Investigation of the Strength of Diffusion Coatings on Cast Iron Friction Pairs in Contact with Hard Abrasive Soil Particles

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Abstract. Replacing steel parts with cast iron is a promising task for agricultural engineering. However, high-strength cast iron VCh 60, widely used in mechanical engineering and studied in this work, is inferior in abrasive resistance to steel parts that have undergone chemical-thermal and subsequent heat treatment. This disadvantage was eliminated by the formation of high-hard diffusion coatings with vanadium or chromium, by the method of saturation of their powders. But these coatings, despite their hardness, are brittle and lie on a softer base of cast iron. This paper estimates the minimum thickness of the above-mentioned coatings that can withstand the specified level of contact load without destruction when solid non-crushed soil particles or particles of other origin enter the interface. Based on the conducted research, the empirical dependences of the minimum thickness of the coating that can withstand a given level of load without destruction are derived from the size of the resulting imprint of the Vickers pyramid pressed into the surface. The graphs are convenient to use when designing gears and worm gears with a given contact load in the engagement, the part of the space located above the critical line 6 in the figures shown in the work is a safe area of coating thicknesses at the identified contact pressure.

1. Introduction
Cast iron has become widespread in agricultural engineering, since it is characterized by high strength and wear resistance [1-2]. Cast iron parts are less sensitive to stress concentrators than steel parts [3-5]. Piston rings of automotive diesel engines and compressors, parts of hydraulic cylinders are made of cast iron. Gears, crankshafts and bushings of a KAMAZ vehicle are also made of ductile iron [6].

The limit wear of cast iron parts is limited to 0.3 mm. Therefore, a hard wear-resistant coating is applied to the surface of cast iron parts by diffusion, which increases their service life [7-10]. When choosing a coating, the possibility of ingress of solid soil particles into the friction zone is taken into account. Solid soil particles cause abrasive wear and compress fragile diffusion layers, leading to unplanned repairs.

Abrasive soil particles come into contact with the surface layer of cast iron parts and create stress concentrators there. The nature of stress distribution depends on the properties of the wear material, hardness, shape, size of particles and the conditions of their interaction with the surface of parts. Soil particles are 71% quartz and granite. The hardness of granite reaches 8200 MPa, and the hardness of
quartz reaches 11300 MPa. Consequently, these soil particles can penetrate the diffusion coating in the contact area of the parts [11-13].

The loading capacity of diffusion coatings depends on the layer thickness and the properties of the substrate material. After diffusion saturation, the metal located under the coating has a significantly lower hardness. Consequently, the diffusion coating is located on a soft substrate. The aim of the study is to determine the maximum load that the hardened layer can withstand under specific operating conditions of cast iron parts.

2. Calculation method

The scheme for determining the maximum value of the load \( P \), at which the punching of the hardening coating of the corresponding thickness \( h \) occurs, is shown in Figure 1.

In the calculations, the shape of the abrasive particles is taken to be spherical with a radius \( R_{ap} \) in the calculations. The load acting on an abrasive soil particle in engagement is [14]

\[
P = \frac{8}{3} G a^3 / R_{ap}
\]

where \( G \) is shear modulus from the action of shear stresses; \( a \) is the size of the imprint of the abrasive particle in the coating; \( R_{ap} \) is abrasive particle radius.

The hardness of diffusion coatings on cast iron cannot be greater than the load of their destruction \( P_{max} = P_{max}^{ap} \). The load of destruction of an abrasive soil particle is [15]

\[
P_{max}^{ap} = \pi R_{ap}^2 [\sigma_{ap}],
\]

where \( [\sigma_{ap}] \) is permissible fracture stress of an abrasive particle.

Equating formulas (1) and (2), we obtain

\[
\pi R_{ap}^2 [\sigma_{ap}] = \frac{8}{3} G a^3 / R_{ap}.
\]

After transformations, we obtain an expression for the size of the imprint of an abrasive particle in the coating

\[
a = R_{ap} \sqrt{\frac{8}{3} \pi [\sigma_{ap}] / G}.
\]

The thickness of the diffusion coating \( h \) directly depends on the size \( a \) of the imprint of the abrasive particle \( h = ca \), where \( c \) is coefficient proportionality. Substituting this expression into
equation (3) and we obtain the relationship between the thickness of the hardening layer $h$ and the radius of the abrasive particle $R_{ap}$:

$$h_{min} = c R_{ap} \sqrt[3]{\frac{3\pi}{h} \left[ \sigma_{ap} \right] / G}.$$  

Equation (4) shows that the thickness of the coating is directly related to the size of the abrasive particle and its strength. The hardness of abrasive quartz particles is 11200 MPa. This corresponds to the permissible stresses $[\sigma_{ap}] = 400$ MPa. Then the minimum thickness of the hardening layer is $h_{min} = \frac{7.78 c R_{ap}}{G^{0.3}}$.

The object of research was high-strength cast iron VCh 60, which is widely used in agricultural engineering. Vanadium and chromium were chosen as hardening coatings on cast iron. Vanadium coatings have a hardness of 22000–26000 MPa [16], chrome coatings have a hardness of 13000-16000 MPa [17]. Vanadium and chromium coatings were formed from a powder reaction mixture containing 60% ferroalloy (ferrovanadium or ferrochrome), 36% aluminum oxide, and 4% ammonium chloride activator. Cast iron samples were placed in a container with a fusible seal, filled with a reaction mixture, the container was closed, and heating was carried out in an SNOL-1300 muffle furnace.

The isothermal holding temperature was 1020–1050 °C. The saturation time was 5 hours for vanadium and 10 hours for chrome coatings. As a result, wear-resistant coatings with a thickness of 45-55 μm were formed on the samples.

The punching of the hardening coatings was carried out on a PMT-3 hardness tester. The Vickers pyramid was pressed into the coating instead of the abrasive particle. The beginning of the appearance of cracks near the indentation indicated the beginning of the destruction of the coating. This load was taken as the maximum load $P_{max}$.

3. Experiment results

First, the dependences of the thickness of the hardened layer $h$ on temperature and time saturation has been experimentally established (Figure 2).

![Figure 2](image)

**Figure 2.** Dependence of the thickness of the hardened layer $h$ on (a) temperature and (b) saturation time: (1) is at time 6 hours, (2) is at time 4 hours, (3) is at temperature 960 °C, (4) is at temperature 1020 °C.

Then, an experimental dependence of the distribution of hardness over the thickness of the hardened layer was obtained at temperatures of 960 °C and 1020 °C (Figure 3).
Figure 3. Distribution of hardness over the thickness of the hardened layer obtained at temperatures (a) 960 °C and (b) 1020 °C: where (1) is hardening time 4 hours and (2) is hardening time 6 hours.

The effective thickness of the hardened layer is 30-40 µm at a temperature of 960 °C and 40-60 µm at a temperature of 1020 °C. The lower value of the thickness corresponds to 4 hours of hardening, and the upper value corresponds to 6 hours of hardening. Increasing the hardening time over 4 hours does not significantly increase the hardness of the vanadium coating. An increase in time of more than 6 hours creates high compressive stresses in the coating, which can lead to destruction of the coating itself.

The spatial relationship between the thickness of the hardening coating and the type of coating is shown in Figure 4.

Figure 4. Spatial diagram of the depth of indentation of a Vickers pyramid into high-strength cast iron VCh 60 after hardening and a load 0.49N with: (a) vanadium coated and (b) chrome plating.

Subsequent hardening of the samples insignificantly increases the hardness of the hardened layer. The hardness of the base and the area adjacent to the coating reaches 7000-8000 MPa. The results of the experiment are shown graphically in Figure 5.

The points of intersection of curve 6 with graphs of load 1, 2, 3, 4, 5 are critical. The coating thickness corresponding to these points is the minimum allowable. A coating thickness above curve 6 is safe for indentations at a given load level. Curve 6 represents the connection between the indentation size and the effective thickness of the hardening coating.
Figure 5. Determination of the critical thickness of the coating (curve 6) on high-strength cast iron VCh 60 (a) after vanadium treatment and (b) after chromium plating under load:

(1) is 0.49 H, (2) is 0.98 H, (3) is 1.47 H, (4) is 1.96 H, (5) is 2.45 H

Mathematical processing of the experimental data using the MathCAD computer package made it possible to write the equation of curve 6 to determine the minimum coating thickness capable of withstanding a given load. The obtained regression dependences make it possible to predict the critical thickness of the hardening coatings by the size $a$ of the Vickers pyramid imprint with a confidence level of 0.95:

- $h_{min} = 24.468 - 24.649e^{-0.06a}$ for vanadium coatings;
- $h_{min} = 22.03 - 21.223e^{-0.068a}$ for chrome coatings.

4. Conclusion

The vanadium coating has a lower value of the minimum thickness of the hardening coating in comparison with the chrome coating in the entire range of the investigated loads. This is because vanadium has a higher hardness than chromium.

The discrepancy between the experimental and calculated (equation 4) values of the minimum thicknesses of the hardening coating did not exceed 10-25% at all load levels. This error is due to the difference in the shape of the pressed body:

- in the calculations, the shape of the abrasive particle is assumed to be round;
- in the experiment, the shape of the pressed body is a pyramid.

The obtained empirical regularities of the critical thickness of the coating make it possible to design wear-resistant hardening coatings based on vanadium and chromium without punching it with hard abrasive particles.

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