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Improving the efficiency of technological preparation of single and small batch production based on simulation modeling

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Technological preparation of production is an integral stage of the production process, which is characterized by high complexity, which is largely felt in the conditions of single and small-scale types of production. The effectiveness of technological preparation of production is increased through automation with the use of simulation modeling. The objective of the study is to develop a simulation model that allows you to determine a rational version of the process for processing a batch of parts. The simulation model described in the article allows to analyze the production schedule of the enterprise, build processing routes, evaluate options for using various types of workpieces and technological equipment, determine the acceptable values of cutting conditions, and choose a rational variant of the technological process of processing a batch of parts. The developed simulation model is based on the principles of modular technologies, the part is considered as a combination of individual elementary surfaces. Each elementary surface contains information about the technological processing route, technological equipment and the type of technological equipment used in its manufacture, cutting conditions and the size of the allowance for each processing stage. The rational choice of the technological process is selected on the basis of multicriteria analysis according to three criteria: the value of variable costs, the production time of a batch of parts and the value of the processing error. The analysis of these criteria is made and the parameters that have the greatest impact on their value are determined. The developed classification of surface elements is described: design elements, technological elements, basic elements, as well as a mathematical model based on which the calculation of the values of the criteria for choosing a rational option.

Key words: simulation modeling; cutting modes; processing error; mathematical model; processing route

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Introduction. Technological preparation of production is an integral part of the production process. Technological preparation of production (TPP) is a set of interconnected processes that ensure the technological readiness of the enterprise to produce products of the required quality at certain time limits, volume of production and costs [3]. The main stages of the TPP are: analysis of the design of the part and formulation of technological tasks, the choice of the method of obtaining the workpiece, the development of technological processing routes, the selection of technological equipment, the design of technological operations, the execution of a set of technological documentation.

Currently, process control in engineering is one of the most promising areas of its development [11]. The stage of technological preparation of production is a rather laborious process. The high complexity of this stage of the production process is largely felt in the conditions of single and small-scale production, the distinguishing features of which are a wide range of products with a small volume of output, the absence of specialized work places, high complexity and a long production cycle of manufacturing products. Reducing the duration of the TPP stage is possible by means of to automation based on information technology. Integrated automation of technological training based on information technology provides [4]: reduction of production preparation time; optimization of labor costs and funds for manufacturing products; prompt implementation of changes in the process when changing external conditions with automatic recalculation of the process.

A large number of scientific articles are devoted to the problems of automation of technological preparation of production. In article [14], a model of technological preparation of production is described, which allows, based on a three-dimensional parametric model, design documentation, and information about the material, to design a route technological process, a workshop route and select preliminary schemes for processing individual surfaces. The article [1] describes an automated system for selecting processing strategies for design and technological elements (DTE), the results of which formulate recommendations on the tool strategy for processing DTEs, cutting tools, cutting modes, as well as a preliminary calculation of the processing time and cost. In the models described in the scientific literature [1, 2, 6-9, 13-20], the multivariance of technological process design and the selection of a rational option for manufacturing a batch of parts based on multicriteria analysis are not considered.

The objective of the study is to develop a simulation model of the technological preparation of production, which allows, based on the simulation of the production process, to choose a rational option for manufacturing a batch of parts taking into account the analysis of various technological parameters (technological processing route, type and parameters of technological equipment, cutting tools, values of cutting modes, etc.).

Description of the simulation model. The developed simulation model of technological preparation of production is based on the principles of modular technologies, according to which the part is divided into separate elementary surfaces. To implement the modular principle, a classification of the elements of the part was developed, according to which all elements of the part are divided into three types.

• Design elements (DE): elementary surfaces of a part forming its contour (external cylindrical and conical surfaces, groove, threaded surface, etc.).

• Technological elements (TE): allowance elements for each processing step.

• Basic elements (BE): the elements of the part forming a set of technological bases at each stage of processing.

Figure 1 shows a diagram of a modular description of individual surfaces of a part.

The design elements are individual surfaces or combinations of surfaces that form the contour of the part (external and internal surfaces of revolution, grooves, threaded surfaces, splined surfaces, etc.). Design elements are divided into two types:

• elementary surfaces (ES) – a cylindrical surface, a conical surface, threads, etc.;

• functional blocks (FB) – a set of elementary surfaces of various types that perform a certain function (mounting holes, center holes, etc.).

Design elements are described by the following parameters:

$$DE = \{B_{DE}, T_{DE}, P_{DE}\},$$

where B_{DE} – design element view; $B_{DE} = 1$ – elementary surfaces; $B_{DE} = 2$ – functional blocks; T_{DE} – design element type; P_{DE} – design element parameters.

For an elementary surface ES $B_{DE} = 1$:

$$T_{DE} = T_{DE}^{ES} = \{T_1; T_2\},$$

where T_1 – type of elementary surface (outer surface of rotation, etc.); T_2 – view of the elementary surface (conical, cylindrical, etc.);

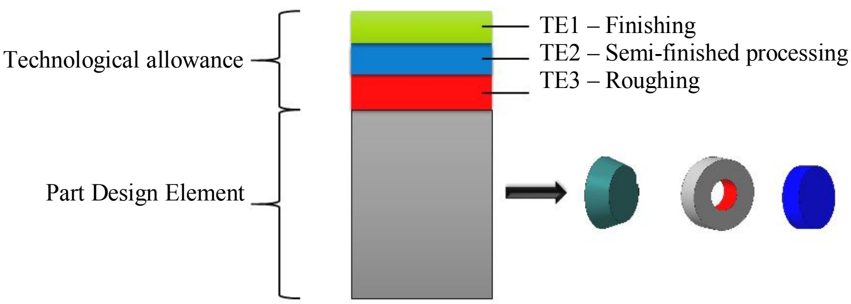

Fig.1. Scheme of modular description of individual surfaces of the part

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$$\Pi_{DE} = \Pi_{DE}^{ES} = \{GP_{DE}, IT_{DE}, Ra_{DE}, PMP_{DE}; TRP_{DE},\},$$

GP_{DE} – ES geometrical parameters; IT_{DE} – surface manufacturing accuracy (tolerance field) of ES; Ra_{DE} – surface cleanliness (roughness) of ES; PMP_{DE} – physical and mechanical properties of ES; TPR_{DE} - technological route for processing of ES.

For function block (FB) $B_{DE} = 2$:

$$T_{DE} = T_{DE}^{FG} = \left\{\Sigma_{i=1}^{n}\left(T_{DE}^{ES}\right)_n\right\};$$

$$P_{DE} = \Pi_{DE}^{FG} = \left\{TPR_{FG}; \Sigma_{i=1}^{n}\left(T_{DE}^{ES}\right)_n\right\},$$

where TPR_{FB} – functional block processing route.

Technological elements are also described on the basis of two groups of parameters – technical and technological:

$$TE = \{T_{DE}^{ES}, TxP; TlP\},$$

$$TxP = \{GP_{TE}, IT_{TE}, Ra_{TE}, PMP_{ES}\},$$

$$TlP = \{PS_{TE}, PM_{TE}, TEq_{TE}, CT_{TE}, CC_{TE}\},$$

where TxP – technical parameters; TlP – technological parameters; GP_{TE} – geometric parameters of the technological element; IT_{TE} – technological element tolerance field; Ra_{TE} – surface roughness of the technological element; PMP_{TE} – physical and mechanical properties of the technological element; PS_{TE} – processing step to which the process element belongs; PM_{TE} – processing method by which the processing of a technological element; TEq_{TE} – technological equipment on which the processing of the technological element is performed; CT_{TE} – cutting tool with which the processing of the technological element; CC_{TE} – cutting conditions in which the processing of the technological element.

The combination of basic elements (BE) forms a set of technological bases (STB), which has the following parameters:

$$STB = \{PS_{TG}; \Sigma_{i=1}^{n} DE_n; \Sigma_{i=1}^{m} TE_m\},$$

where PS_{TG} – processing stage, to which technological elements belong, processed with this set of technological bases; DE_n – design elements forming a set of technological bases; TE_m – technological elements forming a set of technological bases;

Figure 2 shows a diagram of a simulation model of technological preparation of production. The choice of a rational process option can be divided into 7 stages. At the first stage, many of design and technological elements are determined, their parameters are set, and a set of technological bases is formed on the basis of basic elements.

At the second stage, surface blocks (SB) and technological groups (TG) are formed. Under the block of surfaces should be understood as a set of elementary surfaces that are similar in terms of technology. A technological group is a set of technological elements that can be processed in the structure of one technological transition.

Design elements can be combined into a block of surfaces if the following conditions are met:

• design elements included in the block of surfaces belong to one type – the outer surface of rotation, the inner surface of rotation, etc.;

• at each stage of processing, technological elements have at least one common value for each parameter – the processing method, technological equipment, and cutting tools.

Technological elements can be combined into technological groups if the following conditions are met:

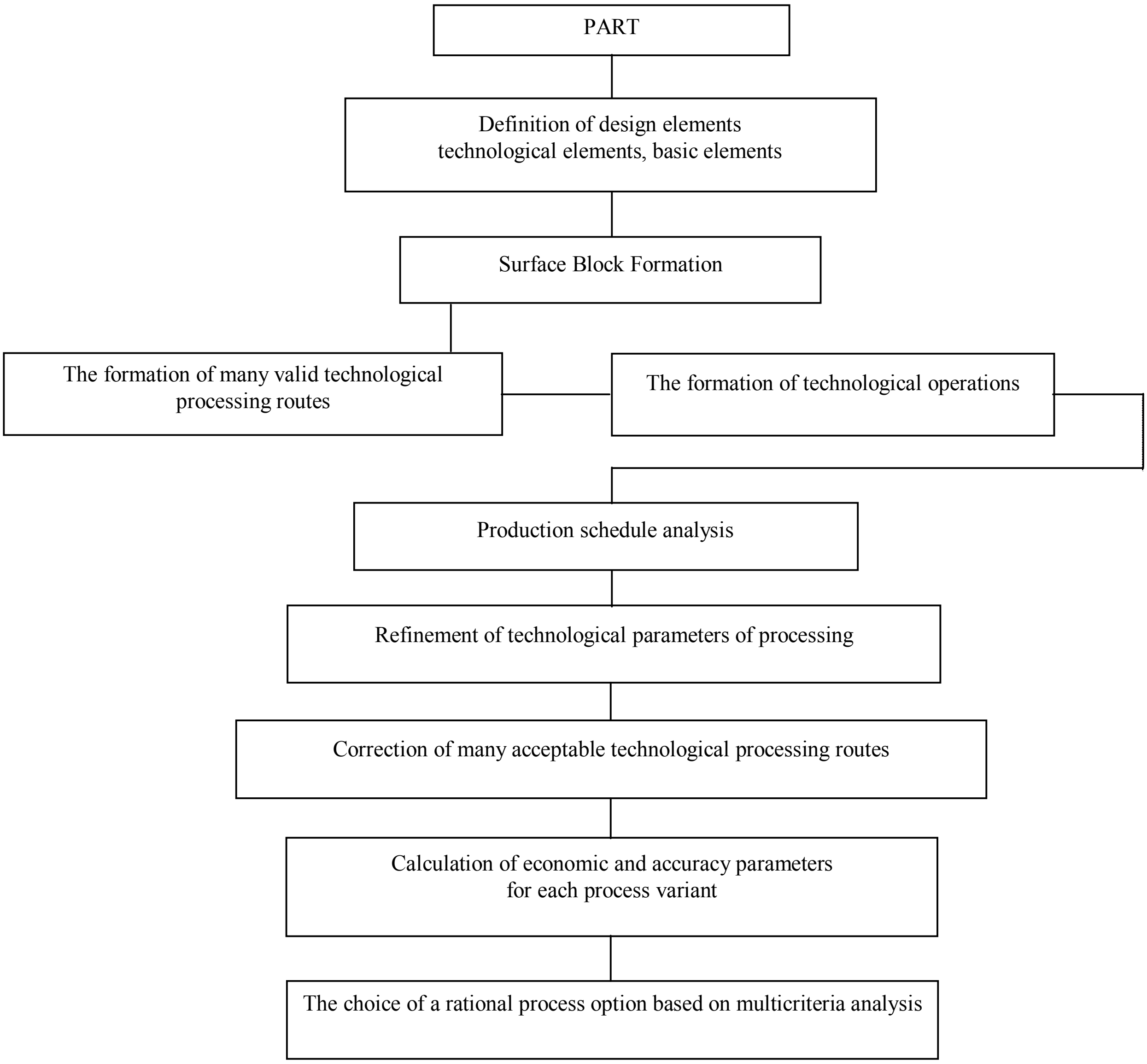

Fig.2. Scheme of a simulation model of technological preparation of production

• technological elements that are part of the technological group belong to one stage of processing PS_{TE} = const;

• for each technological element included in the technological group, the value of the TBP_{TE} parameter (set of technological bases for processing TE) is the same.

At the third stage, permissible technological processing routes are formed, which are determined on the basis of an analysis of the existing technological equipment and the methods used to obtain workpieces.

At the fourth stage, the production schedule is analyzed according to the following conditions:

• the availability of free time intervals that can be used to process a batch of parts;

• the location of free time intervals should correspond to the technological processing route (Fig.3);

• the values of free time intervals should be greater than or equal to the duration of the corresponding technological operations.

Based on the simulation, the correction of the set of valid technological processing routes is performed. Variants of technological processing routes that do not satisfy at least one of the conditions are excluded from the allowable set.

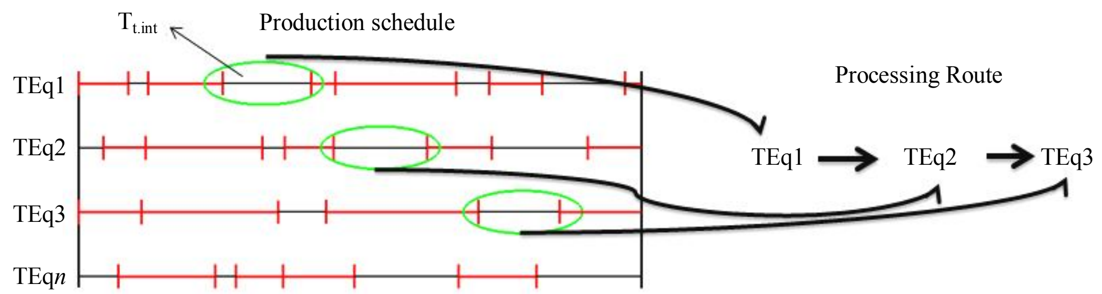

Fig.3. Production schedule analysis

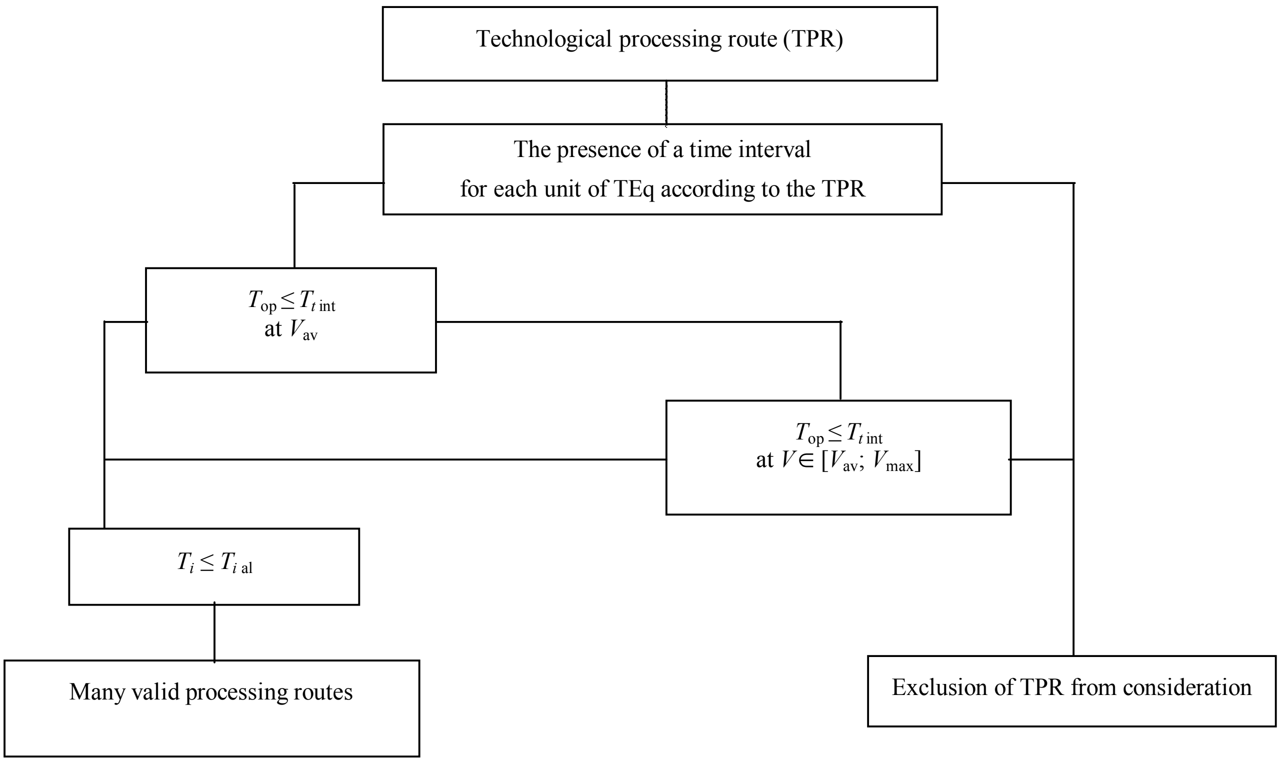

Fig.4. Algorithm for the formation of many valid options

Figure 4 shows the algorithm for generating the set of valid processing options.

Symbols in Fig.3, 4: TEq – technological equipment; T_{op} – the rate of operative time; T_i – production time for a batch of parts; T_{ial} – allowable production time for a batch of parts; $T_{t\,int}$ – value of the time interval on the production schedule; V_{av} – average processing speed; V_{max} – value of maximum processing speed.

At the fifth stage, technological operations are formed for each admissible processing route. Each technological operation in the structure of one technological route is a multivariate. The multivariance of the technological operation lies in the availability of alternative applications for various types of workpieces, technological equipment (cutting tools) and cutting conditions.

At the sixth stage, the analysis of many technological processing routes is carried out taking into account the multivariance of technological operations. Analysis of each technological processing route is based on the production schedule taking into account the loading of each unit of technological equipment.

At the seventh stage, a rational choice of the technological process is made. A rational version of the technological process is determined on the basis of the analysis of three criteria: the value of variable costs, the duration of the production cycle and the value of the processing error. To develop a mathematical model, these criteria were analyzed and the parameters that have the greatest impact on their value were identified. The following parameters have the most significant impact: the type and geometry of the cutting tool, the type and technical characteristics of the technological equipment, the method of obtaining the workpiece, the processing method, and the qualifications of the main production workers.

The content and parameters of each stage of modeling are presented in the table.

Simulation Model Parameters

Processing stage	Stage Content	Input parameters	Output parameters
1	Part Design Analysis The formation of many design elements The formation of many technological elements The formation of many basic elements (sets of technological bases)	Design documentation (detail drawing): technical parameters of individual surfaces	A plurality of design elements A plurality of processing elements, cops A plurality of base elements (sets technological bases)
2	The formation of blocks of surface SB Formation of TG technological groups in each block of surfaces	A plurality of design elements M_{DE} A plurality of processing elements M_{TE} Many basic elements (sets of technological bases) M_{BE}	A plurality of surfaces of blocks M_{SB} Many technology groups M_{TG}
3	Technology Group Analysis Formation of technological processing routes	Many technology groups Type and technical parameters of technological equipment	Many technological M_{TPR} processing routes.
4	Production schedule analysis Determination of the current load of technological equipment Identification of free time intervals for each unit equipment Defining free time intervals	Production schedule	Size and location of free time slots
5	The formation of the structures of technological operations for each processing route	A plurality of process groups A plurality of technological processing routes	Set of technological documentation
6	Modeling of each technological route taking into account its multivariance Determination of the duration of the production cycle, the value of variable costs, the accuracy of processing the most critical surfaces for each variant of the technological process, taking into account its multivariance	Sets of technological documentation Process parameters	Production cycle duration The value of variable costs Processing accuracy of the most critical surfaces
7	Determining the value of the objective function for each variant of the technological process, taking into account weight coefficients Choosing a rational option on based on objective function values	Production cycle duration The value of variable costs Processing accuracy for the most critical surfaces	The rational version of the process

Description of the mathematical model. To determine the rational variant of the technological process of processing a batch of parts, the following parameters are calculated:

• production time for a batch of parts T_{BP};

• variable costs C_{var};

• machining accuracy y_i.

The objective function can be written as follows:

$$F_{\text{BP}} = \frac{(T_{\text{BP}})_i}{(T_{\text{BP}})_{\min}} K_T + \frac{(\text{C}_{\text{var}})_i}{(\text{C}_{\text{var}})_{\min}} K_3 + \sum_{i=1}^{n} \left(\frac{(\Delta_\Sigma)_i}{(\Delta_\Sigma)_{\min}} \right)_j K_\Delta ;$$

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$$K_T + K_C + K_\Delta = 1,$$

where $(T_{BP})_i$ – the duration of the production cycle according to the i-th version of the technological process; $(T_{BP})_{min}$ – minimum duration of the production cycle for TPR included in M^{PC}_{TPR}; $(C_{var})_i$ – the value of the variable costs of manufacturing a batch of parts according to the i-th version of the process; $(C_{var})_{min}$ – minimum value of variable costs for TPR included in M^{PC}_{TPR}; $(\Delta_\Sigma)_i$ – the value of the processing error obtained by the *i*-th process variant; $(\Delta_\Sigma)_{min}$ – the minimum value of the processing error for the estimated parameter obtained during the implementation of the TPR included in M^{PC}_{TPR}; K_T, K_C, K_Δ – weighting factors.

The duration of the production cycle depends on the norm of operating time and the amount of downtime. The norm of operational time is determined by the formula [5]:

$$T_{op} = T_o + T_{aux}.$$

where T_o – base (machine) time, min; T_{aux} – auxiliary time, not covered by the base one, min.

In determining the variable costs of producing a batch of parts, the following cost categories were taken into account: the amount of material costs M, Labor costs C, deductions for mandatory state social insurance O [12];

$$M = \Sigma_{i=1}^{m} Pr_{mj} M_j,$$

where Pr_{mj} – purchase price of the natural unit of the *j*-th material resource, rubles/unit; M_j – the number of natural units of the *j*-th material resource; *m* – number of items of material resources;

$$C = \alpha N\left(1 + \frac{P_{add.w}}{100}\right),$$

α – the average basic salary of one employee of an enterprise for a billing period of time, rubles / person.; N – average number of staff for the same period, people.; $P_{add.w}$ – average value of additional wages as a percentage of the basic, %;

$$O = C\frac{P}{100},$$

P – calculated on the basis of legislation, the total percentage of deduction to funds from the amount of expenses on labor remuneration (rubles).

The processing error (μm) is determined by the formula [10]:

$$y_i = 2[\Delta(i) + u(\tau, i) - \xi_p(i, \tau, u, t) - \xi_д(\xi_p) + \Delta_y(\tau, u)] + \eta_i;$$

total positioning error

$$\Delta_i = K_1(i + 1) + K_2;$$

cutting tool wear

$$u(i, \tau) = K_3\tau + K_3(i - 1) + K_4\left(1 - e^{-\frac{(i-1+\tau)}{K_5}}\right);$$

thermal deformation of the cutting tool

$$\xi_p(i, \tau, u, t) = K_6 t^{0,85}(1 + K_7 u)\left(1 - e^{-\frac{\tau}{K_8}}\right) + e^{\frac{\tau_{охл}}{8}} \xi^{max}_{p(i-1)} e^{-\frac{\tau}{K_8}};$$

thermal deformation of the part

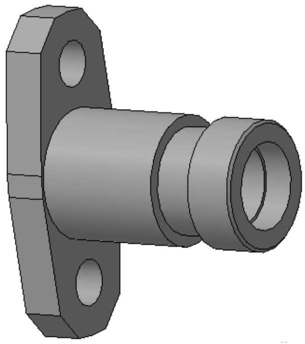

Fig.5. Solid state model of the detail «Vtulka»

$$\xi_d(\xi_p) = K_9\xi_p;$$

elastic deformation of the technological system

$$\Delta_y(\tau, u) = K_{10}\, t(1 + K_{11}\, u)\,(1 - K_{12}\,\tau);$$

unspecified part of the random component of the processing error

$$\eta_i = \pm\sigma,$$

where i – batch part number; τ – processing time of the i-th part; t – cutting depth; τ_{cool} – cutting tool cooling time before machining the i-th part; K_1-K_{12} – coefficients depending on the processing parameters (material of the part, material of the cutting part of the tool, characteristics of technological equipment, etc.)

Practical application of the model. The described simulation model is used at the stage of technological preparation for the production of a ship repair plant (St. Petersburg). The main activity of the enterprise is the repair and maintenance of small vessels, as well as the manufacture of small lots of parts (single and small-scale production). Fig.5 shows the solid model of the «Vtulka»part, which must be manufactured in an amount of 200 pcs.

Solved technological problems. The most accurate surface is the outer cylindrical ϕ23k6, Ra0,8, the accuracy of the manufacture of the remaining surfaces in the range of 11-14 qualifications with the purity of the surface layer Rab.3-Ra12.5.

The options for blanks – round rolling and forging are considered.

The following technological equipment was installed at the enterprise: BMV850 milling machines (2 pcs.), Multus B200 turning and milling machine, Multus B300 turning and milling machine, DUS400 turning machines (2 pcs.), DUS560 lathe, circular grinding machine FCD200.

When simulating the manufacturing process of manufacturing a batch of parts «Vtulka» were considered eight allowable technological processing routes. For each technological processing route the technological processes are designed. Simulation of each technological transition was carried out using three alternative cutting tools.

Taking into account all the possible options for technological processing routes, technological equipment, types of workpieces, and technological equipment, 2531 technological process variants were modeled. For each variant of the technological process, the production time of a batch of parts, the value of variable costs and the error value for the most accurate surfaces were calculated. Based on these indicators, for each variant of the technological process, the value of the objective function is determined taking into account the weight coefficients and a rational option is selected. The following weights were adopted: $K_T = 0.35$, $K_C = 0.45$, $K_\Delta = 0.2$.

Conclusions. The developed simulation model of technological preparation of production allows us to solve the following problems:

• to analyze the production schedule;

• form a set of acceptable options for the technological process of processing for a batch of parts;

• to analyze each variant of the technological process, taking into account its multivariance (the use of various options for technological equipment, cutting conditions, types of workparts, etc.);

• for each process variant, determine the duration of the production cycle, the value of variable costs, the value of the processing error for the most critical surfaces.

• choose a rational version of the technological process of processing a batch of parts based on multicriteria analysis.

Thus, the application of the developed simulation model can significantly reduce the complexity of the stage of technological preparation of production and choose a rational option for manufacturing a batch of parts based on multicriteria analysis.

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