ISSN 2078-7405 Cutting & Tools in Technological System, 2023, Edition 99

UDC 536:621.9 (075.8) **doi: 10.20998/2078-7405.2023.99.13**

STUDYING THE INFLUENCE OF THERMOMECHANICAL PHENOMENA ON GRINDED SURFACE QUALITY PARAMETERS OF PRODUCTS MADE FROM HARD-TO-PROCESS MATERIALS

Anatoliy **Usov** [0000–0002–3965–7611], Yuriy **Zaychyk** [0000–0002–8577–1095]

Odesa Polytechnic National University, 1, Schevchenko av., Odesa, 65044, Ukraine
usov_a_v@op.edu.ua

Received: 11 November 2023 / Revised:18 November 2023 / Accepted: 26 November 2023 / Published: 01 December 2023

Abstract. *Grinded surface quality state of products made from hard-to-process materials is formed under the influence of thermomechanical phenomena during final machining operations. But grinding causes the formation of burns, cracks, and tensile stresses in surface layers of products. These defects significantly influence reliability and durability of products during their operation. High thermal tension of diamond-abrasive processing leads to the fact that thermophysics of these processes is dominating in formation of quality characteristics of processed surface. Existing grinding methods for products made from hard-to-process materials do not allow to fully eliminate defects that occur in surface layer. Among the factors that conduce these defects are inevitable fluctuations of processing allowance, microheterogenity of the material characterized by the size of grain, packaging defects, structural transformations and dislocations, product warping during thermal treating, insufficiently studied thermomechanical phenomena. The mentioned effects accompany grinding process and cause burn marks, microcracks, structural transformations, residual stresses. Exploration of thermomechanical phenomena that form the quality of surface layer considering preceding machining operations of products, determining their influence on cracks and burns formation based on quality analysis of thermal and stress states and make up the objective of this research. This paper proposes more efficient models for studying quantitative connections between technological system parameters, physical and mechanical properties of processed materials, their structure, and thermomechanical processes during grinding. We have developed optimal technological parameters for processing metals and alloys prone to defects in surface layer based on determined relationships. Such defects encompass defects like cracks, burns, and chips.*

Keywords: *grinding; processed surface quality; thermomechanical phenomena; model; defects; technological parameters; defects-free processing criteria.*

1. INTRODUCTION

The development of study of surface quality leads to the establishment of functional dependencies between technological system parameters, instrument properties, processing modes, roughness, hardening, existence of cracks and burns, precision of product surface, and materials. Determining relationships between the most important properties of products (durability, fatigue and long-term strength, contact rigidity, magnetic properties, etc.) made from hard-to-process materials and technological parameters (surface microrelief, microhardness, presence of microcracks and chips, spreading depth of hardened layer) is an important task of machine building technology.

Studying only mechanical processing influence on the operational properties of product is insufficient because preceding processing types (thermal, thermomechanical, thermochemical, etc.) and especially preparation of workpieces contribute significantly to the alternation of surface layer properties exposed to further mechanical processing. The Development of the technological heredity problem is a base of scientific and practical trends in machine building technology aiming to enhance operational qualities of machines details applying technological methods during manufacturing.

Review of the literature. The most widespread final machining operation is grinding which ensures high precision and high manufacturing productivity. But also grinding may cause burns, cracks, and tensile stresses in surface layers of products which affect their reliability and durability during operation [1] [2] [3] [4]. The problem of surface layer quality enhancement can be solved with following approaches:

- Selection of proper grinding modes and appropriate instrument characteristics for particular material.
- Usage of grinding wheels and belts with intermittent working surface.
- Applying system with automatic regulation of cutting power.
- Cutting fluids significantly decreases thermal tension of grinding operation and thus decreasing the probability of burn marks and cracks.

But application of mentioned methods within current manufacturing technology and considering composite materials cannot fully exclude defects that appear in surface layer. This is magnified by processing allowance fluctuations, material heterogeneity, product warping, thermal defects during processing.

High thermal tension of diamond-abrasive processing determines the dominating role of thermal physics of this process in surface layer quality characteristics. This thesis is confirmed by research of a wide range of scientists regarding concrete problems of such processes [5] [6] [7] [8]. Among the most noted results in this trend are the following works: [9] – influence of thermal physics on processed surface quality, [10] – thermal nature of surface quality during grinding; control of thermal physics applying intended process interruption, [11] – influence of thermal physics on stressed state of processed surface, [12] – influence of geometrical form of product and grinding technological parameters on surface layer quality, [13], [14] – determination of grinding temperature that is a consequence of thermal interaction between abrasive grains like heat sources, research of grinding process using similarity theory methods, influence of cutting fluids on thermal physics and quality characteristics of grinded products.

Problem statement. Research of thermomechanical phenomena that form surface layer quality considering preceding machining operations, determining the influence of them on cracks and burns occurrence basing on quantitative analysis of thermal and stressed state and make up the sense of this paper.

In this scientific work we propose more efficient models for studying quantitative relationships between the parameters of technological system parameters, physical and mechanical properties of processed metals, presence technological defects in the surface layer, structure and thermomechanical processes which accompany grinding operation. Optimal technological parameters for processing metals and alloys (prone to defects occurrence) that are being developed based on established relationships.

Research methods and materials. One of the concrete results of this scientific work is the establishment of grinding defects formation patterns depending on heredity and processed material type, its heterogeneity and methods for their removing employing proper technological system. Grinding of machine details is followed by thermal and mechanical phenomena which interact between each other and define surface layer quality. Quantitative description of these phenomena requires the choice of definite models. Considering interconnections of processes during grinding it becomes obvious that stress-strained state of the surface layer is determined mainly by temperature. If we use the model of thermoelastic body that reflects the interconnection of mechanical and thermal phenomena in finite thermal flows, then we can significantly progress in the research of thermomechanical phenomena accompanying grinding process [15].

2. RESULTS

For further studying of the kinetics of thermomechanical processes we will use the following system of differential equations [16] as primary theoretical foundation. This system describes the interaction between deformation field and temperature fileld:

$$G\Delta\vec{U}_j + (\lambda_t + G)\,graddiv\vec{U}_j - \rho\frac{\partial^2\vec{U}_j}{\partial\tau^2} + P_j = \alpha_t\beta_t\,gradT \qquad (1)$$

$$\Delta T - \frac{1}{a}\frac{\partial T}{\partial\tau} - \eta l\frac{\partial}{\partial\tau}div\vec{U}_j = -\frac{W}{\lambda} + C_q^{-2}\frac{\partial^2 T}{\partial t^2} \qquad (2)$$

where λ_t, G – are Lamé constants; $\beta_t = 3\lambda_t + 2G$; ρ - processed material density; α_t – temperature coefficient of metal linear extension; $a = \lambda / C_v$ –

temperature diffusivity coefficient; λ - thermal diffusivity coefficient; C_v – dimensional thermal capacity; $\vec{U}$ (*Φ*, τ) – total displacement vector of internal Φ (*x*, *y*, *z*) in surface layer under the action of thermomechanical forces following grinding process; *l* = 1 + τ_r δ/δ (τ - relaxation time); $\eta = \alpha_t \beta_t T(\Phi, \tau) / \lambda$; W – thermal source power; C_q – heat spread rate in processed material; τ - time; P_j – cutting forces.

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

$$div\vec{U}_j = \frac{\partial U}{\partial x} + \frac{\partial U_y}{\partial y} + \frac{\partial U_z}{\partial z}$$

As thermal effects prevail over force phenomena, we can ignore the component responsible for the transformation of mechanical energy into thermal energy in the thermal conductivity equation. Thus, we can come to thermal conductivity equation of hyperbolic type. To solve the equation system (1), (2) in explicit way we will ignore the influence of inertial components and the limitation of thermal spreading rate. Moreover, we will consider the flat problem to omit the analytical difficulties connected with spatial thermoelasticity problems solution. This step is acquitted because for the research of thermomechanical state of grinded surfaces it is important to consider the information about temperature and deformation spreading along the depth and in the direction of instrument movement as the source of thermal emission in processing zone.

The analysis of the scaled schemes of grinding wheel interaction with processed surface showed that the curvature of the wheel and of the product (in limits of contact zone) insignificantly affects the geometrical schema of the wheel and product interaction. That’s why when building the calculations schema, we assume that product can be presented as partially homogeneous half-plane. This assumption enables us to study thermomechanical processes during grinding of products with several types of coating with thickness Δa_K which are applied to main matrix. Such schema determines thermal and strained conditions for layer coupling along splitting border - a_K.

During material smelting and during technological process the following effects and phenomena may occur: structural heterogeneities as phase transformations of unstable structures, grain films, heredity austenite grains borders, carbide lining, cementite grid, dents, flocks, and other defects. In our model we will consider such defects as inclusions and cracks in surface layer.

The calculation schema for the problem of determining thermomechanical state during grinding of products with heterogeneities as inclusions and cracks in surface layer is described on fig. 1.

The system of equations that determine thermal and stress-strained state of processed product surface includes [17]:

a) Equation of non-stationary thermal conductivity

$$\frac{\partial T}{\partial \tau} = a^2 \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{3}$$

b) L'ame elasticity equations in displacements

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

$$\frac{\partial \theta}{\partial y} \cdot \frac{1}{1-2\mu} + \Delta \vec{U} = b^T \frac{\partial T}{\partial y}; \quad b^T = \frac{4G(1+\mu)}{1-2\mu} \alpha t \qquad (4)\ (5)$$

c) initial conditions

$$T(x, y, o) = 0 \tag{6}$$

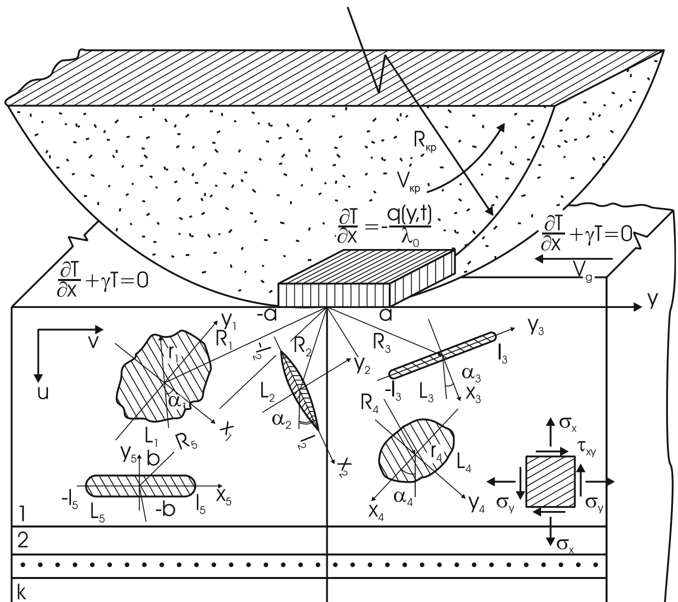

Fig.1. Calculation schema for defining thermomechanical state during grinding of products which contain heterogeneities in surface layer.

d) border conditions

$$\frac{\partial T}{\partial x} = -\frac{q(y,t)}{\lambda}, \quad |y| < a;$$
$$-\frac{\partial T}{\partial x} + jT = 0, \quad |y| > a;$$
$$\sigma_x(x,y,t)\big|_{x=0} = \tau_{xy}(x,y,t)\big|_{x=0} = 0 \qquad (7)\ (8)\ (9)$$

e) for layer coupling
for temperature fields for strain fields

$$\overset{k-1}{T}(a_k - 0, y, \tau) = \overset{k}{T}(a_k + 0, y, \tau) \quad \overset{k-1}{V_j}(a_k - 0, y) = \overset{k}{V_j}(a_k + 0, y) \qquad (10)$$

To consider the constructional peculiarities of the grinding wheels we need to apply the following boundary conditions:

$$q(y,\tau) = \frac{c\sqrt{\tau}}{\lambda}[H(y) - H(y - 2a^*)] \sum_{k=0}^{n} \sigma(y + kl - v_{kp}\tau) \qquad (11)$$

where $H(y)$ — Heaviside step function; $\sigma(y)$ — Dirac delta function; n — number of grains that go through the contact zone by time $\tau = \frac{\sqrt{\pi t_{шл}}}{v_{kp}}$; λ — product's material thermal conductivity; $c\sqrt{\tau}$ — thermal flow from a single grain; v_g, v_{kp}, $t_{шл}$ grinding modes, $2a^*$ — arc length of contact between wheel and product; l^* — distance between cutting grains.

We have obtained theoretically and confirmed by the experiment maximal values of instant temperature T_M and temperature from single grains to a constant component T_K. These values will be used as criterial for predicting burn-like defects appearance conditions and their depth.

The existence of stress concentrators like preceding machining operations defects in the surface layer of grinded products complicates the research for crack formation reasons. That's why to determine the limited balanced state of strained surface layer we need to insert values of the components of stresses and deformations at the corner apex into classic strength criterion. Such approach is used in fracture mechanics [18], [19], where newly formed strength criteria are the invariants in the models of continuum mechanics and in models which consider structural peculiarities of the material. From the existing criteria in fracture mechanics which are divided into energetic, power and strained, the most proper for our case are power criteria which are related to the definition of stress intensity factor [19]. In the most general case, the distribution of strains near 0 point of crack-like defect contour is presented as a superposition of triple deformations which correspond to main types of crack surface displacement. They are: normal separation (I), transverse (II) and lateral (III) displacements.

Stress intensity factors K_I, K_{II}, K_{III} serve as a measure for the singularity of stresses near the apex of crack-like defect. The critical value of the stress intensity K_C is a characteristic of the material. When the load causes stress intensity to become critical, then crack-like defect transforms into primary crack. Critical stress is inversely proportional to the square root from the initial length of crack-like defect [19]:

$$\sigma_C = \frac{K_{1C}}{\sqrt{\pi l}}$$

where *2l* is the initial length of the crack-like defect and index 1 means that this is the first stage of destruction.

Grinding is a multifactor process. Physical and mechanical properties of processed metal, its structure, grinding modes (fig. 2) and grinding wheels characteristics, conditions for preliminary treating with impregnating compounds and cutting fluids characteristics influence product's surface layer quality during grinding [20].

That's why to ensure the quality of processed surfaces we need select processing modes, cutting fluids, and instrument characteristics corresponding to established functional relationships between physical and mechanical properties of materials and grinding process parameters. At the same moment grinding temperature T (x, y, τ) and thermal flow q(y,τ), stresses $\sigma_{p\,max}$ and cutting forces P_Y, P_Z, intensity factor $K_1(S, \alpha, \sigma_{p\,max})$ shall not exceed their limit values which ensure required quality of the surface layer.

Let's consider the following system of bounding inequations obtained by the solution of problems (3) – (11). This fact allows us to develop the algorithm for selecting technological parameters that ensure required quality of processed surfaces.

During the exploration of kinetics of temperature field of the product considering peculiarities of single grains we have established that it consists of regular (constant) and instant (impulse) components. Impulse component – T_M describes temperature state of the metal under the grain. Constant component – TK characterizes metal temperature in the processing zone as a result of cumulative action from instrument grains.

Despite the short duration of instant temperature action and its fast descend along the depth it takes part in forming of structural stressed state of thin surface layer of the product. That's why

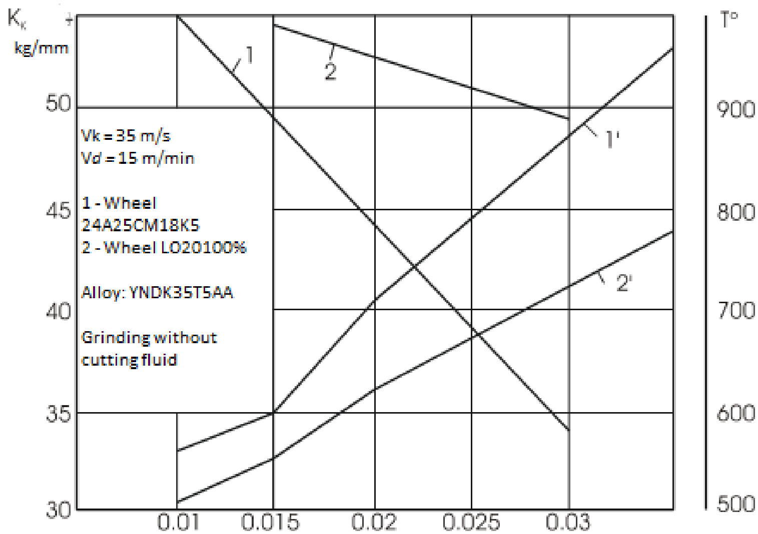

Fig .2. Influence of the grinding depth on the intensity of cracks formation during processing of UNDK magnets in state of α-phase.

bounding inequations for values of the temperature itself and its spreading depth will be correspondingly equal to:

$$T(x,y,\tau)=\frac{C}{2\pi\lambda}\sum_{k=0}^{n}H(\tau-\frac{kl}{V_{kp}})H(\frac{L+kl}{V_{kp}})\int_{\gamma_1}^{\gamma_2} f(\tau,\tau')d\tau' \le [T]_M \tag{12}$$

$$T([h],0,\tau)=\frac{C}{2\pi\lambda}\sum_{k=0}^{n}H(\tau-\frac{kl}{V_{kp}})H(\frac{L+kl}{V_{kp}})\int_{\gamma_1}^{\gamma_2} \psi(\tau,\tau')d\tau' \le [T]_{\text{СП}} \tag{13}$$

where

$$\psi(\tau,\tau')=\exp\left[-\frac{V_\partial(kl-V_{kp}\tau')}{2a}-\frac{V_\partial^2(\tau-\tau')}{4a}-\frac{(kl-V_{kp}\tau')^2+[h]^2}{4a(\tau-\tau')}\right] \tag{14}$$

$[T]_{cp}$ – acceptable temperature of structural transformations of given metal; [h] – limit acceptable depth of structural transformations.

In some cases the loss of quality of the surface layer becomes significant only when structural transformations spread to a certain depth. Its value is determined by operational conditions and indirectly by technical conditions. Limit values of such depth are determined by the zone of deep heating, sic constant component of the temperature field. Bounding inequations in this case have the following form:

$$T_k(o,y,\tau)=\frac{CV_{kp}}{\pi\lambda l\sqrt{V_g}}\int_0^{\tau}\int_{-e}^{e}\frac{x(r,t)e^{-\frac{(y-r)^2}{4(\tau-t)}}}{2\sqrt{\pi(\tau-t)}}\left\{\frac{1}{\sqrt{\pi(\tau-t)}}+\gamma e^{y^2(\tau-t)}\left[1+\Phi(\gamma\sqrt{\tau-t})\right]\right\}drdt \qquad (15)$$

$$T_k([h],0)=\frac{CV_{kp}}{\pi\lambda l\sqrt{V_g}}\int_0^{\sqrt{Dt_{øë}}}\sqrt{[h]^2+y'^2}\,e^{-\frac{V_\partial y'}{2a}}K_{1/2}\left(\frac{V_\partial}{2a}\sqrt{y'^2+[h]^2}\right)dy'\le[T]_{np} \qquad (16)$$

$$T_k^{\max}(L,0)\frac{CV_{kp}a}{\lambda l V_g^2}\sqrt{\frac{a}{\pi}}\left[1-\exp\left(-\frac{V_\partial\sqrt{Dt_{øë}}}{a}\right)\right]\le[T]c.n. \qquad (17)$$

In the last inequation we used limit temperature on the surface (X = 0) as bounding factor.

Grinding cracks formation depends on the value of temporal stresses which originate in the surface layer under the influence of thermomechanical phenomena accompanying this process. Maximum stress originates in the zone of intensive cooling. That’s why the structure of controlling inequation in this case will be the following [21]:

$$\sigma_{\max}(x,\tau)=2G\frac{1+\nu}{1-\nu}\alpha_t T_k^{\max}erf\left(\frac{x}{2\sqrt{a\tau}}\right)\le[\sigma]_{ï÷} \qquad (18)$$

The phenomenological approach in the estimation of cracks formation of metals during don’t consider many technological factors. Particularly the influence of thermal treating modes for these materials and their structure defectivity related to preceding machining operations. That’s why we need more “sensitive” limiting inequation. The structure of such inequation shall include functional connections of technological parameters of diamond-abrasive processing and shall consider technological heredity.

We can use the limitation of stress intensity factor with established relationships with technological parameters in mentioned above role. The main criterion of crack resistance for metals is the coefficient K_{1C} [22]:

$$K_1=\frac{1}{\pi\sqrt{l}}\int_{-l}^{l}\sqrt{\frac{l+t}{l-t}}\{\sigma_{xx},\sigma_{yy}\}dt\le K_{1C} \qquad (19)$$

where *2l* – linear size of structural defect.

Defect-free grinding of materials with low mechanical characteristics is possible if we limit cutting forces, particularly tangential component – P_Z and decrease friction coefficient between the abrasive and processed metal - ρ.

Thus, from the study about the influence of cutting forces on the stressed state in the surface layer we can build another one auxiliary condition for defect-free grinding:

$$P_z \le \frac{\pi\sqrt{Dt_{øë}}}{KP^2 \sin \pi\theta}\left[[\tau]_C - \frac{E\rho\sqrt{Rt}}{2(1-\nu^2)\sqrt{R}}\right] \tag{20}$$

where [τ] – limit value of the tangent stress on the displacement; $\theta = \frac{1}{\pi} arctg \frac{1-2\nu}{2\rho(1-\nu)}$. ρ – minimal possible value of the friction coefficient between the abrasive and processed metal provided by the application of cutting fluids and impregnating compounds; $K = P_Y / Pz$ – relationship factor.

Using known value of crack resistance coefficient K_{1C} of the processed material [23], size of the "weakest" structural parameter *l*, we can determine the range of technological parameters which ensure limit value of thermal flow when structural defects balance is preserved:

$$q^* = \frac{P_z V_{kp} \alpha_b}{\sqrt{Dt_{øë}}} \le \frac{\sqrt{3}\lambda K_{1C}}{Hl\sqrt{\pi l}\,\delta^*} \tag{21}$$

The conditions of the defect-free grinding can be implemented using the information about the structure of processed metal. Thus, in case of prevailing character of structural imperfections with length 2l, their regular location related to contact zone between instrument and product we can use the balance condition in defect as criterial relationships:

$$l_0 < \frac{K_C^2}{\pi\left[GT_k(1+\nu)\alpha_t\right]^2} \tag{22}$$

In this formula the technological part lies in the connection between contact temperature value T_K and grinding modes and instrument characteristics (4.4.6).

Obtained inequations uncover the relationship of limit characteristics of temperature and power fields with controlling technological parameters. They define the area of combinations of technological parameters (modes, cutting fluids, grinding wheel characteristics) which ensure the required quality of processed surfaces.

Based on the obtained criterial relationships we developed the algorithm for providing surface layer quality of products during grinding considering maximum processing productivity (Fig. 3).

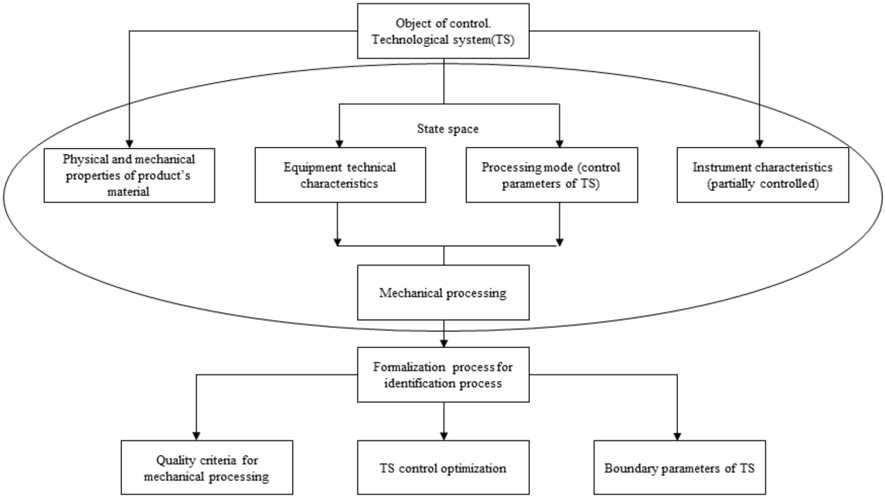

Fig.3 Algorithm for providing quality of mechanical processing corresponding to optimal accepted parameters of technological system.

3. CONCLUSIONS

Prevention of grinding cracks during the processing of products made from hard-to -process materials which have low mechanical properties and anisotropy depends on the right choice of grinding wheel characteristics, proper modes (which provide defect-free processing considering manufacturing technological process and morphology).

Obtained technological criteria proposed in form of bounding inequations (by the limit values of the grinding temperatures, burn mark depth, cutting forces, thermal flow, stress intensity) make possible to find the area of combinations of technological parameters – cutting fluids, grinding wheel characteristics which provide the required quality of products.

We developed the algorithm for providing quality working surfaces of products made from hard-to-process materials prone to defects formation during grinding.

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Анатолій Усов, Юрій Зайчик, Одеса, Україна

ДОСЛІДЖЕННЯ ВПЛИВУ ТЕРМОМЕХАНІЧНИХ ЯВИЩ НА ПАРАМЕТРИ ЯКОСТІ ШЛІФОВАНИХ ПОВЕРХОНЬ ДЕТАЛЕЙ ІЗ СКЛАДНО ОБРОБЛЮВАНИХ МАТЕРІАЛІВ

Анотація. *Стан якості шліфованої поверхні виробів із складно оброблюваних матеріалів формується під впливом термомеханічних явищ, що супроводжують фінішну операцію. Але застосування шліфування пов'язане з появою припіків, тріщин, розтягуючих напружень в поверхневих шарах деталей, що істотно впливає на надійність і довговічність цих деталей в процесі їх експлуатації. Висока теплоємність алмазно-абразивних процесів обробки призводить до того, що теплофізика цих процесів часто є домінуючою у формуванні якісних характеристик оброблюваної поверхні. Існуючі способи шліфування деталей з важкооброблюваних матеріалів не дозволяють повністю усунути дефекти, що виникають в поверхневому шарі. Цьому сприяють: неминучі коливання припусків через помилки в попередніх операціях механічної обробки; Недостатньо вивчені мікронеоднорідність самого матеріалу, що характеризується зернистістю, дефектами упаковки, зміщенням і структурними перетвореннями, короблениям деталей при термічній і подібній обробці, термомеханічними явищами, які супроводжують* *процес шліфування і в результаті яких на оброблюваних поверхнях з'являються припіки, мікротріщини, структурні перетворення, залишкові напруження. Предметом даної роботи є дослідження термомеханічних явищ, що формують якість поверхневого шару, з урахуванням попередніх видів обробки виробів, встановлення їх впливу на утворення тріщин і припіків на основі кількісного аналізу теплового і напруженого станів. У представленій роботі запропоновані більш ефективні моделі для дослідження кількісних співвідношень між параметрами технологічної системи, фізико-механічними властивостями оброблюваних металів, їх структурою і термомеханічними процесами, що відбуваються в поверхневому шарі деталей, що шліфуються. На основі встановлених співвідношень розроблено оптимальні технологічні параметри обробки металів і сплавів, які значно схильні до появи дефектів поверхневого шару, таких як тріщини, відколи, припіки.*

Ключові слова: *шліфування; якість обробленої поверхні; термомеханічні явища; модель; дефекти; технологічні параметри; критерії бездефектної обробки*.