Methodology of Manufacturing Process Design, Providing Quality Parameters and Minimal Costs

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Abstract: The article considers a methodology of manufacturing process design. It contains the parametric and structural optimization elements and based on the dynamic programming method. As a target function is selected the total cost of the technological process. As the technical limitations a vector of quality indicators was chosen. As input parameters the technological modes were used. Effectiveness of the developed methodology is demonstrated by the example of optimization of technological process of manufacturing of electrical machines’ collectors. The manuscript includes the results of theoretical and experimental studies of surface plastic deformation of roller contact surface of the reservoir. An empirical model of the formation of roughness of the surface, methodology minimizing surface waviness, the method of ensuring the required hardness of the surface treated is shown.

Keywords: Optimization of technological processes • Structural optimization • Parametric optimization • Dynamic programming • Collectors for direct-current motors • Surface plastic deformation of roller • Vector of the quality indicators

INTRODUCTION

Majority of machine-building enterprises do not work in optimal conditions and there is a great potential to improve resource and energy consumption. A number of reasons prevents effectively solve the problem of optimization of the production process in general and technological processes in particular. The process of development of mathematical models is not formalized, but the final output depends on adequateness of mathematical model.

A process of optimization of complex products belongs to the class of large systems optimizations. Thereby, the optimization is performed, as a rule, for individual simpler sub-problems. In mechanical engineering the cutting parameters for individual operations are the most commonly optimized. The optimization criteria can contradict each other. These criteria could be the minimum costs and the maximum process speed. The optimization of separate operations does not solve the optimization problem for the system as a whole. This prevents the development on unambiguous technological recommendations and decisions. Therefore, the important task is to develop a methodology of designing of technological processes, allowing to solve the problem of optimization.

Difficulty in solution of the optimization problem is the intersection of structural and parametric optimizations. For example, depending the capabilities of the hardware, the rigidity of the technological systems depends largely on the structure of the turning operation. If technological system has a low malleability, the accuracy can be ensured for one process step. Otherwise, you may have two or more processes steps. Optimization should be tiered. It should solve the problem on a level of the manufacturing route, operation and step.

Methodology: For optimization algorithm of Bellman’s dynamic programming (DP) algorithm in a discrete form is used. The main advantage of this method is the principle of step-by-step optimization taking into account the development of the process in time. Each step is optimized to take the account of all his influences in the future. Dynamic programming determines the optimal solution to
Fig. 1: Graph of the structural variants of the collector manufacturing: $E$ – the vector of final indicators of quality; $E_i$ – the vector of quality indicators on the i-th technological operation

the problem through its decomposition of n stages. Search of optimal technological solution implies many variants of structural decision and the method for DP reduces the number of possible variants of the search using the rules of domination and excludes hopeless variants. Calculations are recursive; i. e. the optimal solution of one sub-task is used as initial data for the following sub-tasks.

Here is the short description of the topics discussed in the main part of the paper. In that part we discuss following aspects of DP algorithm implementation to the design of DC current motor collector.

- Analysis of typical production process in terms of the availability of alternatives, improvement of its productivity and cost efficiency.
- Transition to the formal set of parameters for the optimization: vector of output quality parameters is defined, model for the quality parameters evolution on different stages of the technological process. If preliminary engineering analysis is available, the output parameters vector is defined to match exploitation conditions [6].
- Graph type «tree» (Fig. 1) displaying the possible options for the structure of the technological process is formed.
- Validation of technological parameters of the operations is performed taking into account the operational loads.
- The objective function and the type of criteria of extrema are proposed. For example, we define a minimized cost function depending on technological modes and metal-working machinery structure.
- For each technological operation a system of numerical constraints is formed. Constraints show the relationship provided by quality parameters when performing certain operations. These quality parameters include vibrations in turning [8], the surface microrelief in turning [9] and the output parameters of the quality of the finish of plastic deformation operation [10].
- The analytical optimization solution is derived.

The above sequence is used to optimize the technological process of manufacturing of the collector direct current motor.

Analysis of the model of technological process of manufacturing of reservoirs revealed the following alternative structural decisions and activities, improved theoretical productivity and lead to potentially better cost efficiency.

The Alternative Structural Solutions:

- A method of assembly of direct-current motor depends on the precision of the collector plates. Assembly of collector plates in a circular arch can be performed by a method of complete
interchangeability or using selective assembly. Selective assembly increases the accuracy, however, reduces productivity and increases the cost of manufacture.

- Minimization of time of process heating is a subject to the requirements of quality. It allows to minimize the time and energy costs.
- The structure of the turning operation on the draft turning may consist of one or more steps. It depends on the required accuracy of shape of the collector and on the rigidity of the equipment used in the technological system used.
- Quality indicators for collectors affect the choice of the final processing method. Among these methods are traditional grinding or alternative surface plastic deformation.

As follows from above, the final vector of indicators of the quality of the product can be formed with different content and sequence of operations.

Figure 1 shows a graph presenting the structural variants of the developed technological process. Each structural variant of technological process has different performance and cost and is characterized by a specific sequence of change of parameters of quality.

The aim – to select the sequence and content of technological operations, ensuring the given parameters of quality are at the lowest cost of labour and material resources.

The next step is to assign a target function. As a rule, as a target function uses the maximum performance or minimum cost. These requirements are mutually exclusive and have a number of shortcomings. Increased productivity is often leads to additional costs. For example, the increase in productivity can reduce the tool life. Minimal cost, in contrast, can not provide high-production tool parameters. Therefore, as a target function will accept a complex parameter. It takes into account the performance and cost - total costs of implementation of the technological process.

\[
C = \sum_{i=1}^{n} V_i T_i \rightarrow \min
\]  

where \( C \) – a total costs; \( i \) – the number of the operations of the technological process; \( V \) – present value the \( i \)-operation of the technological process; \( T \) – time of the \( i \)-operation of the technological process.

Usage of the selected target function will allow getting maximum performance at minimum cost.

Recurrence expression used for solution of optimization tasks on i-stage, can be represented in the following form:

\[
C(x_i) = \min \{ C_i T_i + C_{i+1}(x_{i+1}) \}, i = 1, 2, \ldots, n,
\]  

were \( C(x_i) \) – the costs of the i-technological operation, \( C_{i+1}(x_{i+1}) \) – the total costs of all future for the i-technological operation operations.

If the original limit on the total amount of the costs is absent, the optimization solution is to minimize the cost of each operation.

Optimization solution to each sub-task is performed taking into account system constraints. In this case, the set of constraints is formed from given values of the of quality vector parameters. As input parameters we take quality parameters obtained at the previous operation of the technological process and invariable parameters of conducting the operation. For example, the parameters of the metal-cutting equipment, tooling, are cutting tools and others.

Cutting modes are the variable parameters. Output parameters are the vector quality parameters obtained after each step of solution (Figure 2). Important feature of the methodology is a combination of structural and parametric optimization taking into account environment and technological heredity. Structure of the technological process is formed simultaneously with the contents of the operations. Technological conditions of conducting operations are optimized using the method of linear programming with the introduction of limitations for the given values of quality parameters.

The quality parameters obtained at the previous operation are used as input parameters of next technological operation to take account of technological heredity.

It is necessary for systems of mathematical expressions for the technological operations to establish the linkages between the parameters of quality, conditions and modes of operation and output parameters of quality.

One of the important stages of optimization is the stage of establishing the relationship between the target function, the required quality parameters and optimal technological modes with variable criteria of optimality.

Let us discuss in more details the analysis of technological operations of manufacturing of collector direct-current motor and identify these relationships. First of all, we consider the operation of the final processing, as the method of dynamic programming provides selection of the optimum variant recursively, starting with the final stage.
As a final method for a given quality of the collector can be used traditional grinding or surface plastic deformation (roller burnishing).

Consider the operation of roller burnishing. The target function is to provide a minimum costs for implementation of operations

$$C_r = V_r T_r \rightarrow \min,$$

where $C_r$ – the costs of the operation roller burnishing; $V_r$ – the present value of transaction execution of the operation roller burnishing; $T_r$ – duration of execution of the operation roller burnishing.

Minimization of the objective function (3) should be a subject to the required quality parameters. The main parameter of the quality provided by surface plastic deformation operations is the roughness. As functions linking surface roughness with technological regimes we use other ones presented in the work [10]. More specifically, for technological modes, lying in the interval: tool advance is in 0,1-0,4 mm/turn interval, speed of roller burnishing 73-385 m/min interval, force of roller burnishing 200-1000 N:

$$r_a = 3,4 \cdot s^2 + \frac{2259820 + P \cdot (6460 \cdot s - 3005,8 - 53 \cdot \nu) - 31,8 \cdot \nu + 2,166 \cdot P^2}{1520000} \rightarrow \min,$$

where $s$ – roller advance mm/turn; $\nu$ – speed of roller burnishing m/min; $P$ – force of roller burnishing N.

In addition to the roughness of the surface, an important parameter determining the quality of surface modes is the waviness. The waviness should be minimized.

Minimum waviness is provided at an angle of indentation, lying in the interval $\varphi = 2-3^\circ$. Angle pressing in turn is a function of both the geometrical parameters of the treated surface and the technological modes [10]:

$$\varphi = \varphi_a + \varphi_b, \varphi_a = a \cdot \frac{r}{D_r}, \varphi_b = b \left( \frac{2}{D_r} + \frac{2}{D_{coll}} \right),$$

$$a = 2,6n_{a}, \sqrt{\frac{3}{2} \sum k b = 2,6n_{b}, \sqrt{\frac{3}{2} \sum k},}$$

$$\eta = \frac{1 - \mu^2}{E_r} + \frac{1 - \mu^2_{coll}}{E_{coll}},$$

where $D_r$ – diameter of roller, mm; $D_{coll}$ – diameter of collector, mm; $r$ – the radius of the roller profile, mm; $a$ $b$ – axis elliptical contact spot, mm; $n_a$, $n_b$ – the coefficients of the contact form; $P$ – force of roller burnishing, N; $\Sigma_r$ – total relative curvature contact solids at the point of contact, mm; $\mu$, $\mu_{coll}$, $E$, $E_{coll}$ – Poisson's ratio and modules of elasticity of materials roller and collector respectively.

System requirements could be extended by surface hardness, associated with the number of rolling cycles:

$$N = \frac{2}{s} \cdot a,$$

as well as the depth of the hardened layer $h = \omega \sqrt{\frac{P}{2\sigma_y}},$

$$\omega = \frac{1}{1 + 0,07R_{mod}} \cdot \frac{1}{1 + \frac{1}{R_{prof}} + \frac{1}{r}},$$

$\sigma_y$ – yield point of detail material, $N / mm^2$; $R_{mod}$; $r_{prof}$ – relative and profile roller radius, mm; $R$ – diameter of roller, mm; $r_i$ – roller radius, mm.

In all constrains presented the technological modes are included, which will be the control parameters. The productivity function which relates technological modes and objective function through the duration of the operation has the form:

$$P_{r \_turn} = \frac{l_{\_turn} \cdot \pi \cdot D_{coll}}{1000 \cdot s \cdot \nu},$$

where $l_{\_turn}$ – the length of the processed surface.

Taking into account the above expressions, the system of restrictions for the surface plastic deformation operation will have the form (4).
where $Ra_{\text{requisite}}$ – the specified surface roughness, mkm; $N_{\text{requisite}}$ – the specified number of cycles roller; $h_{\text{requisite}}$ – predefined the depth of the hardened layer, mkm; $v_{\text{max}}$, $s_{\text{min}}$, $s_{\text{max}}$, $P_{\text{min}}$, $P_{\text{max}}$ – respectively the minimum and maximum allowable roller speed, roller advance mm/turn; speed of roller burnishing m/min; force of roller burnishing, N.

The system includes all necessary components: the specified quality parameters, geometric and physical-mechanical parameters of the processed product and roller tool, valid intervals of technological modes, the function of the parameters of quality, expressed with regard to the technological modes, the function of the duration of execution of the operation, part of the objective function and expressed in terms of technological modes. If necessary, it may include other restrictions, for example, the surface hardness expressed directly through technological modes, the function of the voltage of the surface layers and others.

CONCLUSION

The algorithm developed was tested in the industrial settings at the collector of traction direct-current -motors production. We were able to confirm following effects and improvements:

- Reduces costs due to the exclusion of a round-grinding machine;
- Increased tool life in 15 times owing to the fact of replacement operation of semi-rough and finishing turning by surface plastic deformation. The surface plastic deformation is performed by spherical profile roller.
- Reduces machining time due to the exclusion of medium turning operations, overlapping operations of finish turning and roller;
- Removes selective assembly. and the basis of the precision of the production of collector plates;
- Cuts the basic run time finish of the operation in 7 times due to the the replacement of grinding with rolling;
- Reduces of the basic operation time spent on finish turning in 15 times. On experimental grounds we found $Ra_{1.25}$ before $Ra_{1.6}$. The new technological regimes found (explain the main idea and reason of changes) $s=0,05$ mm/turn, $v=80$ m/min, $r=1.5$ mm to: $Ra_{1.6}, s=0,2$ mm/turn, $v=310$ m/min, $r=3$ mm;
Reduces error arising from the tool wear 4 times from 15.4 microns to 3.85 microns (instrumental material VK 8).

The application of DP algorithm gives the following advantages for the design of technological processes:

- DP takes into account technological heredity at each step of the computation of technological operation or technological transition.
- Admits simultaneous parametric and structural optimization. I.e. helps to solve problems lying in the traditionally different domains, such as choice of technological regimes, technological operations order and methods of tooling and assembling.
- There is a wide spectrum of technological products where described methodology is applicable. They may have different complexity, technological type, optimization criteria.

Testing of the developed methodology in the manufacturing of collector traction mine motor proves its effectiveness for the performance increase in productivity-performed operations and for the reducing the cost of implementation of the technological process.

REFERENCES