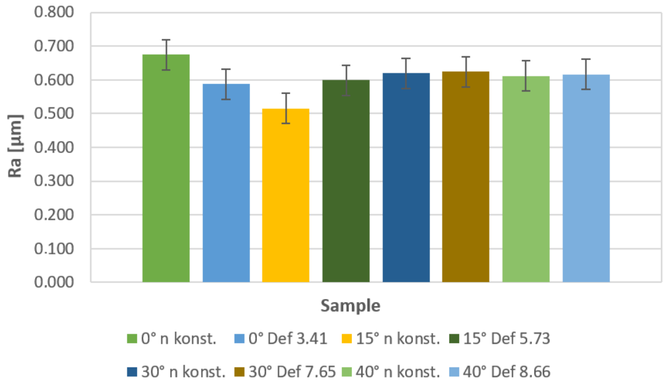


Figure 9. Comparison of roughness parameters Ra for concave parts of surfaces.

Table 11. Measured values of roughness Rz [μm] for the concave part of the surface by contact method.

Roughness Rz [μm]	0° n Constant	0° D_{ef} 3.41	15° n Constant	15° D_{ef} 5.73	30° n Constant	30° D_{ef} 7.65	40° n Constant	40° D_{ef} 8.66
Position 4	3.951	2.897	2.527	2.805	2.584	3.116	2.637	2.935
Position 5	3.901	3.092	2.595	2.794	3.162	3.006	2.749	2.715
Position 6	3.744	2.825	2.721	2.702	2.973	2.697	2.772	3.187
Average	3.865	2.938	2.614	2.767	2.906	2.940	2.719	2.946

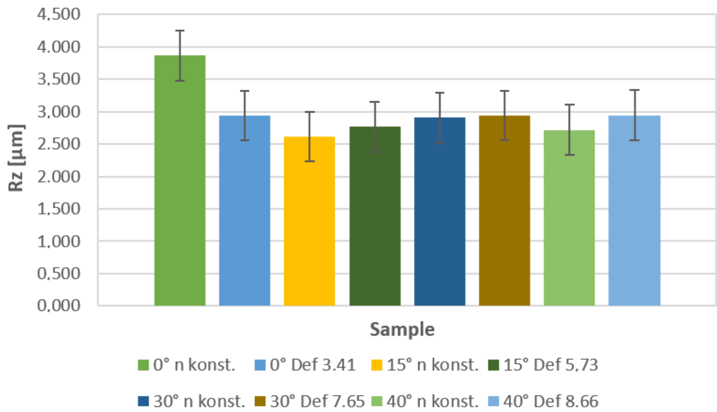


Figure 10. Comparison of roughness parameters Rz for concave parts of surfaces.

The best results of the roughness parameter Ra were achieved in the process of manufacturing samples at the inclination of the tool axis $\beta_f = 15°$, n = constant, both for the convex (Ra—values in the range of 0.459 to 0.519 μm) and for the concave part of the surface (Ra—values in the range of 0.497 to 0.549 μm). The worst results of the roughness parameter Ra were achieved at the inclination of the tool axis $\beta_f = 40°$, n = constant. For the convex part of the surface this was in the range of 0.623 to 0.700 μm, and in the case of the concave part of the surface, it was a sample produced under the conditions of a perpendicular position of the tool axis to the milled surface—sample 0°, n = constant. The roughness parameter Ra reached values in the range of 0.603 to 0.7016 μm.

The best results of the roughness parameter Rz were achieved in the production process also at the inclination of the tool axis $\beta_f = 15°$, n = constant, for both parts of the surface, convex and concave. In the case of the convex part of the surface, the values ranged from 2.665 to 2.791 µm, and for the concave part, the range of values was measured from 2.527 to 2.721 µm. The worst results of the parameter Rz were achieved for both parts of the surfaces for the tool position 0°, n = constant, caused by zero cutting speed at the tool tip. In the case of the convex part of the surface, the measured values were in the range of 3.451 to 3.650 µm, and for the concave part of the surface, 3.744 to 3.951 µm.

3.2. Evaluation of the Roughness of the Milled Surface by the Non-Contact Measuring Method

3.2.1. Roughness Evaluation on the Convex Part of the Surface

Table 12 shows the measured profile values (height and length) of the roughness parameters Ra, Rz, Rp, and Rv. For graphic comparison, the most used roughness parameters in practice, Ra and Rz, were chosen. Inclination of the tool showed, in all cases, lower values of the measured roughness parameters compared to the perpendicular position of the tool axis to the milled surface. The measured values of the Rz parameter showed lower values for surfaces made by maintaining the cutting speed in the form of a change in revolutions.

Table 12. Measured values of roughness for the convex part of the surface by non-contact method.

Roughness [µm]	0° n Constant	0° D_{ef} 3.41	15° n Constant	15° D_{ef} 5.73	30° n Constant	30° D_{ef} 7.65	40° n Constant	40° D_{ef} 8.66
Ra	0.5947	0.5675	0.527	0.511	0.585	0.482	0.5443	0.807
Rz	4.403	3.627	3.200	2.741	3.510	2.544	3.069	3.582
Rp	1.765	1.658	1.692	1.623	1.889	1.681	1.909	2.004
Rv	2.638	1.969	1.508	1.118	1.621	0.8632	1.161	1.578

For samples with a convex part of the surface produced under conditions of 30° D_{ef} 7.65, the best results of the roughness parameters Ra and Rz were achieved. The measured value for the roughness parameter Ra was 0.482 µm and for the parameter Rz the value was 2.544 µm. The worst results of the roughness parameters Ra and Rz were measured in samples with a convex part of the surface produced under conditions of 0° n constant. In the case of the roughness parameter Ra, the highest value of 7495 µm was reached, and for the value of Rz, 50,200 µm. A graphical comparison of the measured average values of the roughness parameters Ra and Rz for the convex part of the surface using the non-contact measurement method is shown in Figures 11 and 12.

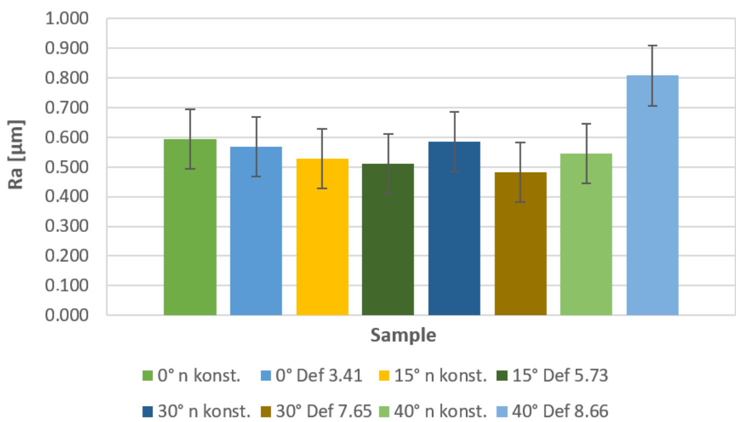


Figure 11. Comparison of roughness parameters Ra for convex parts of surfaces, non-contact method.

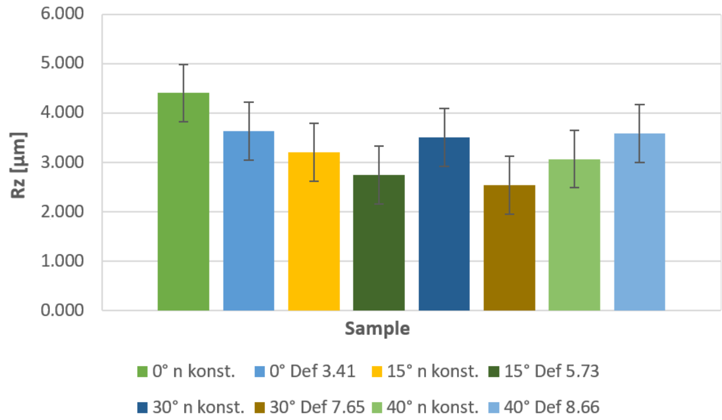


Figure 12. Comparison of roughness parameters Rz for convex parts of surfaces, non-contact method.

The three-dimensional surface texture and extracted roughness profile for the convex parts of the surfaces are shown in Table 13.

Table 13. Three-dimensional surface texture and profiles of convex surfaces.

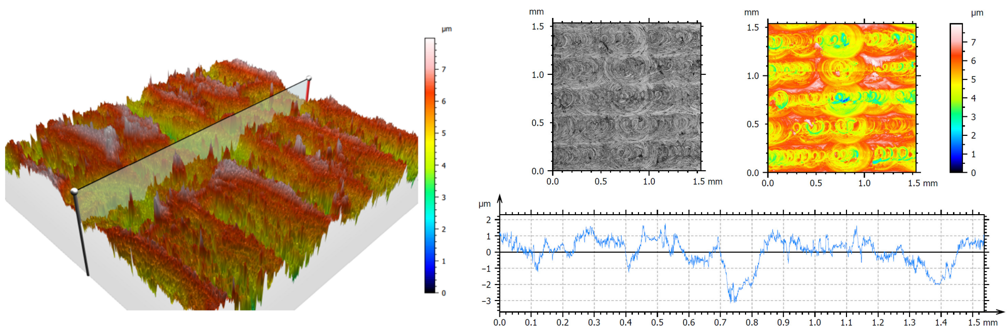
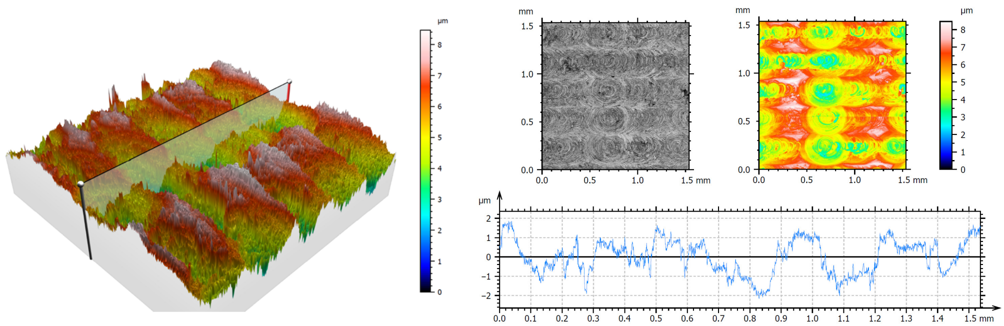
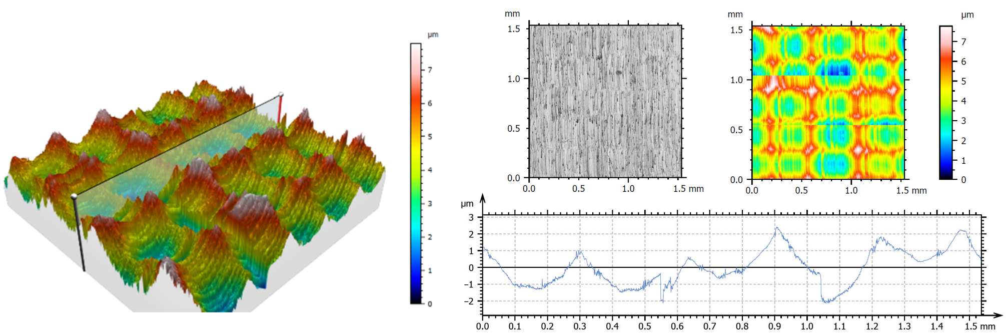

Three-dimensional view of surface texture and roughness profile at 0° n constants

Three-dimensional view of surface texture and roughness profile at 0° Def 3.41

Three-dimensional view of surface texture and roughness profile at 15° n konštant

Table 13. *Cont.*

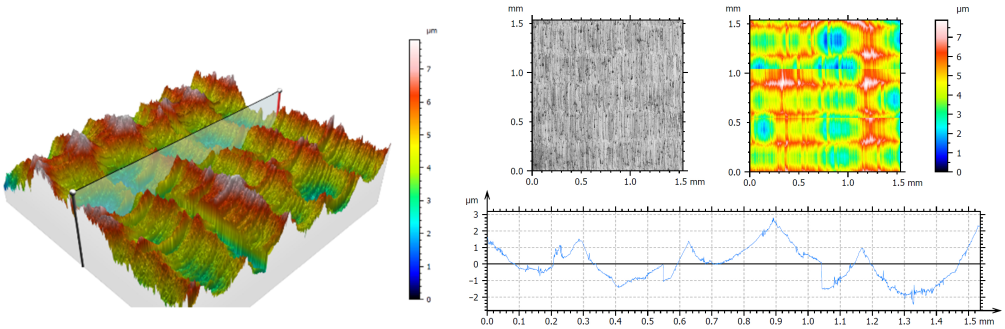
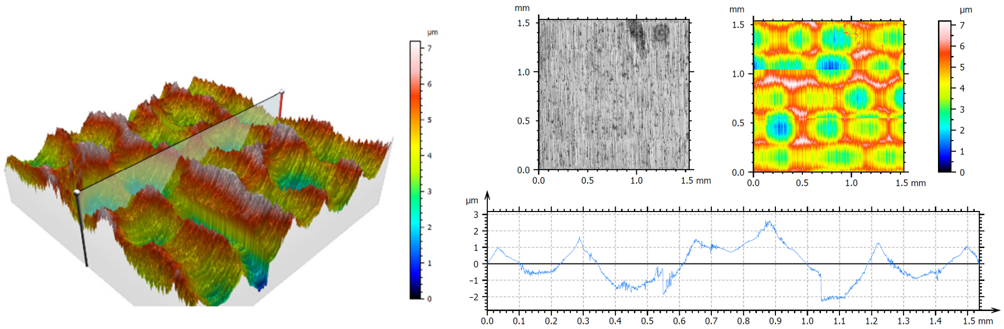
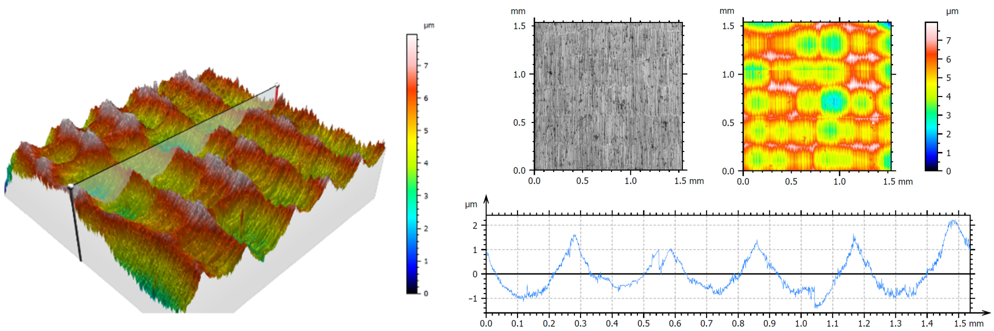
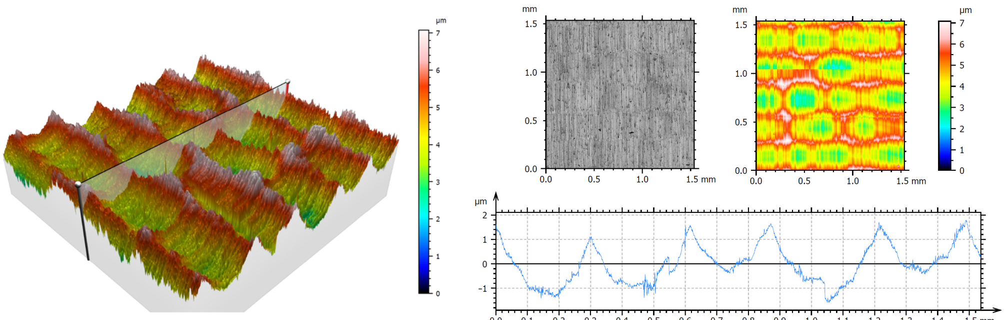
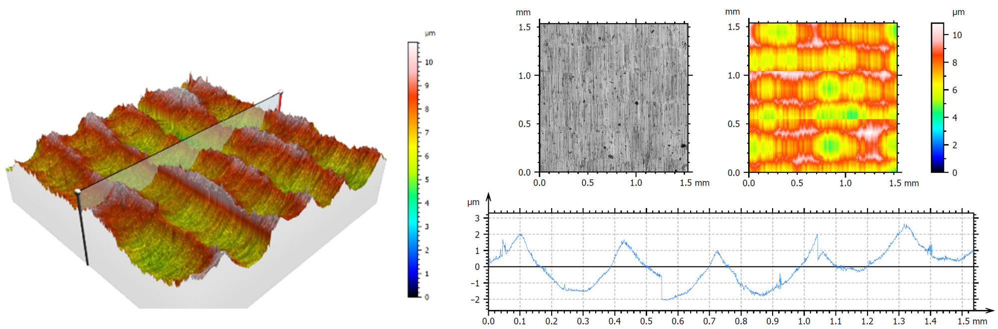

Three-dimensional view of surface texture and roughness profile at 15° Def 5.73

Three-dimensional view of surface texture and roughness profile at 30° n konštant

Three-dimensional view of surface texture and roughness profile at 30° Def 7.65

Three-dimensional view of surface texture and roughness profile at 40° n konštant

Table 13. *Cont.*



Three-dimensional view of surface texture and roughness profile at 40° Def 8.66

3.2.2. Roughness Evaluation on the Concave Part of the Surface

Table 14 shows the measured profile values (height and length) of the roughness parameters Ra, Rz, Rp, and Rv for the concave parts of the surface of the individual samples. Likewise, the most used roughness parameters Ra and Rz were chosen for graphic comparison.

Table 14. Measured values of roughness for the concave part of the surface by non-contact method.

Roughness [µm]	0° n Constant	0° D_{ef} 3.41	15° n Constant	15° D_{ef} 5.73	30° n Constant	30° D_{ef} 7.65	40° n Constant	40° D_{ef} 8.66
Ra	0.806	0.572	0.544	0.699	0.615	0.594	0.568	0.640
Rz	4.208	5.054	2.720	3.615	2.971	2.911	2.876	2.996
Rp	1.633	2.734	1.550	2.005	1.601	1.796	1.463	1.668
Rv	2.575	2.320	1.326	1.610	1.369	1.115	1.257	1.327

The best results of the roughness parameters Ra and Rz in the case of the concave parts of the surfaces were achieved in the samples produced under the conditions $\beta_f = 15°$, n = constant. The Ra parameter reached a value of 0.544 µm and the Rz parameter reached a value of 2.720 µm. The worst results of the roughness parameters Ra and Rz were measured in samples with a concave part of the surface produced at a perpendicular position of the tool axis to the milled surface. The highest value of 0.806 µm was measured for the Ra parameter and 5.054 µm for the Rz parameter.

Comparisons of the measured average values of the roughness parameters Ra and Rz measured using the non-contact measuring method for the concave part of the surface are shown in Figures 13 and 14.

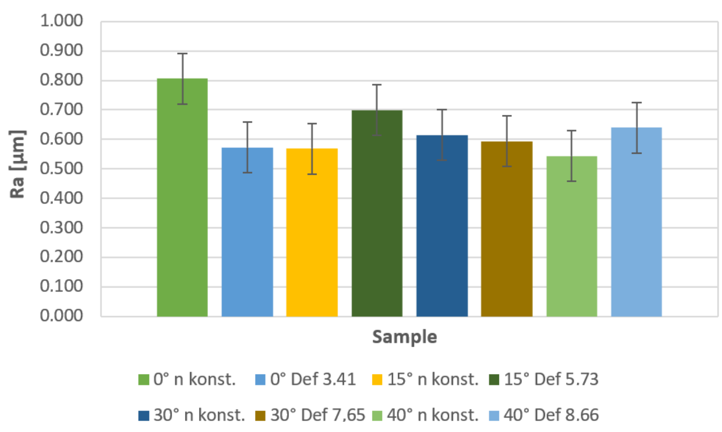


Figure 13. Comparison of roughness parameters Ra for concave parts of surfaces, non-contact method.

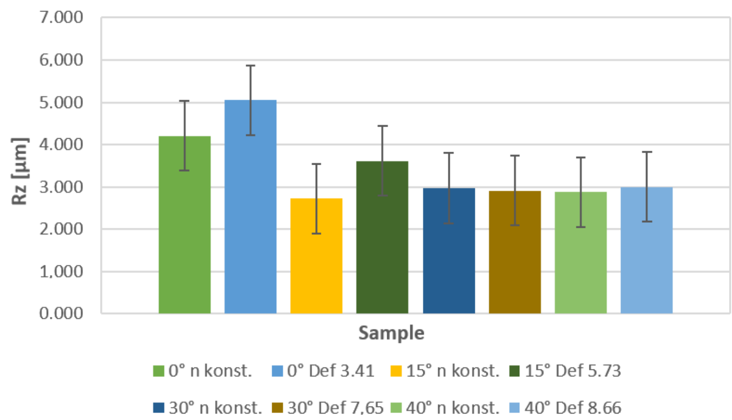


Figure 14. Comparison of roughness parameters Rz for concave parts of surfaces, non-contact method.

The three-dimensional surface texture and extracted roughness profile for the concave parts of the surfaces are shown in Table 15.

Table 15. Three-dimensional surface texture and profiles of concave surfaces.

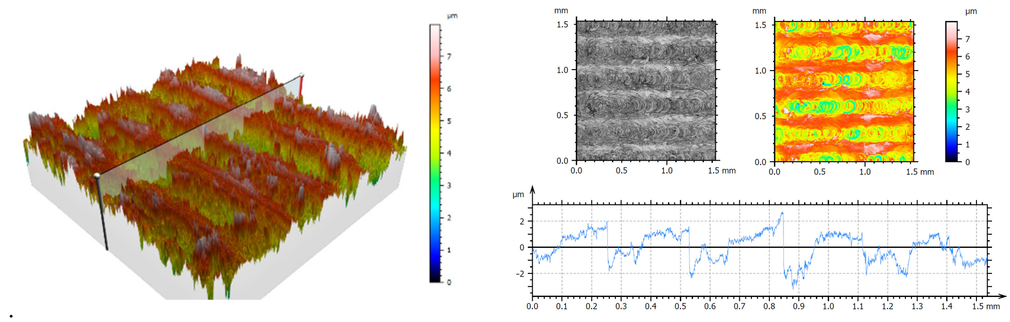
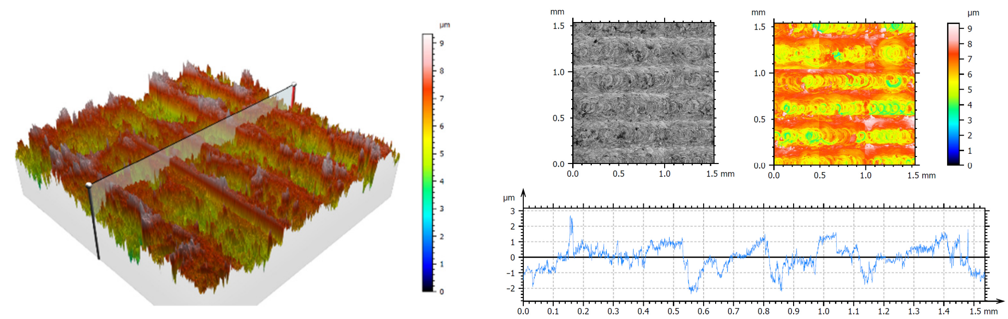
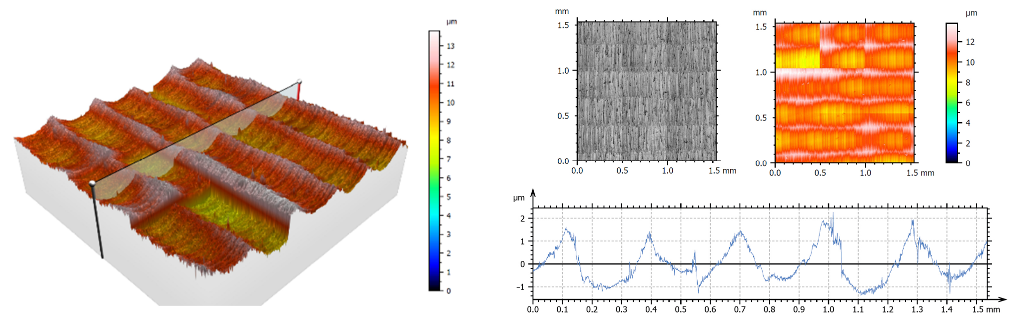
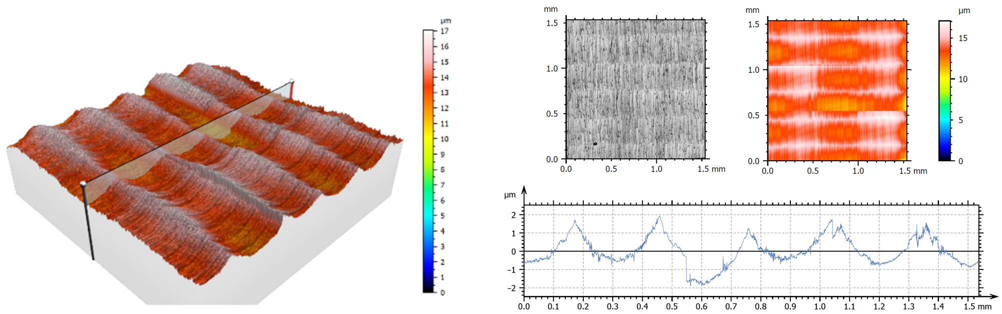
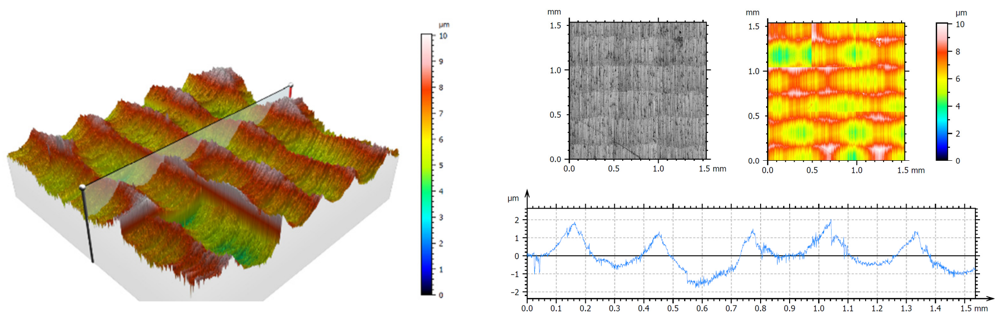

Three-dimensional view of surface texture and roughness profile at 0° n konštant

Three-dimensional view of surface texture and roughness profile at 0° Def 3.41

Three-dimensional view of surface texture and roughness profile at 15° n konštant

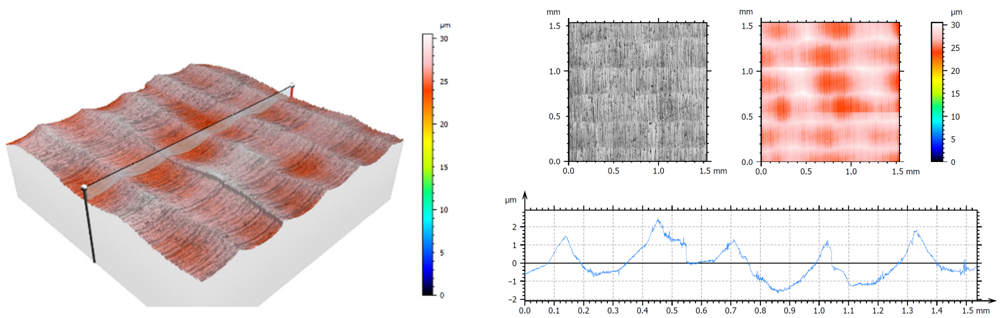
Table 15. *Cont.*



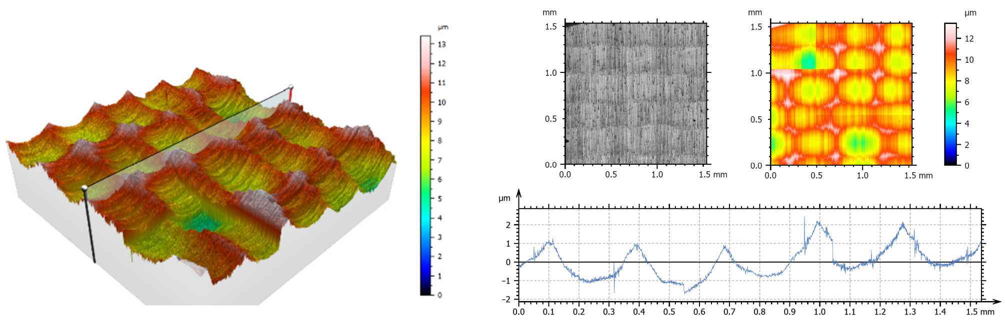
Three-dimensional view of surface texture and roughness profile at 15° Def 5.73



Three-dimensional view of surface texture and roughness profile at 30° n konštant

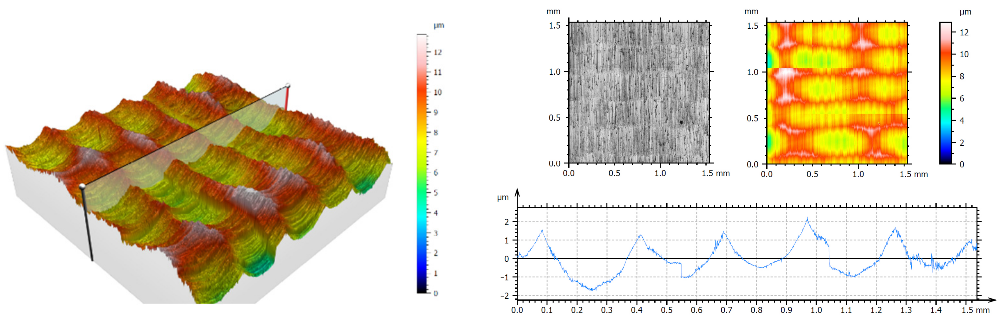


Three-dimensional view of surface texture and roughness profile at 30° Def 7.65



Three-dimensional view of surface texture and roughness profile at 40° n konštant

Table 15. *Cont.*


Three-dimensional view of surface texture and roughness profile at 40° Def 8.66

A comparison of the 2D surface topographies for the convex parts of the surfaces concerning tool axis inclination is shown in Figure 15. A comparison of the 2D surface topographies for the concave parts of the surfaces concerning tool axis tilt is shown in Figure 16.

From the point of view of the analysis of the obtained 2D topographies of the machined convex surfaces produced under the conditions of 0° n = constant and 0° D_{ef} 3.41, it was possible to see grooves (circular traces) created by the rotational movement of the tool compared to all other samples. A comparison of the surface topographies on the convex and concave surface is shown in Figures 17 and 18.

It was possible to observe the tool being pressed into the material, as a result of which there was plastic deformation and the creation of an effect known as "ploughing". The cause was the perpendicular position of the tool axis to the milled surface. By milling with the tool in a perpendicular position, considering the effective diameter of the tool and the cutting speed, it was possible to observe the formation of growths—dark spots on the surface—in the sample marked 0° D_{ef} 3.41.

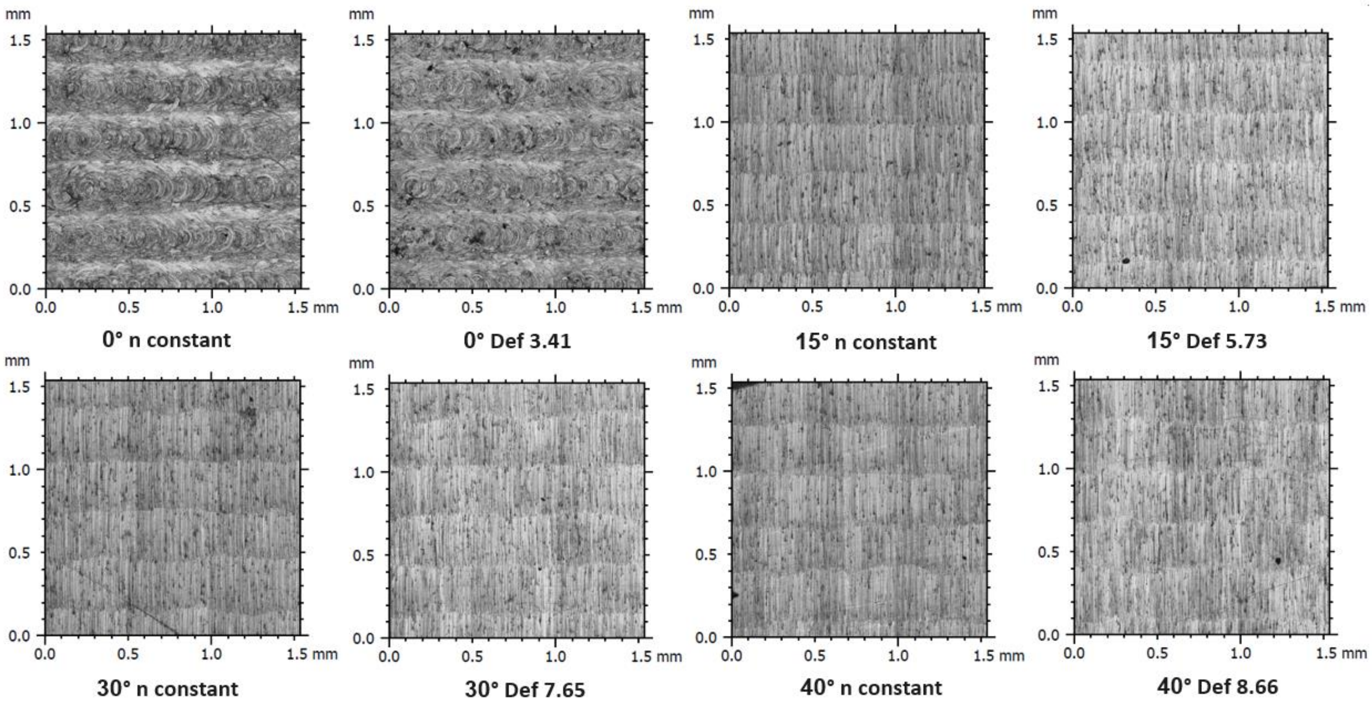


Figure 15. Two-dimensional topography of the convex parts of the surfaces according to the inclination of the tool.

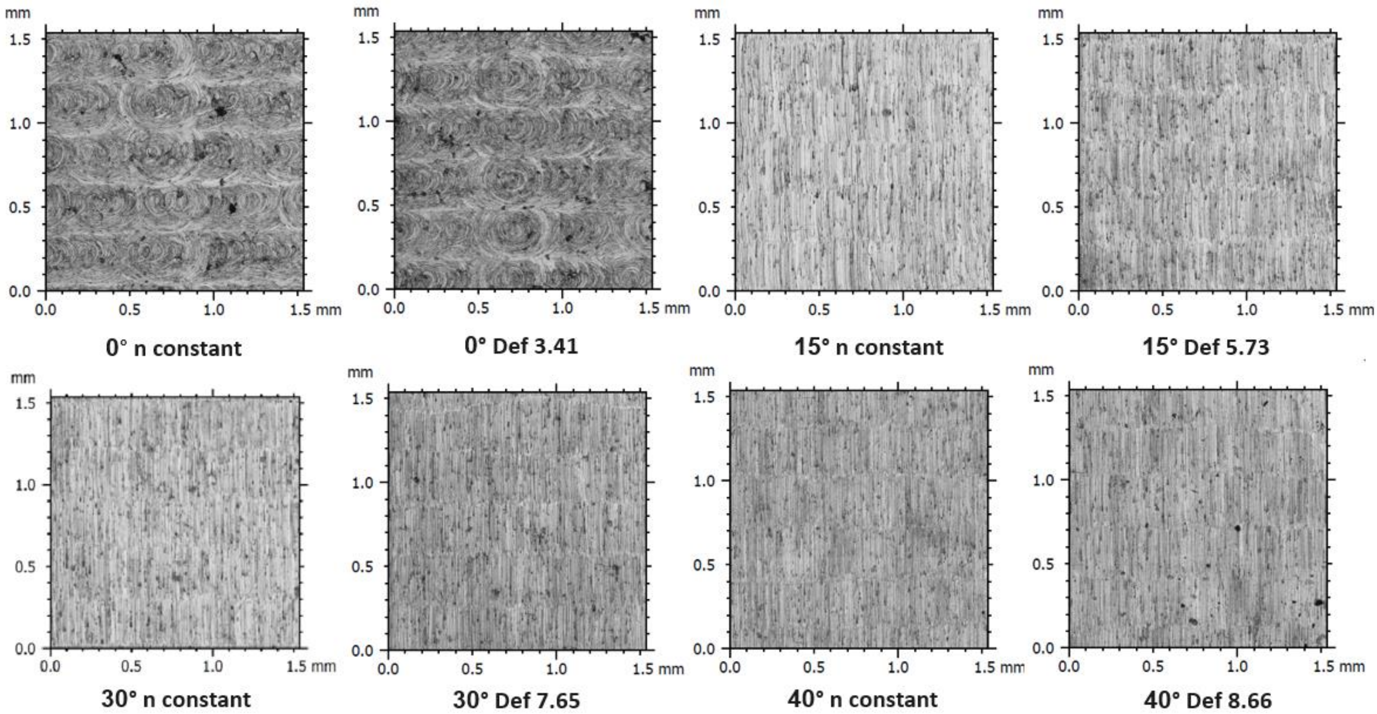


Figure 16. Two-dimensional topography of the concave parts of the surfaces according to the inclination of the tool.

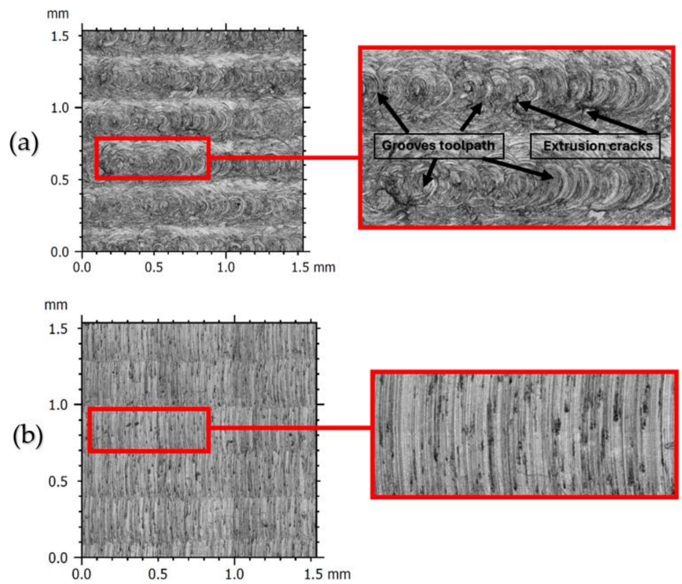


Figure 17. Two-dimensional topography comparison of produced samples, convex surface: (**a**) 0° n constant and (**b**) 15° n constant.

The most uniform paths of the tool can be observed at an inclination of 15°, n = constant and 15° D_{ef} 5.73, where it was possible to recognize regular boundaries defining the radial depth of cut a_e. At a tool axis inclination of 30° and 40°, either at a constant speed or for samples made by maintaining the cutting speed by changing the revolutions, the topography of the milled surface was similar for these samples, with irregular boundaries of the radial depth of cut a_e. When analyzing the 2D topography of the milled surface on convex surfaces, it was possible to observe the same defects on the surface of the same samples as when milling concave surfaces. These were samples produced under the conditions of 0° n = constant and 0° D_{ef} 3.41. In both cases, these defects were defined as "ploughing" of the material. On all other samples, regardless of the conditions of the manufacturing process, it was possible to observe a non-oriented milled surface that did not show any visible boundaries of the radial depth of cut a_e.

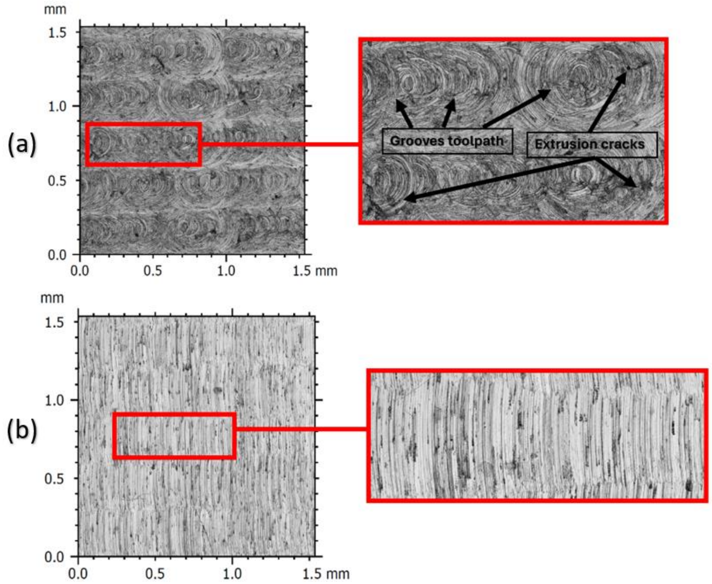


Figure 18. Two-dimensional topography comparison of produced samples, concave surface: (**a**) 0° n constant and (**b**) 15° n constant.

Due to the selection of two assessment methods (CM—contact method, N-CM—non-contact method) of the roughness parameters Ra and Rz, a comparison was made between the selected methods. The measured profile values for the convex part of the surface are shown in Table 16, and the individual graphical comparison of the measured values of the roughness parameters Ra for the convex parts of the surfaces is shown in Figure 19, and for the roughness parameter Rz in Figure 20.

Table 16. Measured values of roughness parameters Ra and Rz in contact and non-contact methods for convex parts of surfaces.

	0° n Constant	**0° D_{ef} 3.41**	**15° n Constant**	**15° D_{ef} 5.73**	**30° n Constant**	**30° D_{ef} 7.65**	**40° n Constant**	**40° D_{ef} 8.66**
Ra CM	0.611	0.616	0.491	0.593	0.607	0.617	0.648	0.630
Ra N-CM	0.5947	0.5675	0.527	0.511	0.585	0.482	0.5443	0.807
Rz CM	3.578	2.856	2.713	2.764	2.721	2.873	2.877	2.964
Rz N-CM	4.403	3.627	3.200	2.741	3.510	2.544	3.069	3.582

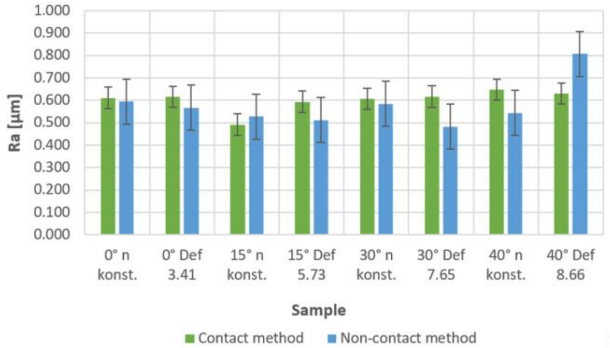


Figure 19. Values of the roughness parameters Ra for the convex part of the surface concerning the measurement method.

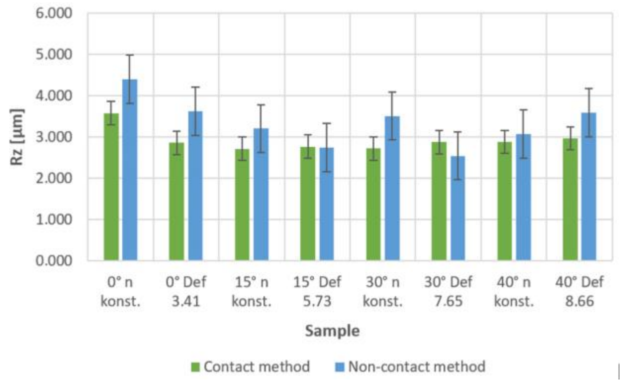


Figure 20. Values of the roughness parameters Rz for the convex part of the surface concerning the measurement method.

From the point of view of the choice of the method intended for the evaluation of the roughness profile parameters Ra and Rz for the convex parts of the surfaces, it can be concluded that there were no significant changes in the measured values for the roughness parameters. In the case of the manufactured convex surfaces, the most significant difference in the measured values was an increase of more than 1.2 times the roughness value for samples with production conditions of 30° Def 7.65 and for the 40° Def 8.66 sample. For the samples with a concave part of the surface, the greatest difference was recorded as roughly 1.3 times the value for the sample produced under conditions of 0° n constant. In the case of a comparison of the touch and non-touch methods when evaluating the roughness, similar values were achieved with minimal differences.

As in the previous case, a comparison of the roughness parameters Ra and Rz was carried out for the contact and non-contact methods, but for the concave part of the surface, as shown in Table 17. Figure 21 shows the measured values of the roughness parameter Ra and Figure 22 shows the values of the roughness parameter Rz for the concave part of the surface concerning the used measurement method.

Table 17. Measured values of roughness parameters Ra and Rz in contact and non-contact methods for concave parts of surfaces.

	0° n Constant	**0° D_{ef} 3.41**	**15° n Constant**	**15° D_{ef} 5.73**	**30° n Constant**	**30° D_{ef} 7.65**	**40° n Constant**	**40° D_{ef} 8.66**
Ra CM	0.675	0.588	0.515	0.599	0.620	0.624	0.612	0.616
Ra N-CM	0.806	0.572	0.544	0.699	0.615	0.594	0.568	0.640
Rz CM	3.865	2.938	2.614	2.767	2.906	2.940	2.719	2.946
Rz N-CM	4.208	5.054	2.720	3.615	2.971	2.911	2.876	2.996

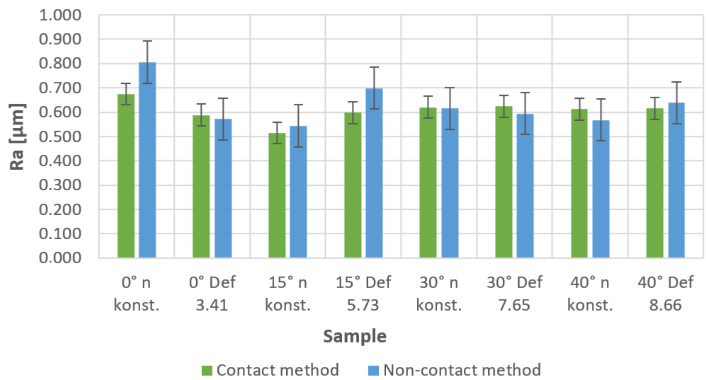


Figure 21. Values of the roughness parameters Ra for the concave part of the surface concerning the measurement method.

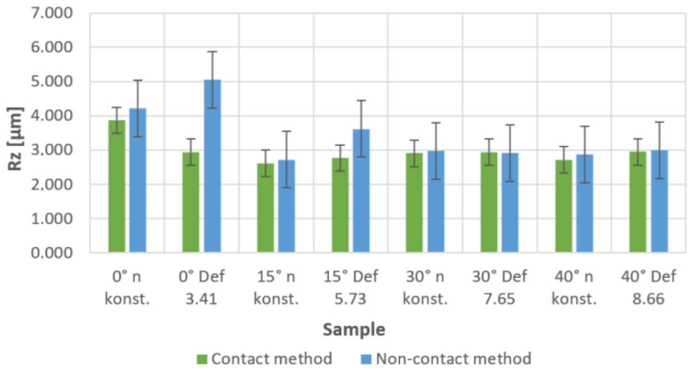


Figure 22. Values of the roughness parameters Rz for the concave part of the surface concerning the measurement method.

When assessing the selection of the method for evaluating the roughness parameter Rz for the concave parts of the surfaces, slightly higher values were achieved with the non-contact measurement method. The most significant difference was achieved in the parameter Rz in the sample produced under conditions of 0° D_{ef} 3.41, where the difference in the measured value was 1.7 times higher compared to the value obtained by the contact measurement method. In the case of the roughness parameter Ra, the differences were minimal. The highest difference was recorded for the sample with cutting conditions of 0°, n = constant, where the difference reached almost 1.9 times the value compared to the value measured by the contact method.

4. Discussion

The sample intended for the experiment represented two different curvatures of the elements. These were convex and concave parts of the surface milled with a copying tool with a diameter of D = 10 mm for finishing operations. Individual samples were divided into two groups. In the first group, samples were made at a constant speed, while only the position of the tool axis β_f was changed, and in the next group, samples were made by maintaining the cutting speed by changing the revolutions. All samples were milled with the same feed per tooth fz, while the linear strategy was chosen as the finishing strategy. Understanding the relationship between the change in the tool axis and the evaluation of the surface quality, including surface topography, dimensional accuracy, or roughness parameters in the cutting process, can facilitate the choice of the inclination of the tool axis when milling parts of the surfaces defined in the experiment. The results of the experiment led to finding out which inclination of the tool axis is the most suitable for the given parts of the surfaces in terms of the considered parameters.

To discuss the surface morphology obtained by the study of Mali [44], it was possible to confirm the morphology of the machined surface as well as the tool path. In their research, they used rowing as a finishing strategy when milling a curved surface containing convex and concave curves and a 3-axis milling machine where the tool axis was perpendicular to the machined surface and showed no tilt. In comparison with this research (Figure 23), it was possible to confirm the paths of the tool in the form of displayed grooves representing the paths of the tool, which was also perpendicular to the machined surface when milling convex and concave areas.

Compared to the results of the author Shi [45], who dealt with the three-dimensional reconstruction of the topography of the machined surface based on gray gradient constraints, the applied method of evaluating surface roughness using Zeiss Smartproof 5 is equally suitable for monitoring the production and processes. In comparison with the author Shi, we expanded in our research and analyzed more deeply the defects formed on the surface of the machined surfaces, which were mainly shown when the tool was oriented perpendicularly in the cutting process. The advantage of this approach was a deeper analysis of the machined surface, which can, if necessary, clarify its effect on the function of the product. Likewise, a deeper analysis and the ability to identify defects on the machined surface allow understanding of the surface characteristics of mechanical parts, such as lubrication, friction, wear, or corrosion resistance.

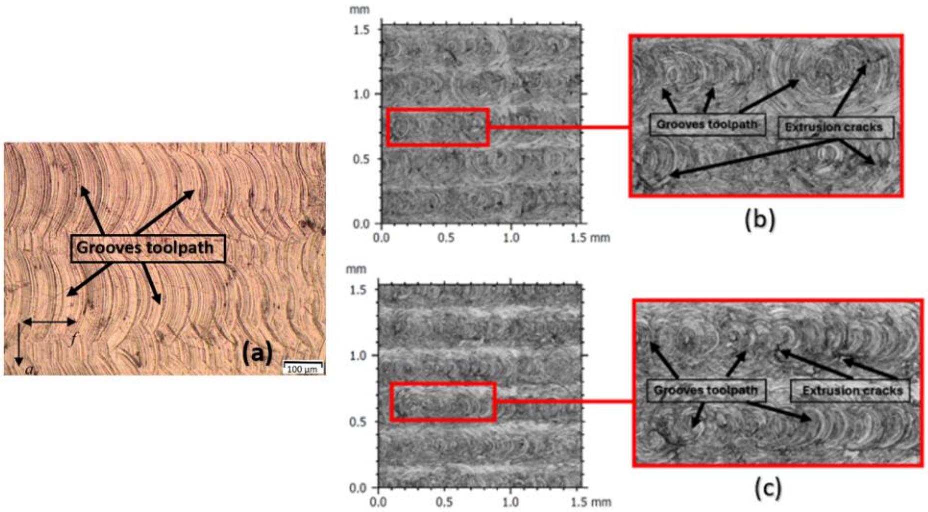


Figure 23. Surface morphology of linear strategy (**a**) 3-axis milling (**b**) 5-axis milling, concave surface 0° n constant (**c**) 5-axis milling, convex surface 0° n constant.

The experiments did not demonstrate a clear influence of maintaining the cutting speed in the form of a change in revolutions on the surface roughness. Only at the vertical position of the tool 0° and the monitored parameter Rz, was there a beneficial effect of setting the cutting speed according to the effective diameter, for both the concave and convex part of the surface. The best value in terms of roughness and overall surface quality was achieved when the angle of inclination of the tool in the cutting process was 15°. The worst value in all cases was achieved at zero-degree tool inclination due to adverse cutting conditions. Likewise, with the non-contact measurement method, the influence of maintaining the cutting speed through the change in speed on the surface roughness was not confirmed. At the tool axis position of 0°, the parameters Ra and Rz even worsened with the increase in cutting speed.

In the case of a comparison of the spatial measurement of the surface texture with the evaluation of one section (profile) of the surface, it can be concluded that the method enabling 3D measurement of the surface texture is not only more objective but also provides more accurate data on the machined state of the surface. As a result, a higher statistical significance of the evaluated characteristic can be attributed to the measurement of the 3D surface texture. The evaluated data obtained from the spatial texture are based on a larger quantity of data and thus have higher reliability. The analysis of the topography of the surface proved the importance of the influence of the inclination of the tool axis in the cutting process. The perpendicular position of the tool to the milled surface containing convex or concave curves caused undesirable effects on the surface, which are a manifestation of plastic deformation, or an effect known as "ploughing" of the material. These are surface defects that ultimately have an impact on the quality of the surface, i.e., roughness parameters, dimensional accuracy, or properties of the surface layer. Because of the perpendicular position of the tool to the milled surface, a low cutting speed is achieved, as a result of which the quality of the milled surface deteriorates. From the analysis of the results of the topography of the milled surface and roughness parameters, it follows that a better quality of the milled surface is achieved when the inclination of the tool axis is $\beta_f = 15°$. The achieved results corresponded to the results of other authors Ko [10] and Schulz [11].

Based on the performed measurements, it is possible to see minimal differences in the values defining the roughness characteristics of the selected parameters Ra and Rz which may occur as a result of the different measurement methods.

5. Conclusions

The paper aimed to investigate how the quality of the milled surface changes depending on the change in the position of the tool axis, using roughness and surface topography evaluations. The experiment investigated how different tool axis positions affect the result while maintaining a constant feed per tooth fz for finishing operations. As a milling strategy for finishing purposes, a linear strategy was used, and the material chosen for research purposes was EN AW-6082 T651.

In the case of the general results obtained from the given research, it can be concluded that the inclination of the tool axis in the cutting process is important not only in terms of topography, but also in the achieved roughness of the milled surface. In the production of some parts, roughness parameters are prescribed and it is necessary to know all the influences to achieve them. In this case, to achieve the best possible roughness, it is recommended to use a tool axis inclination of 15 degrees, at which the effect of the effective diameter of the tool in the tool–workpiece relationship is also optimal.

From the graphic representation of the measured roughness values on the convex and concave parts of the surfaces with both measurement methods, it follows that the optimal values of the parameters were achieved at a tool inclination of 15° n constant. In the case of a convex surface using the contact method, the measured value was Ra = 0.491 μm and Rz = 2.713 μm. For the concave surface using the contact method, the measured value was Ra = 0.515 μm and Rz = 2.614 μm. It can be stated that the inclination of the tool at 15° can be applied to the shape of machined surfaces of a similar nature to achieve a suitable surface roughness. A surface roughness approaching Ra = 0.4 μm requires the most work to manufacture and should only be required when low roughness is the highest priority. It is ideal for high-stress areas.

The process of the 5-axis milling of complex, shaped surfaces not only includes a lot of input data that is entered into the production process, but it is also necessary to monitor and evaluate the results. Due to the wide scope of this information, it is necessary to expand these results with other useful information affecting the very properties of the milled surface when using 5-axis milling. However, it should be noted that one of the limitations of the experiment was the sample size. For example, when milling in mold production, we encounter much larger dimensions of milled parts. The results achieved in this experiment are part of the research that is currently being carried out and will be supplemented with other results in the future due to a better understanding of the importance of the influence of the inclination of the tool axis on the quality of the milled surface in 5-axis milling.

These are the following points for further research:

- Assessment of surface deviations by the 3D scanning method.
- Evaluation of deviations in the shape of the milled surface.
- Deeper analysis of the topography of the milled surface when changing the inclination of the tool axis.
- Measuring the roughness of the milled surface by a non-contact measuring method—the obtained parameters enable a comprehensive assessment of the influence of the inclination of the tool axis on the quality of the surface.
- Change in milled material.
- Analysis of cutting forces and their monitoring.
- The influence of the length of the tool extension, enabling the evaluation of tool stiffness and the analysis of cutting forces.
- Analysis of tool wear due to tilting of the tool axis in the cutting process.

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Nomenclature

CNC	computer numerical control
NC	numerical control
CAM	computer-aided manufacturing
CL	cutter location
CAD	computer-aided design
D	diameter of milling tool
RPM	revolutions per minute
a_e	radial depth of cut
a_p	depths of cut for given strategies
F_z	feed per tooth
F	feed
T	tolerance
P	surface allowance
ISO	International Organization for Standardization
Ra	arithmetical mean height
Rz	maximum height of profile
Rp	maximum profile peak height
Rv	maximum profile valley pepth
µm	micrometer
v_c	cutting speed
D_{ef}	effective tool diameter
β_f	inclination angle
HSM	high speed milling
Sa	arithmetical mean height
Sq	root mean square height
Ssk	skewness
S10z	ten-point height of surface
SH	scallop height
v_{cef}	effective cutting speed
CM	contact method

References

1. Ižol, P.; Varga, J.; Vrabeľ, M.; Demko, M.; Greš, M. Evaluation of 3-axis and 5-axis milling strategies when machining freeform surface features. *J. Prod. Eng.* **2022**, *25*, 1–4. [CrossRef]
2. Siller, H.; Rodriguez, C.A.; Ahuett, H. Cycle time prediction in high-speed milling operations for sculptured surface finishing. *J. Mater. Process. Technol.* **2006**, *174*, 355–362. [CrossRef]
3. Yau, H.T.; Kuo, M.J. NURBS machining and feed rate adjustment for high-speed cutting of complex sculptured surfaces. *Int. J. Prod. Res.* **2001**, *39*, 21–41. [CrossRef]
4. Cai, Y.; Zhangiang, L.; Shi, Z.; Song, Q. Optimum end milling tool path and machining parameters for micro Laval nozzle manufacturing. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2015**, *231*, 1–11. [CrossRef]
5. Varga, J.; Tóth, T.; Frankovský, P.; Dulebová, Ľ.; Spišák, E.; Zajačko, I.; Živčák, J. The influence of automated machining strategy on geometric deviations of machined surfaces. *Appl. Sci.* **2021**, *11*, 2353. [CrossRef]

6. Kuruc, M.; Vopát, T.; Moravčíková, J.; Milde, J. The Precision Analysis of Cutting Edge Preparation on CBN Cutting Inserts Using Rotary Ultrasonic Machining. *Micromachines* **2022**, *13*, 1562. [CrossRef]
7. Antoniadis, A.; Nikolaos, B.; Savakis, C.; Maravelakis, E.; Petropoulos, G. Influence of machining inclination angle on surface quality in ball end milling. In Proceedings of the Advances in Materials and Processing Technologies, Dublin, Ireland, 4–7 September 2003.
8. Sadílek, M.; Poruba, Z.; Čepová, L.; Šajgalík, M. Increasing the Accuracy of Free-Form Surface Multiaxis Milling. *Materials* **2021**, *14*, 25. [CrossRef] [PubMed]
9. Ko, T.J.; Kim, H.S.; Lee, S.S. Selection of the Machining Inclination Angle in High-Speed Ball End Milling. *Int. J. Adv. Manuf. Technol.* **2001**, *17*, 163–170. [CrossRef]
10. Schulz, H.; Hock, S.T. High-Speed Milling of Dies and Moulds—Cutting Conditions and Technology. *CIRP Ann. Manuf. Technol.* **1995**, *44*, 35–38. [CrossRef]
11. Fard, M.J.B.; Bordatchev, E.V. Experimental study of the effect of tool orientation in five-axis micro-milling of brass using ball-end mills. *Int. J. Adv. Manuf. Technol.* **2013**, *67*, 1079–1089. [CrossRef]
12. Shan, C.; Lv, X.; Duan, W. Effect of tool Inclination Angle on the Elastic Deformation of Thin-walled Parts in Multi-axis Ball-end Milling. *Procedia CIRP* **2016**, *56*, 311–315. [CrossRef]
13. Han, S.; Zhao, J. Effect of Tool Inclination Angle on Surface Quality in 5-Axis Ball-End Milling. *Mater. Sci.* **2010**, *97*, 2080–2084. [CrossRef]
14. Kiswanto, G.; Vinsensius, R.; Suntoro, S. Tool Inclination Angle Change Rate Control in Five-Axis Flat-End Milling. *Mater. Sci.* **2012**, *488*, 819–825. [CrossRef]
15. Pașca, I.; Lobonțiu, M.; Čep, R.; Banica, M. Experimental Design Methodology in Ball End Milling of C45 Material by Using Tool Tilt Angle—Analysis and Estimation of Surface Roughness Variation. *Appl. Mech. Mater.* **2013**, *371*, 48–53. [CrossRef]
16. Iqbal, A.; Ning, H.; Khan, I.; Liang, L.; Dar, N.U. Modeling the effects of cutting parameters in MQL-employed finish hard-milling process using D-optimal method. *J. Mater. Process. Technol.* **2008**, *199*, 379–390. [CrossRef]
17. Izamshah, R.; Azam, M.A.; Hadzley, M.; Ali, M.A.; Kasim, M.; Aziz, M.S.A. Study of Surface Roughness on Milling Unfilled-polyetheretherketones Engineering Plastics. *Procedia Eng.* **2013**, *68*, 654–660. [CrossRef]
18. Kruth, J.P.; Kiswanto, G.; Lauwers, B. Gouging elimination through tool lifting in tool path generation for five-axis milling based on faceted models. *Int. J. Adv. Manuf. Technol.* **2007**, *32*, 293–309. [CrossRef]
19. Kuruc, M.; Vopát, T.; Peterka, J. Surface roughness of poly-crystalline cubic boron nitride after rotary ultrasonic machining. In *Annals of DAAAM and Proceedings of DAAAM Symposium, Proceedings of the 25th DAAAM International Symposium, Vienna, Austria, 26–29 November 2014*; Elsevier: Amsterdam, The Netherlands, 2015; Volume 25, ISSN 2304-1382.
20. Peng, Z.; Jiao, L.; Yan, P.; Yuan, M.; Gao, S.; Yi, J.; Wang, X. Simulation and experimental study on 3D surface topography in micro-ball-end milling. *Int. J. Adv. Manuf. Technol.* **2018**, *96*, 1943–1958. [CrossRef]
21. Xu, J.; Zhang, H.; Sun, Y. Swept surface-based approach to simulating surface topography in ball-end CNC milling. *Int. J. Adv. Manuf. Technol.* **2018**, *98*, 107–118. [CrossRef]
22. Layegh, S.E.; Lazoglu, I. 3D surface topography analysis in 5-axis ball-end milling. *CIRP Ann. Manuf. Technol.* **2017**, *66*, 133–136. [CrossRef]
23. Varga, J.; Ižol, P.; Vrabeľ, M.; Kaščák, Ľ.; Drbúl, M.; Brindza, J. Surface Quality Evaluation in the Milling Process Using a Ball Nose End Mill. *Appl. Sci.* **2023**, *13*, 10328. [CrossRef]
24. Varga, J.; Spišák, E.; Gajdoš, I.; Mulidrán, P. Comparison of milling strategies in the production of shaped surfaces. *Adv. Sci. Technol. Res. J.* **2022**, *16*, 267–274. [CrossRef]
25. Daymi, A.; Boujelbene, M.; Linares, J.M.; Bayraktar, E.; Amara, A.B. Influence of workpiece inclination angle on the surface roughness in ball end milling of the titanium alloy Ti-6Al-4V. *J. Achiev. Mater. Manuf. Eng.* **2009**, *35*, 79–89, ISSN: 1734-8412.
26. Uchikata, S.; Takeuchi, J.; Beaucamp, A. 5-Axis Control Finishing for Decreased Tool Wear. *Procedia CIRP* **2017**, *63*, 313–317. [CrossRef]
27. Morishige, K.; Takeuchi, Y.; Nasu, T. Five—Axis Control Sculptured Surface Machining Using Conicoid End Mill. In *Machining Impossible Shapes, Proceedings of the International Conference on Sculptured Surface Machining, Chrysler Technology Center, MI, USA, 9–11 November 1998*; Springer: Boston, MA, USA, 1999; pp. 366–375. [CrossRef]
28. Gdula, M.; Mrówka, G. Analysis of tool wear, chip and machined surface morphology in multi-axis milling process of Ni-based superalloy using the torus milling cutter. *Wear* **2023**, *520–521*, 204652. [CrossRef]
29. Ma, W.; He, G.; Zhu, L.; Guo, L. Tool deflection error compensation in five-axis ball-end milling of sculptured surface. *Int. J. Adv. Manuf. Technol.* **2016**, *84*, 1421–1430. [CrossRef]
30. Vavruska, P.; Bartos, F.; Stejskal, M.; Pesice, M.; Zeman, P.; Heinrich, P. Increasing tool life and machining performance by dynamic spindle speed control along toolpaths for milling complex shape parts. *J. Manuf. Process.* **2023**, *99*, 283–297. [CrossRef]
31. Vavruska, P.; Bartos, F.; Pesice, M. Effective feed rate control to maintain constant feed per tooth along toolpaths for milling complex–shaped parts. *Int. J. Adv. Manuf. Technol.* **2023**, *128*, 3215–3232. [CrossRef]
32. Jun, C.; Lee, J.; Cha, K. Optimizing tool orientations for 5-axis machining by configuration-space search method. *Comput.-Aided Des.* **2003**, *35*, 549–566. [CrossRef]
33. Kobata, T.; Morishige, K.; Takeuchi, J. Tool Path Generation for 5-Axis Control Machining by Means of 2-Dimensional Configuration Space. *J. Jpn. Soc. Precis. Eng.* **2004**, *70*, 287–291. [CrossRef]

34. Koizumi, T.; Nakamoto, K.; Ishida, T.; Takeuchi, J. Tool Path Generation for 5-Axis Control Milling Based on Area Division Method. *Jpn. Soc. Mech. Eng.* **2009**, *5*, 15–20. [CrossRef]
35. Marciniak, K. Influence of surface shape on admissible tool positions in 5-axis face milling. *Comput.-Aided Des.* **1987**, *19*, 233–236. [CrossRef]
36. Le, Y.; Chan, T.C. Machined surface error analysis for 5-axis machining. *Int. J. Prod. Res.* **1996**, *34*, 111–135. [CrossRef]
37. Senatore, J.; Monies, F.; Rubio, W. Chapter 2 5-Axis Flank Milling of Sculptured Surfaces. In *Machining of Complex Sculptured Surfaces*; Springer: London, UK, 2012; pp. 1–42. [CrossRef]
38. Monies, F.; Felices, J.; Rubio, W.; Redonnet, J.; Lagarrigue, P. Five-axis NC milling of ruled surfaces: Optimal geometry of a conical tool. *Int. J. Prod. Res.* **2002**, *40*, 2901–2922. [CrossRef]
39. Varga, J.; Stahovec, J.; Beňo, J.; Vrabel', M. Assessment of surface quality for chosen milling strategies when producing relief surfaces. *Adv. Sci. Technol. Res. J.* **2014**, *8*, 37–41. [CrossRef]
40. Sadílek, M.; Čep, R.; Budak, I.; Sokovic, M. Aspects of Using Tool Axis Inclination Angle. *Stroj. Vestn.—J. Mech. Eng.* **2011**, *57*, 681–688. [CrossRef]
41. Wojciechowski, S.; Maruda, R.W.; Barrans, S.; Nieslony, P.; Krolczyk, G.M. Optimisation of machining parameters during ball end milling of hardened steel with various surface inclinations. *Measurement* **2017**, *111*, 18–28. [CrossRef]
42. *ISO/TR 23276:2020*; Geometrical Product Specifications (GPS)—Surface Texture: Profile Method—Flowchart for PSm, RSm, WSm and Pc, Rc, Wc. ISO: Geneva, Switzerland, 2020.
43. *ISO 25178-1:2021*; Geometrical Product Specifications (GPS)—Surface Texture: Areal—Part 1: Indication of Surface Texture. ISO: Geneva, Switzerland, 2021.
44. Mali, R.A.; Gupta, T.V.K.; Ramkumar, J. The influence of tool-path strategies and cutting parameters on cutting forces, tool wear and surface quality in finish milling of Aluminium 7075 curved surface. *J. Manuf. Processes* **2021**, *108*, 589–601. [CrossRef]
45. Shi, W.-C.; Zheng, J.-M.; Li, Y.; Li, X.-B. Three-Dimensional Reconstruction Method for Machined Surface Topography Based on Gray Gradient Constraints. *Appl. Sci.* **2019**, *9*, 591. [CrossRef]