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PRINCIPLES OF CONSTRUCTION AND IDENTIFICATION OF A MULTILEVEL SYSTEM FOR MONITORING PARAMETERS OF TECHNOLOGICAL CYCLE OF CASTING

O. Shinsky
Doctor of Technical Sciences, Professor, Head of Department*
I. Shalevska
PhD, Associate Professor*
E-mail: into66@ukr.net
P. Kaliuzhnyi
PhD, Senior Researcher*
V. Shinsky
Researcher*
T. Lysenko
Doctor of Technical Sciences, Professor, Head of Department
Department of Foundry technologies
Odessa National Polytechnic University
Shevchenka ave., 1, Odessa, Ukraine, 65044
T. Shevchuk
Director
«P.P.M. UKRAINE», Ltd
Zvirynetska str., 63, Kyiv, Ukraine, 01014
V. Sliusarev
Commercial director**
Ie. Pohrebach
Engineer**
S. Kolomiitsev
Engineer**
*Department of Physical Chemistry of Foundry Processes
Physico-Technological Institute of Metals and Alloys
of the National Academy of Sciences of Ukraine
Vernadskoho blvd., 34/1, Kyiv, Ukraine, 03142
**«MK BUDINVESTSERVISE», Ltd
Kurenivskyi lane, 15, Kyiv, Ukraine, 04073

Для створення багаторівневої системи комплексного контролю та оперативного управління фізико-хімічними та технологічними ливарними процесами визначено детермінований зв’язок між технологічними об’єктами. Ці об’єкти беруть участь в процесах плавки, позапічної і теплової обробки при виробництві виливків з високоміцного чавуну. Це дало можливість розробити блок-схему вибору і оптимізації основних технологічних параметрів, геометрії ливникових систем для одержання виливків за моделями, що газифікуються.

Для забезпечення безперервного контролю за безліччю параметрів технологічних процесів, устаткування та стану екологічної безпеки було визначено основні фактори впливу технологічних параметрів. З цією метою застосовано діаграму Ішікави для оцінки ефективності впливу параметрів і ливарних об’єктів при литті за моделями, що газифікуються, на якість виливків і екологію навколишнього середовища. Встановлено доцільність використання діаграми Ішікави для теорії і практики ливарного виробництва. Розроблено методики з використанням діаграми Ішікави, які дозволяють ідентифікувати і встановити детермінований вплив чинників першого, другого, третього порядку на технологічні процеси і ливарні об’єкти, а також екологію навколишнього середовища. Також дають можливість визначити ефективність використання діаграми Ішікави при отриманні високоякісних литих виробів із залізовуглецевих сплавів, включаючи високоміцний чавун.

Отримані основні дані про ідентифікацію ливарних об’єктів і процесів, як повного циклу виробництва високоміцного чавуну і виливків з нього за моделями, що газифікуються. Це дозволить побудувати багаторівневу систему контролю параметрів повного технологічного циклу з використанням сучасних комп’ютерних інформаційних технологій, а також моніторингу екологічного стану ливарних об’єктів та визначити їх вплив на навколишнє середовище

Ключові слова: якість виливка, високоміцний чавун, детермінований зв’язок, чинники впливу, діаграма Ішікави

1. Introduction

Modern technologies of production of casting designs are multicomponent and can be represented primarily by process stages, which include melting processes and ladle treatment of alloys, modern methods of molding and heat treatment. The combination of these process stages and the corresponding equipment for the implementation of these interconnected processes and technologies determines the quality and competitiveness of casting products in Ukraine and Western Europe.

It is important to emphasize that the complex of interconnected process stages has a multi-level, deterministic multicomponent system with corresponding technological

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processes, materials and equipment. Such a complex integrated system can be stable and determine the possibility of producing castings with a high level of specified properties only under certain conditions. That is, this is possible by providing continuous control of various parameters of technological processes, equipment and environmental safety.

Therefore, the development of automated process control systems (APCS) and identification of controlled indicators and determination of factors of influence of technological parameters are relevant for casting production today.

2. Literature review and problem statement

In the modern scientific periodicals, dealing with management of casting processes, research is usually related to the automation, optimization and management of certain technological operations. In particular, in [1], the authors investigated the effect of shrinkage porosity on the formation of residual stress on the example of the technology for a particular casting and considered the effect of individual technological factors. The formation of a general scheme of a computer-integrated control circuit of the melting process in an electric arc furnace is described in [2]. Also, the processes of automation of the chill casting machine control with the compilation of the algorithm of successive operations, which are important in terms of production automation are considered [3]. Despite the practical significance of such results, for managing the quality of the casting, it is more rational to consider the full production cycle from charge calculation (technology design) to the performance of finishing operations (heat treatment). In this case, it makes sense to identify technological parameters of casting processes for quality control of castings and automation of technological operations. There is an experience in using the typing principle to form an analytical description of controlled processes of casting production [4]. However, in the above works, the system approach to the determination of the key factors of influence on the properties and quality of products is not sufficiently used.

The system approach to the determination of the key factors of influence on the quality of products is possible when using the Ishikawa diagram [5], which is an analytical tool for studying the influence of possible factors and identifying the most important causes, the effect of which leads to specific consequences and is manageable. Basically, the Ishikawa diagram was used in the management system as a supplement to existing methods of logical analysis and quality improvement of processes in the industry [6, 7]. The authors of [8, 9] use the Ishikawa diagram for managing business processes and identifying key factors of influence on the process quality and economic performance, while not considering technological processes.

There are examples [10, 11] of successful use of the Ishikawa diagram to identify the cause-effect relationship between casting quality and technological parameters of casting production. However, as already noted, these works consider only certain stages of the casting process and do not take into account the mold parameters and environmental impact.

Automation and management of casting processes are discussed in [12] in terms of automation of operations, and not the impact on the final product. The bases of gas-hydrodynamic processes in the lost-foam casting obtained in [13] allow considering the relationships between the external impact on the mold and metal and process parameters, the parameters of harmful emissions are given. However, the deterministic causality of process parameters is not defined. The authors of [14] investigated the process of intensification of casting solidification by the introduction of the metal phase into the polystyrene foam pattern for reinforcement and determined conditions and laws of heat-mass transfer and hydrodynamics. It should be noted that all obtained data and mathematical models for further use in APCS for casting production require systematization and determination of key parameters of influence on the casting quality and environment.

For the construction and identification of the process control system, lost-foam casting is chosen as the most promising and «flexible» method in terms of managing the structure and properties of the casting. In this casting method, the mold can be used as an active-functional system and a tool for managing the structure and properties of the casting [15]. However, new methods of directed influence on the casting during molding and parameters of influence on the casting quality investigated in this paper do not consider alloy production indicators and impact of the technology on the environment.

The review makes it possible to assert that the process of lost-foam casting has many factors that influence the final result – casting quality. Therefore, there is a need to systematize and classify the technological parameters of lost-foam casting and to define the deterministic causality of technological objects. For further use in the creation of computer integrated information technologies (IIT) and APCS for casting production, it is necessary to develop a multilevel integrated control and operational control system.

3. The aim and objectives of the study

The aim of the study is to create theoretical, technological bases of the multilevel system of integrated control and operational management of physical-chemical and technological processes, monitoring of the state of casting objects. These casting processes and objects are involved in the production of iron-carbon alloy castings by lost-foam casting. The created multilevel system can further be used in computer IIT and APCS for casting production.

To achieve this aim, it is necessary to accomplish the following objectives:

– to conduct a study of the deterministic causality of technological objects (materials, technologies, equipment, ecology) involved in the processes of production of ductile iron castings, monitoring of environmental safety;

– to develop a block diagram of selection and optimization of the key technological parameters, the geometry of gating systems for lost-foam casting with the gravity metal pouring into the mold;

– to determine the key factors of influence of technological parameters on the casting object in the manufacture of ductile iron castings using the lost-foam casting technology;

– to develop an Ishikawa diagram for determining the casting quality and the influence of technological parameters on the formation of harmful emissions in the manufacture of ductile iron castings by the lost-foam casting method.

4. Methods of determining the relationship between casting parameters and their impact on the casting quality

To determine the parameters for identifying materials and casting processes involved in the manufacture of castings with specified performance characteristics and the number of sources of continuous information retrieval for control, the developed mathematical models were used. These models describe the laws of technological processes of melting, ladle, heat treatment of iron-carbon alloys and castings of them. They also describe varieties of modern methods of molding using physical methods of strengthening of molds and lost patterns and the complex interaction of technological equipment and the environmental state of casting objects.

To determine the key factors of influence on the casting object, the technological process and the final product – casting design, the Ishikawa diagram was used. This made it possible to establish the relationship between the key factors, as well as the deterministic influence of the second level on the key parameters, and the third level – on the parameters of the second level.

5. Classification and identification of the casting quality and the array of process control parameters

The research is devoted to the full cycle of manufacturing ductile iron castings using the lost-foam casting technology. In this case, mathematical dependencies described in detail in [13, 15, 16] were used.

5. 1. Investigation of the deterministic causality of technological objects

At the first stage, the deterministic causality of parameters of various process stages was defined. These process stages determine the full cycle of casting, including melting, ladle treatment, molding and production of lost patterns, as well as heat treatment of cast products, presented in Fig. 1.

The block diagram (Fig. 1) was constructed on the basis of primary relationships between process stages and the use of the core of this technological chain, namely molding and production of polystyrene foam patterns. First, quality characteristics and management parameters of the technological processes for the production of casting designs of iron-carbon alloys are classified.

In order to achieve the maximum quality of castings, including the improvement of mechanical characteristics, the following disperse nonmetallic fillers are used for molds: quartz, zirconium and magnesite sand. To ensure the intensification of heat transfer in the «metal-mold» contact zone, gaseous and liquid coolants were used, as well as high mechanical pressure on the liquid and solidifying metal. These new developments are the basis for the intensification of heat transfer processes in a vacuum mold with the given heat accumulation capacity (block 4.1, Fig. 1) and purging of the latter with gaseous coolants (block 4.2, Fig. 1).

An effective increase in the dimensional accuracy of casting designs can be achieved by reinforcing polystyrene foam patterns with metal and nonmetallic bodies, which are both the reinforcing phase (block 2.3, Fig. 1).

Roughness reduction in casting designs is ensured by an increase in the polystyrene foam density provided that «light» lost patterns with pinhole porosity are used (block 2.5, Fig. 1).

In addition to the listed quality characteristics of the casting design, the classifier also included undesired characteristics acquired in the process of lost-foam casting, because the presence of defects in castings decreases the quality of casting designs. Surface defects on the casting (holes) (block 1.12, Fig. 1) arise due to the violation of temperature-time parameters of lost-foam casting. Also, holes can be formed due to the excess of the permissible density value of the pattern ρ_5, low gas permeability of the coating K_{nc} and mold K_m, as well as unacceptable low vacuuming P_v created in it.

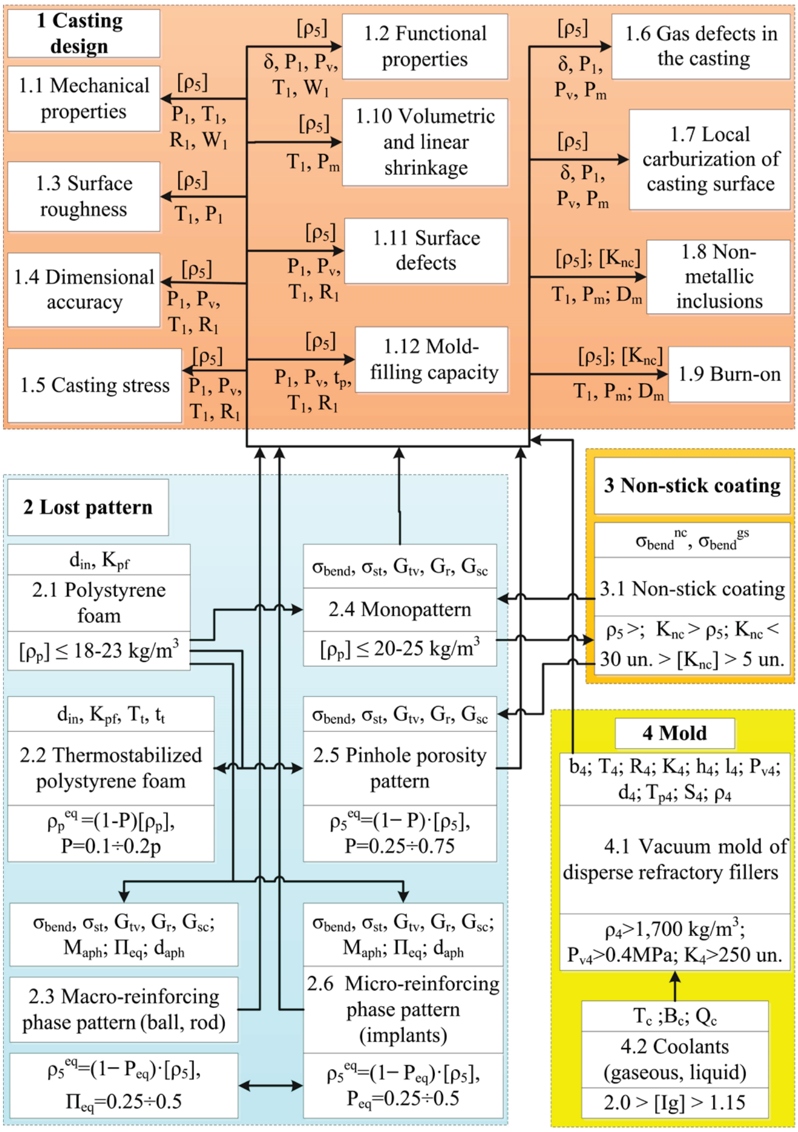

Fig. 1. Key quality characteristics of casting designs and quality control parameters of castings in the lost-foam casting

This reduces the rate or eliminates the filtration of liquid and vapor-gas products of thermal destruction of the pattern due to the «metal-pattern» gap δ, whose area and resistance of transfer of these products from the mold depend on the rate W_1 ($W_{5\text{-const}}$), K_{nc}, K_m. The increase in the volume of generated vapor-gas and liquid thermal destruction products depends on the rate W_1 ($W_{5\text{-const}}$), time of pouring t_p, alloy pouring temperature T_p, metal pressure P_1, density of the lost pattern ρ_5, gap δ and thickness of the casting wall R_1. These factors stimulate the accumulation of thermal destruction products directly on the «metal-coating» boundary during solidification of the casting. The formation of a specific burn-on (block 1.9, Fig. 1) on castings occurs when the vibration compaction of the filler in the container is insufficient. This deviation is characterized by a low index of bulk density ρ_4, high pressure on liquid metal P_1, which is typical for high-pressure casting, unreasonably high alloy pouring temperature T_p. In addition, the size of the burn-on is determined by high gas permeability of the coating K_{nc} and mold K_4 and vacuuming in it P_v. At the same time, the formation of the burn-on during lost-foam casting occurs when liquid metal penetrates in a non-stick coating through pores under the action of a pressure gradient (P_1–P_v). That is, the probability and of the burn-on thickness are proportional to the increase in the value of these indicators.

The mold filling capacity (block 1.12, Fig. 1) during casting using polystyrene foam patterns in many cases depends on the density of the pattern ρ_5, mold filling rate W_1, pouring time t_p, alloy pouring temperature T_p, metal pressure P_1 and casting wall thickness R_1. An increase in density ρ_5 with the simultaneous increase in the rate W_1, gasification time of the pattern in this period τ_g leads to the accumulation of a large amount of liquid products of thermal destruction of the polystyrene foam pattern on the metal flow front. Further gasification of these products occurs with the absorption of the heat of liquid metal, which leads to overcooling and formation of the solid phase in the main part of the flow, and the latter leads to a premature stop of the metal flow and incomplete mold filling.

Casting stresses (block 1.5, Fig. 1) during lost-foam casting occur predominantly in the vacuum mold. They are related to the excessive duration of vacuuming of the filler in the container (P_1, t_v) during the solidification and cooling of the casting, which eliminates the compliance of the mold. This creates conditions for stresses in castings to increase until deformation and cracking. To reduce or remove stresses in castings, it is necessary to optimize the mold vacuuming duration.

Casting shrinkage (block 1.10, Fig. 1) during lost-foam casting increases with high compliance of the mold filler during the solidification of the casting after vacuum removal from the container. To stabilize the mold shrinkage, it is necessary to optimize the value of P_1 and mold vacuuming duration t_v.

5. 2. Selection and optimization of key technological parameters for casting quality management

In order to select and optimize quality management parameters of ductile iron castings, determined by the classifier (Fig. 1), the block diagram was developed, where all these parameters are in a deterministic dependence on each other (Fig. 2), namely:

- chemical composition of cast iron, inoculants, addition alloy, C_1;
- methods and temperature-time parameters of melting, inoculation and spheroidizing treatment of the original liquid iron;
- temperature-time parameters of heat treatment of castings, T_1;
- rate of metal build-up in the mold, W_1;
- molf filling time, t_f;
- metal pouring temperature, T_p;
- pressure on liquid metal, P_1.

First, optimum characteristics of the pattern and mold materials are determined, namely:

- optimum density of the polystyrene pattern, ρ_5;
- gas permeability of the non-stick coating, K_{nc};
- bending strength of the non-stick coating, σ_{bend};
- mold characteristics.

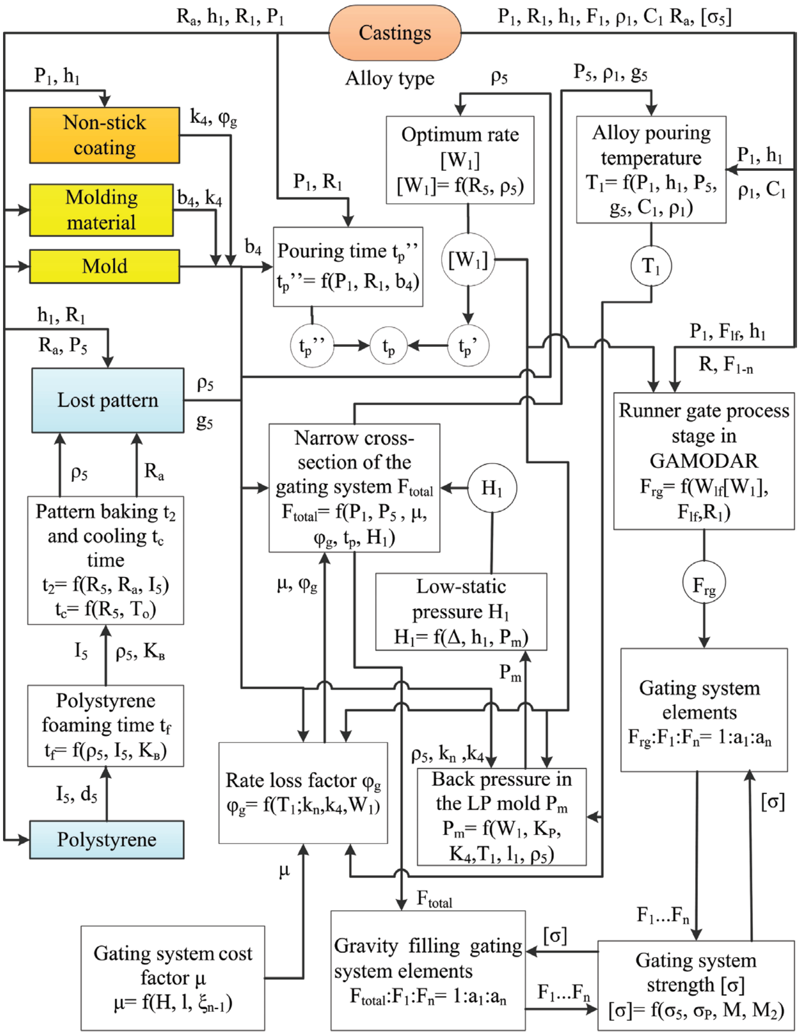

Fig. 2. Block diagram of selection and optimization of the key technological parameters, geometry of gating systems for the lost-foam casting with the gravity metal pouring in the mold

At this qualification level, it is most important to determine the influence of the key parameters of the technological processes of ductile iron production on physical-mechanical and operational properties for further identification in the full cycle of casting production. This makes it possible to create a multilevel computer system for collecting and processing information on a set of parameters of technologies, state of equipment and monitoring of the environmental condition of the casting object and environment.

5. 3. Key factors of influence of technological parameters on the casting object in the production of ductile iron castings using the lost-foam casting technology

According to the developed classifier, the key quality features and process control parameters of iron-carbon alloys are mechanical properties of the casting material under the regulatory and technical documentation (GOST, DSTU, TU, KD, RTM). These include ultimate strength σ_v and tensile yield strength $\sigma_{0.2}$, elongation δ, toughness KCU, hardness HB (HRc) at normal, high and low temperatures throughout the casting section, functional and tribotechnical properties.

For example, the criterion for selecting the brand of ductile iron (DI) for machine parts is the requirements for its physical-mechanical and operational properties. Improvement of the quality of casting designs of DI with optimum structural performance, mechanical and other service properties contributes to decrease in weight, increase in operational reliability and service life of cast parts and machines.

Forecasting of these optimum properties depends on control and management of process parameters of DI production at all casting process stages (Fig. 2). Obtaining of the structure that is regulated and necessary properties of cast iron in castings is ensured by the quality of initial charge materials, melting and melt treatment mode, effective modification, optimum mass fraction of the main and alloying elements, heat treatment and a number of other factors.

6. Development of the Ishikawa diagram of influence of technological parameters on the quality of ductile iron castings

For an objective assessment of the influence of technological parameters on the quality of ductile iron castings with the given operational characteristics, as well as for determining the array of information in its quantitative (retrieval points) and qualitative composition (factors of influence), the Ishikawa diagram was used (Fig. 3).

This type of the Ishikawa diagram allows determining the key factors of influence on the casting object, technological process or final product – casting design. In addition, such nomogram allows establishing the relationship between the key factors, as well as the deterministic influence of the second level on the basic parameters, and the third level – on the parameters of the second level.

To analyze the logical relationship between various factors and the result and to identify the most significant factors influencing the problem under study, the Ishikawa diagram for casting objects was improved and constructed. The technology of producing ductile iron castings (Fig. 3) and influence of technological parameters on the formation of harmful emissions in the manufacture of ductile iron castings was analyzed (Fig. 4).

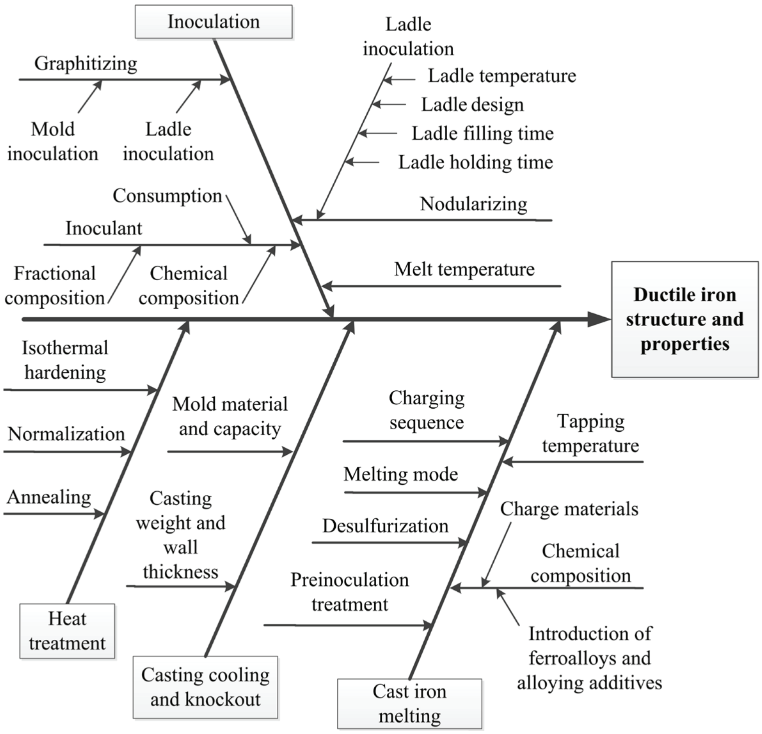

Fig. 3. Ishikawa diagram for the full cycle of ductile iron production

The analysis of this diagram (Fig. 3) allows determining the factors and parameters that determine the properties of ductile iron in casting designs.

The main branches (bones) that determine the structure, mechanical and performance characteristics of casting designs of ductile iron (Fig. 3) are technological processes: melting, inoculation and cooling of castings in the mold. For each technological process, the key factors of the second order are established, variations of which in the established boundary limits are determined by the factors of the first order.

Let's consider qualitative and quantitative characteristics for each of the key technological processes, factors of the second and third order.

It was found that the factors of the second order for the implementation of the main branch of the Ishikawa diagram (Fig. 3) «Chemical composition of cast iron» are the basic chemical elements C, Si, Mn, P, S, Cr, which are included in the original cast iron and determine its quality, the factors of the third order «Chemical composition of cast iron» are:

– charge materials, which are identified by five chemical elements: C, Si, Mn, P, S, Cr;

– charge calculation as a factor regulating the content of the main components;

– ferroalloys and alloying agents as a factor regulating the content of alloying components (Si, Mn, Cr, Mg, Ni, Cu, Mo, Al, Sn, Ca, etc.), which allows controlling the structure formation and formation of the nodular graphite shape, as well as the matrix of the cast iron (ferrite, perlite, bainite, ferrite-perlite, perlite-ferrite);

– dosage of components as a factor regulating the weight of each component of the charge and the alloying elements.

Factors of the third order for the implementation of the main branch of the Ishikawa diagram (Fig. 3) «Inoculation» are identified:

– inoculants, which are identified by the type of inoculant (based on FeSi, FeSiBa);

– temperature-time parameters, which are identified by the type of modification (ladle inoculation, mold inoculation), temperature of the original cast iron on the ladle end and the time of ladle treatment;

– consumption, identified by the specific weight of the inoculant in the ladle (intermediate reactor);

– fractional composition, identified by the average granule size of 0.5–10 mm;

– cast iron structure, identified after inoculation and modification of graphite shape and size and cementite content.

Factors of the third order for the implementation of the main branch of the Ishikawa diagram (Fig. 3) «Nodularizing» are identified by analogy with inoculation.

So, the set of data obtained about the factors of the first, second and third order, determining the cycle of the technology for producing ductile iron with the given characteristics, will allow determining the entire array of information for collecting, processing and managing these parameters.

Similarly, the Ishikawa diagram on the influence of the technological process of producing ductile iron castings on the environment was constructed (Fig. 4).

The main branches (bones) of the diagram are harmful emissions: CO, CO_2, SO_2, SiO_2, NO; NO_2, MgO.

For the production process of ductile iron castings by lost-foam casting, the key factors of the second order are determined, variations of which in the established limits are determined by the given factors of the first order.

Parameters of the second level, variations of which in the established limits are determined by the given factors of the first order, are the basic chemical elements C, Si, Mn, S, Cr. These elements are included in the original cast iron and affect the qualitative composition of emissions, environmental oxygen, technological parameters of melting, such as furnace capacity, melt temperature, melting duration. It was also found that factors of the third order for the implementation of the four main branches of the Ishikawa diagram are: yield and weight of the casting, which indirectly affect the formation of emissions and depend on the type of technological process.

It was found that for the environmental condition of casting objects, as well as the environmental impact in the ductile iron production, factors of the second order, which determine the quantitative and qualitative characteristics of solid and gaseous products are the key.

Thus, the method using the Ishikawa diagram, which allows identifying and defining the deterministic influence of factors of the first, second, third order on the environment was developed. The obtained information can be used in the development of a multilevel computer system for collecting and processing of information and monitoring of the environmental condition of casting objects and processes.

7. Discussion of the results of the study of key factors of influence of technological parameters on the casting object

The processes of producing high-quality alloys and castings are multifactorial and multicomponent, depend on the quality control of each casting process stage. Therefore, it was necessary to systematize the influence of various factors on the final product (casting).

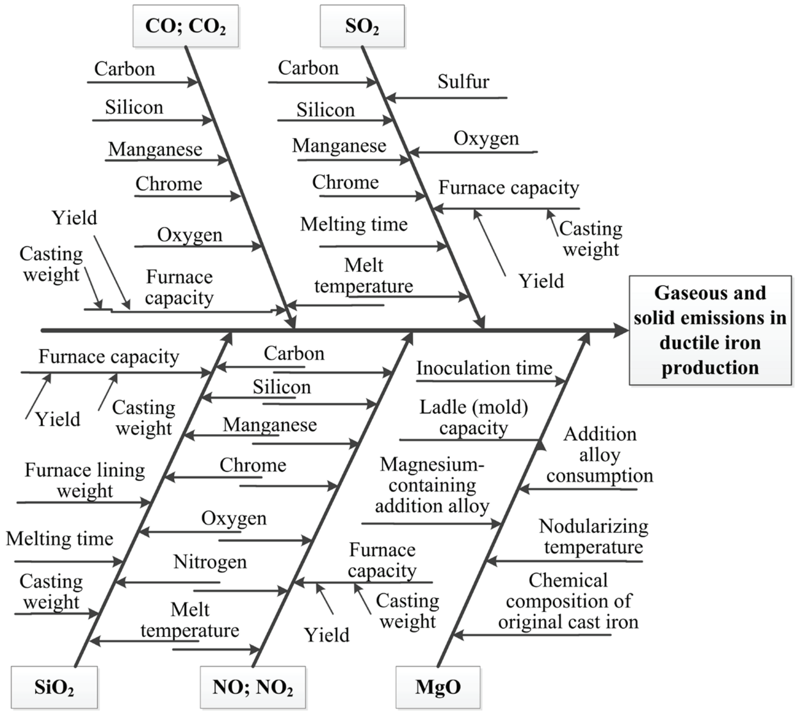

Fig. 4. Ishikawa diagram of influence of technological parameters and chemical composition of the original cast iron on the environment in the ductile iron production

Basic data on the identification of casting objects and processes as the full cycle of production of ductile iron and castings of it by lost-foam casting are obtained. At the same time, in comparison with other studies, it is important to emphasize that deterministic causalities of casting objects and processes in the «metal-pattern-mold-coating» system are established. Also, the influence of technological factors not only on quality, but also on specific functional properties and the environment was determined. Similarly, the systematization of the influence of casting objects for different types of alloys and technological parameters of molding is possible.

For the objective assessment of the influence of technological parameters of producing ductile iron with the given operational characteristics, as well as for determining the array of information in its quantitative (retrieval points) and qualitative composition (factors of influence), the Ishikawa diagram was used. This allows reducing the number of information retrieval points when constructing a multi-level system for controlling the parameters of the full technological cycle, as well as monitoring the environmental condition of casting objects and determining the influence of technological parameters on the environment. It is important to note that such an array of data on the state of technological processes and casting objects in the online mode can not be collected out by traditional methods. That is, by local information collection from each casting object and processing it directly by subjects of the process. In this regard, it becomes expedient to use modern computer information technologies providing high-speed objective information about the state of casting objects during the production of casting designs with the specified characteristics.

It should be noted that this concept on the use of casting objects and parameters as an active quality management system and tool for obtaining the specified properties can be applied only in a specific technological process. This is also possible provided that all process factors are investigated and taken into account as much as possible.

The results of the present study can be used in the creation of computer systems for monitoring the process of ductile iron production by lost-foam casting and the environment.

8. Conclusions

1. The multilevel classification and the system for implementing the quality of castings by identifying materials, control parameters of production processes of iron-carbon alloy castings by lost-foam casting, taking into account the deterministic causalities of casting objects, was developed. For this purpose, the influence of gas-hydrodynamic, heat and mass transfer processes in the «metal-pattern-mold-coating» system on the quality and functional properties of the casting design was determined. Characteristic features of the parameters, including: gas permeability of the coating (K_{nc}) and mold (K_m), vacuuming (P_v), rate (W_1 ($W_{5\text{-const}}$)), pouring time (t_p), alloy pouring temperature (T_p), metal pressure (P_1), pattern density (ρ_5) are determined, casting thickness (R_1) is given.

2. Methods of selection and optimization of key technological parameters, geometry of gating systems for lost-foam casting with the gravity metal pouring in the form of functional dependences were developed. The block diagram of selection and optimization of key technological parameters, which are in the deterministic dependence on each other was constructed, namely:

– chemical composition of cast iron, inoculants, addition alloy, C_1;

– methods and temperature-time parameters of melting, inoculation and spheroidizing treatment of the original liquid cast iron;

– temperature-time parameters of heat treatment of castings, T_1;

– rate of metal build-up in the mold, W_1;

– mold filling time, t_f;

– metal pouring temperature, T_p;

– pressure on liquid metal, P_1.

This gives an opportunity to predict necessary properties of casting designs at the stage of development of the technological process.

3. Types and characteristics of materials of technological processes for the production of original cast iron, ladle inoculation and nodularizing, cooling of castings in molds were determined and identified. The three-level system was developed and key technological parameters of ductile iron casting production using the lost-foam casting technology were determined. The key factors of the process are iron casting, modification, cooling and knockout of castings and heat treatment. The quality of the casting depends on the initial parameters (material, weight and wall thickness of the casting), materials (nodularizing, inoculation, inoculant), technological parameters (melt temperature, melting mode, tapping temperature, heat treatment modes, etc.).

4. The Ishikawa diagram for the technological process of ductile iron casting production by lost-foam casting was developed. The method of cause-effect relationships was improved and the Ishikawa diagram on the influence of casting technology on the environment was developed. It was found that the formation of harmful emissions (CO, CO_2, SO_2, SiO_2, NO; NO_2, MgO) depends on the content of the basic chemical elements (C, Si, Mn, S, Cr), which are included in the original cast iron, materials, lining and environment, and technological parameters of melting. The formation of emissions is indirectly affected by the yield and weight of the casting.

Therefore, determination of the key factors of influence makes it possible to produce casting designs with the specified properties and maintain the level of harmful emissions not higher than the maximum permissible concentrations.

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