Structure and properties of chromium carbide reinforced steel matrix composites produced from powder iron-ferrochrome mixtures

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Abstract: *The influence of high-carbon ferrochrome on the features of structure formation and properties of chromium carbide steels based on the Fe-FKh800 system was investigated. It was shown that the optimal combination of hardness and tensile strength with sufficient crack resistance has a carbide base of 65% Fe - 35% (wt.) FKh800. A typical microstructure of sintered carbide is a metal matrix composite consisting of chromium steel of composition close to Kh17 and double carbide* $(Cr_{0.799}Fe_{0,201})_7C_3$. *The effect of* TiB_2 *additive on the structure, phase composition, mechanical and tribotechnical properties of materials based on the Fe- 35 (%,wt.) FKh800 system was also investigated. Additions of titanium borides in the amount of 0.38-1.48 (% wt.) leads to some increase in hardness, noticeable increase in the flexural strength and leads to increase wear resistance of carbidosteels.*
KEYWORDS: *POWDER MATERIALS, COMPOSITE, SINTERING, FKH800,* TIB_2*, MICROHARDNESS.*

Iron-chromium-carbon alloys, chromium steels and cast irons, are widely used in modern mechanical engineering for the manufacture of machine parts, mechanisms and equipment operated under conditions of simultaneous action of friction forces, abrasive, corrosive and erosive wear [1]. Having a heterogeneous structure, they are characterized by a significant difference in the properties of the components - carbide and metal phases - in their hardness, strength, ability to plastic deformation, resistance to fracture, etc. by changing the ratio of the metal and carbide components, it is possible to obtain material with different contents of hard and soft inclusions. Accordingly, hard inclusions can significantly increase the abrasion resistance, and soft - antifriction properties of alloys.

Along with traditional methods, powder metallurgy technology is widely used to create such heterogeneous structures. In this embodiment, the finished solid additives are artificially introduced into the powder mixture or use special sintering modes that do not lead to homogenization of the structure of the material [2]. The list of such materials includes the materials we study from iron powders and high-carbon ferrochrome FKh800 [3].

In the works [3-5] performed by us earlier, it was shown that the use of high-carbon ferrochrome (8% C by wt.) instead of chromium carbide allows to obtain by powder metallurgy composite material based on iron, which is equivalent in wear resistance and strength exceeds materials type chromium steel - Cr_3C_2. However, the influence of high-carbon ferrochrome content on the sintering temperature, structure formation, mechanical and functional properties of iron - FKh800 composites remain unclear.

The aim of the study was to study the effect of high-carbon ferrochrome content on the phase composition, structure and physical and mechanical properties of powdered chromium carbide steels.

Objects and research methods

For experiments used iron powder and high-carbon ferrochrome powder FKh800 (72.2% Cr, 18.8% Fe, 8.4% C, 0.6% O (% by weight), fractions -200 +100 μm Other properties of FKh800, obtained by mechanical dispersion of lump ferrochrome, are presented in [3] Powder mixtures were obtained by wet grinding in a ball mill according to the modes described in [6]. in 5% increments.

Powder mixtures of materials were prepared by wet milling-mixing in a ball mill in alcohol medium according to the regimes given in [6] article. The samples were pressed in a closed die at 800 MPa. Sintering was carried out in a vacuum electric furnace according to pre-established regimes that ensure the production of materials with maximum density. The mechanical properties of the samples were determined by standard methods for powder materials and hard alloys [7, 8]. The microstructure of the materials was examined on a REM-106I electron microscope. The phase composition of the samples was investigated by X-ray diffraction analysis (XRD) on the diffractometer "UltimaIV, Rigaku" (Japan).

Results and discussion

The construction of the polythermal cross section was carried out by the analytical - graphical method using projections of the solidus and liquidus surfaces and isothermal cross sections of the state diagram of the Cr-Fe-C system, published in the review [9]. The high-temperature region is represented by a compilation of works [10,11] (liquidus surface) and by thermodynamic calculations [12] (solidus surface). Solid-phase transformations are accepted by the results of thermodynamic modeling in [13], for which the authors of [14] later calculated a number of isothermal cross sections. Features of this version of the state diagram of the system Cr-Fe-C - equilibrium stability (γ-Fe) + $(Cr, Fe)_{23}C_6$ from 855 °C to the solidus temperature, which is consistent with detailed experimental studies [15].

The polythermal cross section shows wide areas of biphasic equilibria (γ-Fe) + $(Cr, Fe)_7C_3$ and (α-Fe) + $(Cr, Fe)_7C_3$ and a certain similarity with the eutectic type state diagram (Fig. 1). It should be noted that the data on the position of the three-phase regions have a large variance and therefore in Fig. 1 they are shown in dotted lines. The constructed polythermal cross section allowed to estimate the composition of the eutectic as 73.7Fe-26.3 FKh800 (% by weight), its formation temperature as 1285 °C, as well as to determine the approximate, most suitable, sintering interval of iron-based composites with different content of FKh800 as 1100- 1250 °C.

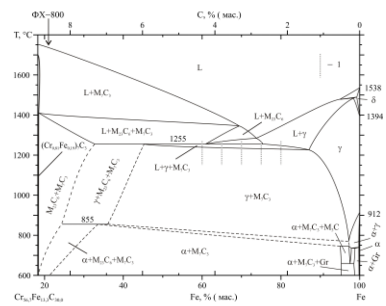

Fig. 1 *- Polythermal cross section* $(Cr_{0,81}\ Fe_{0,19})_7C_3$ *- Fe of the state diagram of the Cr-Fe-C system*

Typical microstructures of carbide steels with 25 and 35% (wt.) FKh800 are shown in Fig. 2. It is seen that their microstructure is heterogeneous and consists of metal and carbide phases and a number of pores. The microhardness of the carbide phase is 10-12 GPa, and the metal 2.5-2.8 GPa.

Micro-X-ray spectral analysis of the sample with 35% (wt.) FKh800 revealed that the metal phase contains 17.1% (wt.) Cr and the composition is close to chromium steel type X17: the average result of 23 measurements of 82.7% Fe - 17, 1% Cr - 0.2% C (% by weight). In the carbide phase received a carbon content of 7% (wt.) or 25% (at.), Which corresponds to the carbide $(Cr, Fe)_3C$: 19.8% Fe - 73.1% Cr - 7.1% C (% by mass). But X-ray phase analysis clearly identifies the main phases as (α-Fe) + $(Cr, Fe)_7C_3$ (Fig. 3). Adjusting the carbon content to 30% (at.), we obtain the composition of the carbide as $(Cr_{0,799}Fe_{0,201})_7C_3$ or 71.7% Cr - 19.4% Fe - 8.9% C (% by weight).

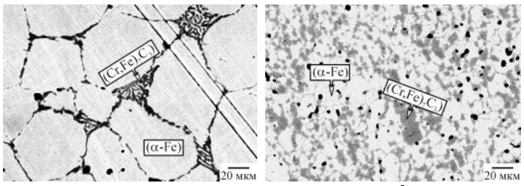

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***Fig. 2** - Influence of sintering temperature and TiB_2 additives on volume shrinkage (a), density (b) of samples from composite material Fe-35%FKh800*

The results of X-ray indexing (Fig. 3) clearly indicate that the metal phase of carbide is a BCC phase based on α-Fe with a period a = 0.2872 nm. The lattice periods of the carbide phase also changed slightly compared to the binary compound: a = 0.6988, b = 1.2076 and c = 0.4500 nm. The texture is observed due to the fact that the diffraction pattern was taken from a section. Peaks that do not belong to the main phases were not detected.

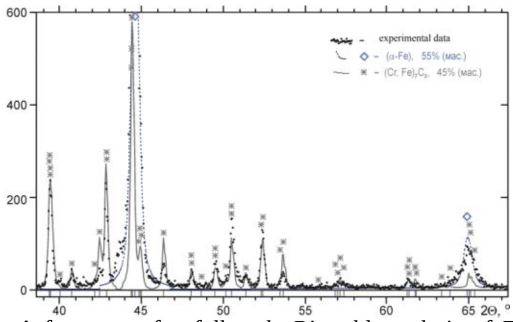

***Fig. 3** - A fragment of a full-scale Rietveld analysis of Fe-35% FKh800 carbide steel obtained by sintering at 1250 °C*

To establish the optimal composition, the effect of FKh800 content on the physical and mechanical properties of carbide steels was investigated. The obtained results showed that increasing the content of FKh800 from 25 to 35% (wt.) leads to an increase in hardness from 67 to 75.5 HRA and bending strength from 1100 to 1712 MPa (Fig. 4). The extreme nature of the concentration dependence of hardness and strength can be explained by the superposition of several factors: the simultaneous increase in hardness and brittleness with increasing content of FKh800 and significantly lower porosity of composites with 35 and 40% (wt.) FKh800 (2.6%) compared with composites with lower content solid component.

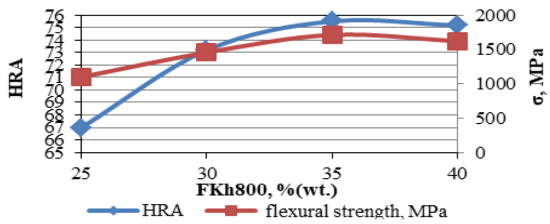

***Fig. 4** - The effect of the content of Fkh800 on the hardness and flexural strength of samples of composite materials*

Along with flexural strength and hardness, an important characteristic is crack resistance, which determines the ability of a material to absorb the energy of cracks that develop in it during fracture. It is known that an increase in strength and hardness is often offset by a decrease in ductility, resulting in a decrease in fracture toughness. The study of the dependence of crack resistance on the content of FKh800 showed (Fig. 5) that, as expected, an increase in the content of the solid component leads to a decrease in the crack resistance of composites.

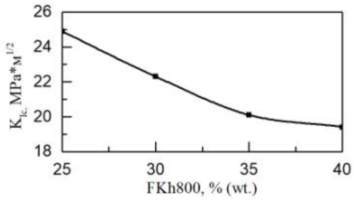

***Fig. 5** - Crack resistance of composites with different content of FKh800, obtained at the optimal sintering mode: 30 min. at 1250 °C*

Concentration dependences of hardness and flexural strength of Fe-FKh800 composites are characterized by maxima at 35% (wt.) FKh800: 75.5 HRA and 1712 MPa, respectively. Crack resistance is reduced from 25 MPa*m$^{1/2}$ at 25% (wt.) FKh800 to 19.5 MPa*m$^{1/2}$ at 40%. The optimal combination of hardness and tensile strength with sufficient crack resistance has a carbide base of 65% Fe - 35% (wt.) FKh800.

It is promising to additionally introduce strong carbide and boride forming elements into the composition of chromium steels and cast irons, which ensure the creation of special carboborides and the redistribution of chromium between the solid phase and the metal matrix. Since the basis of the composite material is iron or chromium steel, it is advisable to study the effect of boron additives on the structure and properties of the material iron - high carbon ferrochrome FKh800. TiB_2 additives were introduced in an amount of 0.38-2.2 (% wt.), which corresponds to the content of titanium 0.25-1.5 (%, wt.) in the alloy Fe-35% FKh800.

The effect of titanium boride additives on the structure and properties of chromium carbide steel Fe-35 FKh800 (%, wt.) was studied. The introduction of titanium borides in an amount up to 1.48 (wt. %) leads to a slight increase in the hardness of carbidosteels, but a further increase in the content of the additive to 2.2 (wt. %) leads to a decrease in rigidity. This dependence can be explained by the fact that as a result of the interaction of titanium borides with the composite components, there is the formation of complex carboborides type Me_3CB, as well as complex iron-chromium carbides type Me_7C_3, which contribute to increase their hardness. The flexural tensile strength of the Fe-35% FKh800 composite with an increase in TiB_2 content is maximum at 0.74 TiB_2 (wt.%), after which a further increase in the amount of titanium diboride leads to its significant fall (fig. 6). This can be explained by the optimal ratio of the amount of Me_7C_3 and $Me_3(CB)$ at 0.74 TiB_2 (wt.%).

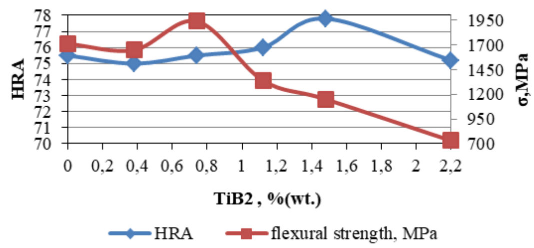

***Fig. 6** - Influence of the amount of TiB_2 additives on the hardness and flexural strength of powder materials*

Metallographic electron microscopic and local micro-X-ray spectral analysis of the Fe- FKh800 doped TiB_2 showed that their structure is microheterogeneous, multiphase and consists of light gray, gray, dark gray and black phases. The doping with TiB_2 affects the structure of the carbide phase of the composite, especially when the content of TiB_2 is 0.74-1.48 (wt. %) (fig.7). The size of the carbides decreases from 8-13 to 4-6 μm. Due to the simultaneous action of two factors, on the one hand, boron affects the decrease in sintering temperature, and, on the other hand, titanium additives contribute to the inhibition of grain growth. To increase the amount of titanium boride additives, dark gray phases appear in the structure of the material, their size being 3-5 μm. However, their number becomes significantly less when the content of the additive is 2.2 (% wt.). According to the results of X-ray spectral analysis, the composition of the dark gray phases indicates that it is a complex chromium carbide of the Me_7C_3, and the gray phases are the carboborides of the $Me_3(CB)$.

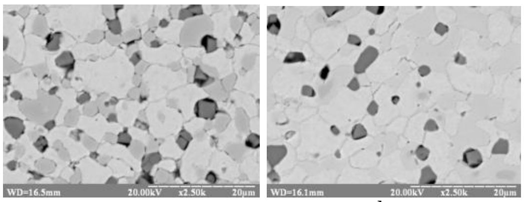

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Fig7 - Electron microscopic image of the microstructure of samples of materials Fe-35% FKh800 with TiB_2 additives 0.74 (a), 1.48 (b) (% wt.)

We studied the effect of TiB_2 additives on the abrasion resistance of Fe-35 FKh800 materials (wt. %.) when they are treated with ASB 160/125 diamond wheel fixed particles according. The tests were carried out under such friction conditions: sliding speed - 1 m/s, load - 0.5 MPa, friction path - 1 km, friction at room temperature in air, without lubrication.

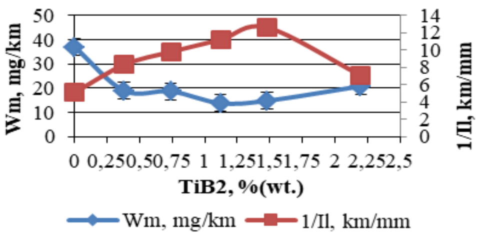

***Fig. 8** - The effect of the amount of TiB_2 additives on the mass wear W_m (mg / km) and the wear resistance of the materials of the Fe- FKh800-TiB_2 system*

The results of the studies showed (Fig. 8) that an increase in the amount of TiB_2 supplement from 0.38 to 1.48 (% wt.) leads to a decrease in mass wear (W_m) from 36.94 to 14.8 mg / km and linear wear (I_L) from 0.197 to 0.079 mm / km. This can be explained by the formation of complex carbides type Me_7C_3 and carboborides type Me_3CB, which increase the microhardness of carbide phases, as well as increase the adhesive strength of solid grains by the metal matrix. However, a further increase in the amount of dopant to 2.2 (wt. %) leads to an increase in mass wear (from 14.8 to 20.8 mg / km) and linear wear of the samples (from 0.079 to 0.141 mm / km).

Conclusions

Studies of the effect of the amount of high-carbon ferrochrome FKh800 25-40 % (wt.) on the mechanical properties of composites showed that the concentration dependences of hardness and flexural strength of Fe-FKh800 composites are characterized by highs at 35% (wt.) FKh800: 75.5 HRA and 1712 MPa in accordance. Crack resistance is reduced from 25 MPa*m$^{1/2}$ at 25% (wt.) FKh800 to 19.5 MPa*m$^{1/2}$ at 40%. The optimal combination of hardness and tensile strength with sufficient crack resistance has a carbide base of 65% Fe - 35% (wt.) FKh800. A typical microstructure of sintered carbide is a metal matrix composite consisting of chromium steel of composition close to Kh17 and double carbide 71.7% Cr - 19.4% Fe - 8.9% C (% by wt.) or $(Cr_{0.799}Fe_{0,201})_7C_3$.

The effect of TiB_2 additive on the structure, phase composition, mechanical and tribotechnical properties of materials based on the Fe- FKh800 system was also investigated. Additions of titanium borides in the amount of 0.38-1.48 (% wt.) leads to some increase in hardness and noticeable increase in the flexural strength of carbidosteels. It has been shown that titanium boride supplements provide the formation of a multiphase, microheterogeneous matrix-filled structure. The doping of the composite with TiB_2 additives in the amount of 0.74-1.48% (wt.) leads to the crushing of the structure of the matrix and carbide phases. Investigation of the effect of TiB_2 additive on abrasion resistance, showed that an increase in the amount of dopant from 0.38 to 1.48 (% wt.) leads to a decrease in mass (W_m) from 36.94 to 14.8 mg / km and linear (I_L) from 0.197 to 0.079 mm / km of carbidosteel wear.

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