https://doi.org/10.15407/scine18.03.087

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PRODUCTION OF IRON CASTINGS WITH GRADIENT STRUCTURE FOR SPECIAL PURPOSE EQUIPMENT BY IN-MOLD MODIFICATION OF ONE BASE MELT

Introduction. *Modern industry requires constant upgrade or modernization of machinery, hardware, mechanisms, equipment and special tools with improved mechanical and operational characteristics and reduced costs. This can be successfully solved by using parts and elements with a gradient structure in local areas, made of cast iron as the cheapest, most common, and available structural material.*

Problem Statement. *The main disadvantage of the known methods for obtaining cast iron parts with a gradient structure is the need for synchronous smelting of liquid cast irons that have different chemical compositions and properties in two smelting units before pouring the mold. Therefore, it is important to find ways and to develop new methods for manufacturing cast iron castings with gradient structure and properties.*

Purpose. *The purpose of this research is to develop optimal technological modes and parameters of casting parts with a gradient structure, with the use of in-mold modification of a base melt.*

Materials and Methods. *The hydrodynamic and temperature processes in mold have been analyzed with the use of computer simulation the experimental castings have been evaluated by the nature of the fracture macrostructure; the metallographic study; the chemical analysis of cast iron, and the comparison of the hardness of local parts of castings.*

Results. *The main technological parameters influencing the nature of cast iron crystallization and, as a consequence, the formation of gradient structure in castings, are configuration and cross-sectional thickness of the casting wall, material and thickness of the insert, and temperature of poured melt. Technological recommendations that ensure the formation of gradient structure and properties in local parts of castings have been given.*

Citation: Smernytskyi, D. V., Huliaiev, A. V., Fesenko, M. A., Melnyk, V. E., and Fesenko, A. M. (2022). Production of Iron Castings with Gradient Structure for Special Purpose Equipment by In-Mold Modification of One Base Melt. *Sci. innov.*, 18(3), 87—94. https://doi.org/10.15407/scine18.03.087

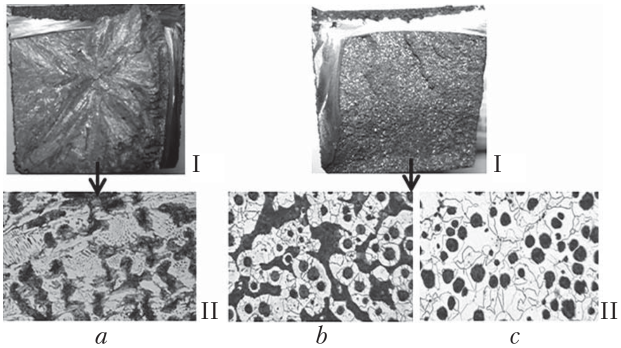
Conclusions. *The proposed method is practicable and promising in terms of the manufacture of cast iron castings of various nomenclature (including special tools and equipment for officers of the Ministry of Internal Affairs of Ukraine, the Ministry of Emergencies, and other rescue services and law enforcement agencies), which undergo static and dynamic loads.*

Keywords: method, in-mold processing, white cast iron, high-strength cast iron, gradient structure, wear resistance, hardness, and impact strength.

The specific official tasks and missions of special units of the Ministry of Internal Affairs (hereinafter referred to as the MIA) of Ukraine, the Ministry of Emergencies (hereinafter referred to as the ME) of Ukraine, the National Guard of Ukraine (hereinafter referred as to the NGU), and the State Border Service of Ukraine require constant upgrade or modernization of equipment, machinery, hardware, and special tools and devices, which shall meet the actual conditions and needs. Among these requirements there are increasing reliability, durability, efficiency, versatility and reducing costs.

Meeting these requirements is possible through the use of elements with a gradient structure in local parts, surfaces or layers, which are made of cast iron as the cheapest, most common and fairly simple construction material that possess necessary process, physical, mechanical, and service qualities [1, 2].

Among the cast iron parts with a gradient structure there are toothed gears, gear wheels, sprockets, support rollers, pulleys, screws, bushings, sleeves, shafts, levers, knives, nozzles, and other tools for various purposes. Their design provides for the work surface or layer of such elements shall have a high hardness and wear resistance, while their other parts that serve as assembly components shall impact resistance, impact strength and, unlike hard surfaces, improved machinability in terms of cutting.



a *b* *c*

Fig. 1. General view of the fracture macrostructure (I), microstructure (×100) ((II) of white cast iron (WCI) with carbide-pearlite eutectic structure (*a*); high-strength cast iron (HSCI) with ferrite-pearlite (*b*) and ferrite (*c*) metal base

White cast iron (Fig. 1, I) with carbide-pearlitic eutectic structure (Fig. 1, II, *a*) is known to have a sufficient wear resistance and hardness (440—450 HB), whereas high-strength cast iron with spherical graphite (Fig. 1, I) with ferritic-perlite (Fig. 1, II, *b*) or ferrite (Fig. 1, II, *c*) metal base possesses increased ductility (d up to 22%) and impact strength (240—260 kJ/m^2) [1, 2].

To date, cast iron parts with a gradient structure and properties in local layers or zones are often produced directly from liquid alloys by the following casting methods: pouring a homogeneous melt into a metal mold or a mold cavity whose surface has been pretreated with special coatings (paints) and alloying additives (surface alloying); pouring into a common mold with a solid partition (barrier) between dissimilar cast irons; successive pouring into a mold or a centrifuge mold with liquid cast irons that have different chemical composition with a pause between the portions; pouring liquid residue of one cast iron and topping up the freed core with a melt of another cast iron [3—6].

The main disadvantage of most of these methods is the need for simultaneous smelting of cast irons that have different chemical composition in two smelters before pouring into mold.

Pouring a homogeneous melt into a metal mold or mold cavity with the surface pretreated with special coatings (paints) and alloying additives

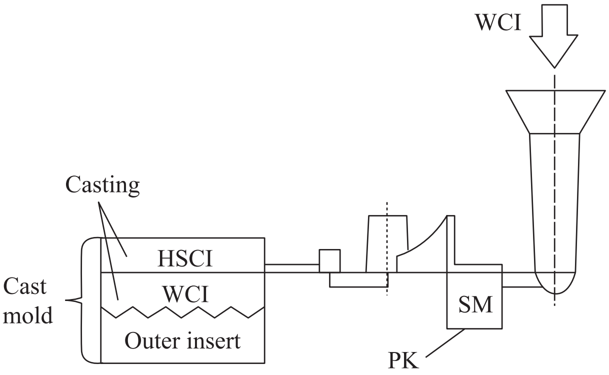


Fig. 2. Flowchart of the proposed method for manufacturing cast iron castings with a gradient structure

does not give stable results in obtaining a casting that has an adjustable (specified) thickness of the wear-resistant layer.

At the same time, there is a fundamentally new and simple method for manufacturing cast iron parts (castings) with a gradient structure, with the use of the known process of in-mold modification (the in-mold process) [7—13].

The essence of the new method is that the base liquid cast iron that crystallizes according to the metastable state diagram ($Fe—Fe_3C$) with bleaching, smelted in one melting unit is poured into a mold where it undergoes modification treatment with a spheroidizing modifier (SM) in the reaction chamber of the casting system and further fills the cavity of the mold to which an outer insert of cast iron or steel is pre-installed. Increased cooling rate of liquid cast iron during its contact with the outer insert leads to crystallizing wear-resistant white cast iron in one part of the cast product, while moderate cooling rate of the other part ensures crystallizing high-strength cast iron with spheroidal graphite (HF) (Fig. 2) [14].

The fundamental novelty of the proposed method requires a series of experimental studies.

The purpose of this research is to develop a method for casting cast iron parts with a gradient structure with the use of the process of in-mold modification of one base melt.

The object of the study is a 10 kg prismatic casting that has dimensions 240 × 120 × 50 mm (Fig. 3). The insert material is carbon steel plates (St 3 grade) and SC20 gray cast iron.

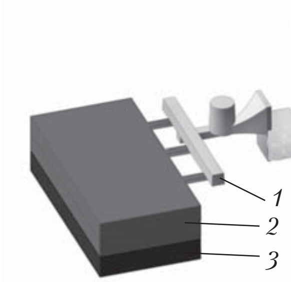


Fig. 3. Model of experimental casting with a foundry-modifying system: *1* — foundry system; *2* — casting; *3* — outer insert

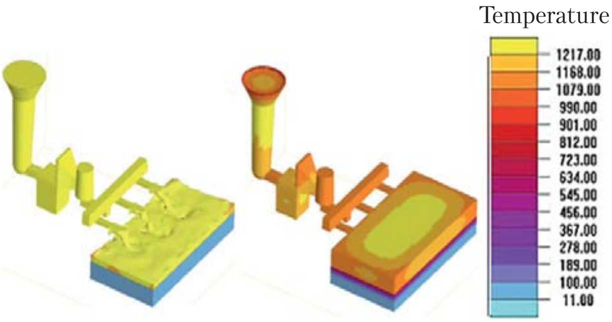


Fig. 4. Mathematical modeling of the technique for manufacturing cast iron castings with a gradient structure

Using *Nova-Flow Solid CV* software, we have pre-analyzed the hydrodynamic processes that occur during the pouring of liquid cast iron, its crystallization and cooling in the mold by the proposed method (Fig. 4).

Among the main parameters that affect the nature of the crystallization of cast iron, and as a consequence, the formation of a gradient structure in castings there are the configuration and thickness of the casting wall, material and thickness of the outer insert, and the temperature of poured melt.

To establish the patterns of influence of these parameters on the process of structure formation in castings, preliminary model studies have been conducted. The parameters of the casting and the outer insert, the dimensions of which vary from 10 to 50 mm with a step of 10 mm, are selected as parameters for the simulation (Fig. 5, *a*).

Liquid cast iron is poured into dry sand-and-clay molds at a temperature of 1420—1450 °C,

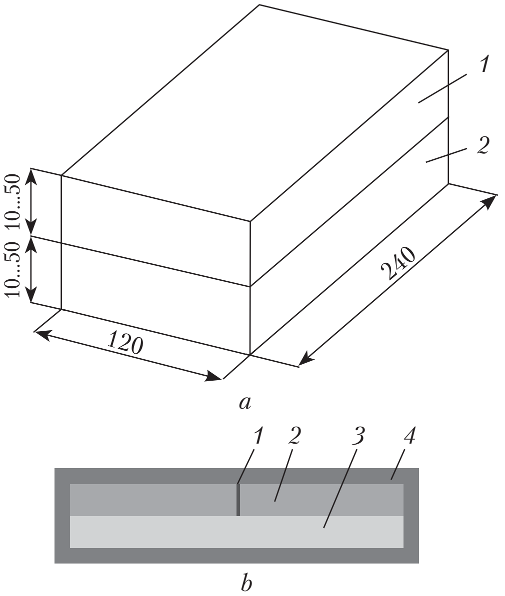


Fig. 5. Studied objects for modeling (*a*) and the arrangement of thermocouples for recording the cooling curves in the cross section of the casting (*b*): *1* — thermocouples; *2* – casting; *3* — outer insert; *4* — sand-and-clay mold

the materials of the outer insert are carbon steel and gray cast iron, like in the previous case.

The nature of the processes of crystallization of cast iron in castings has been studied based on the cooling curves that are recorded with the use of thermocouples located in the casting, along the axis of symmetry, with a step of 1 mm, as shown in Fig. 5, *b*.

During the experiments with cast iron castings, the base cast iron that crystallizes according to the metastable state diagram (Fe-Fe$_3$C) with bleaching (Ce = 3.4%) is smelted in an induction crucible electric furnace IChT-06 on the charge consisting of blast furnace pig iron (PL2 brand) and steel scrap (St 3). The composition of the basic liquid cast iron that crystallizes with bleaching ranges within 2.7—3.1% C, 0.4—0.6% Si, 0.5—0.7% Mn, up to 0.05% P, up to 0.02% S, and Fe residue.

Ferrosilicon-magnesium alloy, brand VL63M (made in Germany) is used as a spheroidizing modifier (SM) for casting liquid white cast iron and obtaining the structure and properties of high-strength cast iron in a part of the casting. The amount of modifiers with particle size of 1.0—5.0 mm, which are loaded into the reaction chambers of the foundry systems, in all experiments varies within 2.0—2.5% in weight of liquid cast iron. The dry sand-and-clay molds are filled from a rotary bucket with liquid cast iron at a temperature of 1420—1450 °C. To ensure accelerated heat dissipation from the part of the casting where the wear-resistant hard surface is formed, an outer insert in the form of a 30 mm thick cast iron plate is used.

The results of the experiments have been evaluated by the nature of the macrostructure of the fracture in the central cross section of the experimental castings. More complete information has been obtained based on the results of metallographic studies, chemical analysis, as well as by comparing the hardness of the castings surfaces.

Based on the results of numerous model studies, data in the form of cooling curves have been obtained separately for each option of the production of a casting of given size and outer insert. A typical example is shown in Fig. 6.

Proceeding from the general nature of changes in the cooling curves, it has been established that the crystallization time of the casting part that contacts the outer insert is minimal as compared with the middle part and with the casting surface that is opposite to the outer insert and contacts the sand form (Fig. 5, *b*, Fig. 6). For example, in the case of modeling the casting process under conditions where the casting thickness and the thickness of the outer insert of cast iron is 30 mm, the crystallization time at the points where the thermocouples are installed varies from 10 s at the minimum distance from the outer insert to 120 s, at the maximum distance from the outer insert (on the surface of the casting, which contacts the sand form) (Fig. 6, *c*).

That is, the minimum crystallization time of cast iron corresponds to the formation of wear-resistant white cast iron in one part of the casting, while the maximum crystallization time is associated with the formation of "viscous" plastic cast iron, in the other part.

Another major factor that determines the structure of cast iron is the rate of its cooling in the

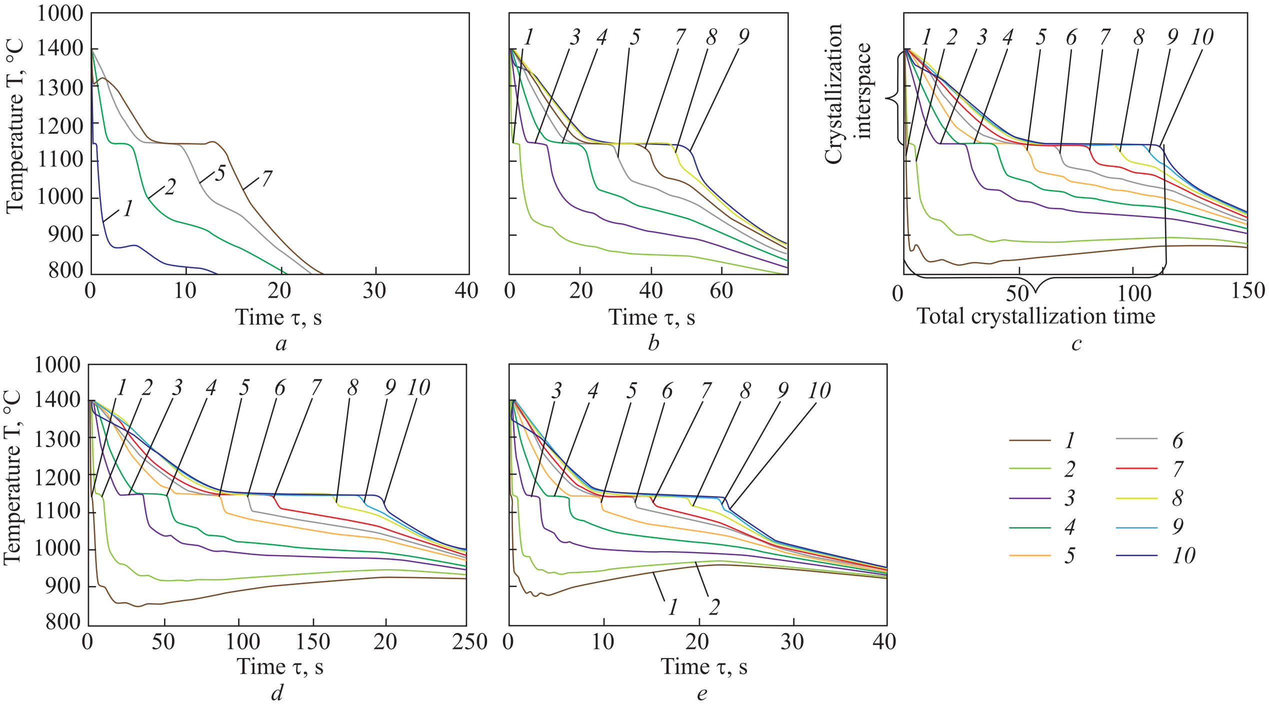


Fig. 6. Example of the cooling curves in castings with a wall section thickness: *a* — 10; *b* — 20; *c* — 30; *d* — 40; and *e* — 50 mm with the use of a 30 mm thick outer cast iron insert

mold. It is known that when it reaches a certain value, cast iron may crystallize either according to the stable Fe-C diagram (i.e. obtaining "viscous" plastic cast iron with free graphite release) or according to the metastable Fe-Fe_3C diagram (i.e. obtaining solid wear-resistant white cast iron with iron carbide inclusions).

During the model experiments, the cooling rates in each local part where a thermocouple is mounted are determined separately for each simulated casting option of the proposed method. These values are calculated by the ratio of the temperature range of crystallization to the total melt crystallization time, which are directly obtained from the cooling curves (see Fig. 6, *c*). Depending on the obtained cooling rates, the dependences of their change during the cooling of cast iron in the mold have been built (Fig. 7).

The obtained data on the cooling rates of modified cast iron coincide with the data in [15].

In [15], it has been found that, for example, the critical cooling rate of cast iron that has a composition close to the eutectic one (Ce = 4.2%), after spheroidizing modification, which ranges within 8.3—10.5 °C/s, leads to cast iron crystallization with bleaching. At lower cooling rates, the same cast iron crystallizes according to the stable state diagram of Fe-C without bleaching.

Under the conditions of computer model experiment, the carbon equivalent of base cast iron is Ce = 3.4%. According to the simulation results (according to the results of these experiments) we have found that, for example, for castings with a thickness of 30 mm and an outer cast iron insert with a thickness of 30 mm, the cooling rate of cast iron in the casting varies within 225—25 °C/s. Since the carbon equivalent of the cast iron chosen for the experiments is lower and the given cooling rates exceed the values given in [15], in this case we assume that the cast iron in castings crystallizes with bleaching.

Based on the obtained data on the changes in the cooling rates in the cross section of the casting and the critical cooling rate for cast iron of

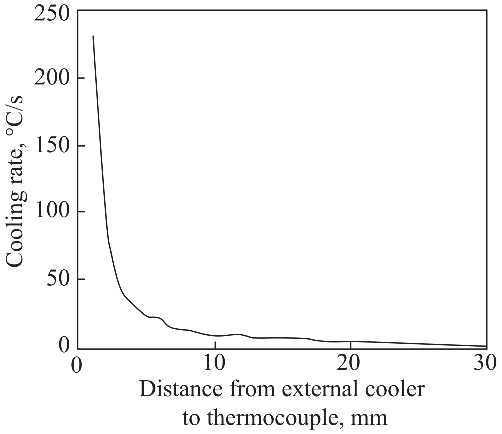


Fig. 7. Dependence of the cooling rate in the casting with a 30 mm thick wall section, with the use a 30 mm thick outer insert

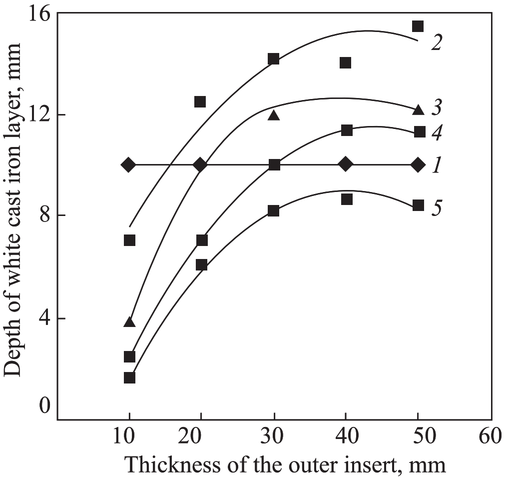


Fig. 8. Influence of the thickness of the outer cast iron insert on the depth (size) of the white cast iron layer: *1* — 10 mm; *2* — 20 mm; *3* — 30 mm; *4* — 40 mm; and *5* — 50 mm

the selected chemical composition, the dependences of the thickness of the outer insert cross section on the depth (size) of the casting layer have been built (Fig. 8).

In order to verify the results of computer simulations, at the next stage of the experiment, we have used full-scale cast iron castings. The castings are made according to the method described above.

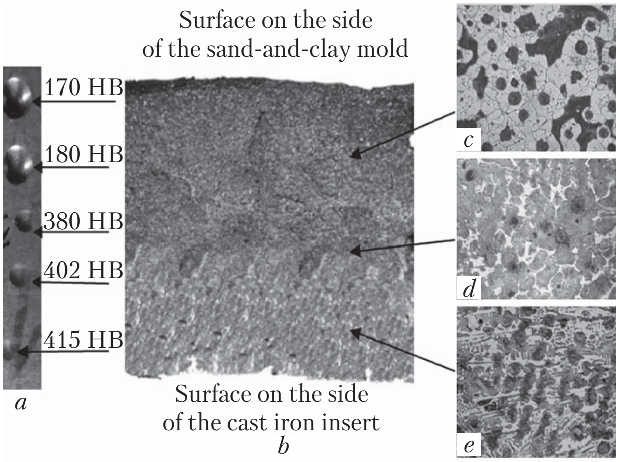


Fig. 9. General view of the macrostructure of the fracture (*a*) and the microstructure (×100) of a 30 mm thick cast iron experimental casting with a gradient structure

The studies have shown that after the spheroidizing modification of the initial cast iron melt and the filling of the mold cavity with a pre-mounted cast iron insert, in the cross sections of castings there is formed a gradient structure with gradient properties between the opposite surfaces (Fig. 9, *b*).

In this case, the solid wear-resistant part of white cast iron on the side of the insert is obtained with a size (depth) of 12 ± 2 mm, which coincides with the results of model studies (Fig. 8). The microstructure of this part consists of perlite and cementite with fine inclusions of spherical graphite (Fig. 9, *c*).

In the same castings, on the side of the sand mold, the melt crystallizes to a depth of 16 ± 2 mm with a fracture that is typical for high-strength cast iron (Fig. 9, *c*). In the microstructure of this part of the casting, spherical graphite is formed in the ferrite-pearlitic metal die. Between the upper and lower parts of the casting, there is formed a transition zone of cast iron. In the microstructure of such a zone, spheres of spherical graphite and cementite are formed in the pearlitic metal die (Fig. 9, *d*). The gradient structure of castings is confirmed by the hardness along the cross section (Fig. 9, *a*). From the surface of the casting on the side of the insert where the bleached cast iron is formed to the layer of high-strength cast iron on the side of the sand mold, the hardness varies from 415—420 HB to 170—180 HB (Fig. 9, *a*).

Thus, the studies have confirmed the possibility of implementing the proposed method for manufacturing cast iron parts (castings) with a gradient structure and properties, with the use of the method of in-mold modification of a base melt.

The introduction of the method at enterprises will simplify and reduce the cost of production of high quality cast iron products with a given structure and required properties, which may work under static and dynamic loads and are resistant to shock and abrasive wear. In addition, this method allows expanding the range of castings.

The use of cast iron parts with a gradient structure in special vehicles and facilities (eg, assault ladders, ladders, training stands, breacher's toolkits, and other multifunctional tools) expands tactical capabilities and raises the efficiency of work of operational units of MIA of Ukraine, NGU, rescue services of ME of Ukraine, and other law enforcement agencies.

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Received 23.04.2021
Revised 13.01.2022
Accepted 18.01.2022

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ОСОБЛИВОСТІ ВИРОБНИЦТВА ЧАВУННИХ ЛИТИХ ДЕТАЛЕЙ З ГРАДІЄНТНОЮ СТРУКТУРОЮ ВНУТРІШНЬОФОРМОВИМ МОДИФІКУВАННЯМ ОДНОГО БАЗОВОГО РОЗПЛАВУ ДЛЯ ТЕХНІКИ СПЕЦІАЛЬНОГО ПРИЗНАЧЕННЯ

Вступ. Сучасна промисловість вимагає постійного оновлення або модернізації техніки, машин, механізмів, агрегатів та спеціальних засобів із підвищеними механічними та експлуатаційними характеристиками при одночасному зменшенні їхньої собівартості. Успішно вирішити це можливо за рахунок використання в їхніх конструкціях литих деталей з градієнтною структурою в локальних частинах із чавунів як найбільш дешевих, поширених та доступних конструкційних матеріалів.

Проблематика. Основним недоліком відомих способів одержання чавунних литих деталей з градієнтною структурою є необхідність синхронного виплавляння різних за хімічним складом і властивостями рідких чавунів у двох плавильних агрегатах до початку заливання форми. Тому важливим є пошук і розроблення нових способів виготовлення чавунних виливків із градієнтною структурою та властивостями.

Мета. Розроблення нового способу виробництва чавунних литих деталей з градієнтною структурою із застосуванням внутрішньоформового модифікування одного розплаву.

Матеріали й методи. Гідродинамічні та температурні процеси в ливарній формі аналізували за допомогою комп'ютерного моделювання; оцінку дослідних виливків виконували за характером макроструктури злому, методами металографічних досліджень, хімічного аналізу чавуну та порівнянням твердості локальних частин виливків.

Результати. Визначено основні технологічні параметрами, які впливають на характер кристалізації чавуну, і як наслідок, формування градієнтної структури в виливках: конфігурація та товщина перерізу стінки виливка, матеріал і товщина вставки, температура заливання розплаву. Наведено технологічні рекомендації, формування градієнтної структури та властивостей в локальних частинах виливків.

Висновки. Підтверджено можливість реалізації запропонованого способу, перспективного для виготовлення чавунних виливків різної номенклатури (зокрема й спеціальних засобів та техніки підрозділів МВС України, служб ДСУНС та інших силових структур), що працюють в умовах статичних, динамічних навантажень.

Ключові слова: спосіб, інмолд-процес, білий чавун, високоміцний чавун, градієнтна структура, зносостійкість, твердість, в'язкість.