MANAGEMENT OF THE QUALITY CHARACTERISTICS OF THE WORKING SURFACES OF COMPLEX PROFILE PRODUCTS DURING MECHANICAL PROCESSING

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The paper considers the temperature field model, which is formed in the surface layer of complex profile products during their processing in finishing operations. These operations are associated with defects in the surface layer of products, such as burns, cracks, and tensile stresses. Which significantly affects the reliability and durability of these parts during their operation. These defects, being local stress concentrators in operational conditions, lead to premature failure of products, even though the load on them forms stresses, the value of which does not exceed the limit values. The model is built based on the solution of the product's initial boundary value problem of thermal conductivity. Functional relationships of technological parameters with the grinding temperature obtained based on the model reflect the state of the treated surfaces for products with complex profiles and allow using appropriate techniques to eliminate burns on the treated surfaces. The study of the conditions for improving the quality of the treated surfaces by eliminating defects such as cracks and burns was carried out mainly at the level of identifying the connections of the temperature fields that are formed with technological parameters, physical and mechanical properties of the polished materials and the geometry of the products. It was established that when grinding complex profile products from a larger radius in the direction to a smaller one, the temperature increased in proportion to the angle of inclination of the treated surface. The adequacy of the built model was checked on the example of grinding conical products made of steel with known physical and mechanical characteristics, the choice of tool, and the designation of processing modes. Analysis of the simulation results shows that the temperature of the machined surface increases as the machining tool approaches a smaller diameter along the conical surface. This area of conical products' machined surface is most prone to defect formation during finishing operations. Therefore, when assigning treatment modes for such surfaces, they should be assigned with the condition that when the processing tool approaches the part of the conical surface with a smaller diameter, the temperature formed on it should not exceed the permissible values that ensure the required quality. Analysis of the results of numerical calculations of temperature fields showed sufficient accuracy according to the boundary conditions of the simulation.

Keywords: complex profiled products, temperature field model, defects, surface layer quality, finishing operations, adequacy.

Introduction

It is known that hereditary technological defects such as burns and micro-cracks are formed in the surface layer during the processing complex profiled products [1]. These defects, being local stress concentrators in operational conditions, lead to premature failure of products, even though the load on them forms stresses, the value of which does not exceed the limit values [2]. When forming the required geometric dimensions of complex profiled products in the processed stochastically located micro inhomogeneities and micro defects are formed on the surfaces [3]. Therefore, when studying the limit state of these products, the surface layer is weakened by micro defects. Building on this basis a justified theory of their bearing capacity, in addition to the deterministic one, a probabilistic statistical approach is also necessary. Finally, the active layer of such products is considered an environment weakened by random defects, the parameters of which are random variables with known distribution laws.
Formulation of the problem

The statistical approach in assessing the load-bearing capacity of products has certain advantages. First, it makes it possible to consider the impact on the strength of all defects and inhomogeneities at once, regardless of their physical nature, size, shape, and location [4]. However, on the other hand, this approach does not allow us to assess the role of the defect in the elementary act of destruction, the reduction of the strength of the surface layer containing the specified defects, and their appearance from the technology of product processing to the final state of the working surface [5]. Their geometry plays a specific role in forming defects in the surface layer of processed products [6]. It especially applies to the finishing methods of processing complex profiled products. The most common final processing method is grinding, which ensures high accuracy and productivity of manufacturing parts [7]. However, the application of grinding is associated with defects such as burns, cracks, and tensile stresses in the surface layers of parts, which significantly affects the reliability and durability of these parts during their operation. Existing functional connections of technological parameters with the grinding temperature [8] make it possible to eliminate burns on the processed surfaces of products that do not contain design and technological inhomogeneities and the material which does not contain significant deviations, using appropriate methods. The study of the conditions for improving the quality of the treated surfaces by eliminating defects such as cracks was mainly conducted at the level of identifying qualitative relationships between technological parameters and the physical and mechanical properties of polished materials [9].

However, the lack of research on the peculiarities of the process of genesis of grinding defects and their impact on the decrease in performance depending on the structural, technological, and structural inhomogeneities of the material of the products do not allow us to unambiguously use the existing recommendations for the elimination of these defects.

The purpose of these studies is to build a model of thermomechanical processes that accompany the finishing of complex profiled products under which defects are formed in the surface layer, which leads to the loss of the load-bearing capacity of these products during their operation.

Research Methodology. Consider the following initial boundary value problem of thermal conductivity for a product in the form of, for example, a truncated circular cone (Fig. 1).

![Fig. 1 Calculation scheme for modeling the temperature field formed in conical products during finishing operations](image)

\[
\begin{align*}
\Delta u(r, \theta, \varphi, t) &= \frac{1}{\rho c} \frac{\partial u(r, \theta, \varphi, t)}{\partial t}, \quad a < r < b, \quad \omega_0 < \theta < \omega_1, \quad t > 0, \\
v(r, \theta, \varphi, t) &= f(r, \theta, \varphi), \quad v(a, \theta, \varphi, t) = v(b, \theta, \varphi, t) = 0, \quad |\varphi| < \pi, \\
a) \quad &v(r, \omega_j, \varphi, t) = g^1(r, \varphi, t), \\
b) \quad &v'(r, \omega_j, \varphi, t) + h v(r, \omega_j, \varphi, t) = g^1(r, \varphi, t), \\
c) \quad &v'(r, \omega_j, \varphi, t) = g^1(r, \varphi, t); \quad j = 0, 1, \\
\end{align*}
\]

where \( \Delta \) is the Laplace operator in the spherical coordinate system, the constants \( \alpha^* \) and \( h \) are the thermophysical constants of the product material, the boundary conditions on the conical surfaces \( r = a \) and \( r = b \) can be of three types, and also heterogeneous. The specified conditions are chosen for the sake of shortening the records. As above, the derivative concerning the variable \( \theta \) is marked with a dot and the derivative concerning the variable \( r \) with a dash. From the given functions, we will require that integral transformation and inversion formulas are valid for them [10].

Consistently applying the integral Laplace transform over time to (1):

\[
v_p(r, \theta, \varphi) = \int_0^\infty v(r, \theta, \varphi, t) e^{-pt} dt,
\]

and the Fourier transform by the angle \( \varphi \):

\[
\left(\right)
\]
\[
\psi_{pn}(r, \theta) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \psi_p(r, \theta, \varphi) e^{-in\varphi} d\varphi, \quad n = 0, \pm 1, \pm 2, \ldots, \quad (3)
\]

instead of (1) we obtain:

\[
\begin{align*}
\left[r^2 v_{pn}(r, \theta)\right] - \nabla^2 v_{pn}(r, \theta) - s^2 r^2 v_{pn}(r, \theta) &= f_n(r, \theta), \\
v_{pn}(a, \theta) &= 0, v_{pn}(b, \theta) = 0, \quad \omega_0 < \theta < \omega_1, a < r < b, \\
a) \quad v_{pn}(r, \omega_j) &= g^j_p(r), \\
b) \quad v_{pn}(r, \omega_j) + hv_{pn}(r, \omega_j) &= g^j_{pn}(r), \\
c) \quad v_{pn}(r, \omega_j) &= g^j_{pn}(r), j = 0, 1.
\end{align*} \quad (4)
\]

The following notations are introduced here:

\[
\begin{align*}
-\nabla f(r, \theta) &= \frac{\sin \theta f(r, \theta)}{\sin \theta} - \frac{n^2 f(r, \theta)}{\sin^2 \theta}, & s^2 &= \frac{p}{k}, \quad k = 0, 1, 2
\end{align*}
\]

Let us apply the integral transformation to the boundary value problem (4), denoting the corresponding transform of the desired function in the form:

\[
v_{pnk}(r) = \int_{\omega_0}^{\omega_1} \sin \theta \varphi_1(\theta, v_k) v_{pn}(r, \theta) d\theta, k = 0, 1, 2, \ldots, \quad (5)
\]

and similarly transforms of given functions.

As a result, the boundary value problem (4) will take the form:

\[
\begin{align*}
L_s v_{pnk} \equiv \left[r^2 v_{pnk}(r)\right] - v_{pnk}(r) - r^2 s^2 v_{pnk}(r) &= f_{pnk}(r) - S_k(r, \omega), \\
\varphi_1(\theta, v_k) &= v_{pnk}(a) = v_{pnk}(b) = 0, \\
S_k(r, \omega) &= \left[\varphi_1(\theta, v_k) \sin \theta v_{pnk}(r, \theta)\right]_{\omega_0}^{\omega_1} - \left[\varphi_1(\theta, v_k) \sin \theta v_{pnk}(r, \theta)\right]_{\omega_1}^{\omega_0}.
\end{align*} \quad (6)
\]

At the same time, the expression for \(S_k(r, \omega)\) is decoded depending on the type of boundary conditions a), b) and c) in (4). This depends on which equation \(v_k\) should be found from, and the type of function \(\varphi_1(\theta, v_k)\). So, in the case of boundary condition a), instead of \(\varphi_1(\theta, v_k)\) in (4), the function \(\varphi_1(\theta, v_k)\) defined by formula (7) should be used:

\[
\varphi_1(\theta, V_k) = P^m_V(\cos \theta) Q^m_V(\cos \omega_1) - P^m_V(\cos \omega_1) Q^m_V(\cos \theta), \quad (7)
\]

where \(P^m_V(\cos \theta), Q^m_V(\cos \theta)\) are linearly independent solutions of the differential equation of the Sturm-Liouville boundary value problem [10], and the numbers \(V_k\) are found from the equation:

\[
\varphi'(\theta, V_k) + \cot \theta \cdot \varphi'(\theta, V_k) + [V_k(V_k + 1) - m^2 \csc^2 \theta] \varphi(\theta, V_k) = 0. \quad (8)
\]

and the expression \(S_k(r, \omega)\) from (6) turns into the following:

\[
S^k_s(r, \omega) = \sum_{j=0}^{1} \sin \sigma_j \varphi_1(\omega_j, v_k) g^j_{pn}(r). \quad (9)
\]

In the case of boundary conditions b) and c), instead of the functions \(\varphi_1(\theta, v_k)\) in (5), the functions \(\varphi_0(\theta, v_k)\) and \(\varphi_c(\theta, v_k)\), which are determined respectively by the formulas:

\[
\varphi_0(\theta, V_k) = P^m_V(\cos \theta) L^1_k Q^m_V(\cos \omega_1) - Q^m_V(\cos \omega_1) L^1_k P^m_V(\cos \theta), \quad (9)
\]

This eigenfunction of the Sturm-Liouville boundary value problem [10]:

\[
\tilde{T}(\theta) + \cot \theta \cdot \tilde{T}(\theta) = -\left[\frac{1}{4} + \frac{m^2}{\sin^2 \theta}\right] \tilde{T}(\theta) = 0, \quad \omega_0 < \theta < \omega_1,
\]

will satisfy the boundary conditions:

\[
\varphi_0(\omega_j, V_k) + h_j \varphi_0(\omega_j, V_k) = 0, \quad j = 0, 1.
\]

When \(h_j = 0, j = 0, 1\) we obtain the eigenfunction \(\varphi_c(\theta, V_k)\) of the boundary value problem in the following form:

\[
\varphi_c(\theta, V_k) = P^m_V(\cos \theta) \frac{d \varphi^m_V(\cos \omega_1)}{d \omega_1} - Q^m_V(\cos \theta) \frac{d \varphi^m_V(\cos \omega_1)}{d \omega_1}. \quad (10)
\]

It satisfies the boundary condition \(\varphi_c(\omega_j, V_k) = 0, j = 0, 1, \) and the numbers \(V_k\) should be found from the equation:

\[
\Delta^m_k \equiv \Omega^m_{V_k}(\omega_0, \omega_1) = 0, \quad k = 0, 1, 2, \ldots \quad (11)
\]

Integral transformations based on the Sturm-Liouville problem are defined by the following expressions [10, 11]:
\[
g_k^m = f_{\alpha_0}^s \sin \theta \cdot q_\alpha(\theta, V_\kappa) g(\theta) d\omega, \quad e = a, b, c,
\]
\[
g(\omega) = -\frac{g_{\kappa}^s q_\alpha(\theta, V_\kappa)}{\sigma_{\kappa k}(\omega_0, \omega_1)} \quad \omega_0 \leq \theta \leq \omega_1.
\]

The asymptotic formula for finding \( V_k \) has the form:
\[
V_k = \gamma k - \frac{3}{2}, \quad \gamma = \pi (\omega_1 - \omega_0)^{-1}.
\]

The formula for \( S_k(r, \omega) \) should be replaced by the following expressions:
\[
\begin{align*}
\left\langle S_k^p(r, \omega) \right\rangle &= -\sum_{j=0}^{1} \frac{\phi_b(\omega j v_k)}{\phi_c(\omega j v_k)} \left| g_{pn}^s (r) \sin \omega j \right| ,
\end{align*}
\]

Thus, in all three cases of boundary conditions \( S_k(r, \omega) \) in (6) is a known function and the solution of the initial boundary value problem (1) is reduced to the solution of the one-dimensional self-adjoint boundary value problem (6). To solve Green's function \( G_n(r, \rho) \) of the boundary value problem (6) should be constructed. It can be done using the technique outlined in [10, 11], taking into account that the whole system of solutions \( y_0(r) \) and \( y_1(r) \) of the differential equation (6) are modified Bessel functions:
\[
y_0(r) = r^{-1/2} l_{v+1/2}(rs), \quad y_1(r) = r^{-1/2} K_{v+1/2}(rs),
\]
where Vronsky determinant \( W(y_0, y_1) = -r^2 \) according to the formula [12].

After performing the operations provided by the mentioned method, we will find:
\[
G_N(r, \rho) = \frac{\sqrt{\Delta}}, \quad \Delta_N(a, b) = l_{v+1/2}(as) K_{v+1/2}(bs) - l_{v+1/2}(bs) K_{v+1/2}(as),
\]
\[
\sqrt{br} \psi_0(r) = K_{v+1/2}(bs) l_{v+1/2}(rs) - l_{v+1/2}(bs) K_{v+1/2}(rs),
\]
\[
\sqrt{br} \psi_1(r) = l_{v+1/2}(as) K_{v+1/2}(rs) - K_{v+1/2}(as) l_{v+1/2}(rs).
\]

Here \( \nu \) should be replaced by \( \nu_k \). Using the constructed Green's function (13), we can find the transformant, and it will have different names depending on the boundary condition in (4):
\[
\begin{align*}
\left\langle u_{pnk}^a(r) \right\rangle &= \int_a^b G_N(r, \rho) \left[ f_{pnk}(\rho) - \sum_{j=0}^{1} \sin \omega j \right] \frac{\phi_a(\omega j, v_k)}{\phi_a(\omega j, v_k)} \left| g_{pnk}^s (\rho) \right| d\rho ,
\end{align*}
\]

After inverting the found transformants, we will find the solution of boundary value problems (4) using formula (14):
\[
\begin{align*}
u_{pnk}(r, \theta) &= -\sum_{k=0}^{\infty} \frac{u_{pnk}^a(r) \psi_a(\theta, v_k)}{\sigma_{pnk}^a (\omega_0, \omega_1)} , \quad e = a, b, c.
\end{align*}
\]

In order to obtain the solution of the original initial-boundary value problems (1), the found Fourier transforms (3) and Laplace transforms (2) should be converted according to the known transformation formulas, taking into account that \( m = |n| \).

Research results

We will examine the adequacy of the built model to ensure the quality characteristics of the surface layer using the example of grinding conical products made of 12X2H4BA steel, the active layer of which is subject to heat treatment. Physical and mechanical characteristics of steel: \( G = 6.13 \times 10^9 \text{N/m}^2 \) is the shear modulus; \( \nu = 0.27 \) is the Poisson's ratio; \( \overline{v}_t = 11.6 \times 10^{-6} \) is the temperature coefficient of linear expansion; \( a_c = 16 \times 10^{-5} W/m^2 \times \text{degrees} \) is the coefficient of thermal conductivity; \( \lambda = 22.2 W/m \times \text{degrees} \) is the thermal conductivity coefficient. The tool is a solid circle 24А25 CM18K5 ПП 250×75×20. Processing modes: \( V_\alpha = 16 m/min \) is the speed of the part; \( P_\alpha = 27 H; V_\text{rot} = 30 m/s \) is the speed of the grinding wheel; \( L_k = 2l = 1.58 \times 10^{-3} m \) is the length of the arc of contact of the tool with the processed surface; \( t_{\text{grind}} = 0.01 mm \) is the grinding depth; \( S_n = 31.6 \times 10^{-6} m^2 \) is the contact area of the tool with the processed surface. The geometry of conical products: \( r = a = 0.03 m, r = b = 0.06 m, L = 0.09 m \). The contact temperature was calculated according to formula (14). In Fig. 2 shows the temperature field formed when grinding the working surface of conical products. Analysis of the simulation results shows that the temperature of the processed surface increases as the processing tool ap-
approaches the conical surface to a smaller diameter. This result is explained by the fact that heat flows into the narrower part of the conical surface.

This area of conical products’ machined surface is most prone to defect formation during finishing operations. Therefore, when assigning treatment modes for such surfaces, they should be assigned with the condition that when the processing tool approaches a narrower part of the surface, the temperature formed on it should not exceed the permissible values that ensure the required quality.

Conclusions

A model has been developed for determining the temperature field formed in the surface layer of complex profiled products during finishing operations, which allows, due to functional connections with technological parameters, to ensure the required temperature level on the processed surface in order to avoid the formation of defects such as burns and cracks on it. Analysis of the simulation results shows that the temperature on the processed surface increases as the processing tool approaches the narrowed surface to a smaller cross-sectional area. This area of the processed surface of complex profiled products is most prone to defect formation during finishing operations. Therefore, when assigning treatment modes for such surfaces, they should be assigned with the condition that when the processing tool approaches a narrower part of the surface, a temperature is formed, which should be within the permissible values that ensure the required quality.

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У РОБОТІ РОЗГЛЯДАЄТЬСЯ МОДЕЛЬ ТЕМПЕРАТУРНОГО ПОЛЯ, ЯКЕ ФОРУМУЄТСЯ В ПОВЕРХНІШЕМУ ШАРИ СКЛАДНО ПРОФІЛЬНИХ ВИРОБІВ ПРИ РОБОТІ ЇХ НА ФІНІШНИХ ОПЕРАЦІЯХ. ІЗ ЗАСТОСУВАННЯМ ЦІХ ОПЕРАЦІЙ ПОВ'ЯЗАНА ПОВЕРХНЯ ПІД ПЛЮСОМ МЕХАНИЧНИМ СВЯЗАНИМ З ДІЕЛЕКТРИКОМ РІЗЬБИ, ІЗ ОСНОВНИМ ФАКТОРІВ ЗВ'ЯЗКУ ТЕХНОЛОГІЧНИХ ПАРАМЕТРІВ З ТЕМПЕРАТУРОЮ ЯКІСНІ ХАРАКТЕРИСТИКАМИ РОБОЧИХ ПОВЕРХОНЬ СКЛАДНО ПРОФІЛЬНИХ ВИРОБІВ ПРИ МЕХАНІЧНІЙ ОБРОБЦIУ

УПРАВЛІННЯ ЯКІСНИМИ ХАРАКТЕРИСТИКАМИ РОБОЧИХ ПОВЕРХОНЬ СКЛАДНО ПРОФІЛЬНИХ ВИРОБІВ ПРИ МЕХАНІЧНІЙ ОБРОБЦI

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У роботі розглядається модель температурного поля, яке формується в поверхневому шарі складно профільних виробів при обробці їх на фінішних операціях. Із застосуванням цих операцій пов'язана поверхня під плосом механічним, який зв'язаний з діелектриком різьби, і з основним фактором зв'язку технологічних параметрів з температурою якісні характеристики робочих поверхонь складно профільних виробів при механічній обробці.

Ключові слова: складно профільні вироби, модель температурного поля, дефекти, якість поверхневого шару, фінішні операції, адекватність.
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