UDC 536:621.9 (075.8) **doi: 10.20998/2078-7405.2024.100.12**

LEVEREGING TECHNOLOGICAL HEREDITY TO INCREASE PRODUCTION EFFICIENCY OF FERROCERRAMIC PRODUCTS DURING FINAL MACHINING

Anatoliy **Usov** [0000-0002-3965-7611], Maksym **Kunitsyn** [0000-0003-1764-8922], Yuriy **Zaychyk** [0000-0002-8577-1095], Yuliia **Sikirash** [0000-0003-0853-582X]

National University "Odessa Polytechnic", Odessa, Ukraine
usov_a_v@op.edu.ua

Received: 22 March 2024 / Revised: 28 April 2024 / Accepted: 27 May 2024 / Published: 15 June 2024

Abstract. *The quality state of grinded surface of ferro ceramic products is formed under the influence of thermomechanical phenomena which occurs during final machining and depends on the technological conditions for workpiece procurement. The mathematical model was formulated to regulate and optimize thermomechanical processes during the acquisition of ferroceramic workpieces. This mathematical model describes thermomechanical processes during workpieces sintering. Thermomechanical processes have a direct influence on defects formation in the workpieces. Grinding can cause the appearance of burns, cracks, tensile stresses in the surface layers of the products. These defects can significantly spoil the quality of products during their operation. High thermal stress of diamond-abrasive processing brings thermophysical aspects as a dominating factor for quality characteristics of processed surface. Existing grinding methods for products made from ferrocerramic materials are not able to fully eliminate the defects in the surface layer. Such defects are inherited from preceding machining operations, particularly from workpiece procurement. Material structure itself is prone or defect occurrence due to micro-heterogeneities, packaging defects, dislocations, and structural transformations. Analysis of the thermomechanical processes that run inside the surface layer made it possible to formulate calculation dependencies for defining technological conditions for eliminating burns and cracks during grinding of ferrocerramic products. Device for automatic stabilization of thermomechanical characteristics that accompany grinding of ferrocerramic products. This is achieved through the selection of optimal technological conditions for machining of the products that have heredity inhomogeneities inside the surface layer. Thus, this approach helps to achieve maximum efficiency within required quality citeria.*

Keywords: *optimization; workpiece; grinding; surface quality; thermomechanical phenomena; model; defects; technological parameters; device.*

1. Introduction

Products from ferrocerramic materials are widely used in the energetics industry (in generators, electric drives, transformers, etc.) because of their wide range of magnetic properties. Unique combinations of electromagnetic properties make ferrites useful in other technical fields. The amount of their production in the world has reached millions of tons annually and keeps growing.

Thus, the improvement of technological processes for wastes recycling (including flawed products) of ferrite production is rather relevant because the amount of waste may be up to 30%. Recycling of wastes into usable half-finished products not only helps to optimize material consumption, energy, and production resources, but also helps to decrease the influence on the environment [1].

Technological loss is connected to loss of the material, half-finished products and usable products due to the imperfection of technological process and technological equipment (leakages, absence of trapping system, frequent failures, etc.). Flaw is connected to the deviations of the parameters of half-finished-products and usable products that overcome acceptable values. Flaw can be divided into 2 types: removable and unremovable. Recycling of the removable flaw into new products (or semi-finished products) requires additional operations connected with deep physical and chemical transformations. To recycle the unremovable flaw, we need additional operations that include shredding, thermal treating, chemical treating of the surface particles, etc. Technological wastes relate to the occurrence of side products during various technological operations (wastes from molding compounds, wastes from the machining operations, wastes from quality assurance stages, etc.) (fig.1). They also can be divided into two types: utilized into usable half-finished products; utilized into ecologically safe forms.

Attention of the researchers was paid to the process of supplying ferrites with quality characteristics during final machining operations [2] [3].

Research showed that sticking of the suspensions is happening in the acid or neutral environment.

Technological loss in the production of forming compounds (press-powders, pastes, and slips) like in the case with technological loss in production of powders is connected with leakages in technological equipment (drying-granulating, mixing, sifting, shredding, etc.). That’s why the same methods for decreasing the loss same methods are used as for the powders.

During the production of forming compounds the flaw can be removed using two main approaches:

- burning of the bundle with the temperature of 400…600°C, followed by shredding of the obtained stock and repeating the preparation of the forming compound;
- repeated preparation of the forming compound without burning the bundle and utilizing auxiliary amount of the bundle or its separate components. For example, flawed press-powder can be repeatedly treated with water inside the attritor. The obtained suspension is used for making press-powder with vaporized drying approach.

The most widespread type of flaw during pressing of the granulated and usual powders is delamination – lateral or diagonal cracks that break workpiece consistency. The reasons for delamination can be the following:

- When pushing the workpiece out of press-form matrix two opposite processes may occur: expanding of the workpiece and squeezing of the matrix. As a result of these deformations cracks can appear alongside deformation borders.
- Incorrect construction of the press-form (e.g. absence of taper in the matrix from the output side) or its skewness during pressing results in irregular force drop which leads to additional stresses inside the workpiece during its removal out of the matrix. Excessively slow extraction of the workpiece (and especially stops during pressing out) can induce cracks. Thin walls and sharp transitions in the workpiece also contribute to crack appearance.

However, to solve this problem it is required to analyze the reasons of flaw appearance through the complete technological cycle of product manufacturing and formulate the recommendations for decreasing defects during each of the technological operations.

Technological wastes during powder manufacturing are caused by sticking of the suspension obtained through wet shredding on the walls of the technological equipment (vaporizing dryers, reactors, tubes) and forming of firm crusts, and big hard conglomerates during thermal treating of the stock.

Decreasing suspension sticking on the working surfaces of the technological equipment has important practical meaning. Suspension sticking can lead to the offset of chemical compound for ferrite powders of different series. That’s why periodic equipment cleaning is required.

Size flaws may occur due to the increased resilient aftereffect in the workpiece in case of high resilience limit, incorrect construction or sizes of the press-form, unprecise powder doze or pressing modes violation (insufficient or excessive pressure). Scratches in the matrix lead to numerous risks for the workpiece surface. Low quality grinding of the puncheon working surface may result in the appearance of chips on workpiece edges.

Loss during sintering occur mainly because of flawed workpieces and can reach up to 20%. In oxide ceramic manufacturing the most common types of flaws during sintering are hidden delamination, insufficient sintering, over-burning, warping.

Control of the technological processes and their correction for various types of magnets has high importance. Problem of finding optimal conditions for sintering is rather relevant [1].

During the sintering of the ferroceramic products the process of consolidation and recrystallization runs faster at higher temperatures. But high temperature also contributes to defects in crystal cell. This means that ferrite crystals which are formed in such conditions will have defective structure. Defects in the crystal cell have significant influence on ferrite’s durability. There is the reason to think that the defects in the crystal cell may also have influence on magnetic properties of the ferrites.

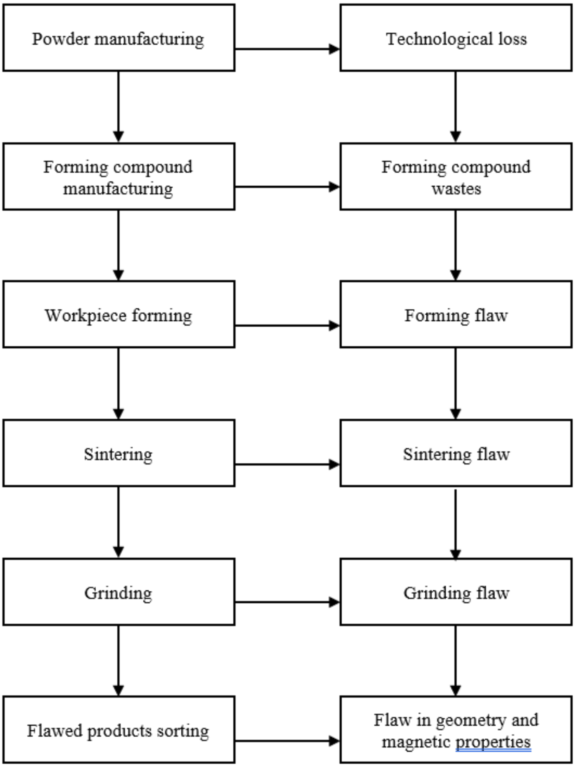

Fig. 1. Main types of wastes in ferrite products manufacturing.

Ferrite sintering is held in continuous furnaces. In order to create a closed optimal control system for sintering temperature it is required that information about the workpiece state have to be continuously sent to the control unit. This information consist of finite set of coordinate values of controlled object. At the same time we may investigate the current object state by the coordinates which are available for measuring.

The complexity of the processes occurring in the near-surface layer of a product subject to machining, as well as during the operation of these parts, makes it necessary to consider the influence of technological heredity both at the stage of obtaining the workpiece and on the final processing operations.

The most common finishing method is grinding, which ensures high precision and high productivity in the production of products. The heat tension of this type of processing affects the change in the thermophysical parameters of the processed materials (tensile strength, thermal conductivity). Therefore, the study of optimal thermomechanical characteristics in the processing zone did not take these factors into account.

Thus, the study and control of the thermomechanical state of workpieces and working surfaces of products made of ferro-ceramic materials during finishing operations, taking into account previous types of processing of products, in order to eliminate cracking and burn formation on the processed surfaces is the subject of this work.

2. Analysis of sources and problem description

The problem of improving the quality of the surface layer of sanded products is currently being solved using the following methods:

- selection of grinding modes that are rational for a given material and the corresponding characteristics of the tool are carried out [4];
- grinding wheels and belts with an intermittent working surface are used [5];
- automatic control systems for active cutting power are used [6];
- cutting fluids are recommended, which significantly reduces the heat stress of the grinding operation and thereby the likelihood of burns and cracks [7].

However, these methods, with the existing technology for manufacturing parts from ferro-ceramic materials, including in connection with the advent of composite materials, do not completely eliminate defects arising in the surface layer. This is facilitated by: inevitable fluctuations in allowance due to errors in previous machining operations [8]; micro-inhomogeneity of the material itself, characterized by grain size, packing defects, dislocations and structural transformations, warping of parts during thermal and similar processing; thermomechanical phenomena accompanying the grinding process and as a result of which burns, microcracks, structural transformations, residual stresses appear on the processed surfaces [9].

The high thermal intensity of diamond abrasive processing processes leads to the fact that the thermophysics of these processes is often dominant in the formation of the qualitative characteristics of the treated surface [10]. The lack of information about the thermomechanical state of the working surfaces of products made of ferro-ceramic materials during finishing operations does not allow to avoid the above-mentioned defects on the processed surfaces.

3. Research objectives

Study and control of the thermomechanical state of the working surfaces of products made of ferro-ceramic materials both during the receipt of workpieces and during finishing operations in order to eliminate cracking and burn formation on the processed surfaces.

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

1. To formulate a mathematical model for optimizing and controlling thermomechanical processes when obtaining workpieces of ferro-ceramic products during sintering, describing thermomechanical processes in workpieces that affect the formation of defects and determine the control of technological parameters of sintering to eliminate these defects.
2. To Obtain calculated dependencies for determining the technological conditions for eliminating pinching and cracking on the working surfaces of ferro-ceramic products when processing them by grinding.

To develop a device for automatic stabilization of thermomechanical characteristics accompanying the grinding operation of ferro-ceramic products by selecting technological conditions for processing parts that have hereditary heterogeneities in the surface layer, ensuring maximum productivity while ensuring the required quality indicators.

4. Research methods

Theoretical studies were carried out using the thermophysics of mechanical and physical-technical processing processes, theories of thermoelasticity, an integrated approach of modern deterministic theories of fracture mechanics and methods for optimizing systems with distributed parameters, as well as numerical methods.

Let us consider the process of sintering a workpiece, described by the following relations [11]:

$$c\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right),\ x \in (0, l),\ t \in (0, \infty), \tag{1}$$

$$T(x, 0) = T^{\circ} = const,\ \ x \in [0, l], \tag{2}$$

$$\lambda(T)\frac{\partial T}{\partial x} = \alpha[v(t) - T(l,t)],\ t \in [0, \bar{t}],\ 0 < \bar{t} < \infty, \tag{3}$$

$$\frac{\partial T(0,t)}{\partial x} = -\frac{q}{\lambda(T)},\ t \in [0, \bar{t}], \tag{4}$$

here: T – temperature (°C); t – time; c – heat capacity coefficient; ρ – density; λ – thermal conductivity coefficient; l – surface layer thickness; x – workpiece movement coordinate inside continuous furnace; α – heat transfer coefficient; $v(t)$ – control; q – heat flow on workpiece's surface layer.

In the range of temperature variation [T_1, T_2] function $\lambda(T)$ is positive and according to the thermophysical properties of the material it has a finite derivative by T. Moreover, let's consider that inside the working temperature range T ∈ [T_1, T_2] values of the function λ(T) are defined using the expression:

$$0 < \beta_1 \leq \lambda(T) \leq \beta_2, \tag{5}$$

Within the mentioned conditions system of equations (1) – (4) for each fixed value $v(t) \in V$ has generic solution.

According to the conditions of the problem, it is unacceptable that, under the influence of thermomechanical processes, the surface layer of the workpiece is heated to a temperature at which the functional properties of the surface layer are lost and thermal cracks form on the surface of the product.

Typically, workpieces use materials that break down brittlely when heated, without any noticeable deformation, or materials that transform into a plastic state under the influence of thermal stresses.

The problem of thermoelasticity in a quasi-static formulation and under the assumption that α_T is the coefficient of linear expansion and E - is the elastic modulus, do not depend on temperature and is solved analytically [8] [9].

Analysis of thermal stresses shows that, under the conditions of the problem under consideration, tensile stresses reach their greatest values in the workpiece at depth, and compressive stresses - on the surface. Taking into account the above, restrictions on thermal stresses in the workpiece can be written in the form:

$$\frac{\alpha_T E}{1-\psi}\left(-T(0,t) + \frac{1+3G}{l}\int_0^l T(\zeta,t)d\zeta - \frac{6G}{l^2}\int_0^l \zeta T(\zeta,t)d\zeta\right) \leq \sigma_1[T(0,t)], \tag{6}$$

$$\frac{\alpha_T E}{1-\psi}\left(T(0,t) - \frac{1-3G}{l}\int_0^l T(\zeta,t)d\zeta - \frac{6G}{l^2}\int_0^l \zeta T(\zeta,t)d\zeta\right) \leq \sigma_2[T(l,t)], \tag{7}$$

where $\sigma_1[T(0,t)] = \begin{cases} \sigma_p[T(0,t)] - \text{for brittle materials} \\ \sigma_{0.2}[T(0,t)] - \text{for flexible materials} \end{cases}$; $\sigma_2[T(0,t)] = \begin{cases} \sigma_c[T(l,t)] - \text{for brittle materials} \\ \sigma_{0.2}[T(l,t)] - \text{for flexible materials} \end{cases}$

ψ - Poisson coefficient; $\sigma_p(T)$, $\sigma_e(T)$, $\sigma_{0.2}(T)$ – tensile, compressive and yield strengths, respectively.

In addition to fulfilling inequalities (1) – (7), we will require fulfilling the limitation on the maximum temperature in the surface layer of the workpiece. It should not exceed, for example, the temperature of structural transformations T_s in the surface layer material, i.e.

$$T(l, t) \leq T_s\,. \tag{8}$$

Let us find the control $v^o(t) \in V$, $t \in [0, t^o]$, which transforms, in a minimum time t^o, $0 < t^o < t^-$, the thermomechanical state of the surface layer, which is described by the system of equations (1) — (4) from the initial position (2) to a given final thermal position $\bar{T}(x)$ with a fixed accuracy:

$$\int_0^l \left[T(x,t^\circ,\nu^\circ) - \overline{T}(x)\right]^2 dx < \epsilon, \ \ \epsilon \geq 0$$

In such way, that for all $t \in [\varphi, t^\circ]$, $\varphi=const>0$ inequations (6) – (8) will be fulfilled. To solve this problem we will use the approach of consecutive approximations [12]. Taking into account the "maximum principle" we get the following [13]:

$$m \leq T(x,t) \leq M, \tag{9}$$

where $M = \max \begin{Bmatrix} \max \nu(t), T^\circ \\ t \in [0,t] \end{Bmatrix}, M = \min \begin{Bmatrix} \min \nu(t), T^\circ \\ t \in [0,t] \end{Bmatrix}$. Let $T_1=m$, $T_2=M$, $\lambda_0 = \frac{\beta_1+\beta_2}{2}$.

The following itational process will be applied to the system of equations (1) – (4):

$$c\rho \frac{\partial T_{k+1}}{\partial t} - \lambda_0 \frac{\partial^2 T_{k+1}}{\partial x^2} = \frac{\partial}{\partial x}\left(\lambda(T_k)\frac{\partial T_k}{\partial x}\right), \tag{10}$$

$$T_{k+1}(x,0)=T^\circ, \ x \in (0,l), \tag{11}$$

$$\lambda_0 \frac{\partial^2 T_{k+1}}{\partial x^2} - \alpha[\nu(t) - T_{k+1}(x,t)] \Big|_{x=l}^{x=-l} = [\lambda_0 - \lambda(T_k)] \frac{\partial T_k}{\partial x}\Big|_{x=l}^{x=-l}, \tag{12}$$

$$\frac{\partial T_{k+1}}{\partial x}\Big|_{x=0}^{x=l} = -\frac{q}{\lambda(T_k)}. \tag{13}$$

We will look for a solution to problem (1) – (4) as the limit of solutions to problems (10) – (13). As function $\lambda(T)$ is positive and fulfills the expression (5) and has a derivative bounded by T at a range $[T_1, T_2]$, then for the arbitrary fixed control value $\nu(t)$ solutions T_{k+1} of the systems of equations (10) – (13) converge to the solution of system (1) – (4) when $k \to \infty$.

For the sake of simplicity of further expressions let's formulate system of equations (10) – (13) and bounds (6) – (7) in dimensionless units:

$$\alpha_0 = \frac{\lambda_0}{c\rho}, u = \alpha_T(\nu - T^\circ), u^+ = \alpha_T(\nu^+ - T^\circ), r = \frac{x}{l}, \theta = \alpha_T(T - T^\circ), \tau = \frac{\alpha_0 t}{l^2}, \sigma_1^* = \frac{(1-\psi)\sigma_1}{E}, \sigma_2^* = \frac{(1-\psi)\sigma_2}{E},.$$

$$\theta_g = \alpha_T(T_{cp} - T^\circ), \tilde{T} = \frac{\alpha_0 \bar{t}}{l^2}, B_i = \frac{\alpha l}{\lambda_0}, \tilde{\theta} = \alpha_T(\tilde{T} - T^\circ), \frac{q}{\lambda_0} = q^*. \tag{14}$$

Then the problem of optimal nonlinear heating of the surface layer of the workpiece with restrictions on thermal stresses and the highest temperature is reduced to solving a system of linear ordinary differential equations:

$$\frac{dx}{d\tau} = A(\tau)x + B(\tau)u + D(\tau), \tau \in [0,T], x(0) = x_0 \neq 0_{RN}, \tag{15}$$

with bounds for phase variables and control values:

$$F_i(x,u,\tau) \leq 0, i = \overline{1,s}, \tag{16}$$

where $x = x(\tau) = (x_1(\tau), \ldots, x_N(\tau))$ – N-dimensional vector, $A(\tau)$, $B(\tau)$, $D(\tau)$ – known matrices with the dimensions (NxN), (Nx1), (Nx1) correspondingly with piecewise continuous coefficients, $u = u(\tau) \in U$ – control.

The proposed approach to solving the nonlinear problem of thermal conductivity with restrictions was tested when checking for the adequacy of controlling the thermomechanical state of the working surfaces of products made of ferroceramic materials at the sintering stage.

A plate of $MnFe_2O_4$ alloy with a thickness of 2l = 0.2 m was sintered with an initial temperature T_0 = 200°C in modes in which sintering zone temperature has reached 11000°C. The maximum permissible temperature in the sintering zone at the furnace outlet should not exceed 7200°C for the minimum time, taking into account restrictions on thermal stress and temperature of the treated surface. The material $MnFe_2O_4$ is brittle. The temperature in the processing zone varied in the range [7200°C – 11500°C]. The dependence of the ultimate strength on temperature was specified in a table [14]:

Table 1. Tensile strength dependence from the temperature.

Temperature, °C		20	720	1050	1100	1150
Tensile strength, MPa	Compression	1500	850	470	310	210
	Extension	980	540	370	200	140

This dependence after the transition to dimensionless quantities, was approximated using the least squares method by nonlinear relations.

The dependence of the thermal conductivity coefficient on temperature was also specified in a table:

Table 2. The dependence of the thermal conductivity coefficient on temperature

Temperature,°C	20	200	500	600	700	800	900	1000
λ(T), W/m°C	10.05	15.07	18.84	20.5	22.1	24.2	26.3	28.05

For this dependance the same was applied: transition to dimensionless quantities, and approximation using the least squares method by nonlinear relations.

Figure 2 shows graphs of the dependences on the time of optimal control, surface temperatures and the main material of the workpiece after 6 iterations. The response time was 3.98 minutes, the optimal control has 135 switchings. Figures 3 and 4 show, respectively, graphs of the dependence of compressive and tensile strengths, as well as compressive and tensile thermal stresses on time under the optimal processing mode. As can be seen from fig. 3, the rate of temperature growth in the sintering zone is limited not only by tensile, but also by compressive thermal stresses. Traditionally, only tensile thermal stresses and restrictions on the sintering temperature of the workpiece were considered active.

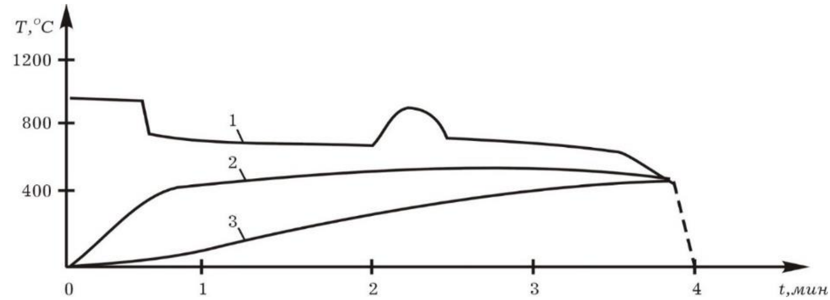

Fig. 2. Graphs of optimal control versus time: 1 – surface temperature, 2 – center temperature, 3 – temperature after 6^{th} iteration.

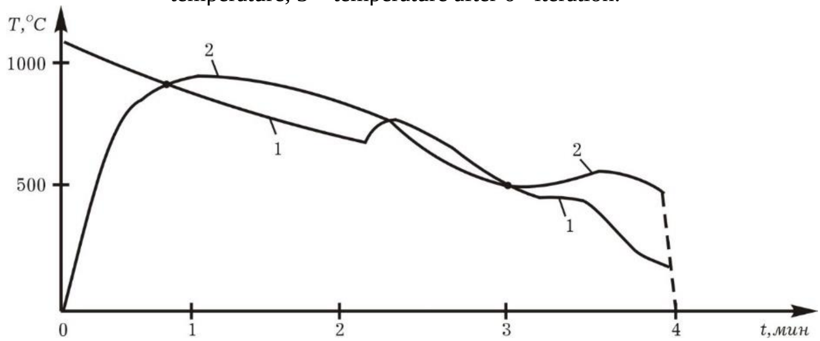

Fig. 3. Graphs of compressive (1) and tensile (2) strength versus time under optimal heating conditions.

As can be seen from Fig. 2, the heating rate limits not only tensile, but also compressive thermal stresses. Traditionally, only tensile thermal stresses and restrictions on the contact temperature of the workpiece surface were considered active.

Implementation of a model for optimizing and controlling thermomechanical processes when obtaining workpieces of ferro-ceramic products during sintering, which describes thermomechanical processes in workpieces, makes it possible to reduce the formation of defects and determine the control of technological parameters of sintering to increase the strength of ferrites.

The process of grinding ferroceramic products is accompanied by both thermal and mechanical phenomena, which, interacting with each other, determine the quality of the surface layer. A quantitative description of these phenomena requires the selection of certain models. Due to the interrelation and interdependence of phenomena and processes during the processing of ferro-ceramic products by grinding, it becomes obvious that the stress-strain state of the surface layer is determined mainly by temperature. If you use a model of a thermoelastic body that reflects the relationship between mechanical and thermal phenomena at finite heat flows, you can make significant progress in research on the thermomechanics of phenomena accompanying the grinding process.

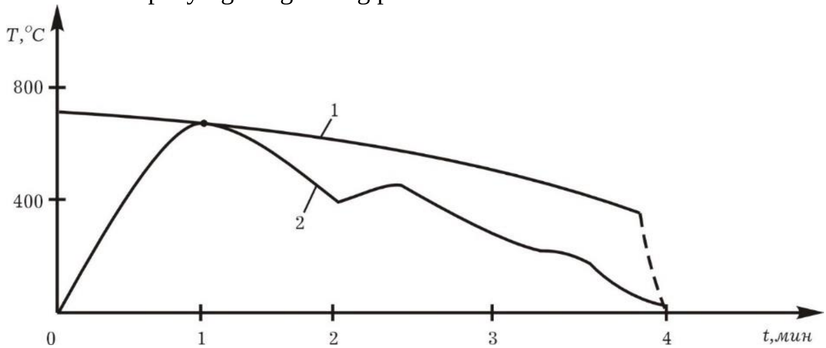

Fig. 4. Graphs of compressive (1) and tensile (2) thermal stresses versus time under optimal heating conditions.

For further studies of the kinetics of the formation of thermomechanical processes, we will use the following system of differential equations [15], which describes the interaction of the deformation field and the temperature field, as the main theoretical premise.

$$G\Delta\vec{U_j} + (\lambda_t + G) graddiv\vec{U_j} - \rho\frac{\partial^2\vec{U_j}}{\partial\tau^2} + P_j = \alpha_t\beta_t gradT, \quad (17)$$

$$\Delta T - \frac{1}{\alpha}\frac{\partial T}{\partial\tau} - \eta l\frac{\partial}{\partial\tau}div\vec{U_j} = -\frac{W}{\lambda} + C_q^{-2}\frac{\partial^2 T}{\partial\tau^2}, \quad (18)$$

where: λ_t, G - Lame constants; $\beta_t = 3\lambda_t + 2G$; ρ - density of the processed material: α_t - temperature coefficient of linear expansion of the metal; $a = \lambda / C_v$ – thermal diffusivity coefficient; λ – thermal conductivity coefficient; C_v - volumetric heat capacity; $\vec{U}(\Phi,\tau)$ – the total vector of displacements of the internal temperature Φ (*x*, *y*) of the surface layer under the influence of thermomechanical forces accompanying the grinding process: $l = 1 + \tau_r\,\delta/\delta$ (τ - relaxation time); $\eta = \alpha_t\beta_t T(\Phi, \tau) / \lambda$; W – power of the heat source; C_q is the speed of heat propagation in the processed material; τ – time; P_j - cutting forces;

$$gradT(x,y,z) = \frac{\partial T}{\partial x}\vec{i} + \frac{\partial T}{\partial y}\vec{j} + \frac{\partial T}{\partial z}\vec{k};$$

$$div\vec{U_j} = \frac{\partial U_x}{\partial x} + \frac{\partial U_y}{\partial y} + \frac{\partial U_z}{\partial z}.$$

The system of equations that determine the thermal and stress-strain state of the machined surface of parts during grinding includes [13]:

a) equation of unsteady thermal conductivity:

$$\frac{\partial T}{\partial \tau} = a^2 \left(\frac{\partial^2 T}{x^2} + \frac{\partial^2 T}{y^2}\right) \quad (19)$$

b) Lamé elasticity equations in displacements:

$$\frac{\partial \theta}{\partial x} \cdot \frac{1}{1-2\mu} + \Delta \vec{U} = b^T \frac{\partial T}{\partial x}; \vec{U} = \frac{U}{2G}; \vec{V} = \frac{V}{2G}; \quad (20)$$

$$\frac{\partial \theta}{\partial y} \cdot \frac{1}{1-2\mu} + \Delta \vec{V} = b^T \frac{\partial T}{\partial y}; b^T = \frac{4G(1+\mu)}{1-2\mu} \alpha t; \quad (21)$$

c) initial conditions:

$$T(x, y, \theta) = 0; \quad (22)$$

d) bounding conditions for temperature and deformation fields:

$$\frac{\partial T}{\partial x} = -\frac{q(y,t)}{\lambda}, |y| < \alpha; \quad (23)$$

$$-\frac{\partial T}{\partial x} + jT = 0, |y| > \alpha; \quad (24)$$

$$\sigma_x(x, y, t) \Big|_{x=0}^{x=l} = \tau_{xy}(x.y.t) \Big|_{x=0}^{x=l} = 0; \quad (25)$$

e) conditions for discontinuity of the solution: for inclusions: for crack-like defects:

$$< \tilde{u} >= 0; < \sigma_x > \neq 0; \quad < \sigma_x > = 0; < \tilde{u} > \neq 0;$$

$$< \tilde{v} >= 0; < \tau_{xy} > \neq 0; \quad < \tau_{xy} > = 0; < \tilde{v} > \neq 0; \quad (26)$$

Taking into account the design features of wheels used for grinding the surfaces of ferro-ceramic products can be realized by satisfying the following boundary conditions:

$$q(y, t) = \frac{c\sqrt{\tau}}{\lambda} [H(y) - H(y - 2a^*)] \sum_{k=0}^{n} \sigma(y + kl - v_{kp}\tau), \quad (27)$$

where *H(y)* is the Heaviside function; *σ(y)* is the Dirac delta function; *n* is the number of grains passing through the contact zone during the time $\tau = \frac{\sqrt{Dt_{gr}}}{v_{kp}}$; λ is the thermal conductivity of the product material; $c\sqrt{\tau}$ — heat flow from a single grain; v_g, v_{kp}, t_{gr} grinding modes, 2a* — the length of the circle contact arc 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, which were used later as criteria for predicting the conditions for the formation of defects of the burn type and their depth.

The solution of the task made it possible to develop technological criteria for controlling the process of defect-free grinding of ferro-ceramic products on the basis of the established functional relationships between the properties of ferro-ceramic materials and the main technological parameters [16].

The quality of the processed surfaces will be ensured if, with the help of the controlling technological parameters we can select such processing modes, cutting fluids, and tool characteristics in a way that the current values of the grinding temperature *T(x,y,t)* and heat flow *q(y,t)*, stress σ*(M)* and grinding forces P_y, P_z, and the coefficient of crack resistance K_{1C} will not exceed their limit values.

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

$$T(x,y,\tau)=\frac{C}{2\pi\lambda}\sum_{k=0}^{n}H\left(\tau-\frac{kl}{v_{kp}}\right)H\left(\frac{L+kl}{v_{kp}}\right)\int_{r_1}^{r_2}f(x,y,\tau,\tau`)d\tau` \leq [T]_M \quad (28)$$

$$T([h],0,\tau)=\frac{C}{2\pi\lambda}\sum_{k=0}^{n}H\left(\tau-\frac{kl}{v_{kp}}\right)H\left(\frac{L+kl}{v_{kp}}\right)\int_{r_1}^{r_2}\psi(x,y,\tau,\tau`)d\tau` \leq [T]_M \quad (29)$$

$$T_k(0,y,\tau)=\frac{Cv_{kp}}{\pi\lambda\sqrt{v_g}}\int_{a}^{\tau}\int_{-l}^{l}\frac{\lambda(\eta,t)e^{\frac{(y-\eta)^2}{4(\tau-t)}}}{2\sqrt{\pi(\tau-t)}}\left\{\frac{1}{\sqrt{\pi(\tau-1)}}+\gamma e^{\gamma^2(\tau-t)}\left[1+\Phi\left(\gamma\sqrt{\tau-t}\right)\right]\right\}d\eta dt \leq [T] \quad (30)$$

$$T_k^{max}(L,0)=\frac{Cv_{kp}\alpha}{\lambda l v_g^2}\sqrt{\frac{\alpha}{\pi}}\left[1-\exp\left(-\frac{v_g\sqrt{Dt_{gr}}}{\alpha}\right)\right] \leq [T] \quad (31)$$

This allows to avoid the violation of the functional properties of products made of ferroceramics due to the elimination of structural changes from grinding burns and can serve as a basis for designing grinding cycles according to thermal criteria.

Processing of ferro-ceramic products without grinding cracks can be ensured if the stresses formed in the zone of intensive cooling are limited to limit values [17]:

$$\sigma_{max}(x,\tau)=2G\frac{1+\nu}{1-\nu}\alpha_i T_k \operatorname{erf}\left(\frac{x}{2\sqrt{\alpha\tau}}\right) \leq [\sigma_{lc}] \quad (32)$$

In the case of the dominant influence of hereditary inhomogeneity in ferro-ceramic products on the intensity of formation of grinding cracks, it is necessary to use criteria, the structure of which includes determinate connections of technological parameters and the properties of the inhomogeneities themselves. As such, it is possible to use the limits of the stress intensity coefficient:

$$K=\frac{1}{\pi\sqrt{l}}\int_{-l}^{l}\sqrt{\frac{l+t}{l-t}}\{\sigma_x,\sigma_y\}dt \leq K_{1c}, \quad (33)$$

or providing, with the help of controlling technological parameters, the limiting value of the heat flow, at which the balance of structural defects is preserved:

$$q^*=\frac{P_z v_{kp}\alpha_S}{\sqrt{Dt_{gr}}} \leq \frac{\sqrt{3}\lambda K_{1C}}{Hl\sqrt{\pi l}\sigma}, \quad (34)$$

Conditions for flawless grinding can be realized using information about the structure of the processed material. Thus, in the case of the prevailing character of structural imperfections along the length of $2l$, their regular arrangement relative to 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:

$$l_0<\frac{K_C^2}{x[GT_k(1+\nu)\alpha_t]^C}. \quad (35)$$

In this formula, the technological part is contained in the connection between the contact temperature T_K and the grinding conditions.

The given inequalities link the limiting characteristics of the temperature and force fields with the controlling, technological parameters. They specify the area of a combination of these parameters that satisfy the obtained thermomechanical criteria. At the same time, the properties of the processed material are taken into account and the required product quality is guaranteed.

Based on the obtained criterion ratios, a device for stabilizing thermomechanical characteristics was developed to ensure the quality of the surface layer of ferrite parts during grinding, taking into account the maximum processing productivity (fig. 5). The device that controls the grinding machine 1 contains sensors 2 temperatures T_k and T_i, radial grinding force and thermoelastic stresses 3, intermediate amplifiers 4, 5 and 6, 10 integrating block 7, differentiating blocks 8 and 9, comparison body 10, setting device 11, block 12 of the control law, logical blocks 13 and 14 for selecting the control parameter and executive bodies, arithmetic blocks 15 and 16 for monitoring the current values of the burn depth depending on the time of thermal exposure and the current values of temperatures T_i and T_k and voltages, as well as executive bodies 20 17 , 18 and 19.

When controlling the grinding process by burn depth, the current values of contact and pulse surface temperatures and stresses in the grinding zone, coming from the output of sensor 2 to the input of the integrating unit 7, which integrates discrete temperature values, forming a continuous signal at the output, are amplified by auxiliary amplifiers 4, 5 and 6. After amplification, the signals arrive at the input of arithmetic blocks 15 and 16. In these blocks, the current value of the burn depth of the ground surface is determined depending on the temperatures T_k, T_i and voltages during the time of their thermal effect on the surface being processed, which is supplied to the inputs of the logical block 14 for selecting a control parameter, selecting the controlled parameter: surface temperature T_k, pulse temperature T_u or burn depth. and a differentiating block 9, which generates a signal at the output corresponding to the first or second time derivative of the signal from the output of block 16, allowing for control and prediction. After appropriate processing, the signals from the input of block 14 are compared by the comparison body 10 with the specified values from the device 11. The mismatch signals are sent to the input of block 12 of the control law, which takes into account the nonlinear dependence of temperatures T_i and T_k, burn depth on grinding factors, thermomechanical stresses σ_{max} (x,τ) and from its output through the intermediate power amplifier 4 - to the logical block 14 for selecting executive bodies, which selects executive bodies 17, 18 and 19 of the machine.

Stabilization of the burn depth and mechanical stresses allows you to control the quality of parts made of ferrites when processing them by grinding, significantly increasing their performance properties.

A device for automatic stabilization of thermomechanical stresses and quality characteristics of grinded parts, containing sensors for contact and pulse temperatures and radial grinding force, stresses, a power amplifier, a logical block for selecting actuators, a control unit with intermediate amplifiers, a comparison body and a master device, characterized in that that, in order to stabilize the burn depth, it is equipped with arithmetic blocks connected in series to the outputs of the sensors for determining the current values of the burn depth from pulse and contact temperatures and a logical block for enabling a control parameter, the output of which is connected to the input of the comparison body, differentiating blocks, the inputs of which are connected to the outputs an arithmetic block for determining the burn depth from the contact temperature and an intermediate amplifier, and the output is connected to the input of the logical block for enabling the control parameter, an integrating block connected between the contact and pulse temperature sensors and an intermediate amplifier, the output of which is connected to the input of the logical block for enabling the parameter control, and a control law block whose inputs are connected to the comparison body and the master device, and the output is connected to the power amplifier.

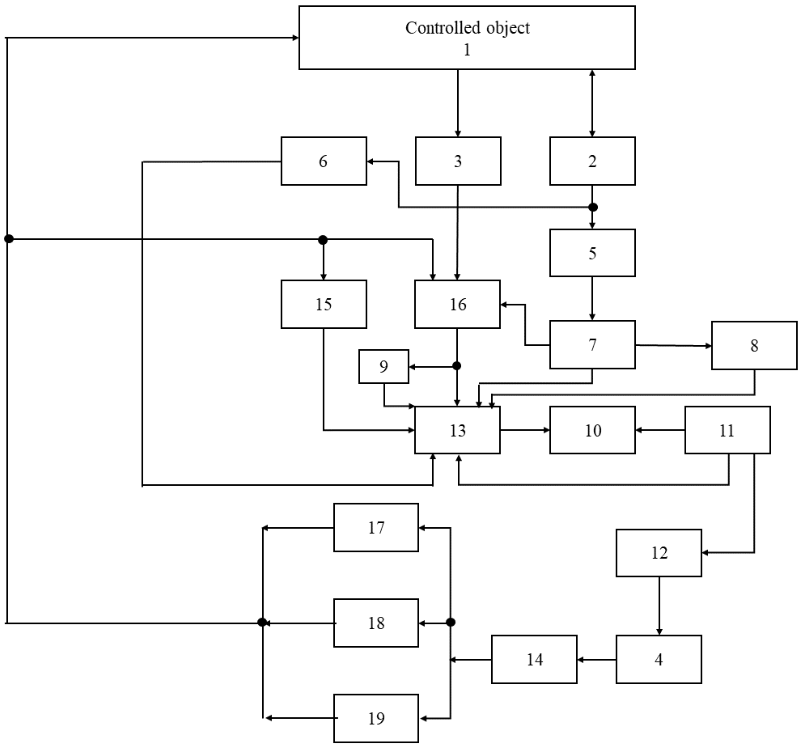

Fig. 5. A device for stabilizing thermomechanical characteristics to ensure the stability of the surface ball of ferroceramic parts when grinding to ensure maximum processing

productivity.

The initial data of the control object (grinding technological process) are [18]:

- Physical and mechanical characteristics of the processed material;
- Technical characteristics of processing equipment;
- Processing modes: depth of cut, speed of the workpiece, transverse feed, the purpose of which is determined from the conditions of limiting the grinding temperature and heat flow, stresses and grinding forces, crack resistance coefficient, which will not exceed their limit values.
- Characteristics of the selected tool (wheel), affecting the heat intensity of the processing process;
- The machining process is described by equations (1) – (6), a system of control relations (7) – (9) and thermoelastic stresses formed in the processing zone (15) – (16);
- Quality criteria for processed surfaces of products are the fulfillment of inequalities (20) – (23) – absence of functional changes in the properties of ferroceramics; inequalities (24) – (26) -- Processing of materials and alloys without grinding cracks.

5. Research results

As a result of the research carried out, a scientific and technical problem was solved consisting of establishing calculated dependencies to determine the influence of hereditary defects formed during the operation of obtaining a workpiece on the crack resistance of the surface layer during grinding and creating control over the thermomechanical state of the working surfaces of products made of ferro-ceramic materials during finishing operations, optimal technological processing conditions taking into account the accumulated damage and inhomogeneities of materials and alloys that are especially prone to crack formation during the grinding process, which is of great national economic importance for reducing defects in finishing operations and increasing the performance properties of ferroceramic parts [19].

6. Conclusions

The scientific novelty of the presented research lies in the establishment of calculated dependencies to determine the influence of hereditary defects formed during the production of workpieces from ferro-ceramic materials on the crack resistance of the surface layer during grinding and the creation of optimal technological processing conditions, taking into account the accumulated damage during sintering of workpieces and inhomogeneities in them, which create the prerequisites to structural changes and cracking during the grinding process.

1. An analysis of the thermomechanical state of the surface layer of products made of ferro-ceramic materials of heterogeneous structure was carried out when obtaining workpieces. An optimal control of the thermomechanical state of the working surfaces of the workpieces was constructed, taking into account the nonlinearity of heat stress in the sintering zone, which made it possible to minimize defects in this operation and reduce the presence of structural defects affecting the strength of ferrites.
2. Technological criteria have been developed to control the process of defect-free grinding of ferro-ceramic products, which are implemented on the basis of established functional connections between the thermomechanical state of the processed materials and the main technological parameters.
3. A device for stabilizing thermomechanical characteristics was developed to ensure the quality of the surface layer of ferroceramic parts during grinding, taking into account the maximum processing productivity.

References: 1. *K. A. Dubrov and A. V. Usov*, Opredelenije ratsionalnykh tekhnologicheskikh parametrov bezdefectnoi obrabotki ferrokerramicheskikh izdelij., in Novyje i netraditsionnyje tekhnologii v resurso- i energosberezhenii, Odessa, 2006. **2.** *K. A. Dubrov, A. V. Usov and G. A. Oborskyi*, O putjah snizhenija jenergoemkosti mehanoobrabotki ferro keramicheskih materialov/, in Sovremennye problemy podgotovki proizvodstva, zagotovitel'nogo proizvodstva, obrabotki i sborki v mashinostroenii i priborostroenii, Kyiv-Svalyava, 2007. **3.** *A. V. Usov and K. A. Dubrov*, Tehnologicheskie vozmozhnosti snizhenija othodov pri proizvodstve ferro keramicheskih izdelij, №. 68, pp. 342-–350, 2005. **4.** *F. V. Novikov and V. I. Polyanskyi*, Viznachennja umov pidvishhennja jakosti mehanichnoї obrobki za temperaturnim kriteriem, Perspektivni tehnologiї ta priladi, № 17, pp. 99–105, 2020. **5.** *O. V. Yakimov, A. V. Usov, P. T. Slobodyanyuk and D. V. Iorgachev*, Teplofizika mehanichnoї obrobki, Odessa: Astroprint, 2000, p. 256. **6.** *Y. M. Kusiy*, Naukovo-prikladni osnovi tehnologichnogo uspadkuvannja parametriv jakosti dlja zabezpechennja ekspluatacijnih harakteristik virobiv. Avtoreferat disertacії na zdobuttja naukoogo stupenja dokt. tehnich. Nauk 131 Prikladna mehanika, Lviv, 2021, p. 44. **7.** *V. G. Lebedev, E. A. Lugovskaya and A. V. Ovcharenko*, Jeksperimental'nye issledovanija processa shlifovanija martensitno-starejushhej stali N18K9M5T, Visoki tehnologiї v mashinobuduvanni, vol. 1, № 27, pp. 69–78, 2017. **8.** *V. O. Dziura and P. O. Marushak*, Tehnologichni metodi zabezpechennja parametriv jakosti poverhon' til obertannja ta їh profilometrichnij kontrol', Ternopil: Palayanytsya, 2021, p. 170. **9.** *Novikov F.*, Optimisation of interrupted grinding parameters according to the temperature criterion, *"Cutting & Tools in Technological System"*, no. 98, pp. 59–72, 2023. https://doi.org/10.20998/2078-7405.2023.98.06 **10.** *S. Malkin and C. Guo*, Grinding Technology: Theory and Application of Machining with Abrasives, 2nd ed. New York, NY, USA: Industrial Press, 2008. **11.** A. Leblond and P. Hild, Mechanics of Materials and Structures: Thermomechanics, 1st ed. Cham, Switzerland: Springer, 2019. **12.** *F. P. Vasiljev*, Chislennye metody reshenija jekstremal'nyh zadach., Kyiv: Naukova dumka, 2009, p. 256. **13.** *B. D. Reddy*, Thermomechanics of Solids: A Dynamical Systems Approach, Computational Mechanics, vol. 54, no. 3, pp. 567–587, 2014. **14.** *R. B. Hetnarski and M. R. Eslami*, Thermal Stresses: Advanced Theory and Applications, 2nd ed. Dordrecht, Netherlands: Springer, 2009. **15.** *S. N. Atluri and A. M. Rajendran*, Modeling and Analysis of Thermal Stresses in Structures, Computational Mechanics, vol. 54, no. 4, pp. 827–841, 2014. **16.** *G. A. Oborskyi, A. F. Dashenko, A. V. Usov and D. V. Dmytryshyn*, Modelirovanie sistem, Odessa: Astroprint, 2013, p. 664. **17.** *Y. Aoyama, S. Morimoto, and Y. Yamada*, Analysis of Grinding Surface Residual Stress and Subsurface Cracks in Magnetic Alloys, Journal of Materials Processing Technology, vol. 209, № 7, pp. 3478–3485, 2009. **18.** *V. I. Pokhmurskyi and Y. I.*

Kryzhanovskyi, Mehanika rujnuvannja i micnist' materialiv, Lviv-Ivano-Frankivsk, 2006, p. 1193. **19.** *A. V. Yakimov*, Modelirovanie termomehanicheskih processov pri shlifovanii neodnorodnyh materialov, in Teplofizika tehnologicheskih processov, Kyiv, 2008.

Анатолій Усов, Юрій Зайчик, Максим Куніцин, Юлія Сікіраш, Одеса, Україна

ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ВИРОБНИЦТВА ФЕРРОКЕРАМІЧНИХ ВИРОБІВ НА ФІНІШНИХ ОПЕРАЦІЯХ З УРАХУВАННЯМ ТЕХНОЛОГІЧНОЇ СПАДКОЄМНОСТІ

Анотація. *Стан якості шліфованої поверхні ферокерамічних виробів формується під впливом термомеханічних явищ, що супроводжують фінішну операцію і залежить від технологічних умов одержання заготівки. Розроблено математичну модель оптимізації та управління термомеханічними процесами при отриманні заготовок феро керамічних виробів при спіканні, що описує термомеханічні процеси у заготовках, що впливають на формування дефектів та визначено управління технологічними параметрами спікання для усунення зазначених дефектів. Із застосуванням шліфування пов'язана поява в поверхневих шарах деталей припіків, тріщин, що розтягують напруги, що значно впливає на якість цих деталей, в процесі їх експлуатації. Висока теплова напруженість процесів алмазно-абразивної обробки призводить до того, що теплофізика цих процесів часто є домінуючою у формуванні якісних характеристик обробленої поверхні. Існуючі методи обробки шліфуванням деталей із ферокерамічних матеріалів не дозволяють повністю виключити дефекти, що виникають у поверхневому шарі. Цьому сприяють спадкові дефекти від попередніх операцій, зокрема при отриманні заготівлі; мікронеоднорідність самого матеріалу, що характеризується величиною зерна, дефектами упаковки, дислокаціями та структурними перетвореннями. Аналіз термомеханічних процесів, що протікають у поверхневому шарі дозволив отримати розрахункові залежності для визначення технологічних умов усунення припіко – та тріщиноутворення на робочих поверхнях ферокерамічних виробів при обробці їх шліфуванням. Розроблено пристрій для автоматичної стабілізації термомеханічних характеристик, що супроводжують операцію шліфування феро-керамічних виробів вибором технологічних умов обробки деталей, що мають у поверхневому шарі спадкові неоднорідності, що забезпечують максимальну продуктивність при забезпеченні необхідних показників якості*.

Ключові слова: *оптимізація; заготовка; шліфування; якість поверхні; термомеханічні явища; модель; дефекти; технологічні параметри; критерії; пристрій*.