Metallophysics and Advanced Technologies
Металофіз. новітні технол.
Metallofiz. Noveishie Tekhnol.
2024, vol. 46, No. 5, pp. 385–413
https://doi.org/10.15407/mfint.46.05.0385
Reprints available directly from the publisher

PACS numbers: 61.66.Dk, 62.20.Qp, 64.70.dj, 81.05.Bx

The Structure and Properties of G-CuZn15Si4 Cast Brass After Inoculation of Its Melt with Dispersed FeCr Intermetallic Component

I. A. Nebozhak, V. G. Novytskyi, Ie. M. Dzevin*, and A. M. Verkhovliuk

Physico-Technological Institute of Metals and Alloys, NAS of Ukraine,
34/1 Academician Vernadsky Blvd.,
UA-03142 Kyiv, Ukraine
**G. V. Kurdyumov Institute for Metal Physics, NAS of Ukraine,*
36 Academician Vernadsky Blvd.,
UA-03142 Kyiv, Ukraine

With using of a dispersed-filled gasifying model, it is possible to inoculate the cast brass of the G-CuZn15Si4 (DIN) alloy with intermetallic FeCr, known in the alloys of the binary Fe–Cr system as the σ phase, and to obtain the test castings. With the use of x-ray spectral microanalysis, the chemical composition of cast samples is determined before and after the process of inoculation of the matrix melt with dispersed intermetallic FeCr. The results of x-ray spectral microanalysis show that the cast composite includes Fe and Cr within 1% that vary along the height of the cast sample, while the chemical composition of the control casting contains half as much Fe and Cr is not detected at all. The metallographic analysis of G-CuZn15Si4 cast brass after inoculation make it possible to detect the inclusions of the σ-phase in the field of the metallographic section that is a sign of the microstructure of the zero-dimensional cast composite material of the Cu–FeCr system, while the microstructure of the control casting is characteristic of G-CuZn15Si4 cast brass. The results of mechanical tests of cast samples and their wear tests under dry-friction conditions allow us to come to the conclusion that the hardness of G-CuZn15Si4 cast brass, which is determined according to the Brinell scale, and its tribotechnical characteristics depend on the height of casts of both types, and on the same properties of cast of the sample after inoculation

Corresponding author: Ivan Anatoliyovych Nebozhak
E-mail: nebozhak@ukr.net

Citation: I. A. Nebozhak, V. G. Novytskyi, Ie. M. Dzevin, and A. M. Verkhovliuk, The Structure and Properties of G-CuZn15Si4 Cast Brass After Inoculation of Its Melt with Dispersed FeCr Intermetallic Component, *Metallofiz. Noveishie Tekhnol.*, **46**, No. 5: 385–413 (2024). DOI: 10.15407/mfint.46.05.0385

with dispersed intermetallide FeCr is affected by Fe and Cr concentrations. Graphical interpretation of the experimental data shows that the mechanical and tribotechnical properties of brass castings after the process of inoculation of the matrix melt by the σ phase significantly exceed the similar characteristics of G-CuZn15Si4 cast brass before inoculation.

Key words: dispersed-filled gas model, dispersed inoculator, composite cast, lost-foam casting process, G-CuZn15Si4 cast brass, matrix melt, tribotechnical properties.

Із застосуванням дисперсно-наповненого моделю, що газифікується, вдалося здійснити інокулювання ливарної латуні марки ЛЦ16К4 інтерметалідом FeCr, відомим у стопах бінарної системи Fe–Cr як σ-фаза, й одержати тестові виливки. За допомогою рентґеноспектральної мікроаналізи було визначено хемічний склад литих зразків до і після процесу інокулювання матричного розтопу дисперсним інтерметалідом FeCr. Результати рентґеноспектральної мікроаналізи показали, що до складу композитного виливка в межах 1% входять Fe і Cr, які змінюються по висоті литого зразка, у той час коли в хемічному складі контрольного виливка Fe вдвічі менше, а Cr взагалі не виявлено. Металографічна аналіза ливарної латуні марки ЛЦ16К4 після інокулювання уможливила виявити в полі металографічного шліфа включення σ-фази, що є ознакою мікроструктури нульвимірного литого композиційного матеріялу системи Cu–FeCr, у той час коли мікроструктури контрольного виливка є характерними для ливарної латуні марки ЛЦ16К4. Результати механічних випробувань литих зразків та їх випробувань на зношування в умовах сухого тертя дали змогу дійти висновку, що твердість ливарної латуні марки ЛЦ16К4, яку було визначено за Брінеллєвою шкалою, та її триботехнічні характеристики залежать від висоти обох типів виливків, а на ті ж самі властивості литого зразка після інокулювання дисперсним інтерметалідом FeCr впливають концентрації Fe та Cr. Графічна інтерпретація експериментальних даних показала, що механічні та триботехнічні властивості латунних виливків після процесу інокулювання матричного розтопу σ-фазою значно перевищують аналогічні характеристики ливарної латуні марки ЛЦ16К4 до інокулювання.

Ключові слова: дисперсно-наповнений газмодель, дисперсний інокулятор, композитний виливок, ЛГМ-процес, ливарна латунь марки ЛЦ16К4, матричний розтоп, триботехнічні властивості.

(Received 25 January 2024; in final version, 28 March 2024)

1. INTRODUCTION

Brass is a unique structural material with good physical, mechanical and technological characteristics. It has become widespread in almost all branches of the economy. This became possible due to a successful combination of high strength and plasticity with aesthetic appeal.

Foundry brasses are intended for shaped casting of workpieces of complex configuration. This includes many special additives that improve the pouring properties. Brass castings are characterized by high corrosion resistance, increased strength, and antifriction properties.

As a structural material the foundry grades of brass are used in transport mechanical engineering, as well as for the manufacture of a wide variety of fittings, however, low hardness and wear resistance limit its use in engineering for the manufacture of parts of the machines and mechanisms operating under conditions of abrasive wear.

In present time, a number of technological methods and techniques for improving foundry brasses are known, among which its inoculation occupies a central place, in our case it is reinforcement or composite strengthening. However, the inoculation of foundry brasses by traditional methods is generally a long and uneconomical process. At the same time, the use of special casting methods allows to avoid the specified disadvantages. The most promising method of inoculating brasses is casting according to gasifying models (lost-foam casting process—LFC process), since its main feature is the use of a model that is not removed before filling of the casting mold (CM) by metal, which determines the main advantages of this technological process in comparison with other methods of casting. In addition, the gas model (GM) can be obtained in the volume of the press form (PF) from granular model material.

These circumstances made it possible to introduce dispersed additives into the composition of GM, and thus to solve a twofold task—to inoculate the matrix melt in the 'volume' of the CM and to carry out the utilization of dust-like waste from the ferroalloy industry and foundry production.

In practice, the implantation of inoculators into the 'body' of the GM is go to cold plating of the granules surface of the model material with dispersed ferroalloys before it is blown or filled into the PF volume.

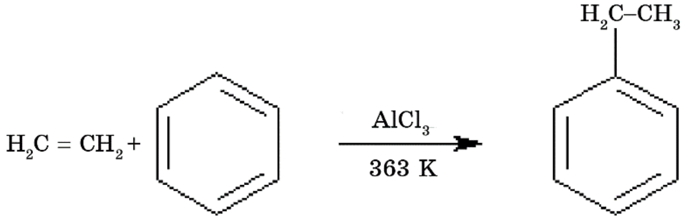
Based on these and other considerations, the goal of this scientific and research work was formulated and set, which consists in the inoculation of molten cast brass of the G-CuZn15Si4 (DIN) alloy with FeCr intermetallic, known in the alloys of the binary system Fe–Cr as the σ phase, with the help of a dispersed-filled gasifying model (DFGM). Since the criteria for evaluating the efficiency of the inoculation process of cast alloys are the absorption indicators of the dispersed inoculant (DI) by the matrix melt, the parameters of the cast samples microstructure, its physical and mechanical and special properties, in order to achieve the goal, it is necessary to investigate the indicators of absorption of the σ phase by the matrix melt, the microstructure of brass castings, its mechanical and tribotechnical properties, as well as to identify factors that significantly effect on these indicators.

2. BASICS OF THEORY AND TECHNOLOGY

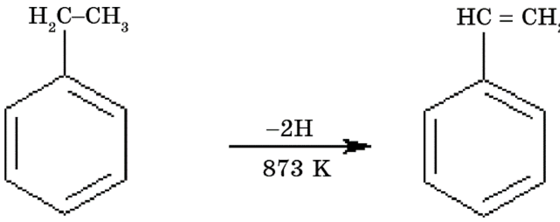
2.1. Physics and Chemistry of the LFC Process

Polystyrene foam (PSF) is used in most cases for the manufacture of GM. On an industrial scale, it is obtained in reactors at increased temperatures by the method of suspension styrene polymerization [1]. The physics-and-chemistry and technology of the two-stage polystyrene production process are described in detail by the author of the monograph mentioned above.

At the first stage, ethylene (rational formula C_2H_4) and benzene (rational formula C_6H_6) in the presence of aluminium chloride (chemical formula $AlCl_3$) as a catalyst, ethylene benzene (rational formula C_8H_{10}) produces, which is then subjected to catalytic dehydrogenation and the output is an intermediate product—styrene (rational formula C_8H_8):

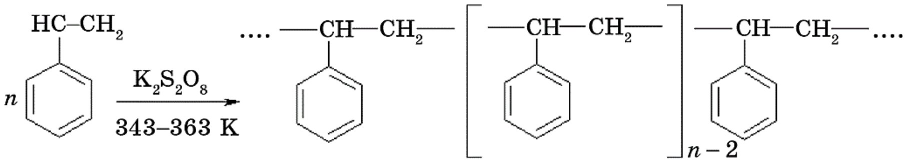


(1)



(2)

At the second stage, as a result, the final product is obtained, *i.e.*, polystyrene (rational formula $(C_8H_8)_{n-2}$) in the presence of a potassium persulfate (chemical formula $K_2S_2O_8$) catalyst, by means of suspension polymerization of styrene (rational formula C_8H_8):



(3)

The physical model of the LFC process as well as the mechanism of the interaction of polystyrene GM with the metal melt are clearly presented and described in the [2]. However, the proposed physical model does not take into account the presence of DI in the system 'metal melt–GM–DI–CM'.

Based on these and other considerations, a physical model of the LFC

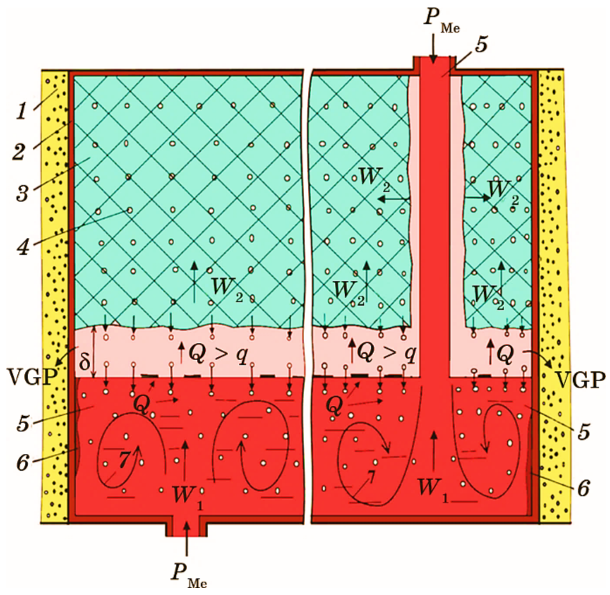


Fig. 1. Physical model of the process of interaction of the matrix melt with the GM and the dispersed inoculator implanted to it during the lower (left) and upper (right) introduction of liquid metal into the 'volume' of the CM [3]: *1* is forming material, *2* is non-stick coating, *3* is gasified model, *4* is dispersed inoculator, *5* is matrix melt, *6* is foundry crust, *7* is convective flows, W_1, W_2 are rates of form filling and thermal destruction of GM, respectively, Q is radiation energy of the matrix melt, q is specific heat of thermal destruction of GM material, VGP is vapour-gas phase, LP is liquid phase, P_{Me} is hydrostatic head of molten metal.

process (Fig. 1) with correction for DFGM was created at the Physico-Technological Institute of Metals and Alloys, N.A.S. of Ukraine (PTIMA) and the heat balance equation of the system under consideration was derived [3]:

$$c_{[Cu-Zn]}\rho_{[Cu-Zn]}\Delta V_{CM}(T_P - T_L^{[Cu-Zn]}) = c_{FeCr}\rho_{FeCr}V_{FeCr}(T_L^{[Cu-Zn]} - T_L^{FeCr}) + \\ + L_{GM}\rho_{GM}\Delta V_{CM} + 1.13 b_{CM}\Delta F_{CM} T_P\sqrt{\tau_P} + L_{FeCr}\rho_{FeCr}V_{FeCr}, \quad (4)$$

where $c_{[Cu-Zn]}$ is the heat capacity of the matrix brass melt, J/(kg·K), $\rho_{[Cu-Zn]}$ is density of matrix brass melt, kg/m^3, ΔV_{CM} is change in the volume of the casting mold in the contact zone with the matrix brass melt, m^3, T_P is pouring temperature, K, $T_L^{[Cu-Zn]}$ is liquidus temperature of matrix brass melt, K, c_{FeCr} is heat capacity of dispersed intermetallic FeCr, J/(kg·K), ρ_{FeCr} is density of dispersed intermetallic FeCr, kg/m^3, V_{FeCr} is volume of dispersed intermetallic FeCr, m^3, T_L^{FeCr} is liquidus temperature of dispersed intermetallide FeCr, K, L_{GM} is specific heat of thermal destruction of expanded polystyrene, J/kg, ρ_{GM} is density of the material of the gasified model, kg/m^3, b_{CM} is heat-accumulating capacity of the casting mold material, W·s$^{0.5}$/(m^2·K), ΔF_{CM} is change in the surface area of the casting mold in the contact zone with the matrix brass melt, m^2, τ_P is duration of form filling, s, L_{FeCr} is the latent heat of fusion of dispersed FeCr intermetallide, J/kg.

An emphasis is also placed on the convective component of the mass transfer process of DI in the volume of the metal bath, which, according to the condition of form filling in the laminar mode and in the process of crystallization of the matrix brass melt, is predominant.

This can be described using a semi-empirical differential equation of convective diffusion, which for the one-dimensional case will have the form [4]:

$$-\frac{\partial}{\partial x}(v^{CM}_{[Cu-Zn]}C^{GM}_{FeCr}S)dxdf =$$
$$= v^{CM}_{[Cu-Zn]}C^{GM}_{FeCr}Sdf - (v^{CM}_{[Cu-Zn]} + \frac{\partial v^{CM}_{[Cu-Zn]}}{\partial x}dx)(C^{GM}_{FeCr} + \frac{\partial C^{GM}_{FeCr}}{\partial x}dx)(S + \frac{\partial S}{\partial x}dx), \quad (5)$$

where x is linear space coordinate (abscissa axis), m, $v^{CM}_{[Cu-Zn]}$ is the average speed of convective flows of the matrix brass melt in the foundry mold, m/s, C^{GM}_{FeCr} is concentration of dispersed intermetallic FeCr in the 'body' of the gasifying model, kg/m^3, S is relative amount of matrix brass melt in the two-phase zone, f is cross-sectional area of the casting mold in the direction perpendicular to the convective flow of matrix brass melt, m^2.

It has been experimentally proven that the hydro- and gas dynamics of the LFC process actively influence on the indicators of absorption of DI by the matrix melt [5, 6], the parameters of the microstructure of composite castings [6, 7], their mechanical [8] and tribotechnical [9] properties.

Quantitative characteristics of the hydro- and gas dynamics of the LFC process are the volume of gaseous products of thermal destruction of the GM material that seep through the wall of the CM, the thickness of the gap between the mirror of the matrix melt and the GM during mold filling, as well as the total cross-sectional area of all feeders. In the conditions of a real CM, there is a one-dimensional parallel laminar filtration of gases released as a result of the thermal destruction of the PSF, which is directed along the normal to the wall of the CM [10]. The regularities of the gases movement in a capillary-porous environment, which is the CM, can be described by the one-dimensional Darcy filtration equation, according to which the flow of these gases along the ordinate axis, that is, perpendicular to the vertical surface of the CM volume, is proportional to their pressure gradient ($\mathrm{grad}P_{CM} = dP_{CM}/dy$); see Ref. [11]:

$$dV = -D\frac{\sum_{i=1}^{n} S_i dP_{\text{CM}}}{\gamma dy} d\tau, \quad (6)$$

where dV is the elementary volume of gas filtered through the thickness of the forming material during the time $d\tau$ due to gradP_{CM}, m^3, D is Darcy filtration coefficient, m^2/s, $\sum_{i=1}^{n} S_i$ is the total cross-sectional area of the filtration flow (including the cross-section of solid particles), m^2, γ is the specific gravity of the filtrate, N/m^3.

The authors of [12], with reference to the results of the study of influence of the various technological factors on the size of the gap between the metal mirror and the GM, obtained by Yu. A. Stepanov and V. G. Moskalyov [13] report that at any moment in time this gap can be described by the equation:

$$\delta = 0.25a\tau_{\text{P}}^{\text{m}} - \mu\frac{F_{\text{F}}}{F_{\text{CM}}}\int_{0}^{\tau_{\text{P}}}\sqrt{2g\left[H_C(\tau) - \frac{F_{\text{CM}}(\tau)}{\rho_{\text{Me}}}\right]}d\tau, \quad (7)$$

where a is the specific coefficient of gas evolution, cm/s, m is relative coefficient of gas evolution, μ is the mass flow coefficient of the shower system, $\mu = 0.5$–0.6 kg/(cm^2·s), F_{F} is cross-sectional area of the feeder, cm^2, F_{CM} is cross-sectional area of the casting mold in the area of interaction of the gasifying model with the matrix melt, cm^2, g is acceleration of free fall, $g = 9.80665$ m/s^2 [14], H_{C} is calculated hydrostatic pressure of the metal melt, cm, τ is current time, s, ρ_{Me} is the density of the matrix melt, kg/m^3.

Calculation of the total cross-sectional area of all feeders in practice is carried out using the ratio proposed by the authors of [15]:

$$\sum_{i=1}^{n}(F_{\text{F}})_i = \frac{m_{\text{C}}}{0.31\mu\tau_{\text{P}}\sqrt{H_C - P_{\text{CM}} / \rho_{\text{Me}}}}, \quad (8)$$

where m_{C} is the mass of cast workpiece, kg, P_{CM} is the pressure of gaseous products of the thermal destruction of polystyrene foam in the gap between the dispersed-filled gas model and the liquid metal mirror, Pa.

First of all, the modes of filling CM with matrix melt and gasification of the model material depend on these factors. Under its influence, the structure of brass castings is formed, which, as a final result, largely effects on the quality indicators of cast samples.

The interaction of the components of system 'metal melt–GM–DI–CM' is a complex thermo-physical and physics-chemical process, and the material presented above is not enough to describe it in detail. A large number of treatises by domestic and foreign researchers are devoted to this topic. The mechanism of the process of interaction of the system components under consideration is revealed on the example of a zero-dimensional cast composite material (CCM) of the Al–FeCr system and is described in detail in the [16].

2.2. Theoretical Basis of Tribology

Cast brasses, which work for wear under conditions of dry friction with other structural materials (materials of the counterbody (MCB)), a tribological system form together with its. The physical quantities that quantitatively characterize this system [17] in practice are the friction coefficient of the 'brass–MCB' pair, the rate of wear and/or wear of cast brass, as well as the operation of the MCB. The physical meaning of these quantities [17–22], from the point of tribology view, is briefly described below.

According to the definition [18], the coefficient of friction is a value that characterizes the force of resistance from friction between interacting bodies. Depending on the type of friction, a distinction is made [17]: the shear friction coefficient (rest friction, incomplete sliding friction, and sliding friction) and the rolling friction coefficient. These coefficients can be represented using mathematical expressions [18], respectively:

$$f = F_{\rm f} / N , \quad (9)$$

$$f = k + A_0 / N , \quad (10)$$

where $F_{\rm f}$ is the force of sliding friction, N, N is the force of the normal reaction of the support, N, k is a coefficient depending on the properties of the surfaces of the bodies in contact, A_0 is the adhesion coefficient of these surfaces, N.

According to the authors of [19], friction processes determine energy flows in tribosystems. In order to manage these flows, you need to know the mechanisms of heat generation and friction force formation. For their analysis [19], they adopted a model of tribological contact in the form of an ensemble of connections, that is, diatomic systems that arise in contact when an external loading is applied, in which the elastic forces of such connections then compensate for this loading. According to the created model, which is described in detail by the authors of the same work, the relative number of such bonds is proportional to the ratio of the loading to the modulus of bulk elasticity, and under real loadings it is in the range of 10^{-6}–10^{-4} of the total number of atoms on the contact area. Since, according to the authors [19], the bond strength is equivalent to grad$E_{\rm pot}$ (where $E_{\rm pot}$ is potential energy, J); the friction force arises under the influence of energy. For their reasons, it can be presented as a dependency:

$$F_{\mathrm{f}} = \frac{n_{\mathrm{A}}P}{K}\int_{r_{\min}}^{r_{\max}} F(r)p(r)dr\,, \tag{11}$$

where F_{f} is the force of sliding friction, N, n_{A} is the number of atoms per unit of contact area, nm^{-2}, P is loading, N, K is modulus of bulk elasticity, GPa, r is interatomic distance, Å, $F(r)$ is the bond strength in the interatomic distance state, N, $p(r)$ is the probability density of states at the interatomic distance, nm^{-1}.

In turn, the bulk elasticity modulus is a value that characterizes the elastic properties of the material under small deformations. It can be determined by the calculation method [20]:

$$K = E/\{3(1-2\mu)\}\,, \tag{12}$$

where E is the modulus of elasticity (Young's modulus) ($E = 70–74$ GPa (Al alloys), $E = 190–210$ GPa (steel), $E = 78–123$ GPa (brass)), μ is Poisson's ratio ($\mu = 0.30–0.33$ (Al alloys), $\mu = 0.27–0.30$ (steels), $\mu = 0.37$ (brass)).

The amount of wear is a change in the geometric dimensions and shape of solids, which are determined by the participation of their substance in the formation of tribostructures. The flow of this substance, averaged over the contact plane of the touching bodies, is equivalent to the wear rate of the material of the test sample [21]:

$$i(t) = dI(t)/dt\,, \tag{13}$$

where t is the current time, s, $I(t)$ is material wear, mg/(cm^2·km).

The process of material wear over time, according to M. V. Kindrachuk and colleagues [19, 21, 22], consists of 2 non-equivalent stages: run-in and steady state. At the preparation stage, tribological structures are formed, and then the process fluctuates in a stationary mode with a constant average value and dispersion. Excessive growth of the tribostructure is limited by entropy, and its lower level is limited by free energy.

Equations that analytically describe the functional dependence of the wear rate of material under test and its wear, respectively, on the current time, are clearly presented below [22]:

$$i(t) = (i_0 - \langle i \rangle)\exp(-t/t_{\mathrm{R}}) + \langle i \rangle\,, \tag{14}$$

$$I(t) = t_{\mathrm{R}}(i_0 - \langle i \rangle)(1-\exp(-t/t_{\mathrm{R}})) + t\langle i \rangle\,, \tag{15}$$

where i_0 and $\langle i \rangle$ are the initial and average steady-state values of material wear rate, respectively, mg/(cm^2·km·s), t_{R} is the relaxation time of running-in, s.

The exponents on the right-hand side of equations (14) and (15), according to the authors describe the evolutionary process of material wear-in, while the wear-in duration estimates the relaxation time, and the contribution of material wear-in to its wear is a functional [22]:

$$I_0 = t_R(i_0 - \langle i \rangle)(1 - \exp(-t / t_R)) . \quad (16)$$

At this stage, the desire for free energy to a minimum prevails, in the contact zone of the bodies that form a friction pair, aggregation of transported particles occurs, internal flows of matter are directed to the formation of a tribological structure and an increase in its volume, and the flow of matter from of the system decreases until it reaches a stationary level [22]. In a stationary state, the tribostructure fluctuates near the average value, during one fluctuation part of the substance leaves this system in the form of material wear products, and then the tribological structure is restored [22].

If the tribological structure of the material under study is restored at a time interval τ, then its wear $I(t)$ at the same interval can be considered as an independent physical quantity. Then, according to the central limit theorem, the authors of [22] develop their opinion: at $t \gg \tau$, the wear of this material $I(t)$ has a normal distribution and can be represented using mathematical expressions as follow:

$$I(t) = t \langle i \rangle \pm \eta\sigma\tau\sqrt{t / \tau} , \quad (17)$$

$$\langle i \rangle = I(t) / t \pm \eta\sigma\tau\sqrt{t / \tau} , \quad (18)$$

where η is a Gaussian variable with unit variance, σ is the root mean square deviation of the arithmetic mean, τ is correlation time interval, s.

According to the authors of [19], the tribostructure is a special state of matter that is arbitrarily formed under conditions of tribological contact that are far from equilibrium. According to M. V. Kindrachuk and E. A. Kulgavyi [19], stable equilibrium states in liquids and gaseous substances correspond to the maximum entropy, that is, the uniform distribution of matter in space. The structure of solids, the authors of the same paper continue their opinion, is determined by the desire of free energy to be minimized, and this determines the crystalline structure of the substance.

3. METHODS

3.1. Subject and Object of Research

As cast brass of the G-CuZn15Si4 (DIN) alloy is characterized by high casting and technological properties [23], which was already mentioned earlier, the influence of the technological parameters of the LFC process and other independent factors during the inoculation of brasses on its mechanical and tribotechnical characteristics was studied using the example of this commercially available alloy. As an inoculator of the matrix melt a dispersed intermetallic FeCr better known in the alloys of the binary system Fe–Cr as the σ phase was used, which was also mentioned earlier, in the amount of 7% of the volume of the control casting which is equivalent to 6.3% wt. More detailed information about these materials and technology of their preparation is given below in the text.

3.2. Technology of the Inoculation Process

Dispersed-filled gasifying model (Fig. 2, *a*) was obtained by the autoclave method [2, 10–12, 15] from PSF with introduced FeCr intermetallide powder. Implantation of the dispersed σ phase in the 'body' of the GM was made by cold plating of the surface of PSF granules with it before PF blowing into the volume [24, 25]. A solution of polyvinyl butyral (rational formula $(C_8H_{14}O_2)_n$) of the 'SDW-3A' trademark in rectified ethyl alcohol (chemical formula C_2H_5OH) was used as an adhesive [24]. GM without additive (Fig. 2, *b*) was also produced by the autoclave method from 'pure' PSF. In order to prevent the formation of scorch on the surface of future castings, a non-stick coating was applied to the GM. The characteristics of model materials will be presented below.

For the manufacture of GM, PSF was used, which was obtained from cast polystyrene (density 1069–1125 kg/m^3) of the 'STMMA-FD' (Castchem, China) trademark. This polystyrene was specially devel-

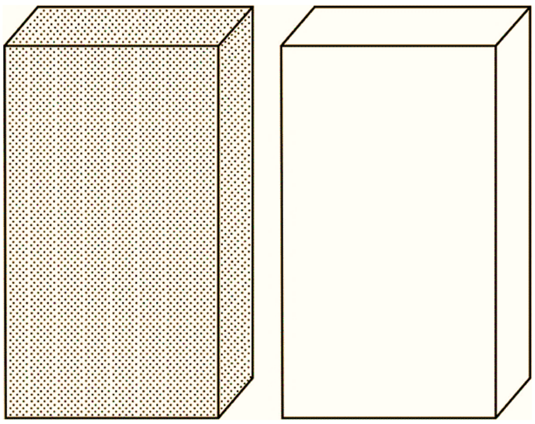


Fig. 2. Appearance of gasified models (diagram): dispersed-filled (*a*), without additive (*b*).

oped for the 'Lost Foam' casting technology, that is, LFC process. The PSF used in the process of implementing this work is characterized by such indicators as: dispersion of the original material (rational formula $(C_8H_8)_{n-2}$) is 0.2–0.4 mm, apparent density is 25 kg/m^3, sintering time is 150 s (DFGM), 120 s (GM without additive).

Dispersed intermetallic FeCr was obtained from cast samples of a high-chromium alloy based on Fe. For this, the piece material was pre-annealed in a laboratory muffle furnace of the model СНО-2,5.5.2,5/13,6 И1 for the formation and separation of the σ phase from a solid solution of Cr in Fe, crushed in a laboratory jaw crusher of the model «Вибротехник ЩД-10 6411-00013» and sifted through sieves. Characteristics of dispersed inoculant (DI): annealing temperature is 1073 K, time of isothermal exposure is 3600 s, dispersion is 20–100 μm, shape of particles is scaly, and unevenness factor is 2–5. The chemical composition of DI (Table 1) is given below in the text.

It was possible to obtain FeCr intermetallide powder of a given dispersion thanks to sieve analysis. For this, a set of laboratory sieves made of woven wire fabric was used, which is regulated by relevant regulatory documents, in particular ДСТУ EN 933-2:201 (EN 933-2:1995, IDT). The average dispersion of the σ phase particles was determined according to the formula [26]:

$$<d>=\frac{\sum_{i=1}^{n} m_i d_i}{\sum_{i=1}^{n} m_i}, \quad (19)$$

where m_i is the mass of the i-th fraction of the powdered σ phase, kg, d_i is the arithmetic mean of dispersion of σ phase particles in the i-th fraction, $\times 10^{-6}$ m.

Depending on the size of the particles (dispersity), the powders are divided into groups. Dispersed FeCr intermetallide, in our case, is a mixture of powders of 2 incomplete groups [26]. Such groups are fine powder (10–40 μm) and medium-sized powder (40–250 μm).

In order to protect the surface of future castings from scorching, an anti-stick coating developed and prepared at PTIMA was used in this work. Anti-stick paint for the LFC process had the following chemical

TABLE 1. Chemical composition (% mass fraction) of the reinforcing phase before reinforcement.

Material	Alloying elements and impurities (Fe—base)							
	Al	Cu	Mn	Ni	Ti	Cr	Mo	W
Intermetallide	0.363	0.147	1.105	0.359	0.297	39.951	0.447	0.930

composition [27], % vol.: pyrophyllite (chemical formula $Al_2[Si_4O_{10}](OH)_2$) or disten-sillimanite (chemical formula $Al_2[SiO_4]O$) is 30.0–50.0, bentonite (60.0–70.0% wt.—montmorillonite, chemical formula $Al_2[Si_4O_{10}](OH)_2 \cdot nH_2O$)—10.0–20.0, acid dextrin (rational formula $(C_6H_{10}O_5)_n$) is 10.0–20.0, technical water (chemical formula H_2O) is the rest. To prevent the fermentation process in the warm season, sodium alginate (rational formula $C_6H_7O_6Na$) was added to the non-stick coating in the amount of 0.3 to 4.0% of the weight of the finished coating.

To obtain the cast samples, the G-CuZn15Si4 (DIN) cast brass was prepared. The studied material, the chemical composition of which (Table 2) is given below, was melted in a pot furnace for melting Cu and alloys based on it, such as brasses and bronzes, model 'CMT-01'. Technological parameters of the LFC process: a) matrix melt temperature, K: at the output from the melting unit—1523, during mold filling—1423, b) speed of mold filling, cm/s: experimental casting—7, control casting—5. The supply of liquid metal into the 'volume' of the CM was carried out from below into the sidewall of the CM along the thickness of the future cast sample (with the lower side siphon), which will be specified later in the text.

The study of the influence of melt inoculation of the G-CuZn15Si4 (DIN) cast brass on its microstructure, mechanical and tribotechnical characteristics was carried out according to the original method proposed by specialists of PTIMA and similar to that described in [6–9]. To do this, brass castings (Table 3, Fig. 3) were pre-marked and cut into templates, from which grindstones for metallographic analysis (MGA), samples for determination of hardness and wear resistance

TABLE 2. Chemical composition (% wt.) of the initial material.

Alloy brand (cast brass)	Alloying elements (Zn—base)									
	Fe	Si	Mn	Ni	P	Al	Cu	Pb	Sb	Sn
G-CuZn15Si4 (DIN)	0.53	4.18	0.75	0.17	0.89	0.04	80.0	0.42	0.91	0.26

TABLE 3. Concentration (% wt. fraction) of thermal dissociation products of FeCr intermetallide in the volume of the composite casting.

Investigated material	Chemical element	The height of the cast sample, $\times 10^{-3}$ m			
		0.015	0.045	0.075	0.105
Zero-dimensional CCM of Cu–FeCr system	Fe	0.980	1.000	1.000	1.010
	Cr	0.750	0.760	0.770	0.780

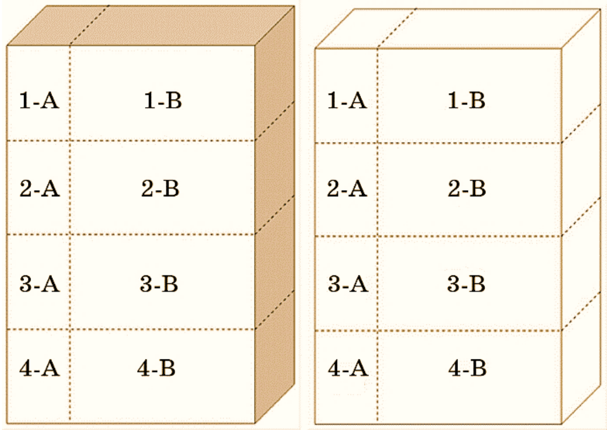


Fig. 3. Scheme of cutting castings into templates for studying the structure (1-A–4-A) and properties (1-B–4-B) of the material according to the height of the cast samples: zero-dimensional CCM of Cu–FeCr system (*a*), G-CuZn15Si4 (DIN) cast brass (*b*).

tests, as well as samples for determination of chemical composition were then made. The overall dimensions of the cast samples (see Fig. 3) were as follows, in mm: length is 50, width is 10, height is 120; and the overall dimensions of each template are 0.25 of the size of the test casting. Coordinates of the feeder (places where the matrix melt is fed into the CM 'volume'), mm: length is 50, width is 5, and height is 0.

The chemical composition of zero-dimensional CCM of the system Cu–FeCr was determined using the x-ray spectral microanalysis (XSM) method. The research was carried out with the help of a raster electron microscope-microanalyser РЭММА-102. The coefficient of assimilation of the σ phase by the melt of the G-CuZn15Si4 (DIN) cast brass can be determined from a ratio similar to the one proposed by the authors of [6]:

$$k_{\text{FeCr}} = \frac{[\text{FeCr}]_1 - [\text{FeCr}]_0}{C_{\text{FeCr}}^{\text{GM}}}, \tag{20}$$

where $[\text{FeCr}]_1$, $[\text{FeCr}]_0$ are the concentrations of dispersed FeCr intermetallide in the matrix melt, respectively, after and before the inoculation process of the G-CuZn15Si4 (DIN) cast brass, % wt. fraction, $C_{\text{FeCr}}^{\text{GM}}$ is FeCr intermetallic content (from the mass of the cast sample) in the dispersed-filled, gasifying model, % wt. fraction.

However, XSM does not allow directly determining the concentration of the σ phase in the studied casting. In this case, the absorption coefficients of Fe and Cr can be taken separately as criteria for evaluating the efficiency of inoculation of the matrix brass melt with a dispersed intermetallic FeCr. In order to solve this problem, it is necessary to convert the content of the σ phase in DFGM into mass fractions, and then determine the concentration of each chemical element (% wt. fraction) that is part of the dispersed intermetallic FeCr. The mass fraction of a given element in a chemical compound, in general, can be calculated using the formula [28]:

$$\omega = 100\frac{nA_r}{M_r}, \tag{21}$$

where n is the number of atoms of an element in a chemical compound, A_r is the relative atomic mass of the element, M_r is the relative molecular weight of the substance.

The metallographic analysis of the material of the cast samples was carried out according to the recommendations of M. V. Maltsev [29]. The microstructure of the metallographic sections was etched using an acid-salt solution with the following chemical composition: 100 ml H_2O, 25 ml HCl, 10 g $FeCl_3$.

Mechanical tests of the materials that were the object of the study were carried out according to standard methods regulated by ГОСТ 1497-84, ГОСТ 9012-59, as well as ГОСТ 25.503-97. Testing of brass castings for wear under dry friction conditions in this work was carried out according to a non-standard method described by the authors of [30], which will be discussed later. The parameters of the process of testing brass castings for wear resistance were: test duration is 1800 s, the contact area of the sample-counterbody pair is 1 cm^2, counterbody rotation frequency is 480 rpm, linear speed of rotation of the counterbody is 1 m/s, normal reaction force of the support (loading) is of 5 kgf, friction path is of 1.8 km.

Cast samples worked in a pair with a counterbody, which had the shape of a hollow washer. Geometric dimensions of the counterbody, mm: outer diameter is 40, inner diameter is 16, and thickness is 12. As the MCB, structural low-chromium steel 41Cr4 (DIN) was used. The hardness of MCB according to the Rockwell scale, after its oil quenching and subsequent tempering [32], is in the range of 52–54 *HRC*. The testing of cast brass of the G-CuZn15Si4 (DIN) for wear resistance was carried out using a laboratory installation (friction machine) of the 'M22M' model, the schematic diagram of which is given in [33]. The change in the mass of the counterbody and cast samples was monitored by weighing them on analytical balances of the 'Radwag XAS 100/C' model.

The amount of wear of the zero-dimensional CCM of the system Cu–FeCr and the G-CuZn15Si4 (DIN) cast brass, as well as the wear of structural low-chromium steel 41Cr4 (DIN), was determined, practically, as the ratio of the mass loss of the material of the cast sample and the counterbody, respectively, to the product of the nominal contact area of the pair 'sample–counterbody' and friction paths [30, 31]:

$$I_q = \frac{\Delta m}{Sl}, \tag{22}$$

where Δm is the mass loss of the studied casting and counterbody, mg, S is the contact area of the sample-counterbody pair, cm^2, l is the friction distance, km.

The loss of material mass by both the cast sample and the counterbody, in turn, was determined using the empirical formula proposed by the authors of [30, 31, 33]:

$$\Delta m = m_1 - m_2, \tag{23}$$

where m_1, m_2 are the masses of the cast sample and counterbody before and after the test process, respectively, mg.

The research was carried out on 5 castings from the experimental alloy (the cast brass G-CuZn15Si4 (DIN) inoculated with 7% vol. fraction dispersed intermetallide FeCr) and 1 from the control (the cast brass G-CuZn15Si4 without additive). The research results were obtained by means of the mathematical processing of experimental data taken from each casting as an arithmetic mean. A cast sample from a control alloy (G-CuZn15Si4) and a test casting were subjected to MGA (G-CuZn15Si4 + FeCr), the properties of which were as close as possible to the arithmetic mean.

4. RESULTS AND DISCUSSION

For convenience and for the purpose of presenting the developed material in an accessible form, research on the inoculation process of the cast brass G-CuZn15Si4 (DIN) with dispersed intermetallic FeCr in the 'volume' of the CM according to the LFC process was carried out in stages. The results of the research showed that zero-dimensional CCM of the Cu–FeCr system has an optimal microstructure, high mechanical and tribotechnical properties, which will be discussed in detail later.

At the first stage, the dependence of Fe and Cr concentrations on the height of the cast sample was studied, and it was also clarified how and to what extent these parameters influence each other. The results of the presented experiment (Table 3) showed that in addition to the main components in the alloy under study.

G-CuZn15Si4 (DIN) + 7% vol. fraction FeCr such elements as Fe and Cr are also present. With the use of XSM, it was possible to establish that the concentrations of Fe and Cr (see Table 3) vary with the height of the composite casting. Graphical interpretation of experimental data is presented in Fig. 4. Visualization of the results of research (see Table 3) made it possible to find out that as the height of the cast sample increases, the concentrations of Fe and Cr in the zero-dimensional CCM of the

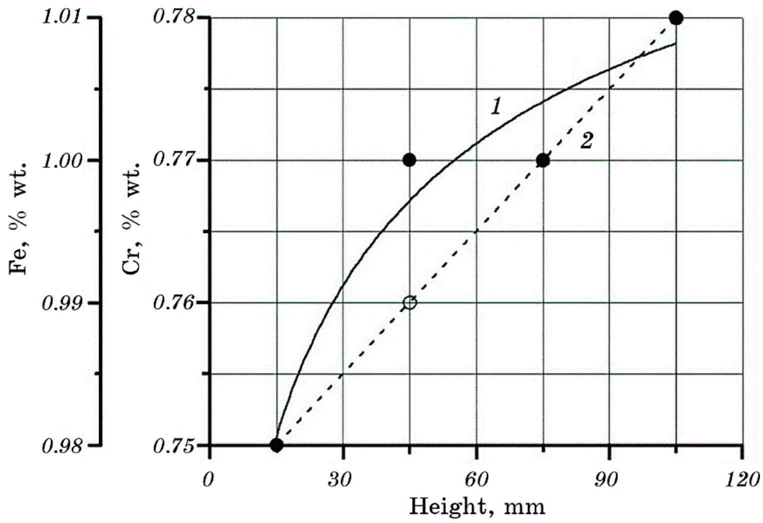


Fig. 4. Distribution of iron and chromium concentration along the height of the composite casting: *1* is iron concentration, *2* is chromium concentration.

system Cu–FeCr gradually increase. Therefore, for example, increasing the height of the composite casting from 15 mm to 105 mm leads to the fact that the concentration of Fe in the volume of the cast sample increases monotonically from 0.98% wt. fraction to 1.01% wt. fraction.

At the same time, the concentration of Cr in the G-CuZn15Si4 (DIN) cast brass after the inoculation process at 15 mm is 0.75% wt. fraction, while at a height of 105 mm this indicator reaches its maximum value and reaches 0.78% wt. fraction. The results of the experiment (see Table 3) and its graphical interpretation also showed that an increase in Cr concentration, which is part of the zero-dimensional CCM of the Cu–FeCr system, from 0.75% wt. fraction to 0.78% wt. fraction is the reason for the increase in Fe concentration in the composition of the composite casting from 0.98% wt. fraction to 1.01% wt. fraction. Since the temperature of the metal melt during mold filling significantly exceeds 1093 K, the σ phase turns into a solid solution of Cr in Fe [15], and in this case, obviously, a chemical reaction occurs:

$$[\mathrm{FeCr}] \xrightarrow{T} [\mathrm{Fe}] + [\mathrm{Cr}], \quad (24)$$

where T is the melting temperature of cast brass of the G-CuZn15Si4 (DIN), K, [Fe] and [Cr] are concentrations of iron and chromium in the matrix melt, respectively, % wt. fraction.

In order to predict, in the future, the influence of height of the cast sample on the concentrations of Fe and Cr in the composition of zero-dimensional CCM of the Cu–FeCr system (Fig. 4) and thus minimize the volume of experimental work, the empirical equations of the corresponding trend lines were derived.

This also applies to the functional dependence (Fig. 5) of Fe concentration on Cr concentration. Such equations analytically describe the influence of independent factors on the characteristics of the test materials ($R^2 = 0.95–1.00$), which were mentioned above. Equations were obtained using computer technologies as a result of mathematical processing of experimental data (Table 3), given in tabular form, and they are given below:

$$[\mathrm{Fe}] = 9.36765 \cdot 10^{-1} - 4.75807 \cdot 10^{-5} H_\mathrm{C} + 1.64249 \cdot 10^{-2} \lg H_\mathrm{C}, \quad (25)$$

$$[\mathrm{Cr}] = 7.45 \cdot 10^{-1} + 3.33333 \cdot 10^{-4} H_\mathrm{C}, \quad (26)$$

$$[\mathrm{Fe}] = 37.6971 - 37.645[\mathrm{Cr}] + 29.4835 \lg[\mathrm{Cr}], \quad (27)$$

where H_C is the height of the brass casting, mm.

This type of dependence (Figs. 4, 5) is explained by the fact that [FeCr] depends on the height of the cast sample under the influence of circulation flows that take place in the volume of the metal bath. The nonlinear nature of these ratios indicates that [Fe] (Table 2) in the alloy of initial composition is imposed on the hydro- and gas dynamics of the LFC process. Since the σ phase in the alloys of the binary system Fe–Cr is formed near the ratio [Fe]:[Cr] = 1:1 [34], this is the nature of the functional connection between the concentration of Fe and the concentration of Cr (see Fig. 5) in the composition of the zero-dimensional

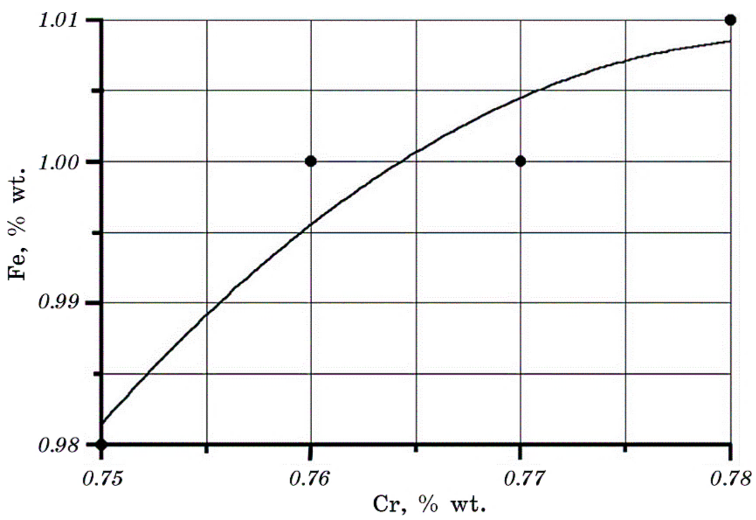
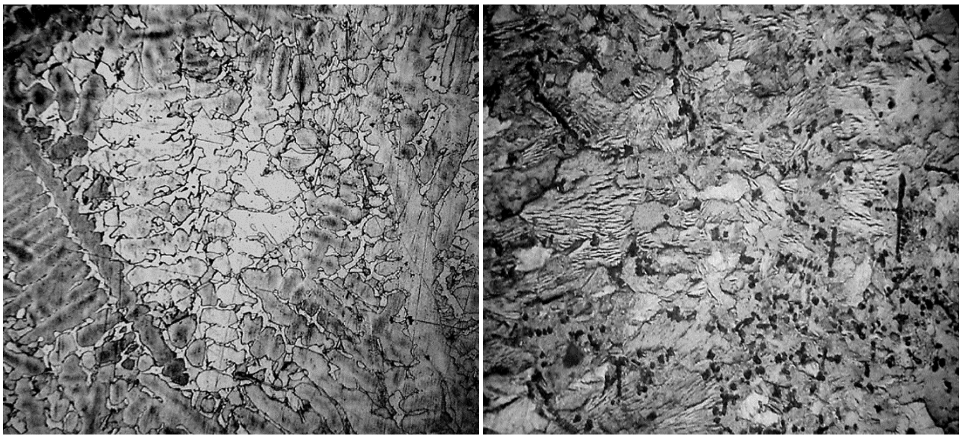


Fig. 5. Dependence of Fe concentration in the G-CuZn15Si4 (DIN) cast brass on the concentration of Cr in it.

CCM of the system Cu–FeCr 'speaks' in favour of the coefficient of assimilation of dispersed intermetallide FeCr and its thermal dissociation products (Eq. (24)) by the melt of the G-CuZn15Si4 (DIN) cast brass. Mathematical processing (Eqs. (20) 21)) of experimental data given in tabular form (Table 3) made it possible to find out that the coefficient of assimilation of dispersed intermetallide FeCr by the matrix melt, provided that the density of cast brass of the G-CuZn15Si4 (DIN) is 8500 kg/m^3 [23], the density of iron is 7874 kg/m^3 [35], and the density of chromium is 7180 kg/m^3 [36], the average is 0.397. The low coefficient of assimilation of the σ phase by the matrix melt can be explained by poor wetting of the powder by the molten G-CuZn15Si4 (DIN) cast brass and the lower supply of liquid metal into the 'volume' of the CM.

The second stage is dedicated to the study of microstructure (Fig. 6) of the control and composite castings. The results of MGA showed that the microstructure of the control casting (Fig. 6, *a*) is typical for the microstructure of the cast brass G-CuZn15Si4 (DIN).

The bright field of metallographic slides is α solid solution of a complex chemical composition and the light inclusions of an irregular outline are eutectoid $\alpha+\gamma$. The basis of this eutectoid is the γ phase, *i.e.*, a chemical compound with a metallic Cu_5Si bond type, while the dark component is the α phase. The increased content of this eutectoid is explained by the imbalance of the considered alloys. MGA of composite casting (Fig. 6, *b*) made it possible to detect in the field of the metallographic section inclusions of the σ phase, which grind the structure of the base of the cast brass G-CuZn15Si4 (DIN), which is a sign of the microstructure of zero-dimensional CCM of the Cu–FeCr system. The darker, compared to the previous case, base of the cast sample indi-



a *b*

Fig. 6. Microstructure (×100) of the material of cast samples: the cast brass G-CuZn15Si4 (DIN) (*a*), zero-dimensional CCM of the Cu–FeCr system (*b*).

cates its possible contamination by products of thermal dissociation of FeCr intermetallide.

At the third stage, the dependence of the hardness determined on the Brinell scale, of the control and composite castings on their height (Fig. 7), as well as Fe and Cr concentrations (Fig. 8) was studied. The results of the research (Table 4) showed that the hardness of brass castings varies not only with their height, but also depends on the concentration of Fe and Cr in the test material.

As a result of the graphical interpretation of experimental data (Fig. 7), it was possible to prove in practice that as the height of the cast samples increases from 15 mm to 105 mm, their hardness increases noticeably. So, for example, at the first horizon, that is, at a height of 15 mm, the hardness of the zero-dimensional CCM of the system Cu–FeCr, which was determined according to the Brinell scale, is 107.0 kgf/mm^2, while the hardness of the cast brass G-CuZn15Si4

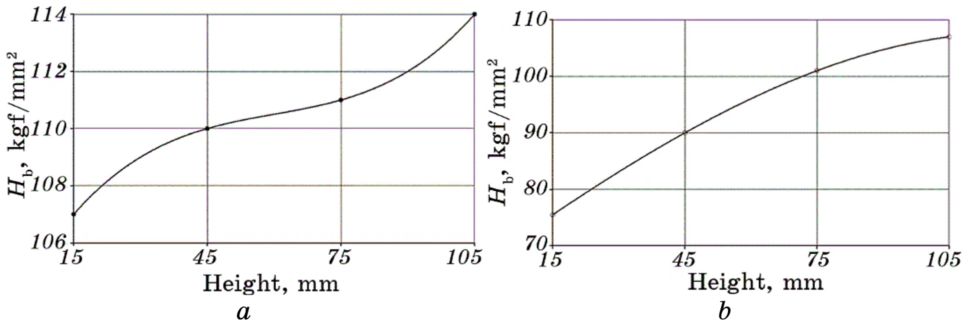


Fig. 7. Distribution of hardness of the test material along the height of the cast sample: zero-dimensional CCM of Cu–FeCr system (*a*), the cast brass G-CuZn15Si4 (DIN) (*b*).

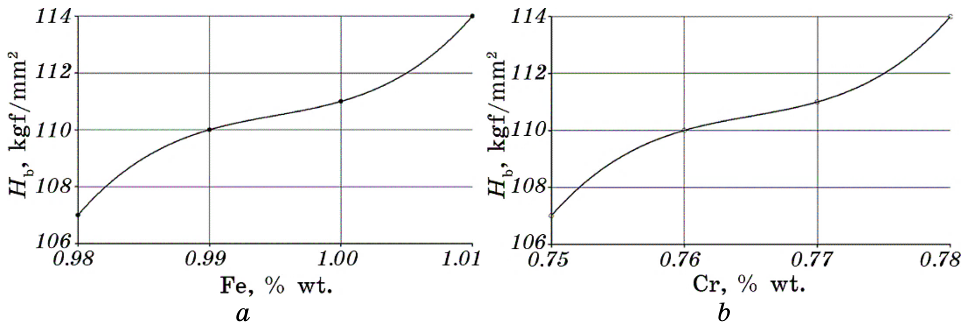


Fig. 8. The influence of the concentration of thermal dissociation products of the intermetallic reinforcing phase on the hardness on the Brinell scale of composite casting: Fe (*a*), Cr (*b*).

TABLE 4. Efficiency indicators of the process of inoculation of the cast brass G-CuZn15Si4 (DIN) with a dispersed FeCr intermetallic.

Position		Coordinates, mm				Thermal dissociation products of σ phase, % wt.		Hardness according to Brinell, kgf/mm^2	Tribotechnical properties			
Casting material	Template index	Summary melt		Control point					I_q, $\cdot 10^{-2}$ g/(cm$^2\cdot$km)	I_{KT}, $\cdot 10^{-3}$ g/(cm$^2\cdot$km)	i_q, $\cdot 10^{-6}$ g/(cm$^2\cdot$km$\cdot$s)	Friction coefficient f
		H_B	a_B	H_B	a_B	Fe	Cr					
001	002	003	004	005	006	007	008	009	010	011	012	013
CCM of Cu–FeCr system	1-B			105		1.01	0.78	114.0	0.54	+3.40	03.000	0.3
	2-B	00	80	075	040	1.00	0.77	111.0	0.57	+3.60	03.167	0.4
	3-B			045		0.99	0.76	110.0	0.73	−0.56	04.056	0.6
	4-B			015		0.98	0.75	107.0	1.00	−3.10	05.556	0.7
The cast brass G-CuZn15Si4	1-B			105		–	–	107.0	1.00	−0.44	05.556	0.8
	2-B	00	80	075	040	–	–	101.0	1.74	−0.28	09.667	0.8
	3-B			045		–	–	090,0	1,90	−0.56	10.556	0.7
	4-B			015		–	–	075,5	2,84	−2.70	15.778	0.7

(DIN), under similar conditions, it is equivalent to 75.5 kgf/mm^2. The increase in the height of the cast samples contributes to the fact that its hardness gradually increases, and subsequently leads to the fact that on the forth horizon, *i.e.*, at a height of 105 mm, it is 114 kgf/mm^2 for the experimental alloy, and 107 kgf/mm^2 for control one.

Graphical interpretation of the results of experiment (Figure 8, *a*) also made it possible to find out that increasing of the concentration of Fe in the composite casting from 0.98% wt. fraction to 1.01% wt. fraction contributes to an increase in its hardness from 107 kgf/mm^2 to 114 kgf /mm^2. The same values (Fig. 8, *b*) acquires the hardness of samples of zero-dimensional CCM system Cu–FeCr at 0.75% wt. fraction Cr and 0.78% wt. fraction Cr, respectively.

Mathematical processing of experimental data (Table 4), which practically amounted to the approximation of the ratios of physical quantities given in tabular form, made it possible to derive a number of empirical equations that analytically describe the influence of height of the cast samples and the concentration of products of thermal dissociation of the σ phase, that is, Fe and Cr, on the hardness of the studied materials. These equations ($R^2 = 1$), which have the form of polynomials of the third order, are given below:

$$HB_{\mathrm{Cu-FeCr}} = 2\cdot 10^{-5} H_{\mathrm{C}}^{3} - 4.4\cdot 10^{-3} H_{\mathrm{C}}^{2} + 2.944\cdot 10^{-1} + 103.5\,, \quad (28)$$

$$HB_{\mathrm{G\text{-}CuZn15Si4}} = 67.406 + 5.521\cdot 10^{-1} H_{\mathrm{C}} - 7\cdot 10^{-4} H_{\mathrm{C}}^{-2} - 9\cdot 10^{-6} H_{\mathrm{C}}^{-3}\,, \quad (29)$$

$$HB_{\text{Cu-FeCr}} = 666667[\text{Fe}]^3 - 2\cdot10^6[\text{Fe}]^2 + 2\cdot10^6[\text{Fe}] - 656689\,, \quad (30)$$

$$HB_{\text{Cu-FeCr}} = 666667[\text{Cr}]^3 - 2\cdot10^6[\text{Cr}]^2 + 10^6[\text{Cr}] - 298418\,. \quad (31)$$

This dependence of the hardness of zero-dimensional CCM of the Cu–FeCr system and the G-CuZn15Si4 (DIN) cast brass on the height of the test castings is explained by the fact that when the matrix melt is introduced from the bottom into the 'volume' of the CM, the density of the material increases from the bottom to the top, and therefore its hardness increases in the same direction. The influence of the concentration of thermal dissociation products of intermetallic AP (amorphous phase) on the hardness of the zero-dimensional CCM of the system Cu–FeCr is explained by the increase of its concentration also from the bottom to the top, and since the hardness of Fe and Cr exceeds the hardness of the binary system Cu–Zn, then the hardness of the cast samples under such conditions, in the end, increases.

The fourth stage of the research is dedicated to the study of the influence of height of the control and composite castings and the products of thermal dissociation of the σ phase on the tribotechnical properties of the G-CuZn15Si4 (DIN) cast brass and zero-dimensional CCM of the Cu–FeCr system. As in the previously discussed case, the results of the experiment showed (Table 4, Fig. 9) that the wear and rate of wear of cast samples, as well as the operation of MCB and the sliding friction coefficient of the 'casting–counterbody' pair depend, first of all, on the height of cast samples, concentrations of Fe and Cr, which are included in their composition. More details on this will be provided below.

Visualization of the results (Table 4) of the research carried out during the implementation of this investigation made it possible to find out (Fig. 9, *a*, *c*, *d*, *e*) that the tribotechnical characteristics of the composite casting improve as its height increases. The same can be said about the tribotechnical properties of the G-CuZn15Si4 (DIN) cast brass (Fig. 9, *b*, *d*, *e*, *g*), which, like the zero-dimensional CCM of the Cu–FeCr system, forms a sliding friction pair with structural low-chromium 41Cr4 (DIN) steel. It has been experimentally proven that in the interval from 15 mm to 105 mm the wear and wear rate of the composite casting decreases from $1.00\cdot10^{-2}$ g/(cm^2·km) and $5.556\cdot10^{-6}$ g/(cm^2·km·s) to $0.54\cdot10^{-2}$ g/(cm^2·km) and $3{,}000\cdot10^{-6}$ g/(cm^2·km·s), respectively. At the same time, at a height of 15 mm, the MCB activation and the sliding friction coefficient of the CCM system Cu–FeCr–41Cr4 (DIN) steel are, respectively, $3.1\cdot10^{-3}$ g/(cm^2·km) and wear rate is 0.7, while when at a height of 105 mm, the same indicators become $3.4\cdot10^{-3}$ g/(cm^2·km) and 0.3, respectively.

In addition, on the first horizon of the cast sample, which is 15 mm, the wear and wear rate of the control alloy, as well as the activation of the MCB and the coefficient of sliding friction of the G-CuZn15Si4 (DIN) cast brass–41Cr4 (DIN) steel, respectively, acquire the value of

$2.84 \cdot 10^{-2}$ g/(cm^2·km) and $15.778 \cdot 10^{-6}$ g/(cm^2·km·s), as well as $-2.70 \cdot 10^{-3}$ g/(cm^2·km) and wear rate is 0.7. A further increase in the height of the brass casting leads to the fact that already at the fourth horizon, equivalent to 105 mm, the same indicators change to $1.00 \cdot 10^{-2}$ g/(cm^2·km), $5.556 \cdot 10^{-6}$ g/(cm^2·km·s), $-0.44 \cdot 10^{-3}$ g/(cm^2·km) and wear rate is 0.8, respectively. The negative values of the coefficients of sliding friction of the 'cast sample–counterbody' pairs indicate that in the process of brass castings testing for wear under dry friction conditions, the base of the test materials adhered to the surface of the counterbody.

As a result of the approximation of the experiment results (Table 4), it was possible to derive a number of empirical equations that analytically describe the functional influence of the height of cast samples on the wear and wear rate of zero-dimensional CCM system Cu–FeCr and the G-CuZn15Si4 (DIN) cast brass, which form a sliding friction pair with the structural low-chromium 41Cr4 (DIN) steel, the triggering of MCB, which works in a pair with the zero-dimensional CCM of Cu–FeCr system and of the G-CuZn15Si4 (DIN) cast brass, the sliding fric-

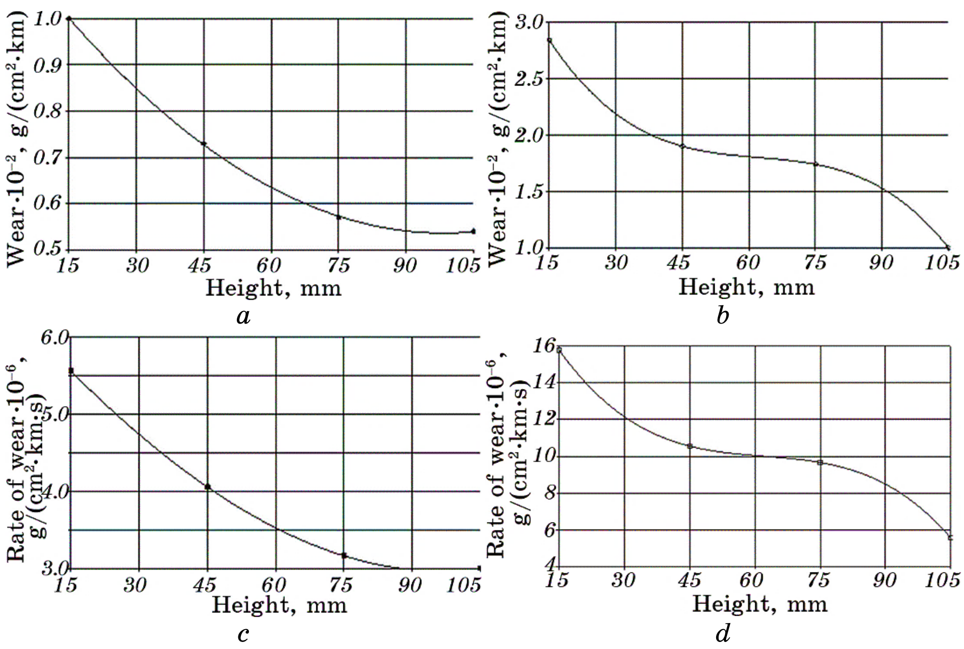
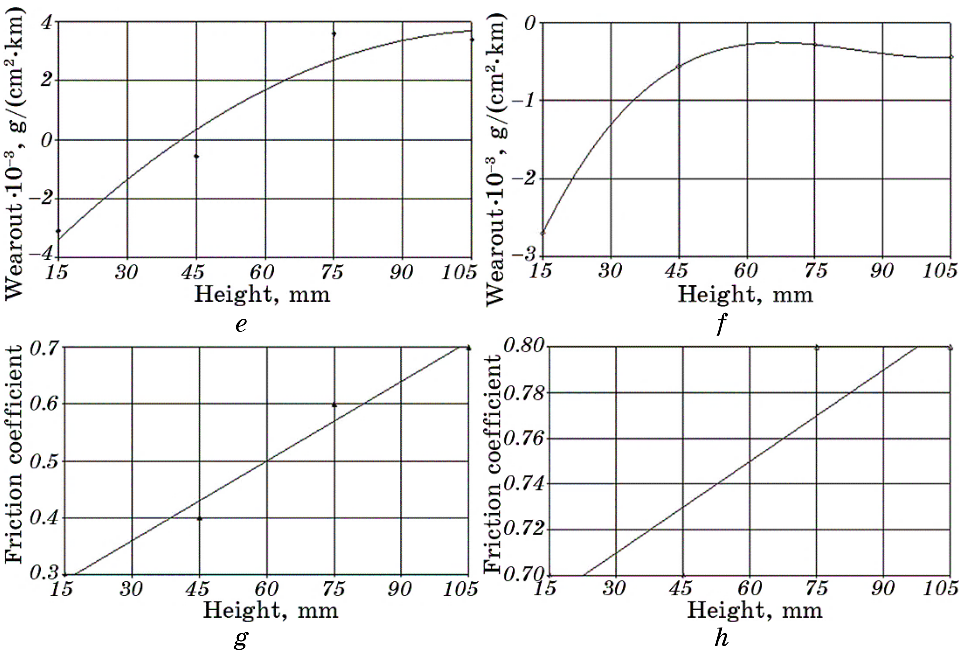


Fig. 9. Distribution of tribotechnical characteristics of zero-dimensional CCM of the system Cu–FeCr (*a*, *c*, *e*, *g*) and the G-CuZn15Si4 (DIN) cast brass (*b*, *d*, *f*, *h*) by the height of the cast samples: casting wear (*a*, *b*), the rate of wear of the cast sample (*c*, *d*), activation of the counterbody material (*e*, *f*), the sliding friction coefficient of the pair 'composite casting–counterbody', 'control casting–counterbody', respectively (*g*, *h*).



Continuation of Fig. 9.

tion coefficients of the pairs 'composite casting–counterbody' and 'control casting–counterbody', respectively. These equations (where I is wear, i is wear rate), in the form of polynomials of the second and third orders, as well as linear dependencies, are given below:

$$I^{41\mathrm{Cr4}}_{q(\mathrm{Cu-FeCr})} = 7\cdot 10^{-5} H_{\mathrm{C}}^2 - 1.31\cdot 10^{-2} H_{\mathrm{C}} + 1.183\,, \tag{32}$$

$$I^{41\mathrm{Cr4}}_{q(\mathrm{G\text{-}CuZn15Si4})} = 4.0275 - 1.008\cdot 10^{-1} H_{\mathrm{C}} + 1.6\cdot 10^{-3} H_{\mathrm{C}}^2 - 8\cdot 10^{-6} H_{\mathrm{C}}^3\,, \tag{33}$$

$$i^{41\mathrm{Cr4}}_{q(\mathrm{Cu-FeCr})} = 7\cdot 10^{-7} H_C^3 + 2\cdot 10^{-4} H_C^2 - 6.68\cdot 10^{-2} H_{\mathrm{C}} + 6.5004\,, \tag{34}$$

$$i^{41\mathrm{Cr4}}_{\mathrm{G\text{-}CuZn15Si4}} = 22.375 - 5.598\cdot 10^{-1} H_C + 8.7\cdot 10^{-3} H_C^2 - 5\cdot 10^{-5} H_C^3\,, \tag{35}$$

$$I^{\mathrm{Cu-FeCr}}_{\mathrm{CB(40X)}} = -8\cdot 10^{-4} H_C^2 + 1.702\cdot 10^{-1} H_{\mathrm{C}} - 5.7807\,, \tag{36}$$

$$I^{\mathrm{G\text{-}CuZn15Si4}}_{\mathrm{CB(41Cr4)}} = 9\cdot 10^{-6} H_C^3 - 2.2\cdot 10^{-3} H_C^2 + 1.787\cdot 10^{-1} H_{\mathrm{C}} - 4.9113\,, \tag{37}$$

$$f^{41\mathrm{Cr4}}_{\mathrm{Cu-FeCr}} = 4.7\cdot 10^{-3} H_{\mathrm{C}} + 2.2\cdot 10^{-1}\,, \tag{38}$$

$$f^{41\mathrm{Cr4}}_{\mathrm{G\text{-}CuZn15Si4}} = 1.3\cdot 10^{-3} H_{\mathrm{C}} + 6.7\cdot 10^{-1}\,. \tag{39}$$

Therefore, the reliability values of the approximation of mathematical expressions presented above are sufficient and, for each ratio, are as follow: $R^2 = 0.9998$, $R^2 = 1$, $R^2 = 1$, $R^2 = 1$, $R^2 = 0.9435$, $R^2 = 1$, $R^2 = 0.98$, $R^2 = 0.8$, respectively. This certainly indicates the fact that the discrepancies between the functional dependencies given in the Table 4 and the corresponding equations of the trend lines (32)–(39) are minimal.

This type of dependences (Fig. 9, Eqs. (32)–(39)) can be explained by the structural heterogeneity of the material of cast samples. Since it was previously proven that there is a functional relationship between the concentration of Fe, Cr and the height of the casting under test (Figs. 4, 5, Eqs. (25)–(27)), it can be asserted with a high degree of probability that on the tribotechnical properties of zero-dimensional CCM of Cu–FeCr system and of the G-CuZn15Si4 (DIN) cast brass are influenced by the concentrations of Fe and Cr. However, this is the subject of especial studies, and it will be discussed further.

The results of the proposed experiment (Table 4), when performing the research task and their graphic interpretation (Fig. 10), confirmed the assumption made above. According to this assumption, the concentration of the products of thermal σ phase dissociation determines the tribotechnical characteristics of the composite and control castings. Such products are Fe and Cr.

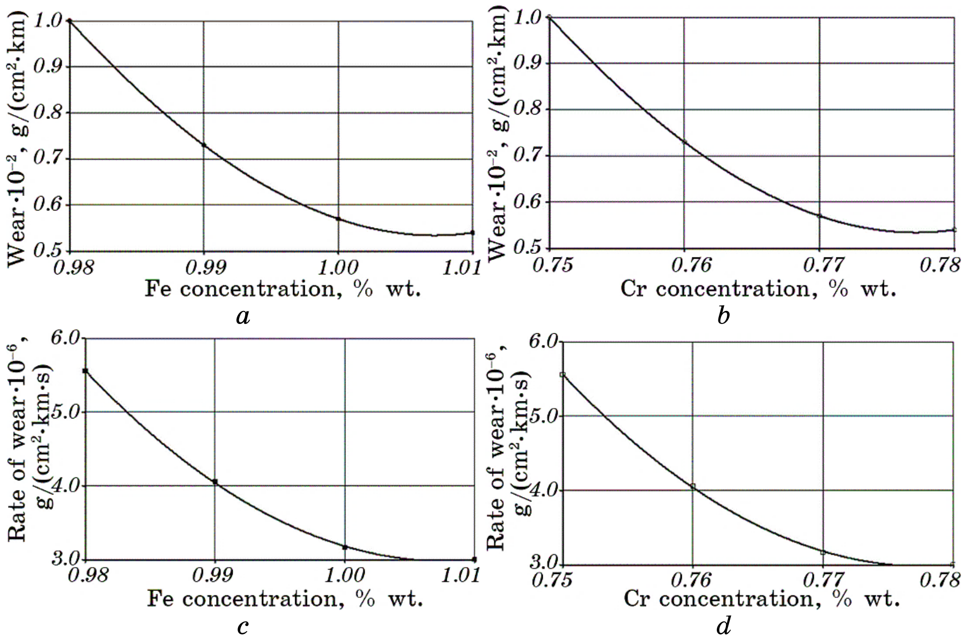
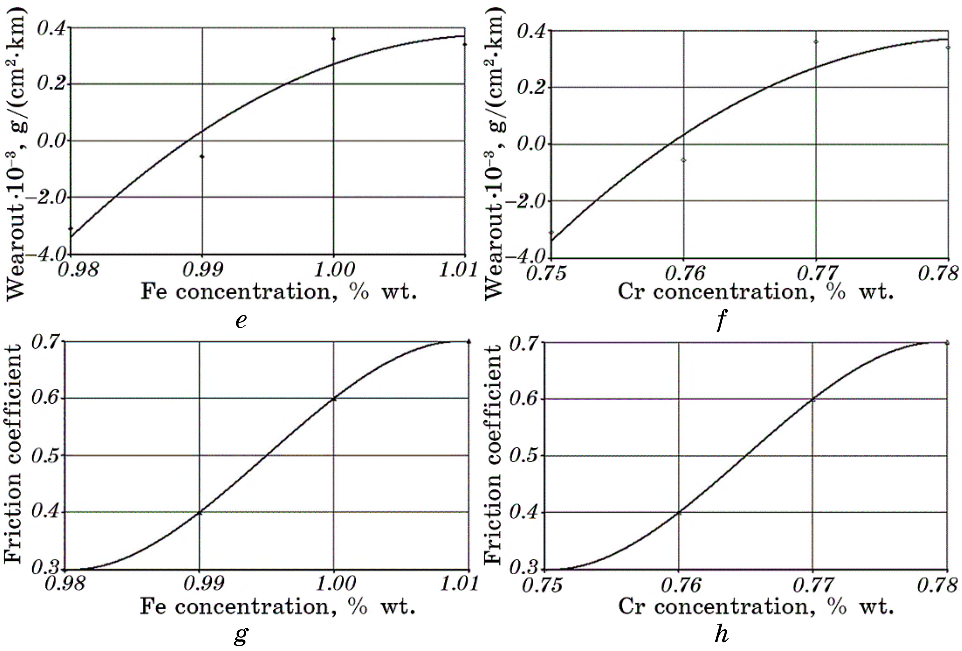


Fig. 10. Dependence of the tribotechnical properties of the zero-dimensional CCM Cu–FeCr system on the concentration of iron (*a*, *c*, *e*, *g*) and chromium (*b*, *d*, *f*, *h*) in the volume of cast samples: wear of the composite casting (*a*, *b*), wear rates of the cast sample (*c*, *d*), activation of the counterbody material (*e*, *f*), the friction coefficient of the sliding pair 'composite casting–counterbody' (*g*, *h*).



Continuation of Fig. 10.

In particular, it was established that increasing of the Fe and Cr concentrations in the cast sample has the same effect as the height on the tribotechnical properties of zero-dimensional CCM Cu–FeCr system (Fig. 9, *a*, *c*, *d*, *e*) composite casting. Since the coordinates of control points, concentrations of products of the σ phase thermal dissociation, mechanical characteristics and tribotechnical properties of the cast sample (Table 4) are linked by the indices of the corresponding templates (Table 4, Fig. 3), then the need for in-depth analysis of graphical interpretation of experimental data (Fig. 10) is currently eliminated. The truth of this statement is also proved by the graphic interpretation of research results (Fig. 4), considered and analysed earlier, which, through the scheme of marking and cutting composite castings into templates (Fig. 3), indirectly demonstrates a functional connection with the tribotechnical characteristics of zero-dimensional CCM system Cu–FeCr.

In order to predict, in the future, the dependence of the tribotechnical properties of a composite casting on the concentrations of Fe and Cr in its composition, it is necessary to approximate the ratios of physical quantities (Table 4) given in tabular form. Empirical equations (polynomials of the second and third orders), which with a sufficient value of approximation reliability ($R^2 = 1$, $R^2 = 1$, $R^2 = 0.9998$, $R^2 = 0.9998$, $R^2 = 0.9435$, $R^2 = 0.9435$, $R^2 = 1$, $R^2 = 1$, respectively) were obtained as a result of mathematical processing of experimental data (Table 4), given below:

$$I^{41\text{Cr}4}_{q(\text{Cu-FeCr})} = 3333.3[\text{Fe}]^3 - 9350[\text{Fe}]^2 + 8690.2[\text{Fe}] - 2672.9\,, \quad (40)$$

$$I^{41\text{Cr}4}_{q(\text{Cu-FeCr})} = 3333.3[\text{Cr}]^3 - 7050[\text{Cr}]^2 + 4918.2[\text{Cr}] - 1128.2\,, \quad (41)$$

$$i^{41\text{Cr}4}_{q(\text{Cu-FeCr})} = 3332.5[\text{Fe}]^2 - 6717.2[\text{Fe}] + 3387.9\,, \quad (42)$$

$$i^{41\text{Cr}4}_{q(\text{Cu-FeCr})} = 3332.5[\text{Cr}]^2 - 5184.3[\text{Cr}] + 2019.3\,, \quad (43)$$

$$I^{\text{Cu-FeCr}}_{\text{CB(40Cr4)}} = -6850[\text{Fe}]^2 + 13868[\text{Fe}] - 7015.4\,, \quad (44)$$

$$I^{\text{Cu-FeCr}}_{\text{CB(41Cr4)}} = -6850[\text{Cr}]^2 + 10717[\text{Cr}] - 4188.1\,, \quad (45)$$

$$f^{41\text{Cr}4}_{\text{Cu-FeCr}} = -33333[\text{Fe}]^3 + 99500[\text{Fe}]^2 - 98982[\text{Fe}] + 32816\,, \quad (46)$$

$$f^{41\text{Cr}4}_{\text{Cu-FeCr}} = -33333[\text{Cr}]^3 + 76500[\text{Cr}]^2 - 58502[\text{Cr}] + 14908\,. \quad (47)$$

The dependence of the tribotechnical characteristics of cast sample on the concentrations of Fe and Cr in its volume is explained by the fact that the hardness and wear resistance of these components significantly exceeds the hardness of the Me-matrix of zero-dimensional CCM Cu–FeCr system. Therefore, increasing the concentrations of Fe and Cr contributes to the reduction of wear and the rate of wear of the composite casting, as well as to the increase of triggering of the MCB and the coefficient of friction sliding of the 'CCM Cu–FeCr system–41Cr4 (DIN) steel'.

5. CONCLUSIONS

During the implementation of this investigation, valuable scientific, technical and practical results were obtained and, in this way, the effectiveness of inoculation of the melt of G-CuZn15Si4 (DIN) cast brass grade with dispersed intermetallic FeCr in the 'cavity' of the CM according to the LFC process was proven. The results of research made it possible to reach certain conclusions and find out that.

1. The assimilation coefficient of dispersed intermetallide FeCr by the matrix melt is 0.397, which is quite acceptable when performing the given task.

2. Composite castings have an optimal microstructure, which is characteristic of zero-dimensional CCM system Cu–FeCr.

3. The hardness of composite castings, determined according to the Brinell scale, on average, is 18.3% higher than the similar value of the G-CuZn15Si4 (DIN) cast brass.

4. The wear and wear rate of the zero-dimensional CCM Cu–FeCr system, on average, is on 62.0% lower than the same characteristics of the control casting, and the sliding friction coefficient of the 'CCM Cu–FeCr system–41Cr4 (DIN) steel' according to average value, on 33.3%

inferior to the similar value of the pair 'the G-CuZn15Si4 (DIN) cast brass–41Cr4 (DIN) steel'; activation of the MCB, which forms a pair of sliding friction with the G-CuZn15Si4 (DIN) cast brass, is on 183.9% lower than the triggering of the MCB, which works in a pair with a zero-dimensional CCM of Cu–FeCr system.

REFERENCES

1. V. A. Pavlov, *Penopolistirol* [Polistirene Foam] (Moskva: Khimiya: 1973) (in Russian).
2. V. S. Shulyak, *Lit'yo po Gazifitsiruyemym Modelyam* [Casting on Gasifying Models] (Saint Petersburg: NPO 'Professional': 2007) (in Russian).
3. O. I. Shinskiy, V. V. Sumenkova, and V. P. Vishniakova, *Casting Processes*, No. 2: 51 (2002) (in Russian).
4. G. F. Balandin, *Osnovy Teorii Formirovaniya Otlivki: Formirovanie Makroskopicheskogo Stroyeniya Otlivki* [Fundamentals of the Theory of Casting Formation: Formation of the Macroscopic Structure of the Casting] (Moskva: Mashinostroenie: 1979) (in Russian).
5. I. A. Nebozhak, V. G. Novytskyy, and O. I. Shynsky, *Casting Processes*, No. 5: 50 (2008) (in Russian).
6. I. A. Nebozhak, V. V. Sumenkova, I. V. Tkachuk, and O. I. Shynsky, *Metal Sci. Treatment Metals*, No. 4: 43 (2001) (in Ukrainian).
7. I. A. Nebozhak and O. V. Derev'yanko, *Metal ta Lyttya Ukrayiny*, **29**, No. 1: 70 (2021) (in Ukrainian).
8. I. A. Nebozhak, O. V. Derev'yanko, A. M. Verkhovlyuk, D. S. Kanibolots'kyy, and V. H. Novyts'kyy, *Metal ta Lyttya Ukrayiny*, **31**, No. 2: 51 (2023) (in Ukrainian).
9. I. A. Nebozhak, V. H. Novyts'kyy, O. V. Derev'yanko, D. S. Kanibolots'kyy, and A. M. Verkhovlyuk, *Metal ta Lyttya Ukrayiny*, **31**, No. 3: 8 (2023) (in Ukrainian).
10. V. A. Ozerov, V. S. Shuliak, and G. A. Plotnikov, *Lit'yo po Modelyam iz Penopolistirola* [Casting from Polystyrene Foam Models] (Moskva: Mashinostroenie: 1969) (in Russian).
11. Yu. A. Stepanov, *Lit'yo po Gazifitsiruyemym Modelyam* [Casting Using Gasified Models] (Moskva: Mashinostroenie: 1976) (in Russian).
12. V. S. Shuliak, S. A. Rybnikov, and K. A. Grigorian, *Proizvodstvo Otlivok po Gazifitsiruyemym Modelyam* [Production of Castings Using Gasified Models] (Moscow: MGIU: 2001) (in Russian).
13. Yu. A. Stepanov and V. G. Moskalyov, *Casting Processes*, No. 7: 1 (1972) (in Russian).
14. B. M. Yavorskiy and A. A. Detlaf, *Spravochnik po Fizike* [Physics Handbook] (Moskva: Nauka: 1985) (in Russian).
15. O. I. Shinskiy and V. S. Shulyak, Lit'yo po gazifitsiruyemym modelyam [Casting on Gasifying Models] (Kiev: Znaniye: 1979) (in Russian).
16. I. A. Nebozhak, O. V. Derev'yanko, A. M. Verkhovlyuk, and D. S. Kanibolots'kyy, *Metal ta Lyttya Ukrayiny*, **30**, No. 4: 36 (2022) (in Ukrainian).
17. D. I. Garkonov, *Tribotekhnika* [Tribotechnics] (Moskva: Mashinostroenie:

1985) (in Russian).
18. *Koehfitsient Tertya* [Friction Coefficient] (Wikipedia: 2023) (in Ukrainian).
19. M. V. Kindrachuk and E. A. Kul'havyy, *Proc. National Aviation University*, No. 4: 67 (2005) (in Ukrainian).
20. *Mekhanichni Vlastyvosti Materialiv* [Mechanical Properties of Materials] (Wikipedia: 2023) (in Ukrainian).
21. M. V. Kindrachuk, E. A. Kul'havyy, D. I. Perro, and V. O. Podlyesnyy, *Proc. National Aviation University*, **4**, No. 4: 32 (2009) (in Ukrainian).
22. M. V. Kindrachuk, E. A. Kul'havyy, O. L. Shevchenko, and A. P. Danilov, *Proc. National Aviation University*, **1**, No. 1: 102 (2009) (in Ukrainian).
23. *Tsvetnoye Lit'yo* [Colour Casting] (Ed. N. M. Galdin) (Moskva: Mashinostroenie: 1989) (in Russian).
24. O. I. Shynsky, L. P. Vyshnyakova, V. N. Plotnikova, and Ye. F. Knyazev, *Sposib Vyhotovlennya Modeley iz Polistyrolu* [Method for Producing Models from Polystyrene Foam], Patent of Ukraine No. 3493216 (Published 1993) (in Ukrainian).
25. A. Wittmoser and J. Schade, *Verfahren zur Herstellung von Gußstücken unter Verwandung Vergasbaren Modelle*, German Patent No. 114482 (in German).
26. *Vlastyvosti Metalevykh Poroshkiv* [The Properties of Metal Powders].
27. O. I. Shynsky, I. O. Shynsky, and Yu. A. Goncharenko, *Protypryharne Pokryttya dlya Lyttya za Modelyamy, shcho Hazyfikuyut'sya* [Non-Stick Coating for Casting by Gasified Models], Patent of Ukraine No. 58824 (Published 2003) (in Ukrainian).
28. *Masova Chastka Elementa* [Mass Fraction of an Element] (Wikipedia: 2023) (in Ukrainian).
29. M. V. Mal'tsev, *Metallografiya Promyshlennykh Tsvetnykh Metallov i Splavov* [Metallography of Industrial Colour Metals and Alloys] (Moskva: Metallurgiya: 1970) (in Russian).
30. L. I. Kuksenova, V. G. Lapteva, A. G. Kolmakov, and L. M. Rybakova, *Metody Ispytaniy na Trenie i Iznos* [Friction and Wear Test Methods] (Moskva: Intermet Inzhiniring: 2001) (in Russian).
31. I. V. Kragelskiy, M. N. Dobychin, and V. S. Kombalov, *Osnovy Raschyotov na Trenie i Iznos* [Basics of Friction and Wear Calculations] (Moskva: Mashinostroenie: 1977) (in Russian).
32. F. I. Maslennikov, *Laboratornyi Praktikum po Metallovedeniyu* [Laboratory Workshop on Metal Science] (Moskva: Mashgiz: 1961) (in Russian).
33. V. P. Gavrilyuk and V. G. Novitskiy, *Metodika Opredeleniya Iznosostoykosti Materialov v Usloviyakh Treniya Skol'zheniya na Mashine Treniya M22M* [Methodology for Determining the Wear Resistance of Materials under Conditions of Sliding Friction on a Friction Machine M22M] (Kyiv: PTIMA: 2002) (in Russian).
34. A. P. Gulyayev, *Metallovedenie* [Metal Science] (Moskva: Metallurgiya: 1977) (in Russian).
35. *Hustyna Zaliza* [Density of Iron] (Wikipedia: 2023).
36. *Khrom* [Chromium] (Wikipedia: 2023).
37. *Sigma phases*.