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# DEVELOPMENT IN MACHINING TECHNOLOGY

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Edited by
Wojciech Zębala
Ildikó Maňková

Cracow University of Technology

This study aims to provide the recent advances in machining for modern manufacturing engineering, especially CNC machining, modern tools and machining of difficult-to-cut materials, optimization of machining processes, application of measurement techniques in manufacturing, modeling and computer simulation of cutting processes and physical phenomena.

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Editors: Wojciech Zębala, Ildikó Maňková

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## PREFACE

Machining is one of the most popular technique to change shape and dimensions of the objects. Machining operations can be applied to work metallic and non-metallic materials such as ceramics, composites, polymers, wood.

Cutting tools have been used since ancient times to remove excess material from forgings and castings. Nowadays, metal cutting became one of the primary manufacturing processes for finishing operations. In the last few years we have observed a rapid development in automation of manufacturing processes, especially in automatic control systems. Progress in cutting stimulates a significant increase in the metal removal rate and achieving high accuracy in terms of dimensions and shape of machine parts. New materials, which play the key role here, are used to produce cutting tools.

To meet today's high demands concerning accuracy and efficiency of the manufacturing process of machine parts, it is necessary to use computer methods for designing of technological processes.

This study aims to provide the recent advances in machining for modern manufacturing engineering, especially CNC machining, modern tools and machining of difficult-to-cut materials, optimization of machining processes, application of measurement techniques in manufacturing, modeling and computer simulation of cutting processes and physical phenomena.

Wojciech Zębala

# PART 2

# CAD/CAE/CAM Techniques

## Chapter 2.3

# THE INFLUENCE OF MILLING STRATEGIES ON THE PRODUCTIVITY AND ACCURACY WHEN MACHINING FREEFORM SURFACE

Kandráč L., Maňková I., Vrabeľ M., Greškovič F.
Technical University Košice, Faculty of Mechanical Engineering, Slovakia

***Abstract:*** *This paper deals with milling strategies and their influence on productivity and quality of the surface. As a basis for the experiment, tool for injection molding for producing advertising items was used. Injection moulding tool was produced on CNC milling machining center. The basic principle to achieve effective production, a compromise between optimization of the tool path, productivity, production time and accuracy of the finished product surface was found.*

***Keywords:*** *CAM system, milling strategy, injection mould, free-form surface*

## 1. Introduction

A wide range of products includes complex surfaces, free-form surfaces respectively. The free-form surfaces are widely used in the automotive, aerospace and other industries, as well as designing and constructing dies, injection molds and other tools which are produced by milling method [1]. Free-form surfaces, cavity molds are designed to comply and improve the aesthetic, functional, constructional and technological requirements [2]. Nowadays CAM systems are essential part in pre-production stages used by manufacturing companies.

One of important factors is choice of CAM software. Popescu [3] pays attention to this subject. The modern CAM systems support 2D, 3D and 5D machining, high speed milling HSS and HSM [4, 5]. Using of simulation and CNC program, as output from the CAM system, it can be set and achieve production of required surface, accuracy and quality in a ratio of the effective productivity which has been observed by Csesznok et al. [6, 7].

Classification of surfaces and shapes, included in moulds modelled by CAD system, and their interpretation of visualization was devoted by Beno et al. [8]. Milling strategies are derived from shapes and structure of mould.

To achieve accuracy and quality of the machined surfaces means to integrate milling strategies. This generally means to use predefined tool paths. Milling strategies are chosen to achieve optimized and effective production variety of shapes and flat surfaces. Milling strategies are generally divided into roughing, semi-finishing and finishing. Roughing strategies are used to maximize material volume removal by the shortest possible time. Due to dimensions of the workpiece it is used the largest possible diameter of cutter. For the roughing milling strategy is mainly used end-mill cutter. The purpose of finishing strategies is to particularly achieve high quality of surface. In order to achieve the lowest depth of cut in finishing cycle the production time is reduced, which also has a positive impact on tool life.

Ball-end mill cutters are selected to achieve high quality of machined surfaces. They are called copy milling cutter. Tool path for milling consists of three basic motions. The first motion is a cutting length, performed by cutting feed. The choice of tool material of workpiece and choice of milling strategy effects cutting length. The second motion is movement without cutting process. This motion is carried out at lead in and lead out of tool. The third motion is rapid feed. It is used to quickly overcome the distances and it is connected with the stroke up to the retraction plane and subsequent starting of cutting process [9]. Research work by Chen a Shi [10] was focused on generating strategies of tool path ball-end mill cutter for complex surfaces. The influence of production strategies for the manufacturing of moulds and dies using CAM system have been investigated by Schützer [11]. Ramos [12] examined the effect of finishing strategies on texture, surface roughness and dimensional deviation when machining complicated surfaces. Lase et al. [13], have produced a report of recent developments in the field of CNC machining of free-form surfaces. There was processed tool path generation, tool orientation identification and selection of tool geometry.

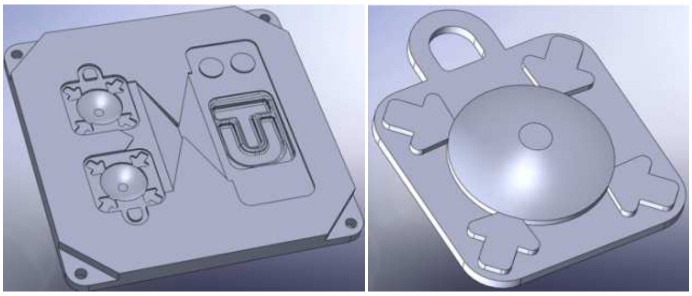
The productivity of milling is limited by production time and tool life of the cutting tool. The production time for surface forming increases proportionally to the requirement of lower values of surface roughness. However, all these factors affect the choice of milling strategies. Based on above mentioned combinations the article presents results and subsequent comparisons of effective and productive milling strategies for producing selected parts. Also depending on cutting parameters and milling strategies cutting tool was chosen. Periodic load of cutting tool during manufacturing is unwanted.

The purpose of setting correct cutting parameters and milling strategies, by given load of the tool, is to provide a constant load, which increases the life of the cutting tool, as well as improve the quality of machined surface.

## 2. Experimental procedure

The aim of experiment was to analyze the milling strategies generated from the CAM software and evaluate their impact on productivity and quality of the machined surface. The emphasis has been taken on the productivity of machining, so the production time and quality of the machined surface was important.

As a basis, the injection mould shown in Fig. 1a, designed for plastic moldings of advertising items, was used. Free-form surface, for which machine cycles were established, is illustrated in Fig. 1b.



a) b)

Fig. 1. Injection mould with moulding

Shaped cavities were designed with technological features that are necessary for the construction, installation and functional parts. According to technological requirements, radiuses corners and edges and 1 ° bevels were chosen, to ensure easy removing of plastic molding from the mould.

The experiment was carried out on CNC milling machine tool Emco 155 Mill with control system Heidenhain TNC 426. The part was modeled in the CAD program SolidWorks2010. Simulations were carried out in extension module SolidCAM2009. Based on post processor, NC program was generated, and was directly entered to the machining center. Table 1 summarizes the characteristics of aluminum alloy material used for manufacturing.

Table 1. Characteristics of semi-finished material

| | | |
|---|---|---|
| **Norm of workpiece** | EN AW 6060 | STN 42 4401 |
| **Chemical sign** | AlMgSi 0,5 | - |
| **Dimension of workpiece** | 130x130x10 | [mm] |
| **Hardness of material** | 70 | [HB] |
| **Strength of material** | 215 | [MPa] |
| **Density of material** | 260 | [kg.m$^3$] |

Cutting conditions and cutting tool selection:

- The tool for roughing operations was end-mill cutter with four cutting edges and diameter Ø 8 mm. Tool sign 141218 with dimensions Ø8x6x38x80.
- The tool for finishing contoured surface. was ball-end mill cutter Ø3 mm. Tool sign G9A70030 R1, with dimensions Ø5x3x3x39. Cutter with two cutting edges.
- The tool for clean-up operation was ball-end mill cutter Ø1 mm. Tool sign G9A70010 R0, with dimensions Ø5x3x3x39. Cutter with two cutting edges.

The cutting conditions were chosen according to workpiece material (Table 1) and according to characteristics of tools determined by supplier. Depth of cut $a_p$ was determined based on the selected milling strategies. The cutting conditions are listed in Table 2.

Table 2. Determined cutting conditions

| Tool | Cutting speed $v_c$ [$m.min^{-1}$] | Feed f | |
|---|---|---|---|
| | | Feed XY [$mm.min^{-1}$] | Feed Z [$mm.min^{-1}$] |
| 141218 | 123 | 210 | 90 |
| G9A70030 | 47 | 60 | 20 |
| G9A70010 | 15 | 14 | 5 |

## 3. The proposal of milling strategies and implementation of production

Current possibilities of modern methods of machining in the CAM system offers variable of settings of machining process as well as various combinations of milling strategies. In our case, the surface was made by 3D model operation. For a given process roughing, semi-finishing and finishing are optional selections. 3D model operation is suitable for machining free-form surfaces, and complex spatial components, respectively. From the available machine cycles, with regard to shape, production time and quality of machined surface, contour strategy, constant Z and pencil machining were chosen. Contour strategy is suitable for outline elements of a complex shape. This method is mainly used in the roughing process which ensures the maximum possible removal rate of material in the shortest possible time. The principle of constant Z strategy is the distribution of several additional horizontal layers. Material is removed in each layer by using 2D cutting paths (at the current XY coordinate system). Strategy is suitable for pre finishing and semi-finishing operations. The principle of the pencil machining is to remove material from the edges and corners from the previous operation.

## 4. Settings parameters of roughing strategy

The first chosen operation for machining of sculptured surfaces is 3D model operation. In this operation, roughing strategy contour was used. Simulation of tool path generation (left) and roughing simulation (right) is shown in Fig. 2. In Data setting, the value of the rounded corner with a radius of 1.3 mm and value of minimum radius 0.3 mm were assigned.

The parameter of tool overlap was defined as the 0.5 mm, depth of cut $a_p$ = 0.25 mm and the addition of an area of 0.25 mm. The planes were at the end of the roughing cleans-up with defined tolerances to 0.01 mm with a requirement for curved surfaces.

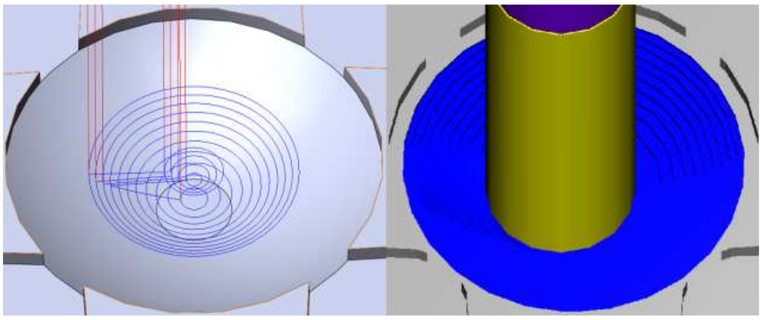


Fig. 2. Simulation of roughing free-form surfaces

Fig. 3 shows the surface after machining of roughing strategy. Transitions in the form of stairs after cutting operation are identical with the simulation in the process of roughing (Fig. 2). The tool in Fig. 3 corresponds to the finishing operations while at this stage of machining it was the beginning of the finishing operation.

Fig. 3. Real production of roughing cycle

## 5. Settings parameters of finishing strategy

Finishing operation is focused on the quality of the machining free-form surface. Chosen operation for this part of production is 3D model. In terms of the shortest production time constant Z strategy milling machining have been chosen and simulated. Due to the radius curved surface ball-end mill cutter was chosen, which is able to effectively copy the manufactured surface. In this case, the value of $a_p$ was given by addition after roughing, however in the CAM system were chosen value of maximum step down 0.6 mm and value of minimum step down 0.02 mm and roughness of 0.5 $\mu$m. The value of the polygon tolerance is defined to 0.005 mm. As lowest this value is, as precisely describe a given curve shape. However it has a negative effect on production time, which is therefore proportionally longer. Generated tool paths in CAM system is shown in Fig. 4 (left) and simulation of finishing is shown in Fig. 4 (right).

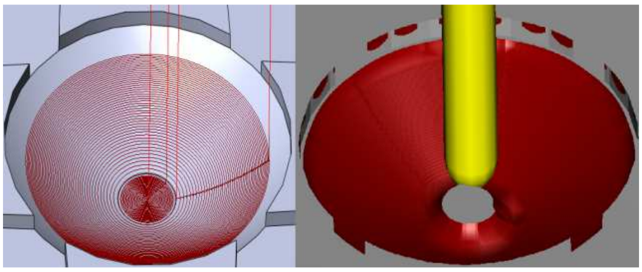


Fig. 4. Simulation of finishing milling strategies

Fig. 5 shows a visual form with complicated shape after finishing operations, which are displayed also tool path after machining.


Fig. 5. State of complex surfaces after finishing operation

Based on the analysis of rest material (Fig. 6) offered by the CAM software a clean-up operation was included. This strategy was selected for purpose of the removal of rest material.

For this section 3D model operation and Pencil machining was chosen (Fig. 7). This strategy belongs to the finishing machining operations.

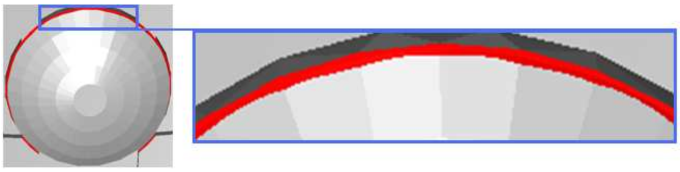


Fig. 6. Analysis of rest material

After finishing each operation, it is appropriate to carry out an analysis of rest material that can be left after previous operations. Rest material can arise from incorrect setting of milling strategies or unsuitable definition of tool paths. Therefore the cutting tool was not able to precisely machine marked region. For additional tool path design only required region for treatment of residual material is used. Also the tool with smaller diameter has been used. The rest material is taken as a negative phenomenon for the process with regard to increasing number of operations, increasing production time and shortening the tool life of the cutting tool.

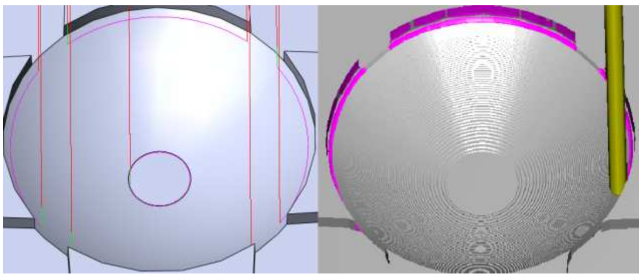


Fig. 7. Pencil machining of residual material at circular area

Fig. 8 shows the real shape of the machined complex surface, with traces of pencil tool paths after machining the rest material.

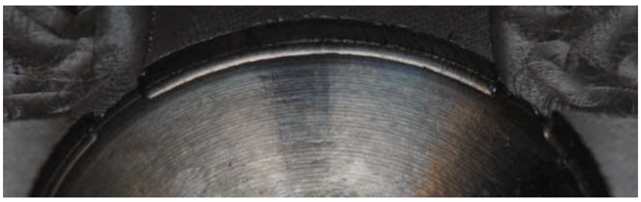


Fig. 8. The tool path after pencil machining of residual material

## 6. Evaluation of machined surface

In the preparation of production different combinations of simulations using various milling strategies have been performed. Based on comparison of machined surface by visual inspection, simulation and virtual CAD model effective milling operations and strategies have been selected. In terms of selected machine cycles the high quality surface is expected. During the finishing operation design finishing milling strategies rowing (Fig. 9) and pocket shape (Fig. 10) were simulated.

Due to the machined surface, which was achieved using these strategies it is easy to noted worse results than the selected strategies. Cutting conditions and cutting tools were not changed.

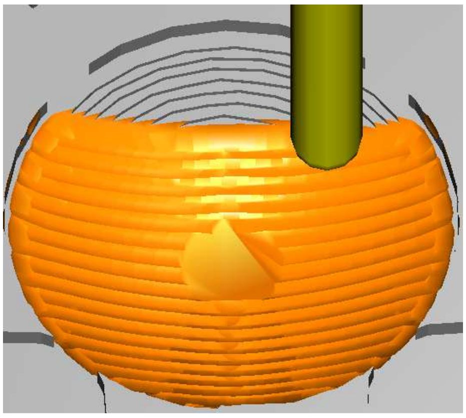


Fig. 9. State of surface after linear finish machining strategy

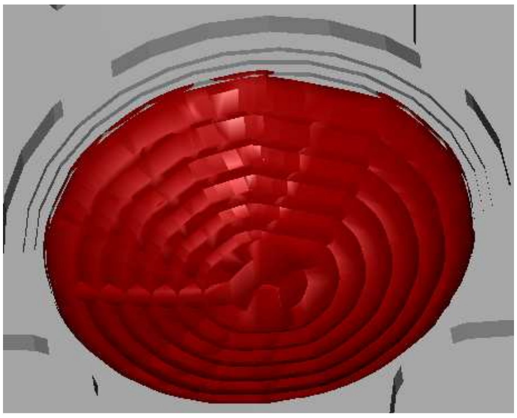


Fig. 10. State of surface after shaped pocket finish machining strategy

On a visual level deficiencies in the production of geometric inaccuracies and insufficient quality of the results of the shape of machined surface were visible. Machined surface contains visible traces of the tool cutting edge. Based on a simplified model of a tool that does not take into account the exact geometry of cutting part such as $\kappa_r$, $\kappa_r'$, $\psi_r$, $r_\varepsilon$, CAM system smooth-down the machined surface. Measurements of surface roughness were performed in previous research work [1]. CAM system offers analyses for virtual comparison of workpiece and of machined surface (Fig. 11). On the basis of suitable setting of color spectrum, which indicates the range of resolution observed deviations of production it can be concluded that there is a maximum deviation between -0.11 mm to 0.01 mm. Therefore large undercut of material layer have been observed as it is shown on Fig 11.

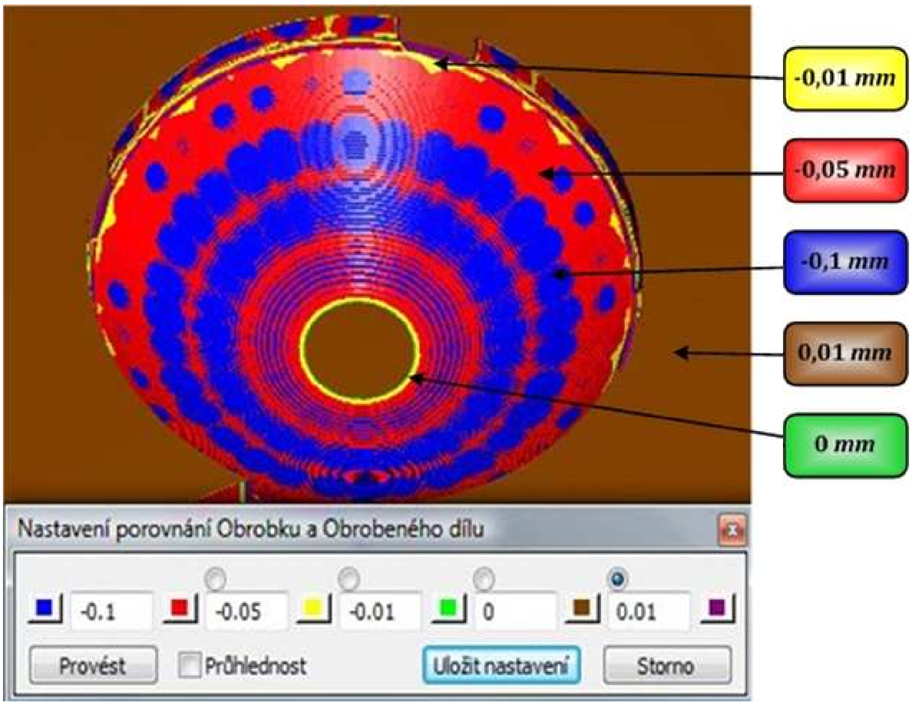



Fig. 11. Virtual comparison of the model with the target surface

## 7. Conclusion

Cutting tools in conjunction with the milling operations and suitably selected strategies are effectively integrated tool for cutting operation, allowing the machining of difficult to access surfaces. With the fusion of 5-axis CNC machine tool and CAM systems the area of free form surfaces machining is opened to new possibilities of production, which is constantly in progress.

The knowledge of choices possibilities and limitations which impact milling strategy creates conditions for their effective use, leads to a reduction of the number of redundant operations, reduction of movements' faster creation of NC programs and, of course, limits the creation of surface defects. Here is a great area for improvement the simulations to approach the reality of production, such as mentioned tool traces.

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