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Determination of optimal coordinates for switching processing cycles on metal-cutting machines

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ABSTRACT

Introduction. One of the ways to improve the efficiency of processing on machines is to coordinate the CNC program with the changing properties of the dynamic cutting system. If this takes into account the tool wear and the associated with it changes in the parameters of the dynamic cutting system, then the cutting speed to ensure the minimum wear rate is reduced along the cutting path. The corresponding feed rate is reduced even faster, since it is necessary to ensure a constant deformation displacement of the tool relative to the workpiece. The evolution of the properties of the cutting process (for matching with which the trajectories of the operating elements of the machine are corrected) depends on the power of irreversible transformations of the energy supplied to cutting. This reduces the processing efficiency. Therefore, a new for the considered subject area problem of determining the coordinates of the tool movement relative to the workpiece is formulated, starting from which further processing is economically inexpedient. In this case, it is necessary, after processing the next part, to ensure the replacement of the tool and carry out its changeover. **Subject.** A metal-cutting machine of a turning group, the trajectories of the executive elements of which are controlled, for example, by a CNC system. **The purpose of the work.** Mathematical simulation and methods for determining the coordinates at which it is necessary to replace the tool. **Method and methodology**. The necessary conditions for the optimality of determining these coordinates are proved. Mathematical tools are provided that allow calculating the coordinates at which the given manufacturing costs take the minimum value according to the given trajectories. The probabilistic characteristics of evolutionary trajectories are taken into account. **Results and discussions.** The analysis of the efficiency of using the technique in industry depending on the cost of the machine and tool together with its replacement and readjustment is given. The proven optimality conditions and the given mathematical tools complement the knowledge about the optimization of controlled machining processes on machines. **Conclusions.** The results of the study show new options for the organization of tool replacement, aimed at improving the efficiency of processing by software methods using a CNC system.

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Introduction

After the publication of works [1, 2], many problems of various systems dynamics interacting with different environments began to be considered with the view of their evolutionary changes and self-organization [3–7]. The paper [3] showed that synergetic coordination of external control with the

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internal dynamics of the controlled system is effective for managing complex interconnected systems. Concerning machine tools processing, this principle means coordination of the machine's executive units trajectories (MEUT) with a dynamic cutting system (DCS) [8–10], whose properties change depending on the development of the cutting tool wear and the produced power in the cutting zone [8–14]. Two circumstances are taken into account. Firstly, the properties of DCS change depending on the wear of the tool and the energy supplied to cutting [8–10]; secondly, evolutionary changes lead not only to a dynamic restructuring of the cutting properties but also change the technological modes with minimal tool wear intensity. The geometric topology of the workpiece surface also changes. These changes follow, first of all, from the thermodynamic nature of wear and the dependence of the wear rate on the energy of the mechanical system introduced into the cutting zone [18–24]. Such features of the cutting process led to the creation of a different class of processing control systems on metal-cutting machines [25–34]. For example, if the choice of the optimal cutting speed relies on the optimal temperature in the contact zone of the tool's planes with the workpiece, the optimal power of the energy consumed in the cutting zone should correspond to the optimal temperature. Consequently, a monotonous decrease in the cutting speed should correspond to ensuring optimal power as wear develops. Besides, to stabilize elastic deformations the feed rate should decrease, i.e. the feed rate should decrease even faster along the cutting path [8–10]. A MEUT decrease along the cutting path leads to the fact that further processing at low cutting speeds and feeds becomes impractical. Therefore, a new problem is formulated to determine the coordinates in which the tool needs to be replaced; this problem is close to the synthesis of optimal performance systems, which is solved, for example, based on using the L. Pontriagin maximum principle. [35, 36]. A similar problem was solved by the authors for drilling deep holes of small diameter [37]. However, in the case of processing, it has certain features the article deals with. The purpose of the article is to develop mathematical algorithms and techniques that allow determining these coordinates.

Research Methodology

Mathematical formulation

We will limit ourselves to the consideration of longitudinal turning on lathes. The obtained results can be easily generalized to other types of processing: milling, drilling, including drilling deep holes [37]. The paths are set: the general path of the tooltip movement L, which is determined by the sum (Fig. 1)

$$L = \sum_{i=1}^{i=n} l_i \, . \tag{1}$$

The path L is the same for a batch of workpieces. We set the task of determining the coordinates $l^{(i)}$ along the tool movement trajectory L ($l^{(1)} = l_1$, $l^{(2)} = l_1 + l_2$, $l^{(3)} = l_1 + l_2 + l_3, \ldots l^{(n-1)} = L - l_n$), at which the cost of manufacturing a batch of parts is minimal. They are determined by the costs for the actual cutting and the replacement of the tool and its changeover. Additionally, along the trajectory, there are set speeds $V_i(l)$ that change depending on the current wear of the tool. Initial speed value $V_0 = \text{const}$. The trajectory of the cutting speed $V_{\text{p}}^{(i)}(l_i)$ along the path is calculated in such a way that the wear intensity of the tool is minimal [10]. The calculation method is based on the hypothesis that the wear intensity is related to the power of irreversible energy transformations. The optimal power corresponds to the optimal temperature; this is the transition region from the prevailing adhesive to diffusion wear of the tool [7, 24]. The speed $V_{\text{p}}^{(i)}(l_i)$ corresponds to the feed $V_i(l)$ rate, which is limited by the value that affects surface roughness formed by cutting. However, the feed rate must be reduced in the course of evolution due to tool wear and the associated increase in the volume of plastic deformation in the cutting zone. Therefore, the feed $V_i(l_i)$ rate along the cutting trajectory decreases faster than along the trajectory of the cutting speed [10].

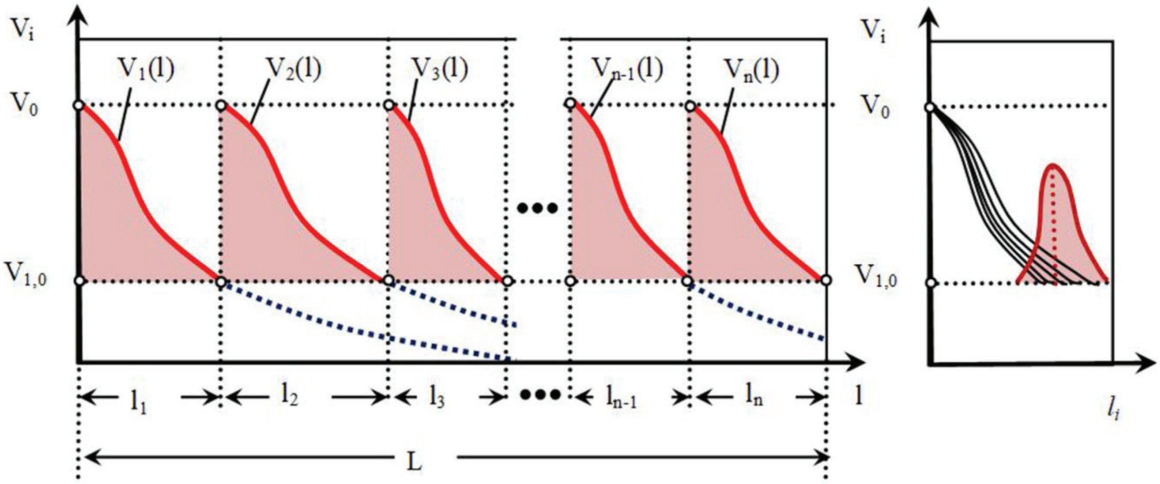


Fig. 1. Scheme for determining the coordinates of processing switching cycles

At the specified speeds $V_i(l)$, the processing costs З are determined by the formula

$$З = \Im(l_1,\ l_2,\ ...,\ l_n) = c_1 \sum_{i=1}^{i=n} \int_0^{l_i} \frac{d\xi}{V_i(\xi)} + (n-1)c_2, \quad (2)$$

where c_1 is the cost of the machine minute in RUB/min; c_2 is the cost of replacing the tool and its adjustment. Drilling deep holes of small diameter with spiral drills has a similar cost structure, but in this case, the switching of the processing cycle corresponds to the cost of removing the tool from the cutting zone to clean it from chips [37]. The solution to the problem is reduced to the calculation l_i for which $З \Rightarrow \min$.

Necessary optimality conditions. Calculation algorithm

Due to the mentioned circumstances, the speed is a monotonically decreasing function. In this case, the optimal coordinates of switching cycles correspond to equal cutting speeds. Moreover, these speeds are equal for various monotonically varying functions $V_i(l_i) \in \aleph_{\mathbf{0}}$. The set $\aleph_{\mathbf{0}}$ is a set of the phase trajectories of speeds at which the condition of a minimal wear intensity and ensuring a given quality of manufacturing is simultaneously met.

Solving the problem requires, firstly, fixing the number of switches n and for the given n and L determining the coordinates of the switches at which in (2) $\Im(l_1,\ l_2,\ ...,\ l_n) = \min$, provided that the requirement (1) is additionally fulfilled. If the conditions (1) are not considered and fixed when determining the optimal coordinates n, the task does not make sense. If the condition $\Im(l_1, l_2, ... l_n) = \Im_i$ is set, the resulting surface can intersect with a hyperplane $L(l_1,\ l_2,\ ...,\ l_n) = \sum_{i=1}^{i=n} l_i$ (Fig. 2). If $\Im_i$ is reduced, the lines of intersection of the surface $\Im_i(l_1, l_2, ... l_n)$ with the hyperplane represent convex closed trajectories that degenerate into a point $\Im_0(l_1,\ l_2,\ ...,\ l\ )$ that corresponds to the desired coordinates. The surfaces $\Im_i(l_1,\ l_2,\ ...,\ l_n)$ are convex since as the wear develops, the speed change function is monotonically decreasing. Therefore, the only optimal point at which the condition $З \Rightarrow \min$ is met is the condition of touching the hypersurface $\Im(l_1,\ l_2,\ ...,\ l_n)$ and the hyperplane $L(l_1,\ l_2,\ ...,\ l_n)$ (Fig. 2). Therefore, it is true for the point $\Im_0(l_1,\ l_2,\ ...,\ l_n)$

$$\partial\Im(l_1,\ l_2,\ ...,\ l_n) / \partial l_i \equiv \partial L(l_1,\ l_2,\ ...,\ l_n) / \partial l_i. \quad (3)$$

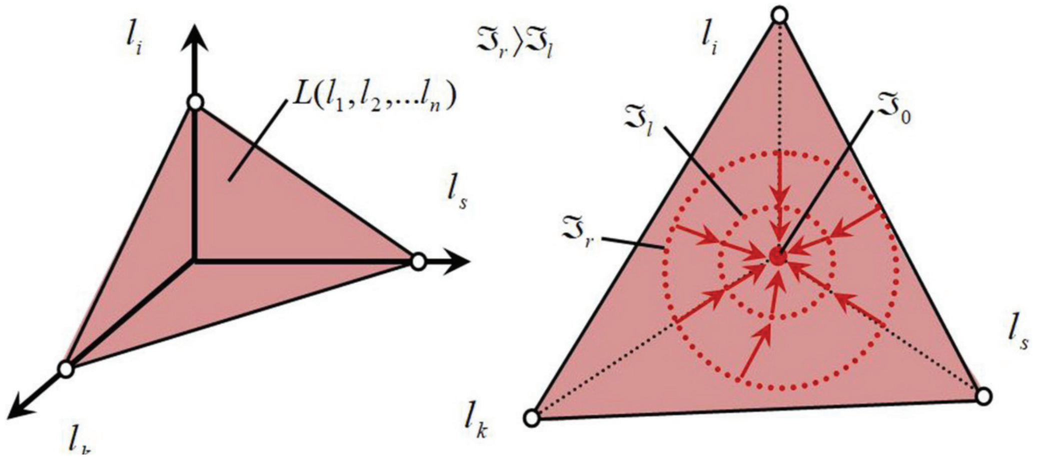


Fig. 2. Diagram explaining the intersection of a hyperplane and a hypersurface $\Im(l_1, l_2, ..., l_n)$

From where it follows

$$V_i(l_i) = V_s(l_s), \quad i, s \Rightarrow 1, 2, 3, ..., n\,. \tag{4}$$

Condition (4) enables simplifying the calculation of coordinates, as well as physically implementing a system that meets the condition $3 \Rightarrow \min$. Moreover, this condition takes into account the physical and economic requirements for optimality. The optimality condition is sufficient if, additionally from (2), n is determined, with $3 \Rightarrow \min$. Earlier in [10], an approximation of the speed change along the cutting path was proposed in the form of an exponential function

$$V^{(i)}(l_i) = V_0 \exp[-\alpha_i l_i], \quad l_i \in (0, \frac{4}{\alpha_i}), V^{(i)}(l_i) \in \aleph_0\,, \tag{5}$$

where V_0 is the initial value of the speed in m/s; α_i is the parameter in m^{-1}. Further, the approximation (5) is considered to be fair without violating the generality.

Papers [8–10] demonstrate that the trajectories (5) determined by the evolutionary properties of the system are sensitive to small variations in the initial parameters and uncontrolled disturbances, for example, beats. Therefore, with the initial speed V_0 unchanged, the parameter α_i may vary. It is considered as a Gaussian random variable with mathematical expectation $M[\alpha_i] = \hat{\alpha}$ and variance σ_α. Then, according to the mathematical expectation $\hat{3}(n)$ for (2) taking into account (5), there is the dependence of the given costs for manufacturing a batch of parts on the number of switches *n*:

$$\hat{3}(n) = \hat{\Im}(n) = \frac{c_1}{V_0 \hat{\alpha}}\left[\exp\left(\hat{\alpha}\frac{L}{n}\right) - 1\right] + (n-1)c_2 \tag{6}$$

Obviously (6), varying n has a minimum which corresponds to the optimal minimum speed $V_{0,1} = V_0 \exp\left(-\frac{\hat{\alpha}L}{n_0}\right)$. Here n_0 is the number of switches that correspond to a minimum (6). If the proven necessary optimality condition (4) is considered, the optimal value n_0 and the corresponding optimal speed are calculated from (6) $V_{0,1}$. Then l_i is calculated, which correspond to $\alpha_i \in (\hat{\alpha} - 3\sigma_\alpha, \hat{\alpha} + 3\sigma_\alpha)$ that characterize the set $\aleph^{(1)}$. They are determined by an obvious dependence $l_i = -\frac{1}{l_i}\ln\left(\frac{V_{0,1}}{V_o}\right)$, $V_{0,1} \langle V_0$. Importantly, all $l_i \in \aleph^{(1)}$ correspond to the speed $V_{0,1} = \text{const}$.

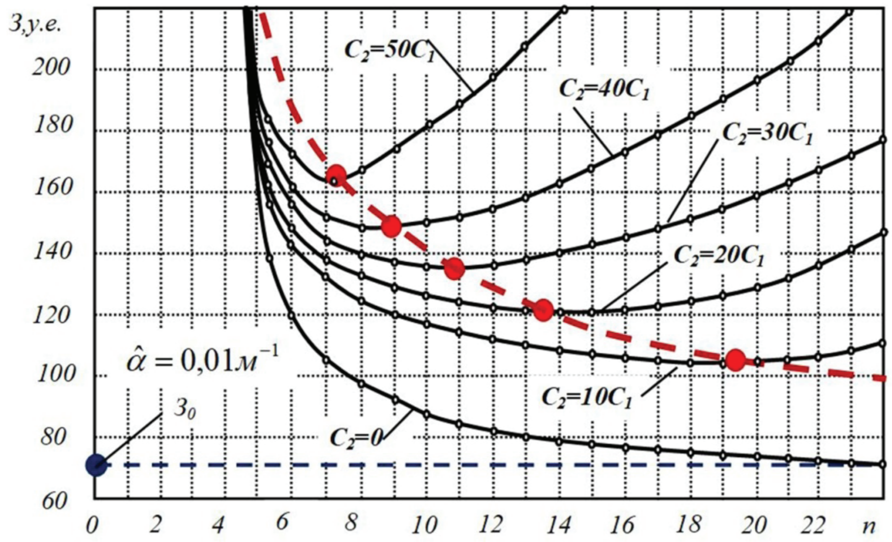
Results and discussion

Example of determining the optimal coordinates of the tool changeover

Here is an example of the effectiveness of the method for selecting speed trajectories and switching processing cycles for longitudinal turning of a shaft with $D = 8.0$ mm made of 08Kh15N24V4TR steel with non-sharpenable plates made of GC2015 hard alloy by SANDVIK Coromant, the plate shape is "W". Cutting depth is $t_P^{(0)} = 2.0$ mm; the initial feed is $S_P^{(0)} = 0.1$ mm/rev.; initial cutting speed is $V_0 = 1.2$ m/s. The length along the axis is 38.0 mm, the cutting path of one workpiece is 9.5 m, the total path is $L = 840$ m. The mathematical expectation of the cutting path to critical wear is 0.8 mm with constant optimal cutting conditions of 20 m. Parameters α that characterize the evolution are $\hat{\alpha}_1 = 0.1$ m^{-1} and $\hat{\alpha}_2 = 0.01$ m^{-1}. The variance value of this parameter is $\sigma_i = 0{,}1\,\hat{\alpha}_i$. The cost parameters c_1 c_2 are taken in conventional units of cost to a unit of time. For this case, Fig. 3 shows the dependence of the cost efficiency on the number of switches n. Here, the optimal values of the number of switches are highlighted with red circles and a dotted line, depending on the cost of replacing and readjusting the tool $c_2 = sc_1$. In any real system, the condition $c_2 \rangle c_1$ is usually met, since the cost of operating the machine is included in c_2. If $c_2 = 0$, the optimal is $n \to \infty$. Then the costs approach their minimum value of C_0 (shown in blue), determined by the hypothetical case of processing with a non-wearable tool in constant modes: $S_P^{(0)} = 0.1$ mm/rev. = const, $V_0 = 1.2$ m/s. The optimal number of the switching also depends on the parameters α that characterize the change in the wear intensity along the cutting path. As shown earlier [10], the parameter α, being an integral estimate of the evolutionary properties of the cutting process, depends on the dynamic properties of this process including the formed attractors of the tool deformation displacements relative to the workpiece. They change during the development of tool wear.

The analysis shows that .., as a rule, it is not an integer, so it is natural to take the optimal number of switches as the nearest integer value. In addition, it is necessary to coordinate the path corresponding to the switching with the length of the tooltip movement when processing a specific part. The given example illustrates the optimization of switching processing cycles for the case when the parameters of the evolutionary trajectories of changing modes are constant and correspond to mathematical expectations α. Since in a real system $\alpha_i \in (\hat{\alpha} - 3\sigma_\alpha, \hat{\alpha} + 3\sigma_\alpha)$, the set is also characterized by random distribution $l_i \in \aleph^{(\mathbf{l})}$. In Fig. 4 $a = V_{1,0}(\hat{\alpha} - \sigma_\alpha)$, $b = V_{1,0}(\hat{\alpha})$, $c = V_{1,0}(\hat{\alpha} + \sigma_\alpha)$. According to the proven position (3) and (4), all coordinates l_i that provide a minimum cost for manufacturing a batch of parts correspond to constant speeds $V_{1,0}$ at which the tool need to be replaced (Fig. 4). Therefore, the replacement of tools must be carried out not in the motion coordinates, but the speed ones $V_{1,0} = \text{const}$.

Currently, the CNC programs for machining parts remain unchanged when processing a batch of workpieces, regardless of the development of tool wear. The wear development changes the parameters of the dynamic cutting system and, as a result, changes its properties, which affect the intensity of tool wear and the quality parameters of the processed parts. Therefore, the MEUT needs to be coordinated with the evolutionarily changing properties of the cutting process. In this case, the MEUT is determined not on the basis of fixed technological modes, but on their trajectories consistent with the evolutionarily changing properties of the dynamic cutting system. This coordination allows minimizing the intensity of tool wear when producing parts of the required quality. It requires reducing the speed vector in the direction of the tooltip motion. Thus, if the elastic-dissipative properties of the tool and workpiece subsystems are unchanged,



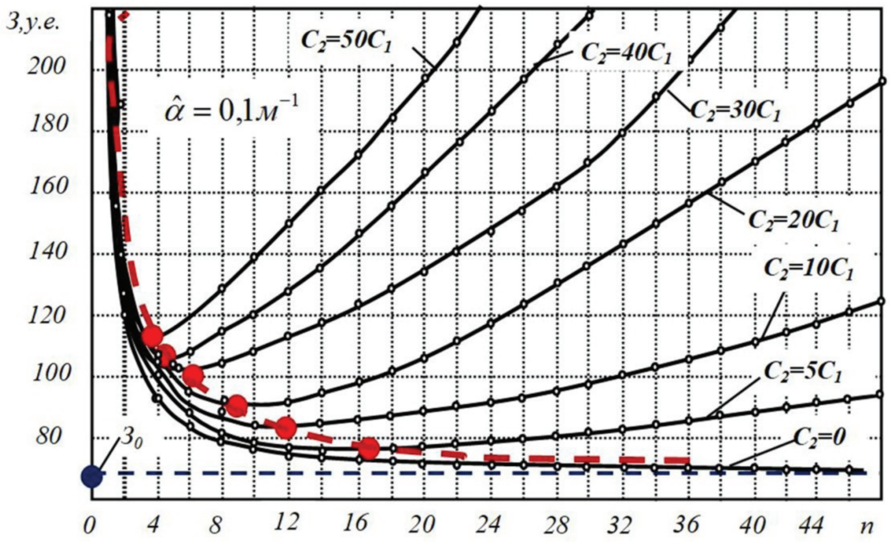


Fig. 3. Diagrams of changes in the cost of manufacturing a batch of one hundred parts depending on the number of processing switching cycles in conventional units

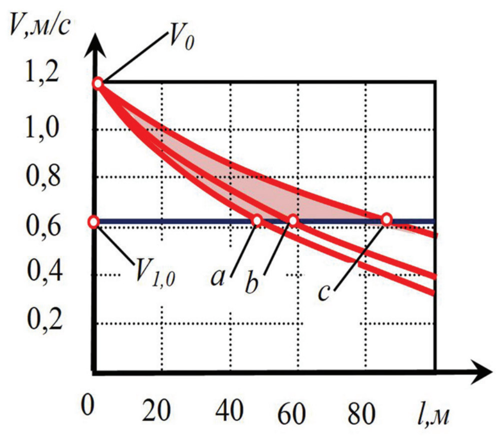


Fig. 4. The relationship of switching coordinates with the changes α

monotonous decreases in both the cutting speed and, to an even greater extent, the longitudinal feed rate correspond to the matching condition. Therefore, a new problem for the subject area is formulated to ensure the economic optimality of processing: to determine the coordinates of the tool subsystem changeover for the minimal costs of manufacturing a batch of parts. The given mathematical tools, algorithms and proven necessary optimality conditions can solve this problem.

An example of changing the optimal coordinates of the tool subsystem changeover showed that they depend on the ratio of the machine tool's minute cost during the actual cutting process to the cost of replacing and changeover of the cutting tool. As the cost of switching increases, their number decreases, and the cutting path increases in each cycle. The number of switches and the cutting path are also affected by the degradation intensity of the processing, which is characterized by the parameter α. It is affected by irreversible energy transformations at the interface of the tool flank face with the workpiece. They depend both on the elastic-dissipative properties of subsystems interacting at cutting, the evolutionarily changing parameters of the dynamic coupling formed by cutting, and on uncontrolled disturbances, for example, spindle beats. Moreover, as we showed earlier [8-10], the trajectories of irreversible energy transformations along the cutting path can have a high sensitivity to small variations in the system parameters and the parameters of uncontrolled disturbances.

The developed technique was tested at Helicopter Service Company, JSC when turning the MI-29 helicopter shaft of the hydraulic system fitting made of 08Kh15N24V4TR steel. Without dwelling on the details, we note that using the practical recommendations consistent with the evolution of the MEUT as well as optimal algorithms for switching processing cycles yielded the following results: according to the traditional program there were 3 processed parts between the changeover of tool systems; according to the adapted program, there were 8 parts; the average machine time for processing one part increased by 1.7 times. The stated costs for the production of a batch of 100 parts decreased by 1.3 times. Importantly, the given efficiency is obtained by software methods without changing the tool and processing conditions. The developed methodology and mathematical tools can be extended to solving problems of controlling other types of evolutionary processing [37].

Conclusion

Creating a CNC program with regard to the alignment of the trajectories of the machine's executive units and the evolutionary changes in the properties of the cutting process requires taking into account the fact that the cutting speed and the corresponding feed rate tend to decrease as the tool wear develops. Therefore, the tool changeover coordinate along the cutting path should be determined for the efficiency of processing. This coordinate is selected on the basis of minimizing the costs for manufacturing a batch of parts. A mathematical simulation of the process is proposed to implement the choice of coordinates; the necessary optimality conditions are stated and a method for calculating the optimal coordinates for tool changeover is proposed. The optimal switching coordinates are shown to correspond to equal minimum cutting speeds in the direction of the tooltip motion. They depend on the ratio of the machine time cost to the cost of changing tools (the cost of switching processing cycles). The paper presents the results of numerical simulation and industrial testing of the developed algorithms. They demonstrate that software methods can increase the cost efficiency of processing by 1.2-1.3 times, even without changing the properties of tools, the state of machines, and others parameters.

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Conflicts of Interest

The authors declare no conflict of interest.