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Comparison of Milling Strategies in the Production of Shaped Surfaces

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ABSTRACT
The production of moulded surfaces in the engineering industry is progressing. One way to produce these surfaces is using CAM systems. As well as the use of a CAM system, the correct choice of milling strategy is also important. The aim of this paper was to increase the knowledge of the finishing milling strategies effect on surface quality in the production of shaped surfaces. For the experiment, a sample containing convex and concave curves produced on a 3-axis milling machine was designed. The material used for experiment was aluminum alloy and five different strategies were compared. The results of experiment included some methods for the comparison of machined surface quality. At the beginning visual comparison of the machined surface in CAM system with the real machined surface was evaluated. Other methods of the surface quality evaluation were roughness measurement and surface texture analysis. At the end the production time with respect to the selected strategies were evaluated and compared. The experiments showed that the best roughness values the strategy Constant Z was obtained and the shortest production time was achieved by the strategy linear and liner 90.

Keywords: milling strategy, shaped surfaces, surface roughness, time machining.

INTRODUCTION

Nowadays, it is very useful to use different milling strategies to achieve the required shape and dimensions. CAM systems are nowadays frequently used because of the different strategies that a CAM system offers. It includes different strategies for machining simple or complex shapes. Complex shapes are often used in mould making, where the production of moulded cavities is very difficult.

The complexity of surfaces in cavity manufacturing corresponds to different shapes. In most cases, these are convex and concave surfaces, which correspond to the surfaces of the future product. Because it is difficult to achieve the required roughness in the production of shaped cavities, it is necessary to finish the moulds by polishing [1]. The contact area between the tool and the surface of the workpiece changes in the process of manufacturing of the shaped surfaces. In some cases, the tool is machined at zero cutting speed, which has a negative effect on the roughness and quality of the machined surface [2]. In the manufacturing process, the choice of the appropriate finishing strategy has a significant impact on the surface quality.

Based on this requirement, which is important in the production process, it is necessary to have enough information not only on the selection of an appropriate strategy, but also on their influence on various parameters such as surface texture, roughness, and others, when milling shaped surfaces [3]. For the efficient machining of complex shapes, various CAM systems are used to select the most appropriate toolpaths in accordance with the geometry of the part. CAM systems have only one disadvantage that the simulation does not provide information regarding the machined surface texture, which is related to the cutting edge of the tool.

Author [4] analysed offset, zig-zag and parallel paths used in the form of finishing strategies.

The optimization of the choice of finishing strategies was studied author [5] focusing on HSM high speed machining. Ramos et al. [6] researched the machining of a part that equally contained concave and convex surfaces. He compared different strategies as linear, raster and 3D offset and evaluated their effect on texture and roughness. The worst results for machined surface texture and roughness were obtained with the linear strategy and the best with the 3D offset strategy.

The effect of toolpath on convex surface milling with a low curvature when using hardened material was investigated by Shaghayegh et al. In [7]. They investigated the influence of milling strategies, concretely linear, 3D offset, spiral and radial strategy on the workpiece-tool relationship, where cutting forces, surface texture and machining time were evaluated. The conclusion of this experiment was that radial strategy had the best surface quality and spiral strategy the worst quality. In terms of time evaluation radial paths achieved the highest machining time compared to the other strategies and the linear strategy achieved the shortest time.

Ikua [8] complemented the results with claims, that the bad sculptured surface machined quality can be influenced by the lower cutting force. Matras and Kowalczyk [9] analysed an influence of milling strategies to the aluminum alloy free form surface topography, when strategies Z level, radial, square, and circular were used. It was found that the lowest roughness parameter was achieved only for the circular toolpath in relation to the defined requirement of achieving roughness.

Authors [10–11] researched the orientation of toolpaths with respect to the origin point on a convex polynomial. Kaymakci and Diciuc [12–13] described various methods describing the possibilities of tool contact with the workpiece. There are not enough studies that evaluate toolpaths and compare them with respect to surface texture in the fabrication of shape-complex surfaces.

A lot of research describes an influence tool path strategies to roughness, but only a few studies deal with the influence tool path strategies to surface topography [14].

Sadeghi et al. [15] evaluated the effects of using strategies such as linear, 3D offset and spiral and machining parameters on the microhardness of a convex surface where the material was steel. The result was that the maximum hardness was achieved by the spiral strategy and the minimum by the radial strategy.

Bagci [16] investigated the importance of milling simulation in CAM systems and compared virtual simulations that resulted in minimizing the differences between toolpaths in the CAM system and toolpaths from the real milling process.

Fagali de Souza [17] compared five different CAM systems, where focus calculated time in CAM system with real produce machining time. In the experiments, Fagali found a match in the simulation of toolpaths obtained by the CAM system, but on the other hand he found differences in the form of NC codes depending on the applied CAM system. Considering these differences, it had an impact on the surface quality and productivity of the machined part. Achieved results showed varied differences between these two parameters such as up to 30% difference on the real machining time. Therefore, the comparison of the calculated time in the CAM system and the time in real production is also one of the subjects of investigation.

The author de Souza [17] founds that tool paths in CAM system ap-pear to be the same, but that every CAM system generates various NC code when pro-cessing identical geometry. In accordance with this various NC code a different machining process is created affecting to real machining time, roughness surface or feed rate oscillation.

EXPERIMENTAL METHODS

The shaped surface represents the convex and concave curves that are most found in freeform or mould making. Design of the sample was realized in CAD system Solidworks and the generation of toolpaths for machining was realized in CAM system SolidCAM. For the experiment aluminum alloy AlCu4Mg was used.

Table 1. Tools and cutting parameters for the experiment

Tool type and diameter [mm]	Cutting Speed [$m.min^{-1}$]	Feed per Tooth [mm]	Spindle Frequency [RPM]	Number of teeth	Tool Code
End Mill D 10	154	0.1	4900	1	AMS 2010S
Ball nose end mill D 9	138	0.03	4900	2	510418.090
Ball nose end mill D 8	123	0.03	4900	2	510418.080

Dimensions of the samples were 80 x 50 x 30 mm. The production of the shaped surface was carried out on an EMCO Mill 155 3-axis milling machine (EMCO MAIER Ges.m.b.H., Hallein/AUSTRIA) with a max. RPM 5000. Table 1 shows the followings tools and cutting parameters for the experiment.

The following parameters have been defined for the individual operations in the production process:

- Roughing operation – end mill tool D10 mm with one replaceable cutting insert APXT11T3PDR-MA, depth of cut a_p = 2 mm, side step a_e = 3 mm, contour strategy with start of machining from the outside, manufacturer Korloy, toolpath tolerance T = 0.1 mm, surface allowance P = 0.5 mm;
- Semi finishing operation – ball nose end mill D 9 mm, cutting material HSS Co8, depth of cut a_p = 2 mm, side step a_e = 2.5 mm, linear strategy, zig-zag machining direction, manufacturer ZPS-FN, toolpath tolerance T = 0.1 mm, surface allowance P = 0.2 mm;
- Finishing operation - ball nose end mill D 8 mm, cutting material HSS Co8, side step a_e = 0.25 mm, manufacturer Korloy, toolpath tolerance T = 0.01 mm, scallop height SH = 0.001 mm.

Using a contour strategy with respect to the 3D model of the shaped surface, toolpaths were created in parallel layers. Their level was defined by the selected depth of cut. The orientation of each layer was perpendicular to the axis of the milling tool. The generated linear toolpaths correspond to the contour of the part. A virtual representation of the toolpaths and rest material in the CAM system is shown in Figure 1.

A non-uniform surface after roughing was obtained and therefore a semi-finish operation was used. The semi-finish operation equally removed the necessary layer of material to the level of the allowance defined for finishing. The toolpaths side by side oriented in the vertical direction, in the X-Z coordinate system plane were generated. A comparison of the virtual representation of the rest material with the real state after machining shows Figure 2.

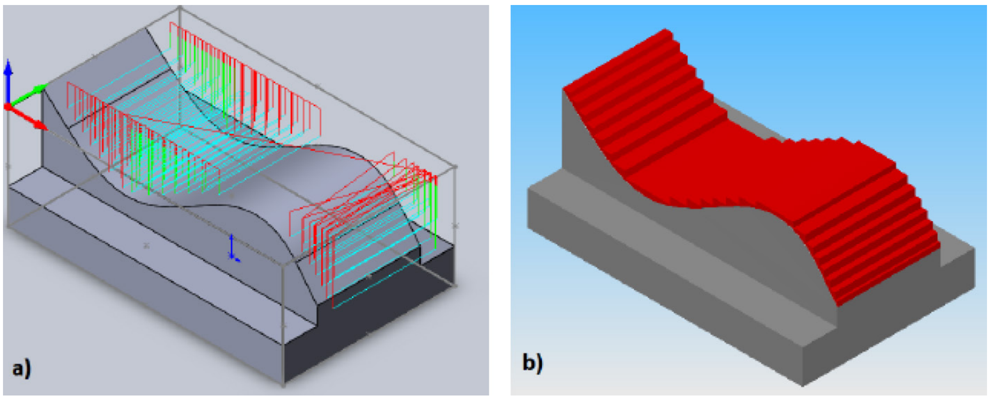


Fig. 1. Roughing operation a) tool – path of the tool b) rest material

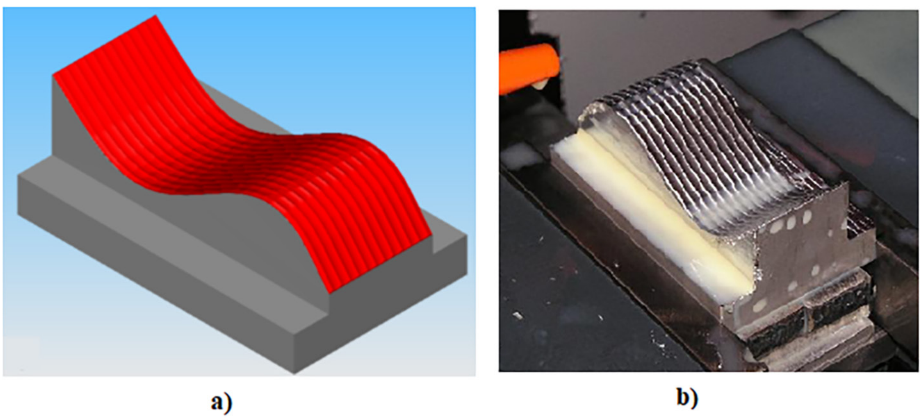
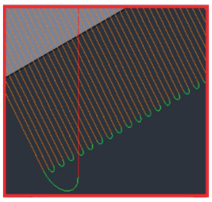
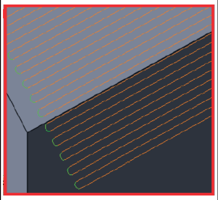
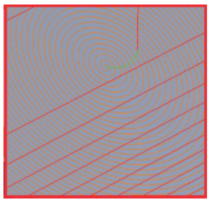
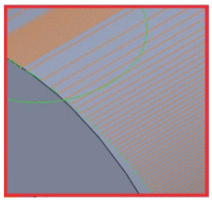
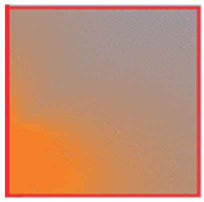


Fig. 2. Semi-finish operation a) view of rest material b) real state

Table 2. Description of selected tool paths for the production

Strategy	Linear	Linear 90°	Spiral	Constant Z	Radial
Toolpath view					
	Creates toolpaths from linear patterns generated by a defined step over projected into a model surface.	The same toolpaths as in strategy linear only rotated by 90° degrees.	A spiral tool path radiating from a central point that keeps constant contact between the cutter and part, as its machines within a given boundary.	Tool path follows a surface contour at different z-heights.	Generates a radial pattern around a defined central point projected onto a model surface.

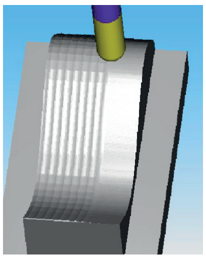
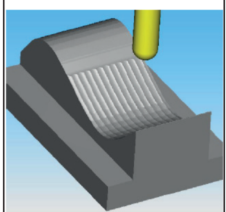
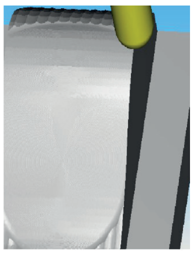
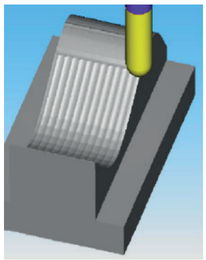
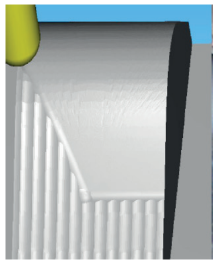
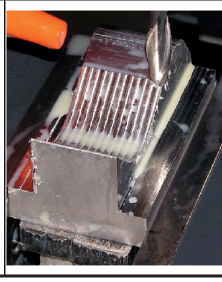
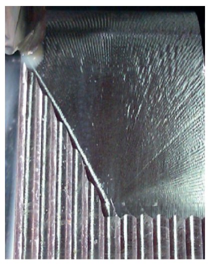
For finishing operations and following comparison, five strategies were selected for the experiment, which are designed for high-speed milling. Strategy linear, linear 90°, spiral, constant Z and radial in the production of shaped samples were used. Description of selected tool paths for the production are described in Table 2.

RESULTS

In production process is important to control the surface obtained by CAM system with the surface after production. Each CAM system contains various options for displaying of the machined surface after simulation. CAM system SolidCAM includes the simulation mode names Solid Verify, where it is possible to control the condition of the machined surface in simulation mode. Visual comparison of the machined surface in CAM system with the real machined surface is shown in Table 3.

The roughness evaluation was carried out using the Mitutoyo ST-301 roughness testing equipment. One main roughness measurement and two additional control measurements with an offset dimension ±0.1 mm on each measured location was made. From these three measurements, the average values were evaluated. The roughness was measured perpendicular to the feed direction. The comparison of average surface profile Ra (Figure 3) and Rz (Figure 4) in accordance to finishing strategy were evaluated. The arithmetic mean surface roughness Ra reached values within 0.79 to 1.36 μm and the surface roughness depth Rz reached values within 3.60 to 6.33 μm. In both

Table 3. Visual comparison between simulated surface and real machined surface

Strategy	Linear	Linear 90°	Spiral	Constant Z	Radial
Toolpath view					
					

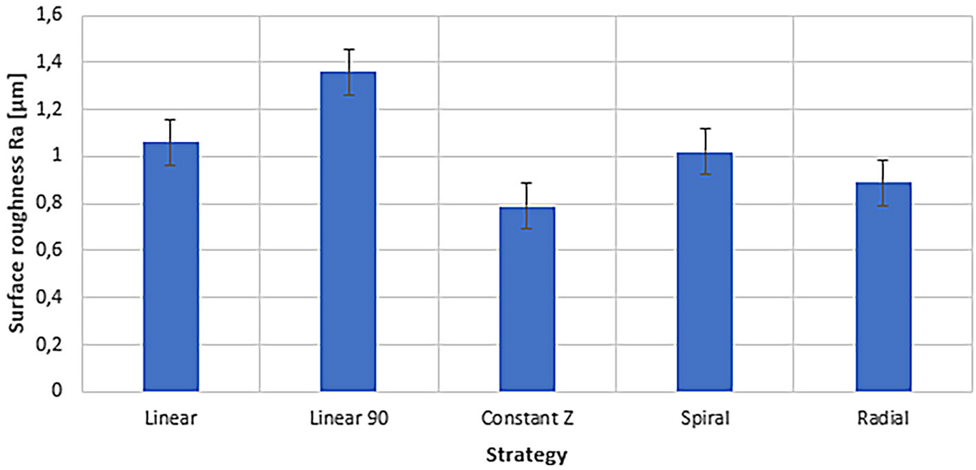


Fig. 3. The arithmetic mean surface roughness Ra comparison

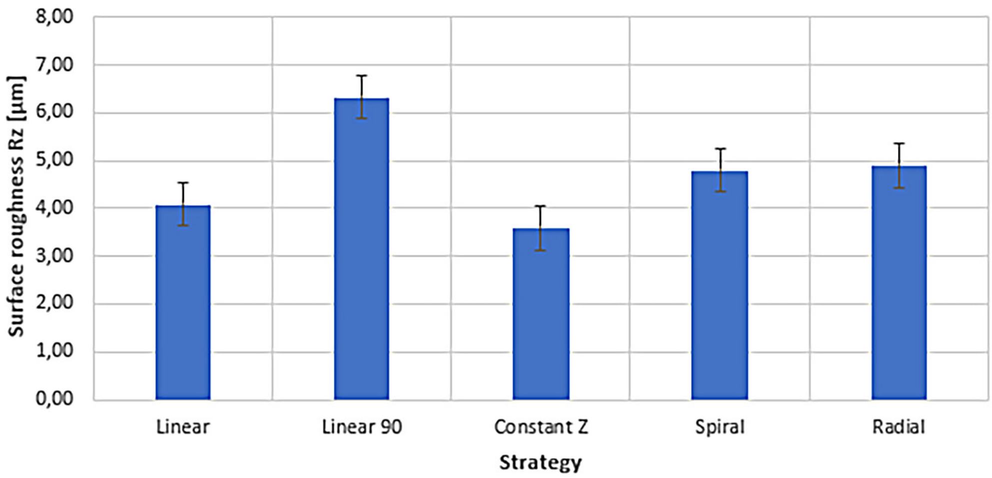


Fig. 4. The arithmetic mean surface roughness Rz comparison

cases the lowest roughness value Ra and Rz with the Constant Z strategy and the highest with the Linear 90° strategy was obtained.

The surface texture allows cutting tool – paths to be analysed. Machined surface textures were examined using an USB optical microscope with UM-5 CAM technology and a viewer software interface at 100x magnification. Comparison of individual surface textures with respect to the selected strategy is shown in Figure 5.

Displayed textures of the machined surface corresponded to the generated toolpaths in the CAM system as shown in Table 2. For the linear 90°strategy, wider and more uniform longitudinal tool marks can be observed on the machined surface compared to the strategy linear. Both Linear and Linear 90 strategies involve parallel oriented toolpaths. On the machined surface made with the spiral strategy, the toolpaths are regular, ordered in circular arcs. With the radial strategy, it is possible to see the concentrating of toolpaths starting from a defined central point projected into the model surface. The edges of the sample were at the furthest point from the central point, which results in more visible tool path movement with a clearly recognizable distance between paths.

The real machining time of the shaped surfaces production were greater than the times given by the simulation as is shown in Figure 6. A short machining time by the strategy linear and linear 90° was achieved. It is caused by generated of simple linear toolpaths during machining process. During linear tool – paths the least number of tool movement changes are achieved.

The time difference between the time obtained from the simulation and the real machining was that the simulation does not calculate with the time required for tool change and the acceleration of the tool movement when changing its direction.

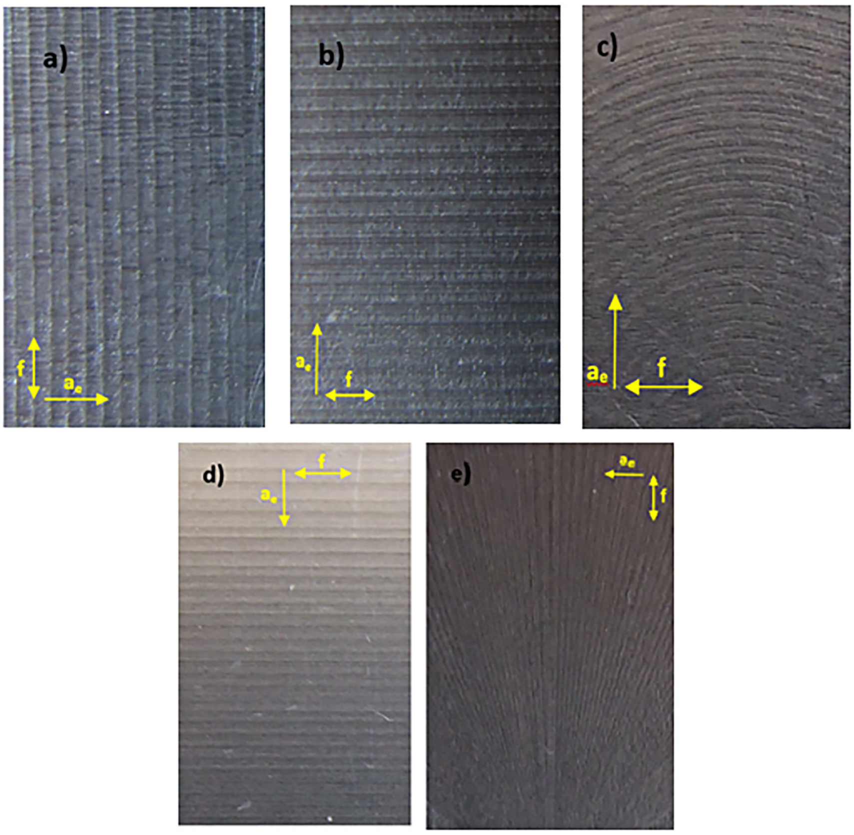


Fig. 5. Surface texture evaluation a) linear b) linear 90° c) spiral d) constant Z e) radial

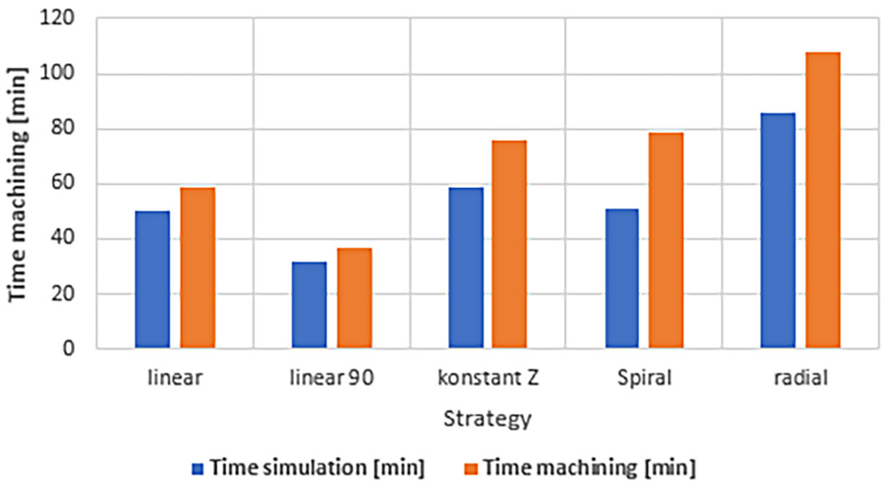


Fig. 6. Comparison between time machining and time simulation

A comparison of the short machining time with other strategies also corresponded to the lower number of lines generated in program (nr = 11 405 in linear strategy and nr = 7 762 in linear 90° strategy). A comparison of the number of lines in the program with the real machining times of the shaped surfaces is shown in Figure 7. The longest machining time (nr = 40 901) with the radial strategy was obtained. Thanks to generated toolpaths starting from the central point to the edges of the machining. The edge of the workpiece is also the boundary for each single toolpath.

CONCLUSIONS

Attention to the creation of NC programs in the form of optimizing toolpaths and comparing them with each other saves time in the actual

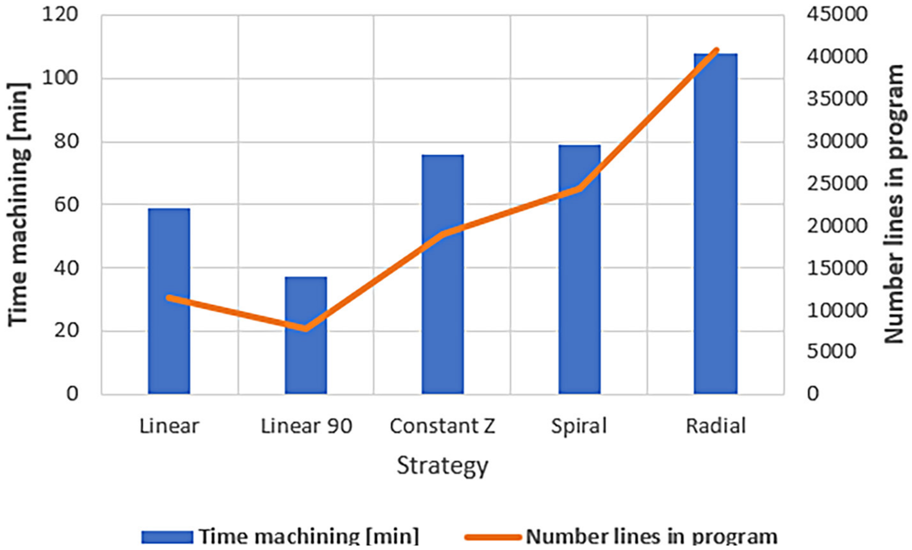


Fig. 7. Comparison of the number of lines in the program with the real machining times

production on the CNC machine and in the final, often manual finishing.

The use of some special strategies for the machining of shaped surfaces has its justification. Universal strategies applying material removal in parallel layers cannot achieve uniform surface quality when machining shaped surfaces. The benefit is therefore a reduction in machining time and a better surface quality, thus reducing the requirements for finishing operations.

The optimization of toolpaths is significant in terms of production process efficiency as well as in the very smoothness of the movements in the machining process, which affects the surface quality itself. The main objective of the paper was to present the influence of the choice of finishing strategies on the machining quality of freeform surfaces. The quality of the machined surface by roughness measuring and surface texture analysis was evaluated. By evaluation of surface roughness and texture analysis it was possible to select the optimal finishing strategy for machining free form surfaces. Finally, the production time with respect to the selected strategies were evaluated and compared.

The main conclusions can be listed as follows. The choice of finishing strategies has an impact on the quality of the machined surface in free form production. The results show that a suitable choice of toolpath can provide time and cost reductions to achieve the final requirements. The results also indicate that there is no direct dependence in the relationship between machining time and surface quality. Free form sample produced with the Linear 90 strategy achieved the shortest production time but provided the worst surface quality in terms of surface roughness Ra and Rz achieved. Comparisons between the simulated surface and the machined surface obtained were identical. Different toolpaths can be observed on the machined surfaces, which produce different surface texture depending on the milling strategy used, while all samples were produced using the same feed per tooth and cutting speed, but with various toolpaths. Based on a visual comparison of the toolpaths on the machined surfaces, it was possible to determine the order of the strategies as follows: Constant Z, Radial, Spiral, Linear and Linear 90°. Highly visible tool marks after machining could be observed with the linear and linear 90 strategies. Oriented toolpath was obtained for each milling strategy. The results of the roughness measurements show that the Constant Z strategy is the most suitable for the following types of shaped surfaces. Comparison of the measured surface roughness values showed higher Ra and Rz values for the Linear 90° strategy. If the shape of the machined part corresponded to the shape of the samples in experiment, the Constant Z strategy would require minimum proportion of finishing operations. However, a part containing shaped surfaces produced by the Linear 90° strategy would require the greatest proportion of finishing operations.

The shortest machining time was achieved by the strategy linear and linear 90°. It is caused by generated of simple linear toolpaths during machining process. The longest machining time of shaped surface production was obtained with the radial strategy. Due to the shape of the sample, the result was a 3D toolpath, which increased the demands on the control system, which had to provide simultaneous control of the tool position in three axes, therefore the production time was longer. It is caused by generated toolpaths starting from the central point to the edges of the machining.

Acknowledgements

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