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Stressed State of Chrome Parts During Diamond Burnishing

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A description of strengthening methods increasing the wear resistance and corrosion resistance of the working surfaces of machine parts is provided. It has been established that the chromium coatings are most often used among metal coatings. These coatings are applied to the surface of machine parts in a calm or flowing electrolyte. The advantages of electrochemical chromium plating in flowing electrolytes compared to electrochemical chromium plating in calm electrolytes are substantiated. Chromium plating has been shown to provide a significant increase in wear resistance and corrosion resistance, but causes a decrease in the fatigue strength of steel machine parts. The analysis of mechanical processing operations was carried out—grinding, honing of surfaces with chrome coatings and their diamond burnishing. The work aims to study the effect of diamond burnishing technological modes on

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the stress-strain state of the electrochemical chromium coating applied to a steel base. A finite-element model of the process of burnishing with a diamond tool chromium coating applied to a cylindrical part made of 40KhN steel was developed. Researched the influence of the depth of diamond burnishing on the stress-strain state of the part with chromium coating. It was established that with the burnishing depth of $t = 8$ μm, the residual compressive stresses are at a depth of 80–100 μm for both investigated coating thicknesses, which will contribute to an increase in the fatigue strength of the parts.

Key words: electrochemical chromium coating, electrolyte, diamond indenter, long-dimensional parts, Mises stress.

Проведено огляд методів зміцнення підвищення зносостійкості та корозійної стійкості робочих поверхонь деталей машин. Встановлено, що серед металевих покриттів найчастіше використовуються хромові покриття. Ці покриття наносять на поверхню сталевих деталей машин у спокійному або протічному електроліті. Обґрунтовано переваги електрохемічного хромування у протічному електроліті порівняно з електрохемічним хромуванням у спокійних електролітах. Доведено, що хромування забезпечує значне підвищення зносостійкості та стійкості до корозії, але викликає зниження втомної міцності сталевих деталей машин. Проведено аналіз операцій механічної обробки — шліфування, хонінгування поверхонь з хромовими покриттями та алмазне вигладжування. Метою роботи є дослідження впливу технологічних режимів алмазного вигладжування на напружено-деформований стан електрохемічного хромового покриття, нанесеного на крицеву основу. Розроблено скінченно-елементний модель процесу вигладжування алмазним інструментом хромового покриття, нанесеного на циліндричну деталь зі криці 40ХН. Досліджено вплив глибини алмазного вигладжування на напружено-деформований стан деталі з хромованим покриттям. Встановлено, що за глибини вигладжування $t = 8$ мкм залишкові напруження стиску знаходяться на глибині 80–100 мкм для обох досліджуваних товщин покриттів, що сприятиме підвищенню втомної міцності деталей.

Ключові слова: електрохемічне хромове покриття, електроліт, алмазний індентор, довгомірні деталі, напруження Мізеса.

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1. INTRODUCTION AND STATEMENT OF THE RESEARCH PROBLEM

Mining equipment operates under extreme conditions at high temperatures, sign-changing loads and contact loads in aggressive environments containing hard abrasive rock particles during drilling [1–3] and mining [4, 5]. Therefore, means are used to increase the service life of the equipment, in particular various wear-resistant and corrosion-resistant coatings are used, which allow to rationally combine the properties of the coating material and the base, in particular, deposited [6–9], laser [10], formed coating by electric spark alloying method [11, 12], formed coating by hybrid ion-plasma discharge system [13] and chrome [14, 15]. Ensuring high-quality balancing [16] and lubrication of elements of friction pairs is also important [17].

During the construction of parts with coatings, a rational selection of materials is carried out, corrosion studies [18, 19] and tribocorrosion tests [20, 21] are carried out, and analytical methods of stress research in layered coatings under local load [22–24] and near cracks [25, 26] are used, and calculate temperature fields in layered compositions [27–29].

The development of coating technology is carried out taking into account technological heredity [30] and optimization of technological processes of manufacturing parts [31]. This approach allows ensuring the operability of mechanical engineering products throughout their life cycle [32, 33]. Theoretical approaches to the selection of the composition and technological parameters of the strengthening process are considered in works [34–37].

A systematic analysis of the sources of scientific and technical, patent and regulatory literature regarding the frequency of use of metal coatings showed that chromium coatings are most often used, which are applied to the surface of machine parts in a still or flowing electrolyte. Chromium plating in a flowing electrolyte, due to the presence of the electrolyte in a closed electrochemical cell, ensures a reduction of its evaporation and environmental pollution and creates safer working conditions for workers compared to chromium plating in a calm electrolyte, where the galvanic baths for coating are open. In addition, electrochemical chromium coatings applied in a flowing electrolyte also require the removal of smaller allowances for mechanical processing.

Chromium coatings [38–40] and chromium-nickel coatings [41] are cathodic and have a more positive electrode potential in relation to steel, therefore, in the presence of through pores, corrosion products of the base are formed in them. Changing the electrical modes of electrolysis, the composition of the electrolyte, and the temperature of the electrolyte during electrochemical chromium plating ensures the production of coatings with different surface hardness and colour. Chromium coatings have high microhardness, wear resistance, low coefficient of friction and absence of burrs on the friction surface. The high corrosion resistance of chromium coatings is ensured by the presence of a dense oxide film on their surface, which is quickly restored during damage. In addition, the ratio of the volume of the formed oxide Cr_2O_3 to the volume of Cr metal is 2.02, and the linear coefficients of thermal expansion ($\alpha_t \cdot 10^{-6}$ per degree centigrade): oxide film—9.6, chromium —8.1, iron—11.2, are close among ourselves.

Chromium coatings are widely used both during the manufacture of new machine parts and during the restoration of worn surfaces of a wide range of parts of piston and plunger pumps, compressors, internal combustion engines, hydraulic and pneumatic cylinders and parts of various machines, *etc.* [42–44].

It is known that residual tensile stresses occur in chromium coatings. If thin chromium coatings do not require further mechanical processing, then thick hard chromium coatings are usually subjected to diamond grinding or honing. The presence of a network of branched microcracks in the surface layers of chromium coatings at a certain depth from the surface can cause the flow of gas or liquid in the friction pair: cylinder sleeve – rubber piston seal; piston rod – a rubber seal of the rod, which can lead to a violation of the tightness of the products. The reason for the appearance of cracks and pores can be non-compliance with electrolysis regimes and/or mechanical treatment regimes (rough grinding) and honing.

The article [45] presents a comparative study of chromium coatings obtained by the traditional method, as well as by combining the process of galvanic coating with its mechanical processing.

Surface plastic deformation and diamond burnishing are used to improve the operational properties of parts, including those with different coatings. These processes make it possible to increase hardness, reduce roughness, smooth out irregularities, increase the reference length of the profile, and create the necessary microprofile of the surface. Residual compressive stresses are also formed. As a result, the wear resistance and fatigue strength of parts increases under various types of load.

The review [46] analyses tool designs and technological processes of burnishing machine parts. In particular, such processes include ultrasonic impact treatment [47, 48], friction hardening, which is used to improve the accuracy and quality of smooth [49–51] and threaded surfaces of parts [52, 53]. The works [54, 55] investigated the process of diamond burnishing of stainless steel and showed an increase in the quality of the surface and their hardness, as well as corrosion resistance.

Brostow *et al.* [56] studied the processes of diamond burnishing of electrochemical hard chromium and diffusion nitride coatings formed on tool steel and proposed a mechanism for strengthening the surface layers of the coating. However, the data given in the technical literature do not provide an opportunity to purposefully make a rational choice of technological modes of diamond burnishing of parts with chromium coatings to ensure their high operational characteristics.

Therefore, there is a need to establish the influence of diamond burnishing modes of chromium coatings on the stress-strain state of parts. This study aims to determine the influence of diamond burnishing depth on the stress-strain state of an electrochemical chromium coating applied to a steel base.

To achieve the goal, the following tasks should be solved:

—to develop a computer model diamond burnishing of chromium coating;
—to investigate the influence the technological parameters the diamond burnishing on the stress-strain the chromium coating state.

2. MATERIALS AND METHODS

2.1. Studied model and materials

The authors simulated the process of diamond burnishing of chromium coatings applied to a cylindrical part (Fig. 1, *a*). A drilling pump rod ($d = 70$ mm) was taken as a prototype part for modelling. The part has

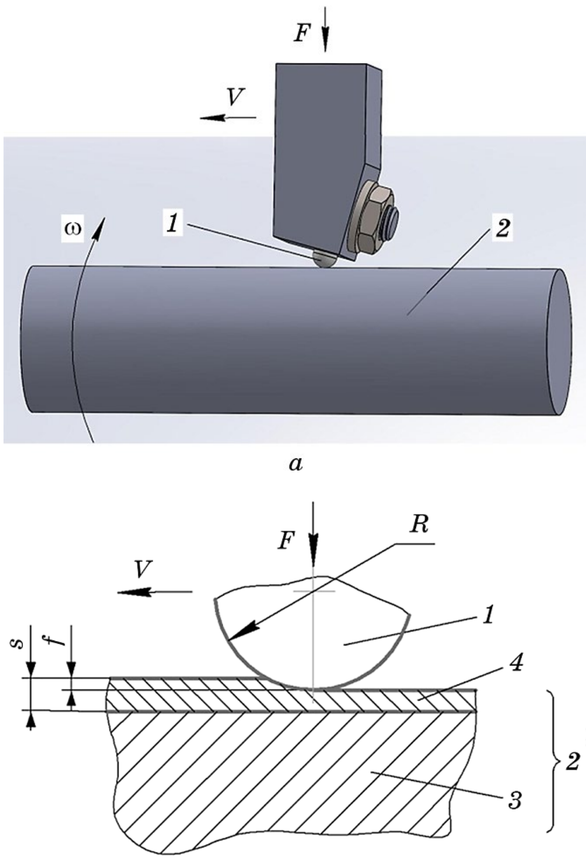


Fig. 1. General view (*a*) and calculation scheme (*b*) of diamond burnishing of chromium coating: *1*—diamond indenter; *2*—cylindrical part; *3*—the base of the part (steel); *4*—chromium coating.

TABLE 1. Physical and mechanical properties of materials.

Material	Modulus of elasticity E, MPa	Poisson's ratio, μ	Yield strength σ_y, MPa
Steel 40KhN	210,000	0.28	900
Chromium coating	170,000	0.30	200

two layers: the base is Steel 40KhN (State standard GOST 4543-2016) and the chromium coating formed by the electrochemical method in the flowing electrolyte (Fig. 1, *b*).

The study of the diamond burnishing was carried out for two thicknesses of the chromium coating—$s = 100$ μm and $s = 200$ μm. The length of the investigated burnishing zone was 10 mm. Table 1 lists the mechanical properties of the used materials.

Burnishing was performed using a diamond indenter with a radius of $R = 2.5$ mm.

The coefficient of friction between the polished surface and the diamond indenter was taken as 0.1.

2.2. Simulation model development method

To study the diamond burnishing of the chromium coating, we developed an algorithm in the ANSYS Academic Research software complex, using plane stress elements.

The part is considered as a body consisting of two layers: the base is steel and an applied layer of chromium coating with a thickness of s. The contact parameters of the model are as follows: *Surface-to-surface contact, contact algorithm: penalty method.*

The bottom of the base of the part is rigidly fixed. Table 1 shows the mechanical properties (modulus of elasticity, Poisson's ratios and yield limits) for layer materials.

The tool is a spherical diamond indenter that interacts with the surface of the coating, which is pressed into it to the appropriate depth and moved along the surface. The tool is considered as a rigid body that has no rotation. The variant of the indenter load is considered, when the burnishing depth is assumed to be constant $t = \text{const}$ and as a result of the simulation, the indenter pressing load is determined.

The Isotropic hardening plasticity model was used during the simulation. The load diagram ε—σ was approximated by a bilinear dependence, the inelastic section of which is horizontal $\sigma = \sigma_y$.

The simulation included two steps: immersion of the tool in the radial direction of the part and longitudinal movement along the part by 8 mm (without lifting at the end).

3. RESEARCH RESULTS AND THEIR DISCUSSION

According to the developed simulation model of diamond burnishing of the chromium coating applied to the steel base, the influence of technological parameters of the process on the stress-strain state of the coating during the rigid fixation of the diamond burnishing tool was investigated.

During the simulations, the value of the initial pressing force F_0 of the diamond indenter, which occurs when the indenter is pressed to different depths, was also determined. It was established that in the coating with the thickness of $s = 100$ μm for the indenter depression depth $t = 1$ μm, the value of the initial pressing force is $F_0 = 19{,}718$ N/m, $s = 100$ μm, $t = 8$ μm is $F_0 = 91029$ N/m; $s = 200$ μm, $t = 1$ μm is $F_0 = 18860$ N/m; $s = 200$ μm, $t = 8$ μm is $F_0 = 90827$ N/m, respectively.

Figure 2 shows the distribution of Mises stresses in the chromium coating and the steel base for different coating thicknesses and burnishing depths. The Mises stresses on the surface of the chromium coating during the action of the indenter reach the yield point for the coating material, and part of the load also acts on the steel base (Fig. 2). For the indentation depth of the diamond indenter $t = 1$ μm, for thicknesses $s = 100$ μm and $s = 200$ μm in the lower part of the coating, the values of the Mises stresses do not reach the yield point of the chromium coating (Fig. 2, *a*, *c*). For the indentation depth of the diamond indenter $t = 8$ μm

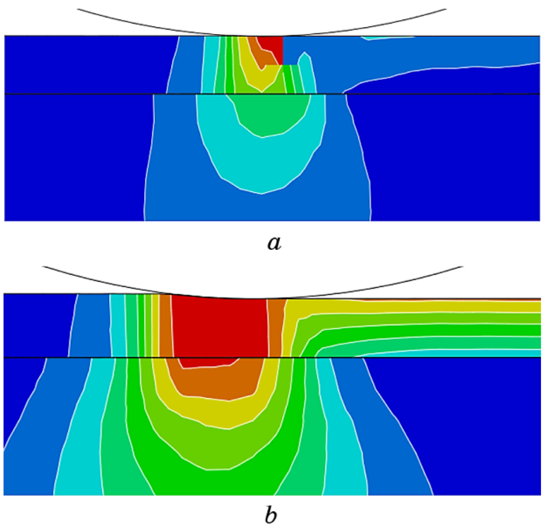


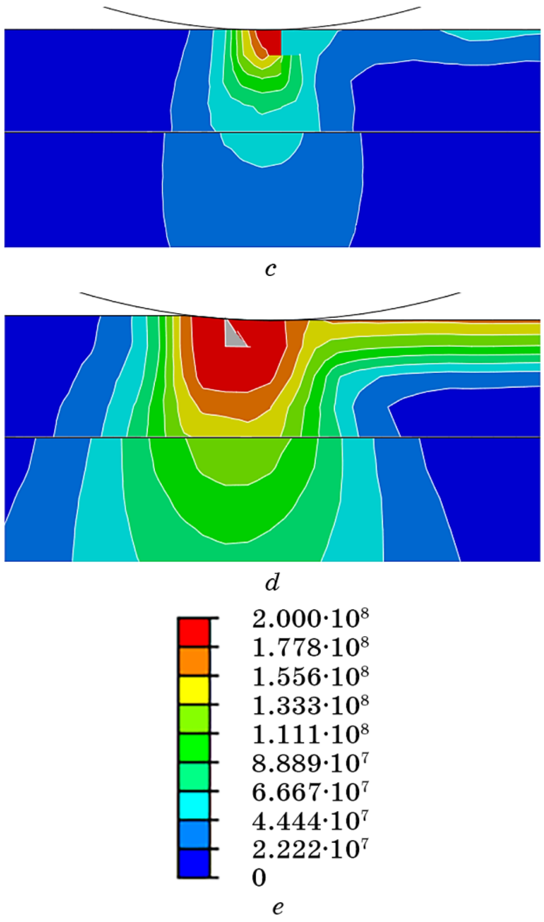
Fig. 2. Mises stress distribution in chromium coating and steel base for different coating thicknesses and burnishing depths: *a*—$s = 100$ μm, $t = 1$ μm; *b*—$s = 100$ μm, $t = 8$ μm; *c*—$s = 200$ μm, $t = 1$ μm; *d*—$s = 200$ μm, $t = 8$ μm; *e*—is the stress scale according to Mises.

and the thickness $s = 100$ μm in the lower part of the coating, the values of the Mises stresses reach the yield point of the chromium coating, and for the thickness $s = 200$ μm they do not, respectively (Fig. 2, *b*, *d*).

As for the residual stresses, they are insignificant at the burnishing depth $t = 1$ μm, and at $t = 8$ μm at a depth of 80–100 μm for both coating thicknesses ($s = 100$ μm and $s = 200$ μm). Significant amounts of residual compressive stresses will cause an increase in the fatigue strength of the surfaces of chromium-plated parts.

Figure 3 shows the vertical movements of the coating nodes along the burnishing length for different coating thicknesses and burnishing depths.

According to Fig. 3, the thickness of the coating practically does not affect the amount of radial movement of its nodes. That is, the radial



Continuation of Fig. 2.

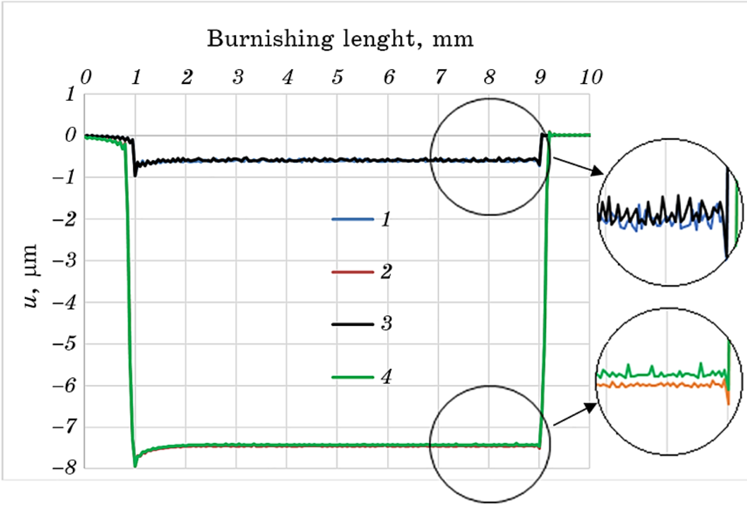


Fig. 3. Radial displacements u of coating nodes along the part during diamond burnishing: *1*—$s = 100$ μm, $t = 1$ μm; *2*—$s = 100$ μm, $t = 8$ μm; *3*—$s = 200$ μm, $t = 1$ μm; *4*—$s = 200$ μm, $t = 8$ μm.

movement of the coating nodes depends mainly on the burnishing depth. Residual movements on the main working length of burnishing are 0.3–0.6 microns smaller than the studied depths of diamond burnishing. Thus, carrying out the diamond burnishing process will reduce the roughness and waviness of the coating, practically without changing the accuracy of the shape and dimensions of the surface. Also, when burnishing is carried out, the chromium blocks shift at the same time, which leads to overlapping cracks in depth. As a result, the open porosity of the chromium coating is reduced and microcracks are closed. As a result, the penetration of aggressive substances through the channels of chromium to the steel base and, as a result, the rate of corrosion is reduced, which will increase the operational properties of the products.

The developed computer model of the process of diamond burnishing of a chromium coating applied to a cylindrical steel part allows to study the distribution of Mises stresses in the coating and the steel base for different coating thicknesses and burnishing depths, as well as radial movements of the surface nodes of this coating.

4. CONCLUSIONS

A finite-element model of diamond burnishing of the chromium coating applied to the cylindrical steel part has been developed. The model can be used to justify the choice of coating thickness and burnishing depth.

The influence of the technological modes of the diamond burnishing on the stress-strain state of the chromium coating was studied. It was established that at the burnishing depth $t = 8$ μm, the residual compressive stresses lie at a depth of 80–100 μm for both investigated coating thicknesses ($s = 100$ μm and $s = 200$ μm). The resulting residual compressive stresses in the surface layer of the chromium coating will cause an increase in the fatigue strength of the parts.

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