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OPTIMIZATION MODEL OF THE PROCESSING PARAMETERS FOR STRUCTURAL ELEMENTS OF A PRODUCT

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Abstract. Optimization of the target indicators of the technological process is a key factor in increasing the efficiency of the product manufacturing process. The efficiency of the optimization process directly depends on the degree of detail of the control object. The purpose of the study is to increase the efficiency of the process of forming individual geometric elements of a part through multi-criteria optimization of the technological process parameters. The paper presents a structural hierarchical model of optimizing the parameters of the process of forming a geometric element. This model is a structural decomposition of the goals to be achieved within the identified control level. Based on the structural decomposition, four levels of process control are identified. This hierarchy of goals allows increasing the efficiency of the geometric element formation process through detailed analysis and optimization of target indicators at each stage of the process. The paper considers an example of optimization of the process parameters for machining a group of threaded holes M27x2-6H in a product made of dispersion-hardened composite alloy SAS-50. Optimum values of the process parameters for each forming stage are determined for the investigated group of holes according to the structural model of the process. As a result of optimizing the process parameters, the accuracy of manufacturing a group of threaded holes increased by 22.2%, while the labor intensity increased by 13.69%.

Keywords: multi-criteria optimization, geometric element, processing route, structural hierarchical model, control level

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МОДЕЛЬ ОПТИМИЗАЦИИ ПАРАМЕТРОВ ОБРАБОТКИ СТРУКТУРНЫХ ЭЛЕМЕНТОВ ИЗДЕЛИЯ

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Аннотация. Оптимизация целевых показателей технологического процесса является ключевым фактором повышения эффективности процесса изготовления изделия. Эффективность процесса оптимизации напрямую зависит от степени детализации объекта управления. Целью исследования является повышение эффективности процесса формообразования отдельных геометрических элементов детали за счет многокритериальной оптимизации параметров технологического процесса. В работе представлена структурная иерархическая модель оптимизации параметров процесса формообразования геометрического элемента. Данная модель представляет собой структурную декомпозицию целей, которые должны быть достигнуты в рамках выделенных уровней управления. На основе структурной декомпозиции выделено четыре уровня управления процессом. Данная иерархия целей позволяет повысить эффективность процесса формообразования геометрического элемента за счет детального анализа и оптимизации целевых показателей на каждом этапе процесса. В работе рассмотрен пример оптимизации параметров процесса обработки группы резьбовых отверстий М27х2-6Н в изделии, изготавливаемом из дисперсно-упрочненного композиционного сплава САС-50. Для исследуемой группы отверстий определены оптимальные значения технологических параметров для каждого этапа формообразования согласно структурной модели процесса. В результате оптимизации параметров процесса точность изготовления группы резьбовых отверстий повысилась на 22,2%, при этом трудоемкость увеличилась на 13,69%.

Ключевые слова: многокритериальная оптимизация, геометрический элемент, маршрут обработки, структурная иерархическая модель, уровень управления

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Introduction

Each product in mechanical engineering, supplied in conditions of fierce competition to the domestic and foreign markets, must have a new level of properties and meet the requirements imposed on potential consumers for the functional properties of the product. Therefore, one of the main goals for machine-building enterprises is the constant improvement of the parameters of both the product itself and the manufacturing process [1].

Modern growth rates of the global economy require machine-building production to produce competitive products with minimal time costs and high performance characteristics. In modern economic conditions, increasing the efficiency of the production process by optimizing technological parameters is a priority for industrial enterprises. Increasing the efficiency of processing is possible by improving existing and creating new methods for assigning processing modes, which will improve the quality of products, ensure high performance and reduce the complexity of processing. The efficiency of the technological operation is determined by the quality of the surface, accuracy and productivity. A large number of works related to the development of methods and models for optimizing production processes are devoted to solving this scientific problem [2–9].

One of the main management tasks in the process preparation of production is the optimization of process parameters. The paper discusses the issues of multi-criteria optimization of the process of forming geometric elements based on a structural hierarchical process model. In this case, the task is to form the best – optimal – management strategy within a multi-level hierarchical system. The general target state of the control object is characterized by a balanced system of targets that determine the overall efficiency of the system.

A large number of scientific papers [10–15] are devoted to the problems of optimizing the parameters of the technological process and the introduction of digital technologies. Today's digital technologies, such as IoT, cloud computing, big data analytics and AI, can dramatically improve the efficiency of the manufacturing process [16].

The optimization of production processes is based on big data analytics, which includes data collection, processing and analysis based on developed methods and algorithms [17–19].

Currently, knowledge graphs are widely used to solve optimization problems [20]. A knowledge graph is a semantic network that contains information about the structural elements of a research object and the relationships between them. The use of knowledge graphs for solving practical production problems is presented in [20–22].

The purpose of the study is to increase the efficiency of the product manufacturing process by optimizing the parameters of the process of manufacturing its individual elements.

The objectives of the study are to analyze the factors affecting the efficiency of the formation process of individual geometric elements; to develop a structural hierarchical model of geometric elements shaping process.

The object of the study is the process of forming geometric elements that form the structure of mechanical engineering products.

Structural model of the control object

Investigation of geometric element shaping process and determination of optimal values of processing parameters is based on structural decomposition of investigated process. The structural model of the process contains the following set of structural elements forming the corresponding control levels (Fig. 1):

- The first process control level: the technological processing route.
- The second process control level: the processing stage.
- The third process control level: the technological transition.
- The fourth process control level: the working stroke, the auxiliary transition.

The control object, which graph is shown in Fig. 1, reflects the sequence of intermediate states of the geometric element (vertex of the graph) and the conditions for the transition of the control object from the i-th state to the $(i + 1)$-th (arcs of the graph). Table 1 presents a list of tasks to be solved within each process control level.

At the first level, the control object has two states S_{wp} and S_{ge} (Fig. 2). The condition for changing the properties of the object within the first process control level can be described by the following expression:

$$S_{ge} = f\left(S_{wp}, U_1\right),\ U_1 \in D, \tag{1}$$

where S_{wp} is the state of the control object corresponding to the stock properties; S_{ge} is the condition of the control object corresponding to properties of a finished product which parameters are regulated by

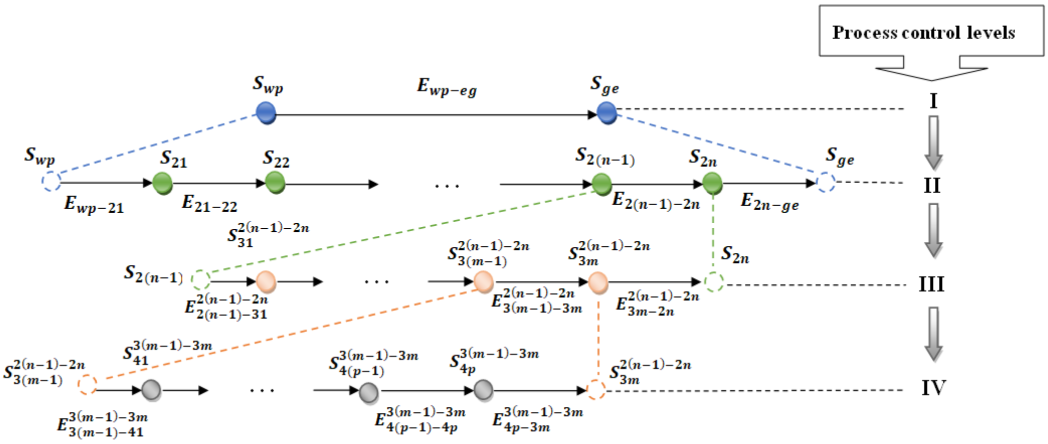

Fig. 1. The structural model of the control object

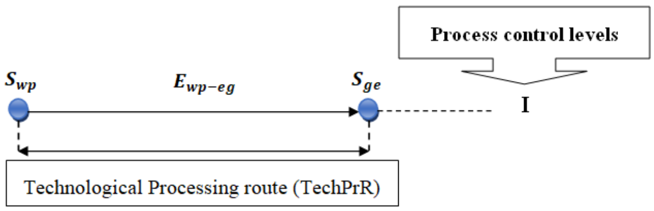

Fig. 2. Object state graph at the first process control level

design documentation; U_1 is the set of the control parameters corresponding to the first process control level; D is the set of the optimization model control parameters.

The U_1 set has the following structure (2):

$$U_1 = \Big\{ N^{PrSt},\ \left(Type_{ShM}^{PrSt}\right)_n,\ \beta_{bas}^{TechPrR},\ \beta_{aux}^{TechPrR},\ \alpha_{ct}^{TechPrR},\ \alpha_{w}^{TechPrR},\ \alpha_{qwq}^{TechPrR},\ \alpha_{am}^{TechPrR},\ \alpha_{rep}^{TechPrR},\ \alpha_{el.en.}^{TechPrR},\ \alpha_{dif}^{TechPrR} \Big\} \qquad (2)$$

where N^{PrSt} is the number of processing stages within the geometric element technological processing route, pcs; $\left(Type_{ShM}^{PrSt}\right)_n$ are the types of shaping methods used to implement the respective processing steps; $\beta_{bas}^{TechPrR}$ is the share of time aimed at implementation of a set of basic actions in the total labor intensity of the technological processing route; $\beta_{aux}^{TechPrR}$ is the share of time aimed at implementation of a set of auxiliary actions in the total labor intensity of the technological processing route; $\alpha_{ct}^{TechPrR}$ is the share of cutting tool costs in the total amount of operating costs for the implementation of the technological processing route; $\alpha_{w}^{TechPrR}$ is the share of costs intended for payment of wages to production workers in the total amount of operating costs for the implementation of the technological processing route; $\alpha_{qwq}^{TechPrR}$ is the share of quick-wear equipment costs in the total amount of operating costs for the implementation of the technological processing route; $\alpha_{am}^{TechPrR}$ is the share of depreciation expenses in the total amount of operating costs for the implementation of the technological processing route; $\alpha_{rep}^{TechPrR}$ is the share of costs intended for maintenance and repair of technological equipment in the total amount of operating costs for the implementation of the technological processing route; $\alpha_{el.en.}^{TechPrR}$ is the share of electricity costs in the total amount of operating costs for the implementation of the

Table 1

The list of tasks to be solved within process control level

Process control level	Tasks solved within the process control level
Process control level No. 1	1. Optimization of technological route processing structure of a geometric element, which consists of determining the optimal number of processing stages and shaping methods used to change the properties of the control object. 2. Optimization of values of the components of the process cost parameter within the implementation of the technological processing route. 3. Optimization of labor intensity of the complex of basic and auxiliary actions within the technological processing route. 4. Optimization of accuracy values of geometrical parameters of the control object generated during implementation of the corresponding processing stage.
Process control level No. 2	1. Optimization of processing stages structure, consisting in determining the optimal number of technological transitions necessary to change the properties of the control object. 2. Optimization of values of process cost parameter components within implementation of n-th processing stage. 3. Optimization of labor intensity of main and auxiliary actions within n-th processing stage. 4. Optimization of accuracy values of geometric parameters of the control object formed as a result of implementation of the m-th technological transition performed within the the n-th processing stage.
Process control level No. 3	1. Optimization of the structure of technological transitions, which consists in determining the optimal number of working strokes used to change the properties of the control object within the m-th technological transition. 2. Optimization of values of the components of the process cost parameter as part of the implementation of the m-th technological transition. 3. Optimization of labor intensity of basic and auxiliary actions as part of the implementation of the m-th technological transition. 4. Optimization of tolerance fields for each geometric parameter, within the p-th working stroke of the m-th technological transition.
Process control level No. 4	1. Optimization of values of the components of the process cost parameter within the implementation of the p-th working stroke. 2. Optimization of labor intensity of p-th working stroke implemented within m-th technological transition. 3. Optimization of the accuracy of a feature's geometric parameters within a specified tolerance field.

technological processing route; $\alpha_{dif}^{TechPrR}$ is the share of other costs in the total amount of operating costs for the implementation of the technological processing route.

Three sets of targets are defined for the first process control level:

$$Tr^{11} = \left\{ \left(Er_1^{PrSt} \right)_1, \ldots, \left(Er_1^{PrSt} \right)_n, \left(Er_i^{PrSt} \right)_1, \ldots, \left(Er_i^{PrSt} \right)_n \right\},\ Tr^{11} \subset Tr^1, \tag{3}$$

where Tr^1 is the set of the targets for the first process control level; Tr^{11} is the subset of target indicators characterizing the accuracy of the parameters of the geometric element after the implementation of the corresponding processing stage; $\left(Er_1^{PrSt} \right)_1, \ldots, \left(Er_1^{PrSt} \right)_n, \left(Er_i^{PrSt} \right)_1, \ldots, \left(Er_i^{PrSt} \right)_n$ is the accuracy of the 1...*i*-th parameter of the geometric element formed during the implementation of the 1...*n*-th processing stage, μm.

$$Tr^{12} = \left\{ C_{ct}^{TechPrR}, C_{w}^{TechPrR}, C_{qwq}^{TechPrR}, C_{am}^{TechPrR}, C_{rep}^{TechPrR}, C_{el.en.}^{TechPrR}, C_{dif.}^{TechPrR} \right\},\ Tr^{12} \subset Tr^1, \tag{4}$$

where Tr^{12} is a subset of target indicators characterizing the cost values for the corresponding calculation items that arise during the implementation of the technological processing route, rubles; $C_{ct}^{TechPrR}$ is the amount of cutting tool costs used in the process of the implementation of the technological processing route, rubles; $C_{w}^{TechPrR}$ is the amount of expenses required for payment of wages to production workers involved in the implementation of the technological processing route, rubles; $C_{qwq}^{TechPrR}$ is the amount of the quick-wear equipment costs used in the process of the implementation of the technological processing route, rubles; $C_{am}^{TechPrR}$ is the amount of depreciation expenses as part of the implementation of the amount of the quick-wear equipment costs used in the process of the implementation of the technological processing route, rubles; $C_{rep}^{TechPrR}$ is the amount of expenses intended for maintenance and repair of equipment used in the implementation of the technological processing route, rubles; $C_{el.en.}^{TechPrR}$ is the amount of energy costs required to the implementation of the technological processing route, rubles; $C_{dif.}^{TechPrR}$ is the amount of other costs required to the implementation of the technological processing route, rubles.

$$Tr^{13} = \left\{T_{bas}^{TechPrR}, T_{aux}^{TechPrR}\right\},\ Tr^{13} \subset Tr^{1}, \tag{5}$$

where Tr^{13} is the subset of target indicators characterizing the labor intensity of performing complexes of basic and auxiliary actions in the process of the implementation of the technological processing route; $T_{bas}^{TechPrR}$ is the amount of time spent on performing a set of basic actions in the process of the implementation of the technological processing route, min.; $T_{aux}^{TechPrR}$ is the amount of time spent on performing a set of auxiliary actions in the process of the implementation of the technological processing route, min.

At the second process control level, parameters are analyzed and optimized within the processing stage (Fig. 3).

The change of object properties within the second process control level is described by the following sequence of intermediate states corresponding to the properties of the control object after the implementation of the corresponding processing step:

$$S_{wp} \to S_{21} \to \cdots \to S_{2(n-1)} \to S_{2n} \to S_{ge}. \tag{6}$$

The condition for changing the properties of the control object within the n-th processing stage can be described by the following expression:

$$S_{2n} = f\left(S_{2(n-1)}, U_2\right),\ U_2 \in D, \tag{7}$$

where S_{2n} is the state of the control object corresponding to the properties of the geometric element after the implementation of the n-th processing stage; $S_{2(n-1)}$ is the state of the control object corresponding to the properties of the geometric element after the implementation of the $(n-1)$-th processing stage; U_2 is the set of control parameters corresponding to the second process control level.

The U_2 set has the following structure:

$$\begin{gathered} U_2 = \left\{\left(N^{TechTr}\right)_n, \left(\beta_{bas}^{PrSt}\right)_n, \left(\beta_{aux}^{PrSt}\right)_n, \left(\alpha_{ct}^{PrSt}\right)_n, \\ \left(\alpha_{w}^{PrSt}\right)_n, \left(\alpha_{qwq}^{PrSt}\right)_n, \left(\alpha_{am}^{PrSt}\right)_n, \left(\alpha_{rep}^{PrSt}\right)_n, \left(\alpha_{el.en.}^{PrSt}\right)_n, \left(\alpha_{dif}^{PrSt}\right)_n\right\}, \end{gathered} \tag{8}$$

where $\left(N^{TechTr}\right)_n$ is the number of technological transitions within the n-th processing stage of geometric element, pcs; $\left(\beta_{bas}^{PrSt}\right)_n$ is the share of the main time for the implementation of the n-th processing stage in the total labor intensity of performing a set of main actions within the technological processing route; $\left(\beta_{aux}^{PrSt}\right)_n$ is the share of auxiliary time for the implementation of the n-th processing stage in the total labor intensity of performing a set of auxiliary actions within the technological processing route;

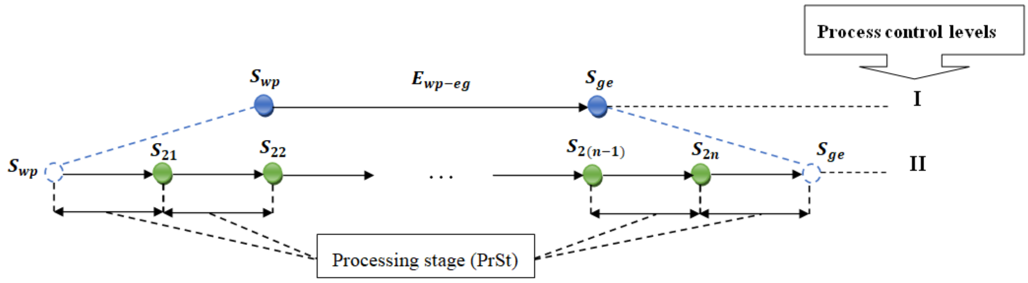

Fig. 3. Object state graph at the second process control level

$\left(\alpha_{ct}^{PrSt}\right)_n$ is the share of cutting tool costs for n-th processing stage in the total amount of operating costs for the cutting tools for the implementation of the technological processing route; $\left(\alpha_{w}^{PrSt}\right)_n$ is the share of costs intended for payment of wages to production workers involved in the implementation of the n-th processing stage in the total amount of operating costs for wages for the implementation of the technological processing route; $\left(\alpha_{qwq}^{PrSt}\right)_n$ is the share of quick-wear equipment costs for n-th processing stage in the total amount of operating costs for the quick-wear equipment for the implementation of the technological processing route; $\left(\alpha_{am}^{PrSt}\right)_n$ is the share of costs intended for depreciation within the n-th processing stage in the total amount of operating costs for depreciation expenses within the implementation of the technological processing route; $\left(\alpha_{rep}^{PrSt}\right)_n$ is the share of costs for maintenance and repair of process equipment within the n-th processing stage in the total cost of maintenance and repair of process equipment within the implementation of the technological processing route; $\left(\alpha_{el.en.}^{PrSt}\right)_n$ is the share of the cost of electricity spent on the implementation of the n-th processing stage in the total cost of electricity spent on the implementation of the technological processing route; $\left(\alpha_{dif}^{PrSt}\right)_n$ is the share of other costs for the implementation of the n-th processing stage in the total amount of other costs required for the implementation of the technological processing route.

Three sets of targets are defined for the second control level:

$$Tr^{21} = \left\{\left(Er_1^{TechTr}\right)_1, \ldots, \left(Er_1^{TechTr}\right)_n, \left(Er_i^{TechTr}\right)_1, \ldots, \left(Er_i^{TechTr}\right)_n\right\},\ Tr^{21} \subset Tr^2, \tag{9}$$

where Tr^2 is the set of the targets for the second process control level; Tr^{21} is the subset of target indicators characterizing the accuracy parameters of the control object after the implementation of the corresponding processing stage; $\left(Er_1^{PrSt}\right)_1, \ldots, \left(Er_1^{PrSt}\right)_n, \left(Er_i^{PrSt}\right)_1, \ldots, \left(Er_i^{PrSt}\right)_n$ is the accuracy of the i-th geometric parameter of the control object generated during the implementation of the n-th technological transition, μm.

$$Tr^{22} = \begin{Bmatrix} \left(C_{ct}^{PrSt}\right)_1, \ldots, \left(C_{ct}^{PrSt}\right)_n, \left(C_{w}^{PrSt}\right)_1, \ldots, \left(C_{w}^{PrSt}\right)_n, \left(C_{qwq}^{PrSt}\right)_1, \ldots, \left(C_{qwq}^{PrSt}\right)_n, \\ \left(C_{am}^{PrSt}\right)_1, \ldots, \left(C_{am}^{PrSt}\right)_n, \left(C_{rep}^{PrSt}\right)_1, \ldots, \left(C_{rep}^{PrSt}\right)_n, \left(C_{el.en.}^{PrSt}\right)_1, \ldots, \left(C_{el.en.}^{PrSt}\right)_n, \\ \left(C_{dif}^{PrSt}\right)_1, \ldots, \left(C_{dif}^{PrSt}\right)_n, \end{Bmatrix},\ Tr^{22} \subset Tr^2, \tag{10}$$

where Tr^{22} is the subset of the target indicators characterizing the sizes of the expenses under the relevant articles of accounting arising during the implementation of the n-th processing stages; $\left(C_{ct}^{PrSt}\right)_1, \ldots,$

$\left(C_{ct}^{PrSt}\right)_n$ is the amount of cutting tool costs used in the process of the implementation of the n-th processing stages, rubles; $\left(C_{w}^{PrSt}\right)_1, \ldots, \left(C_{w}^{PrSt}\right)_n$ is the amount of expenses required for the payment of wages to production workers involved in the implementation of the n-th processing stages, rubles; $\left(C_{qwq}^{PrSt}\right)_1$, …, $\left(C_{qwq}^{PrSt}\right)_n$ is the amount of quick-wearing equipment costs used in the process of the implementation of the n-th processing stages, rubles; $\left(C_{am}^{PrSt}\right)_1, \ldots, \left(C_{am}^{PrSt}\right)_n$ is the amount of expenses allocated for depreciation expenses as part of the implementation of the n-th processing stages, rubles; $\left(C_{rep}^{PrSt}\right)_1, \ldots,$ $\left(C_{rep}^{PrSt}\right)_n$ is the amount of expenses intended for maintenance and repair of equipment used in the implementation of n-th processing stage, rubles; $\left(C_{el.en.}^{PrSt}\right)_1, \ldots, \left(C_{el.en.}^{PrSt}\right)_n$ is the amount of energy costs required to realize n-th processing stage, rubles; $\left(C_{dif}^{PrSt}\right)_1, \ldots, \left(C_{dif}^{PrSt}\right)_n$ is the amount of other costs required for the implementation of the n-th processing stage, rubles.

$$Tr^{23} = \left\{\left(T_{bas}^{PrSt}\right)_1, \ldots, \left(T_{bas}^{PrSt}\right)_n, \left(T_{aux}^{PrSt}\right)_1, \ldots, \left(T_{aux}^{PrSt}\right)_n\right\},\ Tr^{23} \subset Tr^2, \tag{11}$$

where Tr^{23} is the subset of target indicators characterizing the labor intensity of performing complexes of basic and auxiliary actions in the process of the implementation of the n-th processing stage; $\left(T_{bas}^{PrSt}\right)_1, \ldots, \left(T_{bas}^{PrSt}\right)_n$ is the amount of time spent on performing a set of basic actions during the implementation of the n-th processing stage, min.; $\left(T_{aux}^{PrSt}\right)_1, \ldots, \left(T_{aux}^{PrSt}\right)_n$ is the amount of time spent on performing a set of auxiliary actions during the implementation of the n-th processing stage, min.

At the third process control level, process parameters are analyzed and optimized as part of the technological transition (Fig. 4).

The change of object properties within the third process control level is described by the following sequence of intermediate states corresponding to the properties of the control object after the implementation of the m-th technological transition:

$$S_{2(n-1)} \to S_{31}^{2(n-1)-2n} \to S_{32}^{2(n-1)-2n} \to \cdots \to S_{3(m-1)}^{2(n-1)-2n} \to S_{3m}^{2(n-1)-2n} \to S_{2n}. \tag{12}$$

The condition for changing the properties of a control object within a technological transition can be described by the following expression:

$$S_{3m} = f\left(S_{3(m-1)}, U_3\right),\ U_3 \in D, \tag{13}$$

where S_{3m} is the state of the control object corresponding to the geometry properties after the m-th technological transition; $S_{3(m-1)}$ is the state of the control object corresponding to the properties of the geometric element after the $(m-1)$-th technological transition; U_3 is the set of control parameters corresponding to the third process control level.

The U_3 set has the following structure:

$$U_3 = \left\{\begin{matrix}\left(N^{WSt}\right)_{mn}, \left(\beta_{bas}^{TechTr}\right)_{mn}, \left(\beta_{aux}^{TechTr}\right)_{mn}, \left(\alpha_{ct}^{TechTr}\right)_{mn}, \left(\alpha_{w}^{TechTr}\right)_{mn}, \\ \left(\alpha_{qwq}^{TechTr}\right)_{mn}, \left(\alpha_{am}^{TechTr}\right)_{mn}, \left(\alpha_{rep}^{TechTr}\right)_{mn}, \left(\alpha_{el.en.}^{TechTr}\right)_{mn}, \left(\alpha_{dif}^{TechTr}\right)_{mn}\end{matrix}\right\}, \tag{14}$$

where $\left(N^{WSt}\right)_{mn}$ is the number of working strokes within the m-th technological transition of the n-th processing stage; $\left(\beta_{bas}^{TechTr}\right)_{mn}$ is the labor intensity of the complex of main actions within the m-th technological transition in the total labor intensity of the complex of main actions of the n-th processing stage;

$\left(\beta_{aux}^{TechTr}\right)_{mn}$ is the labor intensity of the set of auxiliary actions within the m-th technological transition in the total labor intensity of the set of auxiliary actions of the n-th processing stage; $\left(\alpha_{ct}^{TechTr}\right)_{mn}$ is the share of cutting tool costs for the m-th technological transition in the total amount of operating costs for the cutting tools for the implementation of the n-th processing stage; $\left(\alpha_{w}^{TechTr}\right)_{mn}$ is the share of costs intended for payment of wages to production workers involved in the implementation of the m-th technological transition in the total amount of operating costs for wages to production workers involved in the implementation of the n-th processing stage; $\left(\alpha_{qwq}^{TechTr}\right)_{mn}$ is the share of quick-wear equipment costs for the m-th technological transition in the total amount of operating costs for the quick-wear equipment for the implementation of the n-th processing stage; $\left(\alpha_{am}^{TechTr}\right)_{mn}$ is the share of depreciation costs for the m-th technological transition in the total amount of operating expenses for depreciation for the n-th processing stage; $\left(\alpha_{rep}^{TechTr}\right)_{mn}$ is the share of costs intended for maintenance and repair of technological equipment involved in the implementation of the m-th technological transition in the total amount of operating costs for maintenance and repair of technological equipment involved in the implementation of the n-th stage of processing; $\left(\alpha_{el.en.}^{TechTr}\right)_{mn}$ is the share of the cost of electricity spent on the implementation of the m-th technological transition in the total operating costs of electricity spent on the implementation of the n-th processing stage; $\left(\alpha_{dif}^{TechTr}\right)_{mn}$ is the share of other costs for the implementation of the m-th technological transition in the total amount of other costs for the implementation of the n-th processing stage.

Three sets of targets are defined for the third process control level:

$$Tr^{31} = \left\{ \left(Er_1^{WSt}\right)_{1p}, \ldots, \left(Er_1^{WSt}\right)_{pm}, \left(Er_i^{WSt}\right)_{1p}, \ldots, \left(Er_i^{WSt}\right)_{pm} \right\},\ Tr^{31} \subset Tr^3, \tag{15}$$

where Tr^3 is the set of the targets for the third process control level; Tr^{31} is a subset of target indicators characterizing the accuracy parameters of the i-th geometric parameter of the control object after the implementation of the p-th working stroke within the m-th technological transition; $\left(Er_1^{WSt}\right)_{1p}, \ldots,$ $\left(Er_1^{WSt}\right)_{pm}, \left(Er_i^{WSt}\right)_{1p}, \ldots, \left(Er_i^{WSt}\right)_{pm}$ is the accuracy of the i-th geometric parameter of the control object formed during the implementation of the p-th working stroke within the m-th technological transition.

$$Tr^{32} =$$
$$= \left\{ \begin{matrix} \left(C_{ct}^{TechTr}\right)_{1n}, \ldots, \left(C_{ct}^{TechTr}\right)_{mn}, \left(C_{w}^{TechTr}\right)_{1n}, \ldots, \left(C_{w}^{TechTr}\right)_{mn}, \left(C_{qwq}^{TechTr}\right)_{1n}, \ldots, \left(C_{qwq}^{TechTr}\right)_{mn}, \\ \left(C_{am}^{TechTr}\right)_{1n}, \ldots, \left(C_{am}^{TechTr}\right)_{mn}, \left(C_{rep}^{TechTr}\right)_{1n}, \ldots, \left(C_{rep}^{TechTr}\right)_{mn}, \left(C_{el.en.}^{TechTr}\right)_{1n}, \ldots, \left(C_{el.en.}^{TechTr}\right)_{mn}, \\ \left(C_{dif}^{TechTr}\right)_{1n}, \ldots, \left(C_{dif}^{TechTr}\right)_{mn}, \end{matrix} \right\}, \tag{16}$$
$$Tr^{32} \subset Tr^3,$$

where Tr^{32} is a subset of target indicators characterizing the cost values for the corresponding calculation items arising during the implementation of the m-th technological transition within the n-th processing stage; $\left(C_{ct}^{TechTr}\right)_{1n}, \ldots, \left(C_{ct}^{TechTr}\right)_{mn}$ is the amount of cutting tool costs used in the process of the implementation of the m-th technological transition within the n-th processing stage; $\left(C_{w}^{TechTr}\right)_{1n}, \ldots,$ $\left(C_{w}^{TechTr}\right)_{mn}$ is the amount of costs required to pay wages to production workers involved in the imple-

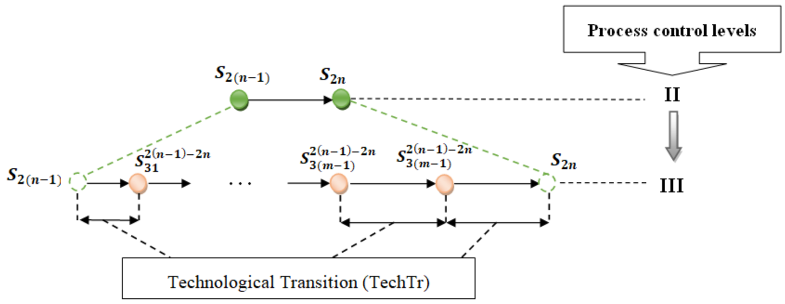

Fig. 4. Object state graph at the third process control level

mentation of the m-th technological transitions of the n-th processing stage; $\left(C_{qwq}^{TechTr}\right)_{1n},\ldots,\left(C_{qwq}^{TechTr}\right)_{mn}$ is the amount of quick-wear equipment costs used in the process of the implementation of the m-th technological transitions of the n-th processing stage; $\left(C_{am}^{TechTr}\right)_{1n},\ldots,\left(C_{am}^{TechTr}\right)_{mn}$ is the amount of expenses allocated for depreciation expenses as part of the implementation of the m-th technological transitions of the n-th processing stage; $\left(C_{rep}^{TechTr}\right)_{1n},\ldots,\left(C_{rep}^{TechTr}\right)_{mn}$ is the amount of costs intended for maintenance and repair of equipment used as part of the implementation of the m-th technological transition of the n-th processing stage; $\left(C_{el.en.}^{TechTr}\right)_{1n},\ldots,\left(C_{el.en.}^{TechTr}\right)_{mn}$ is the amount of energy costs required for the implementation of the m-th technological transition of the n-th processing stage; $\left(C_{dif}^{TechTr}\right)_{1n},\ldots,$ $\left(C_{dif}^{TechTr}\right)_{mn}$ is the amount of other costs required for the implementation of the m-th technological transition of the n-th processing stage.

$$Tr^{33}=\left\{\left(T_{bas}^{TechTr}\right)_{1n},\ldots,\left(T_{bas}^{TechTr}\right)_{mn},\left(T_{aux}^{TechTr}\right)_{1n},\ldots,\left(T_{aux}^{TechTr}\right)_{mn}\right\},\ Tr^{33}\subset Tr^{3}, \tag{17}$$

where Tr^{33} is a subset of targets characterizing the complexity of performing complexes of basic and auxiliary actions during the implementation of the m-th technological transition of the n-th processing stage; $\left(T_{bas}^{TechTr}\right)_{1n},\ldots,\left(T_{bas}^{TechTr}\right)_{mn}$ is the amount of time spent on performing a set of main actions during the implementation of the m-th technological transition of the n-th processing stage; $\left(T_{aux}^{TechTr}\right)_{1n},$ $\ldots,\left(T_{aux}^{TechTr}\right)_{mn}$ is the amount of time spent on performing a set of auxiliary actions during the implementation of the m-th technological transition of the n-th processing stage.

At the fourth control level, the process parameters are analyzed and optimized as part of the working stroke (Fig. 5).

The change of object properties within the fourth process control level is described by the following sequence of intermediate states corresponding to the properties of the control object after the implementation of the p-th working stroke:

$$S_{wp}\to S_{41}^{3(m-1)-3m}\to\cdots\to S_{4(p-1)}^{3(m-1)-3m}\to S_{4p}^{3(m-1)-3m}\to S_{ge}. \tag{18}$$

The condition for changing the properties of the control object within the work stroke can be described by the following expression:

$$S_{4p}=f\left(S_{4(p-1)},U_{4}\right),\ U_{4}\in D, \tag{19}$$

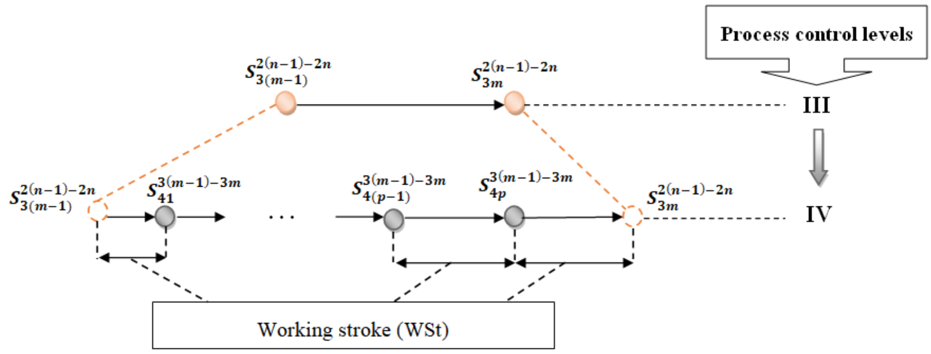

Fig. 5. Object state graph at the fourth process control level

where S_{4p} is the state of the control object corresponding to the product properties after the p-th working stroke; $S_4(p-1)$ is the state of the control object corresponding to the product properties after the $(p-1)$-th working stroke; U_4 is the set of control parameters corresponding to the fourth process control level.

The U_4 set has the following structure:

$$U_4=\Big\{\beta^{WSt}_{pm},\ \beta^{AuxTr}_{rm},\ \left(\alpha^{WSt}_{ct}\right)_{pm},\left(\alpha^{WSt}_{w}\right)_{pm},\ \left(\alpha^{AuxTr}_{w}\right)_{rm},\ \left(\alpha^{WSt}_{qwq}\right)_{pm},$$
$$\left(\alpha^{WSt}_{am}\right)_{pm},\left(\alpha^{AuxTr}_{am}\right)_{rm},\ \left(\alpha^{WSt}_{rep}\right)_{pm},\ \left(\alpha^{AuxTr}_{rep}\right)_{rm},\ \left(\alpha^{WSt}_{el.en.}\right)_{pm},\ \left(\alpha^{AuxTr}_{el.en.}\right)_{rm}, \quad (20)$$
$$\left(\alpha^{WSt}_{dif}\right)_{pm},\left(\alpha^{AuxTr}_{dif}\right)_{rm},\ \left(\gamma^{ElDif.}_{i}\right)^{WSt}_{pm},\ \left(\gamma^{Dim.W}_{i}\right)^{WSt}_{pm},\ \left(\gamma^{ThSt.}_{i}\right)^{WSt}_{pm}\Big\},$$

where β^{WSt}_{pm} is the share of the time spent on the implementation of the p-th working stroke in the total labor intensity of the complex of basic actions within the m-th technological transition; β^{AuxTr}_{rm} is the share of the time spent on the implementation of the r-th auxiliary transition in the total complexity of performing a set of auxiliary actions within the m-th technological transition; $\left(\alpha^{WSt}_{ct}\right)_{pm}$ is the share of cutting tool costs for p-th working stroke in the total amount of operating costs for the cutting tools for the implementation of the m-th technological transition; $\left(\alpha^{WSt}_{w}\right)_{pm}$ is the share of costs intended for payment of wages to production workers involved in the implementation of p-th working stroke in the total amount of operating costs for wages to production workers involved in the implementation of the m-th technological transition; $\left(\alpha^{AuxTr}_{w}\right)_{rm}$ is the share of costs intended for payment of wages to production workers involved in the implementation of the r-th auxiliary transition in the total amount of operating costs for wages to production workers involved in the implementation of the m-th technological transition; $\left(\alpha^{WSt}_{qwq}\right)_{pm}$ is the share of quick-wear equipment costs for p-th working stroke in the total amount of operating costs for the quick-wear equipment for the implementation of the m-th technological transition; $\left(\alpha^{WSt}_{am}\right)_{pm}$ is the share of depreciation expenses incurred during the implementation of the p-th working stroke in the total amount of operating expenses for depreciation expenses incurred during the implementation of the m-th technological transition; $\left(\alpha^{AuxTr}_{am}\right)_{rm}$ is the share of depreciation expenses incurred during the implementation of the r-th auxiliary transition in the total amount of operating expenses for depreciation expenses incurred during the implementation of the m-th technological transition; $\left(\alpha^{WSt}_{rep}\right)_{pm}$ is the share of costs intended for maintenance and repair of technological equipment arising during the implementation of the p-th working stroke in the total amount of operating costs for maintenance and repair of technological equipment arising within the m-th technological transition; $\left(\alpha_{rep}^{AuxTr}\right)_{rm}$ is the share of costs intended for maintenance and repair of technological equipment arising during the implementation of the r-th auxiliary transition in the total amount of operating costs for maintenance and repair of technological equipment arising within the m-th technological transition; $\left(\alpha_{el.en.}^{WSt}\right)_{pm}$ is the share of costs intended to pay for electricity required for the implementation of the p-th working stroke in the total amount of operating costs for electricity for the m-th technological transition; $\left(\alpha_{el.en.}^{AuxTr}\right)_{rm}$ is the share of costs intended to pay for electricity required to implement the r-th auxiliary transition in the total operating costs of electricity for the m-th technological transition; $\left(\alpha_{dif}^{WSt}\right)_{pm}$ is the share of other costs required to implement the p-th working stroke in the total amount of other costs arising from the implementation of the m-th technological transition; $\left(\alpha_{dif}^{AuxTr}\right)_{rm}$ is the share of other costs required for the implementation of the r-th auxiliary transition in the total amount of other costs arising from the implementation of the m-th technological transition; $\left(\gamma_i^{ElDif.}\right)_{pm}^{WSt}$ is the share of error caused by elastic deformations of the process system in the total processing error of the i-th geometric parameter within the implementation of the p-th working stroke; $\left(\gamma_i^{Dim.W}\right)_{pm}^{WSt}$ is the share of the error caused by dimensional wear of the cutting tool in the total error of processing the i-th geometric parameter within the implementation of the p-th working stroke; $\left(\gamma_i^{ThSt.}\right)_{pm}^{WSt}$ is the share of the error caused by thermal deformations of the process systems in the total processing error of the i-th geometric parameter within the implementation of the working stroke.

Four sets of targets are defined for the fourth process control level:

$$Tr^{41} =$$
$$=\left\{\left(Er_i^{ElDif.}\right)_{1m}^{WSt},\ldots,\left(Er_i^{ElDif.}\right)_{pm}^{WSt},\left(Er_i^{Dim.W}\right)_{1m}^{WSt},\ldots,\left(Er_i^{Dim.W}\right)_{pm}^{WSt},\left(Er_i^{ThSt}\right)_{1m}^{WSt},\ldots,\left(Er_i^{ThSt}\right)_{pm}^{WSt}\right\}, \quad (21)$$
$$Tr^{41} \subset Tr^{4},$$

where Tr^4 is the set of the targets for the fourth process control level; Tr^{41} is the subset of target indicators characterizing the accuracy parameters of the i-th geometric parameter of the control object after the implementation of the p-th working stroke of the m-th technological transition; $\left(Er_i^{ElDif.}\right)_{1m}^{WSt},\ldots,$ $\left(Er_i^{ElDif.}\right)_{pm}^{WSt}$ is the value of error of the i-th geometric parameter caused by elastic deformations of the technological system, formed during the implementation of the p-th working stroke of the m-th technological transition; $\left(Er_i^{Dim.W}\right)_{1m}^{WSt},\ldots,\left(Er_i^{Dim.W}\right)_{pm}^{WSt}$ is the value of the i-th geometric parameter error caused by dimensional wear of the cutting tool, formed during the implementation of the p-th working stroke of the m-th technological transition; $\left(Er_i^{ThSt}\right)_{1m}^{WSt},\ldots,\left(Er_i^{ThSt}\right)_{pm}^{WSt}$ is the value of the i-th geometric parameter error caused by thermal deformations of the technological system, formed during the implementation of the p-th working stroke of the m-th technological transition.

$$Tr^{42}=\left\{\begin{matrix}\left(C_{ct}^{WSt}\right)_{1m},\ldots,\left(C_{ct}^{WSt}\right)_{pm},\left(C_{w}^{WSt}\right)_{1m},\ldots,\left(C_{w}^{WSt}\right)_{pm},\left(C_{qwq}^{WSt}\right)_{1m},\ldots,\left(C_{qwq}^{WSt}\right)_{pm}, \\ \left(C_{am}^{WSt}\right)_{1m},\ldots,\left(C_{am}^{WSt}\right)_{pm},\left(C_{rep}^{WSt}\right)_{1m},\ldots,\left(C_{rep}^{WSt}\right)_{pm},\left(C_{el.en.}^{WSt}\right)_{1m},\ldots,\left(C_{el.en.}^{WSt}\right)_{pm},\left(C_{dif}^{WSt}\right)_{1m},\ldots,\left(C_{dif}^{WSt}\right)_{pm},\end{matrix}\right\},$$
$$Tr^{42} \subset Tr^{4}, \quad (22)$$

where Tr^{42} is the subset of target indicators characterizing the amount of costs for the corresponding calculation items arising during the implementation of the p-th working stroke of the m-th technological transition; $\left(C_{ct}^{WSt}\right)_{1m},\ldots,\left(C_{ct}^{WSt}\right)_{pm}$ is the amount of cutting tool costs used in the process of the implementation of the p-th working stroke of the m-th technological transition; $\left(C_{w}^{WSt}\right)_{1m},\ldots,\left(C_{w}^{WSt}\right)_{pm}$ is the amount of costs required to pay wages to production workers involved in the implementation of the p-th working stroke of the m-th technological transition; $\left(C_{qwq}^{WSt}\right)_{1m},\ldots,\left(C_{qwq}^{WSt}\right)_{pm}$ is the amount of costs required for the purchase of quick-wear equipment used in the process of the implementation of the p-th working stroke of the m-th technological transition; $\left(C_{am}^{WSt}\right)_{1m},\ldots,\left(C_{am}^{WSt}\right)_{pm}$ is the amount of expenses allocated for depreciation expenses as part of the implementation of the p-th working stroke of the m-th technological transition; $\left(C_{rep}^{WSt}\right)_{1m},\ldots,\left(C_{rep}^{WSt}\right)_{pm}$ is the amount of costs intended for maintenance and repair of equipment used in the implementation of the p-th working stroke of the m-th technological transition; $\left(C_{el.en.}^{WSt}\right)_{1m},\ldots,\left(C_{el.en.}^{WSt}\right)_{pm}$ is the amount of energy costs required to implement the p-th working stroke of the m-th technological transition; $\left(C_{dif}^{WSt}\right)_{1m},\ldots,\left(C_{dif}^{WSt}\right)_{pm}$ is the amount of other costs required for the implementation of the p-th working stroke of the m-th technological transition.

$$Tr^{43}=\left\{\begin{matrix}\left(C_{w}^{AuxTr}\right)_{1m},\ldots,\left(C_{w}^{AuxTr}\right)_{rm},\left(C_{am}^{AuxTr}\right)_{1m},\ldots,\left(C_{am}^{AuxTr}\right)_{rm},\\ \left(C_{rep}^{AuxTr}\right)_{1m},\ldots,\left(C_{rep}^{AuxTr}\right)_{rm},\left(C_{el.en.}^{AuxTr}\right)_{1m},\ldots,\left(C_{el.en.}^{AuxTr}\right)_{rm},\left(C_{dif}^{AuxTr}\right)_{1m},\ldots,\left(C_{dif}^{AuxTr}\right)_{rm}\end{matrix}\right\}, \tag{23}$$

$$Tr^{43}\subset Tr^{4},$$

where Tr^{43} is the subset of target indicators characterizing the cost of the corresponding calculation items arising during the implementation of the r-th auxiliary transition of the m-th technological transition; $\left(C_{w}^{AuxTr}\right)_{1m},\ldots,\left(C_{w}^{AuxTr}\right)_{rm}$ is the amount of costs required to pay wages to production workers involved in the implementation of the r-th auxiliary transition of the m-th technological transition; $\left(C_{am}^{AuxTr}\right)_{1m}$, $\ldots,\left(C_{am}^{AuxTr}\right)_{rm}$ is the amount of expenses allocated for depreciation expenses as part of the implementation of the r-th auxiliary transition of the m-th technological transition; $\left(C_{rep}^{AuxTr}\right)_{1m},\ldots,\left(C_{rep}^{AuxTr}\right)_{rm}$ is the amount of costs intended for maintenance and repair of equipment used in the implementation of the r-th auxiliary transition of the m-th technological transition; $\left(C_{el.en.}^{AuxTr}\right)_{1m},\ldots,\left(C_{el.en.}^{AuxTr}\right)_{rm}$ is the amount of energy costs required for the implementation of the r-th auxiliary transition of the m-th technological transition; $\left(C_{dif}^{AuxTr}\right)_{1m},\ldots,\left(C_{dif}^{AuxTr}\right)_{rm}$ is the amount of other costs required for the implementation of the r-th auxiliary transition of the m-th technological transition.

$$Tr^{44}=\left\{T_{1m}^{WSt},\ldots,T_{pm}^{WSt},\ T_{1m}^{AuxTr},\ldots,T_{rm}^{AuxTr}\right\},\ Tr^{44}\subset Tr^{4}, \tag{24}$$

where Tr^{44} is the subset of targets characterizing the labor intensity of working strokes and auxiliary transitions within the m-th technological transition; $T_{1m}^{WSt},\ldots,T_{pm}^{WSt}$ is the amount of time spent on the p-th working stroke of the m-th technological transition, min.; $T_{1m}^{AuxTr},\ldots,T_{rm}^{AuxTr}$ is the amount of time spent on performing the r-th auxiliary transition of the m-th technological transition, min.

Optimization of parameters of manufacturing process of a group of threaded holes

Based on the model described above, the problems of optimizing the technological parameters of the process of manufacturing a group of threaded holes M27-2-6H (20 pcs) were solved (Fig. 6). The detail “Plate” is made from dispersed-hardened composite alloy SAS-50.

The following optimization task was determined: increasing the accuracy of manufacturing threaded holes M27x2-6N by at least 20%, while increasing the total labor intensity of the processing route should not exceed 30%.

The structural model of the process of machining a group of holes is shown in Fig. 7.

As a result of optimization, the structure of the investigated process was determined, containing three processing stages. The processing stages have the following structure:

- The first processing stage: two technological transitions, each technological transition contains one working stroke. The processing method is drilling.
- The second processing stage: one technological transition containing 11 working strokes. The machining method is milling.
- The third processing stage: one technological transition containing four working strokes. The processing method is thread milling.

Thus, the technological processing route of the investigated group of threaded holes contains four technological transitions:

- Technological transition No. 1 – “Centering”.
- Technological transition No. 2 – “Hole drilling φ12”.
- Technological transition No. 3 – “Hole milling φ25”.
- Technological transition No. 4 – “Thread milling M27x2-6H”.

The technological route for processing a group of threaded holes M27x2-6N is multi-stage. In this regard, individual optimization problems were identified for each technological transition:

- Technological transition No. 1: reduction of labor intensity of the forming process by at least 20%, while the increase in the processing error should not exceed 15%.
- Technological transition No. 2: reduction of labor intensity of the forming process by at least 15%, while the increase in the processing error should not exceed 20%.
- Technological transition No. 3: reduction of the processing error by at least 15%, while the increase in labor intensity should not exceed 25%.
- Technological transition No. 4: reduction of the processing error by at least 15%, while the increase in labor intensity should not exceed 30%.

The set of cutting tools used as part of the technological processing route and the corresponding ranges of cutting modes are presented in Table 2.

Table 2

List of cutting tools and cutting mode ranges

The type of cutting tools	Cutting modes					
	V, m/min		*S*, mm/vol		*t*, mm	
	min	max	min	max	min	max
Centering φ8 A1174-8	85	115	0.15	0,25	–	–
Drill φ12 A3299XPL-12	160	180	0.35	0.45	–	–
Mill φ10 1P251-1000-XA 1630	80	110	0.5	0.75	1.3	0.5
Thread milling cutter P = 2 326R08-B251100VM-TH 1025	425	450	2		0.1	0.5

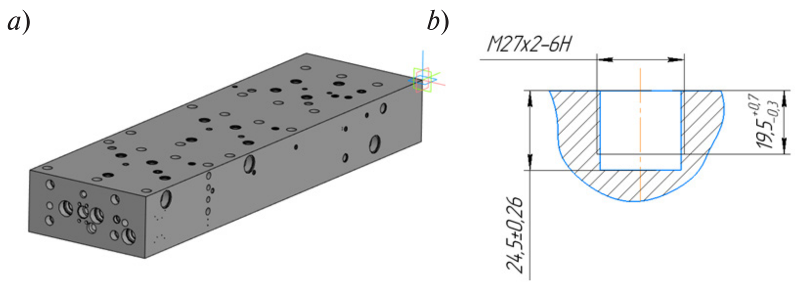

Fig. 6. *a*) solid model of the "Plate"; *b*) the sketch of threaded hole

The following optimization criteria are defined:

- The first processing stages: $\left(T_{bas}^{PrSt}\right)_1 \to \min$; $\left(T_{bas}^{TechTr}\right)_{1/1} \to \min$; $\left(T_{bas}^{TechTr}\right)_{2/1} \to \min$; $T_{1/1}^{WSt} \to \min$; $T_{1/2}^{WSt} \to \min$.
- The second processing stages: $Er_2^{PrSt} \to \min$; $Er_{1/2}^{TechTr} \to \min$; $Er_{1/1...11/1}^{WSt} \to \min$.
- The third processing stages: $Er_3^{PrSt} \to \min$; $Er_{1/3}^{TechTr} \to \min$; $Er_{1/4...4/1}^{WSt} \to \min$.

Tables 3 and 4 present a comparative analysis of target values and processing modes before and after the optimization process. Fig. 8 shows a comparative analysis of the efficiency of implementing a processing route for a group of holes before and after the optimization process.

Table 3

Value of the cut mode settings before and after the optimization process

Processing stage	**Technological transition**	**Cutting parameter**					
1	Technological transition No. 1 – "Centering"	**Before optimization**			**After optimization**		
	Technological transition No. 2 – "Hole drilling φ12"	*V*, m/min	*s*, mm/rev	*t*, mm	*V*, m/min	*s*, mm/rev	*t*, mm
2	Technological transition No. 3 – "Hole milling φ25"	90	0.17	–	105	0.2	–
3	Technological transition No. 4 – "Thread milling M27x2-6H"	160	0.12	–	175	0.19	–
		110	0.055	1.0	95	0.06	0.8
		220	2	0.4	230	2	0.4
		220		0.4	230		0.3
		215		0.2	230		0.2
					215		0.1

Conclusions

The following results were obtained:

1. Technological transition No. 1 "Centering": increase of center hole processing error by 10.2%, while reducing labor intensity by 30%.
2. Technological transition No. 2 – "Hole drilling φ12": increase of processing error by 18%, while reducing labor intensity by 23.2%.
3. Technological transition No. 3 – "Hole milling φ25": reduction in processing error by 25%, while increasing labor intensity by 23.9%.
4. Technological transition No. 4 – "Thread milling M27x2-6H": reduction in processing error by 22.2% while increasing labor intensity by 24.32%.

Table 4

Value of targets for process transitions before and after the optimization process

Processing stage	Technological transition	Targets																	
		Tr^{31}		Tr^{32}														Tr^{33}	
		$\left(Er_i^{WSt}\right)_{1n}$		$\left(C_{ct}^{TechTr}\right)_{mn}$		$\left(C_{w}^{TechTr}\right)_{mn}$		$\left(C_{qwq}^{TechTr}\right)_{mn}$		$\left(C_{am}^{TechTr}\right)_{mn}$		$\left(C_{rep}^{TechTr}\right)_{mn}$		$\left(C_{el.en.}^{TechTr}\right)_{mn}$		$\left(T_{bas}^{TechTr}\right)_{mn}$		$\left(T_{aux}^{TechTr}\right)_{mn}$	
		before	**after**	**before**	**after**	**before**	**after**	**before**	**after**	**before**	**after**	**before**	**after**	**before**	**after**	**before**	**after**	**before**	**after**
1	Technological transition No. 1 – "Centering"	49	54	2.77	1.94	6.8	5.01	–	–	1.28	0.96	0,04	0.03	0.06	0.04	0.5	0.35	0.52	0.41
	Technological transition No. 2 – "Hole drilling φ12"	177	209	3.1	2.38	7.2	5.6	–	–	1.36	1.05	0,05	0.04	0.065	0.5	0.56	0.43	0.52	0.41
2	Technological transition No. 3 – "Hole milling φ25"	24	18	3.26	1.76	11	12.1	–	–	2.01	2.28	0,11	0.13	0.13	0.16	1.13	1.4	0.52	0.41
3	Technological transition No. 4 – "Thread milling M27x2-6H"	18	14	16.18	20.11	22.9	26.9	–	–	4.33	5.1	0,29	0.35	0.34	0.43	2.92	3.63	0.52	0.41

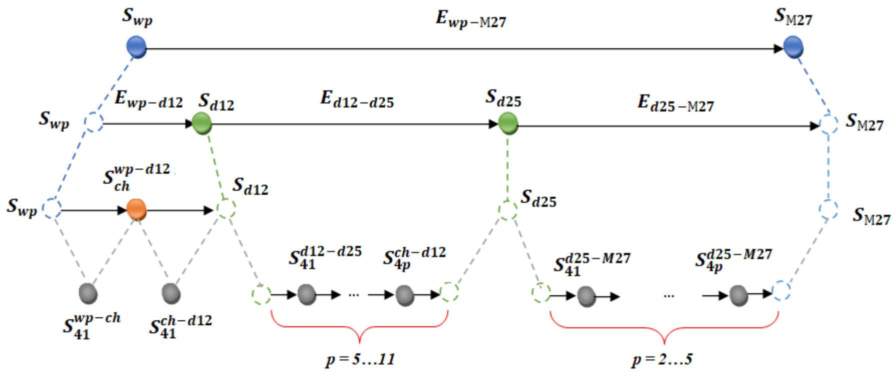

Fig. 7. Structural model of the threaded hole machining process

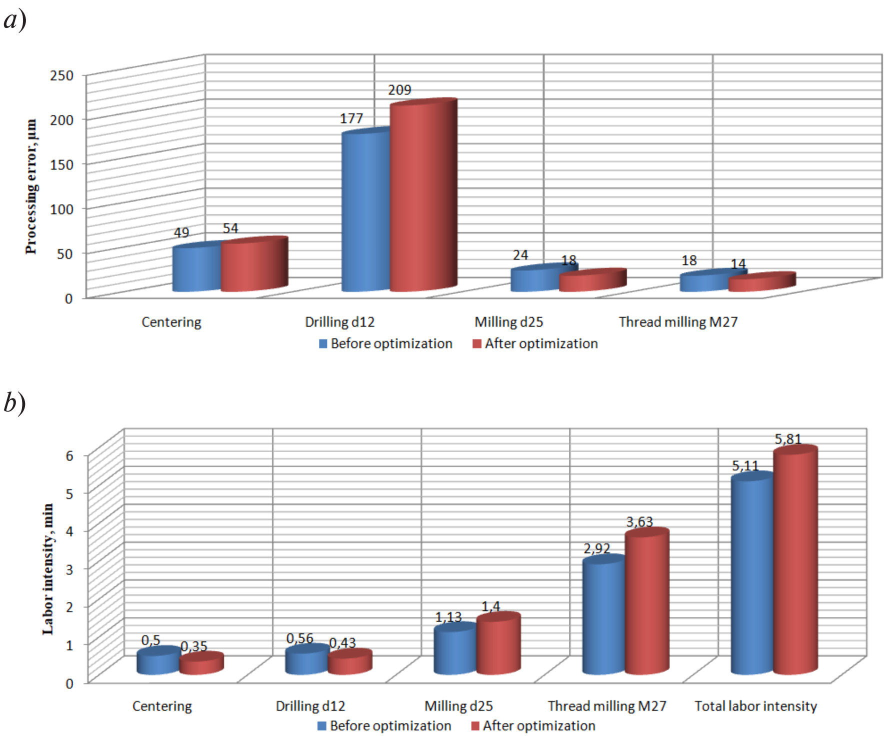

Fig. 8. Benchmarking targets before and after optimization.
a) comparative analysis of processing errors generated as part of the technological transition;
b) comparative analysis of labor intensity of technological transitions

The total labor intensity of the process of manufacturing a group of threaded holes increased by 13.69%. The results obtained correspond to the optimization condition, based on which it can be concluded that the goal of the work has been achieved.

The model of optimization of the parameters of the process of forming threaded holes presented in the work can be considered as a basic element of a complex model of optimization of the parameters of the technological process of manufacturing a product. This model can be used to optimize the parameters of the process of forming geometric elements of various types that form the structure of the product. For this, it is necessary to clarify the calculation formulas for a group of target indicators characterizing the accuracy of the parameters describing the configuration of a geometric element.

REFERENCES

1. **Khrustaleva I.N., Larionova T.A., Lyubomudrov S.A., Chernykh L.G., Stepanov S.N.** Automating production engineering for custom and small-batch production on the basis of simulation modeling. *Journal of Physics: Conference Series*, 2021, Vol. 1753, Art. no. 012047. DOI: 10.1088/1742-6596/1753/1/012047

2. **Kostenko D., Shkodyrev V., Onufriev V.** Solving multicriteria optimization problem for an oil refinery plant. *Proceedings of International Scientific Conference on Telecommunications, Computing and Control*, 2021, Vol. 220, Pp. 131–140. DOI: 10.1007/978-981-33-6632-9_11

3. **Kostenko D.A., Onufriev V.A., Shkodyrev V.P.** Multicriterial optimisation of rectificational process based on SPEA2 algorithm. *St. Petersburg State Polytechnical University Journal. Computer Science. Telecommunications and Control Systems*, 2019, Vol. 12, No. 2, Pp. 39–49. DOI: 10.18721/JCSTCS.12204

4. **Kostenko D., Arseniev D., Shkodyrev V., Onufriev V.** Pareto optimization in oil refinery. *Data Mining and Big Data* (*DMBD 2020*), 2020, Vol. 1234, Pp. 26–33. DOI: 10.1007/978-981-15-7205-0_3

5. **Yassine H.M., Shkodyrev V.P.** The intelligent control system of optimal oil manufacturing production. *Proceedings of the 2020 3rd International Conference on Computational Intelligence and Intelligent Systems*, 2020, Pp. 131–135. DOI: 10.1145/3440840.344084

6. **Ivanov V.K.** Modeling and control integrated system of the enterprise facilities. *Avtomatizatsiia i Sovremennye Tekhnologii* [*Automation and Modern Technologies*], 2012, Vol. 7, Pp. 34–39.

7. **Terekhova A.S., Pervov M.L.** Concept of a technique for the optimum technology selection considering provisions of a specific production division. *Vestnik RGATU imeni P.A. Solov'eva* [*Bulletin of RSATU named after P. A. Solovyov*], 2018, Vol. 46, No. 3, Pp. 88–93.

8. **Krotov K.V.** A branch and bound algorithm for the optimization of batch scheduling in pipeline systems. *Information and Control Systems*, 2023, Vol. 2, Pp. 15–26. DOI: 10.31799/1684-8853-2023-2-15-26

9. **Ivanov A.A., Bochkarev P.Yu.** Formalising of the optimal scheduling problem in multinomenclature production of machining process. *Vestnik of Saratov State Technical University*, 2011, Vol. 56, No. 2, Pp. 61–69.

10. **Golovina L., Bugaenko M.V., Timokhin D.V., Popova G.I.** Using the Technological cycle closure model for digital modeling of the economics of production processes. *Procedia Computer Science*, 2022, Vol. 213, Pp. 808–815. DOI: 10.1016/j.procs.2022.11.138

11. **Radicic D., Petković S.** Impact of digitalization on technological innovations in small and medium-sized enterprises (SMEs). *Technological Forecasting & Social Change*, 2023, Vol. 191, Art. no. 122474. DOI: 10.1016/j.techfore.2023.122474

12. **Xu Y., Yuan L., Khalfaoui R., Radulescu M., Mallek S., Zhao X.** Making technological innovation greener: Does firm digital transformation work? *Technological Forecasting & Social Change*, 2023, Vol. 197, Art. no. 122928. DOI: 10.1016/j.techfore.2023.122928

13. **Martyn Y., Liaskovska S., Gregus M., Izonin I., Velyka O.** Optimization of technological's processes Industry 4.0 parameters for details manufacturing via stamping: Rules of queuing systems. *Procedia Computer Science*, 2021, Vol. 191, Pp. 290–295. DOI: 10.1016/j.procs.2021.07.036

14. **Qin J., Liu Y., Grosvenor R.** A categorical framework of manufacturing for Industry 4.0 and beyond. *Procedia CIRP*, 2016, Vol. 52, Pp. 173–178. DOI: 10.1016/j.procir.2016.08.005

15. **ElMaraghy H., Schuh G., ElMaraghy W., Piller F., Schönsleben P., Tseng M., Bernard A.** Product variety management. *CIRP Annals*, 2013, Vol. 62, No. 2, Pp. 629–652. DOI: 10.1016/j.cirp.2013.05.007

16. **Tao F., Qi Q., Wang L., Nee A.Y.C.** Digital twins and cyber–physical systems toward smart manufacturing and Industry 4.0: Correlation and comparison. *Engineering*, 2019, Vol. 5, No. 4, Pp. 653–661. DOI: 10.1016/j.eng.2019.01.014

17. **Kang K., Zhong R.Y.** A methodology for production analysis based on the RFID-collected manufacturing big data. *Journal of Manufacturing Systems*, 2023, Vol. 68, Pp. 628–634. DOI: 10.1016/j.jmsy.2023.05.014

18. **Ma S., Zhang Y., Lv J., Ge Y., Yang H., Li L.** Big data driven predictive production planning for energy-intensive manufacturing industries. *Energy*, 2020, Vol. 211, Art. no. 118320. DOI: 10.1016/j.energy.2020.118320

19. **Zhang Y., Zhang R., Wang Y., Guo H., Zhong R.Y., Qu T., Li Z.** Big data driven decision-making for batch-based production systems. *Procedia CIRP*, 2019, Vol. 83, Pp. 814–818. DOI: 10.1016/j.procir.2019.05.023

20. **Pan J.Z, Vetere G., Gomez-Perez J.M., Wu H.** Exploiting linked data and knowledge graphs in large organisations. Cham: *Springer*, 2017. DOI: 10.1007/978-3-319-45654-6

21. **Fensel D., Şimşek U., Angele K., Huaman E., Kärle E., Panasiuk O., Toma I., Umbrich J., Wahler A.** How to use a knowledge graph. In: *Knowledge Graphs*. Cham: Springer, 2020. DOI: 10.1007/978-3-030-37439-6_3

22. **Jawad M.S., Dhawale C., Bin Ramli A.A., Mahdin H.** Adoption of knowledge-graph best development practices for scalable and optimized manufacturing processes. *MethodsX*, 2023, Vol. 10, Art. no. 102124. DOI: 10.1016/j.mex.2023.102124

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