Wear resistance and characteristics of the friction surface of the coating metal with carbide-boride-nitride-intermetallic alloying

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Abstract. The metal deposited by flux-cored wire containing 15\% chromium, 0.5\% boron carbide, 0.5\% boron nitride, 2.5\% titanium diboride and 1.0\% zirconium diboride was investigated. The hardness of such a metal reaches a maximum value of 58 HRC. The microhardness of the structural objects is 521-593 HV for the matrix, 829-978 HV for eutectics and 1262-1342 HV for reinforcing phases. It was established that the average value of the relative mass wear per test was 0.0034 g/m, and linear wear was 0.00862 mm/m, which is 2.2 times, respectively, and 2.7 times less than that of the coating metal without borides. The average value of the friction moment for the entire friction path of 452.16 m was 19.075 N·m. The coefficient of friction was 0.364. It is shown that the metal structure is an iron-chromium martensitic matrix with a eutectic component formed on the basis of boride \((\text{Fe, Cr})_2\text{B}\), having a frame structure, dispersed inclusions of \((\text{Fe, Cr})_7(\text{C, B})_3\) carboronides and high strength nitrides \(\varepsilon-(\text{Fe, Cr})_2\text{N}\). High-chromium flux-cored wire alloyed by a complex of boron and nitrogen compounds provides a composite-type metal with high wear resistance and can be used for hardening the surfacing of parts operating under conditions of significant frictional loading.

1. Introduction
One of the rapidly developing areas in the field of hardening high-wear parts and equipment components is the surfacing of powder wire coatings. The longevity of a large group of equipment is determined by the resistance to corrosion. There is a great potential for creating corrosion coatings by surfacing with high-chromium cored wires. At the same time, most of these coatings have high corrosion resistance, but insufficient wear resistance under frictional loading conditions.

One of such effective methods of metal hardening is alloying it by boron compounds such as ferrobor, boron carbide, chromium diboride, titanium diboride [1-6]. Previously carried out studies of the authors established the positive effect of titanium and zirconium diborides on the wear resistance of nickel-chromium martensite-aging steels deposited by flux-cored wires [7, 8]. Nitrogen has found quite wide application for alloying corrosion-resistant steels [9-13]. At the same time, during the deposition, nitrogen is introduced into the metal through the use of nitrated chromium or ferrochrome in the cored wires. However, for these purposes it is possible to use boron nitride, which is due to the similarity of a number of properties as an electronic analogue of carbon [14]. However, boron nitride is extremely rarely used in cored wires.
The authors showed the promise of using filler cored wire alloyed by the B$_4$C-BN-TiB$_2$-ZrB$_2$ complex [15, 16].

At the same time, the current state of the problem of wear requires knowledge of the basic laws of hardening and destruction of the surface layers of the metal during its frictional loading.

Based on this, the purpose of this work is to study the wear resistance and characteristics of the friction surface of a metal deposited by chromium cored wire with a complex of boron and nitrogen compounds.

2. Objects and research methods

Studies were conducted on the effect of boride-nitride alloying on the wear resistance, structure, tribological and durometric properties of chromium steel, obtained by surfacing with flux-cored wire with the composition: 15% Cr; 0.5% B$_4$C; 0.5% BN; 2.5% TiB$_2$; 1.0% ZrB$_2$. For comparison, steel without borides was investigated. The surfacing was carried out on plates made of St3 steel 200×50×10 mm in size by experienced flux-cored wires with a diameter of 2.4 mm in argon in three layers.

Tests under conditions of adhesive wear of metal-to-metal pairs were carried out under sliding friction without lubrication according to the finger-rotating disk (counterbody) scheme, using a UMT-2168 friction machine. The ring surfacing was made on the disk by an OK Weartrode 55 HD (70Kh10GS) coated electrode, providing the hardness of the metal coating 56-59 HRC. After grinding, the deposited coating contacting with samples in the form of a finger, the butt-end of which was surfacing by the studied composition. The test was carried out at a load F=0.75 kN and a counterbody disk rotation speed of 100 rpm.

Electron microscopic studies were performed on a JEOL JSM-6610-LV raster electron microscope with an Inca-350 attachment for energy dispersive analysis.

3. Results of the experiment and discussion

The test results on the adhesive wear of the metal coatings without borides and alloyed with boride compounds are given in Table 1. The main tribological properties of the deposited metal of the investigated coatings are given in Table 2.

| Number of revolutions | Sample 1 | Sample 2 | Sample 3 | Average value | Relative wear, [g/m] |
|-----------------------|----------|----------|----------|---------------|---------------------|
| 0-300                 | 0.965    | 1.1382   | 0.9861   | 1.0297        | 0.0091              |
| 300-600               | 0.6443   | 0.7108   | 0.6670   | 0.6740        | 0.0060              |
| **0-600**             | 1.6093   | 1.849    | 1.6531   | **1.7038**    | **0.0075**          |
| 0-300                 | 0.4292   | 0.3751   | 0.3429   | **0.3824**    | 0.0034              |
| 300-600               | 0.1714   | 0.3587   | 0.3722   | **0.3008**    | 0.0027              |
| 600-900               | 0.4173   | 0.4138   | 0.5101   | **0.4471**    | 0.0040              |
| 900-1200              | 0.4715   | 0.3179   | 0.415    | **0.4015**    | 0.0036              |
| **0-1200**            | 1.4894   | 1.4655   | 1.6402   | **1.5317**    | **0.0034**          |

The metal coating without borides withstood only 600 revolutions with a friction path of 226 m. The average mass wear of samples after 300 revolutions is 1.029 g. After 600 revolutions, the mass wear amounted to 1.70 g, while the wear along the length reached 5.33 mm, the value of which is comparable to the length of the surfacing part of the finger. Therefore, the samples were removed from further testing.

The average value of the relative wear of coating's metal without borides for the test was 0.0075 g/m. Mass wear for the friction path in 113 m was 0.674 g. The average linear wear for the test
was 0.0235 mm/m. As a result of tests, the friction torque decreased from 23.709 N·m (for a friction path of 113 m) to 19.601 N·m (for a friction path of 226 m). The average value of the friction torque for the friction path of 226 m was 21.634 N·m. The friction coefficient decreased from 0.504 (for the friction path of 113 m) to 0.423 (for the friction path of 226 m), and the average value for the test was 0.464.

| Table 2. Tribological properties of metal |
|------------------------------------------|
| Number of revolutions | Coating without borides | Friction coefficient |
|------------------------|--------------------------|----------------------|
|                        | The average value of the friction torque, [N·m] |                      |
| 0-300                  | 23.709                   | 0.504                |
| 300-600                | 19.601                   | 0.423                |
| **0-600**              | **21.634**               | **0.464**            |
|                        |                          |                      |
|                        | Coating with borides     |                      |
| 0-300                  | 19.026                   | 0.390                |
| 300-600                | 15.472                   | 0.354                |
| 600-900                | 20.880                   | 0.363                |
| 900-1200               | 20.910                   | 0.348                |
| 0-1200                 | **19.075**               | **0.364**            |

The boride coating metal withstood 1200 revolutions with a friction path of 452.16 m, and then the samples were removed from further tests. The average mass wear of samples after 300 revolutions was 0.382 g, after 600 revolutions it was 0.683 g, and after 900 revolutions it reached 1.13 g. After 1200 revolutions, wear was 1.531 g. Relative wear slightly increases from 0.0034 g/m at the beginning of the journey friction to 0.0036 g/m at the end. The average value of the relative mass wear per test was 0.0034 g/m, which is 2.2 times less than that of the coating metal without borides. At the same time, wear in length reached 3.9 mm. The average value of linear wear was 0.00862 mm/m, which is 2.7 times less than that of the coating metal without borides. At the same time, the friction torque increased from 19.026 N·m (for a friction path of 113.04 m) to 20.910 N·m (for a friction path of 452.16 m). The average value of the friction torque for the friction path of 452.16 m was 19.075 N·m. The friction coefficient fell from 0.390 (for a friction path 113.04 m) to 0.348 (for a friction path 452.16 m), and amounted to an average for wear tests of 0.364.

In order to compare the results of tribological tests with the microstructure of the surface layers under friction, electron microscopic studies of the topography of the specimens at characteristic loading sites were carried out (Fig. 1).

There is a high degree of fragmentation of the coating metal without borides due to the formation of slip bands (Fig. 1, a).

The microstructure of the formation of these slip bands is characterized by a regular arrangement of dipole dislocation clusters. The loading turns these bands into localized deformation foci in the form of mezholos. This process acquires an avalanche-like character and leads to selective emissions of destruction products from the frictional contact zone.

The local nature of the fracture with a chip along the boundaries of the substructure elements manifests itself. The destruction of the frictional contact zone is characterized as a global loss of shear stability of the surface layer after nucleation and movement of the mezholos by localized plastic deformation [17], which causes a significant wear of such material already on small friction paths.
Microstructural studies of the coating metal with borides after frictional loading reveal the formation of a block structure that is quasi-evenly distributed over the volume of the surface layer (Fig. 1, b). In the surface layer, together with hardening, some plasticity of the material is realized due to the high length of the block boundaries and the boundary slippage. Simultaneous grinding of the block microstructure leads to an increase the limit of macroscopic elasticity and resistance to fatigue failure by reducing grain-boundary cracking \[18\]. There is a strong tendency to textured dislocation clusters in one direction and the development of microstrip localized plastic deformation.

In the microstructure, the presence of small microcracks is noted, which are combined into a main crack by destroying the material separating them, thus forming material wear lobes.

To identify the causes of differences in the hardness of coatings deposited by flux-cored wires of the studied compositions was performed a complex of metallographic and durometric studies.

The microstructure of the metal deposited by flux-cored wire without borides is a mixture of low carbon martensite with highly dispersed perlite. Allocation of strengthening phases is observed along the grain boundaries, and δ-ferrite inside the grains (Fig. 2, a). Such a mixed structure provides the hardness of the metal up to 40 HRC.

The deposited metal of the boride coating after surfacing has a complex composition structure with a martensitic matrix, a large number of eutectics and particles of reinforcing phases (Fig. 2, b). The hardness of such a metal reaches a maximum value of 58 HRC.
Durometric studies showed significant differences in the microhardness of the structural components of the metal of the investigated coatings (Table 3).

Table 3. Microhardness $HV_{0.01}$* and $HV_{0.05}$ structural components of the metal of the coating deposited by flux-cored wires

| Puncture no. | 1 | 2* | 3* | 4* | 5* | 6  | 7  | 8  | 9  | 10 | 11* | 12* |
|--------------|---|----|----|----|----|----|----|----|----|----|-----|-----|
| without borides | 408 | 376 | 358 | 551 | 384 | 424 | 393 | 429 | 389 | 411 | 609 | 572 |
| № puncture with borides | 1 | 2 | 3 | 4 | 5 | 6 | 7* | 8 | 9 | 10 | 11* | 12 |
| 978 | 587 | 540 | 552 | 575 | 546 | 1342 | 521 | 593 | 874 | 1262 | 829 |

As can be seen, the microhardness of the metal matrix without borides varies from 390 to 430 HV, $\delta$-ferrite from 358 to 384 HV, and reinforcing phases 550-610 HV.

The microhardness of the structural components of the metal deposited by flux-cored wire with borides is for the matrix 521-593 HV, the eutectic 829-978 HV and the reinforcing phases 1262-1342 HV.

To identify the mechanism of wear of the deposited metal of the coating with borides, electron microscopic studies were carried out.

The results of a scanning electron microscopic analysis of a metal with borides, the structure of which is shown in Fig. 3 are summarized in Table 4. Energy dispersive analysis (EDA) showed that the metal structure is an iron-chromium martensitic matrix with a eutectic component formed on the basis of boride $(\text{Fe}, \text{Cr})_2\text{B}$, having a frame structure, dispersed inclusions of carborides type $(\text{Fe}, \text{Cr})_7(C, B)_3$ and high-strength nitrides $\varepsilon$–$(\text{Fe}, \text{Cr})_23\text{N}$.

Figure 3. Research by the method of scanning electron microscopy of the structure metal of the coating deposited by flux cored wire

Table 4. The chemical composition of the areas of the coating metal, deposited by cored wire with borides

| Spectrum | B [%] | N [%] | C [%] | Cr [%] | Fe [%] | Ti [%] | Zr [%] |
|----------|-------|-------|-------|--------|--------|--------|--------|
| 1        | 1.95  | 23.37 | 7.59  | 11.40  | 19.13  | 29.47  | 7.09   |
| 2        | 24.32 | 0     | 5.32  | 24.92  | 45.22  | 0.17   | 0.05   |
| 3        | 8.78  | 0.66  | 10.52 | 17.39  | 62.55  | 0.07   | 0.04   |
| 4        | 5.65  | 1.37  | 7.77  | 15.08  | 70.03  | 0.06   | 0.04   |
| 5        | 7.73  | 0.27  | 6.32  | 15.50  | 70.09  | 0.06   | 0.02   |
| 6        | 2.96  | 20.75 | 9.16  | 16.48  | 10.45  | 31.16  | 9.04   |

The study of the distribution maps of the main elements showed that the composite structure of the coating is characterized by the presence of a significant amount of dispersed inclusions by the majority...
of titanium nitrides and carbides and a smaller part by zirconium nitrides ranging in size from 0.2 to 3.4 microns.

The results indicate that the mechanism of wear of the metal of the coating with borides is associated with its increased hardness caused not only by dispersion hardening by particles of boride compounds, but also by the presence of boride eutectics, which are effective obstacles to dislocation slip under conditions of plastic deformation of the surface during wear [18].

The higher wear resistance of the metal with borides can be explained by the combined effect of the framework of solid eutectic carboborides and boride-nitride-intermetallic particles, which, under abrasive wear conditions, effectively protect the coating matrix. As a result, weaker traces of abrasive, adhesive and deep fracture, as well as a very slight crushing of the material, are characteristic of the worn surface of such a metal.

4. Conclusion
The high wear resistance of metal deposited by cored wire PPKh15 + 0.5%B4C + 0.5%BN + 2.5%TiB2 + 1.0%ZrB2 is explained by the presence of solid eutectic carboborides and particles of the carbide-boride-nitride-intermetallic compounds in its structure, which, under abrasive wear conditions, receive a part of contact interaction, which increases the resistance to tearing of a metal operating under abrasion conditions. Apparently, this is due to the fact that the dispersed high-strength phases are effective obstacles to the dislocation slip in the surface layers of the metal during its frictional interaction.

Thus, high-chromium cored wire alloyed by a complex of compounds of boron and nitrogen, provides a composite-type metal with high wear resistance and can be used for hardening the surfacing of parts operating under conditions of significant frictional loading.

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