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THE POSSIBILITIES OF INCREASING THE RELIABILITY AND DURABILITY OF A CYLINDRICAL GROUP BY TECHNOLOGICAL METHODS

А.В. Усов, М.В. Куніцин. **Підвищення надійності робочих поверхонь циліндров технологічними методами.** Розглянуто можливості підвищення надійності і довговічності циліндричної групи технологічними методами зокрема використання покриттів з зносостійких матеріалів на робочі поверхні циліндрів. Фінішні методи обробки виробів зі зносостійкими покриттями призводять до утворення дефектів на оброблюваних поверхнях, що знижують експлуатаційні характеристики цих виробів. Аналіз причин утворення сколів та тріщин на оброблюваних поверхнях зазначених виробів показав, що поява цих дефектів пов'язана з тепловими процесами, які супроводжують механічну обробку. При цьому необхідно враховувати вплив структурної неоднорідності оброблюваного шару виробів на механізм зародження і розвитку дефектів типу тріщин під дією термомеханічних процесів, що супроводжують алмазно-абразивний процес шліфування. Розроблено аналітичну модель по визначенню термомеханічного стану робочої поверхні циліндра з зносостійким покриттям, що має ділянки часткового відшарування в процесі нанесення. Проведено трібокорозійне дослідження композиційних матеріалів на основі Ni/Ni-TiO_2, отриманих методом електрохімічного осадження.

Ключові слова: надійність, довговічність, трібокорозія. зносостійкість, відшарування, термомеханічні процеси, алмазно-абразивна обробка

A. Usov, M. Kunitsyn. **The possibilities of increasing the reliability and durability of a cylindrical group by technological methods.** The possibilities of increasing the reliability and durability of a cylindrical group by technological methods, in particular, the use of coatings from wear-resistant materials on the working surfaces of cylinders are considered. Finishing methods of processing products with wear-resistant coatings lead to the formation of defects on the surfaces to be treated, which reduce the performance characteristics of these products. An analysis of the causes of the formation and cracking on the surfaces of these products showed that the appearance of these defects is associated with the thermal processes accompanying the machining. In this case, it is necessary to take into account the influence of the structural heterogeneity of the workpiece layer on the mechanism of nucleation and development of defects such as cracks under the influence of thermomechanical processes accompanying diamond-abrasive processing. An analytical model has been developed to determine the thermomechanical state of the working surface of a cylinder with a wear-resistant coating that has areas of partial delamination during application. Tribocorrosive studies of composite materials based on Ni/Ni-TiO_2 obtained by electrochemical deposition are carried out.

Keywords: reliability, durability, tribocorrosion, wear resistance, detachment, thermomechanical processes, diamond-abrasive processing

Introduction. The analysis of studies in tribology showed that for the full life cycle of machines the operating costs are several times higher than the costs for manufacturing of new equipment. In developed countries the loss of funds from friction and wear and tear reaches 4...5 % of national income [1].

Increasing the durability of machines is directly related to the wear resistance of machine parts. Thus, increasing the wear resistance of machine parts is an actual direction of research. The durability of many machines is determined by the wear resistance of parts having internal cylindrical surfaces that operate under sliding friction conditions.

Analysis of research and publications. It is known that the task of increasing the wear resistance of a particular product often does not involve a qualitative modification of the structural composition of the material used throughout its entirety, but is transferred to a modification of the surface layer of the material, since the protection of the mating parts from wear is in some cases solved by surface hardening. In the general case, surface hardening is understood as an increase in the hardness of the working surface of the part, which makes it possible to increase the wear resistance [2, 3].

The increase in the mechanical characteristics of rubbing surfaces has been devoted to a large number of works. As a result various ways of hardening have been proposed. Promising areas of de-

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velopment of surface-hardening technologies involve the use of new methods for obtaining wear-resistant coatings, mainly using wear-resistant materials, i.e. Coatings based on compounds such as oxides, nitrides and carbides. The formation of reinforcing coatings from dissimilar materials not only leads to the modification of the surface layer, but also to the formation, in a number of cases, of a fundamentally new composite material of the surface layer possessing as high strength and sufficient ductility as well as an increased wear resistance [3 – 6].

Purpose of work is investigation of thermo mechanical processes in coated products during their processing and operation in order to determine the conditions for the formation of defects in the detachment of coatings from the base material and their elimination, taking into account the physical and mechanical state of the surface layer, the technological parameters of finishing and hereditary defects that arise during the coating process.

When the piston moves in a cylinder having a non-roundness δ (or Ra roughness) in the section (–α; α), zones of partial coating peeling are formed on its working surface. These areas under the action of shearing stresses can reach such values at which the coating peels off from the matrix of the cylindrical surface.

Statement of the main material. We shall find at what parameters the delamination associated with the roughness of the working surface of the cylinder and its geometrical error, as well as the physical and mechanical properties of the coating and the material of the cylinder, the coating itself is destroyed.

The calculation scheme for determining the stress-strain state of the cylinder-coating system is given in Fig. 1.

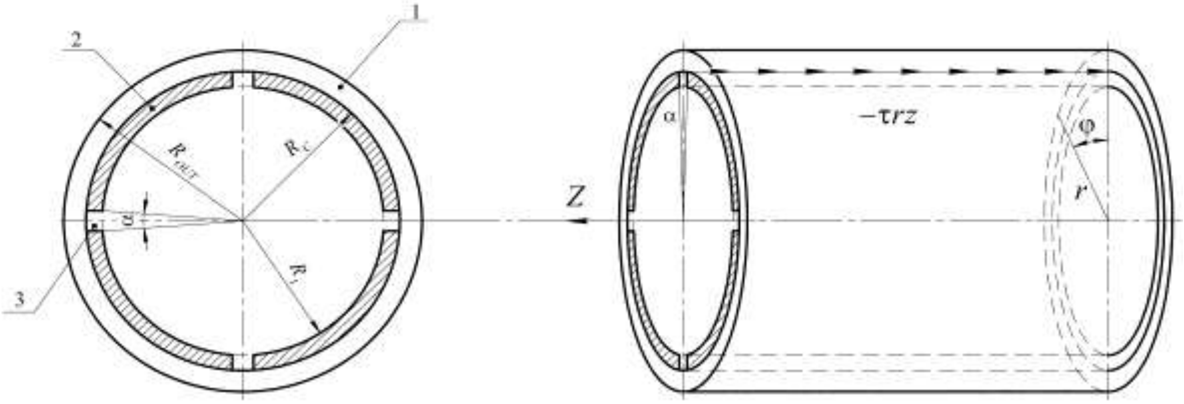


Fig. 1. The calculation scheme for determining the stress-strain state: 1 – the cylinder body; 2 – the body of the coating; 3 – areas of absence (exfoliation) of the coating

Shall we denote with $U_z^{(i)}$, $U_r^{(i)}$, $U^{(i)}$ displacements of cylinder coating system points towards the respective cylindrical coordinate system (z, r, φ). As under the influence of technological stress adhesion τ_{rz} at the matrix-coating system (Fig. 1: 1, 2) the displacement $U_z(r,\varphi)$ shall be nonzero, the Lame equation can be written as:

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

Or $U_z(r,\varphi) = W(r,\varphi)$, $\quad 0 \le r \le R_z$, $\quad -\pi \le \varphi \le \pi$ the equation (1) reshaped as:

$$\varDelta W(r) = \frac{\partial^2 W}{\partial r^2} + \frac{1}{r}\frac{\partial W}{\partial r} + \frac{1}{r^2}\frac{\partial^2 W}{\partial \varphi^2} = 0. \tag{2}$$

Boundary conditions:

$$\tau_{rz}\big|_{z=R_2} = 0, \tag{3}$$

$$\tau_{rz}(R_1-0,\varphi)=\tau_{rz}(R_1+0,\varphi)=-\tau_{rz},\ |\varphi|\le\alpha. \tag{4}$$

Defect conditions:

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

Conditions of tangential stresses continuity at the cylinder-coating boundary:

$$\tau_{rz}(R_1-0,\varphi)=G_1\left|\frac{\partial W}{\partial r}\right._{r=R_1-0};\ \tau_{rz}(R_1+0,\varphi)=G_2\left|\frac{\partial W}{\partial r}\right._{r=R_1+0},$$

$$\tau_{rz}(R_1-0,\varphi)-\tau_{rz}(R_1+0,\varphi)=G_1\left|\frac{\partial W}{\partial r}\right._{r=R_1-0}-G_2\left|\frac{\partial W}{\partial r}\right._{r=R_1+0}=$$

$$=G_1<W'\left(R_1,\varphi\right)>-(G_2-G_1)\left|\frac{\partial W}{\partial r}\right._{R_1}=0.$$

Where from we get:

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

Equations (1) – (6) constitute an antiplane problem for the cylinder-coating system based on the type of delamination defect, which occurs due to the cylinder working surface roughness or its non-roundness.

To solve the problem (1) – (6) we use the finite Fourier transform [7] at the variable φ, defined by the formulas:

$$W_n(r)=\frac{1}{2\pi}\int\limits_{-\pi}^{\pi}e^{\text{-in}}W(r,\varphi)d,\quad W(r,\varphi)=\sum_{n=-\infty}^{\infty}e^{\text{in}}W_n(r), \tag{7}$$

$$\frac{1}{2\pi}\int\limits_{-\pi}^{\pi}W^{(k)}(r,\varphi)e^{-\text{in}}d=(\text{in})^kW_n(r).$$

Thus getting a monoparametric boundary rupture problem:

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

With boundary conditions:

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

At defect conditions:

$$W_n(R_1-0)-W_n(R_1+0)\le W_n(R_1)\ge\chi_n, \tag{10}$$

$$\chi_n=\frac{1}{2\pi}\int\limits_{-\alpha}^{\alpha}\chi(\psi)e^{-\text{in}}d\psi,$$

And conditions of tangential stresses continuity at the cylinder-coating boundary crossing:

$$<W'_n(R_1)\ge hW'_n(R_1+0). \tag{11}$$

Discontinuous problem solution can be obtained as [7]

$$W_n(r)=\int\limits_0^{R_2}G(r,\ \rho)f(\rho)d\rho+\sum_{j=0}^{1}r_jW_{n,j}(r), \tag{12}$$

building a Green's function *G*(*r*, ρ). Moreover, the Green's function itself for *f*(ρ) does not depend here on (*f*(ρ)=0). Given self-adjointness of operator *L*₂ Green's function should be symmetric, i.e. *G*(*r*, ρ)=*G*(ρ, *r*). This feature simplifies building the Green's function.

The required Green's function for our problem shall be alike to:

$$G(r,\rho)=\begin{cases}\dfrac{1}{2nR_2^{2n}}r^n(\rho^n+R_2^{2n}\rho^{-n}),\ r\le\rho;\\[2mm]\dfrac{1}{2nR_2^{2n}}\rho^n(r^n+R_2^{2n}r^{-n}),\ \rho\le r.\end{cases}\tag{13}$$

We use the obtained Green's function shape to build the discontinued problem solution (8) – (11). The $G(r, \rho)$ should conform to (4) – (5). Then the discontinuity problem can be written down as:

$$W_n(r)=\int_0^{R_2}G(r,\,\rho)\,f(\rho)d\rho+R_1[hW_n'(R_1+0)G(r,\,R_1)-\chi_nG^{0,1}(r,\,R_1)].$$

After the corresponding transformations, the last expression is written as:

$$W_n(r)=R_1\left[hW_n'(R_1+0)\frac{1}{2nR_2^{2n}}\begin{Bmatrix}r^n(R_1^n+R_2^{2n}R_1^{-n}),\,r\le R_1\\R_1^n(r^n+R_2^{2n}r^{-n}),\ R_1\le r\end{Bmatrix}\right]-$$

$$\chi_n\begin{Bmatrix}\dfrac{r^n}{2R_2^{2n}}(R_1^{n-1}+R_2^{2n}R_1^{-n-1}),\,r\le R_1\\[2mm]\dfrac{R_1^{n-1}}{2R_2^{2n}}(r^n+R_2^{2n}r^{-n}),\,r\ge R_1\end{Bmatrix}.\tag{14}$$

Checking the compliance to (10) and (11) conditions, we verify the correctness of solution $W_n'(r)$ built with the variable r=R_1+0:

$$W_n'(R_1+0)=\frac{n(1-\gamma^{2n})}{2R_1\left[1+\dfrac{h}{2(1-\gamma^{2n})}\right]}\chi_n,\quad\gamma^{2n}=\left(\frac{R_1}{R_2}\right)^{2n}.\tag{15}$$

Considering (15) for $W_n'(R_1+0)$ and respective transformations, the searched transpositions at transformants $W_n(r)$ will be written as:

$$W_n(r)=\frac{\chi_n}{h(\gamma^{2n}-1)-2}\begin{bmatrix}\left(\dfrac{r}{R_1}\right)^n(\gamma^{2n}-1)(h+1),\,r\le R_1\\[2mm]\left(\dfrac{R_1}{r}\right)^n\left[\left(\dfrac{r}{R_2}\right)^{2n}+1\right],\,r>R_1\end{bmatrix}.\tag{16}$$

As $W(r,\varphi)$ and $\chi(\varphi)$ are non-even φ functions, let we proceed with finite Furrier's sin-transformations: $\tau(r,\varphi)$

$$W_n(r)=\frac{i}{\pi}W_n^s(r);\ W_n^s(r)=\int_0^{\pi}W(r,\,\varphi)\sin(n\varphi)d\varphi;$$

$$\chi_n=\frac{i}{\pi}\chi_n^s;\ \chi_n^s=\int_0^{\pi}\chi(\psi)\sin(n\psi)d\psi.\tag{17}$$

Using the reverse Furrier's sin-transformation we get their original searched transformations [8] and embodying with formula $\sin(n\varphi)\sin(n\psi)=\frac{1}{2}[\cos n(\varphi-\psi)-\cos n(\varphi+\psi)]$ with $i^2=-1,$ the expression $W(r,\varphi)$ can get the form:

$$W_n(r,\varphi)=\frac{1}{2\pi^2}\int_0^{\alpha}\chi(\psi)\left[\sum_{n=1}^{\infty}\frac{\cos n(\varphi-\psi)-\cos n(\varphi+\psi)}{2+h(1-\gamma^{2n})}\right]\times$$

$$\times\left\{\begin{matrix}\left(\dfrac{r}{R_1}\right)^n(\gamma^{2n}-1)(\chi+1), \;\; r\le R_1\\ \left(\dfrac{R_1}{r}\right)^n\left[\left(\dfrac{r}{R_2}\right)^{2n}+1\right], \;\; r>R_1\end{matrix}\right\}d\psi. \tag{18}$$

Now from the unfulfilled boundary conditions remain only the condition (5), describing the cylinder material-to-coating adhesion. Let we satisfy that condition:

$$\tau_{rz}(R_1-0,\varphi)=G_1\left(\frac{\partial W(r,\varphi)}{\partial r}\right._{r=R_1-0}=$$

$$=\frac{(h+1)G_1}{2\pi^2}\int_0^{\alpha}\chi(\psi)\left[\sum_{n=1}^{\infty}\frac{\cos n(\varphi-\psi)-\cos n(\varphi+\psi)}{2+h(1-\gamma^{2n})}n(\gamma^{2n}-1)\right]d\psi=-\tau_{rz}. \tag{19}$$

In the last expression, we can evolve main and regular parts to define the unknown function $\chi(\varphi)$. To do this, let us introduce the expression:

$$\frac{d^2}{d^2}\left\{\frac{(h+1)G_1}{2\pi^2(2+h)},\right.$$

$$\int_0^{\alpha}\chi(\psi)\left[\sum_{n=1}^{\infty}\frac{\cos n(\varphi-\psi)}{n}-\frac{\cos n(\varphi+\psi)}{n}\right]+$$

$$+\frac{(A+1)\gamma^{2n}}{(1+A\gamma^{2n})n}(\cos n(\varphi+\psi)-\cos n(\varphi-\psi))d\psi, \tag{20}$$

$$A=\frac{G_2-G_1}{G_2-3G_1}.$$

In the expression (20) $\sum_{n=1}^{\infty}\frac{\cos n(\varphi-\psi)}{n}=\frac{1}{2}\ln\frac{1}{2(1-\cos(\varphi-\psi))}$ [7] has a singular specific character. The rest is correct. We denote by $R(\varphi,\chi)$ the regular part of (20):

$$R(\varphi,\psi)=\sum_{n=1}^{\infty}\frac{(A+1)\gamma^{2n}}{(1+A\gamma^{2n})n}\left(\cos n(\varphi+\psi)-\cos n(\varphi-\psi)+\ln\sin\left|\frac{\varphi+\psi}{2}\right|\right). \tag{21}$$

In the notation adopted, we reach an integral-differential equation for the searched function $\chi(\varphi)$.

$$\frac{d^2}{d^2}\left\{\frac{(\chi+1)G_1}{2\pi^2(2+\chi)}\int_0^{\alpha}\chi(\psi)\left[\frac{1}{2}\ln\frac{1}{2[1-\cos(\varphi-\psi)]}+R(\varphi-\psi)\right]d\psi\right\}=-\tau_{rz}. \tag{22}$$

Denoting by $f=-\frac{2\tau_{rz}\pi^2(h+2)}{G_1(h+1)}$ and transforming the singular part of the integro-differential equation (22) to the form $\ln\frac{1}{|\varphi-\psi|}$ we get:

$$\frac{d^2}{d\varphi^2}\int_{-\alpha}^{\alpha}\chi(\psi)\left[\ln\frac{1}{(\varphi-\psi)}+R(\varphi,\psi)\right]d\psi=f.$$

When integration limits $[-\alpha,\alpha]$ transformed to $[-1,1]$ by replacing $\psi=\tau\alpha$.

The unknown function $\chi(\alpha\tau)$ should be sought in the form [8, 9]:

$$\chi(\alpha\tau)=\sum_{m=1}^{\infty}\sqrt{1-(\alpha\tau)^2}U_m(\alpha\tau)C_m. \qquad (23)$$

where $U_m(\alpha\tau)$ – Chebyshev’s polynomials of 2nd order, C_m – unknown coefficients.

Applying the Chebyshev polynomials of orthogonality feature [7, 8], we get an infinite system of algebraic equations respectively to the searched solution:

$$N_nG_n\chi_n+\sum_{m=1}^{\infty}d_{nm}\chi_v=f_n,\ n,m=1,\infty, \qquad (24)$$

where:

$$\chi_n=\frac{1}{\ln 2U_n},$$

$$f_n=C_nB\alpha\int_{-1}^{1}U_n^2(\alpha\tau)(1-(\alpha\tau)^2)d\tau,$$

$$G_n=\frac{\alpha}{2\pi}\int_{-1}^{1}U_n^2(\alpha\tau)(1-(\alpha\tau)^2)d\tau;\ N=U_n{}^2.$$

The system (24) get an approximate solution through reduction method, i.e. the (24) replaced with a finite system of algebraic equations:

$$N_nG_n\chi_n+\sum_{m=0}^{N}d_{nm}\chi_m=f_n,\ n,m=0,N. \qquad (25)$$

Here

$$d_{nm}=\alpha\int_{-1}^{1}\int_{-1}^{1}(1-(\alpha\tau)^2)U_m(\alpha\tau)R(\alpha,\tau)d\tau. \qquad (26)$$

In the problem under consideration, of essential practical interest is the stress intensity coefficient (SIC) for delamination edges at $\varphi=-\alpha-0$ and at $\varphi=\alpha+0$, i.e.

$$K_{\text{III}}^{-}=\lim_{\to-\alpha-0}\sqrt{2\pi(-\alpha-\varphi)}\tau_{rz}(R_1,\varphi), \qquad (27)$$

$$K_{\text{III}}^{+}=\lim_{\to\alpha+0}\sqrt{2\pi(\varphi-\alpha)}\tau_{rz}(R_1,\varphi). \qquad (28)$$

Or, due to substitution effected $\varphi=\alpha\varphi'$ and the symmetry those expressions will appear as:

$$K_{\text{III}}^{\mp}=\lim_{\varphi'\to\mp1\mp0}\sqrt{2\pi\alpha(\mp1\mp\varphi)}\tau_{rz}(R_1,\alpha\varphi')$$

At that, according to (19) and (20):

$$\tau_{rz}(R_1,\alpha\varphi')=\frac{-(h+1)G_1}{2\pi^2(2+h)\alpha}\times$$
$$\times\frac{d^2}{d\varphi'^2}\int_{-1}^{1}X(\alpha\tau\varphi')\left[ln\frac{1}{[\varphi'-\psi']}+R(\alpha\tau\varphi',\alpha\tau\psi')\right]d\psi. \qquad (29)$$

Due to its continuity, the regular part will not make any contribution to the SIC transformant, and therefore it can be discarded. As a result, we get:

$$K_{\text{III}}^{\mp}=\lim_{\varphi'\to\mp1\mp0}\sqrt{2\pi\alpha(\mp1\mp\varphi')}A\frac{d^2}{d\varphi'^2}\int_{-1}^{1}X(\alpha\varphi')\ln\frac{1}{(\varphi-\psi')}d\psi',\ A=-\frac{(h+1)G_1}{2\pi^2\alpha(2+h)}.$$

Replacing with (5) we get:

$$K_{\mathrm{III}}^{\mp} = \lim_{\varphi' \to \mp 1 \mp 0} \sqrt{2\pi\alpha(\mp 1 \mp \varphi')} \times$$
$$\times A \frac{d^2}{d\varphi'^2} \sum_{m=1}^{\infty} C_m \int_{-1}^{1} \sqrt{1-(\alpha\psi')^2}\, U_m(\alpha\varphi') \ln \frac{1}{|\varphi' - \psi'|} d\psi. \tag{30}$$

For boundary transition we need for a spectral correlation [7] extending onto the interval $|\varphi'| > 1$. Using the formulas (27), (28), (30). We get:

$$A^{-1} K_{\mathrm{III}}^{\mp} = \sqrt{\frac{\pi\alpha}{2}} \sum_{m=1}^{\infty} (-1)^{m+1} \sqrt{m+1}\, \Psi_m. \tag{31}$$

Where $\Psi_m = 2^{m+1}(m+1)\left[\frac{m+1}{m!} 1F_1\left(\frac{3}{2}+m,\, m+2;\ \frac{3}{2}\right) - 1F_1\left(\frac{3}{2}+m,\, m+1;\ \frac{1}{2}\right)\right]$,

$|\varphi'| > 1;\ 2F_1\left(\frac{3}{2}+m,\, m+1;\ \frac{1}{2};\ \frac{\varphi'+1}{\varphi'-1}\right)$ – generalized hyper geometric function [8].

Using correlation of cylinders working area roughness with the value (–α, α) for coating delamination area at different finishing operations: fine grinding, grinding finishing, polishing, we find the dependence SIC $K_{\mathrm{III}} = f(\alpha)$ (Fig. 2).

To do this, the formulas (31), (27), (24) using the set τ_{rz} strength values for adhesion of the coating to the cylindrical surface we find K_V calculated values, depending on the detachment defect size (–α, α) at different values of working tool surface roughness (Fig. 2).

Analysis of calculated dependency (Fig. 3) indicates that with increasing roughness of the work area the cylinder coating detachment area is increased due to friction against the piston surface.

This means that the coating destruction will occur even in the case where the process stress value will exceed the cohesive strength τ_{rz}.

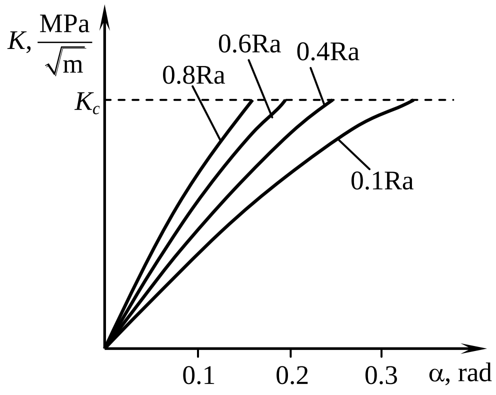


Fig. 2. SIC dependency onto detachment angle α and cylinder surface's working area roughness Ra

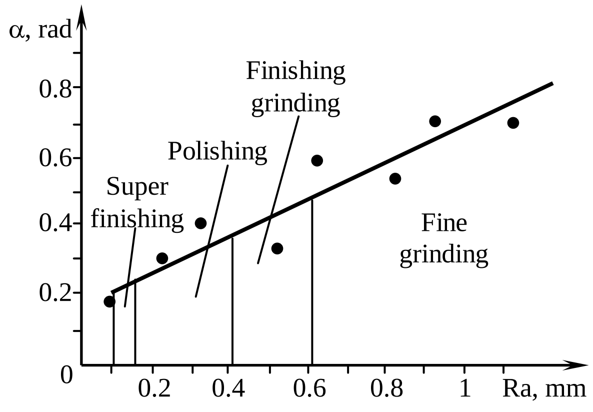


Fig. 3. Influence of coated cylinder group processing modes onto functional characteristics

At existing operational stresses within cylinder-coating system the initial detachment shall remain at the section (–α, α) Fig. 3 illustrates types and modes of cylinder surface processing providing the required roughness to maintain the functionality of piston-cylinder group's coating [9 – 15].

Results. To ensure the required reliability and durability of a cylindrical group with a coating, it is necessary to ensure roughness when applying coatings on their working surfaces $0.8 \le Ra \le 1.2$. This roughness can be achieved by finishing grinding operations and subsequent finishing polishing. In this case, the mathematical expectation of the detachment area $M(\alpha)$ will be within the capabilities of the technological coating process, under which the equilibrium state of the peeling section will be preserved under the action of technological stresses. In the case where, due to the roughness of the working surface of the cylinder, there is a system of areas of coating exfoliations from the cylinder matrix (Fig. 4), it is possible to change the stress intensity factor K_V due to their mutual influence. The dependence of the CIN on the relative distance between the peel areas is shown on Fig. 4.

Dependency between SIC and the relative distance between delamination sections is shown in Fig. 4. With increasing distance d the $2\alpha / d$ coefficient decreases and the intensity of the stresses can reach essential values without trespassing the balanced state.

In the case when due to the roughness of the working surface of the cylinder, there is a system of areas of coating exfoliations from the cylinder matrix (Fig. 5), it is possible to change the stress intensity factor K_{III} due to their mutual influence and operating conditions [16].

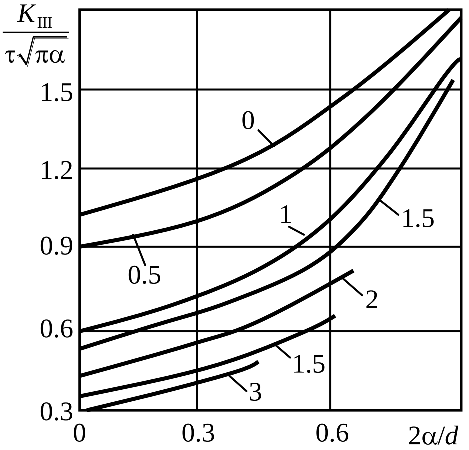


Fig. 4. Dependency of SIC $K_V/\tau\sqrt{\pi\alpha}$ at longitudinal displacement

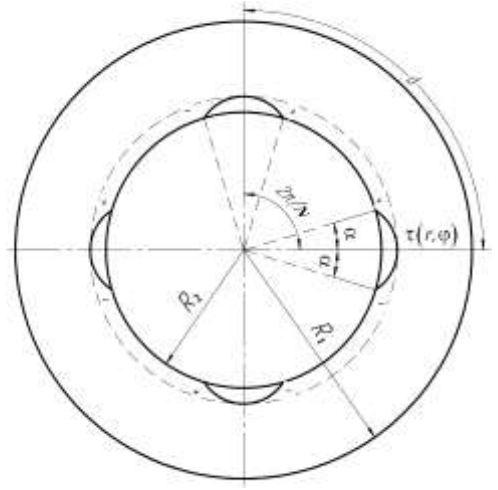
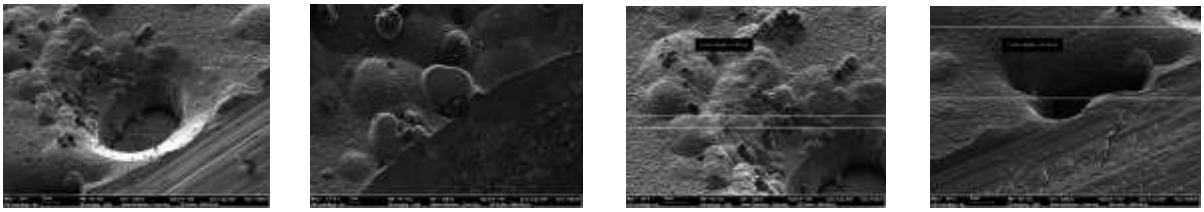


Fig. 5. Calculation scheme for researching the reciprocal influence between detachment areas and stress intensity KV

To confirm the analytical model, tribocorrosive studies of composite materials based on Ni/Ni-TiO_2, obtained by electrochemical deposition (Fig. 5 and Fig. 4) were carried out [16].

After tribocorrosive studies of Ni/Ni-TiO_2 materials, it was determined that for Ni coating, an increase in the depth and width of the cracks is noticeable, depending on the increase in load with constant exposure time. At the same time, the profile of cracks for the coating of Ni-TiO_2 with increasing load and constant time does not change. In this connection, it is possible to single out the positive effect of TiO_2 particles in the coating, which increase the protective functions of the coating from mechanical abrasion, while the load for Ni-TiO_2 ceases to play such a significant role.



a *b* *c* *d*

Fig. 6. Investigation of composite materials based on Ni/Ni-TiO_2 in a scanning electron microscope: breaking the coating (a), TiO2 particles (b), measuring the particle diameter (c), measuring the thickness of the coating (d)

Conclusions: We elaborated the analytical model for determining the thermal-mechanical condition of a wear proof-coated cylinder's working surface at includes areas of partial detachment while coating. Tribocorrosive studies of composite materials based on Ni/Ni-TiO_2 obtained by electrochemical deposition were carried out.

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