Development of Quality Criteria for the Surface Layer of Cylinders with Wear-Resistant Coatings

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Abstract. Criteria for technological support of the quality of finishing the surface layer of cylinders with wear-resistant coatings using composite materials have been developed. In the process of finishing surfaces from wear-resistant materials there are defects on the production surfaces, which reduce the performance properties of products. After analyzing the causes of chips and cracks on the production surfaces, it has been identified that the occurrence of various defects is associated with thermal processes which accompanied the machining of products. During diamond abrasive machining, the structural influence of inhomogeneous surface layers of manufactured products leads to the appearance and development of various defects, such as cracks and chips. To determine the thermomechanical state of the working surface of the cylinder with a wear-resistant composite coating, which has partial delamination areas during the deposition process, an analytical model is available. On the basis of composite coatings Ni/Ni-TiO_2, obtained by the method of electrochemical deposition, tribocorrosive studies were carried out. To ensure the required quality of wear-resistant coatings, rational treatment regimes of the respective groups were applied, as well as the instrument characteristics, taking into account hereditary defects when applying these coatings.

Keywords: Quality criteria · Durability · Reliability · Wear resistance · Delamination · Thermomechanical processes · Diamond abrasive processing · Tribocorrosion

1 Introduction

Analyzing the literature on tribology we revealed that the operating costs of all technological cycles of machines exceed the costs of producing new equipment. In developed countries, the losses caused by friction and wear, account for 4…5% of national income [1–4].

The wear resistance of parts that work in conditions of sliding friction and have cylindrical surfaces, determines the durability of many machines. Solving the problem of wear resistance of machine parts will lead to an increase in machine durability. Thus, the current area of research today is to increase the wear resistance of machine parts [5–8].

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2 Literature Review

Every so often, qualitative modification of the structural composition in all the main elements of the material is not taken into account when protecting related parts from production and improving the quality of products. Therefore, this problem is solved taking into account modification of the composite material surface layer, because in this case only the surface layer is strengthened. Under the hardening of the surface layer is understood to increase the mechanical characteristics such as hardness [1, 3, 5, 9, 10].

Various methods of hardening have been proposed in a large number of works devoted to improving the mechanical characteristics of rubbing surfaces. Nowadays the use of modern methods for producing wear-resistant coatings using composite materials based on compounds such as oxides, nitrides, and carbides is a promising direction for the development of surface-strengthening technologies. Creation of hardening coatings from dissimilar materials leads to the formation of a fundamentally new composite material of the surface layer, which has not only high strength, but also sufficient ductility, as well as increased wear resistance, and not only to the modification of the surface layer [2, 3, 7, 11, 12].

3 Research Methodology

We will study thermomechanical processes in products with reinforcing composite coatings during processing and operation to determine the conditions for the formation of various defects such as cracks, chips and delaminations of coatings from the base material, as well as their elimination, taking into account the technological parameters of finishing, hereditary defects arising during coating operations with the consideration of the physico-mechanical state of the surface layer.

Coating areas with partial delamination are formed on the working surface of the cylinder, with the forward movement of the piston, which has a non-circularity δ (or R_a roughness) in the area $(-\alpha;\ \alpha)$. Peeling of the reinforcing composite coating from the matrix of a cylindrical surface occurs under the action of working tangential stresses.

We find the parameters of delamination at which the destruction of the composite coating occurs, taking into account the roughness of the working surface of the cylinder, its geometrical error, as well as the physico-mechanical properties of the cylinder material and reinforcing wear-resistant composite coating.

The stress-strain state of the cylinder-coating system is depicted in the analytical model (Fig. 1).

Let $U_z^{(i)}, U_r^{(i)}, U_\phi^{(i)}$ denote the cylinder – coating system points in the direction of the corresponding coordinates of the cylindrical system $(z,\ r,\ \varphi)$. Since under the action of the technological stresses of the clutch τ_{rz} in the system 1–2 (Fig. 1), the displacements $U_z(r,\varphi)$ are different from zero, the Lame equations are written in the form:

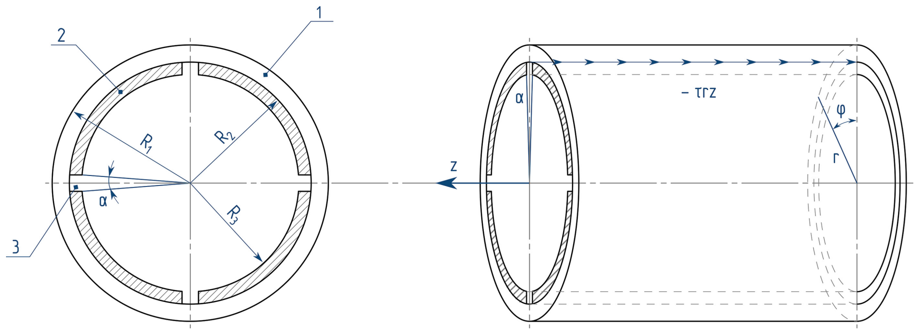

Fig. 1. The calculation scheme for determining the stress-strain state: 1 – the cylinder body; 2 – the body of the coating; 3 – areas of absence (exfoliation) of the coating.

$$\mu^{(i)}\nabla^2 U_z^{(i)} = \mu^{(i)}\left(\frac{\partial^2 U_z^{(i)}}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial U_z^{(i)}}{\partial r} + \frac{1}{r^2}\cdot\frac{\partial^2 U_z^{(i)}}{\partial \phi^2}\right) = 0. \quad (1)$$

Or $U_z(r,\phi) = W(r,\phi), 0 \le r \le R_z, -\pi \le \phi \le \pi$ the Eq. (1) reshaped as:

$$\Delta W(r,\phi) = \frac{\partial^2 W}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial W}{\partial r} + \frac{1}{r^2}\cdot\frac{\partial^2 W}{\partial \phi^2} = 0. \quad (2)$$

Boundary conditions:

$$\tau_{rz}|_{z=R_2} = 0, \quad (3)$$

$$\tau_{rz}(R_1 - 0,\phi) = \tau_{rz}(R_1 + 0,\phi) = -\tau_{\text{сц}}, |\phi| \le \alpha. \quad (4)$$

Defect conditions:

$$W(R_1 - 0,\phi) - W(R_1 + 0,\phi) = \begin{cases} \chi(\phi), -\alpha \le \phi \le \alpha \\ 0, |\phi| > \alpha \end{cases}. \quad (5)$$

At the boundary of the cylinder-coating system, conditions of tangential stresses continuity:

$$\tau_{rz}(R_1 - 0,\phi) = G_1\frac{\partial W}{\partial r}\bigg|_{r=R_1-0}; \tau_{rz}(R_1 + 0,\phi) = G_2\frac{\partial W}{\partial r}\bigg|_{r=R_1+0},$$

$$\tau_{rz}(R_1 - 0,\phi) - \tau_{rz}(R_1 + 0,\phi) = G_1\tfrac{\partial W}{\partial r}\big|_{r=R_1-0} - G_2\tfrac{\partial W}{\partial r}\big|_{r=R_1+0} =$$
$$= G_1 < W'(R_1,\phi) > - (G_2 - G_1)\tfrac{\partial W}{\partial r}\big|_{R_1} = 0.$$

From where we obtain:

$$< W'(R_1, \phi) \geq hW'(R_1 + 0, \phi), h = \frac{G_2 - G_1}{G_1}. \quad (6)$$

The antiplane problem for a cylinder coating system, which takes into account defects such as delamination, arising from the roughness of the working surface of the cylinder or its non-circularity, is presented in the form of Eqs. (1)–(6).

We use Finite Fourier transforms [13] with the variable φ defined by the following formulas to solve the problem (1)–(6):

$$W_n(r) = \frac{1}{2\pi}\int_{-\pi}^{\pi} e^{-\mathrm{in}\phi} W(r, \phi) d\phi, W(r, \phi) = \sum_{n=-\infty}^{\infty} e^{\mathrm{in}\phi} W_n(r), \quad (7)$$

$$\frac{1}{2\pi}\int_{-\pi}^{\pi} W^{(k)}(r, \phi) e^{-\mathrm{in}\phi} d\phi = (\mathrm{in})^k W_n(r).$$

We obtain a one-dimensional discontinuous boundary value problem:

$$L_2[W_n(r)] = rW_n''(r) + W_n'(r) - \frac{n^2}{r} W_n(r) = 0. \quad (8)$$

With boundary conditions:

$$W_n(0) = A < \infty, W_n'(R_2) = 0, \quad (9)$$

At defect conditions:

$$W_n(R_1 - 0) - W_n(R_1 + 0) \leq W_n(R_1) \geq \chi_n, \quad (10)$$

And the conditions of continuity of tangential stresses in the transition through the boundary-cylinder coating system:

$$< W_n'(R_1) \geq hW_n'(R_1 + 0). \quad (11)$$

Discontinuous problem solution can be obtained as [13, 14]:

$$W_n(r) = \int_0^{R_2} G(r, \rho) f(\rho) d\rho + \sum_{j=0}^{1} r_j W_{n,j}(r), \quad (12)$$

construction of the Green function $G(r, \rho)$. In addition, the Green function for $f(\rho)$ n this equation does not depend on $f(\rho) = 0$. The Green function must be symmetric, provided that the operator L_2 is self-adjoint, that is, $G(r, \rho) = G(\rho, r)$. The construction of the Green function is simplified by this function.

Stress intensity factor (SIF) at the edges of the detachment $\phi = -\alpha - 0$ and at $= \alpha + 0$ is of practical interest in this problem. That is:

$$K_{III}^{-} = \lim_{\phi \to -\alpha - 0} \sqrt{2\pi(-\alpha - \phi)}\tau_{rz}(R_1, \phi), \tag{13}$$

$$K_{III}^{+} = \lim_{\phi \to -\alpha + 0} \sqrt{2\pi(\phi - \alpha)}\tau_{rz}(R_1, \phi), \tag{14}$$

Or, taking into account the replacement $\phi = \alpha\phi'$ and symmetry, these relations will take the form:

$$K_{III}^{\mp} = \lim_{\phi' \to \mp 1 \mp 0} \sqrt{2\pi\alpha(\mp 1 \mp \phi)}\tau_{rz}(R_1, \alpha\phi')$$

and wherein:

$$\tau_{rz}(R_1, \alpha\phi') = \frac{-(h+1)G_1}{2\pi^2(2+h)\alpha} \times \frac{d^2}{d\phi'^2} \int_{-1}^{1} X(\alpha\phi')\left[\ln\frac{1}{|\phi' - \psi'|} + R^*(\alpha\phi', \alpha\psi')\right] d\psi'. \tag{15}$$

The regular part, by virtue of its continuity, will not make any contribution to the transformant of the SIF and, therefore, it can be ignored. As a result, we obtain:

$$K_{III}^{\mp} = \lim_{\phi' \to \mp 1 \mp 0} \sqrt{2\pi\alpha(\mp 1 \mp \phi')} A \frac{d^2}{d\phi'^2} \int_{-1}^{1} X(\alpha\phi') \ln\frac{1}{|\phi - \psi'|} d\psi',$$

$$A = -\frac{(h+1)G_1}{2\pi^2\alpha(2+h)}.$$

Substituting (5), we obtain:

$$K_{III}^{\mp} = \lim_{\phi' \to \mp 1 \mp 0} \sqrt{2\pi\alpha(\mp 1 \mp \phi')} \times A\frac{d^2}{d\phi'^2} \sum_{m=1}^{\infty} C_m \int_{-1}^{1} \sqrt{1 - (\alpha\psi')^2} U_m(\alpha\phi') \ln\frac{1}{|\phi' - \psi'|} d\psi'. \tag{16}$$

To complete the limit transition (16) it is necessary to continue the spectral relation [13] for the interval $|\phi'| > 1$.

To do this, we use the formulas (13), (14) and (16). We obtain:

$$A^{-1}K_{III}^{\mp} = \sqrt{\frac{\pi\alpha}{2}} \sum_{m=1}^{\infty} (-1)^{m+1} \sqrt{m+1}\,\Psi_m.$$

Where: $\Psi_m = 2^{m+1}(m+1)\left[\frac{m+1}{m!}1F_1\left(\frac{3}{2}+m, m+2; \frac{3}{2}\right) - 1F_1\left(\frac{3}{2}+m, m+1; \frac{1}{2}\right)\right]$, $|\phi'| > 1; 2F_1\left(\frac{3}{2}+m, m+1; \frac{1}{2}; \frac{\phi'+1}{\phi'-1}\right)$ - generalized hypergeometric function [14].

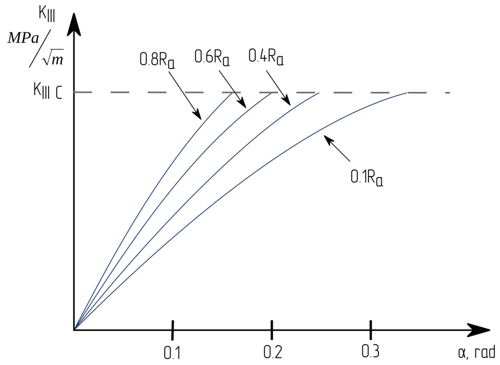

Fig. 2. SIC dependency onto detachment angle α and cylinder surface's working area roughness *Ra*.

Using the correlation of the roughness of the working area of the cylinders with the value (−α, α) or the delamination area of the coatings for various finishing operations such as grinding finishing, fine grinding and polishing, we find the SIF dependence $K_{III} = f(\alpha)$ (Fig. 2).

We find the calculated values of K_{III} depending on the magnitude of the defect (−α, α) delamination by the given values of τ_{adh} of the adhesion of the coating to the cylindrical surface, at different values of the tool surface roughness (Fig. 2).

4 Results

The roughness of the coatings when applied to the working surfaces must be *0.8* $\leq$ *Ra* $\leq$ *1.2* to ensure the necessary reliability and durability of a cylindrical group with a reinforcing composite coating. Such roughness values can be achieved by applying fine grinding and subsequent fine polishing. In this case, the expected delamination of the coating *M (α)* will remain within the capabilities of the technological process of applying a reinforcing coating, in which the equilibrium state of the delamination coating will be maintained by technological stresses.

The relationship between the relative distance of the delamination areas and the stress intensity factor is shown in Fig. 3. The stress intensity can reach significant values, without disturbing the equilibrium state, since the distance *d* increases, and the coefficient $2\alpha/d$ decreases.

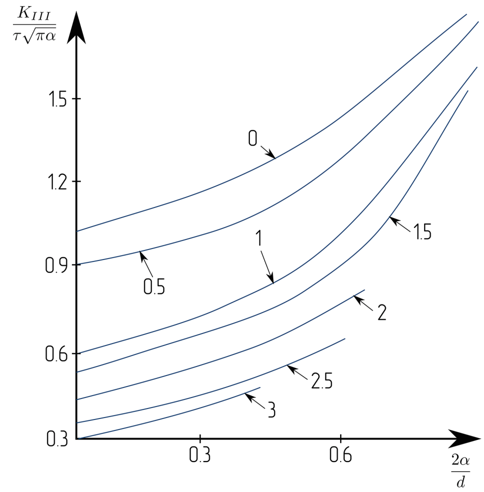

Fig. 3. Dependency of SIC $\frac{K_{III}}{\tau\sqrt{\pi\alpha}}$ at longitudinal displacement.

The stress intensity factor K_{III} may change due to the roughness of the working surface of the cylinder, which leads to the emergence of a system of areas of the detachment of the hardening coating from the cylinder matrix (Fig. 4), their mutual influence, as well as operating conditions [15].

The above analytical model was confirmed by tribocorrosion studies performed on Ni/Ni-TiO_2-based hardening composite materials, which were obtained by electrochemical deposition.

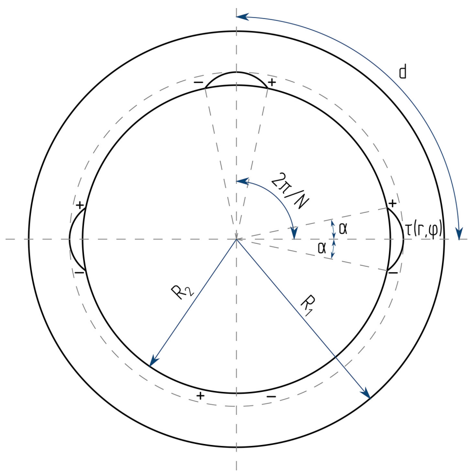

Fig. 4. Calculation scheme for researching the reciprocal influence between detachment areas and stress intensity K_{III}.

As a result of the increase in the load and constant exposure time to the Ni coating, the increase in the depth and width of the cracks occurs. At the same time, with increasing load and constant exposure time, the crack profile for Ni-TiO_2 coating does not change. When conducting tribocorrosion studies of Ni/Ni-TiO_2 materials, a positive effect of TiO_2 particles in the coating was revealed, and it was also determined that TiO_2 particles significantly increase the protective functions of the composite coating against mechanical abrasion. Increasing the load on the crack profile for Ni-TiO_2 coating of such a value does not matter (Fig. 5: a, b) [16].

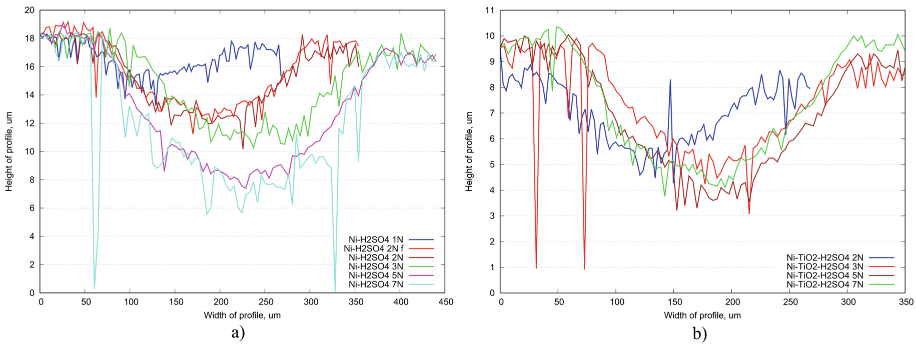

Fig. 5. The effect of particles on the wear resistance of an electrochemical deposited coating: (a) nickel coating, (b) Ni-TiO_2 coating.

The adequacy of the constructed model was tested experimentally on samples of duplex steel (duplex 2463), on the surface of which a wear-resistant coating based on Ni-TiO_2 with a thickness of 0.4–0.6 mm was deposited by electrochemical deposition. To calculate the parameters of defect-free processing, the following physicomechanical characteristics were used: *KS = 2 MPa m1/2; α = 8.58 K−1; G = 168 GPa.*

Given the randomness of the size and distribution of defects in the body, it is necessary to establish the law of the probability distribution of these defects. According to the analysis of microsections of the working surfaces samples under study, before the grinding operation, there was a distribution function of the sizes of defects, which determines the relative frequency *n/m* of the appearance of this size in the area of contact of the wheel with the part (n_i – sum of frequencies of l_i sizes that fell in interval, *m* – length of the partial interval) for each value.

Experimental studies of the distribution of defects – air pores showed that the defect function satisfies the normal distribution (Fig. 6).

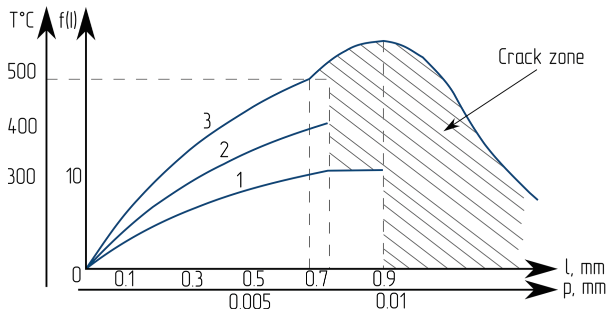

Fig. 6. Calculated and experimental values of the limiting sizes of crack-like defects when grinding wear-resistant coatings based on Ni-TiO_2 coatings in circles: 1 - diamond BCP B1 granular 100/80; 2 - circle made of synthetic diamonds ASC 250/200 MO 16 100%; 3 - circle electrocorundum 24A 25 CM/8K5.

The probability of destruction has been calculated under the assumption that the individual air pores do not interact with each other. Essentially, based on the "weakest link" hypothesis.

To check the criterion for the absence of grinding cracks on the surface to be treated, the contact temperature in the grinding zone was determined. Taking into account the fact that the dominant factor of the grinding modes affecting the thermal stress of the grinding process is h – the depth of grinding, the dependence $T = f(h)$ was found. The remaining modes were selected from the conditions of maximum performance while maintaining the required quality. So, when grinding the coating with diamond ASRB1 with grit 100/80 (curve 1), circles with synthetic diamonds ASC 250/200 MO 16 100% (curve 2), with circles from electrocorundum 24A25CMI8K5 (curve 3), the remaining grinding modes were selected as follows: $V_g = 0.17$ m/s; $V_{cr} = 30$ m/s; $S_{non} = 5$ mm.

Experimental studies have shown that circles from natural and synthetic diamonds have a stable cutting ability, high dimensional stability, a relatively low temperature in the grinding zone, which also affects the absence of cracks at large grinding depths (compared to 24A25CM18K5 circles) [12].

It was found that grinding the coating with diamond ASRB1 with 100/80 grain (curve 1, Fig. 6) with diamond grit was the most productive while maintaining the required quality.

Since the porosity (size and density) during electrochemical deposition of this coating is controlled by the deposition rate and coating properties, as well as other parameters of the deposition process, an appropriate selection of grinding modes and wheel characteristics can avoid the appearance of grinding cracks on the coated surface of cylinders.

The results of the study of the microhardness treated surface and the microstructure of the surface layer indicate that in the range of the studied modes there are no structural changes after grinding the wear-resistant Ni-TiO_2 coating.

The nature of crack formation of coatings depending on the characteristics of the wheels, cutting conditions can be followed using the criterion of the limiting heat flux

q^*. The heat flux entering the part during grinding is not only a function of cutting modes—V_g, V_{cr}, t_{shl}, P_Z, but also the characteristics of wheels—the hardness of the bond, the graininess of the properties of cutting grains, their hardness, etc. Its value of the limiting heat flux at which coatings containing defects of $2l$ in size will not be subject to cracking [9, 11, 12, 17].

5 Conclusions

The criteria for the quality of the surface layer in the final processing of the working surfaces of cylinders using coatings of wear-resistant materials have been developed. The analytical model of the thermomechanical state was developed for the working surface of the cylinder with hardening wear-resistant composite coating, which has areas of partial delamination during the deposition and processing processes. To confirm the analytical model, tribocorrosion studies of Ni/Ni-TiO_2-based composite materials obtained by electrochemical deposition were carried out. A rational choice of processing modes, instrument characteristics taking into account hereditary defects when applying coatings for technological quality assurance of the finishing of cylindrical surfaces with wear-resistant coatings based on Ni-TiO_2 have been presented.

References

1. STP MDV 04.87. Wear resistant coatings. Vacuum-plasma application technology. Enterprise standard. Kharkov (1987)
2. Storozhev, V.P.: Causes and patterns of gradual failures of the main tribological objects of the ship's energy system and increase of their resource. TOC, Odessa (2002)
3. Levchenko, A.A., Evdokimov, V.D.: The influence of technological heredity in the production of spare parts on hydrogenation of parts and their wear resistance. Technol. Issues **2**, 23–28 (2006)
4. Garkunov, D.N., Kornik, P.I.: Types of Friction and Wear. Operational Damage to Machine Parts. MSHA, Moscow (2003)
5. Ueda, T., Hosokawa, A., Yamamoto, A.: Measurement of grinding temperature using infrared radiation pyrometer with optical fiber. J. Eng. Ind. **108**(4), 247–251 (1986)
6. Balohonov, R.R.: Surface Layers and Internal Interfaces in Heterogeneous Materials. SO RAN, Novosibirsk (2006)
7. Sun, Y., Flis-Kabulska, I., Flis, J.: Corrosion behaviour of sediment electro-codeposited Ni–Al2O3 composite coatings. Mater. Chem. Phys. **145**(3), 476–483 (2014)
8. Aruna, S., William Grips, V., Rajam, K.: Ni-based electrodeposited composite coating exhibiting improved microhardness, corrosion and wear resistance properties. J. Alloys Compd. **468**(1–2), 546–552 (2009)
9. Usov, A.V.: Mathematical modeling of control processes for the coating of structural elements based on SIE. J. Mech. Eng. **13**(1), 98–109 (2010)
10. ASTM B254-92(2014). Standard Practice for Preparation of and Electroplating on Stainless Steel. ASTM International, West Conshohocken (2014)
11. Oborskiy, G.A., Daschenko, A.F., Usov, A.V., Dmitrishin, D.V.: System Modeling. Astroprint, Odessa (2013)

12. Yakimov, A.V., Slobodyanik, P.T., Usov, A.V.: Thermal Physics Machining. Lyibid, Kiev (1991)
13. Gradshteyn, I.S., Ryizhik, I.M.: Tables of Integrals, Sums, Series and Products. Fizmatgiz, Moscow (1961)
14. Popov, G.Y.: Concentration of Elastic Stresses Near the Dies of Cuts of Thin Inclusions and Reinforcements. Nauka, Moscow (1982)
15. Panasyuk, V.V. (ed.): Fracture Mechanics and Strength of Materials. Nauk. Dumka, Kiev (1988)
16. Kunitsyn, M.V., Usov, A.V.: Tribocorrosion research of NI-Al2O3/TIO2 composite materials obtained by the method of electrochemical deposition. Mod. Technol. Mech. Eng. **12**, 61–70 (2017)
17. Parkus, G.: Unsteady Temperature Stresses. Fizmatlit, Moscow (1963)