Vol. 2 2012

DEVELOPMENT IN MACHINING TECHNOLOGY

Scientific Research Reports

Edited by
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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.

ISBN 978-83-7242-655-0

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Editors: Wojciech Zębala, Ildikó Maňková

Project of cover: Łukasz Ślusarczyk, Grzegorz Struzikiewicz

Text arrangement: Grzegorz Struzikiewicz

All papers published in Scientific Research Reports issue had been reviewed and revised by Board of Reviewers

ISBN 978-83-7242-655-0

Druk i oprawę wykonano w Dziale Poligrafii Politechniki Krakowskiej
ul. Skarżyńskiego 1, 31-866 Kraków; tel. 12 628 37 29

Zam. 202/2012 Nakład 50 egz.

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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 2.2

SOME ASPECTS OF MILLING PROCESS PLANNING WHEN PRODUCING FORM SURFACES

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Abstract: *The paper deals with manufacturability of form surfaces produced by 3D milling operations. Based on decomposition of form surfaces, which are designed by CAD, virtual elementary operations of milling form surfaces are presented. Some typical engineering components with form surfaces were designed to analyse their features. Forms surfaces are classified to give review of dimensionless basic shapes. Review of milling strategies is introduced to select planning of machining of surfaces taken from virtual components. A representative component was analysed in order to obtain overall length of tool paths related to the elementary surfaces. Examples of process planning of elementary surfaces are discussed.*

Keywords: *Form surface, virtual representation, process planning, CAM, SolidCAM*

1. Introduction

There are various engineering components consisting of form surfaces. In order to reduce time of their production and the first criterion of process planning is that advanced machine tools, metal cutting tools and software have to be used. However, reduction of additional finishing operations is expected too, thus proper surface finish seems to be another criterion of process planning.

Form surfaces, which build up definite engineering components, result from design of product, however, dimensioning and planned production belong to the further factors too. Nowadays, design of engineering components considers standards of geometrical products specification, e.g., [1], such standards are included in their relevant matrices. Therefore, decomposition of geometrical variability of form surfaces into simple features means tools of improving quality of produced components. Decomposition of components with form surfaces fits well into product oriented sequential design by [2] which deals with incorporation of Design for Manufacturing (DFM), Design for Assembly (DFA), Taguchi Loss Function, etc., that do not avoid the necessity of performing the subsequent revisions and adjustments after the retro-alimentation of information coming from the manufacturing. Based on [1] and [2], any product, which includes components with form surfaces seems to be designed within time shift from information sources, five steps below:

1. Analysis of available solutions known for desired design
2. Development of products including design of engineering components
3. Prototypes of sample product and analysis of components (dimensioning, tolerances, process plans and tooling)
4. Quality checking and metrology of produced components
5. Joining of components as well as product assembly.

If true value of components consisting from form surfaces is considered, they are not as easy interchangeable during maintenance and product repair as those of being standardised shapes (screws, bolts, shanks, etc.). If time shift is taken into account, production of form surfaces may be viewed as special case of self similarity, a methodology known in group technology [3].

Because of modern CAD systems, components with free form surfaces became an important part of common engineering components for having found wide applications in mould making. CAM systems play a significant role in process planning; therefore, contribution discusses some main aspects associated with production of real form surfaces as well as discrepancies appearing due to the technology and removal strategies applied.

2. Manufacturing of Form Surfaces

CAM systems provide wide possibilities for process planning in manufacturing of form surfaces in mould making [4]. Besides definition of any form surface, there is choice of various strategies, which enable optimisation of milling tool motion during removal, e.g., [5] and [6]. However, strategies of tool motion, and that is chiefly a way of stock removal, are one of controlling factors, which lead to the final quality of complex product. It can be said that strategies are part of entire technology applied in the free form surface manufacturing. On the other hand, there are other influences as machine tool, applied type of milling cutter, work-piece, free form surface's design, and finally, economics of advanced milling. An entire review of all important factors is shown in Fig. 1.

Based on factors shown in Fig. 1, following notes are added to the machining of any form surface. For the first reason, commercial CAD/CAM systems provide various capabilities for surface design and process planning. However, for another, an efficient process plan needs establishing of proper operation sequences including removal strategies, that is tooling and tool performance. In other words said, no firm rules are available to enter any removal strategy for different manufacturability of designed form surface. Last but not least, economics of free-form machining means considerations to the tool performance, surface quality, and production costs, as well.

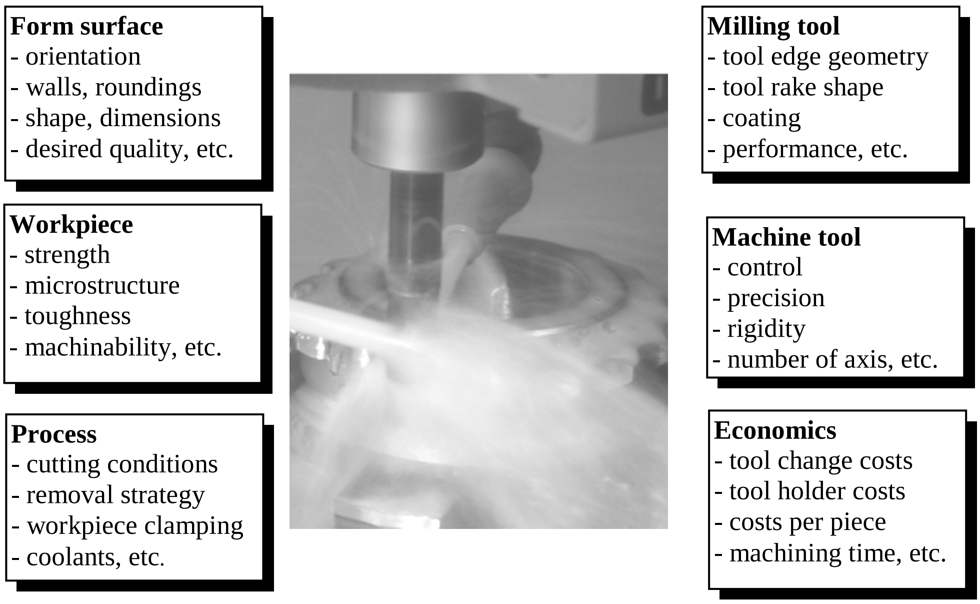


Fig. 1. Factors affecting quality of product when milling any form surface

3. Milling of Form Surfaces

Entire process of milling of form surfaces can be split into three operations consisting of roughing, semi–finishing and surface finishing. Roughing as principal operation must remove the greatest amount of stock under controlling factor of machining time. An allowance for next–coming operation must be left there whereas no concern is assumed for any dimension accuracy. Possibility and choice of milling tool is very wide because of use of end milling cutters (the choice is reasoned by tool inserts' life), toroid cutters (the choice depends on rounding between adjacent surfaces) as well as end ball cutters, the latter is reasoned for the small amount of stock in roughing.

Roughing provides specific feature because of milling cutter diameter. If any surface produced by roughing does not allow a safe access for tool edge, roughing must be performed in the consecutive steps, i.e. milling cutters having two different diameters must be used in order to remove the stock. Such additional roughing is determined by CAM in process plan, however, need of additional roughing can be determined by calculations, too.

Semi–finish milling has quite different purpose for removing traces and burrs remaining in roughing. Two types of milling cutters as toroid and end–ball are chiefly applied because of considering of final shape of part produced. As with additional roughing, semi–finishing may be split into two steps for removing allowances within shapes having bad accessibility as rounding, cornering, hollows, etc. A significant factor is that semi–finish milling removes allowance with chip thickness being approximately constant. Consequently, cutting conditions (speed, tool edge in pass, etc.) need not to be changed in such ways than those in roughing. Thus, semi–finish milling leaves constant allowance for final surface finishing. Constant allowance has high importance for finishing milling because of minimum deflexion of end–ball milling cutter's body and that is increased accuracy of produced form surface.

Finishing milling of any form surface employs chiefly end–ball milling cutter whereas dimension accuracy and surface roughness belong to the basic criteria. Finishing milling, however, consumes the large amount of total production time for being applied small depth of cut and feed speed, as well. Surface finishing must be done because of remaining tool edge traces on previous surfaces and that means of tool edges made of advanced tool materials provided by coatings.

4. Decomposition of form surfaces

As indicated above, design and production of sample prototypes seem to be the core in sequence of new product development. For various kinds of technology are being involved (semi-manufacture by casting, forging, etc., machining, heat treatment, surface finishing) any of them needs to make out proper process plan. The same situation occurs in process planning for component with form surfaces.

Components consisting of form surfaces are very hardly classified by their principal shape. Any of them represents definite design solution and that can be illustrated by four virtual forging pieces shown in Fig. 2.

a) b) c) d)

Fig. 2. Designed forging pieces for virtual analysis of manufacturing of form surfaces a) balance lever b) connecting rod c) covering plate d) fit flange

Fig. 2 indicates clearly that there are no unified signs of silhouettes of components designed, there only apparent similarity can be found out, for instance, profiles in cross sections and dimensions of holes, as well. Then the very similarities of individual design shapes are emerging from decomposing of designed components. Scope of decomposition is to create not only basic form surfaces, but also to find proper manufacturing strategy for them. In other word said, basic form surface have no definite dimensions, they determine options of available manufacturing by 3D milling.

Methodology of classifying of basic shapes of form surfaces has been developed which considers collocation of form surfaces within the framework of designed components. Methodology consisting of five distinctive marks is shown in Fig. 3.

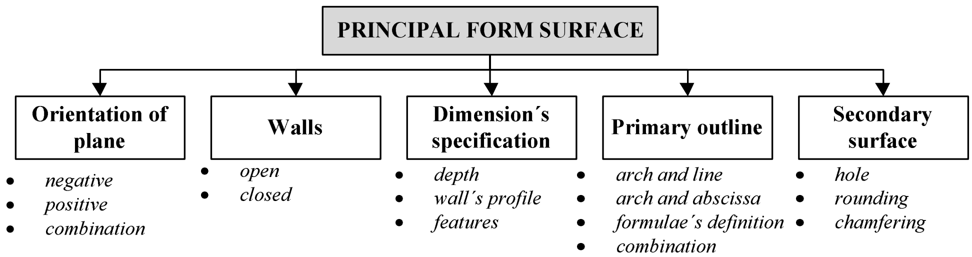


Fig. 3. Classifying of the basic shapes of form surfaces

Based on that methodology, five basic shapes were taken from designed engineering components in order to include principal form surfaces and their features by Fig. 3. Fig. 4 introduces such selection of basic shapes. If any definite dimension is being set into such basic shapes, manufacturability options can be analysed. Here one can distinguish the first feature, i.e. an orientation and that means rather any direction which origins from coordinates. In practice, it means of how final shape is being programmed. Wall represents a feature which can be either open or closed, and that is usually given in terms of any dimension, e.g. wall thickness. Considering specification of any dimension, it means, for instance any profile of wall. Primary outline of form surface gives comprehensive representation, and that are arch and line either, however, any mathematical expression can be allowed. Finally, the secondary surfaces appear in design of any form surface, and that are the elements, which cannot be excluded in any case. The simplest case is that any surface joins another chamfering or rounding, there are no rules which design has to be used but applied end mill cutters as rounded or chamfered.

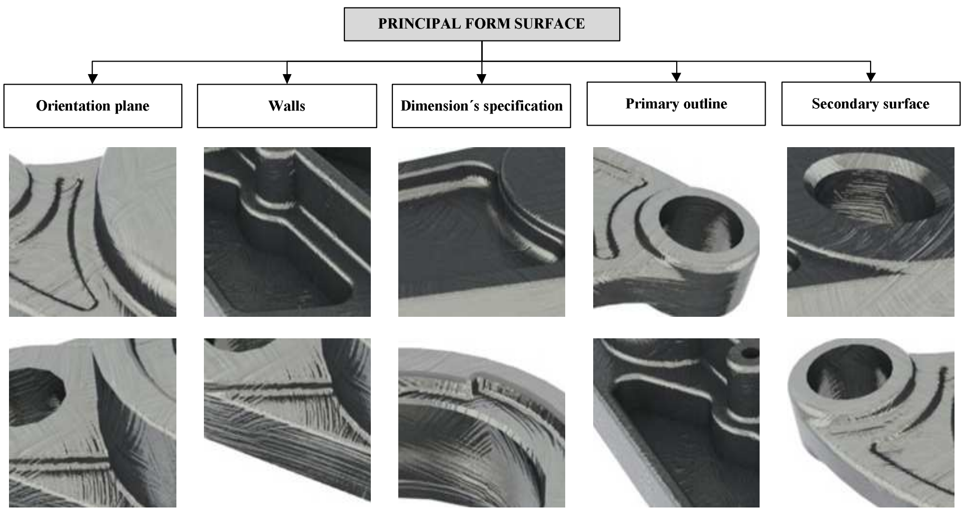


Fig. 4. Examples of basic surfaces taken from designed engineering components

5. Analysis of metal removal strategies to machine basic form surfaces

Many research results have shown that choice of any strategy of removal is characterised by three factors as cutting force, machining time and entire length of tool path as well. Data from [7] and [8] point out that final effect of milling of form surface depends on optimisation. Controlling the values of cutting forces, stresses and temperature in cutting zone, it is possible the decreasing of cutting parameters in the places where the admissible values are exceeded which significantly influences on the tool life. On the other hand, there is no generally accepted rule how to choose any strategy. Thus, there is a universal and widely applied removal strategy known either as "Constant Z" or as Contouring. Any milling operation is performed as layer – like removal, any layer starts to produce a part of "contour", and distance between "Constant Z " means depth of cut. It must be noted that "contour" starts to appear at a certain "level" while operations of roughing and semi – finishing leave defined allowance for final finishing by end – ball milling.

Many results and case studies associated with various CAM systems have shown that total machining time when milling with Constant Z strategy does not depend on depth of cut a_p (that is, in fact, the Constant Z). Machining time is affected chiefly by a way as the paths in the "Constant Z" strategy are being optimised. Such conclusion is valid for not only strategy mentioned above but also for such strategies a "spiral" and "circular" as has been proved in [7]. Otherwise, total machining time is affected by dimension of milling cutters applies as well as need for additional roughing and semi–finishing operations.

Studies related to the principal form surfaces can be found in [8] as milling of planar surfaces, walls and rounding. Roughing of cavities is analysed in [9] while [10] examines colliding points of milling cutter when machining negative surface orientation. Surface with definite curvature was used in [11] while [12] gives analysis of uniform and non uniform spacing of tool path at planar surface.

Strategies of milling tool motion when producing certain basic form surfaces was studied by means of SolidCAM software which is an upgrade of SolidWorks package. Upper and lower dies to produce fit flange shown in Fig. 2(d) were chosen to being divided into basic form surfaces defined in Fig. 2.

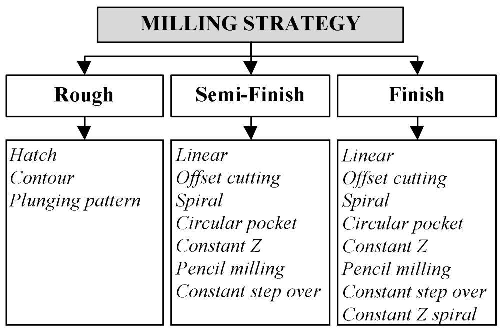


Fig. 5. Milling strategies from SolidCAM program

Milling strategies in Fig. 5 are applicable to produce any basic form surface located at any part of both forging dies shown in Fig. 6 and 7. Both semi-finished dies are supposed to include constant depth of cut a_p = 0,5 mm for finish cut is being assumed to analyse process planning.

Let combine milling strategies and classing of form surfaces in Fig. 2 According to machining plan in Fig. 6, semi-finished die is supposed to include four milling operations, orientation of planes is fully positive. The first operation refers to as milling surfaces with DIMENSION'S SPECIFICATION, i.e., three cylindrical features being set to datum surface. The second operation means PRIMARY OUTLINE as combination of arches and lines. The third operation is positive ORIENTATION OF PLANE; however, PRIMARY OUTLINE borders the former. The last operation, milling of dividing plane, in fact a datum surface and that is, in principle, the complement of the third operation, ORIENTATION OF PLANE.

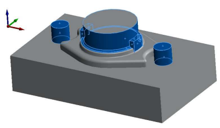
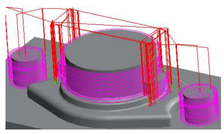
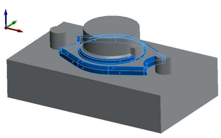
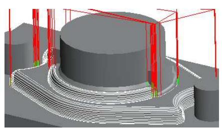
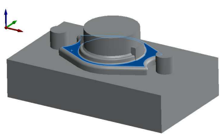
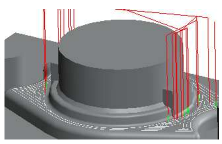
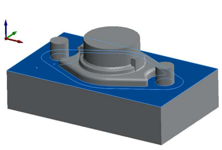
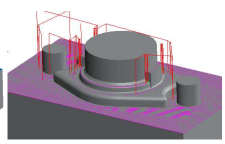
Selected zone	Detail of the toolpath	Cutting conditions	Milling strategy	Toolpath lenght
		END MILL Ø 3 mm ap: 0.5 mm Spin rate: 5000 rpm Feed XY: 100 mm.min^{-1} Feed Z: 33 mm.min^{-1} Time: 1:12:01	Constant step over	12623.72 mm
		BALL NOSE MILL Ø 3 mm ap: 0.5 mm Spin rate: 5000 rpm Feed XY: 100 mm.min^{-1} Feed Z: 33 mm.min^{-1} Time: 0:34:35	Constant Z	5861.20 mm
		BALL NOSE MILL Ø 3 mm ap: 0.5 mm Spin rate: 5000 rpm Feed XY: 100 mm.min^{-1} Feed Z: 33 mm.min^{-1} Time: 0:09:04	Constant Z	1689.32 mm
		END MILL Ø 3 mm ap: 0.5 mm Spin rate: 5000 rpm Feed XY: 100 mm.min^{-1} Feed Z: 33 mm.min^{-1} Time: 1:03:13	Constant Z	7510.29 mm

Fig. 6. Manufacturability analysis of the upper die to produce fit flange

Analysis of manufacturability of the lower die in Fig. 7 has been done within its cross section for lower die being involved negative orientation of the produced surfaces. With regard to Fig. 7, four operations of form surface milling are associated with following basic surfaces:

No 1: PRIMARY OUTLINE – arch and abscissa

No 2: FORMULAE'S DEFINITION – circle and abscissa

No 3: SECONDARY SURFACE – rounding
No 4: NEGATIVE ORIENTATION – datum surface and abscissa

6. Combination of milling strategies

In production of form surfaces as moulds, cavities, forging dies, etc., resultant surface quality is the main effort to achieve desired surface roughness. In order not to increase production costs by additional surface finishing operations, proper choice of milling cutters and cutting conditions play decisive role. Combination of milling strategies from Fig. 8 shows, how applied strategies can be combined when desired surface roughness is taken into account. Data from tool makings' recommendations in Table 1, which determine roughing and finishing cut are assumed in terms of analysis, i.e., surface finish within Ra = 1,5 – 2,5 μm and that is the range requiring nothing but manual polishing.

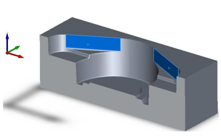
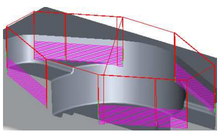
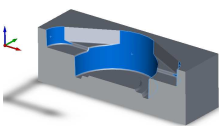
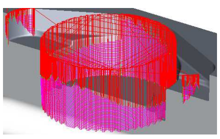
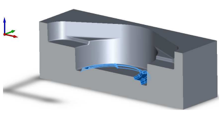
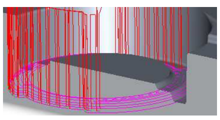
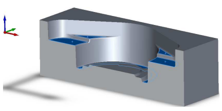
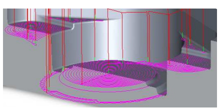
Selected zone	Detail of the toolpath	Cutting conditions		Milling strategy	Toolpath lenght
		BALL NOSE MILL ap: Spin rate: Feed XY: Feed Z: Time:	Ø 3 mm 0.5 mm 5000 rpm 100 mm.min^{-1} 33 mm.min^{-1} 0:24:56	Constant step over	6448.49 mm
		BALL NOSE MILL ap: Spin rate: Feed XY: Feed Z: Time:	Ø 3 mm 0.5 mm 5000 rpm 100 mm.min^{-1} 33 mm.min^{-1} 0:50:19	Circular pocket	14793.57 mm
		BALL NOSE MILL ap: Spin rate: Feed XY: Feed Z: Time:	Ø 3 mm 0.5 mm 5000 rpm 100 mm.min^{-1} 33 mm.min^{-1} 0:15:31	Constant Z	4601.73 mm
		END MILL ap: Spin rate: Feed XY: Feed Z: Time:	Ø 3 mm 0.5 mm 5000 rpm 100 mm.min^{-1} 33 mm.min^{-1} 0:28:58	Constant Z	4075.27 mm

Fig. 7. Manufacturability of the lower die

Fig. 8 indicates how milling strategies are combined to achieve surface finish within a range of mean arithmetic deviation. Strategy of roughing was chosen by machining time criterion – there are two different strategies of rough milling, contour and hatch. The former is capable of achieving minimum time for stock when stock removing from upper die. The latter makes possible the efficient removal of stock from upper die for leaving required machining allowance to perform finish cut. One can see in Fig. 8, there are similar strategies of finishing for quite different surfaces. However, virtual software analysis is not capable of exploring surface texture as such and that means experimental verification, e. g., [13] and [14].

Table 1. Cutting conditions applied in analysis

	Roughing	Finishing
Tool diameter	6 mm	3 mm
Flutes	4	2
Speed	60 m/min	87 m/min
Feed	0,015 mm/tooth	0,006 mm/tooth
Spin	3200 1/min	5000 1/min
Depth of cut	1 mm	0,5 mm
Width of cut	1,2 mm	0,6 mm

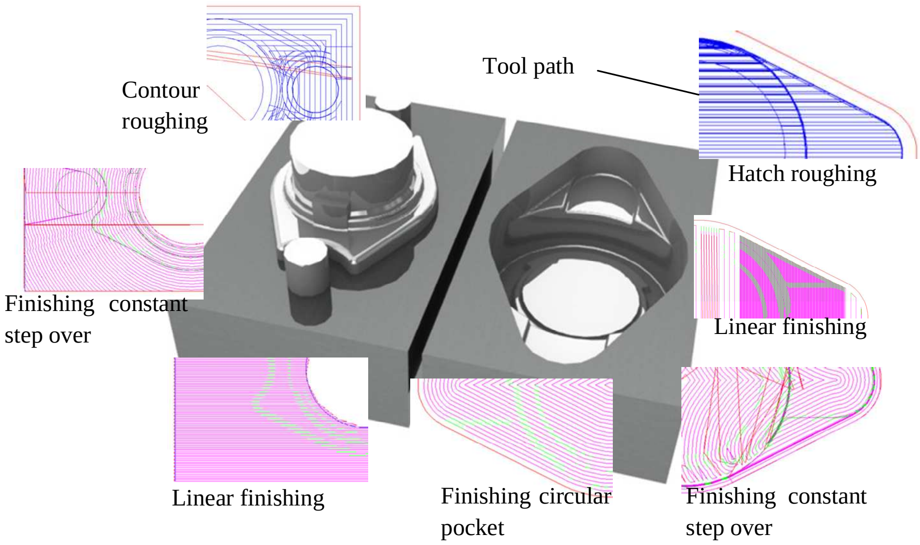


Fig. 8. Combination of milling strategies to achieve desired surface finish

7. Conclusion

Decomposition of produced engineering components into basic surfaces as well as assignment of milling strategy set to any basic surface seem to be another approach to the efficiency of form surface milling. Approach is expected to apply in process planning when produced more complicated components with cavities and sculptured surfaces. It has been shown that assignment of milling strategy set to any basic surface requires mainly proper definition of that surface in terms of object geometry. Further aspect is about how workpiece properties (i.e., microstructure, toughness, machinability, etc.) affect on performance of milling tools in both roughing and finishing cut. Because of known relationships between surface finish and entire tool path length in programming, definite trade-off between surface quality and machining time must be made for reduction of additional finishing operations is being permanently expected in making of tooling.

Acknowledgement

Presented results have been achieved within 1/0500/12 VEGA Project „Research on Quality Improvement when Milling Formed Surfaces by

Advanced Coated Tools"supported by Ministry of Education, Science, Research and Sports of Slovak Republic.

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