Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2023 vol. 25 no. 2 pp. 45–67
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2023-25.2-45-67

NSTU NETI

Obrabotka metallov - Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

Hybrid technological equipment: on the issue of a rational choice of objects of modernization when carrying out work related to retrofitting a standard machine tool system with an additional concentrated energy source

Vadim Skeeba [a, *], *Egor Zverev* [1, b], *Pavel Skeeba* [2, c], *Aleksey Chernikov* [3, 1, d], *Andrey Popkov* [1, e]

[1] Novosibirsk State Technical University, 20 Prospekt K. Marksa, Novosibirsk, 630073, Russian Federation
[2] JSC "Novosibirsk switch plant", 7 Aksenov str., Novosibirsk, 630025, Russian Federation
[3] LLC "GLK-Industrial Technologies", 177 Bolshevistskaya st., shop 16, Novosibirsk, 630083, Russian Federation

[a] https://orcid.org/0000-0002-8242-2295, skeeba_vadim@mail.ru, [b] https://orcid.org/0000-0003-4405-6623, egor_z@ngs.ru,
[c] https://orcid.org/0000-0002-0327-992X, Pavel_skeeba_ptm@mail.ru, [d] https://orcid.org/0009-0006-9412-7687, aleksey.chernikov.97@mail.ru,
[e] https://orcid.org/0009-0006-5587-9990, andrej.popkov.2013@mail.ru

ARTICLE INFO

Article history:
Received: 15 March 2023
Revised: 17 April 2023
Accepted: 15 May 2023
Available online: 15 June 2023

Keywords:
Hybrid equipment
Multipoint machining
High energy heating
Cutting
Induction hardening

Funding
This research was funded by Russian Science Foundation project N 23-29-00945, https://rscf.ru/en/project/23-29-00945/.

Acknowledgements
Researches were conducted at core facility of NSTU" Structure, mechanical and physical properties of materials".

ABSTRACT

Introduction. Improving the competitiveness of manufactured products is impossible without achieving high rates of resource and energy saving, while providing modern machine tools with the proper level of production flexibility in combination with guaranteed high values of processing productivity and the required level of parts manufacturing quality. Insufficient or excess capacity of technological equipment leads to a decrease in its economic efficiency, an increase in capital costs and, as a result, an increase in the cost of production. In the machine tool industry, which is a strategically significant and basic industry for the modernization of mechanical engineering, there is a special interest in the development of a new type of technological equipment that makes it possible to implement methods for modifying the surface layers of parts by processing it with concentrated energy sources. The combination of two processing technologies (mechanical and surface-thermal operations) in the conditions of integrated equipment makes it possible to level the shortcomings of monotechnologies and obtain new effects that are unattainable when using technologies separately. Ensuring an optimal level of quality — one of the unconditional requirements of a market economy — is a priority when developing the overall concept of technological equipment. Thus, it should be noted that the required and specific set of consumer properties are laid down during the design. And, therefore, the problem of quality optimization belongs to the field of forecasting and should be comprehensively addressed at the initial stage of developing the concept of technological equipment. The purpose of this research is to rationally choose the objects of modernization when carrying out work related to retrofitting a standard machine tool system with an additional concentrated energy source. **Methods:** Theoretical studies of the possible structural composition and layout of hybrid equipment during the integration of mechanical and surface-thermal processes were carried out taking into account the main provisions of structural synthesis and components of metal-cutting systems. During the research, issues related to the main provisions of system analysis, the geometric theory of surface formation, the design of metal-cutting equipment, methods of mathematical and computer modeling were raised. **Results and discussion.** Theoretical studies is found that currently, most of the parameter-oriented (dimension) series of general-purpose metal-cutting machines, built according to the law of geometric progression with a constant denominator, are the cause of multiple duplication of individual size ranges on machines of the same series. This gives grounds to talk about an unreasonable increase in the number of its members and, as a result, to an increase in the cost of designing, manufacturing and operating equipment. The authors adhere to the point of view that in order to ensure maximum efficiency of hybrid metal-cutting equipment, it is necessary to implement a parameter-oriented series built with a variable denominator. Such a principle of forming a parameter-oriented series makes it possible to provide an almost equal probability of processing a surface of any size with maximum productivity with a threefold overlap of ranges. Approbation of the technique for forming the structure of parametric series is carried out. It is theoretically proven that during the operation of vertical milling machines of the operating parameter-oriented series with the denominator $\varphi = 1.26$ (GOST 9726-89), there is a multiple overlap of individual size ranges, reaching a ninefold value in a certain range of sizes, which, of course, affects the efficiency of the existing machine tool holding. In turn, when synthesizing a promising parametric series of vertical milling machines with a cross table, it was shown that the new parameter-oriented series has a smaller number of members. Reducing the range of manufactured and modernized machine tools will increase the serial production and reduce current expenses on repairs and maintenance. Moreover, this effect is achieved while maintaining the flexibility of the machine tool holding.

For citation: Skeeba V.Yu., Zverev E.A., Skeeba P.Yu., Chernikov A.D., Popkov A.S. Hybrid technological equipment: on the issue of a rational choice of objects of modernization when carrying out work related to retrofitting a standard machine tool system with an additional concentrated energy source. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2023, vol. 25, no. 2, pp. 45–67. DOI: 10.17212/1994-6309-2023-25.2-45-67. (In Russian).

*** Corresponding author**
Skeeba Vadim Yu., Ph.D. (Engineering), Associate Professor
Novosibirsk State Technical University,
20 Prospekt K. Marksa,
Novosibirsk, 630073, Russian Federation
Tel: 8 (383) 346-17-79, **e-mail:** skeeba_vadim@mail.ru

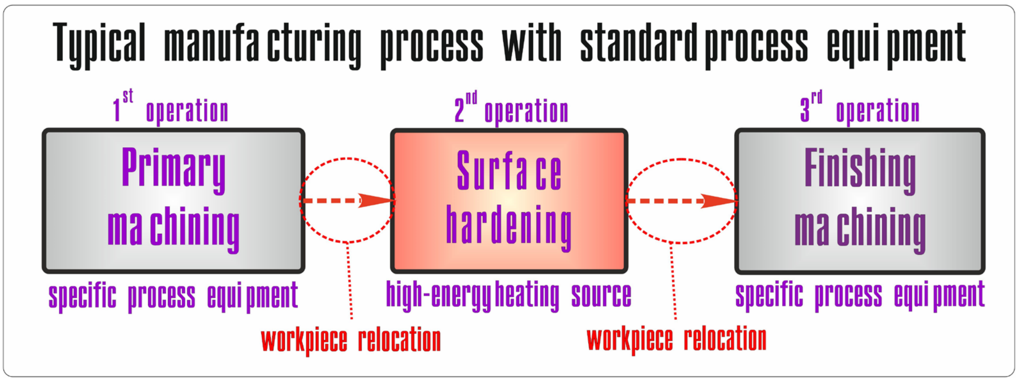
Introduction

Under intensification of market production, there is a desire to reduce energy, material and human resources, which requires an increase in the efficiency of technological equipment to a large extent by choosing the most rational technical characteristics. This trend, aimed at increasing energy and resource saving, due to the use of modern high-performance machine tools with the necessary level of production flexibility, leads to an increase in the competitiveness of high-quality products [1–18]. The use of equipment with a capacity margin that is insufficient or exceeds the required one reduces economic efficiency, increases the level of capital costs, which leads to an increase in the cost of production [19, 20].

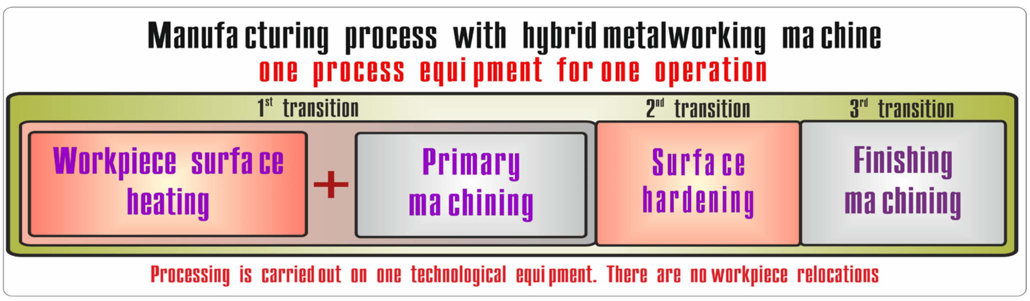
One of the main vectors for the development of modern mechanical engineering is the development and creation of high-tech equipment. So in machine-tool building, the leading engineering industry, high-tech equipment is complex metal-cutting systems [21–32], the construction of which is based on the principle of multifunctional integration [5, 7, 17, 21, 33–46].

One of the ways to increase the technological potential of metal-cutting equipment [1, 5, 17, 21, 24, 26, 27, 38, 42, 44] is the integration of several technological operations on one hybrid machine (for example, preliminary milling + surface hardening + fine milling , abrasive grinding + surface hardening, turning + hardening + ultrasonic hardening and finishing, turning + hardening + diamond burnishing [28, 31, 37–64]) (Fig. 1), which makes it possible to ensure autonomous operation of individual pieces of equipment in flexible production. This will reduce the range of machine tools, which in turn will lead to a decrease in the area of workshops and enterprises as a whole [1, 5, 7, 17, 21, 38, 62]. Solving production problems with the use of such equipment will be less resource-intensive, and, in addition, will lead to a reduction in the production cycle for the manufacture of machine parts.

In the typical process of parts manufacturing, individual operations (surface-thermal hardening and machining) are carried out on different equipment and in different areas of the workshops, which contributes to the appearance of significant errors at each stage of the technological process: deformation of the material during heat treatment, chucking error and others on each piece. All this leads to the need to assign large



a



б

Fig. 1. Typical manufacturing process (*a*) and manufacturing process with hybrid metalworking equipment (*b*)

allowances for finishing, which can be up to 30–40 % of the specified depth from the hardened layer [7, 17, 28, 38, 62]. Therefore, it is necessary that the depth of hardening provided by heat treatment should be somewhat larger than indicated in the documentation. In addition, the most effective part of the hardened surface layer is removed by finishing machining. As a result of using this technology, the productivity of both surface thermal and mechanical operations decreases, and energy costs increase. Combining these two processes on the same equipment allows leveling the above disadvantages and achieving better results. The developed technological recommendations implemented on the proposed hybrid equipment will improve the technical and economic efficiency of production; reduce losses [7, 17, 28, 38, 62, 64]. The introduction of the proposed new technology, in turn, will increase the competitiveness of manufactured products. The effectiveness of the use of integrated technologies is also significantly affected by the reduction of time losses for intermediate and auxiliary operations in the general technological process.

The emergence of a new method of parts processing associated with the use of high frequencies – high-energy heating with high-frequency currents (*HEH HFC*) – was facilitated by developments in the field of miniaturization of inductors and equipping it with ferrite magnetic cores. The proposed method is currently one of the most interesting ones for structural steels hardening [38, 42, 65–70]. Its competitiveness with respect to other methods of metal hardening without melting (Fig. 2), such as laser, electron beam, is due to the possibility of implementing the hardening process at specific heating powers of the order of 400 MW/m^2. It should be noted that the combination of two production processes (mechanical and surface-thermal) on a single machine base [7, 28, 38, 42, 62] ensures the constancy of the required gap between the inductor and the workpiece, which is $\delta = 0.1$–0.2 mm, and this is a necessary condition for the *HEH HFC* processing.

The creation of new standard equipment is associated with high financial and labor costs, while the modernization of existing machines is much cheaper. Based on this, we propose the following solution: modernization of a standard metal-cutting machine, which consists in equipping it with an additional concentrated energy source, which can be used as an *HFC* generator. As a source of energy of high concentration, we will consider microwave generators. This is due to the design features of the standard machine tool system and the current level of development of microprocessor technology in the field of high-frequency industrial installations of the thyristor type [7, 28, 38, 42, 62].

Changes made during the modernization of the standard machine tool system should not have a negative impact on the quality of the equipment. Based on the requirements of a market economy, ensuring the optimal level of product quality is a priority task, the solution of which should be carried out already at the stage of developing the general concept of technological equipment. The quality of the product is determined by a certain set of consumer properties, laid down at the initial stage of the conceptual design, which makes it possible to predict its optimal level. So, for example, the choice of the structure of the parameter-oriented (dimension) range of machine tools and the justification of the technical characteristics of its elements should be carried out in parallel, which in the conditions of the modern development of

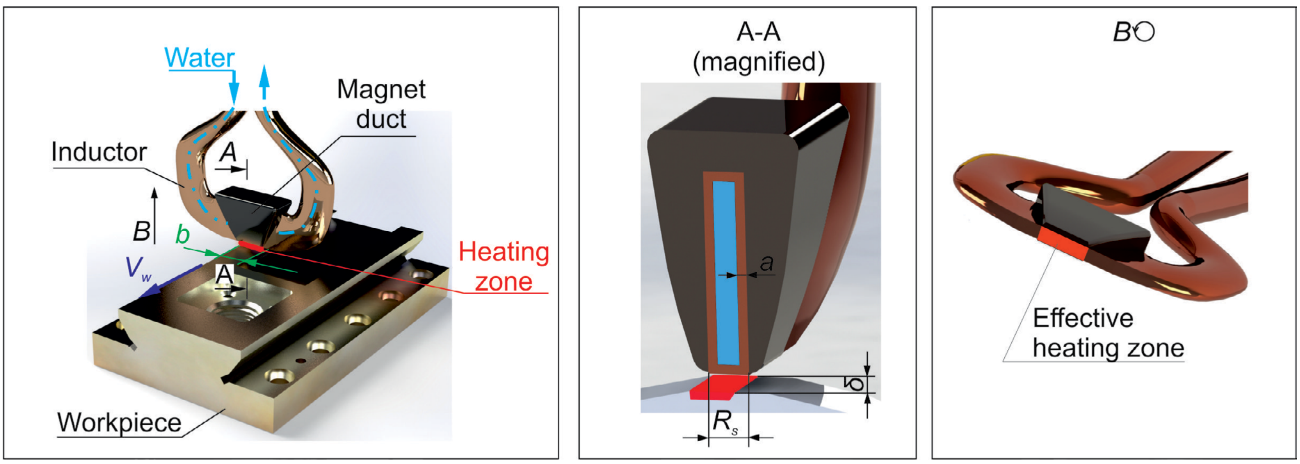


Fig. 2. The scheme of *HEH HFC* processing

mechanical engineering is an integral part of automatic design systems for technological equipment [19, 20]. Despite some scientific results in this direction, there is no single generalized theory for solving this issue.

Quality is a multifaceted and capacious definition; it reflects a number of properties of the object under consideration, characterizing the ability of products, in accordance with its purpose, to satisfy certain consumer requirements. From an engineering point of view, quality is assessed by the method of comparative analysis of the product properties with the properties of a standard or similar product, taken as the basis for comparison. The forecast of the quality of the planned product should begin with determining the minimum set of properties necessary for its evaluation. Properties should be selected from a system of fundamental categories and concepts, and should be meaningful. These include space and time – categories that reflect the forms of matter existence – the extent and relative position of material objects, the duration and sequence of events. As a general measure of the motion and interaction of all types of matter, another category is used – energy [19, 20].

However, these properties and parameters or characteristics that describe it, inherent in natural objects, are usually not enough to describe human-created technical systems. In this case, it is necessary to use the standard nomenclature of the main groups of indicators, which makes it possible to comprehensively assess the quality of the products in question. In the machine-tool industry, a certain set of private and complex indicators is traditionally used, which in most cases are used when choosing equipment to perform certain functions, as well as when identifying its technical level and competitiveness [7, 17, 19, 20]. Efficiency, productivity, manufacturability, flexibility, precision, reliability, ergonomics and aesthetics of machine tools are usually the main indicators of equipment quality.

Obviously, when substantiating the main parameters and technical characteristics of equipment, one usually operate with a quantitative assessment of it: the dimensions of the operating area (space), speed capability (time) and drive power (energy). Additional parameters that determine the differences between some objects from others, in most cases can be presented in the form of qualitative assessments, for example, different accuracy classes, types of control (manual or software), architecture, and other characteristics of hybrid metal-cutting machines [7, 17, 19, 20, 38, 42].

The difference between the design capabilities of the equipment and the capabilities required to perform its functions in accordance with the purpose is a loss (excessive or insufficient margin of capability).

Factors affecting the occurrence of losses include incomplete use of the operating area, electric motor power, spindle speed range, etc. As an example, we can consider the results of a study of the operating conditions of *CNC* milling machines, which show that when performing 90% of operations, the power consumed by the main motion drive is no more than 50% of the nominal value, the load capacity of the table is used by no more than 20%, the applied working feeds actually do not exceed 1/6 of the maximum allowable, etc. For machine tools of other groups, a similar situation is observed [19, 20, 71, 72]. Studies of foreign scientists in its results are practically identical to domestic ones. The data obtained for universal metal-cutting machines with manual control and *CNC* machines in terms of using its technological capabilities also do not have significant differences.

The *purpose of this research* is to make rational choice of objects of modernization when carrying out work related to retrofitting a standard machine tool system with an additional concentrated energy source, which can be an *HFC*-generator.

To achieve this purpose, the following tasks should be solved:

1. To propose a method of structural analysis that allows effectively carrying out pre-project studies in the development of hybrid metal-cutting equipment.

2. Develop a method for forming the structure of parameter-oriented range of machine tools, taking into account the equality of average productivity losses.

Theory and methodology of experimental research

The executive movements of the hybrid metal-cutting system (*HMS*) and the required number of its adjustable parameters were determined by applying the structural-kinematic synthesis of the mechanisms of metal-cutting machine tools [73–76]. The main provisions of the structural synthesis and components of the systems under consideration, given in [75–85], were used to study the proposed structural composition and configuration of *HMS*, in which surface heat treatment and mechanical operations are integrated.

When developing integral metal-cutting equipment, it is planned to implement the method of high-energy heating by high-frequency currents on one of the technological transitions of a hybrid machine.

The generating lines of the surface being treated are formed by local heating areas. The dimensions of these lines are contingent on the design features of the inductors for the *HEH HFC* and are determined by the width of the active wire of the inductor and the length of the ferrite magnetic core (Fig. 2). It is obvious that the operations of surface hardening and shaping by milling (Fig. 3) require the same coordinated relative movements of the workpiece and the cutting tool. The results of the structural-kinematic analysis showed that at all transitions of complex machining (preliminary milling, *HEH HFC* hardening and finishing milling), the executive movements and the set of parameters configured in it are identical.

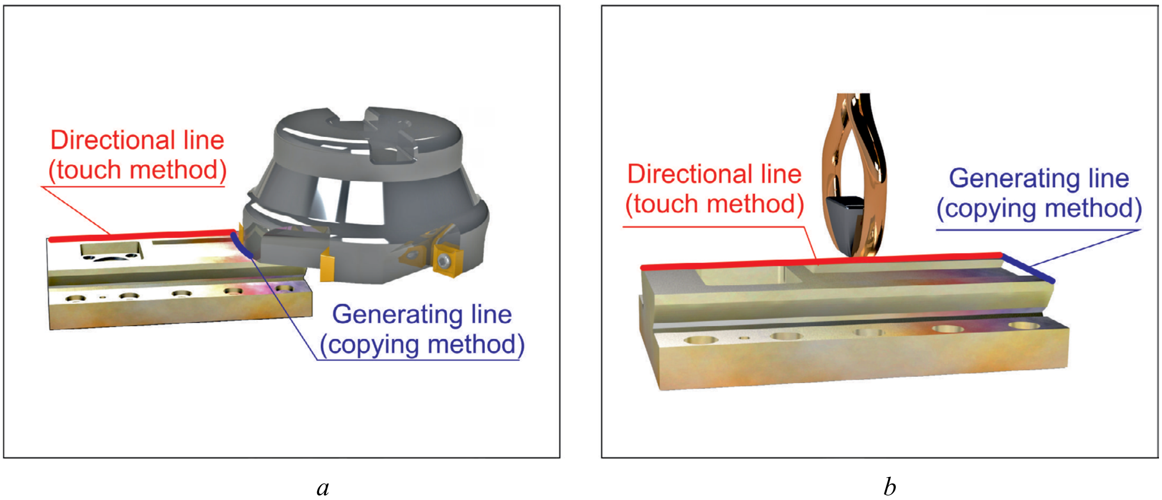


Fig. 3. Generation of geometry (flat surface):
a – during machining (milling); *b* – during surface hardening by *HEH HFC* with loop inductor with a magnetic core

Figure 4 shows particular structural kinematic formulas in conjunction with structural-kinematic diagrams (*SKD*) for each processing method individually.

The subsequent synthesis of the generalized kinematic structure of the developed hybrid metal-cutting system based on a bracket-milling machine was carried out according to the scheme of the machine modular layout (Fig. 5). With this method, the structural kinematic formula can be represented as follows:

$$XYZ0b(w_1\widehat{C}_v + w_2),$$

where X, Y – longitudinal and transverse movement of the cross table; Z – vertical movement of the console; b – rotation of the spindle head; w_1 – manual movement of the spindle sleeve along the spindle axis; $\widehat{C}_v$ – rotation of the spindle with the cutting tool; w_2 – manual movement of the inductor along the spindle axis. The C_v block that performs the primary motion in milling is additionally marked with a $\wedge$.

Currently, most of the parameter-oriented (dimension) series of general-purpose machine tools are built according to the law of geometric progression with a constant denominator φ equal to 1.26 or 1.41. The range of sizes of workpieces or cutting tools used for each member of the ranges, as a rule, significantly exceeds this value. Therefore, there is some overlap in the size ranges *D* of equipment for adjacent members of the parameter-oriented series. It provides certain flexibility in the machine tool holding of machine-building enterprise, which allows it quickly and practically without a decrease in productivity switch to the production of new products without equipment replacing. However, multiple duplication of individual size ranges on machines of the same series leads to an increase in the number of its members and, as a result, to an increase in the cost of designing, manufacturing and operating equipment. Therefore, the problem of establishing the optimal structure of parameter-oriented series of technological equipment is very relevant.

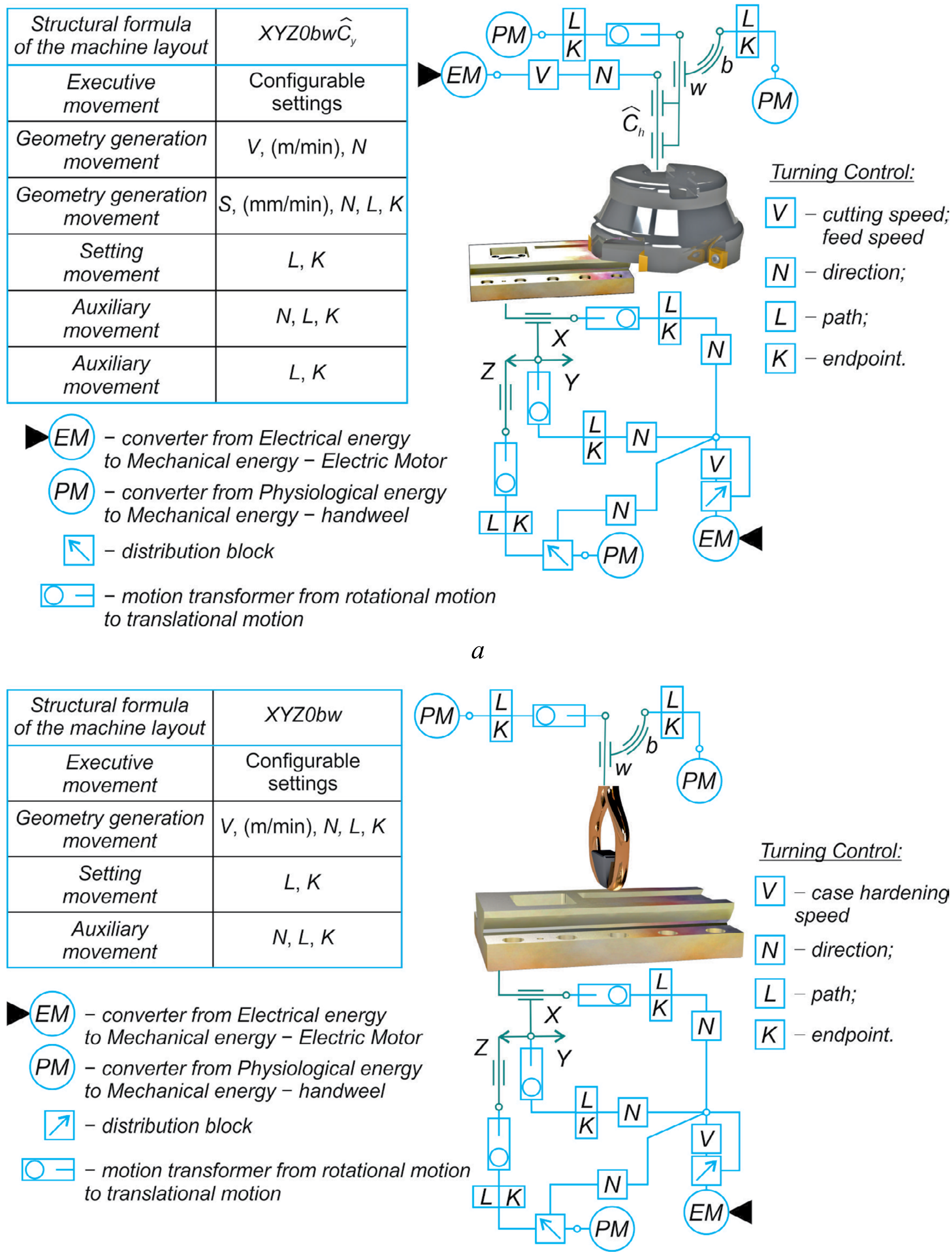


Fig. 4. Structural kinematic schemes for processing a flat surface:
a – milling; *b* – surface hardening by *HEH HFC* with loop inductor with a magnetic core

The work [86] shows that the functional ability of the i^{th} technological system, determined by its parameters (and characteristics), can be estimated through the so-called criterion of conditional average losses R_i, which provide a minimum of decision error

$$R_i = RC_i \left[1 - \prod_{j=1}^{r} p_{ij} \left\{ \frac{DC_j - UC_j}{[\chi_j]} \le 1 \right\} \right] \tag{1}$$

where RC_i – reduced costs; p_{ij} – loss free probability in the technological system by the j^{th} parameter; DC_j – design capabilities of the equipment for the j^{th} parameter; UC_j – the used capabilities of the metal-cutting machine for the j^{th} parameter; $[\chi_j]$ – allowed value of capabilities stock for the j^{th} parameter. In the process of optimizing the machine tool technological system, they try to find the minimum of the specified equation [19].

Structural formula of the machine layout	$XYZ0b(w_1\widehat{C}_y+w_2)$
Executive movement	Configurable settings
Geometry generation movement	*V*, (m/min), *N*
Geometry generation movement	*S*, (mm/min), *N*, *L*, *K*
Setting movement	*L*, *K*
Auxiliary movement	*N*, *L*, *K*
Auxiliary movement	*L*, *K*

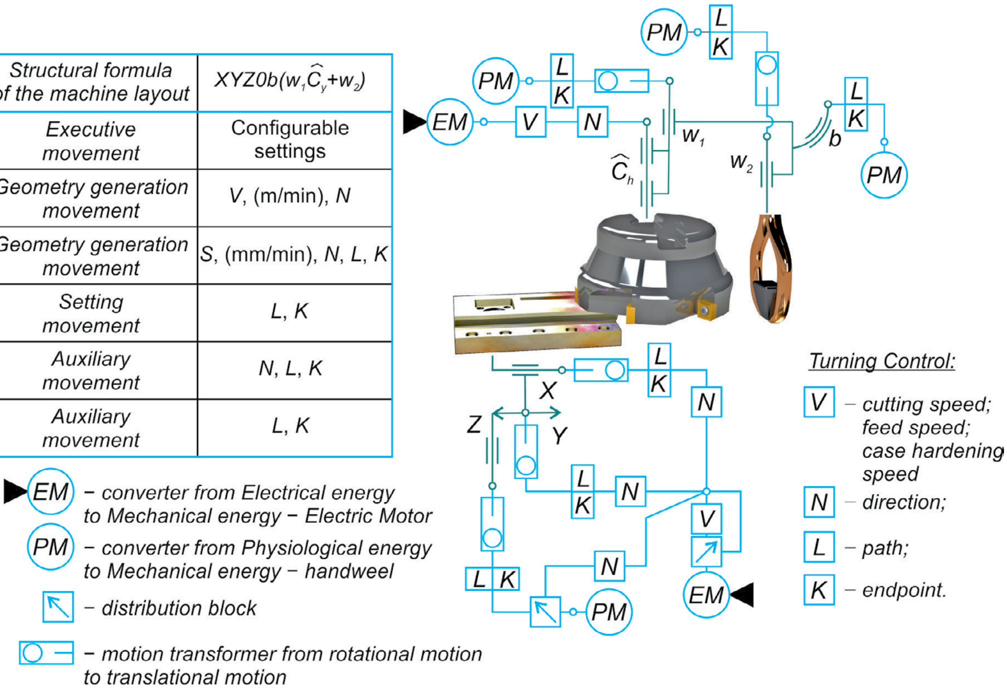


Fig. 5. Structural kinematic scheme of the hybrid metalworking system: the structural formula is $XYZ0b(w_1\widehat{C}\quad w_2)$

It is obvious that the definition of the type of the parameter-oriented series structure has a significant impact on the stock of capabilities of its individual members. So, in order to ensure maximum efficiency of hybrid metal-cutting equipment, when designing it, it is necessary to strive for such a construction of a technological system in which the stock of its capabilities would have the least value. But this requirement is quite well fulfilled and is realized only in conditions of mass production. However, in the situation of small-scale and individual production, the factor of the necessary increase in the flexibility of technological equipment comes to the fore, forcing the creation of machines with an increased value of the allowed value of capabilities stock, which invariably leads to some decrease in its efficiency. The solution to this problem, i.e. finding the option of the most rational use of the range of universal machines is the equality of conditional average losses for all members of the parameter-oriented series:

$$R_1 = R_2 = \ldots = R_i = \ldots = R_m = \text{const}, \qquad (2)$$

where m is the number of members of the size range.

When forming the parameter-oriented series of metal-cutting machine tools, its main parameter is subjected to standardization. For example, for lathes, this is the machining diameter above the frame, and for milling metal-cutting equipment, it is the width of the table, etc. In this case, the ratio between the main parameters of neighboring members of the series will determine its normative capabilities stock. Taking this fact into account, dependence (1) can be transformed into an objective function of the form

$$R = \sum_{i=1}^{m} RC_i \left[1 - p\left\{ \frac{\varphi_i}{\varphi_i - 1}(1 - \Psi_i) \le 1 \right\} \right] \to \min, \qquad (3)$$

where $\Psi = UC_i / DC_i$ – duty factor of metal-cutting machine capabilities stock.

Since as the main parameter of the equipment grows, the reduced costs increase, it follows from the analysis of equation (3) that the equality of conditional average losses for all machines of the line can be ensured if the parameter-oriented series is built with a variable denominator [19, 71]

$$\varphi_1 > \varphi_2 > \ldots > \varphi_i > \ldots > \varphi_m \qquad (4)$$

It should be noted that it is advisable to change the values of φ_i exponentially with the denominator δ.

An additional option for solving the problem of meeting requirements (2) for all members of the parameter-oriented series is the formation of conditions under which the dimensions of the used cutting tools or workpieces X will be close to the maximum allowable. The logical consequence of this condition will be the inevitable decrease in the ranges of variation D of parameter X with an increase in the dimensions of the technological equipment [19, 71]

$$D_1 > D_2 > \ldots > D_i > \ldots > D_m. \tag{5}$$

In turn, the ability of the enterprise to quickly switch to the production of new products based on the existing one (or, at least, with a minimum replacement of equipment), i.e. the mobility of the machine tool holding should also be ensured in the synthesis of parameter-oriented series. This additional condition is achieved by overlapping the size ranges of individual members of the parameter-oriented series. But, as noted earlier, multiple duplication, significantly increasing the cost of manufacturing and operating machine tools, essentially eliminates all efforts aimed at improving its mobility.

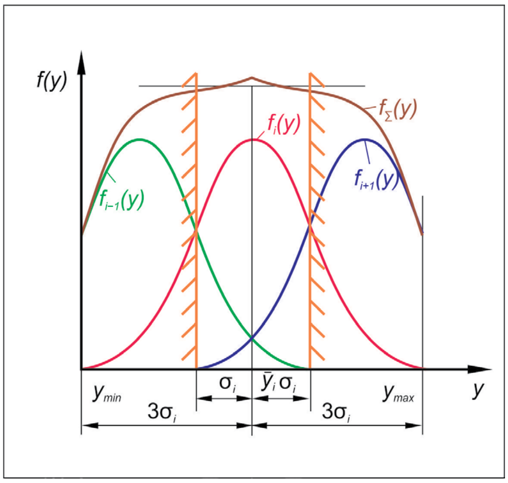


Fig. 6. Logarithmically normal distribution of tool sizes and surfaces machined on metal-cutting machines

Numerous statistical studies in industrialized countries have shown that the size distributions of tools and machined surfaces usually have a unimodal character with positive asymmetry. It has been proven that for machines of a certain size, the parameter X usually has a log-normal distribution [19, 20, 71, 72]

$$f_i(y) = \frac{1}{\sigma_i\sqrt{2\pi}} e^{-\frac{\left(y-\overline{y_i}\right)^2}{2\sigma_i^2}}$$

where y is the natural logarithm of the random variable X; $\overline{y_i}$ – average value (mathematical expectation) of the value y; σ_i – standard deviation of y from $\overline{y_i}$.

From the analysis of the log-normal distribution pattern (Fig. 6), it can be seen that the middle part of the range is the main one for the i^{th} standard size of equipment, and the side parts serve for duplicating the production functions of adjacent members of the series.

It is advisable to divide the range of variation of the logarithmically normal distribution into three approximately equal intervals (subranges). Then, within the average (main) sub-range, processing with a maximum productivity of more than 2/3 of the work will be provided. The remaining third of the work will be assigned to both other duplicating intervals a_i min and $a_{i\,max}$ (Fig. 7). In this case, it is possible to use equipment outside this size range, but with some loss of productivity as a result of the discrepancy between the technical characteristics of machine tools and optimal operating conditions [19, 20, 71, 72].

This principle of forming a parameter-oriented series makes it possible to process a surface of any size with maximum productivity, while there is a threefold overlap of the range.

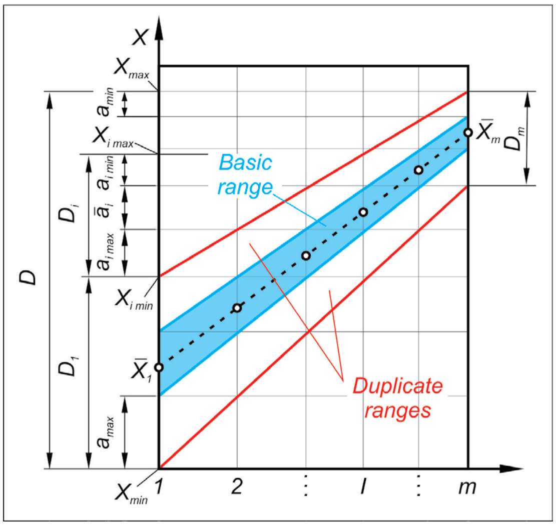


Fig. 7. Image of the proposed parameter-oriented series (in logarithmic coordinates) with a variable denominator:

a_{max} and a_{min} – the maximum and minimum size of the interval; $\overline{X}_1$ and $\overline{X}_m$ – the average values of the parameter $\boldsymbol{X}$ for the first and m[th] members of the series

Results and discussion

At the first stage of the synthesis, an analysis of the operating conditions of the same type of machine tools is carried out and the area of its rational use is established, i.e. the limits $X_{\min}$ and $X_{\max}$ of the variation of the parameter X are assigned. The number of members of the series m and the main parameters of the equipment $X_{\max i}$ are to be determined.

Initially, the minimum size of the interval is assigned and the value of its increment δ is chosen. In practice, to ensure the required accuracy, the most preferred values are $a_{\min} = 1.26$ with increment $\delta = 1.12$. In turn, it should be noted that in real design conditions, other options are also acceptable.

The presented parameters are interconnected by the following relation

$$D = a_{\min}^{z} \delta^{(z^2 - z)/2}, \tag{6}$$

where z is the number of intervals of the random variable $\boldsymbol{X}$; $D = X_{\max} / X_{\min}$ is the range of variation of the random variable $\boldsymbol{X}$.

Taking the logarithm of the indicated expression and solving it with respect to z, one finds the number of members of the parameter-oriented series

$$m = z - 2. \tag{7}$$

Then set the values of the denominators of the series for each of its members

$$\varphi \;=\; {}_{\min}\delta \quad , \tag{8}$$

where $k_i = m - i$.

Analyzing the obtained results, it can be stated that with an increase in the serial number of a member of the series, the value of φ decreases, while finding the main parameter of the equipment will be carried out according to the equation

$$X_{\max i} = X_{\max} \Big/ \phi_m^{k_i} \delta^{\left(k_i^2 - k_i\right)/2}, \tag{9}$$

where φ_m is the minimum value of the variable denominator of the series.

The values of the base (average) $\bar{a}_i$ and total D_i ranges of variation of the X value of each of the members of the parameter-oriented series will be calculated according to the following dependencies $\bar{a}_i = a_{\min} \delta^{k_i + 1}$ and $D_i = (\bar{a}_i)^3$.

Using the data obtained, the boundary lines of the size ranges are plotted on the graph (Fig. 8), after which you can proceed directly to the construction of the parameter-oriented series. To do this, from point A, corresponding to the upper boundary of the main subrange of the first member of the series, a horizontal line is drawn until it intersects at point B with the line defining the lower boundary of the subrange. The abscissa of point B specifies the main parameter of the second member of the series. Then the upper limit of the main subrange of the second member of the series (point C) is found and the process is repeated.

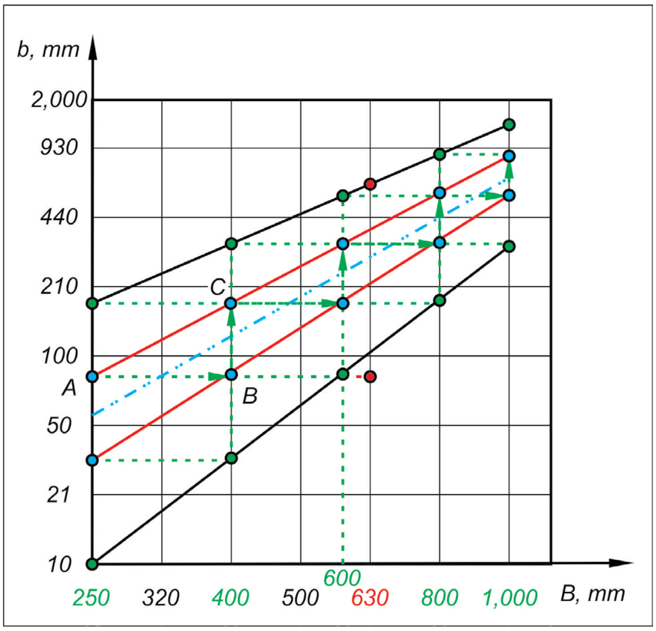


Fig. 8. A promising parameter-oriented series of vertical milling machines with a cross table, upgraded to the level of hybrid technological equipment

The values of the main parameters obtained in this way should be reduced to the nearest standard ones. This can be done by slightly changing the position of the boundary line of the minimum values of the dimensional characteristic.

The considered graphic-analytical method is implemented in the synthesis of a promising parameter-oriented series of vertical milling machines with a cross table (GOST 9726–89). As an analysis of the technical characteristics and operating conditions of domestic milling machines and its foreign counterparts showed, there is a certain correlation between the maximum dimensions of machined parts and the main parameter of the equipment:

$$b_{\max} = 0.4657 \cdot B^{1.1059};\ \bar{b} = 0.0045 \cdot B^{1.7171}, \tag{10}$$

where $b_{\max}$ is the maximum width of workpieces to be processed on the machine table; $\bar{b}$ is an average width of workpieces; B is the maximum width of the working surface of the milling machine.

As a result of the data analysis, it was recorded that there is a clear trend towards a decrease in the range of variation in the dimensions of the dimensions of the machined products R_b as the main machine parameter B increases:

$$R_b = \frac{22082}{B^{1.3027}}. \tag{11}$$

As a result, during the operation of vertical milling machines of the current parameter-oriented series with the denominator φ = 1.26 (GOST 9726–89) [87], there is a multiple overlap of individual size ranges, reaching a ninefold value in a certain range of sizes, which, of course, affects the efficiency operating machine tool holding.

The new parameter-oriented series has two times fewer members defined by GOST 9726–89, and consists of machines with the following values of the main parameter B: 250; 400; 630(600); 800; 1,000 mm.

If you build a parameter-oriented series on the basis of the current one, then the transition to it can be carried out with minor changes in machine-tool production. New are only machines with B = 600 mm, created by minimal modernization of existing standard equipment of similar sizes. Thus, having reduced the range of manufactured and modernized machines, we will be able to increase the serial production of it, reduce current costs for maintenance and repair work, while maintaining the flexibility of the machine tool holding. In order to draw final conclusions about the economic feasibility and efficiency of using the proposed parameter-oriented series instead of the traditional one, it is necessary to determine the values of the reduced costs for both options. It was already noted earlier that, along with the main parameter, it is necessary to optimize other main technical characteristics of the equipment. These include limit values for spindle speeds, permissible torque on it and limits for the use of effective power. Even with a slight change in the structure of the parameter-oriented series, it automatically becomes necessary to change the above characteristics.

The substantiation of technical characteristics based on modeling the operational parameters of machine tools using the proposed methodology is described by the authors in [17, 19, 20, 71, 72, 75, 88]. As operational parameters, in this case, the characteristics of the machine drives are considered, the values of which depend on the processing modes, but at the same time lie within the range of technical characteristics. Given that the diameter of the cutting tool (for example, the diameter of the end mill) is in a rigid relationship with the width of the workpiece being processed, the approach to solving this problem is based on the prediction of the distribution of the system of these random variables. The values of the distributions of speeds and cutting forces when the machine performs the specified functions are the initial data that are obtained statistically when processing the relevant information. In turn, the indicators of the distribution of the speeds of the cutting tool used to process the workpiece, and the size of the product being processed, can be calculated from the following dependencies:

$$\sigma_i = \frac{\ln \overline{a_i}}{2};$$

$$\overline{\ln X_i} = \ln X_{\max i} + (\ln \delta - 3\sigma_i);$$

$$\overline{X_i} = \exp\left\{\overline{\ln X_i} + \frac{\sigma_i^2}{2}\right\},$$

where σ_i is a standard deviation of a random variable X; $\overline{\ln X_i}$ is an average value of the logarithm of a random variable X; $\overline{X_i}$ is a mean value of X.

A rather visually simulated system is shown in Figure 9, where it is depicted as a pattern of distributions. Here, the characteristic values are shown in logarithmic coordinates: horizontally – spindle speed n, vertically – torque M, and diagonally – effective power N.

The figure shows lines of equal probabilities of work performed on the machine and the optimal boundaries of the limit values of the simulated performance are plotted. It corresponds to the extreme maximum values of the second derivative of the differential functions *f(y)* of the final (resulting) distributions of machine characteristics y

$$f(y) = \sum_{q=1}^{\omega} p_q f_q(y),$$

where p_q is a probability of realization of processing conditions q; $f_q(y)$ is a differential function of the elementary (private) distribution of the characteristic for the processing condition q (y is the natural logarithm of n, M or N); ω is a total number of machining conditions on the machine.

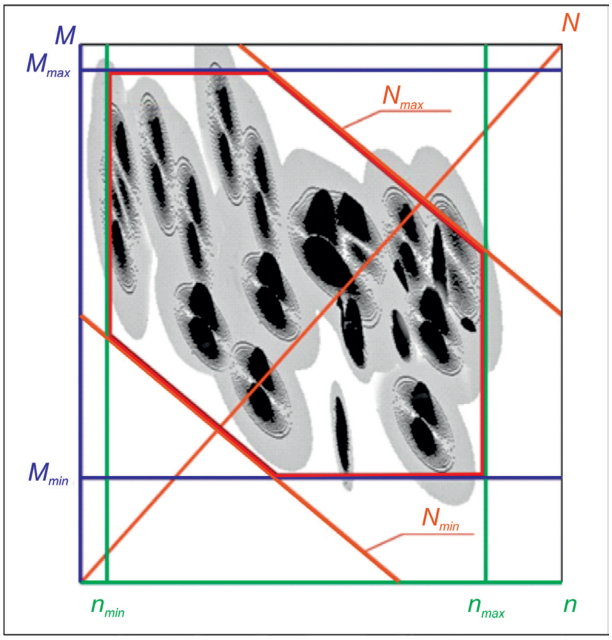


Fig. 9. The distribution pattern of the hybrid process equipment operational characteristics

The proposed methodology differs from the traditional approach in that it allows introducing restrictions on the minimum used power values. This feature significantly increases the average motor power factor (cos φ) and reduces energy consumption.

The characteristic values obtained in this way are subsequently corrected, if necessary, based on standard series of preferred numbers, typical motor power values, etc.

Taking into account the fact that the optimization of technical characteristics is carried out according to the productivity of the machine, the choice of the values of these characteristics at the modeling stage for greater convenience is carried out in accordance with the results of calculating the percentage component of work performed on the machine at maximum productivity, taking into account the established limitations of operational parameters.

Conclusions

An original technique for conducting structural-kinematic analysis for pre-project studies of hybrid metal-cutting equipment is presented. The research results showed that in most cases, parameter-oriented (dimension) series of general-purpose machine tools with constant denominators, built in accordance with the law of geometric progression, lead to the need to duplicate individual size ranges on machines of the same series, and, as a result, to an inappropriate increase in the number its members. In this regard, the costs of design work, manufacturing and operation of equipment are growing. In the case of using a parameter-oriented series, built using a variable denominator, the maximum efficiency of hybrid metal-cutting equipment is achieved, which has been theoretically proven. Thanks to the use of this principle of forming a parameter-oriented series, it becomes possible to provide an almost equal probability of processing surfaces of various sizes with maximum productivity with a threefold overlap of ranges. Approbation of the technique for forming the structure of parameter-oriented series was carried out. It has been established that during the operation of vertical milling machines of the current parameter-oriented series with the denominator φ = 1.26 (GOST 9726-89), there is a multiple overlap of individual size ranges that reach a ninefold value in a certain range of sizes, which, of course, affects the efficiency of the existing machine tool holding. The synthesis of a promising parameter-oriented series of a vertical milling machine with a cross table showed that the new parameter-oriented series is characterized by the presence of a smaller number of members. Thus, the application of the proposed methodology makes it possible to reduce the range of manufactured and modernized machine tools, and this, in turn, will lead to an increase in serial production, a reduction in the cost of repair and maintenance of equipment, but at the same time it will allow maintaining the flexibility of the machine tool holding.

References

1. Hügel H., Wiedmaier M., Rudlaff T. Laser processing integrated into machine tools – design, applications, economy. *Optical and Quantum Electronics*, 1995, vol. 27, iss. 12, pp. 1149–1164. DOI: 10.1007/BF00326472.

2. You K., Yan G., Luo X., Gilchrist M.D., Fang F. Advances in laser assisted machining of hard and brittle materials. *Journal of Manufacturing Processes*, 2020, vol. 58, pp. 677–692. DOI: 10.1016/j.jmapro.2020.08.034.

3. Anderson M.C., Shin Y.C. Laser-assisted machining of an austenitic stainless steel: P550. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 2006, vol. 220, iss. 12, pp. 2055–2067. DOI: 10.1243/09544054JEM562.

4. Sun S., Brandt M., Dargusch M.S. Thermally enhanced machining of hard-to-machine materials – A review. *International Journal of Machine Tools and Manufacture*, 2010, vol. 50, iss. 8, pp. 663–680. DOI: 10.1016/j.ijmachtools.2010.04.008.

5. Makarov V.M., Lukina S.V. Unikal'naya sinergiya gibridnykh stankov [Unique synergy of hybrid machines]. *Ritm: Remont. Innovatsii. Tekhnologii. Modernizatsiya = RITM: Repair. Innovation. Technologies. Modernization*, 2016, no. 8, pp. 18–25.

6. Widłaszewski J., Nowak M., Nowak Z., Kurp P. Curvature change in laser-assisted bending of Inconel 718. *Physical Sciences Forum*, 2022, vol. 4, iss. 1, p. 26. DOI: 10.3390/psf2022004026.

7. Skeeba V.Yu. Gibridnoe tekhnologicheskoe oborudovanie: povyshenie effektivnosti rannikh stadii proektirovaniya kompleksirovannykh metalloobrabatyvayushchikh stankov [Hybrid process equipment: improving the efficiency of the integrated metalworking machines initial designing]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2019, vol. 21, no. 2, pp. 62–83. DOI: 10.17212/1994-6309-2019-21.2-62-83.

8. Borisov M.A., Lobanov D.V., Yanyushkin A.S. Gibridnaya tekhnologiya elektrokhimicheskoi obrabotki slozhnoprofil'nykh izdelii [Hybrid technology of electrochemical processing of complex profiles]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2019, vol. 21, no. 1, pp. 25–34. DOI: 10.17212/1994-6309-2019-21.1-25-34.

9. Sun S., Harris J., Brandt M. Parametric investigation of laser-assisted machining of commercially pure titanium. *Advances Engineering Materials*, 2008, vol. 10, iss. 6, pp. 565–572. DOI: 10.1002/adem.200700349.

10. Madhavulu G., Ahmed B. Hot machining process for improved metal removal rates in turning operations. *Journal of Materials Processing Technology*, 1994, vol. 44, pp. 199–206. DOI: 10.1016/0924-0136(94)90432-4.

11. Parida A.K., Maity K. Experimental investigation on tool life and chip morphology in hot machining of Monel-400. *Engineering Science and Technology, an International Journal*, 2018, vol. 21, iss. 3, pp. 371–379. DOI: 10.1016/j.jestch.2018.04.003.

12. Özler L., İnan A., Özel C. Theoretical and experimental determination of tool life in hot machining of austenitic manganese steel. *International Journal of Machine Tools and Manufacture*, 2001, vol. 41, iss. 2, pp. 163–172. DOI: 10.1016/S0890-6955(00)00077-8.

13. Ul Hasan S., Ali S., Jaffery S.H.I., Ud Din E., Mubashir A., Khan M. Study of burr width and height using ANOVA in laser hybrid micro milling of titanium alloy (Ti6Al4V). *Journal of Materials Research and Technology*, 2022, vol. 21, pp. 4398–4408. DOI: 10.1016/j.jmrt.2022.11.051.

14. Ding H., Shen N., Shin Y.C. Thermal and mechanical modeling analysis of laser-assisted micro-milling of difficult-to-machine alloys. *Journal of Materials Processing Technology*, 2012, vol. 212, iss. 3, pp. 601–613. DOI: 10.1016/j.jmatprotec.2011.07.016.

15. Bermingham M.J., Kent D., Dargusch M.S. A new understanding of the wear processes during laser assisted milling 17-4 precipitation hardened stainless steel. *Wear*, 2015, vol. 328–329, pp. 518–530. DOI: 10.1016/j.wear.2015.03.025.

16. Mohammadi H., Patten J.A. Laser augmented diamond drilling: a new technique to drill hard and brittle materials. *Procedia Manufacturing*, 2016, vol. 5, pp. 1337–1347. DOI: 10.1016/j.promfg.2016.08.104.

17. Skeeba V.Yu., Ivancivsky V.V. Povyshenie effektivnosti poverkhnostno-termicheskogo uprochneniya detalei mashin v usloviyakh sovmeshcheniya obrabatyvayushchikh tekhnologii, integriruemykh na edinoi stanochnoi baze [Improving the efficiency of surface-thermal hardening of machine parts in conditions of combination of processing technologies, integrated on a single machine tool base]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2021, vol. 23, no. 3, pp. 45–71. DOI: 10.17212/19946309202123.34571.

18. Venkatesan K. The study on force, surface integrity, tool life and chip on laser assisted machining of inconel 718 using Nd:YAG laser source. *Journal of Advanced Research*, 2017, vol. 8, iss. 4, pp. 407–423. DOI: 10.1016/j.jare.2017.05.004.

19. Skeeba V.Yu. Parametric optimization of hybrid metalworking machinery quality. *IOP Conference Series: Earth and Environmental Science*, 2019, vol. 378, p. 012030. DOI: 10.1088/1755-1315/378/1/012030.

20. Skeeba V.Yu., Skeeba P.Yu. Determining the operational loads of the hybrid metalworking machines drive. *IOP Conference Series: Earth and Environmental Science*, 2019, vol. 378, p. 012031. DOI: 10.1088/1755-1315/378/1/012031.

21. Makarov V.M. Kompleksirovannye tekhnologicheskie sistemy: perspektivy i problemy vnedreniya [Well integrated technological systems: prospects and problems of implementation]. *Ritm: Remont. Innovatsii. Tekhnologii. Modernizatsiya = RITM: Repair. Innovation. Technologies. Modernization*, 2011, no. 6 (64), pp. 20–23.

22. Mitsuishi M., Ueda K., Kimura F., eds. *Manufacturing systems and technologies for the new frontier*: the 41st CIRP Conference on Manufacturing Systems, May 26–28, 2008, Tokyo, Japan. London, Springer, 2008. 556 p. ISBN 978-1-84800-267-8. DOI: 10.1007/978-1-84800-267-8.

23. Yanyushkin A.S., Lobanov D.V., Arkhipov P.V. Research of influence of electric conditions of the combined electro-diamond machining on quality of grinding of hard alloys. *IOP Conference Series: Materials Science and Engineering*, 2015, vol. 91, p. 012051. DOI: 10.1088/1757-899X/91/1/012051.

24. Lauwers B., Klocke F., Klink A., Tekkaya A.E., Neugebauer R., Mcintosh D. Hybrid processes in manufacturing. *CIRP Annals*, 2014, vol. 63, iss. 2, pp. 561–583. DOI: 10.1016/j.cirp.2014.05.003.

25. Garro O., Martin P., Veron M. Shiva a multiarms machine tool. *CIRP Annals – Manufacturing Technology*, 1993, vol. 42, iss. 1, pp. 433–436. DOI: 10.1016/S0007-8506(07)62479-2.

26. Brecher C., Özdemir D. *Integrative production technology: theory and applications*. Springer International Publ., 2017. 1100 p. ISBN 978-3-319-47451-9. ISBN 978-3-319-47452-6. DOI: 10.1007/978-3-319-47452-6.

27. *Moriwaki T.* Multi-functional machine tool. *CIRP Annals – Manufacturing Technology*, 2008, vol. 57, iss. 2, pp. 736–749. DOI: 10.1016/j.cirp.2008.09.004.

28. Skeeba V., Pushnin V., Erohin I., Kornev D. Integration of production steps on a single equipment. *Materials and Manufacturing Processes*, 2015, vol. 30, iss. 12. DOI: 10.1080/10426914.2014.973595.

29. Yamazaki T. Development of a hybrid multi-tasking machine tool: integration of additive manufacturing technology with CNC machining. *Procedia CIRP*, 2016, vol. 42, pp. 81–86. DOI: 10.1016/j.procir.2016.02.193.

30. Punugupati G., Kandi K.K., Bose P.S.C., Rao C.S.P. Laser assisted machining: a state of art review. *IOP Conference Series: Materials Science and Engineering*, 2016, vol. 149, p. 012014. DOI: 10.1088/1757-899X/149/1/012014.

31. Olsson M., Akujärvi V., Ståhl J.-E., Bushlya V. Cryogenic and hybrid induction-assisted machining strategies as alternatives for conventional machining of refractory tungsten and niobium. *International Journal of Refractory Metals and Hard Materials*, 2021, vol. 97, p. 105520. DOI: 10.1016/j.ijrmhm.2021.105520.

32. Ginta T.L., Amin A.K.M.N. Thermally-assisted end milling of titanium alloy Ti-6Al-4V using induction heating. *International Journal of Machining and Machinability of Materials*, 2013, vol. 14, iss. 2, pp. 194–212. DOI: 10.1504/IJMMM.2013.055737.

33. Boivie K., Karlsen R., Ystgaard P. The concept of hybrid manufacturing for high performance parts. *South African Journal of Industrial Engineering*, 2012, vol. 23, iss. 2, pp. 106–115.

34. Yang Y., Gong Y., Qu S., Rong Y., Sun Y., Cai M. Densification, surface morphology, microstructure and mechanical properties of 316L fabricated by hybrid manufacturing. *The International Journal of Advanced Manufacturing Technology*, 2018, vol. 97, iss. 5–8, pp. 2687–2696. DOI: 10.1007/s00170-018-2144-1.

35. Lobanov D.V., Arkhipov P.V., Yanyushkin A.S., Skeeba V.Yu. Research of influence electric conditions combined electrodiamond processing by on specific consumption of wheel. *IOP Conference Series: Materials Science and Engineering*, 2016, vol. 142, p. 012081. DOI: 10.1088/1757-899X/142/1/012081.

36. Ding H.T., Shin Y.C. Laser-assisted machining of hardened steel parts with surface integrity analysis. *International Journal of Machine Tools and Manufacture*, 2010, vol. 50, iss. 1, pp. 106–114. DOI: 10.1016/j.ijmachtools.2009.09.001.

37. Ivancivsky V.V., Skeeba V.Yu. Sovmeshchenie operatsii poverkhnostnoi zakalki i finishnogo shlifovaniya na odnom tekhnologicheskom oborudovanii [Combining the operations of surface hardening and finish grinding on the same processing equipment]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2006, no. 1 (30), pp. 16–18.

38. Skeeba V.Yu., Ivantsivsky V.V. *Gibridnoe metalloobrabatyvayushchee oborudovanie: povyshenie effektivnosti tekhnologicheskogo protsessa obrabotki detalei pri integratsii poverkhnostnoi zakalki i abrazivnogo shlifovaniya* [Hybrid metal working equipment: improving the effectiveness of the details processing under the integration of surface quenching and abrasive grinding]. Novosibirsk, NSTU Publ., 2018. 312 p. ISBN 978-5-7782-3690-5.

39. Berenji K.R., Karagüzel U., Özlü E., Budak E. Effects of turn-milling conditions on chip formation and surface finish. *CIRP Annals*, 2019, vol. 68, iss. 1, pp. 113–116. DOI: 10.1016/j.cirp.2019.04.067.

40. Skeeba V.Yu., Ivancivsky V.V., Vakhrushev N.V., Parts K.A., Cha G.O. Efficiency of hybrid equipment combining operations of surface hardening by high frequency currents and abrasive grinding. *IOP Conference Series: Earth and Environmental Science*, 2018, vol. 194, iss. 2, p. 022038. DOI: 10.1088/1755-1315/194/2/022038.

41. Salonitis K., Chondros T., Chryssolouris G. Grinding wheel effect in the grind-hardening process. *The International Journal of Advanced Manufacturing Technology*, 2008, vol. 38, iss. 1–2, pp. 48–58. DOI: 10.1007/s00170-007-1078-9.

42. Ivantsivsky V.V., Skeeba V.Yu. *Gibridnoe metalloobrabatyvayushchee oborudovanie. Tekhnologicheskie aspekty integratsii operatsii poverkhnostnoi zakalki i abrazivnogo shlifovaniya* [Hybrid metal working equipment. Technological aspects of integrating the operations of surface hardening and abrasive grinding]. Novosibirsk, NSTU Publ., 2019. 348 p. ISBN 978-5-7782-3988-3.

43. Witte J., Huebler D., Schroepfer D., Boerner A., Kannengiesser T. Wear behavior of innovative niobium carbide cutting tools in ultrasonic-assisted finishing milling. *Wear*, 2023, vol. 522, p. 204722. DOI: 10.1016/j.wear.2023.204722.

44. Kim J., Zani L., Abdul-Kadir A., Roy A., Baxevanakis K.P., Jones L.C.R., Silberschmidt V.V. Hybrid-hybrid turning of micro-SiCp/AA2124 composites: A comparative study of laser-and-ultrasonic vibration-assisted machining. *Journal of Manufacturing Processes*, 2023, vol. 86, pp. 109–125. DOI: 10.1016/j.jmapro.2022.12.045.

45. Xu M., Wei R., Li C., Ko T.J. High-frequency electrical discharge assisted milling of Inconel 718 under copper-beryllium bundle electrodes. *Journal of Manufacturing Processes*, 2023, vol. 85, pp. 1116–1132. DOI: 10.1016/j.jmapro.2022.12.026.

46. Lv B., Lin B., Cao Z., Liu W., Wang G. Numerical simulation and experimental investigation of structured surface generated by 3D vibration-assisted milling. *Journal of Manufacturing Processes*, 2023, vol. 89, pp. 371–383. DOI: 10.1016/j.jmapro.2023.01.010.

47. Jeon Y., Lee C.M. Current research trend on laser assisted machining. *International Journal of Precision Engineering and Manufacturing*, 2012, vol. 13, iss. 2, pp. 311–317. DOI: 10.1007/s12541-012-0040-4.

48. Kim E.-J., Lee C.-M., Kim D.-H. The effect of post-processing operations on mechanical characteristics of 304L stainless steel fabricated using laser additive manufacturing. *Journal of Materials Research and Technology*, 2021, vol. 15, pp. 1370–1381. DOI: DOI.org/10.1016/j.jmrt.2021.08.142.

49. Ahn J.W., Woo W.S., Lee C.M. A study on the energy efficiency of specific cutting energy in laser-assisted machining. *Applied Thermal Engineering*, 2016, vol. 94, pp. 748–753. DOI: 10.1016/j.applthermaleng.2015.10.129.

50. Dumitrescu P., Koshy P., Stenekes J., Elbestawi M.A. High-power diode laser assisted hard turning of AISI D2 tool steel. *International Journal of Machine Tools and Manufacture*, 2016, vol. 46, iss. 15, pp. 2009–2016. DOI: 10.1016/j.ijmachtools.2006.01.005.

51. Venkatesan K., Ramanujam R., Kuppan P. Laser assisted machining of difficult to cut materials: research opportunities and future directions – a comprehensive review. *Procedia Engineering*, 2014, vol. 97, pp. 1626–1636. DOI: 10.1016/j.proeng.2014.12.313.

52. Brecher C., Emonts M., Rosen C.-J., Hermani J.-P. Laser-assisted milling of advanced materials. *Physics Procedia*, 2011, vol. 12, pp. 599–606. DOI: 10.1016/j.phpro.2011.03.076.

53. Zaeh M.F., Wiedenmann R., Daub R. A thermal simulation model for laser-assisted milling. *Physics Procedia*, 2010, vol. 5, pp. 353–362. DOI: 10.1016/j.phpro.2010.08.062.

54. Kim I.-W., Lee C.-M. A study on the machining characteristics of specimens with spherical shape using laser-assisted machining. *Applied Thermal Engineering*, 2016, vol. 100, pp. 636–645. DOI: 10.1016/j.applthermaleng.2016.02.005.

55. Choi Y.H., Lee C.M. A study on the machining characteristics of AISI 1045 steel and inconel 718 with circular cone shape in induction assisted machining. *Journal of Manufacturing Processes*, 2018, vol. 34, pp. 463–476. DOI: 10.1016/j.jmapro.2018.06.023.

56. Woo W.S., Lee C.M. A study on the optimum machining conditions and energy efficiency of a laser-assisted fillet milling. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 2018, vol. 5, iss. 5, pp. 593–604. DOI: 10.1007/s40684-018-0061-2.

57. Ha J.-H., Lee C.-M. A study on the thermal effect by multi heat sources and machining characteristics of laser and induction assisted milling. *Materials*, 2019, vol. 12, iss. 7, p. 1032. DOI: 10.3390/ma12071032.

58. Kim E.J., Lee C.M. A study on the optimal machining parameters of the induction assisted milling with Inconel 718. *Materials*, 2019, vol. 12, iss. 2, p. 233. DOI: 10.3390/ma12020233.

59. Kim J.-H., Kim E.-J., Lee C.-M. A study on the heat affected zone and machining characteristics of difficult-to-cut materials in laser and induction assisted machining. *Journal of Manufacturing Processes*, 2020, vol. 57, pp. 499–508. DOI: 10.1016/j.jmapro.2020.07.

60. Kim E.-J., Lee C.-M. Experimental study on power consumption of laser and induction assisted machining with Inconel 718. *Journal of Manufacturing Processes*, 2020, vol. 59, pp. 411–420. DOI: 10.1016/j.jmapro.2020.09.064.

61. Xu D., Liao Z., Axinte D., Sarasua J.A., M'Saoubi R., Wretland A. Investigation of surface integrity in laser-assisted machining of nickel based superalloy. *Materials and Design*, 2020, vol. 194, p. 108851. DOI: 10.1016/j.matdes.2020.108851.

62. Skeeba V.Yu., Ivancivsky V.V., Martyushev N.V. Peculiarities of high-energy induction heating during surface hardening in hybrid processing conditions. *Metals*, 2021, vol. 11, iss. 9, p. 1354. DOI: 10.3390/met11091354.

63. Ma Z., Wang Z., Wang X., Yu T. Effects of laser-assisted grinding on surface integrity of zirconia ceramic. *Ceramics International*, 2020, vol. 46, iss. 1, pp. 921–929. DOI: 10.1016/j.ceramint.2019.09.051.

64. Skeeba V.Yu., Ivancivsky V.V., Lobanov D.V., Zhigulev A.K., Skeeba P.Yu. Integrated processing: quality assurance procedure of the surface layer of machine parts during the manufacturing step "diamond smoothing". *IOP Conference Series: Materials Science and Engineering*, 2015, vol. 25, p. 012031. DOI: 10.1088/1757-899X/125/1/012031.

65. Gao K., Qin X. Effect of feed path on the spot continual induction hardening for different curved surfaces of AISI 1045 steel. *International Communications in Heat and Mass Transfer*, 2020, vol. 115, p. 104632. DOI: 10.1016/j.icheatmasstransfer.2020.104632.

66. Areitioaurtena M., Segurajauregi U., Urresti I., Fisk M., Ukar E. Predicting the induction hardened case in 42CrMo4 cylinder. *Procedia CIRP*, 2020, vol. 87, pp. 545–550. DOI: 10.1016/j.procir.2020.02.034.

67. Li F., Li X., Wang T., Rong Y.(K.), Liang S.Y. In-process residual stresses regulation during grinding through induction heating with magnetic flux concentrator. *International Journal of Mechanical Sciences*, 2020, vol. 172, p. 105393. DOI: 10.1016/j.ijmecsci.2019.105393.

68. Hammouma C., Zeroug H. Enhanced frequency adaptation approaches for series resonant inverter control under workpiece permeability effect for induction hardening applications. *Engineering Science and Technology, an International Journal*, 2022, vol. 27, p. 101006. DOI: 10.1016/j.jestch.2021.05.010.

69. Asadzadeh M.Z., Raninger P., Prevedel P., Ecker W., Mücke M. Hybrid modeling of induction hardening processes. *Applications in Engineering Science*, 2021, vol. 5, p. 100030. DOI: 10.1016/j.apples.2020.100030.

70. Javaheri V., Haiko O., Sadeghpour S., Valtonen K., Kömi J., Porter D. On the role of grain size on slurry erosion behavior of a novel medium-carbon, low-alloy pipeline steel after induction hardening. *Wear*, 2021, vol. 476, p. 203678. DOI: 10.1016/j.wear.2021.203678.

71. Ptitsyn S.V., Skeeba V.Yu., Chesov Yu.S., Merezhko E.V. Nadezhnost' prognoza kachestva tekhnologicheskogo oborudovaniya [Reliability prediction of quality process equipment]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2013, no. 2 (59), pp. 33–38.

72. Skeeba V.Yu., Ivancivsky V.V. Reliability of quality forecast for hybrid metal-working machinery. *IOP Conference Series: Earth and Environmental Science*, 2018, vol. 194, iss. 2, p. 022037. DOI: 10.1088/1755-1315/194/2/022037.

73. Fedotenok A.A. *Kinematicheskaya struktura metallorezhushchikh stankov* [Kinematic structure of machine tools]. Moscow, Mashinostroenie Publ., 1970. 408 p.

74. Ptitsyn S.V., Levitskii L.V. *Strukturnyi analiz i sintez kinematiki metallorezhushchikh stankov* [Structural analysis and kinematics synthesis of machine tools]. Kiev, UMK Publ., 1989. 70 p.

75. Skeeba V.Yu., Ivantsivsky V.V., Nos O.V., Zverev E.A., Martynova T.G., Vakhrushev N.V., Vanag Yu.V., Titova K.A., Cha G.O., Skiba P.Yu. *Povyshenie effektivnosti proektirovaniya gibridnogo metalloobrabatyvayushchego oborudovaniya, ob"edinyayushchego mekhanicheskuyu i poverkhnostno-termicheskuyu operatsii* [Improving the efficiency of the conceptual design of the integrated metal-cutting equipment, combining mechanical and surface thermal operation]. Report on the research work of the project N 9.11829.2018/11.12. State registration no. AAAA-Б19-219020690026-1, 2018. 197 p.

76. Kazantsev M.E. *Postroenie strukturnykh skhem stankov i nastroiki ispolnitel'nykh dvizhenii* [Construction of block diagrams of machine tools and adjustment of executive movements]. Novosibirsk, NSTU Publ., 1997. 54 p.

77. Ivakhnenko A.G. *Povyshenie effektivnosti rannikh stadii proektirovaniya metallorezhushchikh stankov na osnove strukturnogo sinteza formoobrazuyushchikh sistem.* Diss. dokt. tekhn. nauk [Improving the efficiency of the early stages of designing machine tools based on the structural synthesis of shaping systems. Dr. eng. sci. diss.]. Moscow, 1998. 244 p.

78. Ivakhnenko A.G., Kuts V.V., Erenkov O.Y., Ivakhnenko E.O., Oleinik A.V. Effectiveness of structural-parametric synthesis of metal-cutting systems. *Russian Engineering Research*, 2017, vol. 37, no. 10, pp. 901–905. DOI: 10.3103/S1068798X17100112.

79. Ivakhnenko A.G., Kuts V.V. *Strukturno-parametricheskii sintez tekhnologicheskikh sistem* [Structural-parametric synthesis of technological systems]. Kursk, KurskSTU Publ., 2010. 151 p.

80. Kuts V.V. *Metodologiya predproektnykh issledovanii spetsializirovannykh metallorezhushchikh sistem.* Diss. dokt. tekhn. nauk [Methodology of pre-design studies of specialized metal-cutting systems. Dr. eng. sci. diss.]. Kursk, 2012. 365 p.

81. Vragov Yu.D. *Analiz komponovok metallorezhushchikh stankov (Osnovy komponetiki)* [Analysis of the layout of machine tools. The basics of compositing]. Moscow, Mashinostroenie Publ., 1978. 208 p.

82. Ivakhnenko A.G. *Kontseptual'noe proektirovanie metallorezhushchikh sistem. Strukturnyi sintez* [Conceptual design of metal-cutting systems. Structural synthesis]. Khabarovsk, KhGTU Publ., 1998. 124 p.

83. Nakaminami M., Tokuma T., Moriwaki M., Nakamoto K. Optimal structure design methodology for compound multiaxis machine tools–I – Analysis of requirements and specifications. *International Journal of Automation Technology*, 2007, vol. 1, no. 2, pp. 78–86. DOI: 10.20965/ijat.2007.p0078.

84. Nakaminami M., Tokuma T., Matsumoto K., Sakashita S., Moriwaki T., Nakamoto K. Optimal structure design methodology for compound multiaxis machine tools–II – Investigation of basic structure. *International Journal of Automation Technology*, 2007, vol. 1, no. 2, pp. 87–93. DOI: 10.20965/ijat.2007.p0087.

85. Mekid S., ed. *Introduction to precision machine design and error assessment*. *Mechanical and Aerospace Engineering Series.* Boca Raton, CRC Press, 2008. 302 p. ISBN 0849378869. ISBN 978-0849378867.

86. Grigoryan G.D. *Nadezhnost' gibkikh tekhnologicheskikh sistem v usloviya bezlyudnoi tekhnologii* [Reliability of flexible technological systems in the conditions of deserted technology]. Odessa, OPI Publ., 1985. 104 p.

87. GOST 9726–89. *Stanki frezernye vertikal'nye s krestovym stolom. Terminologiya. Osnovnye razmery. Normy tochnosti i zhestkosti* [State standard 9726–89. Vertical milling machines with compound table. Terminology. Basic dimensions. Standards of accuracy and rigidity]. Moscow, Standartinform Publ., 1989. 41 p.

88. Chesov Yu.S., Ptitsyn S.V. *Proektirovanie metallorezhushchego* oborudovaniya [Design of metal-cutting equipment]. Novosibirsk, NSTU Publ., 2005. 105 p.

Conflicts of Interest

The authors declare no conflict of interest.