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MODELING THE IMPACT OF NONLINEAR OSCILLATIONS ON THE QUALITY OF THE WORKING SURFACE OF PARTS IN FINISHING OPERATIONS

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Abstract. *To establish analytical conditions for detecting hereditary defects in ferroceramic and ferromagnetic parts and to define machining parameters that prevent crack formation. Magnetic induction scattering is modelled to estimate defect geometry and depth; thermomechanical processes during grinding are analysed using the "weakest link" hypothesis and criteria based on temperature, heat flux, forces, and stress intensity. Obtained expressions describe magnetic field perturbation and allow evaluating defect size, while derived conditions prevent their growth into main cracks. A unified analytical framework combines magnetic defect detection with crack-resistance modelling. The results support selecting grinding modes and tool characteristics for defect-free finishing of materials prone to cracking.*

Keywords: *hereditary defect; crack formation; finishing operation; ferromagnetic modeling; analytical dependencies.*

1. Introduction

For high-quality processing of ferromagnetic materials in finishing operations, it is necessary to have information about the presence of hereditary defects in the surface layer, the size and depth of which affect crack formation on the processed surfaces under the influence of thermomechanical phenomena accompanying these operations. Magnetic methods of quality control of ferromagnetic materials and parts made of them are among the most common types of flaw detection [1]. They are based on the registration of a magnetic field on the surface of a part because of the presence of a defect. In this case, Hall sensors, magnetic diodes, or magnetic tape can be used as field indicators, as an intermediate information carrier. After being recorded on magnetic tape, the information is read using induction heads. Magnetic control methods require mandatory magnetization of parts and search for insignificant magnetic fields on their surfaces, which are called defect scattering fields [2]. These methods are used to check the blades, shafts, gear wheels, and other critical parts of the machine.

This paper considers the mathematical formulation of the problem of detecting defects in ferromagnetic parts during their magnetization. Mathematical expressions are obtained to estimate the geometric shape and depth of a defect beneath the surface of a part based on the results of measuring the distribution of magnetic induction on its surface.

When ferromagnetic parts are magnetized with alternating current, a defect of non-magnetic material located deep inside the part distorts the magnetic field pattern and partially displaces it above the surface of the part. The following task was set: based on the results of measuring the distribution of the magnetic field induction on the surface of the part and specifying the magnetic field induction value for magnetization, calculate the depth of placement and give an estimate of the shape of the defect under the surface of the part.

2. Analysis of sources and problem description

The critical challenge in manufacturing high-quality components from ferroceramic materials lies in managing defects, particularly those inherited from previous processing stages (hereditary defects), which can develop into critical cracks during final finishing operations. Addressing this requires a unified approach encompassing both reliable non-destructive testing (NDT) and robust thermomechanical process control.

Magnetic Nondestructive Testing (NDT) methods are widely acknowledged for their role in quality control, especially for detecting subsurface defects in ferromagnetic materials [3]. Recent advancements, such as phase-extraction-based Magnetic Flux Leakage (MFL), have significantly improved the subsurface detection depth, with reported limits up to 12 mm in steel plates [3]. Techniques utilizing pulse magnetization or chirp-waveforms further enhance sensitivity and reliability for detection [4].

However, significant limitations persist, particularly concerning the reliable detection and quantification of small, deep, or hereditary defects. Most magnetic techniques are inherently constrained by the skin effect and signal attenuation, which restrict reliable detection to moderate depths [3], [5]. Crucially, many existing NDT methods, even advanced hybrid systems, struggle with the accurate quantification of a defect's geometric size and depth [6], [7]. The over-reliance on complex signal processing and the variability introduced by material properties or environmental interference often diminish the intuitiveness and repeatability of quantitative results [6]. This gap highlights the necessity for a rigorous mathematical formulation that can directly link the measured distribution of the magnetic field to the precise geometric shape and depth of an internal hereditary defect.

In brittle materials like ceramics and ferroceramics, failure during processing is predominantly modeled through the weakest link hypothesis [8], [9]. This statistical framework posits that material strength is governed by the single most critical flaw present in the loaded volume, often formalized through Weibull statistics to predict failure probability based on the distribution of flaws [10], [11], [12]. Modern fracture research continues to rely on this concept, integrating it with advanced models to predict crack initiation influenced by both intrinsic and extrinsic defects [8].

To achieve defect-free finishing during high-stress operations like grinding, researchers have proposed various process criteria [13], [14]. These criteria typically focus on controlling thermal fields, mechanical loads, and the local stress intensity to ensure they remain below the material's fracture toughness (K_{IC}) or intrinsic strength thresholds [11], [15]. Extending this foundation, the concept of the hereditary defect (R_0) provides a specific, deterministic criterion within the weakest link framework, allowing process optimization to be tied directly to the size of the largest known inherited flaw [15], [16]. This specific focus on an inherited, process-traceable defect is essential for establishing safe technological windows during finishing.

To operationalize defect-free processing, numerous studies have focused on linking grinding parameters to the resulting thermomechanical fields. Phenomenological and mathematical models have been developed that relate variables like cutting force, wheel speed, and depth of cut to the local temperature and stress state of the surface layer [16].

Central to this work is the establishment of limiting inequalities or criteria for key thermomechanical parameters, which must not be exceeded to prevent crack formation [15], [17]. For instance, research explicitly defines maximum allowable heat flux and tangential stress based on material properties and defect characteristics [15], [17]. Experimental validation has confirmed that by keeping these thermomechanical fields below the critical thresholds for crack initiation—such as by establishing explicit process windows—surface quality can be guaranteed, even in materials prone to cracking [18]. The integration of such robust limiting criteria with the quantification of the specific hereditary defect (R_0) forms the basis for a comprehensive technological assurance methodology for precision finishing.

3. Research objectives

The objectives of this study are as follows:

1. To develop a mathematical model for detecting hereditary subsurface defects in ferromagnetic parts by analysing magnetic induction distributions and estimating defect geometry and depth.

2. To investigate the mechanisms of technological crack formation in ferroceramic materials based on the “weakest link” hypothesis and the influence of inherited structural defects.
3. To derive analytical conditions and limiting inequalities for thermal, mechanical, and fracture-related parameters that prevent the growth of structural defects into main cracks during finishing operations.
4. To determine optimal grinding modes and tool characteristics that ensure defect-free machining of ferroceramic products and to establish technological guidelines for improving the quality of machined surfaces.

4. Research methods

Consider the mathematical basis of the problem. Fig. 1 schematically shows the location of a part of the ferromagnetic material under the surface at a depth h of a cylindrical defect with radius R. The part is magnetized by a magnetic field source. Typically, defects have a shape similar to an elongated ellipse along one axis. If magnetization occurs along this axis, the magnetic field dispersion will be insignificant compared to magnetization across the axis. Therefore, it is important to determine the most effective direction of magnetization. The resistance of the defect to the magnetizing field should be as high as possible. Therefore, a cylinder that resists the magnetizing magnetic field, the cross-section of which is a circle (Fig. 1), was chosen as the calculation model.

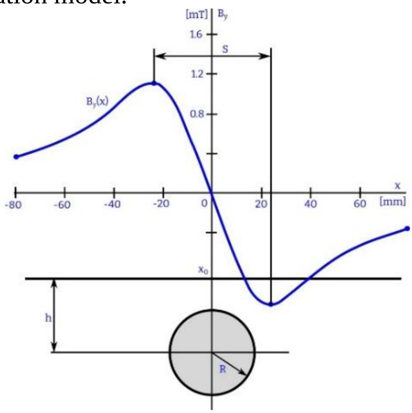

Fig. 1. Distribution of the normal component of the magnetic induction vector $\vec{B}_y(x)[mT]$ on the surface of the part along the x-axis, [mm] from the center of the defect

The magnetic induction of the magnetizing magnetic field B_0 is set by the magnetizing source. The magnetic permeability of the material of the part is μ_F. It is necessary to establish the distribution of the induction of the magnetic field displaced by the defect to the surface of the part. The problem is described by Laplace's differential equation, which in polar coordinates for the vector magnetic potential $A(\varphi, r)$ has the form [19]:

$$\frac{\partial^2 A(\varphi,r)}{\partial r^2}+\frac{1}{r}\cdot\frac{\partial A(\varphi,r)}{\partial r}+\frac{1}{r^2}\cdot\frac{\partial^2 A(\varphi,r)}{\partial \varphi^2}=0 \qquad (1)$$

The solution to the problem was obtained using Fredholm integral equations of the second kind and the principle of mirror reflections [20]. First, let us consider the problem without taking into account the influence of the surface of the part. The cylindrical defect is located in an unlimited ferromagnetic space (Fig. 2).

In polar coordinates, we will seek the expression for the vector magnetic potential in the following form: $A(\varphi, r) = C(\varphi)\cdot r + D(\varphi)/r$, where $C(\varphi)$ and $D(\varphi)$ are unknown functions of the argument φ. For the region occupied by the defect, we write:

$$A_1(\varphi,r)=C_1(\varphi)\cdot r+\frac{D_1(\varphi)}{r} \qquad (2)$$

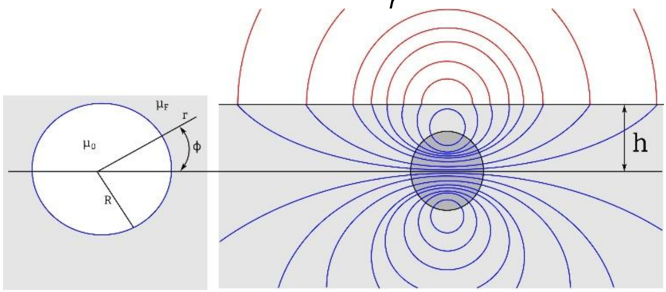

Fig. 2. Cylindrical defect in unlimited space and the pattern of magnetic field scattering by the defect in the form of magnetic field lines

For the region occupied by the ferromagnet:

$$A_2(\varphi,r)=C_2(\varphi)\cdot r+\frac{D_2(\varphi)}{r} \qquad (3)$$

Components of the magnetic induction vector:

$$B_r(\varphi,r)=\frac{1}{r}\cdot\frac{\partial A}{\partial \varphi}=\frac{\partial C(\varphi)}{\partial \varphi}+\frac{1}{r^2}\frac{\partial D(\varphi)}{\partial \varphi} \qquad (4)$$

$$B_\varphi(\varphi,r)=-\frac{\partial A}{\partial r}=-C(\varphi)+\frac{1}{r^2}\cdot D(\varphi) \qquad (5)$$

The unknown functions $C_1(\varphi)$, $C_2(\varphi)$, and, $D_1(\varphi)$, $D_2(\varphi)$ for each of the regions, respectively, are found through boundary conditions, taking into account the physical characteristics of the magnetic field at individual points. At the point $r = 0$, the vector magnetic potential cannot reach infinity. Therefore, $D_1(\varphi) = 0$. In polar coordinates, the components of the magnetic induction vector will be: $B_r = B_0 \cdot cos\,\varphi$ and $B_\varphi = B_0 \cdot sin\,\varphi$.

Therefore, in the ferromagnetic region: $C_{2\varphi} = B_0 \cdot sin\,\varphi$. At the boundary between the two regions, the following boundary conditions must be satisfied: $B_{1r} = B_{2r}$ and $H_{1\varphi} = H_{2\varphi}$. After taking into account the above conditions in (4) and (5), we obtain a system of equations for two unknown functions:

$$\frac{\partial C_1(\varphi)}{\partial\varphi} = \frac{1}{R^2} \cdot \frac{\partial D_2(\varphi)}{\partial\varphi} + B_0 \cdot cos\,\varphi$$

$$-\frac{1}{\mu_0} \cdot C_1(\varphi) = -\frac{1}{\mu_F} \cdot B_0 \cdot sin\,\varphi + \frac{1}{\mu_F} \cdot \frac{1}{R^2} \cdot D_2(\varphi)$$

Omitting detailed mathematical calculations, we write expressions for the vector magnetic potential and the components of the magnetic induction vector of the magnetic field scattered by the defect.

For the region inside the defect:

$$A_1(\varphi, r) = \frac{2 \cdot \mu_0}{\mu_F + \mu_0} \cdot B_0 \cdot r \cdot sin\,\varphi \tag{6}$$

$$B_{1r}(\varphi, r) = \frac{2 \cdot \mu_0}{\mu_F + \mu_0} \cdot B_0 \cdot cos\,\varphi \tag{7}$$

$$B_{1\varphi}(\varphi, r) = -\frac{2 \cdot \mu_0}{\mu_F + \mu_0} \cdot B_0 \cdot sin\,\varphi \tag{8}$$

For the area outside the defect:

$$A_2(\varphi, r) = B_0 \cdot r \cdot sin\,\varphi - \frac{\mu_F - \mu_0}{\mu_F + \mu_0} \cdot B_0 \cdot R^2 \cdot \frac{1}{r} \cdot sin\,\varphi \tag{9}$$

$$B_{2r}(\varphi, r) = \frac{1}{r} \cdot \frac{\partial A}{\partial\varphi} = B_0 \cdot cos\,\varphi - \frac{\mu_F - \mu_0}{\mu_F + \mu_0} \cdot B_0 \cdot R^2 \cdot \frac{1}{r^2} \cdot cos\,\varphi \tag{10}$$

$$B_{2\varphi}(\varphi, r) = -\frac{\partial A}{\partial r} = -B_0 \cdot sin\,\varphi - \frac{\mu_F - \mu_0}{\mu_F + \mu_0} \cdot B_0 \cdot R^2 \cdot \frac{1}{r^2} \cdot sin\,\varphi \tag{11}$$

The tangential component in the ferromagnetic region has the following form:

$$B_{1sx} = B_0 + \frac{(\mu_F - \mu_0) \cdot R^2 \cdot B_0 \cdot [h^2 - (x - x_0)^2]}{(\mu_F + \mu_0) \cdot [(x - x_0)^2 + h^2]^2} \tag{12}$$

In the non-ferromagnetic region $B_{2sx} = \mu_0/\mu_F \cdot B_{1sx}$. The value of this component will be two, or even three orders of magnitude smaller. That is, its influence can be neglected externally. However, the normal component is continuous:

$$B_{2sy} = B_{1sy} = \frac{2 \cdot (\mu_F - \mu_0) \cdot (x - x_0) \cdot h}{(\mu_F + \mu_0) \cdot [(x - x_0)^2 + h^2]^2} \cdot R^2 \cdot B_0 \tag{13}$$

Analysis of expression (13) shows that at the point $x = x_0$ the normal component passes through zero. The maxima of the normal component are located symmetrically around zero at a distance $s = 2 \cdot h/\sqrt{3}$ one from another. At these points, the value of the normal component is equal to:

$$B_{xm} = \frac{(\mu_F - \mu_0)}{(\mu_F + \mu_0)} \cdot \frac{9 \cdot R^2}{8 \cdot \sqrt{3} \cdot h^2} \cdot B_0 \tag{14}$$

The results of the analysis of the normal component allow us to estimate the depth of the defect location:

$$h = 0.5 \cdot s \cdot \sqrt{3}$$

and, based on the maximum value of the normal component, its radius:

$$R = \frac{2}{3} \cdot \sqrt{2 \cdot \sqrt{3} \cdot \frac{\mu_F + \mu_0}{\mu_F - \mu_0} \cdot \frac{B_{ym}}{B_0} \cdot h} \tag{15}$$

The mechanism of formation of technological cracks on the machined surface of parts made of ferroceramic materials can also be studied from the standpoint of the "weakest link" hypothesis, which should be understood as a structural parameter, the size of which is selected as a criterion for defect-free machining according to the formula [21]:

$$R_0 < \frac{K_C^2}{\pi[GT_k(1+\nu)\alpha_t]^2} \tag{16}$$

where G is the modulus of elasticity of the second kind of ferroceramic material; K_C^2 is the crack resistance of the ferroceramic material of the blank after sintering; α_t is a temperature coefficient of the blank material; T_k is the contact temperature in the grinding zone of the blank; ν is the Poisson's ratio.

Formula (16) provides a simple sufficient criterion under which a crack-like defect R_0 will not turn into a main crack.

If the inclusions are elliptical in shape, instantaneous local heating of the surface layer of the magnet in the contact zone may result in the formation of a disk-shaped crack. This is because during grinding, under the influence of both thermoelastic stresses and cutting forces on the edges of a disk-shaped defect with radius R, forces P arise along the axis of this defect [22]:

$$P = G(1+\nu)\alpha_t T_k \iint_{(S)} (\vec{n}_z, \overline{ds}) = G(1+\nu)\alpha_t T_k S_0 \tag{17}$$

where S_0 is the area of the defect boundary projection on the crack plane.

The stress intensity factor is determined for this case using the formula:

$$K_I = \frac{P}{(\pi R)^{3/2}} \tag{18}$$

Using viscosity, the destruction of ferrites at the radius of the disk-shaped defect found is achieved, which, when the conditions are met:

$$R \leq \frac{1}{\pi}\left[\frac{G(1+\nu)\alpha_t T_k S_0}{K_{1C}}\right]^{2/3} \quad (19)$$

will not develop into a main crack. In the case of an ellipsoidal shape, we have the following:

$$S = 4ab, \qquad R = \frac{1}{\pi}\left[\frac{4G(1+\nu)\alpha_t abT_k}{K_{1C}}\right]^{2/3} \quad (20)$$

Here, a and b are the major semi-axes of the ellipse in the cross-section of the ellipsoid of the disk-shaped crack.

The obtained analytical conditions (16), (19), (20) for the equilibrium of structural defects, the size R (in the case of the "weakest" link) depend on the crack resistance coefficient K_{1C}, the coefficients ν, G, α_t as well as the value of the contact temperature T_k, which is determined by the operating part in the finishing operations.

5. Research results

When developing technological criteria for controlling the defect-free machining process, it was taken into account that this process is multifactorial. The quality of the surface layer during the processing of parts is influenced by the physical and mechanical properties of the material being processed, its structure, grinding modes, and wheel characteristics, the conditions of preliminary treatment with lubricating and cooling media (LCM) for the tool, as well as the characteristics of the cooling and lubricating fluids used.

Therefore, to ensure the quality of the processed surfaces, it is necessary to select the processing modes, LCM, and tool characteristics based on the functional relationships between the physical and mechanical properties of the materials and the grinding process parameters, so that the current values of the grinding temperature $T\ (x, y, \tau)$ and heat flux $q(y, \tau)$, stress $\sigma_{p\,max}$ and grinding forces P_Y, P_Z stress intensity factor $К_1(S, \alpha, \sigma_{p\,max})$ do not exceed their specific values for defects of certain geometric dimensions, ensuring the required quality of the surface layer [23], [24].

Consider the following system of boundary inequalities which allows us to proceed to the construction of an algorithm for selecting technological parameters that ensure the required quality of the machined surfaces.

When studying the kinetics of the temperature field of a part, taking into account the peculiarities of cutting with single grains of the tool, it was found that it consists of regular (constant) and instantaneous (pulse) components. The impulse component T_m describes the temperature state of the machined surface directly under the cutting grain. The constant component, T_k, characterizes the heating of the product surface in the machining zone as a result of the combined action of many tool grains.

Despite its short duration, instantaneous temperature on the treated surface, and rapid decay in depth, it nevertheless participates in the formation of a structurally stressed state of the thin surface layer of the part. Therefore, the limiting inequalities of the temperature itself and the depth of its propagation will be equal [25]:

$$T(x,y,\tau) = \frac{C}{2\pi\lambda}\sum_{k=0}^{n} H\left(\tau - \frac{kl}{V_s}\right) H\left(\frac{L+kl}{V_s}\right)\int_{\gamma_1}^{\gamma_2} f(\tau,\tau')d\tau' \leq [T]_M \qquad (21)$$

$$T([h],0,\tau) = \frac{C}{2\pi\lambda}\sum_{k=0}^{n} H\left(\tau - \frac{kl}{V_s}\right) H\left(\frac{L+kl}{V_s}\right)\int_{\gamma_1}^{\gamma_2} \psi(\tau,\tau')d\tau' \leq [T]_{avg} \qquad (22)$$

where

$$\psi(\tau,\tau') = exp\left[-\frac{V_d(kl - V_s\tau')}{2a} - \frac{V_d^2(\tau-\tau')}{4a} - \frac{(kl - V_s\tau')^2 + [h]^2}{4a(\tau-\tau')}\right] \qquad (23)$$

and $[T]_{avg}$ is the permissible temperature for the functional properties of this material; $[h]$ is the maximum permissible depth of loss of their properties.

In some cases, the loss of surface layer quality becomes significant only when structural transformations spread to a certain depth, the value of which is determined by the operating conditions of the products and, possibly, indirectly, by technical conditions. The limit values of this depth are determined by the zone of deeper heating, i.e., the constant component of the temperature field. The limit inequalities in this case are as follows [26]:

$$\begin{aligned} T_k(o,y,\tau) = \frac{CV_s}{\pi\lambda l\sqrt{V_\text{d}}}\int_0^\tau\int_{-e}^{e}\frac{x(r,t)e^{-\frac{(y-r)^2}{4(\tau-t)}}}{2\sqrt{\pi(\tau-t)}}\left\{\frac{1}{\sqrt{\pi(\tau-t)}}\right. \\ \left. + \gamma e^{y^2(\tau-t)}\left[1+\Phi(\gamma\sqrt{\tau-t})\right]\right\} drdt \leq T_{str} \end{aligned} \qquad (24)$$

$$\begin{aligned} & T_k([h],0) \\ & = \frac{CV_s}{\pi\lambda l\sqrt{V_d}}\int_0^{\sqrt{Dt_{gr}}}\sqrt{[h]^2+y'^2}e^{-\frac{V_d y'}{2a}}K_{1/2}\left(\frac{V_d}{2a}\sqrt{y'^2+[h]^2}\right)dy' \leq [T]_{pr} \end{aligned} \qquad (25)$$

$$T_k^{max}(L,0)\frac{CV_s a}{\lambda l V_d^2}\sqrt{\frac{a}{\pi}}\left[1 - exp\left(-\frac{V_d\sqrt{Dt_{gr}}}{a}\right)\right] \leq [T] \qquad (26)$$

In the last inequality, the limiting temperature at the surface ($X = 0$) is used as the limiting coefficient.

The formation of grinding cracks depends on the magnitude of temporary stresses formed in the surface layer under the influence of thermomechanical phenomena accompanying this process. Maximum stresses occur in the zone of intensive cooling. Therefore, the structure of the control inequality for defect-free processing in this case will be as follows [23], [24]:

$$\sigma_{max}(x,\tau) = 2G\frac{1+\nu}{1-\nu}\alpha_t T_k^{max} erf\left(\frac{x}{2\sqrt{a\tau}}\right) \le [\sigma] \quad (27)$$

The phenomenological approach to assessing metal cracking phenomena during grinding does not take into account many technological factors, in particular, the influence of the heat treatment modes of these metals and the defectiveness of their structure associated with previous types of mechanical processing. Therefore, a more "sensitive" limit parameter is needed, the structure of which would include functional links between the technological parameters of diamond-abrasive processing and take into account technological inheritedness [13], [27].

As such, the stress intensity factor limit can be used, with its established ratios to technological parameters, as the main criterion for the crack resistance of metals – the K_{1C} coefficient, i.e. [24], [27]:

$$K_1 = \frac{1}{\pi\sqrt{l}}\int_{-l}^{l}\sqrt{\frac{l+t}{l-t}}\{\sigma_{xx},\sigma_{yy}\}dt \le K_{1C} \quad (28)$$

where $2l$ is the characteristic linear size of the structural defect.

Defect-free processing of materials with low mechanical characteristics is possible if the cutting forces, in particular the tangential component – P_Z, are limited and the friction coefficient between the tool and the processed metal – ρ is reduced.

Thus, based on studies of the effect of cutting forces on the stress state of the surface layer, another additional condition for defect-free processing can be formulated [24]:

$$P_z \le \frac{\pi\sqrt{Dt_{gr}}}{KP^2 \sin\pi\theta}\left[[\tau]_C - \frac{E\rho\sqrt{Rt}}{2(1-\nu^2)\sqrt{R}}\right] \quad (29)$$

where $[\tau]$ is the limit value of the tangential shear stress; $\theta = \frac{1}{\pi}arctan\frac{1-2\nu}{2\rho(1-\nu)}$; ρ is the minimum possible value of the friction coefficient between the abrasive and the metal being processed, which is ensured by the use of a heat transfer medium and impregnating substances; K is the ratio coefficient, P_Y/P_Z.

To verify criterion (29) for the absence of grinding cracks on the machined surface of ferroceramic materials, we will determine the contact temperature in the grinding zone. Taking into account that the dominant factor among the grinding modes affecting the thermal stress of the grinding process is h - the grinding depth, the dependence $T = f(h)$ was found (Fig. 3). The remaining modes were selected from the conditions of maximum productivity while maintaining the required quality and were selected as follows: $V_d = 0.17$ m/s; $V_s = 30$ m/s; $S_{non} = 5$ mm. The following grinding wheels were selected for the study: wheel 1 – the ACP B1 diamond wheel with grain size 100/80, represented by its European analogue Tyrolit

4BT9 D91; wheel 2 – the ASK synthetic diamond wheel 250/200 MO16 (100% concentration), substituted with the DIAMOS metal-bond diamond wheel 1A1R DIA126 C100 BX; and wheel 3 – the electrocorundum wheel 24A 25 CM/8K5, replaced by the aluminium-oxide wheel Flexovit A24 V-BF42 (e.g., article 66252831164).

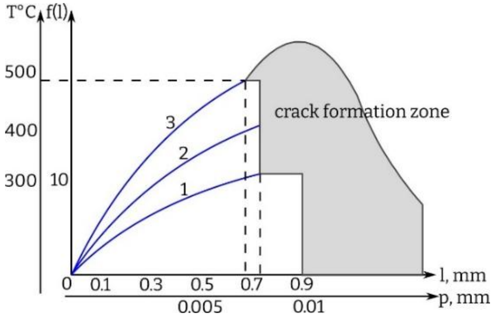

Fig. 3 Calculated and experimental values of the maximum sizes of crack-like defects when grinding ferroceramic products with wheels

Experimental studies have shown that wheels made of natural and synthetic diamonds have stable cutting ability, high dimensional stability, and a relatively low temperature in the grinding zone, which also affects the absence of cracks at large grinding depths (compared to 24A25CM18K5 wheels).

It was found that the most productive way to maintain the required quality of grinding the working surface of ferroceramic products is with ACPB1 diamond wheels with a grain size of 100/80 (curve I, Fig. 3).

Since porosity (size and density) during sintering of the workpiece is regulated by the temperature regime, as well as the speed of passage through the tunnel kiln [28], it is possible to avoid the appearance of grinding cracks on the machined surface by selecting the appropriate grinding modes and wheel characteristics.

The results of studying the microhardness of the treated surface and the microstructure of the surface layer indicate that in the range of modes studied, there are no cracks or chips during the grinding of ferroceramic products.

The nature of crack formation in ferroceramic products depending on the characteristics of the wheels and cutting modes can be traced using the criterion of the limiting heat flux q^* [29]:

$$q^* = \frac{P_z V_s \alpha_s}{\sqrt{D t_{gr}}} \leq \frac{\sqrt{3}\lambda K_{1c}}{H l \sqrt{\pi l}\sigma} \tag{30}$$

The heat flow entering the part during grinding is not only a function of the cutting modes, V_d, V_s, t_{gr}, P_Z, but also of the characteristics of the wheels – the hardness of the bond, the grain size of the cutting grains, their hardness, etc. Therefore, it should be expected that each wheel has its own limit heat flow value at which the machined surface of a ferroceramic product containing pores of size $2l$ will not be subject to cracking.

The following studies were conducted to rank the wheels according to the maximum heat flux criterion. Products made of ferroceramic MnFe2O4 materials containing air pores were ground with different wheels at grinding depths at which cracks appeared on the surface. At the same time, the heat flux q was measured by cutting power, the contact temperature T_K (using a semi-artificial thermocouple), and the instantaneous temperatures T_M and specific grinding work were recorded. It was found that the intensity of crack formation on the machined surfaces for different wheels was fairly well corrected with the limit values of the heat flux. The lowest heat flux q^* is possessed by diamond wheels with a grain size of 100/125 on organic bonds, which can be recommended for grinding ferroceramic products.

Diamond wheels with a grain size of 200/250 can be recommended for preliminary grinding operations, which ensures better quality and productivity.

The resulting irregularities are related to the limiting characteristics of the temperature and force fields with the controlling technological parameters. They determine the range of combinations of technological parameters (modes, cooling lubricant medium, tool characteristics) that ensure the required quality of the working surfaces of products made of ferroceramic materials [14], [30].

6. Conclusions

As a result of the research, information support for technological capabilities for defect-free processing of ferroceramic materials prone to cracking has been created, which consists in establishing calculated dependencies for determining the influence of hereditary defects formed at the stage of sintering the blank on the crack resistance of the surface layer in the finishing operations. technological processing conditions, taking into account the accumulated defects in the surface layer of ferroceramic parts, which are particularly prone to cracking during processing, which is of great economic importance for reducing defects in finishing operations and improving the operational properties of parts made of these materials.

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ВПЛИВ СПАДКОЄМНИХ ДЕФЕКТІВ, НА ТРІЩИНОУТВОРЕННЯ В ОБРОБЛЮВАНИХ ПОВЕРХНЯХ ВИРОБІВ ІЗ ФЕРОКЕРАМІЧНИХ МАТЕРІАЛІВ НА ФІНІШНИХ ОПЕРАЦІЯХ

Анотація. *Для забезпечення якості оброблюваних поверхонь, необхідно за функціональними зв'язками між фізико-механічними властивостями матеріалів і параметрами на фінішних операціях підбирати такі режими обробки, і характеристики інструменту таким чином, щоб поточні значення температури шліфування* $T(x,y,\tau)$ *і теплового потоку* $q(y,\tau)$ *напруження* $\sigma_{p\,max}$ *сил шліфування* P_Y , P_Z , *коефіцієнта інтенсивності* $K_1(S,\alpha_t,\sigma_{p\,max})$ *перевищували їх питомих значень, для дефектів певних геометричних розмірів, що містяться в поверхневому шарі і мають спадкоємний характер гарантувати необхідну якість робочих поверхонь виробів. В даній роботі розглянута математична постановка задачі по виявленню дефектів в феромагнітних деталях від попередніх операцій при їх намагнічувані. Отримано математичні вирази для оцінки геометричної форми і глибини розміщення дефекту в поверхні деталі за результатам вимірювання розподілу магнітної індукції на її поверхні. Механізм утворення технологічних тріщин на фінішних операціях поверхні деталей із ферокерамічних матеріалів розглядається з позицій гіпотези про «найслабшу» ланку, під яким слід розуміти спадкоємний дефект, розмір якого вибирається в якості критерію бездефектної обробки. У результаті виконаних досліджень створено інформаційне забезпечення технологічних можливостей для бездефектної обробки виробів із матеріалів, схильних до тріщиноутворення, що полягає у встановленні розрахункових залежностей щодо визначення впливу спадкових дефектів, сформованих від попередніх операцій на тріщиностійкість поверхневого шару на фінішних операціях. технологічних умов обробки з урахуванням накопичених пошкоджень і неоднорідностей у поверхневому шарі деталей із матеріалів і сплавів, особливо схильних до тріщиноутворення в процесі обробки, що має важливе значення для зменьшення дефектів на фінішних операціях та підвищення експлуатаційних властивостей деталей машин.*

Ключові слова*: спадкоємний дефект; тріщино-утворення; фінішна операція; феромагнітне моделювання; аналітичні залежності.*