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Features of the Fabrication of High-Alloy Wear-Resistant Cast Irons for Operation in Conditions of Hydroabrasive Wear

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The formation of the structure of the metal matrix of wear-resistant cast irons and its effect on their mechanical properties are investigated. As found out, it is useful to add 0.15–0.20% Ti and 0.15–0.25% of rare earth metals at the final stage of melting (after additive) in order to improve the structure, to neutralize the influence of harmful impurities, and to enhance wear resistance of the cast irons, which contain chromium and manganese. Enhanced hydroabrasive wear resistance of the parts of some mechanisms of thermal-power plants is achieved by reduced content of such alloying elements as chromium and manganese that increases the service life. It is recommended to use chromium–manganese cast irons with a manganese content of up to 2.5–2.7% for the fabrication of cast wear-resistant parts, and to heat treatment such cast irons with careful selection of the optimal austenitizing temperature and isothermal holding. The effect of isothermal annealing on

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reducing the hardness of chromium–manganese cast iron to 39–40 HRC to further facilitate machining of parts is presented.

Key words: alloyed cast iron, hydroabrasive wear, wear-resistant cast iron, chromium, manganese, titanium carbides, heat treatment.

В роботі досліджено закономірності формування структури металевої матриці зносостійких чавунів та її вплив на механічні властивості. Встановлено, що для поліпшення структури, нейтралізації впливу шкідливих домішок і підвищення зносостійкості хромоманганових чавунів їх доцільно перед випусканням із топильного агрегату додатково обробляти 0,15–0,20% Ti та 0,15–0,25% РЗМ (за присадкою). Підвищення гідроабразивної зносостійкості деталей теплових електростанцій досягається через зменшення витрат легувальних елементів, таких як Хром і Манган, що збільшує термін експлуатації. Рекомендовано для виготовлення литих зносостійких деталей використовувати хромоманганові чавуни з вмістом Мангану до 2,5–2,7%, а термічне оброблення таких чавунів проводити з ретельним підбором оптимальної температури аустенізації й ізотермічною витримкою. Представлено вплив ізотермічного відпалу на пониження твердості хромоманганового чавуну до 39–40 HRC для подальшого полегшення механічного оброблення деталей.

Ключові слова: легований чавун, гідроабразивне зношування, зносостійкий чавун, Хром, Манган, карбіди Титану, термічне оброблення.

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1. INTRODUCTION

The thermal-power industry is one of the main consumers of wear-resistant alloys. The parts of the systems for solid pulverized fuel preparation and slag and ash removal from boiler units of thermal power plants work under hard conditions of abrasive and hydroabrasive wear.

During the combustion of fuel in boiler units, a significant amount of slag and ash is formed, which is removed by water flow. The mixture of water and slag in the form of pulp enters the hydrosol-removal (HSR) system and is transported to the ash-disposal area. The turns of slime conveyer screws, rotors, casings and discs of dredging pumps, elbows of sludge lines work under conditions of abrasive and hydroabrasive wear in the HSR systems of thermal-power stations (TPSS). They are produced from wear-resistant Cr₂₈Ni cast iron by casting [1].

The slag and ash are the main abrasives, which cause wear of the parts of HSR systems. The concentration of abrasives in the pulp reaches 25–30%. The particles of slag that enter the hydrosol removal system have sizes from 0.04 to 100 mm. The main components of ash slag are oxides SiO₂, Al₂O₃, Fe₂O₃, CaO, and MgO, a small amount of sulphates CaSO₄, MgSO₄, and FeSO₄, and smaller amount of phosphates, alkali-metal oxides K₂O, Na₂O, *etc.* [2, 3].

Slag particles have various shapes—from needle-like to spherical. The shape of slag particles depends on their melting point, which is determined by the ratio of the content of the calcium and iron oxides to the content of the silicon and aluminium oxides [4]:

$$M = \frac{[\text{CaO}] + [\text{Fe}_2\text{O}_3]}{[\text{SiO}_2] + [\text{Al}_2\text{O}_3]}.$$

The higher this ratio, the more rounded the particles are, and *vice versa*—the slag takes on a needle-like shape and a more abrasive effect at lower M that can affect the HSR system parts.

In addition to the shape and size of slag and ash particles, the rate of wear of cast parts of HSR systems in TPSs is significantly affected by the corrosive components of the hydroabrasive medium. Corrosion activity of ash and slag pulp is determined by the mineral composition of slag and ash, which, in turn, affects the acidity or alkalinity of the aqueous suspension.

The destruction of working parts of machines and mechanisms used at TPSs occurs mainly due to intensive abrasive and hydroabrasive wear, *i.e.*, due to the action of abrasive particles on the materials and the erosive effect of water. An analysis of the operating conditions of parts in a hydroabrasive environment [5] showed that the resistance of metals and alloys to wear depends on their chemical composition and previous heat treatment. Appropriate composition and heat treatment provide optimal structure with high hardness and wear resistance [1–4].

In Ref. [6], the effect of the incidence angle of abrasive on hydroabrasive wear of white cast irons was studied. It was shown that white cast irons had high wear resistance at small incidence angles (10°). At small incidence angles, the wear resistance increased at higher carbon content (*i.e.*, at larger amount of the carbide phase). At larger incidence angles (over 70°), the wear resistance was almost constant at any carbon content.

Brittle materials have the lowest wear resistance at an incidence angle of 90° , *i.e.*, at right angle incidence [6]. For a material with increased ductility, the incidence angle corresponding to the maximum rate of wear decreases: it is of $50\text{--}70^\circ$ for quenched steel and of $30\text{--}40^\circ$ for the same steel in as-cast state.

In addition to the abrasive hardness, the rate of wear is also affected significantly by the size and shape of abrasive particles, and their extent of fixation [7]. The rate of wear increases with increasing size of the particles, their acuteness (*i.e.*, at smaller radii of their tips), and the extent of fixation [7, 8].

Cast irons with high wear resistance contain a significant amount of finely dispersed carbides with high microhardness ($10\text{--}16 \text{ kN/mm}^2$) (*e.g.*, $(\text{Cr,Fe})_3\text{C}$ or $(\text{Cr,Fe})_7\text{C}_3$), which are formed at high chromium content and have alloyed matrix [8, 9].

In cast irons, which contain up to 7% Cr, cementite-type Me_3C carbides are formed; the microhardness of these carbides reaches 1100 HV [10]. When a cast iron with 3% C contains more than 7% Cr, the amount of cementite-type carbides decreases due to the formation of chromium carbides with higher microhardness, and the wear resistance of the cast iron increases. Cast irons with $(Cr,Fe)_7C_3$ carbides have the maximum wear resistance. This effect is explained by the increased microhardness of these carbides, when the chromium content is of 11–13% [11].

Larger amount of carbides increases the wear resistance of cast irons, provided the type of carbides does not change. In a cast iron with 13% Cr and 3.2–3.4% C, the amount of Me_7C_3 carbides is of $\approx 30\%$ [10]. A further increase in the C content and the amount of carbides does not enhance wear resistance, since Me_3C carbides appear. The wear resistance of a cast iron reduces with increasing size of carbide particles. Coarse carbide particles crack, deform and crush under action of abrasive particles. Fine carbides partially transfer stresses to the metal matrix and do not fail.

For microcutting in a hydroabrasive medium, the critical size of carbides is of 7–8 μm . When this size is exceeded, the wear resistance drastically drops [10, 11]. For example, an increase in the amount of $(Cr,Fe)_7C_3$ -type carbides from 12% to 32% leads to an increase in the wear resistance of a cast iron with a pearlitic matrix by only 50%, whereas it increases by three times for a martensitic matrix [12].

Wear resistance significantly decreases, when just a small amount (less than 10%) of soft products of the pearlite transformation of austenite appears. The highest wear resistance of white cast iron is provided by a high-strength and hard martensitic matrix. In the conditions of impact abrasive wear, the transformation of residual austenite into martensite can increase wear rate due to tensile stresses that appear during this transformation.

As shown in Refs. [13, 14], wear resistance can be significantly increased only for the alloys, which undergo phase transformations during plastic deformation that precedes the fracture in microvolumes during wear. Cast iron with unstable alloyed austenite after rapid cooling of an ingot in a cold metal mould has a wear resistance 4–5 times higher than cast iron with an excessive amount of carbides; however, the latter does not undergo phase transformations during deformation [15].

Therefore, the wear resistance of cast irons with the same characteristics of the carbide component is related linearly to the microhardness of their matrix, which provides a higher wear resistance. An important issue in choosing a wear-resistant structure is the retention of carbides in the metal matrix even after phase transformations.

The aim of the work was the development of new wear-resistant alloys with high chromium content, the investigation of their properties

depending on chemical composition, and the determination of the effect of microalloying, modification and heat treatment on operating under severe extreme conditions.

2. MATERIALS

Wear-resistant alloys were smelted from steel scrap and recycled cast iron. The alloys were smelted in an induction furnace ИСТ-0,06 with a basic lining. Melting was carried out by remelting technique. Large pieces of ferrochrome, steel scrap, cast iron, and small pieces of ferrochrome were sequentially fed into the furnace. After, the charge was completely melted and the melt heated up to 1450–1470°C; appropriate additives were added to the crucible: preheated nickel, ferrovandium, ferrotitanium, ferromanganese, ferroboron or REM. The melt was kept until the additives were completely dissolved or melted; then, it was poured into a ladle and moulds. As a deoxidizer, aluminium was added in calculated amounts into the ladle during its filling with liquid metal; then, the melt was stirred with a rod.

The chosen shape of the samples (Fig. 1) made it possible to produce ingots in the lower mould in a horizontal position, which provided their maximum density in the zones, which were subjected to wear testing.

The moulds were filled with melt at 1380–1410°C. After cooling and punching out the ingots, the samples were mechanically processed in order to provide the same dimensions and surface cleanliness.

The determination of the wear resistance of iron-based alloys is suffi-

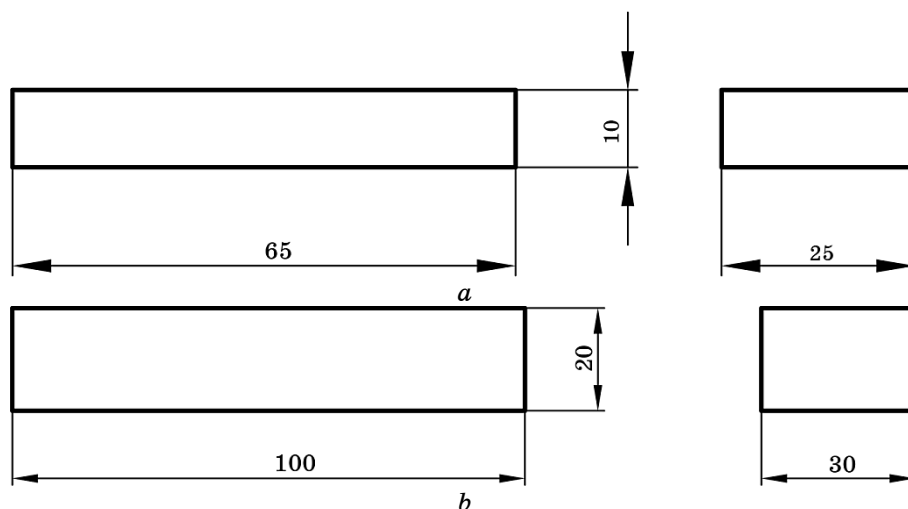


Fig. 1. Samples for investigations of wear resistance in a hydroabrasive medium (*a*) and hardness (*b*).

ciently accurate and useful for practical calculations, only if the wear process during testing is the same as during the operation of a real part.

The hydroabrasive wear resistance of materials is mostly carried out at uncontrollable incidence angles of abrasive particles. The samples are tested in a flux of abrasive liquid that affects their surfaces at varying angles (from 0° to 90°). The behaviour of samples in a hydroabrasive medium is estimated taking into account the following requirements: high reproducibility of results, metal losses sufficient to assess the wear of a sample during a relatively short test time, and the most stable conditions of testing. Pit sand was used as an abrasive material. Due to the irregular shape of its particles, this sand has a higher abrasive effect as compared to river sand. The test parameters under laboratory conditions were determined using $280 \times 28 \times 2$ alloy samples. The wear resistance of the investigated alloys was compared with that of these samples.

3. RESULTS AND DISCUSSION

The effect of chromium on the hardness of wear-resistant cast iron in the range of its concentrations from 4.5% to 31.6% at the C content up to 3.0% was studied. It is known that Cr-containing cast irons without additional alloying with austenite-stabilizing elements have low hardenability, so the original cast iron additionally contained 4.0–5.0% Mn [15]. This Mn content in chrome and manganese white cast irons with Me_7C_3 carbides provides the hardenability of ingots with an equivalent wall thickness of up to 350 mm that is valid almost for any ingot produced in industry.

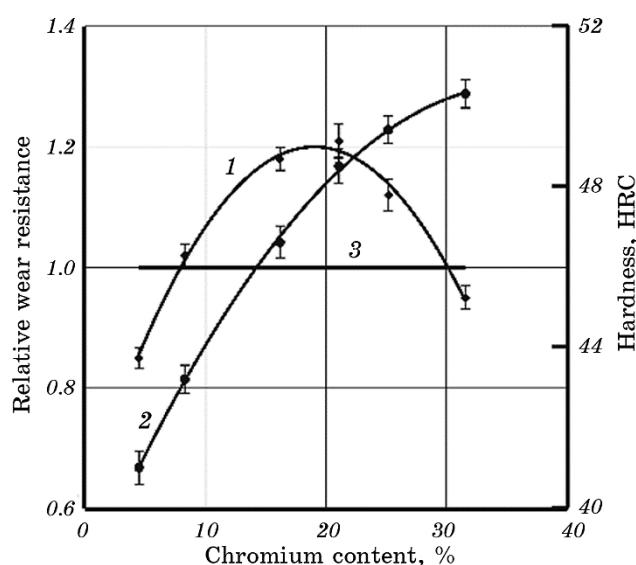
The relative wear resistance was determined in a hydroabrasive medium. The $Cr_{28}Ni_2$ alloy samples were used for reference. The chemical compositions and properties of cast irons are listed in Table 1 and shown in Fig. 2.

It is known that chromium contributes to intense chilling of cast iron. This element reduces the solubility of carbon in α - and γ -iron, increases the stability of the solid solution and the amount of the eutectic component. A Cr-enriched carbide phase of the cementite type is formed in cast irons even at low chromium content [15, 16].

It is found out that an increase in Cr content from 4.5% to 21.1% significantly enhances the operational properties of Mn-containing cast irons. When Cr content in cast iron increases, the amount of cementite-type carbides reduces due to the formation of chromium carbides $(Cr,Fe)_7C_3$ at more than 7% Cr, and $(Cr,Fe)_{23}C_6$ at more than 20% Cr, which have high microhardness [12]. The ledeburite-type eutectic is replaced by the eutectic with various fine complex carbides $(Cr,Fe,Mn)_7C_3$ (Fig. 3) that corresponds to the Charpy principle [8, 9] (hard carbides in a softer matrix).

TABLE 1. Chemical composition and properties of wear-resistant white cast irons with different chromium content.

Melting index	Content, % wt.						Relative wear resistance	Hardness, <i>HRC</i>
	C	Cr	Mn	Si	P	S		
					max			
101	2.91	4.5	4.2	0.65	0.05	0.05	0.85	41.0
102	2.85	8.3	4.5	0.70	0.05	0.05	1.02	43.2
103	2.82	16.2	4.1	0.72	0.05	0.05	1.18	46.6
104	2.92	21.1	4.6	0.68	0.05	0.05	1.22	48.5
105	2.94	25.2	4.2	0.65	0.05	0.05	1.12	49.4
106	2.86	31.6	4.3	0.78	0.05	0.05	0.95	50.3


Fig. 2. Dependence of hardness and wear resistance of cast irons on Cr content: 1—relative wear resistance, 2—hardness, 3— $\text{Cr}_{28}\text{Ni}_2$ alloy (reference).

Higher amount of the ledeburite eutectic and lower volume fraction of austenite contribute to an increase in the hardness and wear resistance of the alloy. An increase in the chromium content in cast iron above 20% leads to the appearance of coarse hypereutectic crystallites of Cr_7C_3 carbides, and to a higher amount of Cr-alloyed ferrite [6]. Cr_7C_3 carbides solidify as long needle-like hexagons (Fig. 3). These carbides reduce the wear resistance and especially the strength of ingots, although the hardness of the alloy increases (Fig. 2).

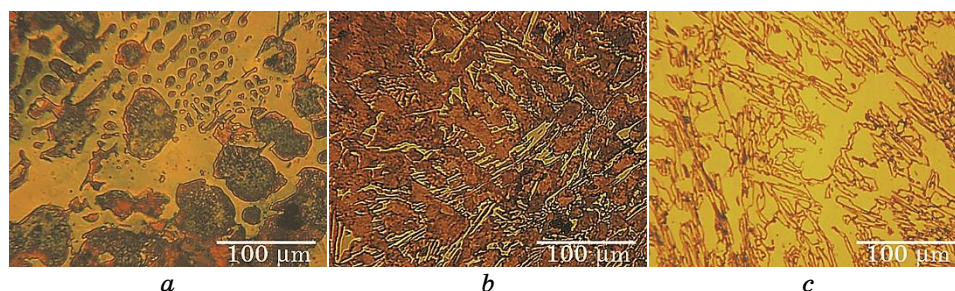


Fig. 3. Effect of chromium on microstructure of high-alloyed cast iron: 4.5% Cr (*a*), 21.1% Cr (*b*), 25.2% Cr (*c*).

TABLE 2. Chemical composition and properties of wear-resistant high-chromium cast iron with different Mn content.

Melting index	Content, % wt.						Relative wear resistance	Hardness, <i>HRC</i>
	C	Cr	Mn	Si	P	S		
					max			
107	2.89	18.6	2.1	0.64	0.05	0.05	1.38	52.0
108	3.02	18.8	4.2	0.72	0.05	0.05	1.22	48.5
109	2.91	19.2	7.8	0.79	0.05	0.05	1.05	44.0
110	2.86	19.4	10.3	0.68	0.05	0.05	0.98	42.5
111	2.79	18.9	11.9	0.70	0.05	0.05	0.95	42.0

The effect of manganese on the wear resistance and hardness of cast iron with about 19% Cr (this chromium content provides the highest wear resistance) and about 3.0% C was studied in the concentration range of 2.1–11.9% Mn. The chemical composition of cast irons and test results are shown in Table 2 and Fig. 4.

Manganese contributes to the stabilization of austenite in chromium-enriched cast irons. As the manganese content in cast irons increases, the hardness decreases that is explained by higher amount of residual austenite in the matrix and its stabilization (Fig. 4). In addition, manganese increases the solubility of carbon in the γ -iron that leads to a decreased total amount of chromium carbides.

Based on the data of Refs. [8, 9, 17], one can assume that every Mn percent in the chromium–manganese cast irons can reduce the content of the carbide phase by 1.0–1.4%. The wear resistance of the alloy also decreases—at about 9% Mn, it becomes lower as compared to the $\text{Cr}_{28}\text{Ni}_2$ alloy. Thus, the chromium–manganese cast irons should contain no more than 9.0% Mn in order to have high wear resistance (higher than chromium–nickel cast iron $\text{Cr}_{28}\text{Ni}_2$) (see Fig. 5).

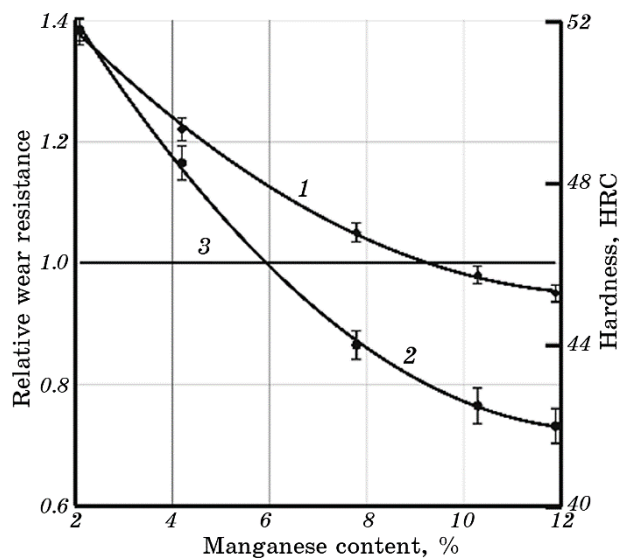


Fig. 4. Dependence of hardness and wear resistance of cast irons on Mn content: 1—relative wear resistance, 2—hardness, 3— $\text{Cr}_{28}\text{Ni}_2$ alloy (reference).

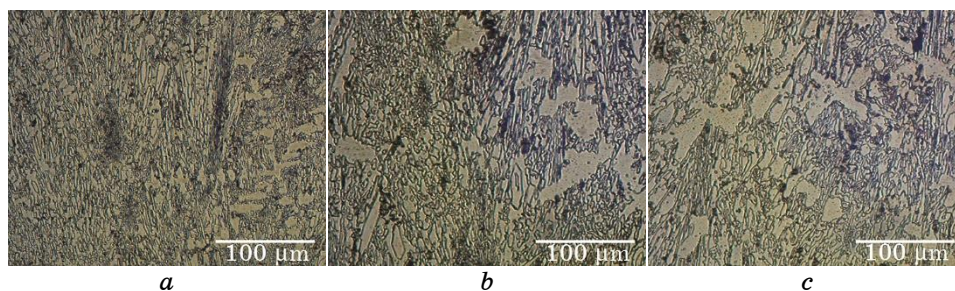


Fig. 5. Effect of Mn content on microstructure of Cr-rich cast iron: 2.1% Mn (a), 4.2% Mn (b), 11.9% Mn (c).

Taking into account the fact that manganese increases the hardenability of Cr-containing cast irons, and residual austenite in cast irons can strengthen under the impact of abrasive particles at low Cr concentrations, a high-chromium cast iron should contain 3.0–5.0% Mn. According to the results of investigations of mechanical properties and operational characteristics, a new chromium–manganese cast iron with 18–20% Cr and 3.5–4.5% Mn was developed. This alloy is mentioned below as $\text{Cr}_{19}\text{Mn}_4$ and is taken as a reference one. Cast iron with this chemical composition has a wear resistance 20–25% higher than the $\text{Cr}_{28}\text{Ni}_2$ cast iron.

Further, the effect of titanium content up to 1.2% on the structure and characteristics of chromium–manganese cast irons is investigated. Given the high affinity of titanium for oxygen, it was added in the form of ferrotitanium after deoxidizing the melt with aluminium. The deoxidation of cast iron with aluminium was carried out to increase the integrity of test. The $\text{Cr}_{19}\text{Mn}_4$ cast iron developed by the authors was used as a reference. The chemical compositions and properties of the cast irons depending on titanium content are listed in Table 3; the test results and microstructures are shown in Figs. 6 and 7, respectively.

TABLE 3. Chemical composition and properties of chromium–manganese iron $\text{Cr}_{19}\text{Mn}_4$ with different titanium contents.

Melting index	Content, % wt.						Relative wear resistance	Hardness, HRC	
	C	Cr	Mn	Si	Ti	P			S
						max			
118	2.85	18.9	3.92	0.64	–	0.05	0.05	1.00	48.0
119	2.90	19.1	3.80	0.60	0.11	0.05	0.05	1.05	51.0
120	2.87	19.0	3.86	0.69	0.24	0.05	0.05	1.11	52.0
121	2.98	18.7	4.10	0.71	0.49	0.05	0.05	1.15	53.0
122	3.02	19.4	4.05	0.69	0.87	0.05	0.05	1.04	51.0
123	2.96	19.2	4.20	0.72	1.20	0.05	0.05	1.01	47.0

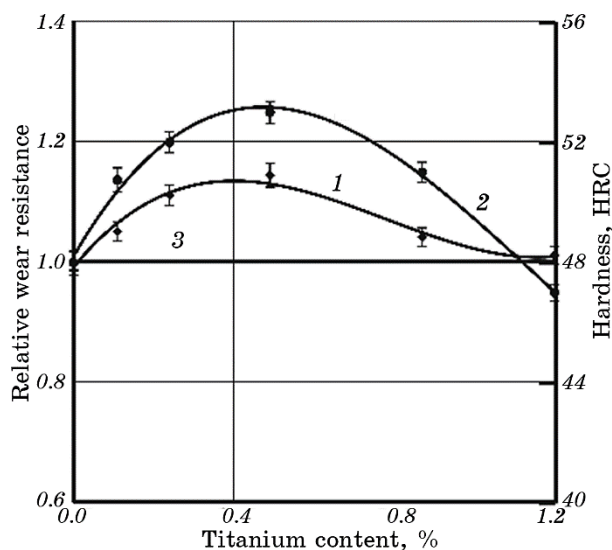


Fig. 6. Dependence of wear resistance and hardness of cast irons on Ti content: 1—relative wear resistance, 2—hardness, 3— $\text{Cr}_{19}\text{Mn}_4$ alloy (reference).



Fig. 7. Effect of Ti content on microstructure of chromium–manganese cast iron: no Ti (a), 0.49% Ti (b), 0.87% Ti (c).

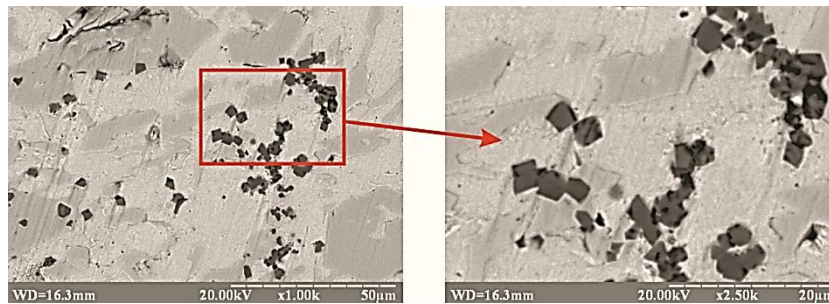


Fig. 8. Colonies of titanium carbides, nitrides, and carbonitrides in cast iron with 0.87% Ti.

Titanium has a higher affinity for carbon than iron; so, it precipitates, first of all, in the form of carbides or carbonitrides (at a sufficient N content) during the solidification of Ti-containing iron–carbon alloys. Titanium promotes the subcooling of molten iron, which contributes to the solution of titanium carbides in the iron melt and the precipitation of carbides during the solidification [10, 14].

The alloy with 0.5% Ti had the highest wear resistance and hardness. At higher Ti content, titanium carbides and carbonitrides were distributed inhomogeneously in the matrix and formed colonies (Fig. 8), which were stress concentrators and crushed under abrasive impact.

In thick ingots, due to their slow solidification and insolubility in molten iron, titanium carbonitrides, which begin to precipitate below 1220°C [17], can accumulate in local volumes of the metal (Fig. 8) and contribute to local embrittlement and deterioration of mechanical processing [13, 16].

This complicates the overall technological production of high-quality parts from these cast irons, increases the costs of mechanical processing of cast parts and the total cost of production, and reduces the service life of parts and equipment.

In addition, higher Ti content in a cast iron increases the infiltration of the melt by silicon from the lining of melting furnace (especially, when the lining is acidic), which increases the number of non-metallic inclusions of various morphologies (most often nitride and sulphide phases) [14]. Therefore, it is advisable to add 0.25–0.50% Ti into the melt before removing from a melting furnace in order to improve the operational characteristics of chromium–manganese cast irons. This approach increases the wear resistance of cast parts by 15–20% under intensive hydroabrasive wear.

The REM on the operational characteristics of chromium–manganese cast irons was studied at concentrations up to 0.8% (by additive). The REM was added to the melt as a master alloy $MeC_{50}Fe_3$ (48.9% Ce, 29.3% La, and 14.8% Nd) at a melt temperature of 1440–1460°C.

During the adding of REM into molten cast iron in a laboratory ladle (up to 30 kg of melt), the modification effect was not completely fulfilled. This was due to the rapid cooling of the melt (compared to the cooling in industrial ladles), as well as the small height of the laboratory ladle, which prevented floating of non-metallic inclusions and transferring them into the slag. Therefore, the REMs were added to the crucible of the furnace immediately before the removal of the melt. The chemical compositions and test results are listed in Table 4 and shown in Fig. 9.

It was found out that the addition of REM additives into the chromium–manganese cast iron (up to 0.25%) increased the wear resistance and hardness of the alloy (Fig. 9). REMs effectively bind sulphur and oxygen in the chrome–manganese cast irons, and change the shape of non-metallic inclusions from angular or elongated to globular. Therefore, these harmful inclusions less deteriorate the properties of the alloy and easily float to the slag [10, 16].

TABLE 4. Chemical compositions and properties of chromium–manganese cast iron $Cr_{19}Mn_4$ modified by REM.

Melting index	Content, % wt.							Relative wear resistance	Hardness, HRC
	C	Cr	Mn	Si	REM	P	S		
						max			
142	2.91	18.9	4.00	0.64	–	0.05	0.05	1.00	48.0
143	2.88	18.5	4.05	0.65	0.10	0.05	0.05	1.07	51.0
144	3.00	19.8	4.10	0.74	0.20	0.05	0.05	1.20	50.0
145	2.90	19.2	4.15	0.72	0.50	0.05	0.05	1.10	52.0
146	3.05	18.7	4.22	0.76	0.60	0.05	0.05	1.09	50.0
147	2.95	19.7	4.10	0.69	0.80	0.05	0.05	1.00	49.0

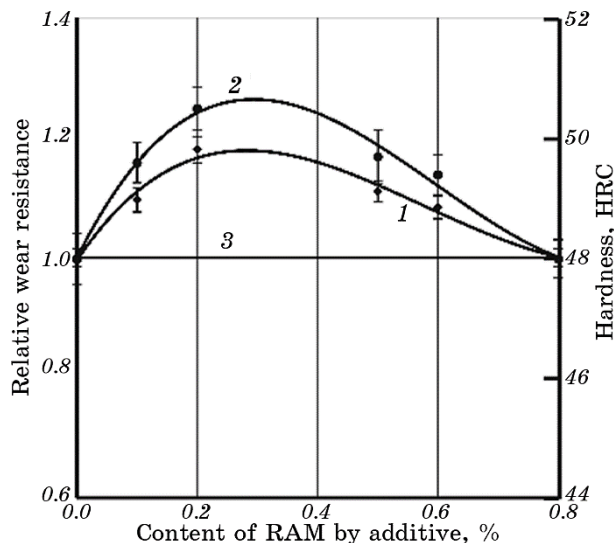


Fig. 9. Dependence of wear resistance and hardness of cast irons on REM additive: 1—relative wear resistance, 2—hardness, 3—Cr₁₉Mn₄ alloy (reference).

The REM additives noticeably refine the microstructure of the reference chromium–manganese cast iron (Fig. 10). Cerium, lanthanum, and neodymium compounds act as surface-active substances (SASs) at the boundaries of austenite dendrites and limit their growth during solidification. This effect is similar to the effect of antimony. In addition, the eutectic $\gamma + (\text{Cr,Fe,Mn})_7\text{C}_3$ has a more fine structure in the alloy containing 0.1% REM [14].

Usually, the REM are good degassers, dephosphorizers and desulfurizers of iron-based alloys, which improve the quality of the ingots, because the REM bind oxygen, nitrogen, hydrogen, sulphur, etc. in stable chemical compounds.

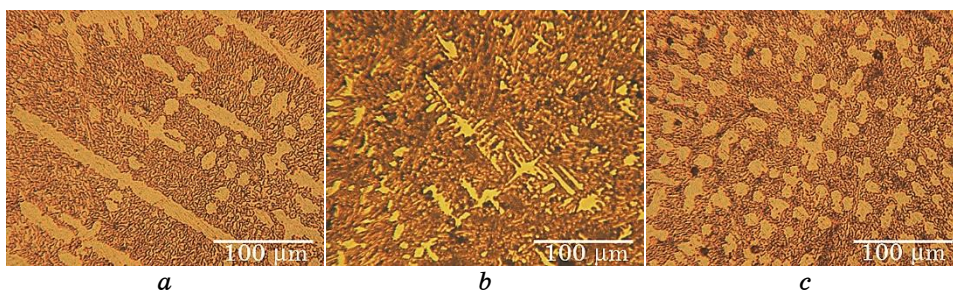


Fig. 10. Evolution of microstructure of Cr₁₉Mn₄ chromium–manganese cast iron depending on REM additive: no REM (a), 0.2% REM (b), 0.5% REM (c).

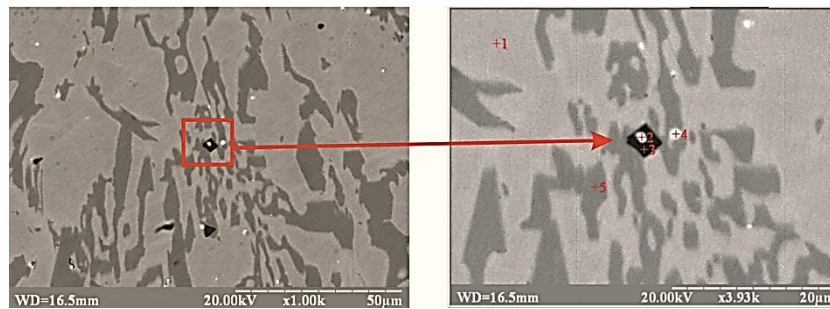


Fig. 11. Microstructure of chromium–manganese $\text{Cr}_{19}\text{Mn}_4$ cast iron containing titanium and REM (spots of local chemical analysis are indicated).

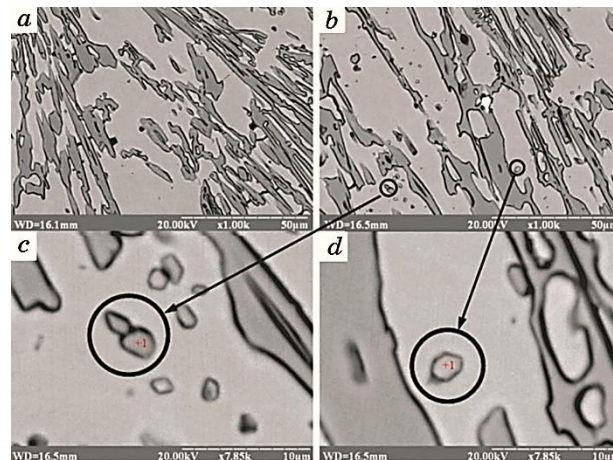


Fig. 12. Microstructure of $\text{Cr}_{19}\text{Mn}_4$ cast iron in initial state (*a*), after modification with 0.20% Ti and 0.20% REM additives (*b*), fine complex carbides (*c*, *d*).

Therefore, it is advisable to modify chromium–manganese cast irons with REM additives in the range of 0.10–0.25% in order to improve the microstructure and increase the wear resistance and hardness.

According to local chemical analysis (Fig. 11), particle 2 is a REM sulphide located in titanium carbonitride (point 3 in Fig. 11); however, there are titanium and REM (La, Ce) in the sulphide and carbide.

Considering the high affinity of titanium to sulphur [14], it can be assumed that it is a carbo-sulphide with a complex chemical composition. The microstructure of the etched samples was investigated using optical and scanning microscopy. Fine particles with sizes from 1 μm to 4 μm were observed in the austenite dendrites in the cast iron modified with titanium and REM (Fig. 12, *a*, *b*), which increased the microhardness of primary austenite grains from 3.2 GPa to 4.2 GPa. The

TABLE 5. Distribution of chemical elements in Cr₁₉Mn₄ cast iron (see Fig. 12, *c, d*).

Spot	Content, % wt.											Probable phase
	Si	Mn	Cr	Ti	P	S	Ce	La	Nd	Pr	Fe	
12, <i>c</i>	0.18	3.57	47.57	0	0.15	0.01	0	0	0	0	48.52	(Cr,Fe,Mn) ₇ C ₃ carbide
12, <i>d</i>	0.13	4.17	33.53	0	0.11	0.10	0	0	0	0	61.96	(Cr,Fe,Mn) ₇ C ₃ carbide

largest number of these inclusions was observed after adding 0.2% and 0.5% REM. It is obviously that these inclusions are fine complex (Cr,Fe,Mn)₇C₃ carbides containing chromium and manganese (Fig. 12, *c, d*), which are not constituents of the eutectic. This is confirmed by local chemical analysis (Table 5). It is likely that the fine carbides observed in the modified alloy formed during the solidification on very fine particles of REM or their compounds, which could act as additional centres of solidification. The authors of [18] came to similar conclusions, but the nature and chemical composition of these particles were not analysed.

In the industrial ingots of cast irons even of eutectic composition, a significant number of primary austenite dendrites are usually observed near the eutectic areas as a result of varying local chemical composition, segregation, *etc.* These zones have a lower microhardness; so, they wear out, first of all, during the operation of parts, thus accelerating the wear of the entire surface. Therefore, the hardening of the primary austenite dendrites with fine hard carbides and carbonitrides helps to increase the abrasive wear resistance of the cast parts. The alloy modified with 0.2% Ti and 0.2% REM additives has the maximum wear resistance (20% higher than the reference cast iron), while the hardness of the cast iron is of 48–50 *HRC* [14].

Therefore, it is useful to add 0.15–0.20% Ti and 0.15–0.25% REM (by additive) before at the final stage of melting in order to improve the microstructure, neutralize the effect of harmful impurities, and increase the wear resistance of chromium–manganese cast irons. In most cases, the ingots of wear-resistant cast irons are machined. The hardness of as-cast chromium–manganese cast irons is of 40–55 *HRC*. This makes difficult mechanical processing by traditional methods. Besides, the surface hardness of chromium–manganese cast irons can increase because of martensitic transformation in microvolumes of alloyed austenite as a result of high pressures, which appear during machining.

For reliable and long-term operation of cast parts and successful mechanical processing, it is necessary to select correctly the optimal chemical composition and heat treatment of a chromium–manganese cast iron.

TABLE 6. Chemical composition of the studied chromium–manganese cast irons: *—by additive, **—additionally contain 0.02% B and 0.1% V.

Alloy number	Cast iron marking	Content, % wt.						Hardness, <i>HRC</i>			
		C	Si	Cr	Mn	Ti	REM*	P	S	As-cast state	After annealing
1	Cr ₂₀ Mn ₃	3.0	0.6	19.6	2.5	–	–	0.05	0.05	56.0	40.0
2	Cr ₁₉ Mn ₃	3.2	0.8	19.1	3.0	–	–	0.05	0.05	53.0	48.0
3	Cr ₂₀ Mn ₃	3.2	0.7	19.8	3.2	–	–	0.05	0.05	51.5	47.5
4	Cr ₂₀ Mn ₄ TiREM	2.8	1.0	20.0	4.4	0.11	0.1	0.05	0.05	49.0	56.0
5	Cr ₁₉ Mn ₄ Ti	2.9	0.9	19.2	3.9	0.11	–	0.05	0.05	50.0	50.0
6	Cr ₁₉ Mn ₃ TiREM**	2.9	1.0	19.1	2.7	0.20	0.2	0.05	0.05	54.0	43.0

The hardness of cast ingots varied from 40 *HRC* to 56 *HRC* (Table 6); it depended to a lesser extent on the content of carbon (2.8–3.2%), silicon (0.6–1.0%), chromium (19.1–20.0%), and modifying additives (up to 0.2% Ti and up to 0.2% REM). The main alloying element that affects the hardness of as-cast samples is manganese, which contributes to the austenization of cast iron in the greatest extent and changes the microstructure and hardness.

In the austenite of this cast iron alloyed with chromium and manganese, a large amount of secondary carbides precipitate (austenite has a dark colour), which increase the microhardness of austenite, and, as a result, contribute to the increase in the hardness of the cast iron. The hardness of the cast iron did not decrease significantly after annealing.

The only exception is the Cr₂₀Mn₃ cast iron with a hardness of 40 *HRC*, which meets the requirements for standard machining. The reduction in the hardness of cast iron is explained by the decomposition of austenite into granular pearlite due to slower cooling in the pearlite field. At the same time, the austenite in the complex alloyed Cr₁₉Mn₃TiREM cast iron decomposes partially.

When the Mn content increased from 2.5% to 4.4%, the hardness of heat-treated samples increased from 39.5 *HRC* to 56 *HRC*. At 3.9% Mn and above, the hardness of the samples did not decrease after annealing; it even increased. This can be explained as follows. In the as-cast state, the samples contained mainly primary dendrites of austenite and $\gamma + (\text{Cr, Fe, Mn})_7\text{C}_3$ eutectic [18, 19]. Therefore, the difference in the hardness of as-cast samples can be explained by the different amount of austenite due to the different Mn content, since the latter stabilizes the austenite and increases the solubility of carbon in the γ -iron. This somewhat reduces the amount of chromium carbides in the

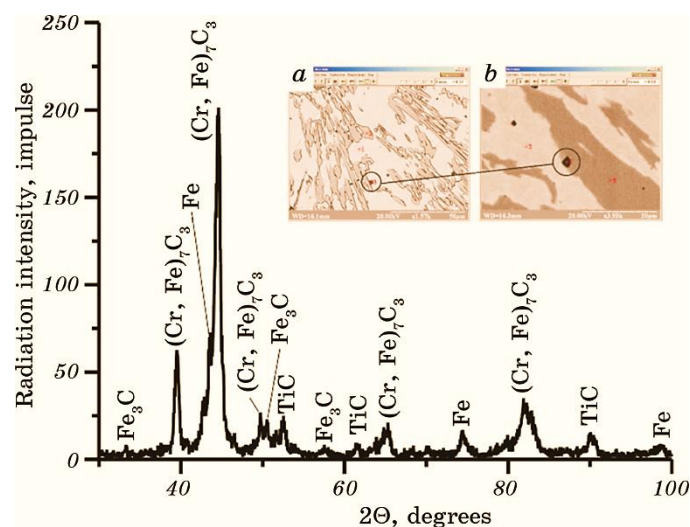


Fig. 13. Phases in wear-resistant chromium–manganese cast iron $\text{Cr}_{20}\text{Mn}_4\text{Ti}$ REM and their volume fractions: Fe_3C —31%, $(\text{Cr, Fe})_7\text{C}_3$ —32%, TiC —16%, $\gamma\text{-Fe}$ —21%.

cast iron. All these factors reduce the hardness of the cast iron.

During step annealing, the austenite in the cast irons with a minimum Mn content decomposes completely into granular pearlite (relatively soft) of different sizes, which leads to a decrease in the hardness to 39–40 HRC. In the alloys with an average Mn content, the hardness decreased by only 5–10 units. The matrix in these alloys consists of the austenite hardened with secondary carbides, which do not decompose, and partly from the austenite decomposition products. As a result, the hardness of the alloy decreases insufficiently for mechanical processing under normal conditions.

Manganese-saturated austenite in these cast irons decomposes only partially; instead, a large amount of secondary carbides precipitate in it that strengthens additionally the alloy and increases its hardness. The partial decomposition of the austenite obviously begins in zones with a minimum Mn content, which appear due to the chemical segregation in the dendrites. As an example of the carbides of different composition in the cast iron, Fig. 13 shows the microstructural constituents of the chromium–manganese cast iron (local chemical compositions in several spots are listed in Table 7).

4. CONCLUSIONS

It is found out that it is necessary to use chromium–manganese cast irons with a reduced Mn content (up to 2.5–2.7%) for the production

TABLE 7. Local chemical compositions.

Chemical composition, % wt. (see Fig. 13, insert a)									
Spot	C	Si	Mn	Cr	Ti	P	S	Fe	Σ
1	2.95	0.25	4.11	5.12	0.00	0.18	0.08	87.31	100.00
2	3.05	0.18	4.33	51.55	0.00	0.05	0.15	40.69	100.00
3	2.20	0.07	0.00	6.36	86.91	0.02	0.01	4.43	100.00
Chemical composition, % wt. (see Fig. 13, insert b)									
Spot	C	Si	Mn	Cr	Ti	P	S	Fe	Σ
1	2.51	0.08	0.23	8.50	86.19	0.01	0.00	2.98	100.00
2	2.93	0.20	3.52	4.89	0.00	0.07	0.09	88.31	100.00
3	2.21	0.10	3.50	60.04	0.00	0.18	0.11	33.87	100.00

of cast wear-resistant parts that require mechanical processing.

In order to reduce the hardness of chromium–manganese cast irons to about 40 HRC, they should be heat-treated as follows: heating up to 870°C, exposure for 1 hour, cooling in a furnace to 610°C, exposure for 3 hours, heating to 690°C, exposure for 2 hours, and cooling in a furnace (step annealing).

The step isothermal annealing is found to be a promising heat treatment of the chromium–manganese cast irons with 18–21% Cr, especially, at a low Mn content (2.7% and below). This reduces the hardness of as-cast cast iron from 54–56 HRC to 39–40 HRC. This heat treatment of ingots of chromium–manganese cast irons significantly facilitates subsequent mechanical processing.

It is found out that the step annealing is particularly effective for the cast irons with carbon content at the lower limit. It is shown that optimal austenization and isothermal-ageing temperatures should be chosen (taking into account the manganese content).

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