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The effect of complex modification on the structure and properties of gray cast iron for tribotechnical application

Denis Gabets [1, a], *Andrey Markov* [1, b], *Mikhail Guryev* [1, c], *Evgeny Pismenny* [2, d], *Alina Nasyrova* [3, e, *]

[1] I.I. Polzunov Altai State Technical University, 46 Lenina avenue, Barnaul, Altai region, 656038, Russian Federation
[2] Railway Research Institute of JSC Russian Railways, 10, 3rd Mytishchinskaya st., Moscow, 129851, Russian Federation
[3] Novosibirsk State Technical University, 20 Prospekt K. Marksa, Novosibirsk, 630073, Russian Federation

[a] https://orcid.org/0000-0003-0304-4407, gabets22@mail.ru, [b] https://orcid.org/0000-0002-3101-9711, andmarkov@inbox.ru,
[c] https://orcid.org/0000-0002-9191-1787, gurievma@mail.ru, [d] https://orcid.org/0000-0002-7454-0830, pysmennyi.eug@gmail.com,
[e] https://orcid.org/0000-0003-2551-3657, nasyrova.alina98@mail.ru

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ABSTRACT

Introduction. An approach based on the complex modification of cast irons makes it possible to improve its mechanical properties by changing the structure of the metal matrix, as well as the shape of graphite and its distribution. **The aim of this work** is to study the influence of alloying elements on the structure and mechanical properties of gray cast irons obtained for operation under friction wear conditions. **Research methods.** The paper describes the process of obtaining complex modified gray cast irons. Fractographic investigation of dynamically destroyed samples is carried out. Structure's features of *SCh35*, *ChMN-35M* and *SChKM-45* gray cast irons are studied. Tribological testing under sliding friction conditions is carried out. **Results and its discussion.** It is established that the complex modification of *SCh35* gray cast iron with molybdenum, nickel and vanadium makes it possible to increase its hardness to 295 HB and tensile strength to 470-505 MPa. Alloying with nickel (0.4-0.7 wt.%), molybdenum (0.4-0.7 wt.%) and vanadium (0.2-0.4 wt.%) leads to a decrease in the interlamellar distance of perlite by 2 times, as well as to the metal matrix grain refining. The length of graphite lamellas of modified cast irons is reduced by 3-5 times. An additional effect on the tensile strength of cast iron is due to the alloying of ferrite with molybdenum and vanadium, which is fallen out along the boundaries of graphite inclusions. Alloying of ferrite with molybdenum and vanadium increases the level of its microhardness by 1.4 times in comparison with the α-phase of *SCh35* serial cast iron. The results of tribotechnical tests of the designed materials are presented. **Conclusions.** It is established that the wear of specimens made of *SChKM-45* cast iron is approximately 20-30% lower compared to cast iron *SCh35* cast iron and 10-15% lower compared to *ChMN-35M* cast iron. Fractographic studies show that complex alloying with molybdenum, vanadium and nickel, contributing to the refining of pearlite colonies, leads to a decrease of the size of the cleavage facets.

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Introduction

Low-alloyed gray cast irons are widely applied for manufacturing critical duty structures operating under wear condition at high mechanical loads [1–4]. These details are body panels, parts of brake systems, working parts of mining machines, parts of railway wagon bogies. The cast irons, from which these details are made, should not only be characterized by high strength properties, but should also provide corrosion resistance, tribotechnical properties under conditions of sliding friction, shock-friction wear. Considering

*** Corresponding author**
Alina Nasyrova K., Junior researcher
Novosibirsk State Technical University,
20 Prospekt K. Marksa,
630073, Novosibirsk, Russian Federation
Tel.: +79059376536, **e-mail**: nasyrova.alina98@mail.ru

the influence of the structure on the formation of cast iron's mechanical properties it is necessary to control its structural features including the uneven distribution of graphite inclusions in the volume of the material, the presence of chill zones which are the cause of embrittlement of cast iron, etc. Improving the structure of cast irons, reducing the amount of structural defects and increasing mechanical properties is facilitated by the alloyage with nickel, molybdenum, phosphorus, vanadium, aluminum, boron, etc. The role of alloying elements and modifying additives in the formation of the structure and complex of mechanical properties of cast irons is reflected in the works [1–10].

The shape, size and volume fraction of graphite inclusions as well as its distribution in the bulk of the material are the most significant structural features determining the level of mechanical properties of gray cast irons [2, 9, 10]. Graphite plates distributed in cast iron, on the one hand, can be considered as natural concentrators of mechanical stresses that contribute to the formation of cracks and destruction of the material, and on the other hand, graphite plates can be "pockets" where microvolumes of solid lubricant are concentrated, helping to reduce the friction coefficient and as a result increase the service life of friction pairs. Graphite distributed in gray cast iron prevents the seizing of surfaces worked as dry sliding friction units [9–14].

According to the Application standards of the Russian Railways, the main requirements for cast irons used for the manufacture of parts of railway transport, are ensuring the ultimate strength during deformation at a level of at least 350 MPa according to the tensile scheme and hardness in the range of 250–350 HB. Typical parts made from these materials should provide at least 160,000 km of mileage of railway transport. The search for technical solutions that provide the possibility of improving the mechanical properties of cast irons is an urgent task of applied importance. One of these solutions is related to the alloying of gray cast iron. Previous studies [1–14] indicate a significant effect of nickel, molybdenum and vanadium on the physical and mechanical properties of gray cast irons.

The previously developed cast iron grade *ChMN-35M* [12] produced in correspondence with *tech spec 0812-001-10036140-2014* does not fully meet the requirements for parts operating under frictional conditions. First of all we are talking about the harsh operating modes of the equipment (dry sliding friction with a high level of contact loads). It has been experimentally established that seizure centers appear under such conditions on the surfaces of parts made of *ChMN-35M* cast iron, the development of which results in an increase in wear intensity.

The aim of this work is to study the effect of alloying elements (nickel, molybdenum, vanadium) on the structure and mechanical properties of gray cast iron intended for the manufacture of structural components operating under conditions of dry sliding friction.

The level of tensile fracture resistance was the main parameter controlled during the study. Its value was not less than 450 MPa (with hardness in the range of 250–350 HB). The limiting requirement was the cost of the material provided that the minimum required level of tensile strength was guaranteed.

Research methods

SCh35 gray cast iron was chosen as the base material for the research. Smelting was carried out in an induction melting furnace with a crucible volume of 150 kg. Scrap 4A *GOST 2787–75* weighing 100 kg was used as a charge. Samples were taken to assess the chemical composition after charge melting and carburizing of the material. Cast iron was alloyed with nickel, molybdenum and vanadium, the concentration of which was varied in the range from 0.1 to 0.8 wt. % in order to increase the strength properties. Alloying was carried out by addition the calculated amount of ferroalloys of nickel, vanadium and molybdenum directly into the *SCh35* gray cast iron melt. The temperature of the melt before draining from the furnace was 1,425–1,440 °C. The mold filling time did not exceed 5 minutes [11].

An optical emission spectrometer *GNR Solaris CCD Plus* was used to determine the chemical composition of the studied materials.

Tensile tests of the samples were performed on a universal electromechanical testing system *Instron 3360* according to *GOST 27208–87*. Sample preparation was carried out in obedience to *ISO 185–88*.

The hardness of cast irons was determined according to *GOST 24648–90* on a hardness testing machine *ITRB-3000*. Microstructural studies were carried out on a metallographic microscope *Carl Zeiss Axio Observer Z1m* in accordance with *ISO 945–75* using the «*Thixomet Pro*» software [15–26].

The microhardness of the samples was evaluated according to *ISO 6507–1:2005* on a microhardness testing machine *MN-6* at a load of 0.2452 N. An array of indents from diamond pyramid in the amount of 15×15 was applied to the surface of each of the weakly etched samples. Indents located on the ferrite/pearlite, ferrite/graphite boundaries as well as on the graphite plates were not taken into account.

The evaluation of tribotechnical properties under dry friction conditions was carried out according to the "shaft-block" scheme on a friction machine *2168 UMT*. Friction pairs "the material under study – steel *30CrMnSiA* (0.28–0.34 % *C*, 0.8–1.1 % *Cr*, 0.8–1.1 % *Mn*, 0.9–1.2 % *Si*) / *20MnL* (0.15–0.25 % *C*, 1.2–1.6 % *Mn*, 0.2–0.4 % *Si*) / *09Mn2Si* (< 0.12 % *C*, 1.3–1.7 % *Mn*, 0.5–0.8 % *Si*)" were studied. Impact bending tests were carried out on a pendulum impact tester *Metrocom* in accordance with *ISO 83–76*. Samples with a *U*-shaped stress concentrator 2 mm deep cut on a *Sodick AG400L* electric spark wire machine were used for testing.

SCh35 cast iron and its closest analogue *ChMN-35M* cast iron were used as a reference material for mechanical characteristics [12].

Results and discussion

Experiments for choosing optimal concentration of alloying additives were carried out to develop the chemical composition of *SChKM-45* cast iron with increased complex of mechanical properties. In accordance with the results of the studies, concentration of nickel providing the required level of hardness (at least 250 HB) is 0.4–0.7 wt. %. In this case the ultimate strength exceeds 450 MPa (Fig. 1) [11, 27]. A similar conclusion can be drawn regarding the amount of molybdenum. The addition of more than 0.7 wt. % of molybdenum is not rational due to a significant increase in the level of hardness (more than 350 HB) and material embrittlement. In this case, the ultimate strength increases to a lesser extent (Fig. 2) [11, 27].

Concentration of vanadium which ensures the requirements for the level of hardness and ultimate strength is in the range from 0.2 to 0.4 wt. %. With the addition of this element in an amount of less than 0.2 wt. % level of ultimate strength does not reach 450 MPa. The excess of the vanadium content of more than 0.4 wt. % is accompanied by chilling of cast iron and the appearance of islands of skeletal eutectic. It should be emphasized that an increase in the vanadium content does not lead to an increase in the ultimate strength of the material (Fig. 3), but the cost of the material increases. The noted circumstance is one of the factors that significantly limit the efficiency of the alloyed alloy [11, 27].

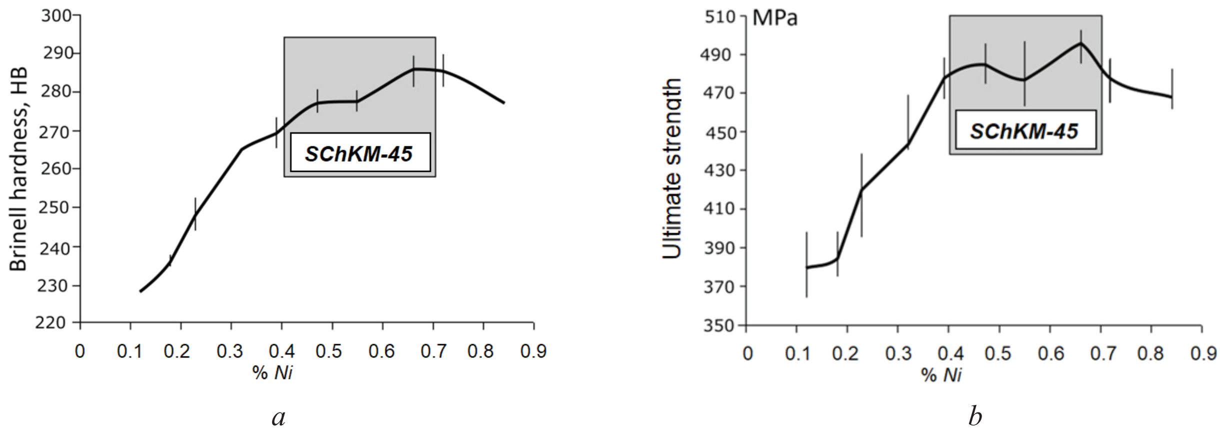


Fig. 1. Effect of nickel concentration in *SChKM-45* gray cast iron containing 0.45 wt.% of molybdenum and 0.34 wt.% of vanadium:

a – on hardness; b – on ultimate strength

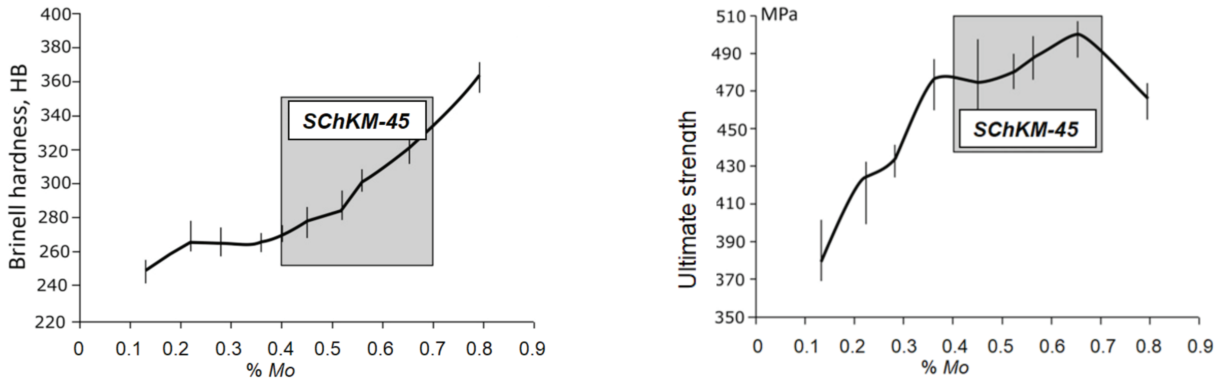


Fig. 2. Effect of molybdenum concentration in *SChKM-45* gray cast iron containing 0.52 wt.% of nickel and 0.38 wt.% of vanadium:

a – on hardness; *b* – on ultimate strength

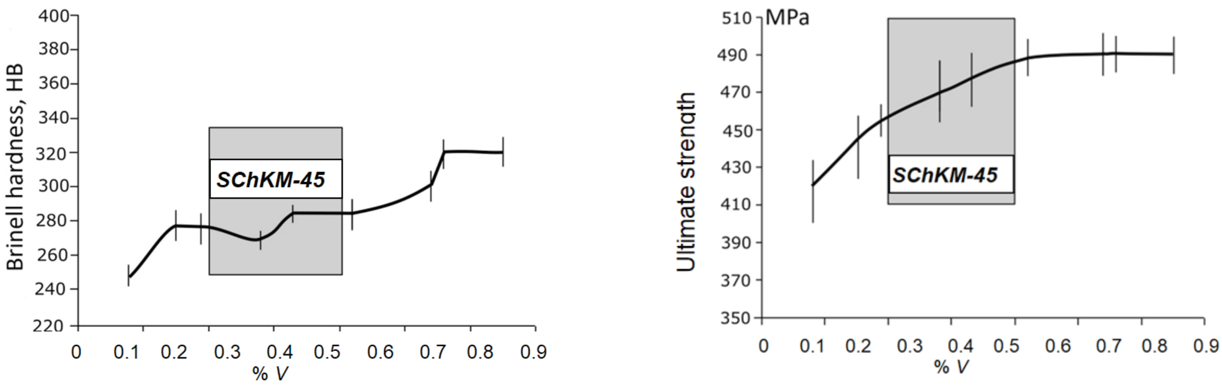


Fig. 3. Effect of vanadium concentration in *SChKM-45* gray cast iron containing 0.6 wt.% of molybdenum and 0.55 wt.% of nickel:

a – on hardness; *b* – on ultimate strength

The result of the experiments to determine the optimal chemical composition for an alloy with a complex of high properties is the development of gray cast iron grade *SChKM-45* alloyed with nickel, molybdenum and vanadium. The authorship of the development is entrenched by the *RF* patent for the invention No. 2733940 [13].

The chemical composition of alloys *SCh35*, *ChMN-35M* and *SCHKM-45* is presented in Table 1.

Mechanical properties of *SChKM-45* cast iron compared to basic *SCh35* cast iron and developed earlier *ChMN-35M* cast iron are presented in Table 2.

The properties of alloyed gray cast irons are largely determined by the structure of its metal matrix, the shape and distribution of graphite inclusions. Comparative analysis results of the structure of cast irons analyzed in this work are presented in Table 3 [11].

Table 1

Chemical composition of *SCh35*, *ChMN-35M* and *SChKM-45* cast irons

Cast iron grade	Mass fraction of elements, % *Fe* – balance									
	C	*Si*	*Mn*	*Mo*	*Ni*	*V*	*Cr*	*Cu*	*S*	*P*
SCh35	2.92	1.45	0.88	–	–	–	0.04	0.03	0.04	0.01
ChMN-35M	2.85	1.39	0.86	0.82	0.75	–	0.05	0.03	0.03	0.02
SChKM-45	2.65	1.35	0.89	0.45	0.52	0.34	0.05	0.03	0.03	0.02

Table 2

Mechanical properties of *SCh35*, *ChMN-35M* and *SChKM-45* cast irons

Cast iron grade	Ultimate tensile strength, MPa, at least	Brinell hardness, HB	
		from	to
SCh35	345–365	272	288
ChMN-35M	362–395	277	319
SChKM-45	470–505	268	321

Table 3

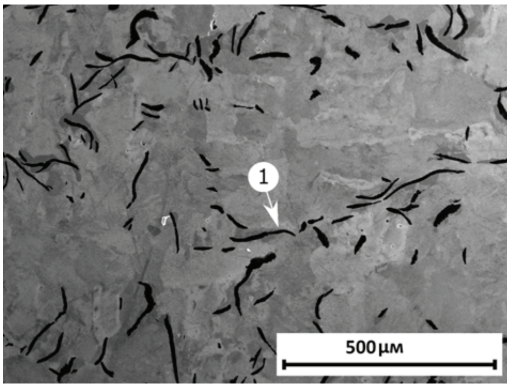
Structural parameters of *SCh35*, *ChMN-35M* and *SChKM-45* cast irons

Characteristic of microstructure according *ISO 945–75*	Cast iron grade		
	SCh35	*ChMN-35M*	*SChKM-45*
Shape of graphite inclusions, scale 1A, ×100	vermicular	vermicular	vermicular
Length of graphite inclusions, scale 1Б, ×100	60–120 µm	30–60 µm	30–60 µm
Distribution of graphite inclusions, scale 1B, ×100	reticular	equilibrium	equilibrium
Type of the structure of the metal base of cast iron, scale 5, ×500	lamellar pearlite	lamellar pearlite	lamellar pearlite
Number of graphite inclusions, scale 1Г, ×100	≤ 3 %	3–5 %	5–8 %
The content of pearlite and ferrite in the structure of cast iron. % scale 6A, row 1, ×100	perlite ≥ 98 % ferrite ≤ 2 %	perlite 90–94 % ferrite 6–10 %	perlite 80–90 % ferrite 10–20 %
Perlite dispersion	distance between cementite plates ≥ 1.6 µm	distance between cementite plates 1.3–1.6 µm	distance between cementite plates 0.8–1.3 µm

Cast iron *SCh35* is characterized by the formation of graphite inclusions with a length of ~ 10–200 µm. The shape of graphite is lamellar, partially swirling (Fig. 4, *a*) [28, 29]. The structure of *ChMN-35M* cast iron is characterized by a uniform distribution of graphite inclusions with the size of ~ 10–150 µm (Fig. 4, *b*) [11, 27]. Simultaneous alloying of cast iron with molybdenum and vanadium contributes to the formation of the corresponding solid solutions mainly in the α-phase, which contributes to a higher degree of graphitization; at the same time the melt volumes enriched in molybdenum and vanadium are characterized by an increased number of crystallization centers [28]. Thereby with an increase in the degree of alloying, the size of graphite inclusions decreases. The length of graphite inclusions observed in *SChKM-45* cast iron (10–110 µm) is approximately two times less than in *SCh35* gray cast iron. The shape of the inclusions in *SChKM-45* cast iron is lamellar, partially swirling (Fig. 4, *c*).

The main structural component of the metal matrices of all three cast iron grades is lamellar perlite. Its content ranges from 92 vol. % in *ChMN-35* cast iron up to 100 vol. % in *SCh35* cast iron. The pearlite fraction in the *SChKM-45* alloy is ~ 86 vol. %. Thereby the result of alloying elements addition into cast irons is an increase of the fraction of the ferrite in the structure [1, 2, 10, 31]. The effect of molybdenum on the volume fraction of ferrite is more significant since it is more soluble in the α-phase compared to vanadium. It is also noted that thermodynamic stability of ferrite can be increased by alloying with molybdenum and vanadium [31, 32].

Structural features of the metal matrix analyzed by light microscopy are shown in Fig. 5. Ferrite precipitated in *ChMN-35* and *SChKM-45* cast irons is mainly localized near graphite inclusions. The reason for this phenomenon is the presence of nickel and molybdenum in alloys, the complex effect of which leads to the same effect as a decrease in the cooling rate of the melt. Thus a ferrite rim is formed along the edges of graphite inclusions in these cast irons [32, 33]. Ferrite observed in *ChMN-35* cast iron is predominantly



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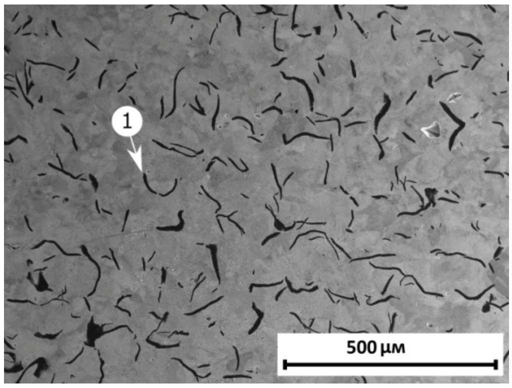

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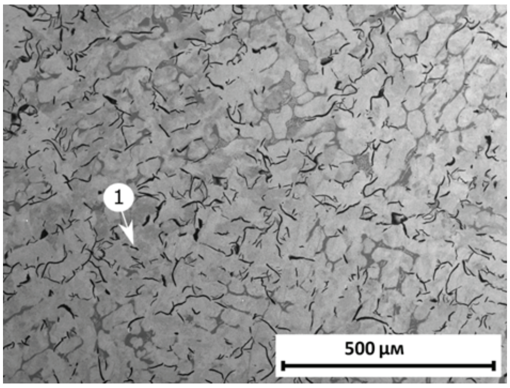

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Fig. 4. Distribution of graphite in:
a – SCh35; *b – ChMN-35M*; *c – SChKM-45* (number 1 denotes graphite)

alloyed with molybdenum according to the energy dispersive analysis. Vanadium is also recorded in the ferrite of *SChKM-45* cast iron along with molybdenum. Nickel is evenly distributed over the volume of the studied materials.

The result of alloying with molybdenum and nickel is an increase in the dispersion of lamellar pearlite. The reasons for this effect are reflected in [31–33]. The interlamellar distance is 2.2 µm and corresponds to *PD1.6* in *SCh35* cast iron. Alloying cast iron with molybdenum and nickel leads to a decrease of interlamellar distance to ~ 1.4–1.5 µm (*PD1.4*). Perlite observed in *SChKM-45* cast iron alloyed with molybdenum, nickel and vanadium is characterized by an even higher level of perlite dispersion (*PD1.0*) [30, 34–36].

The results of measuring the microhardness of the volumes of structurally free ferrite and lamellar pearlite in the analyzed cast irons are presented in Table 4. A comparative analysis of obtained data allows to conclude that with an increase in the degree of alloying the microhardness of single structural components of the metal matrix increases [37, 38]. Structural analysis established that small amounts of primary cementite are present in *SChKM-45* cast iron, the particle size of which is in the range from ~ 8 to ~ 35 µm (see Fig. 4, *e*). Works [31, 32] describe similar effect.

The values of the friction coefficient and the weight wear of the friction pair elements were chosen as criteria characterizing the tribological properties of the analyzed materials. The test results of the samples are presented in Table 5. The obtained data testify the high tribological properties of *SChKM-45* cast iron. The wear amount of samples from this alloy is approximately 1.3–1.8 times lower compared to *SCh35* cast iron and 1.1–1.2 times lower compared to *ChMN-35M* cast iron. The efficiency of complex alloyed *SChKM-45* cast iron used in friction pairs with steels *30CrMnSiA*, *20MnL* and *09Mn2Si* was confirmed [39, 40–42].

The fractographic research data shown in Figs. 6 allow to conclude that the fracture of all specimens is brittle. The brittleness of the investigated alloys conditioned by the presence of graphite inclusions sharply

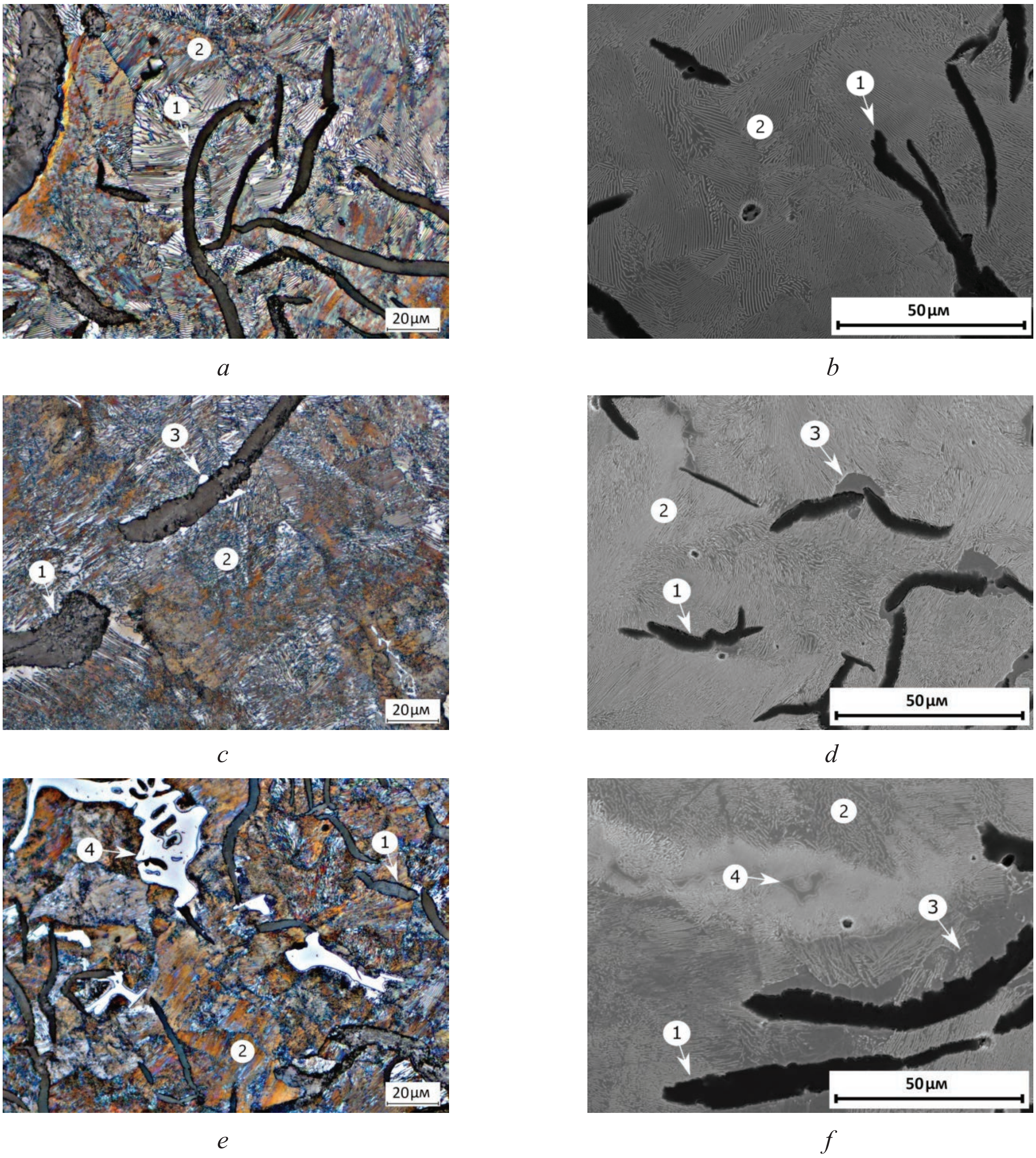


Fig. 5. The structure of metal matrices in cast irons:
a, *b* – *SCh35*; *c*, *d* – *ChMN-35M*; *e*, *f* – *SChKM-45* (number *1* denotes graphite, *2* – pearlite, *3* – ferrite, *4* – cementite)

Table 4

Average values of microhardness of structural components in *SCh35*, *ChMN-35M* and *SChKM-45* alloys

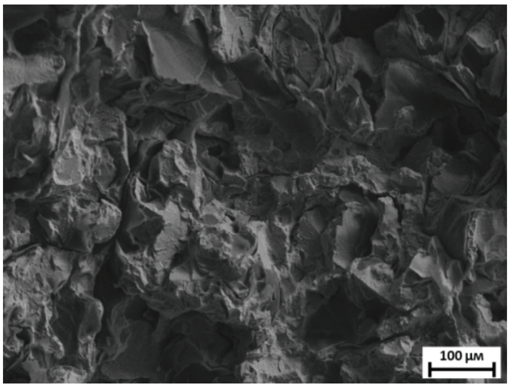
Microhardness	Cast iron grade		
	SCh35	*ChMN-35M*	*SChKM-45*
Ferrite	195	235	270
Perlite	290	315	370

reduces the sensitivity of gray cast irons to stress concentrators. The fractures of samples made of *SCh35* cast iron (Fig. 6, *a*) and *ChMN-35M* cast iron (Fig. 6, *b*) both in the zones of initiation and in the zones of crack propagation are the same. The destruction predominantly occurs according to the transcrystalline mechanism with an insignificant fraction of the intercrystalline component [11, 27, 39].

Table 5

Results of tribotechnical tests

No.	Friction pair (hob – shaft)	Friction coefficient	Weight wear, g		Total wear, g
			Hob	Shaft	
1	*SCh35 – 0.3C-Cr-Mn-Si*$_{(high\ quality)}$	0.11–0.13	0.11	0.84	0.95
2	*ChMN-35M – 0.3C-Cr-Mn-Si*$_{(high\ quality)}$	0.10–0.12	0.15	0.45	0.60
3	*SChKM-45 – 0.3C-Cr-Mn-Si*$_{(high\ quality)}$	0.10–0.12	0.10	0.43	0.53
4	*SCh35 – 0.2C-Mn*$_{(cast)}$	0.11–0.13	0.24	0.86	1.10
5	*ChMN-35 – 0.2C-Mn*$_{(cast)}$	0.11–0.12	0.23	0.60	0.83
6	*SChKM-45 – 0.2C-Mn*$_{(cast)}$	0.12–0.12	0.22	0.58	0.80
7	*SCh35 – 0.09C-2Mn-Si*	0.13–0.14	0.40	0.45	0.95
8	*ChMN-35M – 0.09C-2Mn-Si*	0.11–0.12	0.24	0.66	0.90
9	*SChKM-45 – 0.09C-2Mn-Si*	0.11–0.12	0.20	0.55	0.75



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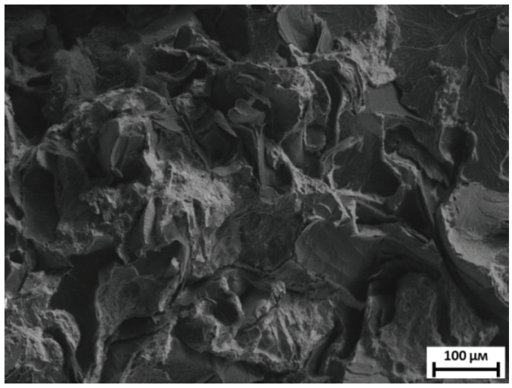

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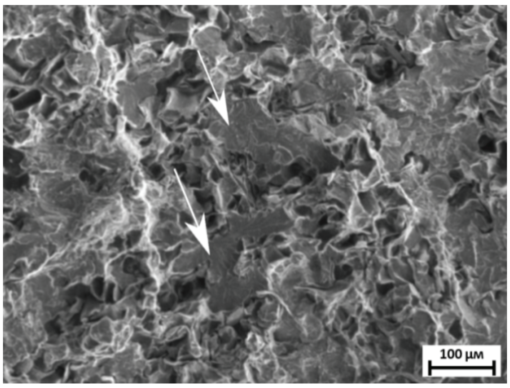

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Fig. 6. Structure of fractures of cast irons after impact bending tests:
a – SCh35; *b – ChMN-35M*; *c – SChKM-45*

The fractures shown in Fig. 6 have a characteristic facet structure. A morphology analysis shows that graphite inclusions played a significant role in the initiation and development of cracks. Microcracks extending deep into the material were fixed at the points where the graphite plates came to the surface. The structure of fracture surfaces of *ChMN-35M* is more uniform. The size of the cleavage facets is approximately 1.5 times smaller compared to *SCh35* cast iron, which is explained by the more dispersed structure of the cast iron metal base [11]. The arrows in Fig. 6 indicate characteristic fracture zones of the transcrystalline mechanism of the material. The formation of fracture zones of this type can be explained by the strength properties of the metal matrix of *ChMN-35M* cast iron as well as by the increased level of relaxation properties of the material alloyed with molybdenum and nickel. However alloying cast iron with molybdenum and nickel does not have a significant effect on the overall picture of destruction.

Complex alloying of *SChMN-45* cast iron with molybdenum, nickel and vanadium accompanied by an increase in the dispersion of the pearlite structure leads to a significant refinement of the cleavage facets (Fig. 6, *c*). Approximately 30 % of the fracture surface is formed by the mechanism of intercrystalline fracture. The sensitivity of *SChMN-45* cast iron to the presence of stress concentrators is also less noticeable which indicates the decisive role of graphite inclusions of lamellar morphology in the manifestation of the mechanisms of crack initiation and development [11, 27, 39].

Conclusions

1. Complex alloying with molybdenum, nickel and vanadium provides the hardness of *SChMN-45* gray cast iron at the level of 295 HB and the ultimate strength during tests according to the tensile scheme at the level of 470–505 MPa, which exceeds the values corresponding to *SCh35* gray cast iron (290 HB and 365 MPa, respectively).

2. The addition of nickel (0.4–0.7 wt. %), molybdenum (0.4–0.7 wt. %) and vanadium (0.2–0.4 wt. %) into gray cast iron leads to a decrease in the interlamellar distance in pearlite by 2 times and a decrease in the length of graphite inclusions. These changes explain the increase in the strength properties of alloyed cast iron in comparison with the *SCh35* cast iron.

3. Alloying of gray cast iron with molybdenum and vanadium provides an increase in the microhardness of ferrite grains decorating graphite inclusions by about 1.4 times. This factor has an additional effect on the level of strength properties of the materials under study.

4. Cast iron alloyed with nickel, molybdenum and vanadium is characterized by a higher complex of tribotechnical properties compared to serial gray cast iron. The total wear of shafts made of *SChMN-45* cast iron is approximately 1.3–1.8 times lower compared to *SCh35* cast iron and 1.1–1.2 times lower compared to *ChMN-35M* cast iron. Analysis of the research results testify to the efficiency of using *SChMN-45* cast iron in friction pairs with counter bodies made of steels *30CrMnSiA*, *20MnL* and *09Mn2Si*.

5. Significant refinement of cleavage facets at fractures of dynamically fractured specimens recorded by the method of fractographic studies of the complexly alloyed *SChMN-45* cast iron indicates an increased level of energy consumption for the process of destruction of the material compared to unalloyed cast iron.

The chemical composition of cast iron providing the required parameters of mechanical properties (ultimate strength 450–505 MPa, hardness 265–330 HB) includes: 2.3–2.8 % *C*, 1.3–1.5 % *Si* , 0.6–1.0 % *Mn*, 0.4–0.7 % *Mo*, 0.2–0.4 % *V*, 0.4–0.7 % *Ni*. Such cast iron can contain no more than 0.3 % *Cr*, 0.3 % *Cu*, 0.2 % *P*, 0.1 % *S*.

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Conflicts of Interest

The authors declare no conflict of interest.