Tribological properties and wear resistance of the metal deposited by chromium flux-cored wire with carbide-boride alloying

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Abstract. The wear resistance and the tribotechnical properties of chromium steel of the Fe-C-Cr-B system deposited by flux-cored wire with boron carbide alloyed were investigated. It is shown that this steel has high wear resistance. The average values of the mass wear of the deposited metal is 0.0028 g/m, and the linear values are 0.00723 mm/m. The average value of the friction moment was 21.82 N·m, and the coefficient of friction was 0.412. The hardness of such a metal reaches a maximum value of 58 HRC. The microhardness of structural objects for the matrix is 499-603 HV, for hardening phases is 859-924 HV. The metal structure is a martensitic matrix with a large number of reinforcing phases, formed on the basis of type carboboride (Cr, Fe)$_7$(CB)$_3$. It is shown that the mechanism of metal wear is associated with its high hardness due to the dispersed hardening by particles of compounds, which are effective obstacles to dislocation slip under conditions of plastic deformation of the surface during wear and a decrease in the role of the abrasive component of wear.

1. Introduction
One of the directions in modern engineering is the surface hardening of relatively cheap steels used for the manufacture of machine parts and mechanisms operating in difficult exploitative conditions. One of the methods of hardening, which is actively developing at the present time, is surfacing working surfaces by wear-resistant flux-cored wires.

A significant range of parts of various industries, is made of stainless chromium steel, combining a fairly high strength and corrosion resistance [1]. Such steels are used as surfacing materials to obtain wear-resistant coatings on parts for a wide range of purposes. Based on this, flux-cored wires of the Fe-Cr system have been developed [2, 3]. At the same time, the wear resistance of the metal deposited by such wires is not very high. This is due to the small number of hardening phases in the structure of coatings deposited by such wires. On this basis, a promising way is the development of coatings of their chromium steel with reinforcing phases of high hardness. One of the ways to improve the properties of the deposited metal is dispersion hardening due to the introduction of boride compounds into it [4–7]. Alloying by boron carbide opens up special prospects [8–11]. At the same time, the tribotechnical properties and wear resistance during frictional interaction of friction pairs of such coatings has been insufficiently studied.

2. Objects and research methods
In connection with the above, structural transformations during wear and the main tribological properties of the metal deposited by flux-cored wire PPKh15 alloyed with 2% boron carbide were 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. Surfacing mode: current 230 A; voltage 24 V; surfacing speed of 20 m/h.

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. The test was carried out at a load F=0.75 kN and a counterbody disk rotation speed of 100 rpm. Samples were weighed after every 300 revolutions of the disk, i.e. the time of one cycle was 3 minutes, and the friction path of the sample (finger) was 113.04 m. One of the compositions was tested until the wear value equal to the change of the sample length did not exceed 4-5 mm.

Metallographic studies of the deposited metal were performed on an AXIO Observer A1m (Carl Zeiss) optical microscope. The microstructure was detected by chemical etching in the reagent composition: $CuSO_4$ – 4 g; HCl – 20 ml; H_2O – 20 ml.

The hardness of the deposited metal was measured by the Rockwell method on a TK-2 instrument, and the microhardness of the structural components was determined by the Vickers method on a Shimadzu HMV-2 microhardness meter with loads of 10 g and 50 g.

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

3. Experimental results and discussion

Metallographic studies have established that a composite structure is observed in metal obtained by surfacing with PPKh15+2.0% B_4C wire (Fig. 1). It has a pronounced dendritic character. Along the boundaries of the dendritic cells is a eutectic. In the martensin matrix, a large number of precipitates of hardening phases are observed. The total hardness of such a metal after surfacing reaches 58 HRC.

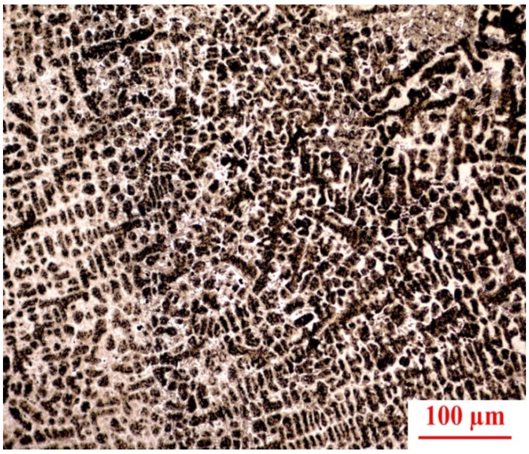


Figure 1. The microstructure of the metal obtained by surfacing with wire PPKh15+2.0%B_4C

The results of the study of the microhardness of the structural components of such a metal are shown in Fig. 2 and are given in Table 1.

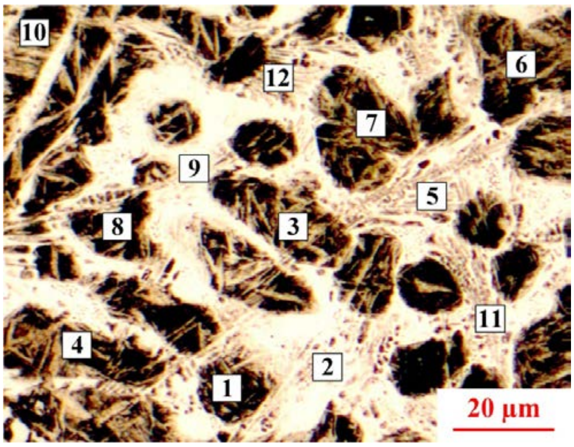


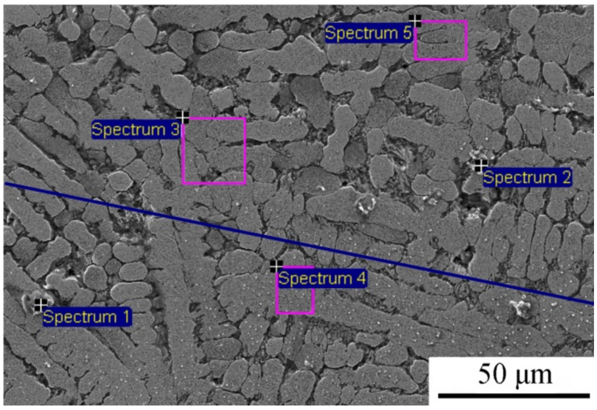
Figure 2. Measurement areas of microhardness of the structural components of the deposited metal

Table 1. Microhardness $HV_{0.05}$ structural components of the weld metal

№ puncture	1	2	3	4	5	6	7	8	9	10	11	12
HV	499	859	548	586	924	532	603	509	800	529	891	924

From table 1 it can be seen that the microhardness of the matrix of the deposited metal is within 499...603 HV. There is a large number of eutectics. The microhardness of the released hardening phases is within 859...924 HV.

The results of a scanning electron microscopic analysis of such a metal with the location of the scanning areas and the distribution of the main alloying elements over the surface of the coating are shown in Fig. 3. It is noted that carbon and boron are located mostly in eutectic, while in the matrix are mainly iron and chromium.



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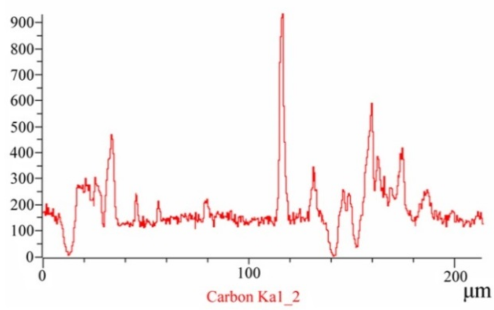

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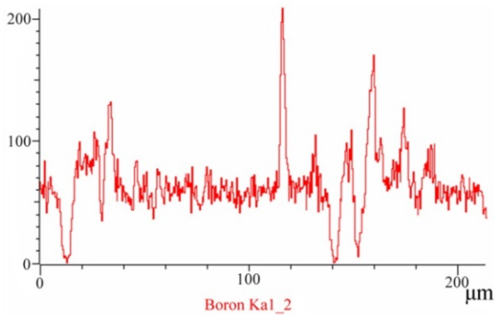

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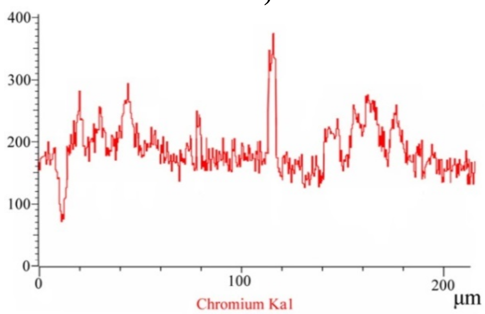

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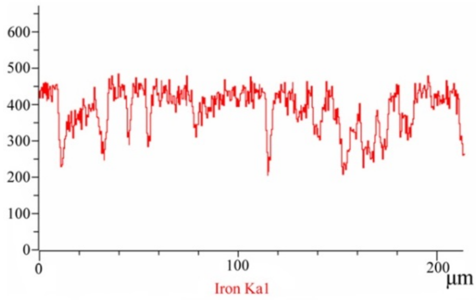

e)

Figure 3. The results of the scan of the structure of the deposited metal:
a) the image of the scanned microstructure; b-e) concentration spectrograms of the distribution of elements along the scan line

The results of the chemical composition of the scanned areas of the identified structure are given in Table 2. It has been established that all boron is in eutectic, which consists of borides and chromium and iron carboborides, while boron is absent in the matrix.

From the research results, it follows that the structure of the metal under study is an iron-chromium martensitic matrix with a eutectic component, formed mostly by chromium and iron borides of the (Fe, Cr)$_2$B type and dispersed inclusions of carboboride of (Fe, Cr)$_7$(C,B)$_3$ type. Due to their large number, boride eutectic is characterized by high microhardness.

Table 2. Results of the chemical composition of the deposited metal areas

Spectrum	C, %	B, %	Cr, %	Fe, %
1	22.70	20.34	8.81	48.15
2	21.92	24.89	7.70	45.49
3	9.16	0	15.50	75.34
4	12.10	5.17	14.39	68.34
5	7.59	0	13.78	78.63

The test results on the adhesive wear of the metal obtained by surfacing PPKh15+2.0%B_4C are given in Table 3-6 and Fig. 4.

The mass of the investigated samples with holders before testing and after testing are given in Table 3, and their mass wear and reduction of their length in Table 4 and 5.

Table 3. Change of mass of samples with holders, gr. as a result of testing

Number of turns	Sample 1	Sample 2	Sample 3	Average value
0	20.2583	20.18	19.8615	**20.0999**
0-300	19.8841	19.6563	19.3482	**19.6295**
0-600	19.5632	19.3877	18.9645	**19.3051**
0-900	19.4251	19.0427	18.7203	**19.0627**
0-1200	19.1361	18.7132	18.6329	**18.8274**
0-1500	18.8191	18.437	18.2957	**18.5173**

Table 4. Mass sample wear, gr.

Number of turns	Sample 1	Sample 2	Sample 3	Average value	Relative wear, g/m
300	0.3742	0.5237	0.5133	**0.4704**	0.0042
300-600	0.3209	0.2686	0.3837	**0.3244**	0.0029
600-900	0.1381	0.345	0.2442	**0.2424**	0.0021
900-1200	0.289	0.3295	0.0874	**0.2353**	0.0021
1200-1500	0.317	0.2762	0.3372	**0.3101**	0.0027
0-1500	1.4392	1.743	1.5658	**1.5827**	0.0028

Table 5. The change in the length of the sample, mm

Number of turns	Sample 1	Sample 2	Sample 3	Average value
0	18.07	18.05	18.08	**18.0667**
1500	14.3	13.56	14.08	**13.98**
Wear on the length of the samples, mm				
0-1500	**3.77**	**4.49**	**4**	**4.08667**

The main tribological properties of the deposited metal are given in Table 6.

Table 6. Change of friction moment and friction coefficient of the deposited metal

Number of turns	The average value of the friction torque, N·m	Friction coefficient
0-300	24.999	0.546
300-600	21.283	0.447
600-900	20.289	0.375
900-1200	21.163	0.357

1200-1500	21.387	0.336
0-1500	**21.822**	**0.412**

Studies show that the metal deposited by flux-cored wire PPKh15+2.0%B_4C has a rather high wear resistance. Samples with such a metal withstood 1500 revolutions with a friction path of 565.2 m, and then were removed from tests. Mass wear for the friction path of 226.048 m is only 0.794 g. Mass wear at the friction path of 565.2 m has reached 1.5827 g (Table 4), and the shortening of the sample was 4.08 mm (Table 5). The relative mass wear significantly drops from 0.0042 g/m at the beginning of the friction path to 0.0027 g/m at the end. The average value of the relative mass wear per test was

0.0028 g/m. The average value of linear wear was 0.00723 mm/m. At the same time, the friction torque fell from 24.99 N·m (for a friction path of 113.04 m) to 21.38 N·m (for a friction path of 565.2 m). For this way in 452.16 m, the magnitude of the decrease in the average value of the frictional moment was 3.61 N·m. The average value of the friction torque for the friction path of 565.2 m was 21.822 N·m. The friction coefficient decreased from 0.546 (for a friction path of 113.04 m) to 0.336 (for a friction path of 565.2 m) and amounted to an average value during testing 0.412.

The dependence of the friction moment of the deposited metal on the number of revolutions (friction path) is shown in Fig. 4.

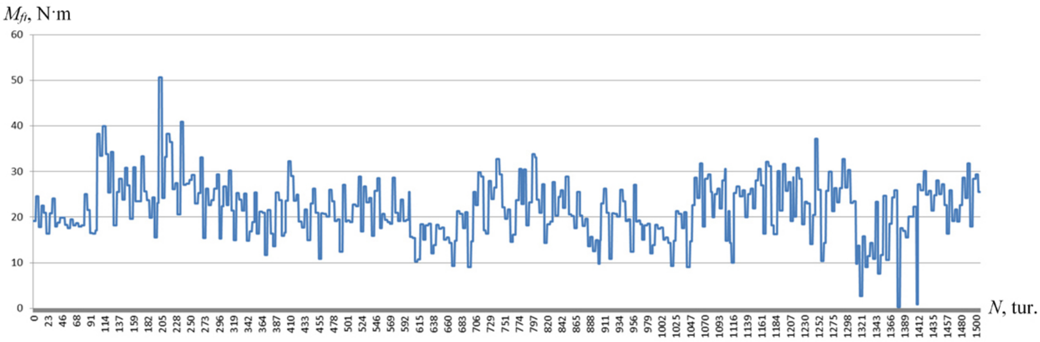

Figure 4. Values of friction torque of the deposited metal on the number of revolutions

A gradual change in the oscillating curve is noted. After break-in, the achievement of a critical level of elastic deformation energy ensuring maximum hardening occurs at average values of friction torque of about 30 N·m, and fracture at average values of friction torque of about 10 N·m and even lower.

The fall of the friction coefficient of the coating during the tests is due to a decrease in the roughness of the friction surface and the area of actual contact and a decrease as a result of this contact pressure.

Additional information about the processes of destruction of the surface layer provides an analysis of its topography (Fig. 5).

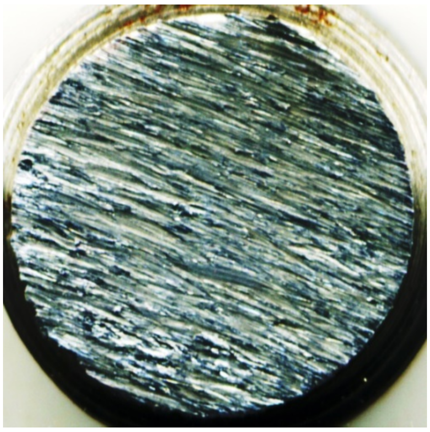

Figure 5. The end surface of the sample of the deposited metal after wear testing

The surface of the sample of the deposited metal has a relatively smooth appearance and is characterized by insignificant deep tears of the coating metal.

Microstructural studies of the metal end of the sample after frictional loading reveal the formation of a block structure that is quasi-evenly distributed over the volume of the surface layer (Fig. 6).

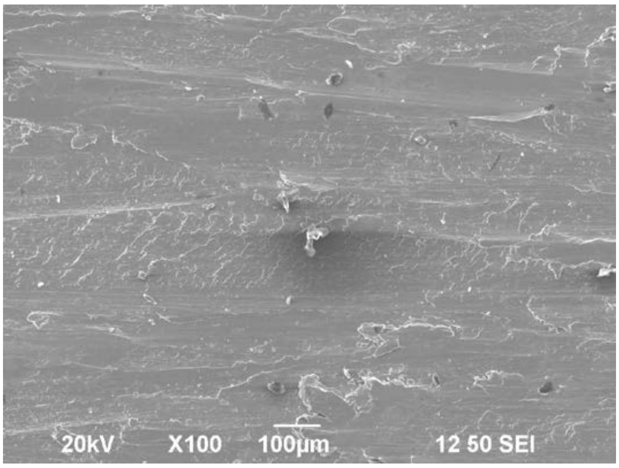

Figure 6. General view of the wear surface of the sample of the deposited metal

In the surface layer, along with a high degree of hardening, a certain plasticity of the material is realized due to the high extent of the block boundaries and the boundary slippage. There is an increasing tendency to textured dislocation clusters in one direction and the development of microbands by localized plastic deformation.

The positive effect of boron carbide on the wear resistance of the metal is apparently connected not only with structural changes in the metal base of the matrix, but also directly with the nature of boron, which, due to its specific atomic-crystalline structure and physical and mechanical properties, serves as an internal lubricant that reduces the coefficient of friction in contact medium [12, 13]. This is confirmed by the topography of the worn surface - the traces of abrasive interaction are very weakly expressed. This also indicates that boron contributes to the formation of durable passivating films, which do not break even with heavy forms of abrasive wear, thereby preventing the formation of hardening foci. As a result, such a metal is characterized by a smaller depth of traces of abrasive impact of the counterbody and, more importantly, a significantly smaller area of destruction of oxide films on a worn surface, which, as is well known, prevents the formation of setting points and slows down the rate of abrasion during abrasive wear [14, 15].

Thus, the mechanism of metal wear, deposited by cored wire PPKh15+2.0%B_4C, is associated primarily with its high hardness due to the dispersion hardening of particles of eutectic carboboride compounds, which are effective obstacles for dislocation slip [16] under conditions of plastic deformation of the surface when wear, and reducing the role of the abrasive component of wear. The more developed the grid of eutectic carboborides, the higher the wear resistance of the metal.

4. Conclusion

High wear resistance of metal deposited by cored wire PPKh15+2.0%B_4C can be explained, first of all, by the presence of solid eutectic carboborides in its structure, which, under conditions of oxidative and abrasive wear, effectively protect the coating matrix. The results obtained indicate that with an increase in the degree of hardening of the coating matrix, the safety of its structure during frictional interaction is higher. Apparently this is due to the fact that the dispersed high-strength phases are effective obstacles to the dislocation slip under conditions of plastic deformation of the planes during wear.

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

Acknowledgments

This research was made possible through the Russian Science Foundation grant (project №17-19-01224).

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