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Algorithm for Optimization of Idle Tool Moves when Milling Complex Surfaces on a Triaxial CNC Milling Machine

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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.**

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

I. INTRODUCTION

When making parts with a complex shape on CNC milling machines the longest technological process is the finish machining. As it is known, the trajectory of movement of the tools used in this type of processing includes cutting moves and idle moves.

The idle moves of the machine working units are in fact the sum of the idle moves for changing the milling cutter and changing the section to be machined. A large number of milling cutters are used for finishing details with complex shapes 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.

It follows from the above that the productivity of the process of finish machining on triaxial CNC milling machines can be increased, on the one hand, by reducing the cutting time, and, on the other hand, by reducing the time, spent on performing idle moves.

A number of researchers have dedicated their works [1], [2], [3], [4], [5] to defining the parameters and strategies for milling each individual section, to rational breakage of the complex surfaces into separate structural and technological sections, to selection of milling cutters of a certain size for processing each individual section, to finding and presenting methods and algorithms, allowing to optimize the process and reduce the cutting time. Positive results are thus obtained and the problem for minimizing the cutting time has been solved.

The auxiliary time optimization problem has not received much attention so far. The sequence of processing the individual sections and the sequence of tool change is determined by the technologist based on personal experience, without applying modern modeling and optimization methods. The number of options for performing the tool moves is often significant, however. Hence the choice of an optimal variant based on an exhaustive analysis of the consequences from the particular choice is impossible without the use of specific algorithms and means of programming.

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All mentioned above determines the relevance of the present study. 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 time, spent on performing idle moves.

A number of studies of university and scientific laboratories in Austria, Great Britain, Russia, USA, Ukraine, Germany have been devoted to the choice of specific processing strategies [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18]. Papers [1], [3], [4], and [16] present results from conducting a study and implementing a developed theory of optimization of the strategy for forming complex surfaces (optimal path of the milling cutter) on a triaxial CNC milling machine. The task of dividing the surfaces into sections and choosing tools for their shaping is solved in the works [1], [2], [10], [19].

As a result of the optimization of the specific processing strategies, the sections to be machined are defined, including: their boundaries, the tools and their geometry, the path of tool moves during machining, and, as a final result, the coordinates of the starting points, and the trajectory of tool incision and withdrawal.

The length of the idle-running tool moves differs significantly for the different sequences of transition from one machined section to another. Moreover, the guaranteed run time of each tool is limited by its service life, which results in additional increase in the duration of the idle running due to the need of changing the tools to guarantee the required surface quality. In this regard, to reduce the tool change time, it is necessary to minimize the number of milling cutters used to shape the sections of complex surfaces while maximizing their resource utilization.

It follows from this that the task of optimization of the general machining strategy is a search for the most profitable option, in which the idle moves during the tool passage from one section to another and during the tool change will lead to a minimum time consumption, while taking into account the minimum length of the idle tool moves from one section to another without changing the tool.

II. MATERIALS AND METHODS

The study is aimed at the following:

- Type of equipment – a triaxial CNC milling machine, most frequently used in practice;
- Type of machining – finish milling, providing the required quality of the machined surfaces. The required quality is achieved by using low speed of idle running to reduce the influence of the dynamic error, which, in turn, results in increasing the auxiliary time. Under the high quality requirements in finish machinng and limited service life of the milling cutters, regular changes of the tool typically occur. This leads to an increase in the additional time for performing idle running moves by the machine nodes;
- Tool type – tail milling cutters – flat face cylindrical, spherical face cylindrical and conical ones, all of which intended for machining complex surfaces and widely used in practice;
- Speed of idle-running moves when machining the sections by one size tool – a constant for all idle moves of the same size cutters. This assumption provides simplification in calculating the auxiliary time, and the change in the idle running tool speed by magnitude and direction has insignificant influence on the additional time;
- A guaranteed life span of the tool – in the the event of a finishing type of milling it is assumed to be the same for all cutters of one size. When processing different sections, the wear rate of the cutters of one size may be different. However, under the same cutting conditions, the tool life period of the milling cutters of one size can be assumed to be equal.

The movement of the milling cutter from one section to another and the movement for its change can be represented schematically (Fig.1).

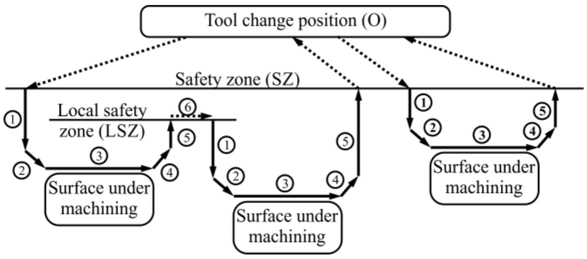

Fig. 1. Scheme of the milling cutter movement during pure machining of surfaces on a triaxial CNC machine.

The safety zone (SZ) is located at a height, greater than the highest section of the part geometry, and the local safety zone (LSP) is between two sequentially machined sections. The additional passage 1 serves to bring the cutter with an increased feed speed $V_{f\ ff}$ (fast feed) from the safety zone to the point of starting the cut. The cutting movement 2 serves to move the cutter from the ending cutting point to its starting point at a speed $V_{f\ sp}$. The cutting movement 3 is carried out at the speed of the working move $V_{f\ wm}$, during which the cutter comes into contact with the surface of the workpiece. The movement for tool withdrawal 4 serves to move the milling cutter from the ending point to the starting point to bring the tool back at a speed of the working move $V_{f\ wm}$. The return movement of the tool 5 is a movement of the cutter with an increased feed speed $V_{f\ ff}$ from the ending point of withdrawal 4 to the SZ or the LSZ. The transition (idle move) 6 is a rapid horizontal movement of the milling cutter at a speed of $V_{f\ ff}$ from the ending point of withdrawal of the milling cutter 5 to the starting point of the next transition 1.

The idle moves with an increased feed speed take place when the tool moves from the ending point of its withdrawal to the point for its change O, and if there is a need of changing the milling cutter - during the movement from point O to the starting point of incision and during movement from the ending point of tool withdrawal to the starting point of its incision into the workpiece to machine the next section.

Determining such a route of cutter moves, in which the length of the idle moves will have a minimum value, will allow to optimize the auxiliary time and significantly increase the productivity of the machining process and reduce the total machining time.

The operating time for machining T_o is obtained by summing the basic and the auxiliary time and can be determined by the formula:

$$T_o = \sum_{k=1}^{p} T_{b\,k} + \sum_{i=1}^{q} T_{a\,i}\,, \qquad (2)$$

where T_{bk} is the basic time for performing the k^{th} technological transition; p – the number of technological transitions; T_{ai} – the auxiliary time for performing the i^{th} auxiliary transition; q – the number of the auxiliary transitions;

The auxiliary time T_{ai} for performing the i^{th} transition within the technological process when there is a need for changing the cutter (this includes indexing the tool magazine, transporting the tool from the magazine to the point of change, feeding it to the starting point of the section to be machined and withdrawing it from the ending point of the trajectory to the point for its change) is accepted to be calculated by the formula:

$$T_{a\,i} = T_{cch} + T_{im\,i} + \frac{l_{i0} + l_{0i}}{V_{f\,ff}}\,, \qquad (3)$$

where T_{cch} is the time, spent on the cutter change; $T_{im\,i}$ – time for indexing the magazine, related to the sequence of arrangement of the cutters in it and the sequence of execution of the operations within the technological process; l_{i0} – length of the idle move from the ending point of the processed section to the tool change point; l_{0i} – length of the idle move from the tool change point to the starting point of the i^{th} section for machining; $V_{f\,ff}$ – rate at which the idle (fast) move is performed.

The length l_{0i} includes the length of the idle move from the cutter change point O to the safety zone SZ and the length of the auxiliary transition for feeding the cutter 1. The length l_{i0} includes the length of the auxiliary transition for returning the cutter from the ending point of its withdrawal to the safe zone SZ 5 and the length of the idle move from the safe zone SZ to the point for changing the milling cutter O (Fig.1).

The auxiliary time $T_{a\,i}$ for performing the i^{th} transition for changing the machined sections during the technological process is determined by the expression:

$$T_{a\,i} = \frac{l_i}{V_{f\,ff}}\,, \qquad (4)$$

where l_i is the length of the idle move, which includes the tool movement from the ending point of one machined section to the starting point of the next machined section.

The length of the idle move l_i is determined by the distance traveled by the milling cutter from the ending point of its withdrawal from the machined section to the local safe zone 5, and the length of the transition 6 and the length of feeding the milling cutter for machining the next section 1.

Taking this into account, the auxiliary time T_a can be determined from the dependence:

$$T_a = \sum_{i=1}^{q} T_{a\,i} = \sum_{j=1}^{n} (T_{cch} + T_{im\,i} + \frac{l_{i0} + l_{0i}}{V}) + \sum_{i=1}^{m} \frac{l_i}{V_{f\,ff}}\,, \qquad (5)$$

where n + m = q; n is the number of technological transitions for changing the cutter; m – the number of technological transitions for changing the machined sections.

It follows from formula (5) that the change in the sequence of machining the individual sections is accompanied by a change in the auxiliary time value.

In order to increase the productivity when machining complex workpiece surfaces by milling, the transition of the tool from one machined section to another and to the machine tool magazine for its change, should be done following the shortest route. When moving the tool along such a trajectory, the auxiliary time, spent on idle moves, should be minimum. The technological process should be realized with a minimum number of tools used and with minimum idle tool moves from one machined section to another. It should also be taken into account that when milling complex surfaces, the starting point of the cut does not coincide with the point of the tool withdrawal, and that the movement along the entire route should be carried out with a minimum number of idle moves. At the same time, the tool life period should also be taken into consideration (Fig.2).

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 cutters of each size, used to machine sections, belonging to one group.

Based on the conducted research, an algorithm is proposed for determining the optimal route of milling cutters of one size when moving between a group of sections subject to machining (Fig. 3).

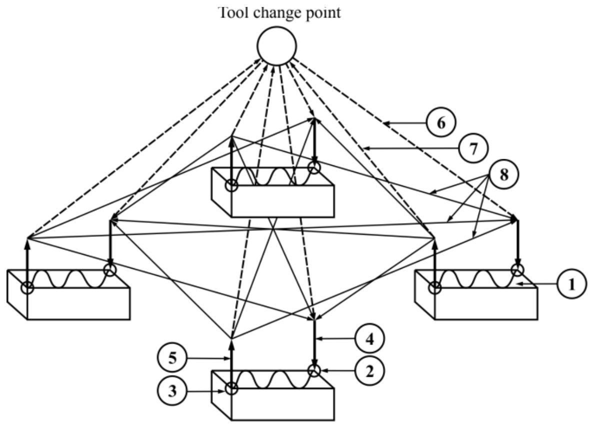

Fig. 2. Graph of the possible variants for a sequence of machining the individual sections.

1 – machined surface; 2 – point of incision of the tool; 3 – tool withdrawal point; 4 – auxiliary transition; 5 – auxiliary transition; 6 – movement of the milling cutter from the tool change point to the starting point of the machined section (fast run); 7 – movement of the milling cutter from the ending point of processing the section to the tool change point (fast run); 8 – idle tool move between two machined surfaces

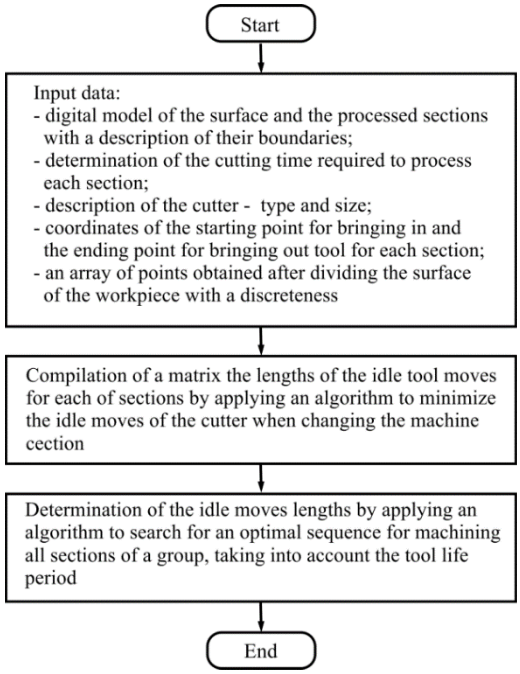

Fig. 3. Basic stages of solving the task to optimize the tool idle moves when milling complex surfaces.

The algorithm is implemented in two stages.

At the first stage, an option is sought to minimize the idle running of the tool when changing the machined section. The length of each pair of sections entering a group is checked. In doing so, it is necessary to determine the position of the local safe zone for every two consecutively machined sections.

The length l_i of the i[th] idle tool move from the ending point T_1 with coordinates (x_{i1}, y_{i1}, z_{i1}) of the tool withdrawal from the i[th] machined section to the starting point T_2 of incision into the next section with coordinates (x_{i2}, y_{i2}, z_{i2}) is determined by the formula:

$$l_i = 2z_{sz} - z_{i1} - z_{i2} + \sqrt{(x_{i1} - x_{i2})^2 + (y_{i1} - y_{i2})^2}\ , \quad (6)$$

where z_{SZ} is the height at which the local safety zone lies.

It follows from here that l_i will have a minimum value when z_{sz} is minimum, i.e. $z_{sz} \to \min \Rightarrow l_i \to \min$.

The minimum value of l_i can be determined from the dependence:

$$l_{i\,\min} = 2z_{sz\,\min} - z_{i1} - z_{i2} + \sqrt{(x_{i1} - x_{i2})^2 + (y_{i1} - y_{i2})^2}\ . \quad (7)$$

The minimum height of the local safe zone z_{sz} is equal to the sum of three parameters: the height z_t, at which the milling cutter during its movement touches the controlled geometry of the workpiece; the allowance a, and the reserve height h_r:

$$z_{sz\,\min} = z_t + a + h_r\,. \quad (8)$$

Cluster analysis of the model was used to determine z_t. A feature of this method is breaking the digital model of the detail into clusters (array of points with coordinates x, y, z). The coordinates of these points can be obtained from the CAD system (e.g., Unigraphics).

The cluster analysis when solving the problem of determining z_t is carried out in stages:

- Determination of the points, belonging to the controlled geometry, and forming of the set U;
- Determination of a coordinate z_{tj}, describing the local safe zone, at which the milling cutter touches points, belonging to the set U, at the j[th] height during its movement in the direction of tt′;
- Determination of the maximum value from the set $\{ z_{tj} \}$, which represents the height z_t, at which the cutter touches the controlled geometry of the digital 3D model when describing the movement of the cutter along the direction tt′.

A detailed description of the developed mathematical model is presented in the work [20]. Its application results in a set of minimum values of the cutter idle run lengths when modeling all transitions from one section to another.

During the second stage, the most advantageous sequence for machining all the sections of one group is determined, taking into account the milling cutter life period and the minimum length of idle moves of the cutter determined within the first stage.

Finding a solution to the problem of searching for a minimum length of the idle moves during the tool transitions between two sections while considering the geometry of the workpiece and the task to optimize the sequence of performing the tool transitions is possible when using the well known approaches to solving vehicle routing problems for shipment.

A problem of this type can be solved in two ways: exact and approximate.

The exact method is applicable and gives an optimal solution when the machined sections are a small number.

The approximate method of finding a solution is applied in the case of a large number of machined sections. When applying it, the obtained solution approaches the optimal one.

To solve a problem, in which the number of the machined sections is less than ten, the so-called "Greedy algorithm" [21], [22], [23], [24], [25] can be applied, which belongs to the heuristic algorithms "Adaptive Large Neighborhood Search" (ALNS) [26], [27], [28], [29], [30]. The ALNS can be used to solve a problem with a number of machined sections more than ten.

III. RESULTS AND DISCUSSION

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 program working algorithm is shown in Fig.4.

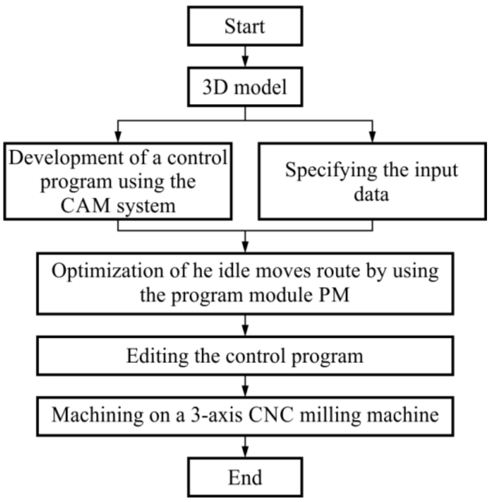

Fig. 4. Technological scheme for processing complex surfaces by milling, while using the developed PM.

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.

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.

The experimental studies were carried out with a test detail, modeled by using NX 11 (Fig.5).

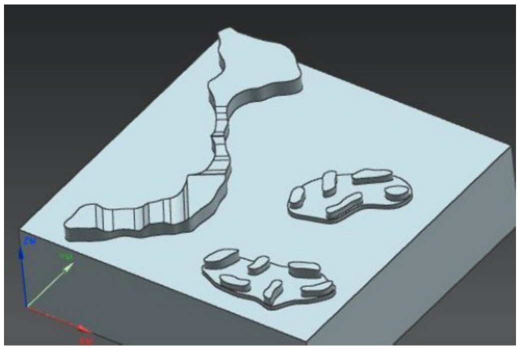

Fig. 5. 3D model of the test piece.

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

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, then with a 4 mm diameter flat face cylindrical cutter and finally with a spherical face cylindrical cutter 10 mm in diameter. The dimension tolerance after roughing was 0.1mm, the allowance for finish milling - 0.5mm.

The depth of cut and the machining allowance for rough milling for a flat face cylindrical cutter with D = 36 mm was 2 mm, for the same type cutter with D = 10 mm it was 1.6 mm and for the same type cutter with D = 4 mm it was 1.2 mm.

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

TABLE 1
CUTTING MODE PARAMETERS IN ROUGH MILLING

Cutter diameter D, mm	Spindle rotation frequency n, min^{-1}	Tool feed rate V_f, mm/min	Cutting feed S_m, mm/min
Flat face cylindrical, D = 36 mm	***Rough milling***		
	6200	3000	1800
Flat face cylindrical, D = 10 mm	***Rough and finish milling***		
	9000	3000	2500
Flat face cylindrical, D = 4 mm	***Rough and finish milling***		
	9000	3000	800
Spherical face cylindrical, D = 10 mm	***Rough and finish milling***		
	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 (variant 2), 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).

The number of individual sections machined using the different cutters is presented in Table 2.

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	6
Flat face cylindrical, D = 4 mm	8
Spherical face cylindrical, D = 10 mm	18

From the table, it can be seen that the number of sections machined with Flat face cylindrical, D = 10 mm and Flat face cylindrical, D = 4 mm are less than 10. Therefore, the strategy for determining the machining sequence of these sections is by optional 1, i.e. without optimization.

As a result of the finish machining of the surfaces by means of the specified cutters, the details presented in Fig.6, were obtained.

(a) detail 1 after finish milling by the variant without optimization

(b) detail 2 after finish milling by the variant with optimization

Fig. 6. Test details after finish milling.

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 WEEN PREPARING THE CONTROL PROGRAM

Cutter	Variant of machining	
	1	2
Total length of the auxiliary moves L, mm		
Spherical face cylindrical, D = 10 mm	1823,27	1277,94
Total time, spent on performing the auxiliary moves T_a, min		
Spherical face cylindrical, D = 10 mm	00.00.36	00.00.26
Total time, spent on perfoming the working moves T_o, min		
Spherical face cylindrical, D = 10 mm	00.02.35	00.02.25

From the results in the table, it can be seen that even if some of the surfaces are not treated with the variant with optimization, they are reduced total length of the auxiliary moves L, total time, spent on performing the auxiliary moves T_a and total time, spent on perfoming the working moves T_o .

Based on the algorithm and the mathematical apparatus, a programming module (PM) has been developed to optimize the sequence of performing the technological transitions. The PM has been tested in practice and its performance in solving problems for minimizing the idle tool moves when machining complex surfaces by milling on CNC machines has been confirmed.

IV. CONCLUSIONS

The efficiency of the cutting tool route, which takes into account the mutual interests of all participants in the system, is taken as a criterion for optimizing the general strategy for mechanical processing, which means: minimum number of tools used, minimum length of idle moves during tool transitions between successively machined sections, minimum length of the idle moves when the most profitable complete tool route between all machined sections has been found.

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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