The influence of tool path strategies for 3- and 5-axis milling on the accuracy and roughness of shaped surfaces

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Abstract: *Free form or shaped surfaces are found on a large number of modern engineering products. 3- or multi-axis CNC milling is usually used in their production. CAM systems are almost exclusively used in the creation of control programs. The aim of the presented research was to compare the quality of shaped surfaces made by 3- and 5-axis milling using three frequently used strategies. A sample with hemispherical surfaces was designed for the experiment. The surfaces predicted by the CAM system were compared with the surfaces actually produced. The disagreement of the predicted surface deviations with the deviations of the produced surfaces was demonstrated. In the evaluation of surface roughness, the advantage of 5-axis milling was partially demonstrated when one of the strategies achieved lower roughness, at two strategies the roughness was identical to 3-axis milling.*
KEYWORDS: *CNC MACHINE-TOOL, FREE FORM SURFACES, MILLING STRATEGIES, SURFACE QUALITY*

1. Introduction

The requirement to produce increasingly complex parts with better quality requires the use of efficient production processes. Product diversity increases and seriality decreases, which complicates process standardization and the use of known technological settings. Shaped surfaces occur on an increasing number of engineering products, and CNC milling is considered to be the most productive and flexible method for manufacturing such surfaces.

3- or 5-axis milling machines are most often used in the production of parts with shaped surfaces. the decision to use a 3- or 5-axis milling machine is not simple. Decides the complexity and required accuracy of parts, operating costs of machines, their productivity, knowledge and, last but not least, the experience of CNC programmers and machine operators [1]. In general, the following applies to the use of a 5-axis machine:

- production time is shortened because one clamping and one zero point are used instead of several clamps and individual zero points for each clamping,
- the accuracy of the parts is higher, because in 3-axis milling, every loosening and clamping has an adverse effect on the accuracy.

But the use of 5-axis machines also has its drawbacks:

- the machine price and production costs are higher than with a 3-axis machine,
- staff with a higher level of education and experience are needed, whether they are programmers or operators,
- programming and supplementary systems (CAM system, post processors) are more expensive, the cost of training people is necessary.

Reference [2] points out the differences between the shaped surfaces made by 3-axis, 3 + 2-axis and 5-axis milling. Lists the advantages of 5-axis milling over 3 + 2-axis milling, which include increased milling accuracy, shortened cutting time, extended tool life, improved functional properties of the machined surface, reduced cutting forces, and more. When comparing the machining accuracy of 3-axis, 3 + 2-axis and 5-axis milling, the highest accuracy was achieved in 5-axis milling. 3 + 2-axis milling shows more favourable surface roughness values. CAM prediction of residual material corresponded most to the actually measured residual material in 5-axis milling. The results are valid for the CAM system used. Similar comparisons indicate the quality of the computational algorithm used in the CAM system.

Sadílek et al. [3] compares 3-axis and 5-axis milling in making some basic geometric shapes. It is stated that both milling methods achieve almost the same shape deviations. However, the deviations achieved by 5-axis milling were smaller with a better quality of the machined surface.

Stejskal et al. [4] describes a method for optimizing the orientation of tool axes in multi-axis milling. the toolpath is optimized to achieve a more constant cutting speed, which leads to improved surface quality and increased productivity. However, the authors state that the position of the tool is limited by the shape of the machined surface, the kinematics of the machine and the shape of the machined part due to possible collisions. Therefore, it is not always possible to achieve the ideal value of the contact diameter of the tool on the entire machined surface.

The mathematical model for predicting the roughness of the milled surface is defined in [5], the model for ensuring a constant scallop height is described in [6]. Kolar et al. [7] describes a virtual model of the machine, which can be used not only in simulations of the milling process but also for accurate determination of the milling time and surface condition after machining. The model allows to influence the accuracy, quality and productivity of machining by setting the interpolator.

Deviations from the required shapes or dimensions are caused by machine errors, incorrect clamping or deformation of the workpiece and incorrect clamping of the tool, etc. Surface roughness is one of the primary requirements in the design of engineering products. It is a widely used product quality indicator and is usually measured off-line when the component has already been machined [8]. The quality of the milled surface also depends on various technological parameters such as cutting conditions or the properties of the coolants. The source presents a series of mathematical models for determining the surface roughness for commonly used shape milling methods (vertical, push, pull, oblique, oblique push and oblique pull) and determines the effect of the milling method used on the resulting surface roughness in ball-nose end milling.

Machining of shaped surfaces is generally associated with the concept of machining strategy. The milling strategy used depends on the relative position of the cutting tool and the workpiece, as well as the kinematics of the cutting tool during the operation. Strategies must meet increasing requirements for accuracy and surface integrity, shortening cutting times or reducing cutting forces.

Bagci et al. [9] defines a simulation and optimization system based on body modelling, integrated with a CAD/CAM system. Experimental results show the impact of milling strategies on cutting time and their importance for shortening production time and reducing costs. Strategies also affect tool deflection, material removal rate values, cutting forces, and cutting errors.

The use of different strategies in ball end milling on low-curvature convex surfaces has a significant impact on cutting forces, surface texture, and machining time [10]. Radial paths provide good results in terms of a more even surface structure and lower cutting forces but have the highest machining time. Cutting forces are highest when using a spiral strategy due to the contact area between the tool and the material. Overall, the use of a spiral toolpath strategy to finish milling these types of surfaces is not recommended.

Mali et al. [11] examines three strategies - linear, linear rotated by 90°, and offset. 3D offset is the best finishing strategy because it ensures uninterrupted tool work, which is favourable for milling. The tool life is increased and a better surface condition is achieved. The active cutting speed and the position of the contact surface are important parameters that control the chip removal mechanism, affect the cutting forces, and the overall surface quality of the shaped surfaces.

The influence of strategies on surface roughness in the application of dies and molds is addressed in [12]. The path strategy influences real machining time, polishing time and costs. When comparing several strategies, the best results were achieved by 3D offset and spiral which slice the part in a horizontal manner.

Ramos et al. [13] compares three typical milling strategies, namely radial, raster, and 3D offset. Their effect on surface roughness, texture, and dimensional deviations was evaluated. Even in this case, the 3D offset strategy proved to be the most suitable. However, as the authors state, the results cannot be generalized. The study provides a general trend in machining surfaces similar to those tested.

Logins et al. [14] evaluates three strategies of high-speed milling, namely linear, linear in two perpendicular directions and circular. surface roughness and texture were evaluated parameters. To achieve the lowest possible surface roughness, a linear path is recommended, the most even surface structure is provided by a circular strategy. The authors recommend avoiding a linear strategy in two perpendicular directions, and also emphasize that the results depend on the material being machined.

Sales et al. [15] evaluates eight finishing strategies for 3- and 5-axis milling in terms of machining time and the average residual load per unit area. The comparison was performed with NC codes directly from the CAM system and NC codes modified by the optimization software. The authors determined the best strategies for specific types of surfaces and at the same time showed that the feed optimization balances the machining times of different strategies. By optimizing the feed rate, the machining time is reduced by 20 to 50%.

2. Descriptions of experiments

The aim of the experiments was to compare 3-axis and 5-axis milling using 3 different strategies commonly used in the production of components with shaped surfaces. The following steps have been taken to achieve the goal:

1. Analysis of deviations of areas virtually machined by the CAM system and analysis of deviations obtained by scanning actually produced surfaces.
2. Comparison of deviations and determination of the reliability of the CAM system in predicting the accuracy of milled surfaces.
3. Measuring and comparing the surface roughness of milled surfaces.

The sample with six hemispherical surfaces on cylindrical protrusions was designed - Fig. 1. The purpose of the protrusions is to allow good access of the tool and measuring devices to the assessed areas. The dimensions of the base are 100 x 67 mm, the radius of the hemispherical surfaces is 10 mm. The material of the sample is aluminium alloy EN AW 6061 T651. The workpiece has the same floor plan dimensions as the sample, its height is 26 mm.

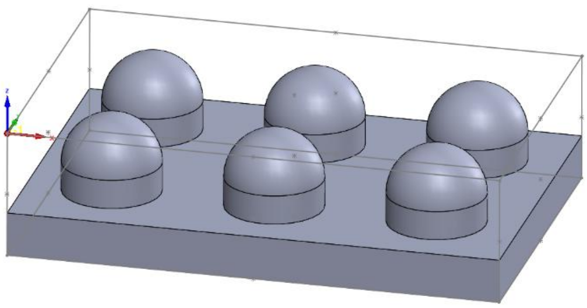

Fig. 1 *Sample with the outline of the workpiece*

Three frequently used strategies were selected, namely Constant Z, Radial, and Linear. The Linear strategy used the option of automatically generating additional paths rotated 90 ° to improve surface quality. The arrangement of the surfaces on the sample is shown in Fig. 2.

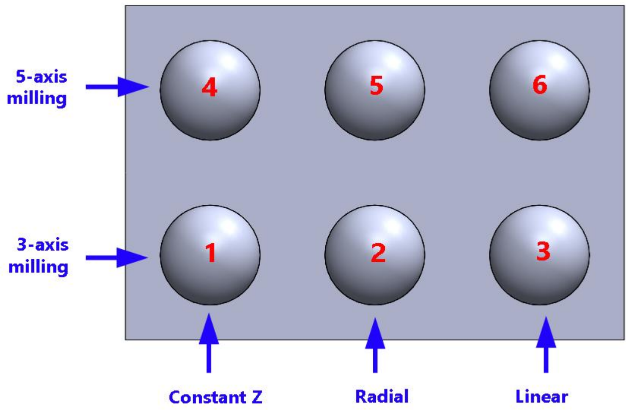

Fig. 2 *The arrangement of the surfaces on the sample*

The SolidCAM CAM system was chosen for the creation of NC programs. The advantage of the system is the ability to convert 3-axis milling operations to 5-axis while maintaining the main settings, which was fully utilized in the experiment. The postprocessor for a 5-axis continuous milling machine DMG Mori DMU 60 eVo was used to generate NC programs. The sample was made on this machine.

This machine is equipped with the Heidenhain TNC 640 control system. The generated NC programs were transmitted by the DNC network to the machine control system. The functionality of NC programs was checked in the simulation mode of the control system.

The roughing of the sample was carried out so that an addition of 0.25 mm remained on the hemispherical surfaces. The same parameters were used in the settings of all finishing strategies. The main requirement was the scallop height after machining, set at 0.005 mm and a tolerance of deviations of the shape of 0.01 mm.

The ball-end mill N.RD.10,0.45°.Z4.HA.K TI1000 with a diameter of 10 mm, manufactured by WNT with a set cutting speed v_c = 400 m.min^{-1} and a feed per tooth of 0.04 mm was chosen to finish the shaped surfaces. By converting 3-axis operations to 5-axis operations, the monitored settings were maintained. The position of the tool axis was controlled by a curve (circle) at a defined distance below the shape surface. The size of the circle and the distance control the inclination of the tool axis relative to the Z axis. The angle of the tool axis improves cutting conditions because a tool area with a low cutting speed is excluded from the cut.

3. Experimental works

A separate NC program was generated for each hemispherical surface of the sample. For the first three surfaces, made by 3-axis milling, the generation of orders was allowed only for three axes - X, Y and Z. For the other three areas, the generation of orders was also allowed for rotary movements A and B. The sample after the production of all shaped surfaces is shown in Fig. 3.

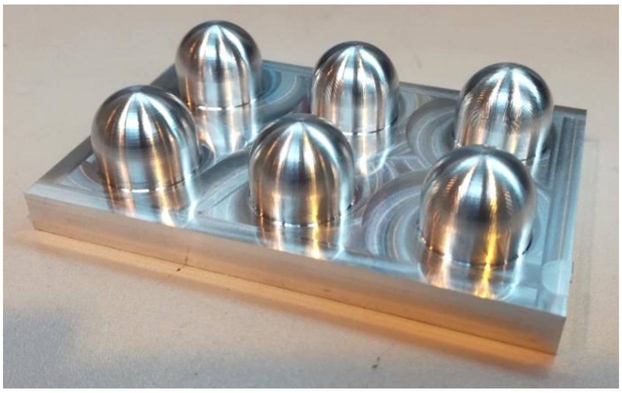

Fig. 3 *The sample after the production*

The HandySCAN BLACK Elite scanner was used to scan the samples, and the VXelements Viewer software was used to evaluate the scans. For comparison purposes, the color scale with the assigned deviation values was set identically in the CAM software and in the VXelements Viewer evaluation software - Fig. 4 and Fig. 5.

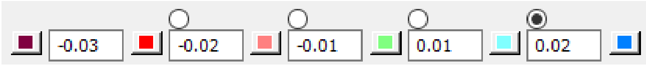

Fig. 4 *Color scale with assigned deviation values for CAM software*

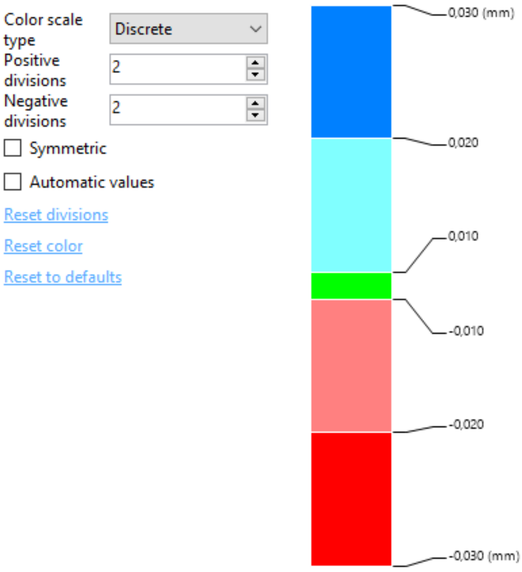

Fig. 5 *Color scale with assigned deviation values in the scanner evaluation software*

The result of the simulated CAM machining is shown in Fig. 6. The CAM system presented the virtual machined surfaces only with undercutting, the deviation in the positive direction (overcutting) was not presented. In 3-axis milling, undercutting exceeded -0.03 mm in all three strategies, the difference was in the distribution of undercut areas. The most significant undercutting is reflected in the Radial strategy in the form of several concentric circles.

In the 5-axis milling and Constant Z strategy, a surface without deviations was obtained. On the contrary, the Radial strategy undercut almost the entire hemispherical surface, with the undercut value exceeding -0.03 mm. With the Linear strategy, undercutting took place on about 50% of the area, the maximum value of undercutting also exceeded -0.03 mm.

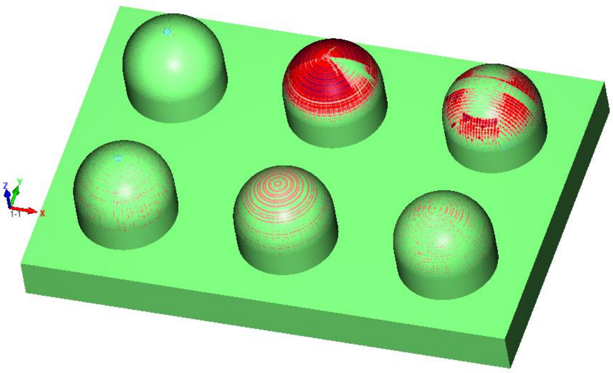

Fig. 6 *Deviations presented by the CAM system*

Scanning of the finished surfaces showed overcutting on all surfaces in the maximum value of 0.03 mm. The distribution of undercuts is similar in all cases – Fig. 7.

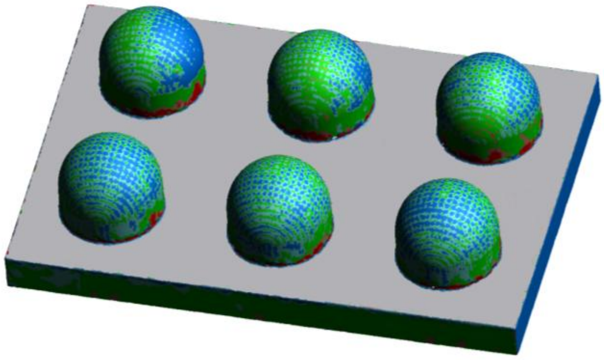

Fig 7 *Deviations obtained by scanning*

Mitutoyo Surftest SJ 410 was used to measure surface roughness. Four measurements were made on each surface – Fig. 8. The first two measurements were in the X-axis direction of the machine coordinate system on which the sample was made. The other two measurements were in the Y-axis direction. The instrument software recorded each measurement. The obtained profile is the result of filtering the measured profile by suppressing long-wave components, in this case in the shape of a semicircle. The results thus became relevant for roughness analysis. The cut-off value 0,8 mm was selected as recommended by standard ISO 4287: 1997. In Fig. 9 is an example of a roughness measurement record for one of the surfaces.

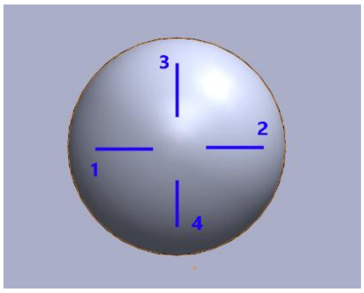

Fig. 8 *The order of measurements on each surface*

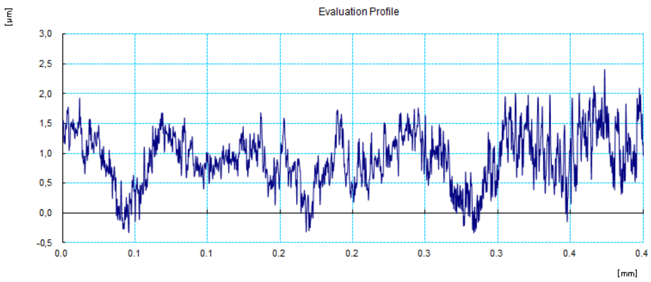

Fig. 9 *Surface roughness measurement record*

The values of the most common parameters Ra (arithmetical mean roughness value) and Rz (mean roughness depth) were recorded. The mean value was calculated from four measurements on each area. The values thus obtained are given in Tab. 1.

Table 1 *Mean values of parameters*

Milling method	Strategy	Ra [μm]	Rz [μm]
3-axis	Constant Z	1,05	4,33
	Radial	0,98	2,73
	Linear	1,26	5,54
5-axis	Constant Z	1,04	4,43
	Radial	0,94	2,44
	Linear	1,13	4,00

The comparison of the roughness of surfaces made by 3-axis and 5-axis milling through the parameter Ra is in Fig. 10, the comparison through parameter Rz is in Fig. 11. The Constant Z and

Radial strategies achieved very similar values. There are more significant differences in the Linear strategy, where the values are lower in 5-axis milling.

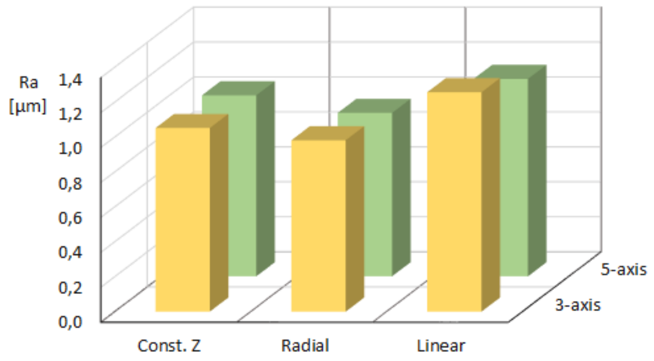

***Fig. 10** Comparison of the surface roughness parameter Ra*

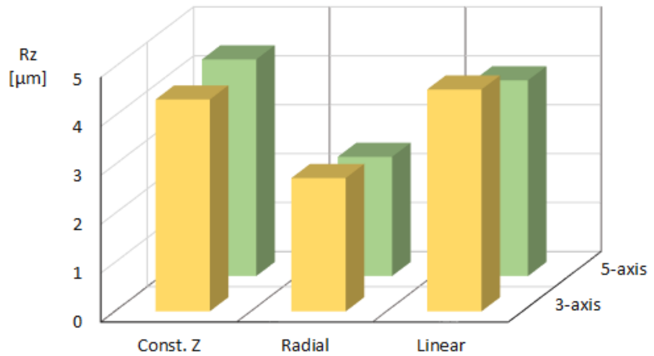

***Fig. 11** Comparison of the surface roughness parameter Rz*

4. Discussion

The prediction of residual material and undercutting in the CAM system did not correspond to the facts actually found. In all cases, the CAM system predicted only negative deviations (undercutting). On the contrary, positive deviations were found by scanning the produced surfaces. The prediction of milled surfaces by the CAM system is not convincing. However, such predictions are not unnecessary, they allow CNC programmers to better evaluate the milling process when selecting an effective toolpath strategy and milling method. The obtained results cannot be generalized, because each CAM system works with a different mathematical model and the results, especially in 5-axis milling, depend on the setting of a number of parameters.

Finishing operations take up approximately 70% of the total machining time for the production of shaped surfaces. Surface roughness is a key indicator of surface quality. Therefore, it is important to optimize the relationship between the milling parameters and the surface roughness of the finished part. This will eliminate or minimize finishing operations such as polishing or EDM.

The evaluation of the achieved surface roughness shows that with the Constant Z and Radial strategies, the milling method has a small effect on the surface quality. Linear strategy achieved better results with 5-axis milling compared to 3-axis milling.

Surface roughness depends on many factors. The parameters with the greatest influence are stepover and feed per tooth, the position of the tool in relation to the machined surface is also important. In general, 5-axis milling produces a more favourable surface quality, a smaller and more balanced value of the parameter Rz due to the constant position of the tool relative to the surface to be machined. This finding was only partially confirmed by the performed experiments.

It should be noted that the results obtained by similar experiments depend on many decisions and settings. The results can be influenced by the sample material, tool, strategies, machine, programming method, and the used programming system. The study provides a trend in the quality of treated surfaces under conditions similar to those used.

Acknowledgement: This research was funded by the Scientific Grant Agency of the Ministry of Education of the Slovak Republic (projects VEGA 1/0457/21 and KEGA 048TUKE-4/2020).

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