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Experimental Studies of an Algorithm for Minimizing the Idle Tool Moves when Milling Complex Surfaces on Triaxial CNC Machine Tools

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Abstract. **The idle running times of the working units of a machine tool are the sum of the idle running times for the tool change and for changing the section uder treatment. The time, spent on idle running is the extra machining time. A large number of milling cutters are used for purely mechanical machining of details with complex surfaces and for a significant number of machined sections, where the complex surface is broken as a rule. This leads to an increase in the extra time for treatment. Reducing the auxiliary time in machining the parts will significantly increase the productivity of the actual milling process. When modeling the process of machining details with complex surfaces on triaxial milling machines, the optimization of the sequence of moves will allow to reduce the idle running time by up to 50% without causing deterioration in the quality of the surface layer.**

In modern production a method is needed, which would allow to automatically and quickly enough make a choice of an optimal option for a sequence of performing tool moves while taking into account the durability of the metal cutting tool.

Keywords: pure/actual/finish milling, complex surfaces, CNC machine tool, optimization.

I. INTRODUCTION

This paper presents a fragment of a research, aimed at increasing the efficiency of triaxial CNC milling machines when milling parts with complex surfaces by reducing the auxiliary time for performing the individual operations, and more precisely by reducing the time for performing idle tool moves. The latter can be achieved, on the one hand, by minimizing the length of the idle tool moves when changing the machined section, and, on the other hand, by finding the most advantageous sequence for machining the sections.

In order to find an optimal route for all the selected tools of different sizes, it is necessary to determine the most profitable route for each cutter size, used to machine the sections, belonging to one group.

Based on a conducted literature review [1], [2], [3], [4], [5], [6], [7], [8], [9] a method is proposed for determining the optimal route of cutters of one size when moving among one group of sections subject to machining. The method is implemented in two stages:

- at the first stage, an option for minimizing the idle moves of the tool when changing the machined section is sought. The length of each pair of sections, included in a group, is checked. In doing so, it is necessary to determine the position of the local safety zone for every two consecutively processed sections [10];
- at the second stage, the most advantageous sequence for machining all the sections in a group is determined, taking into account both the tool life period and the minimum-length idle moves of the cutter, determined during the first stage.

To solve a problem, in which the number of machined sections is below ten, the so-called "Greedy algorithm" can be applied, which belongs to the group of the heuristic algorithms. When the number of machined sections is bigger than ten, the "Adaptive Large

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Neighborhood Search" (ALNS) can be applied to find the solution to the problem [11], [12], [13].

To implement the proposed methodology for minimizing the idle moves when milling details with complex surfaces, a programming module (PM) has been developed. The PM is a synthesis of two modules. The first one, PM1, implements the method of minimizing the idle moves when the tool passes from one machined section to another, while the second one, PM2, is based both on the program module PM1 and on the method of searching for the most advantageous milling sequence for all sections, belonging to the group under processing.

The working algorithm of the PM1 module is as it follows:

Step 1: Specifying the input data: coordinates of nodal points from the surface of the part; number of sections processed with cutters of one size; coordinates of the entry and exit points for each section processed with cutters of one size; shape and dimensions of the cutters; extra safety distance.

Step 2: Based on the input data, by means of programming, PM1 compiles a matrix with the minimum lengths of the idle moves during the transition of the tool from one machined section to the next, and the minimum height of tool lifting, guaranteeing the operation of the equipment without coming into contact with the workpiece.

The working algorithm of the PM2 module is the following:

Step 1: Entering the input data: data, obtained after the implementation of the PM1 module; cutting time when machining each of the sections; idle moves speed; tool life period; time, spent on changing the cutter.

Step 2: Based on the input data and using the means of the PM2 module, the optimal sequence of milling the sections, machined with one size milling cutters at a minimum length of the idle moves is determined.

II. MATERIALS AND METHODS

A. *Methodology for conducting the experiment*

The confirmation of the effectiveness of the proposed method for automatic determining of the sequence of execution of the technological transition during pure/finishing milling of parts with a complex shape on a triaxial CNC milling machine should be done by comparing results, obtained for the same details after applying a program module CAM of the Unigraphics system and the developed program module PM.

Test details need to be produced, following a compiled control program.

The results of both the virtual modeling and the physical realization of the machining process, which allow to determine the values of the machine time and the auxiliary time, including the time for idle moves and the time for tool change, should be presented in a tabular format. On the basis of the obtained data, an analysis should be carried out and corresponding conclusions drawn up.

The test details, obtained by milling, should be evaluated for compliance with the dimensions and the shape of the digital model, as well as for the quality of the resulting surface layer.

B. *Stages of conducting the experiment*

The experimental part of the study was conducted in several stages (Fig.1).

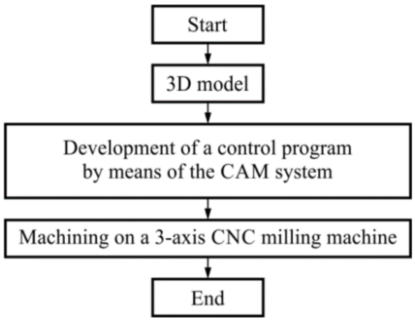


Fig. 1. Technological scheme for processing complex surfaces by milling, when using the Unigraphics system.

At the first stage, a selection of test details with surfaces of complex shape was made so that they include pieces, having biconvex and biconcave sections, as well as sections with a cylindrical, conical and spherical shape, with smooth transitions between them and with flat sections of the machined surface. When selecting the details, those were chosen, which have no less than 10 sections, and the sections can be machined by tail cylindrical cutters - flat face, spherical face and conical ones. In addition, the machining had to be carried out using a set of tools, comprising no less than three milling cutters of different sizes, made of the same material.

At the second stage, a 3D model of the test details was developed, using NX 11 Unigraphics.

The third stage consisted in developing a technology and a control program for processing the test details using the CAM module of the NX 11 Unigraphics system and the optimization options included in it.

At the fourth stage, a technology and control program for processing the test details was developed, this time using the CAM module of the NX 11 Unigraphics system, the optimization option, and the programing module (PM) for determining the sequence of machining and minimizing the idle moves when milling complex surfaces.

The program working algorithm is shown in Fig.2.

The first step is related to specifying the input data: coordinates of nodal points from the surface of the workpiece, coordinates of the starting and ending points of the idle tool moves, number of machined sections, cutting time for each machined section, idle moves speed, tool life period, cutter change time.

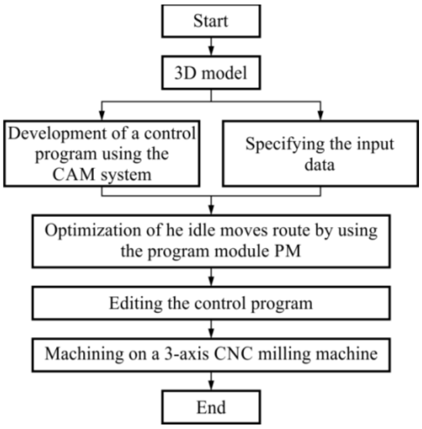


Fig. 2. Technological scheme for processing complex surfaces by milling, while using the developed PM.

Then, by using the PM, the sequence of processing the local sections is determined under the condition of minimizing the idle moves when passing from one machined section to another.

At the third stage of the algorithm, a process of editing the control program in accordance with the results, obtained from the previous stage, occurs.

The next stage consists in activities, related to the production of the test details. Their machining is carried out on a CNC vertical milling machine under the same modes, including cutting speed and feed rate for the same sections of the two test details with the same name, as well as the provision of tools with which the forming is carried out. The rough machining of the pair of parts is carried out by the same technology and control program, providing the same allowance for finish machining. The private cutting strategies (incision trajectory, cutting, and tool withdrawal) for the same sections of the details in purw/finish machining remain constant.

At the last stage of the experimental research, a check is made to assess the dimension accuracy of the pair of details and the microgeometry of the surface layer by using modern control and measuring devices.

III. RESULTS AND DISCUSSION

The experimental studies were carried out with a test detail, modeled by using NX 11 (Fig.3).

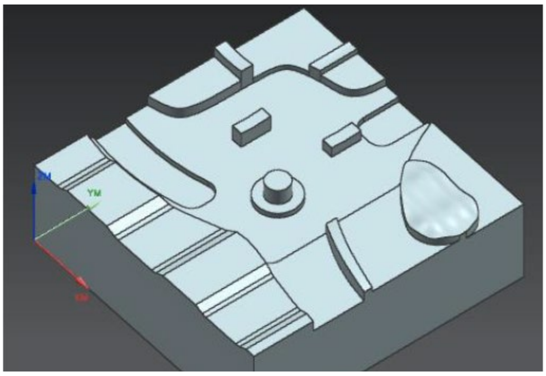


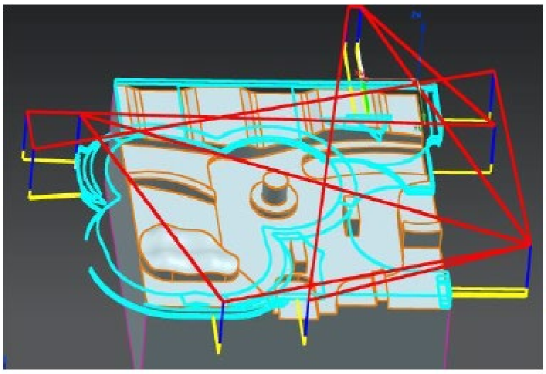
Fig. 3. 3D model of the test piece.

Details with dimensions 105 x 105 x 10 mm, made of B95 aluminum alloy, were selected for conducting the experiments.

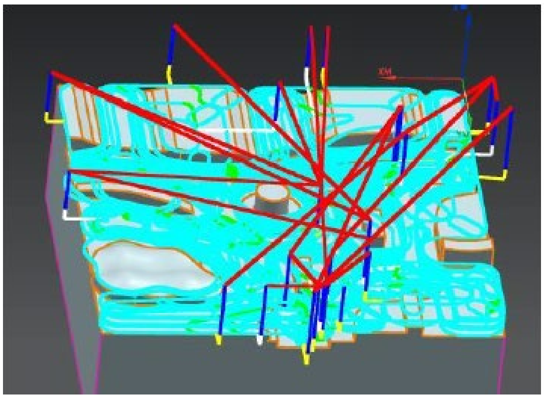
A. Detail processing technology

The mechanical processing of the details was done on a vertical milling machine DMS 635 V, produce of the Deckel Maho company.

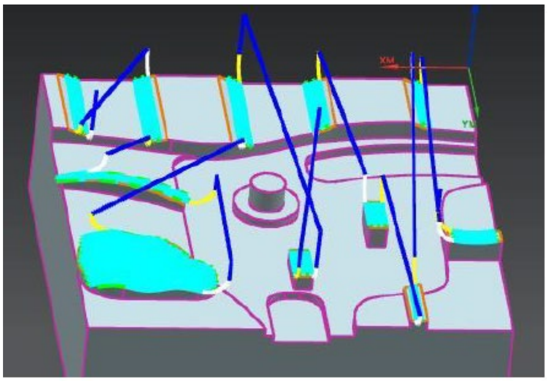
The basic rough milling was carried out initially with a 36 mm diameter flat face cylindrical cutter, then with a 10 mm diameter flat face cylindrical cutter and finally with a spherical face cylindrical cutter 10 mm in diameter (Fig.4). The dimension tolerance after roughing was 0.1mm, the allowance for finish milling - 0.5mm.



(a) flat face cylindrical cutter with D = 36 mm.



(b) flat face cylindrical cutter with D = 10 mm.



(c) spherical face cylindrical cutter with D = 10 mm.

Fig. 4. Path of tool moves during rough milling.

The depth of cut and the machining allowance for rough milling for a flat face cylindrical cutter with D = 36 mm was 2 mm and for the same type cutter with D = 10 mm it was 1.6 mm.

The parameters of the rough milling mode are presented in Table 1.

TABLE 1 CUTTING MODE PARAMETERS

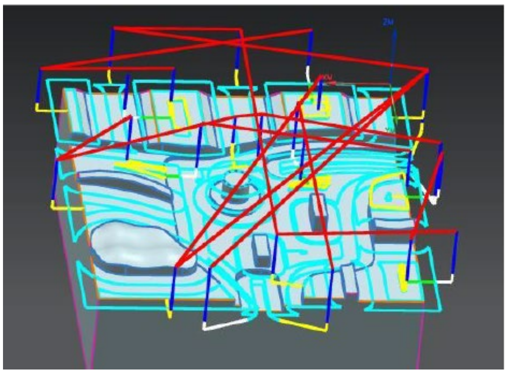
Cutter diameter D, mm	**Spindle rotation frequency n, min^{-1}**	**Tool feed rate V_f, mm/min**	**Cutting feed S_m, mm/min**
Cutting mode parameters in rough milling			
Flat face cylindrical, D = 36 mm	6200	3000	1800
Flat face cylindrical, D = 10 mm	9000	3000	2500
Spherical face cylindrical, D = 10 mm	9000	3000	1800
Cutting mode parameters in finish milling			
Flat face cylindrical, D = 10 mm	9000	3000	2500
Spherical face cylindrical, D = 10 mm	9000	3000	1800

The finish machining of the test details, which is the purpose of the study, was carried out in two ways. In the first case, the sequence of finish milling of the sections was determined by means of the NX 11 system (variant 1). In the second one, the sequence of finish milling of the sections was determined by using the PM optimization program module.

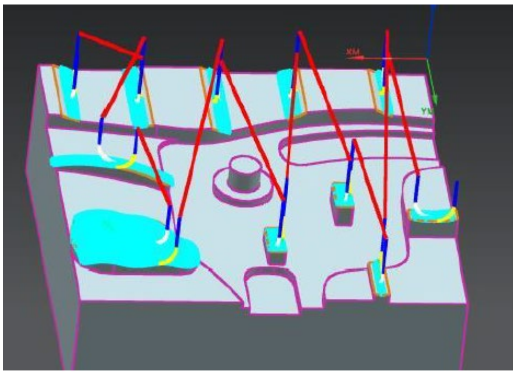
The parameters of the finish milling mode for both variants remained constant (Table 1). A 10 mm diameter four-tooth flat face cylindrical cutter, 10 mm in diameter, and a spherical face cylindrical cutter, 10 mm in diameter, were used for the experiments.

The strategy for finish machining by means of flat face cylindrical cutters with D =10 mm and spherical face cylindrical cutters with D=10 mm according to variant 1 (without optimization) is presented in Fig.5.

The number of individual sections machined by means of a flat face cylindrical cutter with 10 mm diameter and a spherical face cylindrical cutter with 10 mm diameter, is presented in Table 2.



(a) flat face cylindrical cutter with D = 10 mm.



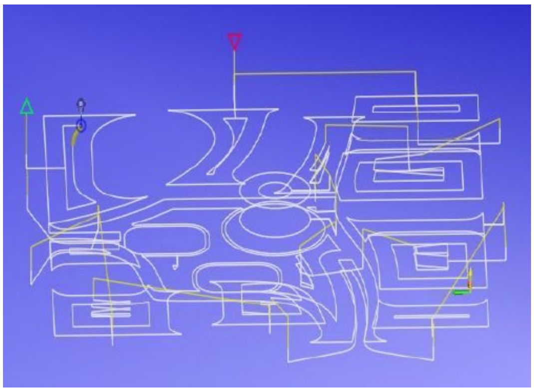
(b) spherical face cylindrical cutter with D = 10 mm

Fig. 5. Path of tool moves during finish milling of a test detail according to variant 1 (without optimization).

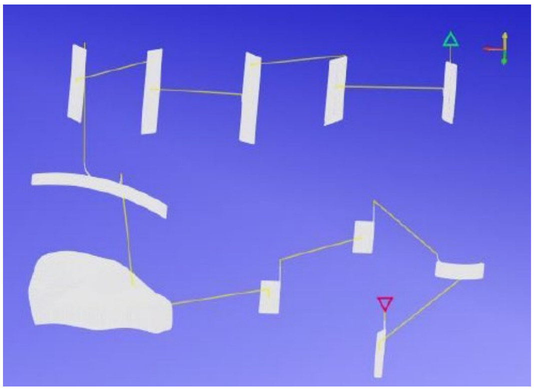
TABLE 2 NUMBER OF SECTIONS, MACHINED WITH CUTTERS OF ONE SIZE

Cutter	**Number of sections, machined with cutters of one size**
Flat face cylindrical, D = 10 mm	17
Spherical face cylindrical, D = 10 mm	11

The finish machining strategy, realized by means of a flat face cylindrical cutter with diameter of 10 mm, and by a spherical face cylindrical cutter 10 mm in diameter, according to variant 2 (with optimization), is presented in Fig.6.



(a) flat face cylindrical cutter with D = 10 mm.



(b) spherical face cylindrical cutter with D = 10 mm.

Fig. 6. Trajectory of tool movement during finish milling of a test detail according to variant 2 (with optimization).

Tables 3 present the results of the calculations obtained when preparing the control program for processing the test details based on the NX 11 system without using the optimization program module PM (variant 1), as well as the computational data, obtained by means of the algorithm, which allows to optimize the auxiliary time of idle tool moves when milling complex surfaces on triaxial CNC milling machines (variant 2).

TABLE 3 RESULTS OF THE CALCULATIONS OBTAINED WHEN PREPARING THE CONTROL PROGRAM

Cutter	Variant of machining	
	1	2
Total length of the auxiliary moves L, mm		
Flat face cylindrical, D = 10 mm	2665,8	1484,47
Spherical face cylindrical, D = 10 mm	1768,1315	1287,48
Total time, spent on performing the auxiliary moves T_a, min		
Flat face cylindrical, D = 10 mm	00.00.53	00.00.29
Spherical face cylindrical, D = 10 mm	00.00.35	00.00.25
Total time, spent on perfoming the working moves T_o, min		
Flat face cylindrical, D = 10 mm	00.02.14	00.01.50
Spherical face cylindrical, D = 10 mm	00.06.05	00.05.55

B. Determination and comparison of the roughness parameters

A Form Talysurf i200 profilometer was used to determine and compare the surface roughness parameters of the test details, processed on a triaxial CNC milling machine. Measurements were carried out to determine the roughness parameters of the surfaces of each section, depending on the dimensions of the section along a certain route. The speed of the probe was 1 mm/s. As a result, average values of the roughness parameters were obtained for each measured section.

The determination of the roughness parameters was made for 28 sections (Fig.7) in accordance with the number of sections to be machined, differing in shape and size.

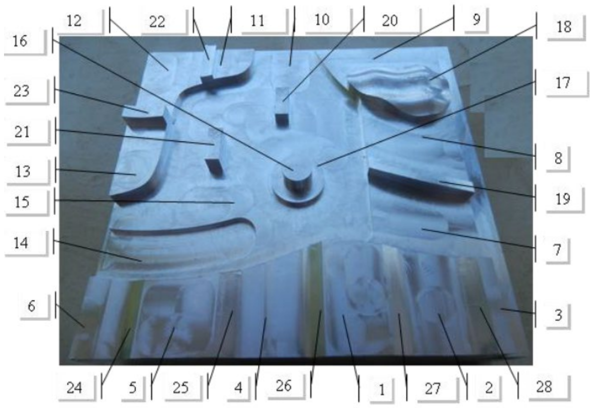


Fig. 7. The sections of the detail.

The results of the measurements are presented in Table 4.

TABLE 4 ROUGHNESS PARAMETERS RA OF THE SECTIONS OF A DETAIL

Section №	Roughness parameters Ra of the surfaces of the details (μm)	
	Variant with optimization	*Variant without optimization*
1	0.2570	0.2268
2	0.4257	0.4085
3	0.2975	0.3265
4	0.3054	0.3047
5	0.2697	0.2309
…	…	…
25	0.0728	0.0774
26	0.0819	0.0906
27	0.0680	0.0890
28	0.0841	0.0674

To compare the roughness parameters of the sections of the surfaces of the details, a graphical dependence was drawn, juxtaposing these parameters for the variant with and the variant without optimization (Fig. 8).

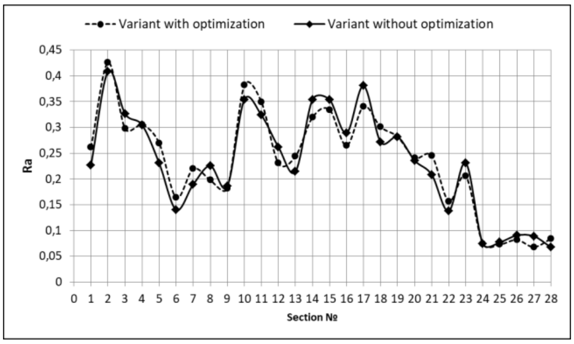


Fig. 8. Graphical dependence, presenting the deviation of the roughness parameters of the detail surfaces.

From the graphical dependence, presented in Fig.8 and the data in Table 4, it can be seen, that the deviations of the roughness parameters of the detail surfaces for the corresponding sections, machined by following the program module PM and without its use, are within the limits of the measurement error. The roughness parameter R_a for the machined sections is different and varies from 0.05 to 0.4 μm, which is explained by the different cutting trajectories and the specific cutting strategies planned within the technological process for machining each section.

As a conclusion it can be said that the change in the sequence of machining the sections at an unchanged specific strategy for machining each section does not lead to deterioration in the surface quality of the machined detail.

C. Determination and comparison of the deviation in shape and size of the test samples from the digital models

A Contura G2 Carl Zeiss coordinate measuring machine was used to determine and compare the deviations from the dimensions and the shape of the test details, machined on a triaxial CNC milling machine. In order to provide the same metrological conditions, the measurements were carried out in the same points on the surfaces of the controlled details.

The accuracy of measurement is determined by the technical capabilities of the coordinate measuring machine, i.e., is 0.001 mm. The measurement results, obtained in digital form, were imported into the automated control system for comparison with the digital reference of the test detail and determination of the deviations [15]. To compare the parameters of deviation in shape of sections of the details' surfaces, a graph was drawn, presenting the deviations of their points for the two variants of processing - with using the program module PM and without it (Fig.9).

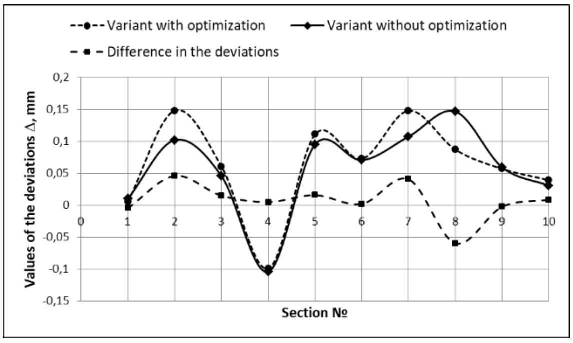


Fig. 9. Deviation in shape in points on the surface of a detail, processed both ways.

The results, obtained after comparing the deviations of the test details in shape and size from the digital model, show that the difference of the deviation parameters Δ in the points of carrying out the measurements is within the limits of the tolerance field. This is confirmed by the fact that the change in the sequence of machining sections of complex surfaces and the application of the program module PM in order to optimize the idle tool moves preserve the accuracy of the complex surfaces of details, processed by milling.

IV. CONCLUSIONS

The obtained experimental data allow to conclude that the application of the program module PM to optimize the idle moves of the machine when processing complex surfaces, allows to ensure high quality of the microgeometry of the detail surface and accuracy of machining, while reducing the total machine time for processing a detail.

The greatest effect of applying the program module can be obtained for details, containing 10 or more sections to be machined.

In the calculations, the joint application of mathematical models for minimization of the idle moves in case of changing the machined sections and optimization of the sequence of machining of the individual sections, allows to obtain the most advantageous tool route when machining the individual sections with cutters of one size. The auxiliary time, spent on the idle moves when changing the milling cutter and changing the machined sections is minimized at the same time.

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