DOI: **https://doi.org/**10.15276/hait.06.2023.17 “*In the course of discussion*”
UDC 519.816

An information model concept for a thermomechanical process in grinding

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ABSTRACT

The purpose of the work is to present the concept of an information model of the thermomechanical process in grinding of products from materials prone to defect formation due to the fact that their surface layer has hereditary defects of structural or technological origin. The products' strength and functionality depend on the inhomogeneity and defectiveness of the structure of the materials from which they are made. Such materials have many different micro defects formed in the surface layer of parts during the technological operations of their production. Reducing number of defects in the finishing operations of these materials and increasing the operational properties of products made of these materials is an essential national and economical task, the solution of which leads to a significant saving of material resources, labour intensity and cost of manufacturing parts. The currently available information on the thermal processes of diamond abrasive processing is obtained on the assumption of the homogeneity of the materials being polished and needs to consider the presence of defects in the technological heredity of the products. The phenomenological approach in studying the causes of cracking of materials prone to this type of defect does not allow to reveal the mechanism of genesis and development of grinding cracks. The choice of the method of investigation of the mechanism of crack formation is based on micro-research related to inhomogeneities, which are formed in the surface layer of parts during previous technological operations. A mathematical model has been developed that describes thermomechanical processes in the surface layer during grinding of parts made of materials and alloys, taking into account their inhomogeneities, which affect the intensity of the formation of grinding cracks. Calculated dependences between the crack resistance criterion and the main controlling technological parameters were obtained. According to the known characteristics of hereditary defects, the limit values of thermomechanical criteria, which ensure the necessary quality of the surfaces of the processed products, are determined. Based on the obtained criterion ratios, an algorithm for selecting technological possibilities for defect-free processing of products from materials prone to loss of quality of the surface layer of parts was built. A decision support system has been developed to increase the efficiency of the finishing process management.

Keywords: Information support; technological capabilities; defect-free processing algorithm; support system; models; heterogeneity

***For citation*: Usov A. V., Kunitsyn M. V., Zaychyk Yu. I. “An information model concept for a thermomechanical process in grinding”. *Herald of Advanced Information Technology.* 2023; Vol. 6 No.3: 250– 262. DOI: https://doi.org/10.15276/hait.06.2023.17**

INTRODUCTION. PROBLEM STATEMENT

Various technological operations contribute to the appearance of hereditary defects in the surface layer, which include non-metallic inclusions, flakes, air pores, microcracks of a shrinkage nature (melting), deformation of crystal grains, cracks of liquation origin (forging, drawing), coarse-graining, accumulation of carbides (heat treatment, thermo-mechanical treatment, chemical-thermal treatment), chips, tears, surface cracks, internal cracks, delamination (finishing operations), grinding burns.

These defects, being stress concentrators, contribute to the formation of cracks, both in processing the material and during their operation.

Losses due to hereditary defects in finishing operations are especially significant. Grinding, the final operation for most parts, which significantly increases operational properties due to high accuracy and low roughness, is accompanied by high-temperature exposure, which leads to burning and significant defects from the output of suitable products due to the formation of cracks.

Reducing defects in the finishing operations of these materials and improving the operational properties of products made of these materials is an essential national and economical task, the solution of which leads to a significant saving of material resources, labour intensity and cost of manufacturing parts.

The scientific task is to provide information about crack formation during finishing technological operations, taking into account the influence of hereditary defects formed during previous operations, namely, thermal and thermomechanical processing, coating, etc. This task is especially important when processing materials and alloys that are prone to cracking during the grinding process.

It establishes the regularities of the formation of grinding cracks during the processing of parts made of materials and alloys prone to this type of defects, taking into account the hereditary micro-uniformities that arise throughout the technology of their manufacture, starting with the methods of obtaining blanks and, on this basis, the development of information support for the technological conditions of defect-free grinding based on constructed mathematical models and obtained functional dependencies.

LITERATURE OVERVIEW

The grinding operation is the central processing operation of heavily loaded parts made of high-strength steel and alloys, which include gears, shafts, stamps, elements of electric machines, and electronics [1, 2], [3]. This operation also applies to products whose working surfaces have increased requirements for accuracy and roughness, which significantly affect their operational properties. Such products include parts with wear-resistant coatings and highly coercive magnets of the cast iron-nickel-aluminum-based hard magnetic type, e.g., Alnico 8HC (R1-1-13), which is used in modern electrical machines, devices, and apparatus [4, 5].

The tendency of metals to form cracks during grinding depends on metallurgical and structural heredity, which is determined by smelting methods and the degree of deoxidation, phase transformations in alloys, and modes of thermal, chemical-thermal treatment. Operations preceding the finish [6, 7], [8, 9]. At the same time, the parameters that take into account the dependence of the stress state on the structural components are a set of mechanical characteristics (K_{1C}, K_C, K_{ISC}, K_{th}) of fracture mechanics [10, 11].

A distinctive feature of the grinding operation is the release of a large amount of heat, the central part of which is perceived by the processed part and causes structural changes in its parts - burns. These defects contribute to the reduction of the initial hardness of the surface, the formation of tensile residual stresses, and the reduction of contact endurance and fatigue strength of parts [12, 13], [14, 15].

For a large group of metals and alloys that are not prone to structural transformations in the process of processing them by grinding, a characteristic type of defect is defects such as cracks, which significantly reduce the operational properties of the products.

The nature and intensity of cracking in products are primarily determined by the thermophysical properties of the processed materials, their structure, the heredity of previous and subsequent technological operations, and their parameters. During the operation of parts whose surface layer contains hereditary defects, the destruction of products occurs at the places of their accumulation.

The quality of the surface layer is formed under the influence of thermomechanical phenomena accompanying the final operations. Therefore, in works [1, 2], [3, 7], [8, 9], [10], the thermal tension of diamond abrasive processing is used as the leading indicator of the physical and mechanical condition of the treated surfaces. Based on the models of temperature fields developed by them, the regularities of the formation of defects such as cautery and the technological possibilities of their elimination were studied depending on the thermophysical properties of the processed materials and the technological parameters of their processing.

However, currently, available models of thermal processes of diamond-abrasive processing are obtained on the assumption of homogeneity of the materials being polished and need to consider the presence of defects in the technological heredity of the products [14, 15], [16]. In these works, the condition of the surface layer of the part is considered mainly from a qualitative point of view or evaluated in each case by experimental methods. Thus, the susceptibility of magnetic alloys to crack formation during grinding is associated with the peculiarities of their magnetic and crystal structure, designed to obtain high magnetic properties [17, 18], [19]. The absence of quantitative relationships between the crack resistance of magnets and other properties does not allow us to unambiguously use the existing information base of defect-free grinding. There is a study of the influence of structural transformations and steels on the formation of grinding cracks, according to which the presence of a large amount of austenite in the subsurface layer of parts leads to the formation of tensile stresses, which are realized in the form of brittle cracks [20].

Structural transformations in the materials of the products cannot be determined as an "independent" cause of the appearance of grinding cracks since structural stresses, reaching destructive values, are formed over a considerable period. Grinding is characterized by short duration and high heating and cooling rates, during which structural changes are insignificant and thermomechanical stresses reach extreme values.

The mechanism of the formation of cracks in the surface layer of parts with coatings is explained by the effect of temporary tensile temperature stresses exceeding the limit values and the peeling of the coating from the base metal by the effect of residual stresses in the surface layer [20]. The considered models of the stress-strain state of parts with coatings need to consider piecewise inhomogeneity (coating-matrix), and studies of the effect of coating inhomogeneity on the mechanism of defect formation are absent [20, 21].

The phenomenological approach in studying the causes of cracking of materials prone to this type of defect does not allow to reveal the mechanism of genesis and development of grinding cracks. The choice of the method of investigation of the mechanism of crack formation is based on micro-research related to inhomogeneities, which are formed in the surface layer of parts during previous technological operations.

The intensity of the appearance of cracks is primarily determined by the presence of various inhomogeneities that arise in the surface layer during the manufacturing technology of the part. Hereditary defects such as flakes, sharp cavities, domains, and foreign inclusions are hazardous from the crack initiation point of view. Therefore, constructing the theory of crack formation during grinding using the criteria of fracture mechanics is possible only based on an in-depth study of the mechanism of crack initiation in the tops of concentrators, which are metallurgical, structural and technological defects.

To control the quality of the part during grinding, it is necessary to study the patterns of formation of the thermomechanical state of the surface layer, taking into account its heterogeneity. High-performance, defect-free grinding of materials sensitive to crack formation must be carried out, considering residual defects at the limit modes while maintaining an equilibrium state that does not yet cause cracks. There still needs to be an informational provision of technological possibilities for defect-free processing of products made of materials prone to cracking.

When setting the task of improving the quality of finishing operations of parts, the problem of assessing the impact of inhomogeneities and choosing technological parameters that exclude the formation of defects on the processed surfaces arises. The wide range of materials prone to cracking, the variety of their properties, and the size, orientation, location and distribution of hereditary defects contributed to the currently available recommendations for eliminating grinding cracks during the treatment of product surfaces. In this regard, it is necessary to develop information support for optimizing the thermomechanical state of the surface layer of products, taking into account hereditary defects, which prevent the occurrence of defects such as cracks and burns during finishing operations.

Therefore, determining the information provision of technological conditions for defect-free grinding of products whose materials are prone to defect formation is urgent.

THE AIM AND OBJECTIVES OF THE RESEARCH

To develop information technology of normative decision-making theory for high-quality processing of products from materials prone to defect formation.

Achieving this goal required setting and solving the following main tasks:

1. Development of methods, models and tools for solving the problem of choosing effective solutions for technological assurance of quality characteristics of the surface layer of parts made of materials and alloys prone to defect formation during their grinding processing, taking into account previous operations and hereditary inhomogeneities.
2. Create an algorithm for ensuring the technological conditions for grinding materials with hereditary heterogeneities, which provide the necessary quality indicators and a decision support system to increase the efficiency of the management of the finishing process.

GENERAL PROVISIONS

When choosing and substantiating the mathematical model, it was considered that both thermal and mechanical phenomena accompany the process of grinding parts. However, temperature fields exert a predominant influence on the stress-strain state of the surface layer. Considering that the central mass of the surface layer of the metal during grinding is in an elastic state, it is possible to use the model of a thermoelastic body, which reflects the relationship between mechanical and thermal phenomena at finite values of heat flows. Since information on the distribution of temperatures and stresses along the depth and in the direction of the tool movement is essential for studies of the thermomechanical state of polished surfaces, a flat problem is considered.

When drawing up the calculation scheme (Fig. 1 in [22]), it is assumed that a workpiece-type detail can be represented in the form of piecewise homogeneous conventional layers with different properties located on the primary matrix material, which allows studying thermomechanical processes during grinding of parts with several types of coatings, fillings Δa_k applied to the base material. Such a scheme determines the thermal and deformation conditions of the connection of layers outside their interface – a_k.

The influence of inhomogeneities in the form of phase transformations of unstable structures, intergranular films, boundaries of the contour of hereditary austenite grains, carbide striations, non-metallic inclusions, shells, flakes and other defects that arise in the surface layer due to their presence in the surface layer in the form of conditional cracks.

The system of equations that determine the thermal and stress-strain state when grinding the surface of parts with coatings, the upper layer of which has inhomogeneities such as inclusions and cracks, contains [1, 2], [3].

Equation of non-stationary thermal conductivity:

$$\frac{\partial T}{\partial \tau} = a^2\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad \begin{matrix} 0 \le x < \infty; \\ -\infty < y < \infty. \end{matrix} \tag{1}$$

Lame's equation of elasticity in displacements:

$$\begin{gathered} \frac{\partial \Theta}{\partial x}\frac{1}{1-2\mu} + \Delta \bar{u} = B^T \frac{\partial T}{\partial x}; \\ \bar{u}(x,y) = \frac{u}{2G}; \\ \bar{v}(x,y) = \frac{v}{2G}; \end{gathered} \tag{2}$$

$$\begin{gathered} \frac{\partial \Theta}{\partial y}\frac{1}{1-2\mu} + \Delta \bar{v} = B^T \frac{\partial T}{\partial y}; \\ B^T = \frac{4G(1+\mu)}{1-2\mu} a_t; \\ \Delta = \frac{\partial^2}{dx^2} + \frac{\partial^2}{dy^2}, \end{gathered} \tag{3}$$

where $T(x,y,\tau)$ is the temperature at a point with coordinates (x,y) and at any moment τ; a is the thermal conductivity of the material; a_t is the temperature coefficient of linear expansion; μ, G are Lamé constants; υ, v are the components of the vector of displacements of the point (x,y); $\Delta = {}^{\partial^2}\!/_{\partial x^2} + {}^{\partial^2}\!/_{\partial y^2}$ is the Laplace operator.

The initial conditions for this task can be taken as:

$$T(x,y,0) = 0. \tag{4}$$

Boundary conditions for temperature and deformation fields that take into account heat exchange from the surface outside the tool contact zone with the part and intense heat release in the processing zone are as follows:

$$\begin{gathered} \frac{\partial T}{\partial x} = -\frac{q(y,\tau)}{\lambda}, |y| < a^*, \\ -\lambda\frac{\partial T}{\partial x} + \gamma T = 0, |y| > a^* \end{gathered} \tag{5}$$

$$\sigma_x(x,y,\tau)|_{x=0} = \tau_{\tau y}(x,y,\tau)|_{x=0} = 0, \tag{6}$$

where $q(y,\tau)$ is the intensity of the heat flow formed as a result of the interaction of the circle with the part; λ is the coefficient of thermal conductivity of the material being ground; $2a^*$ is the length of the contact zone of the circle with the processed surface; γ is the coefficient of heat exchange with the environment; σ_x, τ_{xy} are normal and tangential stresses.

Conditions for combining layers (coatings):
for temperature fields:

$$\begin{aligned} \overset{k-1}{T}\,(a_k - 0, y, \tau) &= \overset{k}{T}(a_k + 0, y, \tau), \\ \lambda_{k-q}\frac{\partial \overset{k-1}{T}}{\partial x}(a_k - 0, y, \tau) & \\ &= \lambda_k \frac{\partial \overset{\sigma}{T}}{\partial x}(a_k + 0, y, \tau), \end{aligned} \tag{7}$$

for deformation fields:

$$\begin{gathered} \overset{k-1}{\upsilon}{}_j(a_k - 0, y) = \overset{k}{\upsilon}_j(a_k + 0, y); \\ \overset{k-1}{\sigma}{}_x(a_k - 0, y) = \overset{k}{\sigma}_x(a_k + 0, y); \\ \overset{k-1}{\tau}{}_{xy}(a_k - 0, y) = \overset{k}{\tau}_{xy}(a_k + 0, y), \end{gathered}$$

where λ_k is the thermal conductivity of the k-th layer; α_k is the thickness of the k-th layer; $\overset{\upsilon}{\upsilon} k_j$ are components of movements in the k-th layer.

For surface layers with structural and technological inhomogeneities, the discontinuity conditions of the solution, depending on the type of defect, will be:

on inclusions:

$$\begin{gathered} \langle \bar{\upsilon} \rangle = 0, \langle \sigma_x \rangle \neq 0, \\ \langle \bar{\upsilon} \rangle = 0, \langle \sigma_x \rangle \neq 0, \end{gathered}$$

on crack-like defects:

$$\begin{gathered} \langle \sigma_x \rangle = 0, \langle \bar{\upsilon} \rangle \neq 0, \\ \left\langle \tau_{xy} \right\rangle = 0, \langle \bar{\upsilon} \rangle \neq 0. \end{gathered} \tag{8}$$

Classical strength criteria evaluated the limit equilibrium state of the deforming surface layer.

Of the available failure criteria, which take into account the local physical and mechanical properties of heterogeneous materials, the most appropriate for this case are the criteria of the force approach associated with the use of the concept of the stress intensity factor (SIF) [4, 5], [10, 11]. When the load leads to the stress intensity K_I becoming equal to the limit value K_{Ic}, the crack-like defect turns into a main crack.

Modeling of the influence of initial piecewise homogeneity of materials being ground (coated parts) on thermomechanical processes is carried out by the method of discontinuous solutions [9, 12]. They mean solutions that satisfy the equations of Fourier heat conduction and Lamé elasticity everywhere except at the boundaries of defects. When passing through the boundary of inhomogeneities, the displacement and stress fields experience discontinuities of the first kind. That is, their jumps appear $\langle \upsilon \rangle$, $\langle v \rangle$, $\langle \sigma_x \rangle$, $\langle \tau_{xy} \rangle$.

The application of generalized Fourier transformations by the variables x and y to equations (1)-(7), taking into account (8), allows us to obtain recurrent relations connecting displacements and stresses in the k-th layer with stresses and displacements formed in the first layer under the influence of non-stationary temperature fields.

The effect of inhomogeneities in the surface layer of steels and alloys on the intensity of defect formation during grinding is investigated as follows. In conditions of uneven heating, thermal deformations occur in the surface layer, which causes temperature stresses. Under the influence of these stresses, which are concentrated in the locations of defects, the formation of grinding cracks occurs.

Of most significant interest is the behavior of stresses in the region of the top of defects such as cracks, sharp inclusions, and structural imperfections, i.e. stress features at $y \to \pm l_k$. The nature of the stress field near the end of the defect, obtained within the framework of the classical theory of elasticity, is determined by the stress intensity coefficients $K_I = iK_{II}$ [6, 7], [8].

Thus, the study of the stress intensity at the vertices of a defect of length $2l$, located at a depth of σ^*, when the heat flow q is given on the surface of the body ($x = 0,\ |y| \le a^*$), made it possible to establish the limiting value of this flow q^* at which the specified defect begins to develop into a main crack [10]:

$$q^* = \frac{2\sqrt{3}\lambda(1-\nu)K_{4C}}{\alpha_2 El\sqrt{\pi l}\sigma^*}. \tag{9}$$

The mutual influence of defects on the stress intensity is indicated when they are located at a distance from each other slightly more than $\sigma^* = 1/3$. At the same time, the lowest crack resistance of the material is achieved if the defects are oriented relative to each other at an angle $\phi = \pi/6 + \pi/4$. The geometry and properties of inclusions can create conditions for both inhibition and the development of grinding cracks. If the heat flow is directed parallel to the larger axis of an elliptical inclusion and a rectilinear thermally insulated crack, then if the coefficient of linear temperature expansion α_t^B of the inclusion is greater than that of the primary material $\alpha_t^M(\alpha_t^B > \alpha_t^M)$, the stiffness increases to growth K_I regarding different relations of thermal conductivity coefficients, components of the material.

It leads to a decrease in the crack resistance of the surface layer. For defects of the crack type, which are in the layer with a smaller coefficient α_t, the orientation of the defect strongly affects the value of the SIF [12, 13].

When a crack located in a more complex layer is significantly removed from the interface line, SIF K_I takes maximum values when the defect is oriented parallel to this line. As the crack approaches the interface, the maximum K_I is reached when it becomes perpendicular to this interface. If the crack is in a less rigid material, the maximum K_I is reached when the crack is perpendicular to the dividing line. The coefficient K_{II} becomes maximum at angles between the line of separation of the layers close to $\pi/6$, regardless of the relative stiffness of the layers.

For defect-free processing of steels and alloys with crack-like defects and inclusions, the selection of processing modes and tool characteristics should be guided by the limit values of the heat flow formed during grinding so that hereditary defects do not leave the equilibrium state.

The surface layer of polished materials contains inhomogeneities and defects of hereditary origin, which have one or another degree of randomness. The stochasticity of micro inhomogeneities in cast iron-nickel-aluminum-based hard magnetic alloys, e.g., Alnico 8HC (R1-1-13), cemented steels, and various coatings are especially significant. In this case, the hypothesis of the weakest link – the defect with the largest geometric size – is used [14, 17].

The influence of the design parameters of the tool on the thermomechanical state of the surface layer was determined using the model problem (1)-(5) and boundary conditions in the form:

$$q(y,\tau) = \frac{c\sqrt{\tau}}{\lambda}[H(y) - H(y-2a^*)]\sum_{k=0}^{n}\sigma\big(y + kl - v_{kp}\tau\big), \tag{10}$$

where $H(y)$ is the Heaviside function; $\sigma(y)$ is the Dirac delta function; n is the number of grains passing through the contact zone; λ is the thermal conductivity of the product material; $c\sqrt{\tau}$ is the heat flow from a single grain; v_g, v_{tor}, t_{gr} are grinding modes, $2a^*$ is the length of the contact arc of the circle with the part; l^* is the distance between the cutting grains. The maximum values of the instantaneous temperature T_M, from single grains to the constant component – T_K, were obtained theoretically and confirmed experimentally. They were used later as criteria for predicting the conditions for forming grinding defects.

The influence of technological heredity on the crack resistance of metals during grinding was studied using the fracture mechanics parameter K_{Ic}, which considers the stress-strain state's dependence on the structural components of the surface layer.

An increase in the strength of steels with an increase in carbon content or a decrease in the tempering temperature after hardening naturally leads to a decrease in K_{Ic} and, therefore, to an increase in the process of crack formation during their grinding. In order to achieve the appropriate level of crack resistance, it is quite justified to use a high temper and improve such steels before finishing operations. Such measures make it possible to eliminate the tendency of these steels to the appearance of grinding cracks.

Steels in the state of reverse temper embrittlement are particularly prone to the intense occurrence of grinding cracks. Studies of fracture surfaces of steel samples in this state showed that increasing vacation length causes significant changes in microfracture. In high-strength steel, cracks develop by a viscous micromechanism, and in the state of reverse tempering brittleness, destruction by intergranular chipping and cracking of carbide particles became predominant [16].

Thus, the influence of impurities on the crack resistance of steels and alloys is significant.

Thus, in particular, a negative influence of sulfur content (0.008-0.009 %) in high-strength steels of the SNCM815 (18NCD6, 820A16, 14NiCrMo13) type on their crack resistance was established. Based on factographic studies, it is shown that the foci of microfracture in these steels are sulfide inclusions.

Alloying of steels, accompanied by grain crushing, contributes to a certain extent to the growth of K_{Ic}.

An increase in the purity of alloys due to impurities is always combined with a simultaneous increase in crack resistance and short-term strength. The same favorable factor in reducing the susceptibility of steels to crack formation during their grinding is the processing of the surface layer on an ultrafine grain. Grinding of steel grain by cyclic electrothermal treatment from 15 – points (I-2 μm) increases K_{Ic} by 40-50 %, and the yield of suitable products from materials that are particularly sensitive to grinding cracks increases by 2.5-3 times.

Elimination of grain-boundary brittleness, to which high-strength alloys are prone, can be carried out by increasing the tempering temperature or by high-temperature thermomechanical treatment, which contributes to the deformation of the austenite grain boundaries, as a result of which the smooth boundaries are subject to fragmentation and acquires a specific serration. It leads to an increase in the strength of boundaries and the elimination of grain-boundary destruction during the grinding of such alloys.

Quantitative evaluations of the crack resistance of magnetically hard alloys were carried out depending on the methods of obtaining blanks and their subsequent heat treatment to the γ-phase and thermomagnetic treatment to the $a + a'$ phase at different relaxation modes and cooling rates. The controlled parameters were the values of bending stress σ_{bend}, stretching σ_s, coefficient K_{Ic} and magnetic properties characteristics – the material's coercive force on magnetization h_C and residual induction B_r. Experimental data show that the values of K_{Ic} are different for mono- and polycrystals of cast iron-nickel-aluminum-based hard magnetic alloy, e.g., Alnico 8HC (R1-1-13), in the preparation stage. It indicates that the percentage content of non-metallic inclusions in alloys obtained by various methods varies widely. The phase composition of these alloys changes the value of the coefficient K_{Ic}. Thus, for polycrystals in the initial state, $K_{Ic} = 30$ MPa m, while the presence of the γ-phase increases K_{Ic} to 97 MPa m. It was established that the γ-phase, more plastic than this alloy's main matrix, helps inhibit microcracks.

Therefore, the analysis of the structure of the manufacturing process of magnets is an essential step in identifying reserves for increasing the output of suitable magnets during final grinding operations since the primary defects – cracking and chipping – occur precisely during the final processing of these magnets.

Blanks of permanent magnets from alnico and tykonal alloys are obtained mainly by casting. Currently, the following methods of casting are used: open and vacuum. The most common open-casting method is melting [17, 18], [19].

Fractographic analysis of fractures in the gamma-phase state shows that the fracture zone has an intercrystalline character with pronounced slip lines. However, the presence of this phase in the cast iron-nickel-aluminum-based hard magnetic alloy (e.g. Alnico 8HC (R1-1-13)) reduces the coercive force by 40 %, the residual magnetic induction by 15-20 %, and the maximum magnetic energy by more than 60 %. Therefore, these alloys are subjected to further thermomagnetic treatment. A feature of the structure of the highly coercive state of the considered alloys is the periodic alternation of elliptical particles of the α'-phase surrounded by the matrix of the α-phase. Further processing of these alloys by grinding causes the formation of defects, such as cracks in the surface layer.

Moreover, the intensity of crack formation is related to the heat treatment regimes, which, in turn, affect the particle size of the α'-phase and the direction of the thermo-mechanical treatment about the longitudinal feed during grinding. Dominant technological parameters affecting crack resistance and contact temperature are grinding depth and tool characteristics [20]. Thus, in the case of grinding with different depths with diamond wheels, the crack resistance is measured insignificantly, in contrast to the range of change of K_{Ic} when processing with 25AF46O7B wheels. The contact temperature in the first case is significantly lower than in the second.

Based on the built model, the mechanism of the appearance of grinding cracks was studied from the positions of influence of the geometry and physical properties of the α'-phase and its orientation concerning the direction of grinding these magnets in a highly coercive state. At the same time, the equilibrium conditions of the structural components of the α'-phase depending on the dominant factors of the grinding process and the fracture toughness K_{Ic} of the magnet were also used, the implementation of which does not lead to the appearance of cracks on the treated surface [21].

The development of technological criteria for managing the process of defect-free grinding was carried out based on the established functional relationships between the physical and mechanical properties of the processed materials and the main technological parameters.

The quality of the processed surfaces will be ensured if, with the help of controlling technological parameters, such technological processing conditions (modes, lubricating and cooling media and tool characteristics) are selected that the current values of the grinding temperature $T(x, y, \tau)$, the heat flow $q(y, \tau)$, stresses $\sigma(M)$ and coefficient K_{Ic} will not exceed their limit values [23].

Implementation of the system of limiting inequalities in terms of the values of the temperature itself and the depth of its distribution in the form of:

$$T(x,y,\tau)=\frac{C}{2\pi\lambda}\sum_{k=0}^{n}H\left(\tau-\frac{kl}{\upsilon_{kp}}\right)\times H\left(\frac{L+kl}{\upsilon_{kp}}\right)\int\limits_{\gamma_1}^{\gamma_2} f(x,y,\tau,\tau')d\tau' \leq [T]_M, \tag{11}$$

$$T([h],0,\tau)=\frac{C}{2\pi\lambda}\sum_{k=0}^{n}H\left(\tau-\frac{kl}{\upsilon_{kp}}\right)\times H\left(\frac{L+kl}{\upsilon_{kp}}\right)\int\limits_{\gamma_1}^{\gamma_2} \psi(x,\tau,\tau')d\tau' \leq [T]_{\text{с.п.}}, \tag{12}$$

$$\begin{gathered} T_k(0,y,\tau)=\frac{C\upsilon_{kp}}{\pi\lambda l\sqrt{\upsilon_g}}\int_a^{\tau}\int_{-e}^{e}\frac{\chi(\eta,t)e^{\frac{(y-\eta)^2}{4(\tau-t)}}}{2\sqrt{\pi(\tau-t)}}\times \\ \times\left\{\frac{1}{\sqrt{\pi(\tau-1)}}+\gamma e^{\gamma^2(\tau-t)}\left[1+\Phi\left(\gamma\sqrt{\tau-t}\right)\right]\right\}d\eta dt \leq [T] \end{gathered}, \tag{13}$$

$$T_k^{max}(L,0)=\frac{C\upsilon_{kp}\alpha}{\lambda l\upsilon_q^2}\sqrt{\frac{\alpha}{\pi}}\left[1-exp\left(-\frac{\upsilon_q\sqrt{Dt_{gr}}}{\alpha}\right)\right] \leq [T], \tag{14}$$

allows to avoid the formation of grinding burns and can serve as a basis for modeling thermophysical processes in the technological system of grinding according to the thermal criterion (Fig. 1).

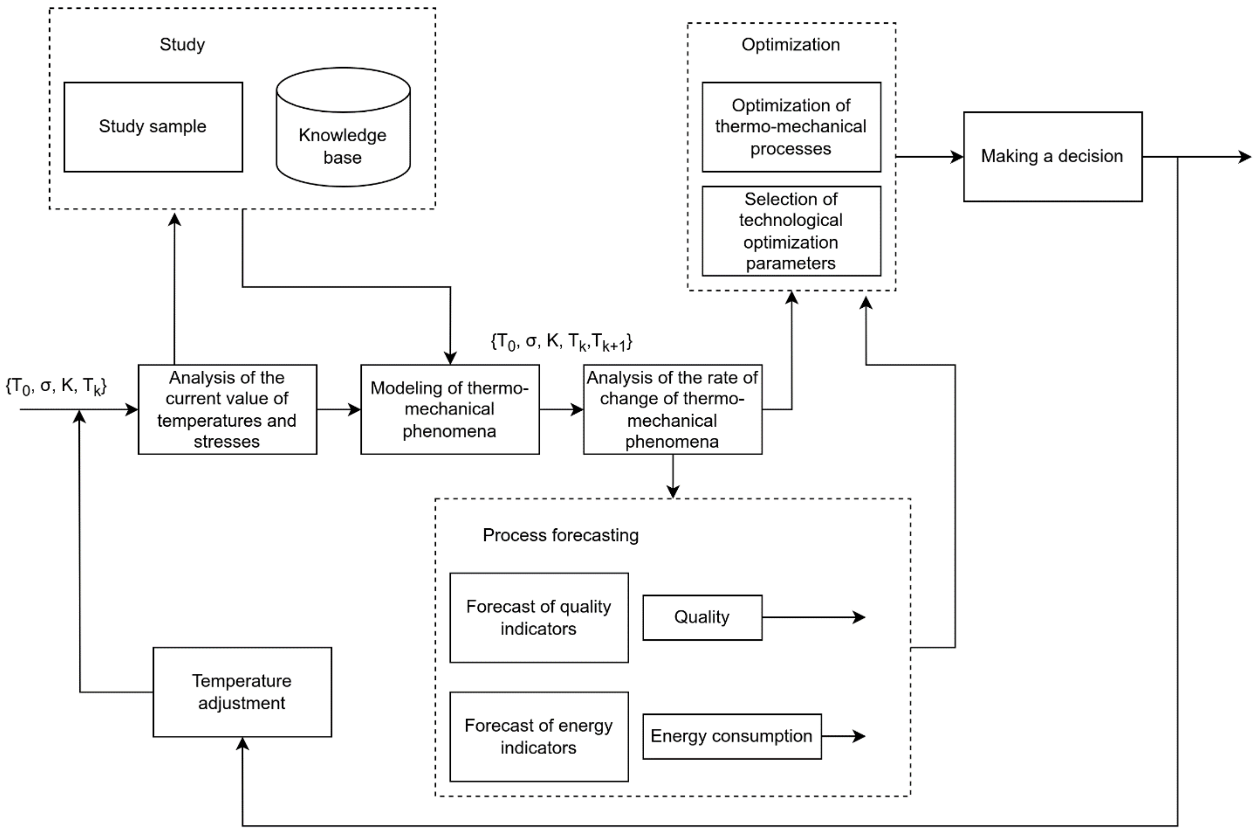

Fig. 1. **An information model for determining the relationship between the thermomechanical state of products and the technological parameters of processing**
Source: **compiled by the authors**

Considering the shortcomings of such approaches, which do not ensure maximum efficiency, which is determined by the ratio between the quality of the final product and the costs for its production, it is advisable to introduce the method, the scheme shown in fig. 1, with the help of which, based on the knowledge of the current parameters, it is possible to obtain the predicted values of the temperature in the next step, which will make it possible to calculate the control influences, taking into account the quality of the products and energy savings during their manufacture. The idea of the proposed generalized method is to use neural networks, which are characterized by the ability to approximate any dependencies.

Processing of materials and alloys without grinding cracks can be ensured if limited by the limit values formed in the zone of intense cooling stress:

$$\sigma_{max}(x,\tau) = 2G\frac{1+\nu}{1-\nu}\alpha_t T_k erf\left(\frac{x}{2\sqrt{\alpha\tau}}\right). \le [\sigma_i] \qquad (15)$$

In the case of the dominant influence of hereditary heterogeneity on the intensity of the formation of grinding cracks, it is necessary to use criteria that include deterministic connections of technological parameters and the properties of the heterogeneities themselves.

As such, it can use the limitation of the stress intensity factor:

$$K = \frac{1}{\pi\sqrt{l}}\int_{-e}^{e}\sqrt{\frac{l+t}{l-t}}\sigma_x, \sigma_y dt \le K_{Ic.} \qquad (16)$$

Alternatively, ensuring, with the help of controlling technological parameters, the limiting value of the heat flow at which the balance of structural defects is maintained:

$$q^* = \frac{P_z \upsilon_{kp} \alpha_s}{\sqrt{Dt_{gr}}} \le \frac{\sqrt{3}\lambda K_{Ic}}{Hl\sqrt{\pi l}\sigma}. \qquad (17)$$

Defect-free grinding conditions can be implemented using information about the material's structure being processed. Thus, in the case of the prevailing nature of structural imperfections with a length of $2l$, their regular location concerning the contact zone of the tool with the part, it is possible to use as a criterion ratio the condition of equilibrium of the defect in the form:

$$l_0 < \frac{K_C^2}{x[GT_k(1+\nu)\alpha_t]^2}. \qquad (18)$$

In this formula, the technological part is connected with the value of the contact temperature T_k and the processing conditions.

The indicated inequalities can be an information base (Fig. 2) [23] for determining the relationship between temperature and force fields with controlling technological parameters. They specify the range of combinations of these parameters that meet the obtained thermomechanical criteria. At the same time, the properties of the processed material are taken into account, and the necessary quality of the products is guaranteed [24, 25], [26].

Based on the obtained criterion ratios, an algorithm was built to select technological parameters that ensure the quality characteristics of the surface layer of parts during grinding, taking into account the maximum processing productivity (Fig. 2).

The algorithm (Fig. 2) for selecting parameters for finishing parts from materials prone to defect formation includes the following steps.

1. At a certain point in time t_i, the current value of the temperature in the chamber T_i is determined, and the deviation of this value from the regulated value is analyzed. Knowing the current temperature and the temperature that should be at this moment according to the temperature curve determines whether the temperature is within the specified limits. Depending on the size of the deviation, there are two possible ways of further passing the process of controlling the temperature regime of the processing.

a) If the temperature is within the specified limits, it is necessary to determine the rate of its change ${}^{\Delta T}/_{\Delta\tau}$, to predict the value of the temperature T_{i+1} in the next interval T_{i+1} after the i-th measurement.

b) If, in the next step, the T_{i+1} temperature deviates from the limits set by the processing regulation, it is necessary to determine the controlling influence that allows returning the T_{i+1} temperature value to the specified limits.

c) If the temperature at the next step meets the specified limits, it can proceed to the next step in the algorithm.

2. If the temperature is outside the limits set by the processing regulation, it is necessary to determine the necessary level of control influence, which allows returning the value of temperature T_{i+1} to the set limits.

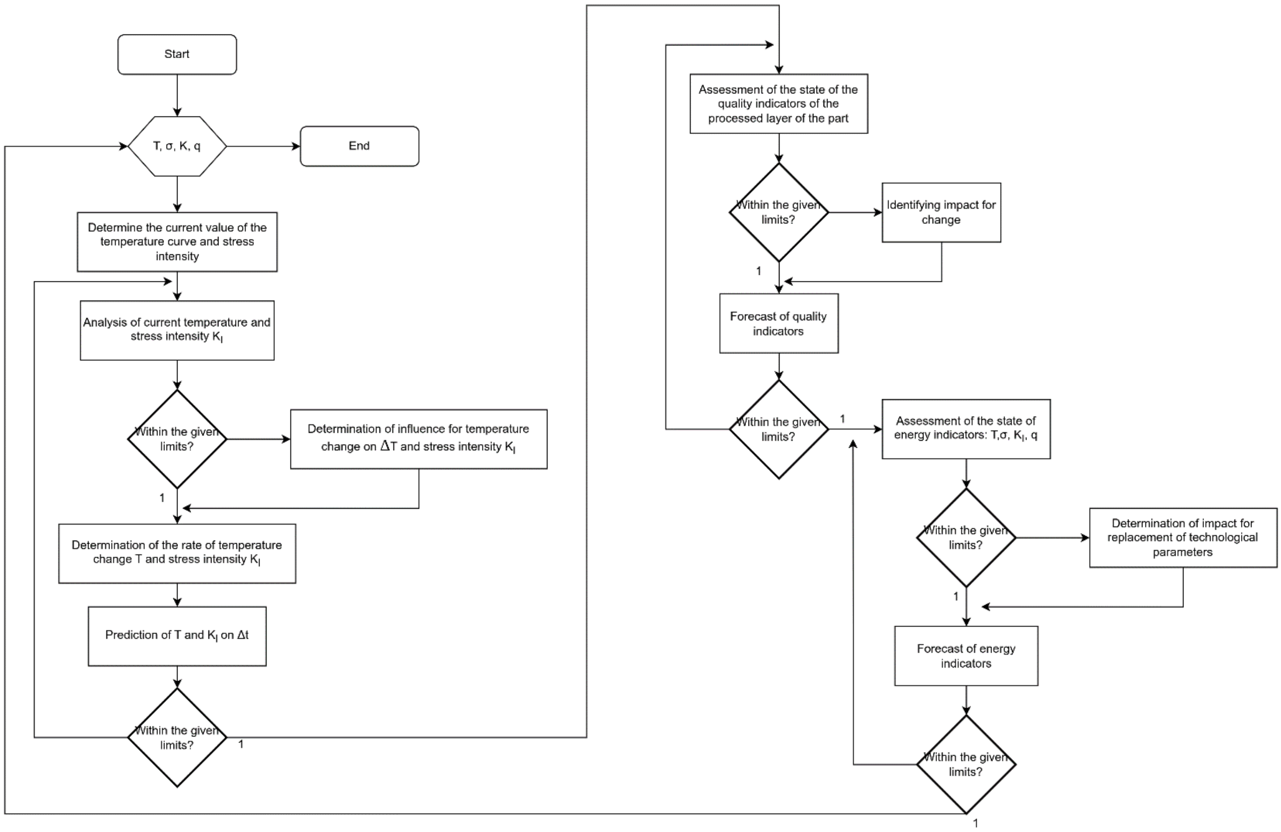

Fig. 2. **Algorithm for selecting parameters for finishing parts from materials prone to defect formation**
Source: **compiled by the authors**

3. Assessment of the state of physical and chemical processes. At the same time, two further development paths are possible.

a) If the process parameters satisfy the specified conditions and restrictions, predicting their values at the next time interval T_{i+1} is necessary.

b) If during the time interval T_{i+1}, the indicators of processes do not deviate from the normative ones, it is possible to continue processing and proceed to the next step of the algorithm. Otherwise, the value of the controlling influence is determined, and step 1 is repeated.

c) If the indicators of the parameters of processes are outside the limits, it is necessary to determine the required level of control influence and steps a, b, c and whether the necessary temperature regimes will not change simultaneously.

4. Evaluation of energy process parameters. At the same time, two further development paths are possible.

a) If the values of the energy process parameters satisfy the conditions and restrictions set by the processing regulation, then it is necessary to predict their values at the next measurement T_{i+1}. If by T_{i+1} the values of the parameters of the energy processes do not deviate from the normative ones, it can continue and go to step 1 of the algorithm; otherwise, it is necessary to determine the controlling influence and repeat step 4 to check whether the necessary temperature regimes will not change.

b) If the parameters of energy processes are outside the specified limits, it is necessary to determine the value of the controlling influence and repeat step 4 to check whether the specified temperature regimes and parameters of processes will not change.

The necessary conditions for the effectiveness of decision-making to increase the efficiency of the management of the finishing process (Fig. 3) are their completeness, timeliness and optimality.

Fulfilling the condition of completeness leads to the need to consider all the properties of the technological system as fully as possible. The requirement of optimality of the solution determines the need to move to normative formalized procedures based on mathematical models [27, 28].

The work presents a structural diagram, the general view of which is shown in Fig. 3. Let us consider the features of the main blocks of the system.

- The “Data Collection” block contains measuring process parameters and data transfer from the measuring devices to the analysis block.
- The “Data Analysis” block contains the determination of the coolant flow rate and the analysis of the change in speed compared to the technological regulation.
- The unit for determining the damper's opening percentage includes the forecasting method.
- The decision-making block includes creating recommendations for further management of the process.
- The knowledge base contains a set of “if-then” type rules for determining the causes of deviations from the established temperature regime of the process.

CONCLUSIONS

As a result of the conducted research, information provision of technological possibilities for defect-free processing of products from materials prone to cracking was created, which consists of establishing calculation dependencies regarding the determination of the influence of hereditary defects formed from previous operations on the crack resistance of the surface layer during grinding, technological conditions of processing taking into account the accumulated damage and inhomogeneities of materials and alloys, especially prone to defect formation in the grinding process, which has an essential national economic significance for reducing defects in finishing operations and improving the operational properties of machine parts.

1. A mathematical model was developed that describes thermomechanical processes in the surface layer during grinding of parts made of materials and alloys, taking into account their inhomogeneities, which affect the formation of grinding defects. At the same time, the calculated dependences between the crack resistance criterion and the main controlling technological parameters were obtained for the first time. According to the known characteristics of hereditary defects, the limit values of the heat flux, which ensure the required quality of polished surfaces, are determined.

2. Based on the obtained criterion ratios, an algorithm was built to ensure technological capabilities for defect-free processing of products from materials prone to loss of quality of the surface layer of parts and a decision support system for increasing the efficiency of process management, taking into account the maximum processing productivity.

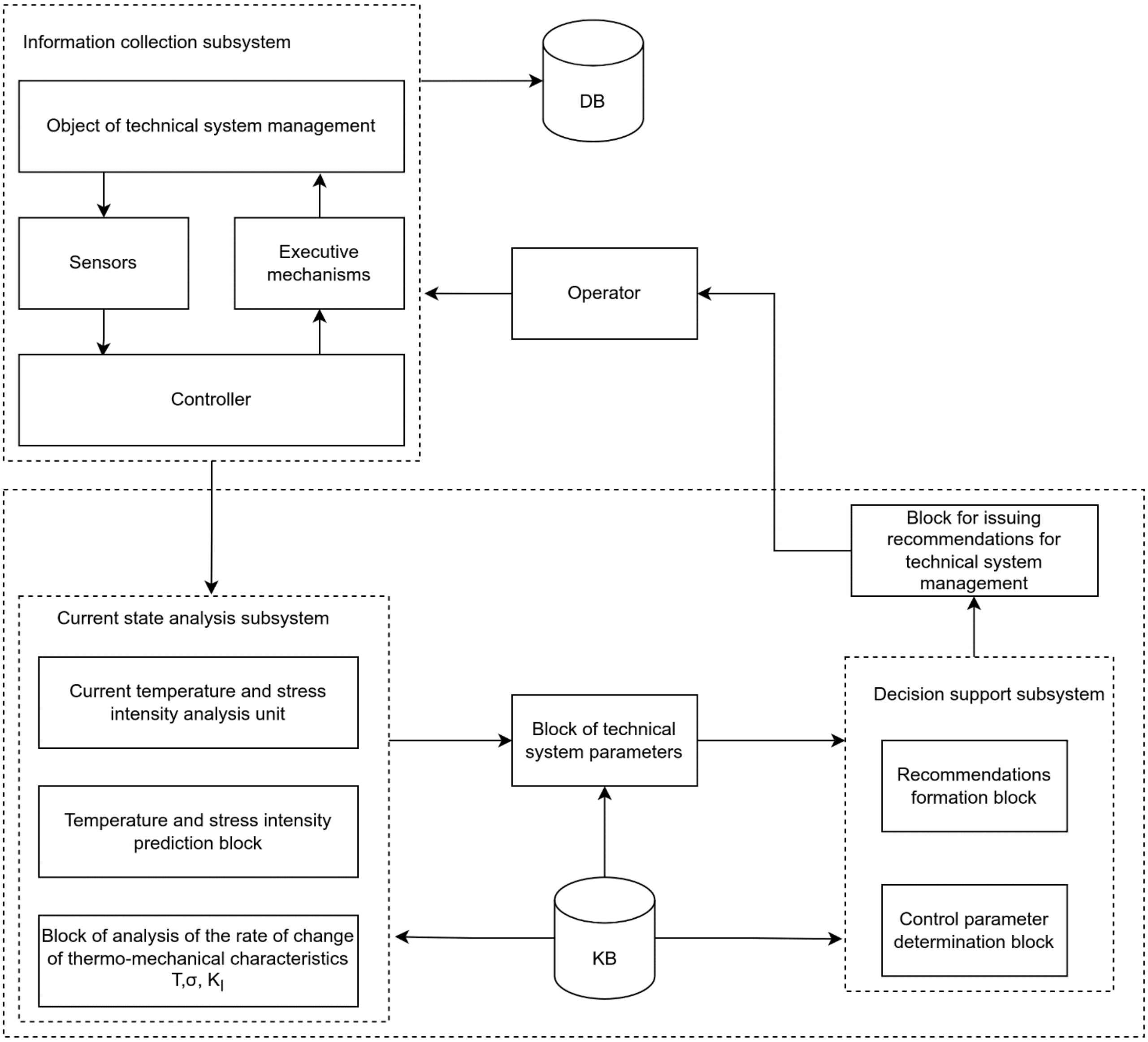

Fig. 3. **Decision support system for increasing the efficiency of the finishing process management**
Source: **compiled by the authors**

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Conflicts of Interest: The authors declare no conflict of interest

Received 02.08.2023
Received after revision 15.09.2023
Accepted 20.09.2023

DOI: https://doi.org/10.15276/hait.06.2023.17 **«*У порядку дискусії*»**
УДК 004.519.816

Концепція інформаційної моделі термомеханічного процесу при шліфуванні

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АНОТАЦІЯ

Метою роботи є представлення концепції інформаційної моделі термомеханічного процесу при шліфуванні для бездефектної обробки виробів із матеріалів, схильних до дефектоутворення завдяки тому, що їх поверхневий шар має спадкоємні дефекти структурного або технологічного походження. Міцність виробів і їх функціональні можливості залежать від неоднорідності й дефектності структури матеріалів, з яких вони виготовляються. У таких матеріалах є велика кількість різних мікродефектів, які формуються в поверхневому шарі деталей по ходу технологічних операцій їх одержання. Зниження кількості дефектів на фінішних операціях даних матеріалів, підвищення експлуатаційних властивостей виробів із цих матеріалів є важливим народно-господарським завданням, вирішення якого призводить до значної економії матеріальних ресурсів, трудомісткості та собівартості виготовлення деталей. Наявні в даний час інформаційні відомості про теплові процеси алмазно-абразивної обробки отримані в припущенні однорідності матеріалів, що шліфуються, і не враховують наявність дефектів технологічної спадковості виробів. Феноменологічний підхід у вивченні причин тріщиноутворення матеріалів схильних до цього виду дефектів не дозволяє розкрити механізм зародження та розвитку шліфувальних тріщин. Вибір методу дослідження механізму тріщиноутворення ґрунтується на мікродослідженнях, пов'язаних із неоднорідностями, які формуються в поверхневому шарі деталей на попередніх технологічних операціях. Розроблено математичну модель, яка описує термомеханічні процеси в поверхневому шарі при шліфуванні деталей із матеріалів та сплавів з урахуванням їх неоднорідностей, що впливають на інтенсивність формування шліфувальних тріщин. Отримано розрахункові залежності між критерієм тріщиностійкості та основними керуючими технологічними параметрами. За відомими характеристиками спадкових дефектів визначено граничні значення термомеханічних критеріїв, що забезпечують необхідну якість поверхонь виробів, що обробляються. На основі отриманих критеріальних співвідношень побудовано алгоритм вибору технологічних можливостей для бездефектної обробки виробів із матеріалів, схильних до втрати якості поверхневого шару деталей. Розроблена система підтримки прийняття рішень для підвищення ефективності управління процесом фінішної обробки.

Ключові слова: Інформаційне забезпечення; технологічні можливості; алгоритм бездефектна обробка; система підтримки; моделі; неоднорідність

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