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Investigation of the Possibility of Cast Production of Hard- and Wear-Resistant Alloyed Iron–Carbon and 'High-Entropy' Alloys Using the CGM Process

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It is presented the description of the testing method of alloyed Fe–C alloys and 'high-entropy' alloys (HEAs) for wear under dry friction conditions and data of laboratory equipment. For comparison with alloyed steels and cast irons, test samples of HEAs are obtained using the cast by gas model (CGM) process, and, thus, the possibility of its cast production is proven in practice. The structural features of the test castings are identified, and their hardness is determined on the Brinell's scale. The tribotechnical properties of the cast samples are also investigated, and it is established experimentally that these

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characteristics are not affected by their hardness, which is determined on the Brinell's scale. The dependences of the slide friction force and the slide friction coefficient of the pair 'cast (liner)–counter body (shaft)' on the friction path are analysed, and functional relations of the type $I_q = f(\tau)$ and $i_q = \varphi(\tau)$ are derived, which describe analytically how the wear and wear rate of the test material change, respectively, on an arbitrary segment of the time interval. The microstructure of the of cast iron is characteristic of the microstructure of alloyed cast irons with special properties, and the microstructure of cast steel samples depends on microalloying and the regime of their heat treatment. The main structural components of the experimental HEAs are single-phase (b.c.c., f.c.c.) and multiphase (b.c.c. + f.c.c.) solid solutions, which further determine their properties. Graphical interpretation and mathematical processing of experimental data show that the structure and properties of the obtained HEAs primarily determine its chemical composition.

Key words: 'high-entropy' alloys, cast, wear, sliding friction coefficient, counter body, hardness, tribotechnical properties, wear rate.

Описано методику випробування леґованих Fe–C-стопів і «високоентропійних» стопів (ВЕС) на зношування в умовах сухого тертя та наведено дані про лабораторну установку. Для порівняння із леґованими крицями та чавунами за ЛГМ-процесом (лиття за газифікованими моделями) одержано тестові зразки ВЕС, а тим самим на практиці доведено можливість їхнього ливарного виробництва. Із застосуванням металографічної аналізи виявлено особливості структуроутворення піддослідних виливків, а також визначено їхню твердість за Брінеллевою шкалою. Досліджено триботехнічні властивості литих зразків та експериментально встановлено, що на ці характеристики не впливає їхня твердість, яку було визначено за Брінеллевою шкалою. Проаналізовано залежності сили тертя ковзання й коефіцієнта тертя ковзання пари «виливок (вкладиш)–контртіло (вал)» від шляху тертя та виведено функціональні співвідношення типу $I_q = f(\tau)$ й $i_q = \varphi(\tau)$, що аналітично описують як змінюються зношування та швидкість зносу піддослідного матеріялу, відповідно, на довільному відрізку часового інтервалу. Результати металографічної аналізи чавунних виливків показали, що мікроструктура матеріялу є характерною для мікроструктури леґованих чавунів зі спеціяльними властивостями, а мікроструктура литих зразків з криці залежить від мікролеґування та режиму їхнього термічного оброблення. Основними структурними складовими піддослідних ВЕС є однофазні (ОЦК, ГЦК) та багатофазні (ОЦК + ГЦК) тверді розчини, які у подальшому визначають їхні властивості. Графічна інтерпретація та математичне оброблення експериментальних даних показали, що структуру та властивості одержаних ВЕС, у першу чергу, визначає їхній хемічний склад.

Ключові слова: «високоентропійні» стопи, лиття, коефіцієнт тертя ковзання, контртіло, твердість, триботехнічні властивості, швидкість зносу.

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1. INTRODUCTION

In many branches of the national economy, in particular in the machine-building sector of the economy, for the implementation of modern technological processes, products made of metals and alloys based on them with high physical and mechanical, special, technological properties are often required. This is due, first of all, to the operating conditions of the detail, its cost and other factors. Such a set of characteristics, today, can only be provided by high-alloy steels and alloys, among which high entropy alloys (HEAs) occupy a worthy place.

It is known [1–16] that HEAs have an optimal microstructure and high physical, mechanical and special properties. There are the factors that ensure, in particular, the mechanical characteristics of HEAs, which are [3, 5, 11]: temporary resistance to fracture (σ_v, MPa), relative elongation (δ_5, %), Brinell's hardness (HB, kgf/mm^2) and impact toughness (a_n, J/cm^2), which will be discussed further in the text. Such factors include significant distortion of the crystal lattice, which occurs due to the presence of atoms of chemical elements with different electronic configuration, sizes and thermodynamic characteristics, slow diffusion of atoms of components that are part of the HEAs and their cooperative movement ensure the stability of its phase composition during heat treatment (HT), interaction of impurity atoms, which form, among other things, hybrid bonds in the crystal lattice of the solid solution, which provides a compositional effect of strengthening the HEAs at the atomic level [3]. At the same time, HEAs have the prospect of practical application as a coating of the working surface of a tool for metal cutting, casting moulds, stamps, moulds and spinnerets [5], and can also be used as diffusion barriers and targets for magnetron sputtering.

However, the production of HEAs by traditional methods [3–5, 10–14] is generally a low-productivity and uneconomical process. In addition, the mass-dimensional parameters of such products are limited. The production of workpieces from HEAs by casting allows avoiding the above-mentioned disadvantages [2, 7–9, 15, 16]. The most promising method of cast production of HEAs, which combines high dimensional accuracy with low cost of suitable casting, is the cast by gas model (CGM) process [17].

Based on these and other considerations, the goal of this research was formulated and set, which was to select a HEAs with such chemical composition that would allow it to be effectively used for operation in dry friction conditions. Since the main characteristics of such material are its hardness in combination with high tribotechnical properties, when performing the task, it was necessary to investigate, first of all, the hardness of cast samples, determined by the Brinell scale, their wear and/or wear rate, wear of the counter body material (CBM) and the coefficient of sliding friction of the 'HEAs–CBM' pair. To justify the economic feasibility of the research, a parallel can be drawn between the tribotechnical characteristics of the studied HEAs and similar properties of traditional wear-resistant materials (cast steels and cast irons), as well as to work out the progressive technology of its cast production.

The object of investigation was the analysis of the structure of cast samples and the analysis of the dependence of the tribotechnical properties of Fe–C alloys and HEAs on their hardness and friction path, as well as the determination of the type and nature of the relationship of an arbitrary segment of the time interval with wear and wear rate of the test material during its wear testing under dry friction conditions. The microstructure, hardness and wear resistance of non-standard high-alloy cast irons with special properties of alloy 1 and alloy 2, wear-resistant low-alloy steels of alloy 3 and alloy 4 (Table 1), as well as a number of HEAs are the subject of this research.

The research methods were: optical microscopy analysis of the structure of steels and alloys, determination of the hardness of castings on the Brinell's scale and testing of cast samples for wear under dry friction conditions, which involved computer processing of the functional dependencies $f = f_1(l_f)$ and $F = f_2(l_f)$. The reliability of the obtained results was ensured by graphical interpretation and mathematical processing of the experimental data. The type and character of the influence of an arbitrary segment of the time interval on the wear and wear rate of the tested material during its testing for wear resistance under dry friction conditions were found out using the provisions of the theory of differential and integral calculus.

The methodology for testing alloys of ferrous and non-ferrous metals for wear under dry friction conditions, proposed by the authors, should be attributed to scientific novelty and practical value. The idea of cast production of HEAs can also be considered scientific novelty, as well as an analytical description of the influence of the duration of testing of the tested steels and alloys on its wear, wear rate and wear of the HEAs.

2. GENERAL TERMS AND DEFINITIONS

In this section made an emphasis on the tribotechnical characteristics of HEAs and their hardness, and also clarifies the type and nature of the bond between its.

2.1. HEAs

HEAs, by formal criteria, are nothing more than baseless alloys containing 5 or more metal elements and it is worth noting that the concentration of each of its should range from 5% to 35% (atomic fraction). From the standpoint of classical physical chemistry, any multicomponent alloy will be high-entropic one, if its entropy factor ($T\Delta S$) in the Gibbs phase equation, which from a mathematical point of view can be represented as dependence [19]

$$\Delta G = \Delta H - T\Delta S, \quad (1)$$

where ΔG is the change in the isobaric-isothermal potential (Gibbs free energy) of the system [J], ΔH is the enthalpy of formation (enthalpy factor) of the chemical compound [J], T is the temperature of the system [K], ΔS is the change in the entropy of the alloy [J/K], is greater than the enthalpy of formation (ΔH) of the most stable chemical compound on the binary or ternary phase diagrams of the elements forming this system [18], *i.e.*,

$$T\Delta S > \Delta H. \quad (2)$$

The types of HEAs known to materials scientists today [19]: amorphous, single-phase (b.c.c., f.c.c.), multiphase (b.c.c. + f.c.c.), and also ordered solid solutions. Multicomponent intermetallic systems deserve special attention of researchers. Such intermetallics are usually: Laves phases (hexagonal $MgZn_2$ ($C14$), cubic $MgCu_2$ ($C15$)), σ phases (such as FeCr), μ phases (such as Fe_7Mo_6), R phases (such as $Mo_3Fe_5Cr_2$).

2.2. Tribology Studies

Tribology studies the processes of contact interaction of solid bodies that are deformed. In other words [18–20], tribology studies the processes of interaction of solid bodies during their relative movement. The field of tribological research is, in particular, the processes of friction and wear. Tribology directly studies friction processes, and tribotechnical studies its application in practice in machine and mechanism assemblies.

Today, the well-known cast HEAs [8], which operate on wear under dry friction conditions in contact with other structural materials, for example, CBM, form a tribological system with its. The physical admeasurements that quantitatively characterize this system [18] in practice are the coefficient of slide friction of the pair 'HEAs–CBM', the wear rate and/or wear of the cast sample, as well as the wear of the CBM. The physical meaning of these admeasurements, from the standpoint of classical tribology and tribotechnics, is described in detail in the works [18–22].

A special case of tribosystems are antifriction systems [18, 19]. A distinctive feature of such systems is low tribotechnical characteristics [8]: wear I_q and wear rate i_q of the material of the experimental cast, wear I_{CBM} and wear rate i_{CBM} of the CBM, as well as the coefficient of sliding friction f of the pair 'cast sample–counter body'.

Antifriction systems largely ensure the engine life, safety, reliability and durability of all technical equipment and they are among the main objects of research in tribology [2]. During these studies, problems arise that are associated with the lack of equilibrium and the dynamics of states in tribological contact, as well as the complexity of the measurement process, which is connected not only with low resolution of devices and tools, but also with the internal mechanism of tribological processes [20]. Friction and wear are generally considered as types of the destruction process [2], in particular, friction is the overcoming of resistance to the destruction of cold-welding bridges and surface deformation by irregularities of the counter body, and wear is the result of microcutting, cohesive fatigue detachment of particles from the surface of a solid body or brittle destruction of films of chemical compounds on its surface [2]. Such mechanistic representations [20] do not correspond to real processes in antifriction systems. Even under the condition of constancy of the initial dimensions and mass of solids, in heavily loaded tribological systems complex physical-and-chemical and thermal-and-physical processes occur, synthesis of new substances and formation of structures occurs, and any forms of destruction and deformation of the friction surface are considered as signs of their future failure [18]. The author of Ref. [20] showed that in the process of wear in tribological contact tribostructures are spontaneously formed, which fluctuate near the average value in the stationary regime. At the same time, at certain time intervals the dimensions of solids can even increase due to the temporary growth of tribological structures, therefore, due to the limited test time, unreliable results can be obtained [2, 18, 20].

The mathematical apparatus underlying practical calculations of tribotechnical properties of materials and friction pairs (I_q, I_{CB}, i_q, i_{CB}, f) was reflected in a number of publications [7, 8, 23–26]. The authors made their calculations with reference to the scientific works of domestic authors [18–22].

2.3. Mechanical Properties of Materials

The conditional maximum possible mechanical stress [27] that occurs in the material under the influence of an external load on the sample during deformation leads to the destruction of the tested material (rupture of the sample), and corresponds to the maximum on the deformation diagram [27]. The ultimate strength or temporary resistance to fracture [MPa] is determined by the formula [28]

$$\sigma_в = R_m / S_0, \quad (3)$$

where R_m is the fracture force (load) of the test material [N], S_0 is the initial value of the cross-sectional area of the cast sample [mm^2].

The next important mechanical characteristic of the material is its relative elongation (%)—a quantitative measure of deformation, which is given by the relation [28]:

$$\varepsilon = \Delta l / l_0 , \tag{4}$$

where l_0 is the length of the body (rod) before deformation [mm], Δl is the increase or decrease in this length during tension or compression [mm].

Relative elongation is a simplified characteristic of body deformation (4), which is usually used for long thin bodies, *i.e.*, rods. In the general case, the deformation should be characterized by the deformation tensor, since elongation is usually accompanied by a change in the transverse dimensions of the body, and therefore in the notation of the deformation tensor [28]:

$$\varepsilon_{xx} = \Delta l / l_0 . \tag{5}$$

A distinction is made between engineering elongation and true elongation. Engineering elongation is given by formula (4), while true elongation is determined from the relationship given below [29]:

$$d\varepsilon_{\tau} = \Delta l / l , \tag{6}$$

where l is the length of the body at any moment of deformation [mm].

Therefore, for finite deformation the following mathematical transformation is valid [29]:

$$d\varepsilon_{\tau} = \int_{l_0}^{l_0+\Delta l} (dl / l) = \ln\left|1 + dl / l_0\right| = \ln\left|1 + \varepsilon\right| . \tag{7}$$

At small deformations, the true and engineering elongations coincide, and at large deformations, the true elongation is usually less than the engineering one.

In cast production, the most widespread method of determining the hardness of the test material is the Brinell scale. The Brinell hardness value is mathematically the ratio of the load acting on the ball to the surface area of the resulting imprint:

$$HB = P / F , \tag{8}$$

where P is the applied load [kgf], F is the surface area of the ball segment [mm^2]:

$$F = \pi D h , \tag{9}$$

where D is the diameter of the ball [mm], h is the depth of the impression (hole) [mm]:

$$h = \frac{D - \sqrt{D^2 - d^2}}{2}, \quad (10)$$

where d is the diameter of the imprint (hole) [mm].

Then, the surface of the spherical segment will be given as

$$F = \frac{\pi D}{2}(D - \sqrt{D^2 - d^2}), \quad (11)$$

and the formula for determining the hardness value on the Brinell's scale will have the following form:

$$HB = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})}. \quad (12)$$

Knowing the hardness by the Brinell's scale, it is possible to determine the strength limit by the formula

$$\sigma_в = KHB, \quad (13)$$

where K is the proportionality coefficient, which is a constant value for a particular material depending on the hardness of tested cast (for carbon steels, $K = 0.36$ at $HB > 175$ kgf/mm^2; for alloyed steels, $K = 0.34$ at $HB < 175$ kgf/mm^2).

When calculating the temporary resistance to fracture of grey cast irons, in practice, a dependence of the following form is used:

$$\sigma_в = (HB - 40)/6. \quad (14)$$

Impact toughness is estimated by the work done to break a notched specimen during impact bending, related to its cross-sectional area at the notch [3, 5, 11, 28].

The specific impact toughness at bending is defined as the ratio of the work required to break a special specimen by impact to the cross-sectional area at the notch:

$$a_н = A/S, \quad (15)$$

where A is the work spent on the destruction (breaking) of the sample upon impact [J], S is the cross-sectional area of the cast sample at the incision site [cm^2].

The work spent on the destruction of the test sample upon bending is defined as

$$A = mg(H - h), \qquad (16)$$

where m is the mass of the pendulum [kg], g is the acceleration of gravity, H is the height of the pendulum centre of gravity before impact [m], h is the height of the pendulum centre of gravity after impact [m].

3. METHODS

This section includes a description of the method of melting and casting cast iron, steel and HEAs, methods of experimental castings for wear under dry friction conditions testing and mechanical testing of cast samples.

The laboratory equipment is descripted below.

3.1. Melting and Cast of Steels and Alloys

The metal was melted in an induction furnace of the IST type with a frequency of 20 kHz and a capacity of 6 kg. The schematic diagram of the melting unit is described in Ref. [8].

The charge was calculated using the program ‘Charge’ (version 2.0) which was created by specialists of the Physico-Technological Institute of Metals and Alloys, N.A.S. of Ukraine in 2000.

The chemical composition of wear-resistant low-alloy steels of alloy 3 and alloy 4 is regulated by ТУ 4112-78269737-001-2005. The composition of the experimental HEAs is described in Ref. [8], and the chemical composition of high-alloy cast iron and steels with special properties are given in Table 1.

The experimental castings were obtained by the CGM process. The parameters of the CGM process were described by V. S. Shulyak in Ref. [17].

Samples for testing cast steels and alloys for wear resistance were made by cutting. The HT regime of wear-resistant complex Alloy 4 is given in Ref. [30].

TABLE 1. Chemical composition (% wt.) of high-alloy cast iron with special properties.

Alloy	Alloyed elements (Fe—base) (% wt.)									
	C	Si	Mn	Cr	Ni	Cu	V	Ti	P	S
1	3.00	2.00	1.00	02.00	16.00	3.00	–	–	0.035	0.025
2	2.96	0.615	2.005	22.358	01.95	0.00	0.252	0.241	0.10	0.08
3 (70ХЛ)	0.751	0.434	0.852	0.958	–	–	–	–	0.029	0.020
4(75ХФТЛ)	0.782	0.487	0.906	0.953	–	–	0.075	0.115	0.030	0.021

3.2. Metallographic and Phase Analysis of Casting Alloys

The microstructure of the experimental cast irons, casting steels and HEAs was studied using an automatic microscope-analyser 'Epiquant'. The method of making metallographic sections of steel and alloys is described in Ref. [8]. The microhardness of the phases was determined using a microhardness tester ПМТ-3.

Using an x-ray microprobe MS-46 from Cameca, the chemical composition of individual phases was studied. Phase analysis was carried out by x-ray diffractometer 'ДРОН-3' using radiation CoK_{α} and MoK_{α}. Measurements were carried out in the angular range of 10–60° with a step of 0.02° and a pulse acquisition time of 2 s [8]. To determine accurately the crystal lattice parameters in the region of distant peaks at large angles, a step of 0.01° and a pulse acquisition time equivalent to 12–16 s were chosen, depending on the type of sample [8].

3.3. Mechanical Testing Methods

Mechanical testing of cast specimens (tensile strength, relative elongation, Brinell's hardness, impact toughness) was carried out according to standard methods. For this purpose, universal equipment was used.

Static tensile tests of steels and alloys were carried out using a universal hydraulic tensile machine P-50. For this purpose, standard samples were used to determine the temporary resistance to fracture and relative elongation of cast alloys. The optimal test temperature is 20 ± 15°C, the highest limit load of the machine is 50 tf, which is equivalent to 500 kN and the power consumption is 2.8 kW.

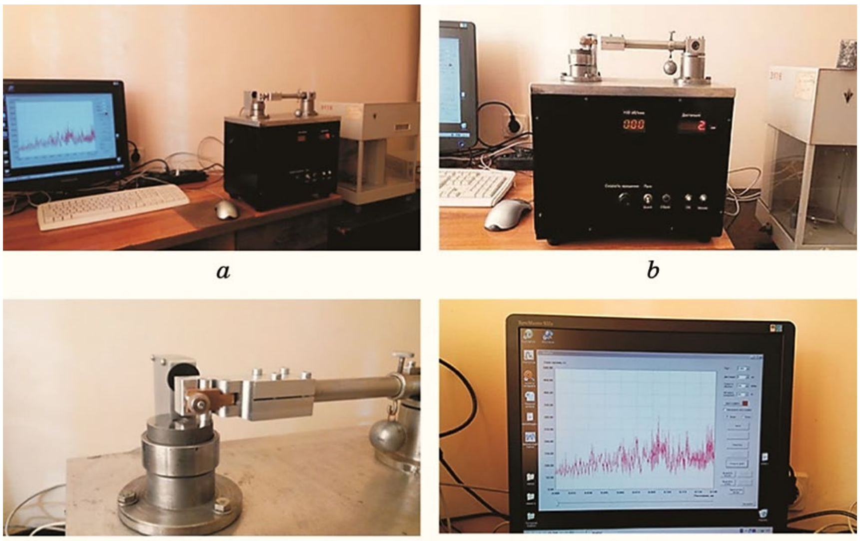
The hardness of the castings from high-alloyed cast irons, low-alloyed steels and HEAs was determined by the standard Brinell method. The most advanced device for determining the hardness of metals and alloys by the Brinell's scale is the lever-mechanical device of the ТШ-2 model.

Impact testing of cast samples from high-alloy cast irons, low-alloy steels and a number of HEAs was carried out on a pendulum-type of МК-30 model. The limiting energy of a pendulum die is 300 J. The speed of the blade of such a die varies from 4 to 7 m/s, which corresponds to raising the blade of the pendulum to a height of 0.8 to 2.6 m.

3.4. Methods for Testing Steels and Alloys for Wear under Dry Friction Conditions

The study of cast samples for wear under dry friction conditions was carried out according to the original methodology proposed by specialists of the Physico-Technological Institute of Metals and Alloys, N.A.S. of Ukraine. For this purpose, in the Department of AI and technological processes of casting of aluminium alloys at the Physico-Technological Institute of Metals and Alloys, N.A.S. of Ukraine laboratory equipment (friction machine) was designed and manufactured for testing cast alloys for wear resistance (Fig. 1).

This equipment provides for computer processing of experimental data ($F_f = \varphi_1(l_f)$, $f = \varphi_2(l_f)$) and the principle of its operation is similar to the principle of the friction machine of the model M-22M [31]. Testing of experimental castings for wear under dry friction conditions was carried out according to the scheme 'sample–counter body (shaft)', which is described in [32–36]. The algorithm for mathematical processing of the results of experiment, which is the basis of the methodology for calculating the tribotechnical characteristics, is given in Refs. [31, 33, 34, 36]. As a counter body material in the research, tool steel alloyed with Cr, W and Mn of the 01 AISI was used, the hardness of which after HT was about 66 *HRC*. Overall dimensions of the counter body [mm]: diameter is of 40, thickness is of 12, overall dimensions of the cast sample [mm]: diameter is of 8, height is of 24 ± 1. Parameters of the friction process: test duration is of 6000 s, contact area of the pair 'sample (liner)–counter body (shaft)' is of $5.024 \cdot 10^{-1}$ cm^2, counter body rotation frequency is of 1000 rpm, linear speed of rotation of the counter body is of 2.1 m/s, the normal reaction force of the support (load)



a *b* *c* *d*

Fig. 1. Laboratory equipment (friction machine) for testing of the cast alloys for wear under conditions of dry friction: general view of the equipment for testing samples for wear resistance [8] (*a*), control unit and measurement of loading and coefficient of sliding friction (*b*), mounting unit of test sample (*c*), program interface for recording the sliding friction force (*d*).

is of 0.25 kgf (except for wear-resistant high-alloy cast iron of alloy 1, for which this parameter is of 0.5 kgf), the friction path (distance) is of 10 km. The change in the mass of the counter body and cast samples at the beginning and end of the studied interval was controlled by weighing on an analytical balance of the Radwag XAS 100/C.

The amount of wear of the casting alloy, as well as the wear of the tool chromium–tungsten–manganese of 01 AISI steel (CBM), is determined as the ratio of the mass loss of the material of the investigated cast sample and counter body, respectively, to the product of the nominal contact area of the pair 'sample–counter body (shaft)' and the friction path [31, 33, 34, 36]:

$$I_q, I_{CB} = \Delta m / Sl_f, \quad (17)$$

where Δm is the mass loss of the cast sample and counter body [mg], S is the contact area of the pair 'sample–counter body' [cm^2], l_f is the friction path [km].

The mass loss of the material by both the test casting and the counter body, in turn, can be determined as

$$\Delta m = m - m_f, \quad (18)$$

where m_0, m_f are masses of casting and counter body before and after testing, respectively [mg].

Both wear rate of the cast steels and alloys (cast irons, HEAs), and the wear rate of CBM, *i.e.*, tool steel alloyed with Cr, W and Mn, can be determined, if necessary, using the ratio (13) given in Ref. [26]. The sliding friction coefficients of pairs 'HEAs–01 AISI steel' as well as the sliding friction force were obtained experimentally.

4. RESULTS AND DISCUSSION

This section studies the structure and properties of high-alloy cast irons of alloy 1 and alloy 2 (Table 1), wear-resistant low-alloy steels of alloy 3 and alloy 4, as well as the HEAs of systems $Fe_{24}Ni_{18}Cr_{20}Mn_{15.5}Cu_{17}C_{3.7}Si_{1.8}$, $Fe_{24}Ni_{19.5}Cr_{18}Al_{12}Cu_{21}Mn_{0.3}C_{3.2}Si_2$, $Fe_{20.5}Ni_{19.4}Cr_{16.5}Cu_{20}Mn_{19}C_{2.3}Si_{2.3}$, $Fe_{24}Ni_{19}Cr_{15.5}Cu_{20.5}Al_{15}Mn_{0.5}C_{3.5}Si_2$, $Fe_{22}Ni_{21}Cr_{14}Cu_{23}Al_{19.5}Mn_{0.5}$, $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$, respectively. Working formulas for calculating the wear and wear rate of the material of cast samples from the duration of their testing, *i.e.*, $I_q = f(\tau)$ and $i_q = \varphi(\tau)$ are also derived.

4.1. Microstructure of Steels and Alloys

Typical microstructures (Fig. 2) of alloy 1 and low-alloy alloy 4 steel,

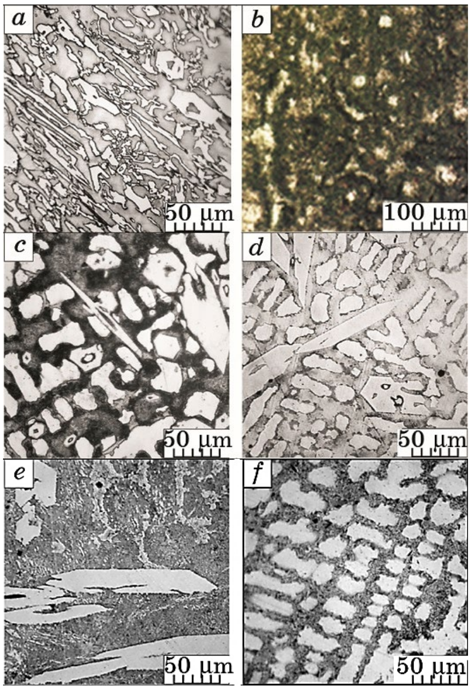


Fig. 2. Microstructure (×500 (*a*, *c*, *d*, *e*, *f*), ×100 (*b*)) of steel and alloys: high-alloy cast iron of the alloy 1 (*a*), low-alloy steel of the 75ХФТЛ type (*b*), HEAs of systems $Fe_{24}Ni_{18}Cr_{20}Mn_{15.5}Cu_{17}C_{3.7}Si_{1.8}$, $Fe_{20.5}Ni_{19.4}Cr_{16.5}Cu_{20}Mn_{19}C_{2.3}Si_{2.3}$, $Fe_{24}Ni_{19}Cr_{15.5}Cu_{20.5}Al_{15}Mn_{0.5}C_{3.5}Si_2$, $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$ (*c*–*f*).

as well as the HEAs systems of the Fe–Ni–Cr–Cu–Al and Fe–Ni–Cr–Cu–Mn are given below. The structure of alloy 1 (Fig. 2, *a*) consists of an austenitic matrix and acicular high-chromium carbides of the $(Cr, Fe)_7C_3$ type. The influence of HT on the microstructure of wear-resistant low-alloy alloy 4 steel was also investigated. For this purpose, the steel samples were heated for quenching to 1333 K, held at this temperature for 1200 s and subsequently cooled through water into oil. To remove residual stresses material was subjected to low tempering. The tempering temperature of the steel castings was 473 K, and the duration of the isothermal holding was 3600 s. After that, the samples of alloy 4 steel were cooled together with the furnace. The composition of the studied material includes martensite and retained austenite, and also Me_mC_n inclusions occur (Fig. 2, *b*).

The amount of retained austenite in the structure of the steel castings is 45–50% (by area). Alloys of the Fe–Ni–Cr–Cu–Mn system have a two-phase structure which consists of primary dendrites and a second phase (Fig. 2, *c*, *d*, *e*), which is formed from the residual liquid and forms the interdendritic space. The branches of the dendrites have an elongated oval shape. In the HEAs samples of the Fe–Ni–Cr–Cu–Al system, granular dendrites and lamellar eutectic (Fig. 2, *e*) are observed in the interdendritic space. The formation of needle-shaped Me_mC_n, which in cross section have a hexagonal shape (Fig. 2, *c*, *d*, *e*), is due to the high content of C and Cr. C appeared in the HEAs, since cast iron was used as the source of Fe. In the cast structure of the sample presented in Fig. 2, *e*, Me_mC_n does not occur due to the low content of C in the starting materials. The charge material used was stainless Cr–Ni steel (Fe–10% wt. Cr–18% wt. Ni–L (cast steel)). Preliminary microprobe analysis of the HEAs of both systems showed that in the branches of the dendrites there are more refractory elements such as Fe and Cr, and in the interdendritic space there are elements with a lower melting point: Cu, Mn, Al, and Ni in equal concentrations is distributed between the 2 phases. The concentration of valence electrons indicates the probability of the formation of 2 solid solutions with f.c.c. and b.c.c. lattices in the HEAs of the Fe–Ni–Cr–Cu–Al system, and 2 f.c.c. lattices with different atomic lattice parameters: f.c.c.-1 (structure similar to the γ-Fe structure), f.c.c.-2 (structure similar to the Cu structure).

4.2. Hardness of the Test Castings

The hardness (Table 2) of the cast samples (Fig. 3) by the Brinell's scale is in the range from 156.0 kgf/mm^2 to 635.3 kgf/mm^2. Such a 'fluctuation' of this characteristic is due, first of all, to the structure of the test materials, which, in turn, depends on their chemical composition and HT regime.

For example, in the structure of steel castings, such a metastable phase as residual austenite during operation transforms into deformation martensite. At the same time, the microstructure of high-alloy cast irons and HEAs has been sufficiently considered and described in [8].

4.3. Wear Resistance of Cast Samples

It was studied the tribotechnical characteristics (Table 2) of cast irons, steels and HEAs. These characteristics were as follow: wear of the test casting, wear of the CBM and the coefficient of sliding friction of the contact pair 'cast sample–01 AISI Steel'.

Graphical interpretation of the experimental data (Fig. 4) made it possible to find out that the wear of the test casting (Fig. 4, *a*) is in the range from −0.106 mg/(cm^2·km) to +1.358 mg/(cm^2·km), wear of the MCT (Fig. 4, *b*) varies from 0.060 mg/(cm^2·km) to 1.781 mg/(cm^2·km), and the coefficient of sliding friction (Fig. 4, *c*) of the contact pair 'cast sample–01 AISI Steel' is 0.243–0.904.

As in the previous case, this is due to the structure of the material, which is described in [7, 8, 30].

TABLE 2. Hardness and wear resistance of cast irons, steels and HEAs, where WHT—without heat treatment, QOLT—quenching with oil cooling and low-temperature tempering.

Sample	Alloy	*HB*, kgf/mm^2	I_q, mg/(cm^2·km)	I_{CBM}, mg/(cm^2·km)	*f*
001	Alloy 1	410.5	+0.740	0.361	0.637
002	Alloy 3 (WHT)	362.5	+0.995	0.348	0.609
003	Alloy 4 (WHT)	415.4	+0.786	0.119	0.666
004	Alloy 4 (QOLT)	635.3	+0.438	0.617	0.589
005	$Fe_{24}Ni_{18}Cr_{20}Mn_{15.5}Cu_{17}C_{3.7}Si_{1.8}$	227.0	−0.106	1.380	0.904
006	$Fe_{24}Ni_{19.5}Cr_{18}Al_{12}Cu_{21}Mn_{0.3}C_{3.2}Si_2$	363.0	+0.352	1.781	0.798
007	$Fe_{20.5}Ni_{19.4}Cr_{16.5}Cu_{20}Mn_{19}C_{2.3}Si_{2.3}$	207.0	−0.106	0.647	0.813
008	Alloy 2	158.0	+1.111	0.318	0.831
009	$Fe_{24}Ni_{19}Cr_{15.5}Cu_{20.5}Al_{15}Mn_{0.5}C_{3.5}Si_2$	336.0	+0.113	0.727	0.900
010	$Fe_{22}Ni_{21}Cr_{14}Cu_{23}Al_{19.5}Mn_{0.5}$	228.0	+1.358	0.524	0.620
011	$Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$	156.0	+0.033	0.060	0.243

4.4. Dependence of Sliding Friction Force and Sliding Friction Coefficient on Sliding Friction Path, the Influence of Sliding Friction Force on Sliding Friction Coefficient

It has been experimentally proven (Fig. 5) that the sliding friction force and sliding friction coefficient of the contact pair 'HEAs system $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$–01 AISI Steel' depend on the friction path. For example, Figure 5, a clearly demonstrates the presence of insignificant peaks on the filtration line $F_f = \varphi_1(l_f)$, which indicates, hypothetically, the chemical and, as a consequence, the structural heterogeneity of the HEAs in the zone of its contact with the CBM. The same can be said about the functional dependence of the sliding friction coefficient of the pair under consideration on the sliding friction path (Fig. 5, *b*), *i.e.*, $f = \varphi_2(l_f)$.

Graphical interpretation (Fig. 5, *c*) of the ratio of physical quantities $f = \varphi_3(F_f)$, which were initially given in tabular form and its mathematical processing allowed us to derive, as a result, an empirical equation that analytically describes the influence of the sliding friction force on the sliding friction coefficient of the contact pair 'HEAs $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$ system–01 AISI Steel'. This equation, with the maximum possible value of the approximation reliability ($R^2 = 1$):

$$f = 4 \cdot 10^{-3} F_f + 2 \cdot 10^{-5}. \quad (19)$$

The long process of testing materials ($\tau_f = 6000$ s), which took place under conditions of dry sliding friction without a running-in stage, and the hardness and wear resistance indicators (Table 2) of the com-

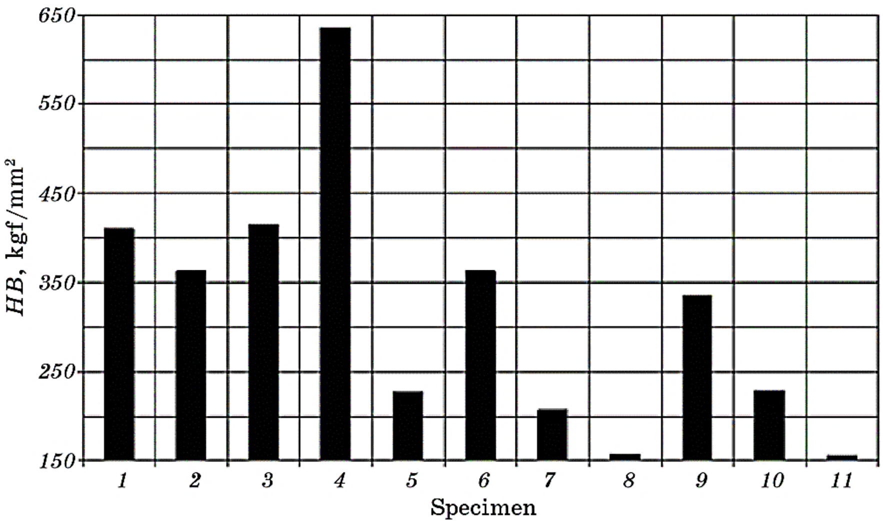


Fig. 3. Hardness of cast steels and alloys: *1*—high-alloy cast iron alloy 1, *2*—low-alloy steel alloy 3 (WHT), *3*—low-alloy steel alloy 4 (WHT), *4*—low-alloy steel alloy 4 (QOLT), *5*—HEAs system $Fe_{24}Ni_{18}Cr_{20}Mn_{15.5}Cu_{17}C_{3.7}Si_{1.8}$, *6*—HEAs system $Fe_{24}Ni_{19.5}Cr_{18}Al_{12}Cu_{21}Mn_{0.3}C_{3.2}Si_2$, *7*—HEAs system $Fe_{20.5}Ni_{19.4}Cr_{16.5}Cu_{20}Mn_{19}C_{2.3}Si_{2.3}$, *8*—high-alloy cast iron Alloy 2, *9*—HEAs system $Fe_{24}Ni_{19}Cr_{15.5}Cu_{20.5}Al_{15}Mn_{0.5}C_{3.5}Si_2$, *10*—HEAs system $Fe_{22}Ni_{21}Cr_{14}Cu_{23}Al_{19.5}Mn_{0.5}$, *11*—HEAs system $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$.

ponents of the contact pair indicate high mechanical and tribotechnical characteristics (I_q, I_{CBM}, f) of the cast samples. Based on these and other considerations, the HEAs system $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$ can be used in tribotechnics as an antifriction material.

4.5. The Influence of the Duration on Wear and Wear Rate

Since the wear rate of the tested material, in the general case [22], is nothing more than the first derivative of its wear with respect to time, *i.e.*:

$$i_q = dI_q / d\tau , \quad (20)$$

and the wear of cast specimens [35, 40, 41, 43] can be represented in the form of dependence (17), then given as

$$l_f = v_f \tau , \quad (21)$$

where v_f is the linear speed of rotation of the counter-body (friction speed), m/s, τ is the current time, s, at the output we obtain the following relation:

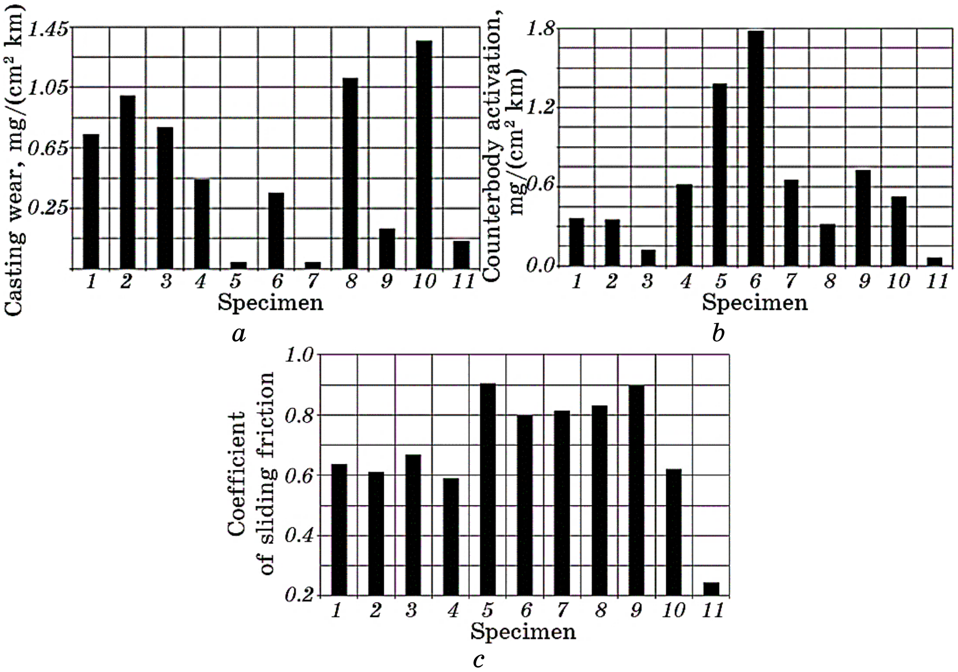


Fig. 4. Tribotechnical properties of cast alloys [8]: *1*—cast iron alloy 1, *2*—steel grade alloy 3 (WHT), *3*—alloy 4 (WHT), *4*—alloy 4 (QOLT), *5*—HEAs system $Fe_{24}Ni_{18}Cr_{20}Mn_{15.5}Cu_{17}C_{3.7}Si_{1.8}$, *6*—HEAs of $Fe_{24}Ni_{19.5}Cr_{18}Al_{12}Cu_{21}Mn_{0.3}C_{3.2}Si_2$ system, *7*—HEAs system $Fe_{20.5}Ni_{19.4}Cr_{16.5}Cu_{20}Mn_{19}C_{2.3}Si_{2.3}$, *8*—Alloy 2, *9*—HEAs of $Fe_{24}Ni_{19}Cr_{15.5}Cu_{20.5}Al_{15}Mn_{0.5}C_{3.5}Si_2$ system, *10*—HEAs of $Fe_{22}Ni_{21}Cr_{14}Cu_{23}Al_{19.5}Mn_{0.5}$ system, *11*—HEAs of $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$ system, the wear of the test casting (*a*), the wear of the MCT (*b*), the coefficient of sliding friction (*c*).

$$I_q = \Delta m/(Sv_f\tau)\,. \quad (22)$$

If we determine the first derivative of the wear of the test material with respect to time:

$$\frac{dI_q}{d\tau} = \frac{\Delta m^{I}(Sv_f\tau) - \Delta m(Sv_f\tau)^{I}}{(Sv_f\tau)^2} = \frac{\Delta m Sv_f}{(Sv_f\tau)^2} = \frac{\Delta m}{Sv_f\tau^2}\,, \quad (23)$$

then, the wear rate of cast samples (cast irons, cast steels and HEAs) and their wear can be represented using mathematical expressions, respectively:

$$i_q = \frac{\Delta m}{Sv_f\tau^2}\,, \quad (24)$$

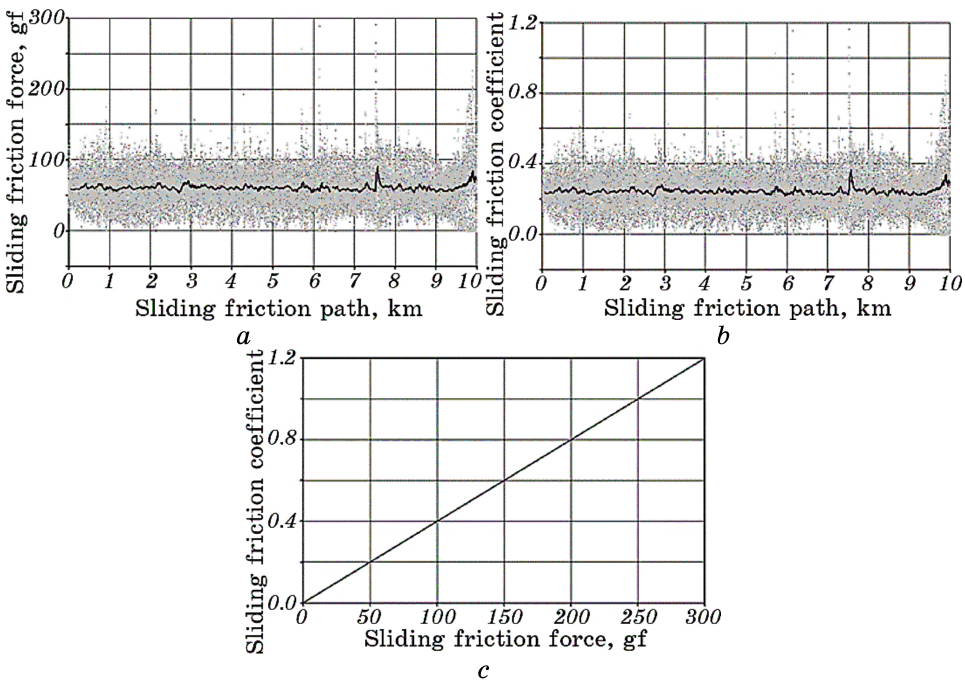


Fig. 5. Dependence of the sliding friction force (*a*) and the sliding friction coefficient (*b*) of the contact pair 'HEAs system $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$–01 AISI steel' on the sliding friction path, as well as the influence of the sliding friction force on the sliding friction coefficient (*c*) of the contact pair 'HEAs system $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$–01 AISI steel'.

$$dI_{\mathrm{q}} = -\frac{\Delta m d\tau}{S v_{\mathrm{f}} \tau^2}. \tag{25}$$

Integrating relation (25) and given Δm [35, 40, 41, 43], we obtain as a result

$$I_{\mathrm{q}} = -\frac{\Delta m}{S v_{\mathrm{f}}} \int_{\tau_{\mathrm{f}}}^{\tau_0} \frac{d\tau}{\tau^2} = -\frac{\Delta m}{S v_{\mathrm{f}}} \left(-\frac{1}{\tau_0} + \frac{1}{\tau_{\mathrm{f}}} \right) = \frac{\Delta m}{S v_{\mathrm{f}}} \left(\frac{1}{\tau_0} - \frac{1}{\tau_{\mathrm{f}}} \right), \tag{26}$$

where τ_0, τ_{f} are the initial and final moments of the casting wear test, respectively, s,

$$\Delta m = m_0 - m_{\mathrm{f}}, \tag{27}$$

where m_0, m_{f} are mass of the cast sample before and after testing it for wear, respectively, mg, and also semi-empirical equations that analytically describe the dependence of the wear rate and wear of steels and alloys on the duration of their testing under dry friction conditions, respectively:

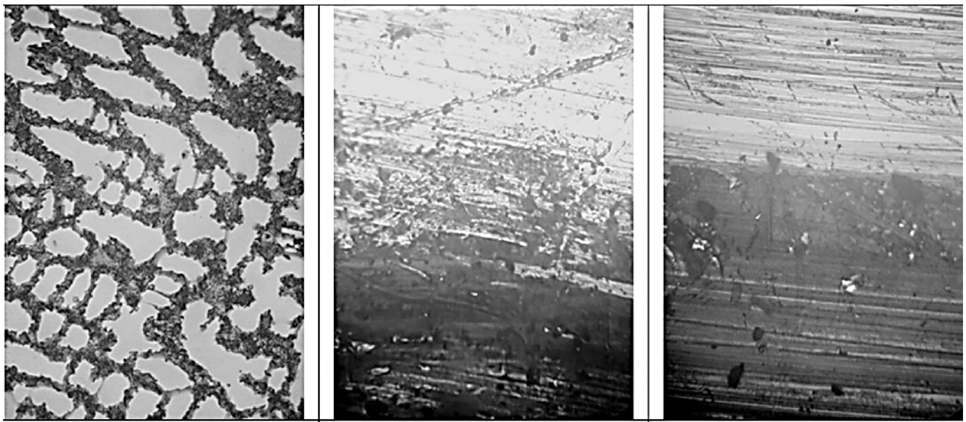
$$\dot{i}_{\text{q}} = -\left.\frac{m_0 - m_{\text{f}}}{S v_{\text{f}} \tau^2}\right|_{\tau \neq 0}, \quad (28)$$

$$I_{\text{q}} = \left.\frac{m_0 - m_{\text{f}}}{S v_{\text{f}}}(\tau_0^{-1} - \tau_{\text{f}}^{-1})\right|_{\tau_0 \neq 0, \tau_{\text{f}} \neq 0}. \quad (29)$$

The mathematical relations (20)–(29) presented above can also be applied to the CBM material, *i.e.*, tool alloy HVG steel after its heat treatment. For this, in formulas (20), (22)–(26), (28), (29) it is necessary to replace the symbols of physical quantities, such as 'i_{q}' and 'I_{q}', with the symbols 'i_{CBM}' and 'I_{CBM}', respectively.

4.6. Studies of the Tribostructure of Sliding Friction Pair Components

The results of metallography showed (Fig. 6, *a*) that the microstructure of $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$ without HT is typical for the microstructure of HEAs of this class. HEAs of the 'Fe–Ni–Cr–Mn–Cu' system, which include C as an impurity, have a heterogeneous two-phase structure. The main structural components of these alloys are primary dendritic-type crystals and a secondary phase that is released after the formation of dendrites and forms the interdendritic space. The branches of the dendrites have an elongated oval shape. It was showed (Fig. 6, *a*) that relatively refractory elements (Fe, Cr) are present in



a *b* *c*

Fig. 6. Micro- (×500 (*a*)) and tribostructure (×200 (*b*, *c*)) of friction pair components: HEAs $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$ (*a*, *b*), 01 AISI steel (*c*).

significant quantities in the branches of the dendrites, and elements with a lower melting point (Cu, Mn) are present in the interdendritic space, while Ni is distributed in equal concentrations between the two phases. The increased concentration of Cr and Fe in the branches of the dendrites led to the fact that their microhardness is approximately in 1.1 times higher than the microhardness of the substance of the interdendritic space. The concentration of valence electrons indicates the probability of the existence of 2 solid solutions based on phases that have an f.c.c. lattice (f.c.c.-1 is similar to γ-Fe in its crystal structure), and f.c.c.-2 in the branches of the dendrites and the interdendritic space is close in structure to the Cu crystal lattice, which is confirmed by the results of x-ray diffraction.

In the process of synthesis of the compositions, a microheterogeneous structure was formed, which is presented below (Fig. 6, *b*, *c*), and which is the subject of future research: the plastic component of casting alloys—thermally stable solid solutions of the elements of the studied alloy, with b.c.c. or f.c.c. lattices; the strengthening phase of the experimental castings is intermetallics ($Me^{I}_{m}Me^{II}_{n}$) and possibly a mixture of solid solutions of the components of the HEAs and intermetallics, *i.e.*, an eutectic, which is allocated in the form of a closed network at the boundaries of crystal grains.

During the wear test of a material under dry friction conditions, on the one hand, its plastic deformation and fracture occur, and on the other hand, the interaction of the environment with its surface occurs, which change the chemical and phase composition, as well as the structure of the friction surface material and play a significant role in the process of testing the contact pair 'HEAs $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$ system–01 AISI steel'. Accordingly, in the friction process, the determining factor is not so much the initial state of the material structure (Fig. 6, *a*), but the structure of its surface layer (Fig. 6, *b*). The latter depends on the primary structure of the material, the formation and occurrence of which is characteristic of the complex conditions of the friction process. Based on these and other considerations, it is necessary to investigate not only the initial structure and phase composition of the tested material, but also the structure and phase composition of the friction surface.

Under the influence of sliding speed, pressure from the applied load and temperature in the dry friction zone during the wear test of the contact pair 'HEAs $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$ system–01 AISI steel', complex physics-and-chemical processes occur in the studied HEAs system, which lead to the formation of a tribological structure on the friction surface (Fig. 6, *b*, *c*). We are talking about the so-called secondary structure, that is, a fundamentally new structure of the material that is formed on its surface during the tribosynthesis process. This is usually a thin deformed layer of material, the chemical composition of which, structural state, physical-and-mechanical and special properties are radically different from those they were before the friction process began. In this case, we are talking about oxide films on the surface of both the HEAs $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$ system and the CBM (Fig. 6, *c*), *i.e.* high-carbon tool 01 AISI steel, which determine the tribotechnical and operational properties of this friction pair.

5. CONCLUSIONS

An original and progressive method for testing steels and alloys for wear under dry friction conditions was proposed. The possibility of cast production of hard and wear-resistant cast irons, cast steels and HEAs using the LGM process was proven.

The peculiarities of the structure formation of high-alloyed cast iron with special properties of the alloy 2, wear-resistant low-alloy alloy 4 steel after heat treatment, as well as cast HEAs $Fe_{24}Ni_{18}Cr_{20}Mn_{15.5}Cu_{17}C_{3.7}Si_{1.8}$, $Fe_{20.5}Ni_{19.4}Cr_{16.5}Cu_{20}Mn_{19}C_{2.3}Si_{2.3}$, $Fe_{24}Ni_{19}Cr_{15.5}Cu_{20.5}Al_{15}Mn_{0.5}C_{3.5}Si_2$, $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$ were clarified.

The main structural components of wear-resistant high-alloy cast iron of the alloy 2 are hard needle-like inclusions of high-chromium carbides of the $(Cr, Fe)_7C_3$ type in a soft austenitic matrix, and the composition of the wear-resistant low-alloy steel of the alloy 4 includes martensite and residual austenite (45–50% (by area)) after heat treatment and single inclusions of Me_mC_n, while the HEAs structure is formed by solid solutions of the elements included in its composition, with b.c.c. and f.c.c. lattices, as well as $Me^{\mathrm{I}}_m Me^{\mathrm{II}}_n$ type intermetallics and a mixture of solid solutions of HEAs components and intermetallics, *i.e.* eutectic, which is separated in the form of a closed network at the boundaries of crystal grains.

Mechanical tests of cast samples made it possible to find out that the hardest of all the test materials is the wear-resistant low-alloy alloy 4 after heat treatment—its hardness according to the Brinell scale is equivalent to 635.3 kgf/mm^2.

An original and progressive method of testing steels and alloys for wear under conditions of dry sliding friction is proposed, which allows computer processing of the results of experiment in real time.

The HEAs of $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$ system can be used as an antifriction material in tribotechnics, since its wear (0.033 $mg/(cm^2 \cdot km)$), the wear of the CBM (0.060 $mg/(cm^2 \cdot km)$) working with it in a pair, and the sliding friction coefficient of this pair (0.243) are the lowest among all the tested materials.

The sliding friction force and the sliding friction coefficient of the contact pair 'HEAs of $Fe_{24}Ni_{20}Cr_{15}Mn_{18}Cu_{22}Si$ system–01 AISI steel' depend on the friction path, which indicates the chemical and structural heterogeneity of the HEAs in the area of its contact with the CBM.

In the process of dry sliding friction, the determining factor is not so much the initial state of structure of the material under test, but the structure of its surface layer, because it is the surface layer that absorbs deformation energy, which determines the ability of the material to resist wear.

AUTHORS' CONTRIBUTIONS

I. A. Nebozhak: introductory part, research methodology, planning and setting up of the experiment in the part of foundry production, analysis of the results of research, conclusions. V. D. Babiuk: testing of cast samples for wear under dry friction conditions. R. A. Sergiienko: justification of the choice of materials and methods of testing for wear under friction conditions without lubrication. Ye. A. Zhydkov: methodology for testing the test material for wear under dry friction conditions. Ie. M. Dzevin: graphic interpretation of experimental data, conclusions. O. V. Derev'yanko: obtaining micro- and tribostructures of cast samples. I. A. Shalevska: analysis of results, editing. T. M. Chevychelova: metallographic analysis of the material. V. P. Shkolyarenko: justification, conclusions. O. Yo. Shinsky: research tasks in the field of foundry production, conclusions. A. M. Verkhovliuk: formulation of the task of metallographic analysis and testing of cast samples for wear, conclusions.

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