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INFORMATION SUPPORT FOR PROCESSES OF QUALITY FUNCTIONALS MEASUREMENT IN THE CAD OF CASTING OF STEEL CASTINGS IN SAND MOLDS

Показано, що проектування і управління технологією ливарного виробництва через його багатофакторність, інтенсивність і недоступність для вимірювань вкрай утруднено, через що значна кількість виливків в реальному виробництві бракується.

Запропоновано метод застосування замість частинних вимірюваних параметрів функціоналу, що їх об'єднує, який використаний також в якості безрозмірного чисельного критерію бездефектності виливків. Метод випробуваний в реальному ливарному виробництві з позитивним технічним ефектом.

Ключові слова: *ливарне виробництво, якість виливків, вимірювання параметрів, комплексний функціонал, критерій якості.*

1. Introduction

Foundry production is characterized by high dynamism, multidimensionality, high intensity, wide range of values, inaccessibility for measurements, latency and delay. Therefore, there is a great need for a lot of information about the current state of the casting process, and therefore, in the metrological support of all its stages.

The problem is that it is almost impossible to accurately and adequately measure anything in the foundry industry.

And it's not even that the relevant methods and means of measurement have not yet been created. After all, some parameters of the foundry production often do not have physical meaning, and they have to «collect» from other, more or less measured characteristics. At the same time, founders are moving farther and farther from the adequacy of the measurement results by the real parameters of casting.

It's like finding not where you lost, but where it's light. Therefore, foundry specialists often resort to «handicraft» methods of measurement, and the result of this «initiative» is that more than 50 % of steel castings obtained in sand molds are rejected.

Another important feature of the foundry industry is that its measured internal parameters are not very informative from the point of view of the final result – the quality of the casting.

On the other hand, modern metrological science and practice allow today to find and use new complex parameters – functionals that unite the main particular characteristics of objects of measurement and at the same time significantly affect the final product. Closing such complex parameters on the result of the technological process, researchers and foundry technologists try to achieve their adequacy and accuracy, which ultimately should positively affect the results of design and management of foundry technology.

Unfortunately, to date, there are no such functionals that could serve as criteria for casting quality, and therefore there are no methods and means for measuring and interpreting them.

2. The object of research and its technological audit

The object of research is the processes of design and management of foundry production, based on measuring its particular parameters in the system «steel casting – sand mold» with subsequent recalculation of them into complex functionals.

Technological audit is a way to diagnose the innovation and production subsystems of the foundry, and it allows to obtain a description of the innovative potential of the foundry. Technological audit gives the company the opportunity to formulate a strategy for extracting revenue from the results of innovation activities. It is assumed that the enterprise-developer uses the results of innovation directly at home, producing new products (steel castings) using the created process innovations.

The procedure for assessing the commercial potential of the innovation idea is carried out according to an algorithm consisting of seven consecutive steps [1]:

– conducting preliminary studies;
– search for analogues;
– verification of the technical feasibility of an innovative idea;
– identification of the product (information technology) for comparison with analogues;
– determination of market advantages of the product;
– evaluation of market prospects for created product;
– practical feasibility of the innovative idea.

The conducted studies confirm the high commercial potential of the innovative idea: the use of the new functional as a quality criterion for the surface of steel castings.

3. The aim and objectives of research

The aim of research is quality improvement of steel castings obtained in sand molds by increasing the design efficiency and improving the management of their production process by providing new information support for the processes of measuring quality functionals in the CAD of foundry.

To achieve this aim, it is necessary to solve the following tasks:

1. To develop and perform an analysis of the parameter-functional «gas discharge» in the system «casting – sand mold».
2. To estimate the accuracy and reliability of the use of the complex parameter-functional as a criterion of defect-free casting.
3. To implement the practical use of the research results with an assessment of their technical and economic advantages over known methods.

4. Research of existing solutions of the problem

It is generally accepted [2, 3] that only an experiment can provide reliable information about the physical properties of the vast majority of substances. In this statement (as well as in many others) the word «experiment» can be uniquely replaced by the word «measurement», since the research consists in creating certain conditions for the object and measuring the response of the object's parameters to these conditions [4].

In any case, measurement is the cornerstone of any research and on its accuracy and reliability depends the achievement of the purpose for which this research was generally conducted. This approach is especially important, when the conditions of research and object response are multidimensional, high-intensive and difficult to measure, as is often the case for casting.

To date, in the foundry industry there are dozens of methods for measuring various parameters of interest for more than 100 methods of casting and affecting the quality of castings. Here, first of all, modern infrared methods of measuring temperature [5–7], hydraulic ones – gas permeability [8], capacitive – densities [9], eddy current – sand burning [10]. Structural [11] and intellectual [12] identifiers and much more are used for obtaining information about the casting process.

In these casting methods, hundreds of defects in castings are described [13], which contradict the notion of «quality» and, as a rule, lead to rejection. Therefore, let's narrow the problem and consider:

– sand casting: sand-clay, sand-resin, ceramic, etc.;
– defects of the surface layer: sand burning, blown holes, chips, non-metallic impregnations, etc.;
– parameters affecting these defects: technological, thermal, hydraulic, electrical, mechanical and the like.

To measure the latter, there are standard methods and corresponding metrological support. The shortcomings of the existing methods follow directly from the following considerations.

The measurement ranges for existing tools do not match the actual values of the parameters that occur during the casting process, for example, the gas permeability of the mold is measured at room temperature, and the casting of steel into this mold is carried out at temperatures of 1600–1800 °C. Therefore, the existing means do not allow to obtain any exact value of the measured quantity as a function of the space-time of the casting-form system.

Objectively, there is a large interdependence between the individual measured parameters (for example, the gas content of the molding mixture depends essentially on the temperature, the gas permeability of the form – on the gas mixture, the temperature – on the gas permeability, etc. in a circle) [14].

All this leads to the fact that the values of the parameters obtained by individual measurements are, as a rule, not informative from the point of view of designing and controlling the foundry processes.

5. Methods of research

To solve these problems, it is suggested to perform measurements of many parameters at different points in the space-time of the «casting-mold» system with subsequent convolution of their values to a single number – the result of the measurement.

To them, in the first place, were attributed the parameters resulting from the design and technological characteristics of the directly found object – laboratory or real production:

δ_C – 1/2 of the thickness of the flat casting, m;
δ_m –the thickness of the flat wall of the mold, m;
ρ_m – the density of the mold material, kg/m^3;
α_b –concentration of the binder in the mold material;
F_1 – the unit area of the gas exchange «tube» (Fig. 1), m^2.

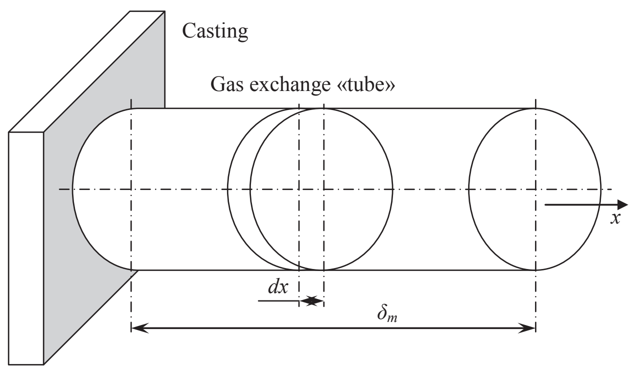

Fig. 1. Gas exchange «tube» within the boundaries of a mold wall with a thickness of δ_m

Secondly, the parameters are taken into account. These parameters were measured in the molding mixture before the mold was made and poured.

GP – gas permeability of the molding material, measured according to the standard procedure, m^4/(N·s). Gas permeability is the ability of a molding mixture to pass through itself a predetermined amount of gases at a standard pressure.

GPr – gas production of the molding material, measured by the standard method, m^3/(kg·s).

Great gas production has a mixtures with synthetic resins, low – mixtures with inorganic binders, for example, liquid glass, clay [13].

The third group of parameters is the result of dynamic measurements directly in the «casting-mold» system after casting. Here the determined value varies with time:

$T_1(\tau)$ – the temperature of the inner (working) layer of the mold, K;

$T_2(\tau)$ – the temperature of the middle layer of the mold, K;

$T_3(\tau)$ – the temperature of the outer layer of the mold, K;

$T_4(\tau)$ – the casting temperature, K;

$P_1(\tau)$ – the pressure of gases in the inner (working) layer of the mold, Pa;

$P_2(\tau)$ – the pressure of gases in the middle layer of the form, Pa.

Finally, the fourth group includes the parameters – the consequences: the quality of the surface layer of the castings. The surface layer of the finished castings is evaluated in points by two factors: sand burnings and shells on a 5-point scale for each factor.

As a result, the scheme of the dependence «process parameters – casting quality» looks like it is shown in Fig. 2, and the main dependence «measured parameters – quality» has the following form:

$$D_1 = D_1(\delta_C, \delta_m, \rho_m, \alpha_b, F_1, GPr, GC, T_1, T_2, T_3, T_4, P_1, P_2), \quad (1)$$

$$D_2 = D_2(\delta_C, \delta_m, \rho_m, \alpha_b, F_1, GPr, GC, T_1, T_2, T_3, T_4, P_1, P_2). \quad (2)$$

Next, it is necessary to pay attention to the fact that a functional is a mapping defined on an arbitrary set and having a numerical range of values: usually a set of real numbers – mathematical objects arising from the need to measure geometric and physical quantities [15].

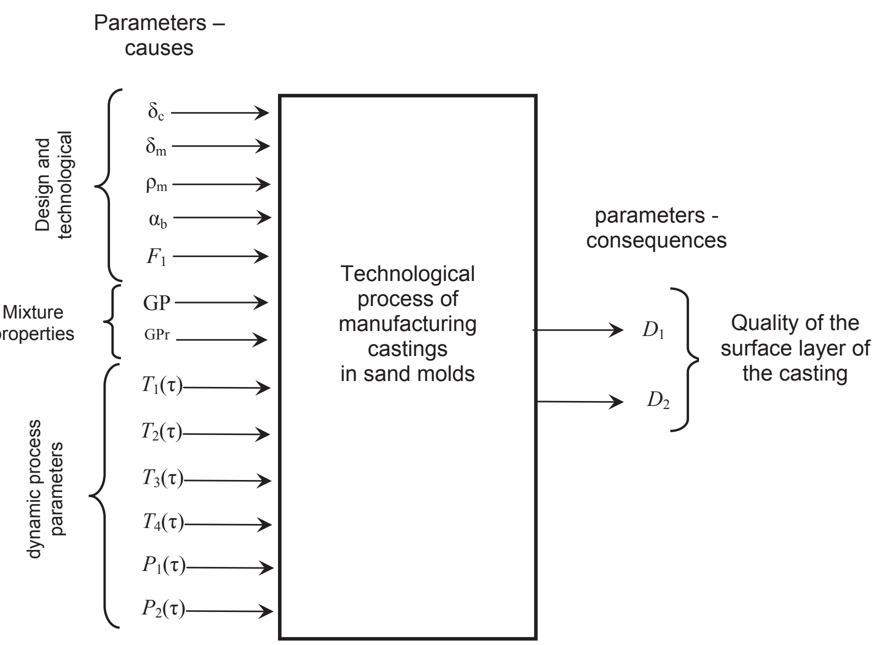

Fig. 2. Information scheme of dependencies «parameters-causes – parameters-conswquences» (process parameters – quality parameters)

Proceeding from this, let's combine all the above-mentioned «parameters-causes» into dimensionless intermediate functionals: technological, temperature and hydraulic.

Technological dimensionless intermediate functional:

$$K_M = \frac{GPr \cdot \rho_m \cdot \delta_b \cdot F_1 \cdot \delta_C}{GP \cdot P \cdot \delta_m}. \quad (3)$$

Temperature intermediate functionals, dimensionless temperatures:

$$K_{T_1} = \frac{T_1}{T_4}; \quad K_{T_2} = \frac{T_2}{T_4}; \quad K_{T_3} = \frac{T_3}{T_4}. \quad (4)$$

Hydraulic intermediate functional, dimensionless pressure:

$$K_G = \frac{P_1}{P_2}. \quad (5)$$

And, finally, let's create a common final functional, which will call «gas removal» in the system «casting – sand mold»:

$$GR = \frac{K_{T_1} \cdot K_{T_2} \cdot K_{T_3}}{K_G \cdot K_M}, \ [\text{n/v}]. \quad (6)$$

Thus, *a new complex dimensionless parameter «gas removal» and the method of its measurement* are obtained. This method, of course, refers to an indirect measurement, that is, to one which result is obtained by combining many direct measurements [16].

Since the components of such measurement are dynamic parameters, this functional also refers to dynamic ones. By mathematical methods (for example, by integration or averaging), it can be reduced to a static average value, that is, to a single dimensionless number.

6. Research results

6.1. Development and analysis of a complex parameter-functional «gas removal» in the «casting – sand mold» system. To analyze the new complex parameter «gas removal» in the «casting-sand mold» system, it is necessary to obtain experimentally the real form of dependences (1) and (2).

For this purpose, a laboratory measuring complex is developed and created, allowing in the framework of one experiment to choose the appropriate methods [17] and to measure gas permeability and gas production of the molding mixture. Then make the test mold from the last and execute a series of experiments on the casting with the measurement of the dynamic parameters of the system during its cooling. After that, the surface quality of the castings (D_1 in the sand burning [18] and D_2 in the blown holes [19]) is measured in a five-point system.

The experiments are carried out in accordance with the developed plan. Their results are shown in Fig. 3, 4.

If in these experiments $GR_{\min} < GR_{\max}$, then, combining the graphs shown in Fig. 3, 4, let's obtain the final minimax graph with the guaranteed quality zone of the casting surface (Fig. 5). Within the framework of this graph, with some certainty, the forecast for the casting quality according to the GO gas removal criterion should come true.

For the experimental conditions (steel casting with a thickness of 20 mm, obtained in sandy-resin molds 50 mm thick and with a binder content of 5 %, casting temperature of 1700 °C) $GR_{\min} = 119$, $GR_{\max} = 143$. Thus, a new criterion for defect-free casting: «gas removal» functional is proposed and the limits of its values are shown, ensuring the quality of steel castings during casting in sandy-resin forms.

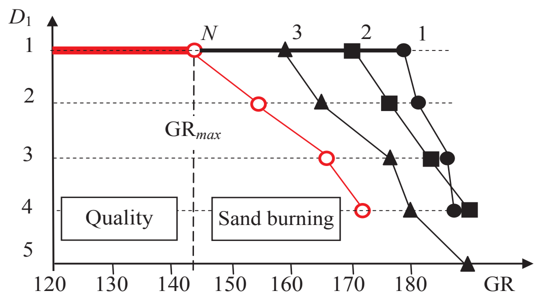

Fig. 3. Dependence of the final quality of the surface of the steel casting (D_1) on the gas removal (GR) in the «casting-sand mold» system during the cooling of the casting: 1, 2, ..., N – number of the experiment

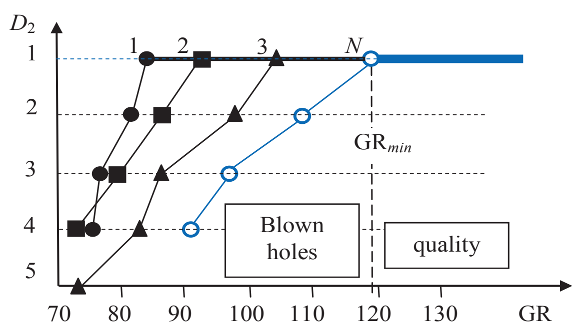

Fig. 4. Dependence of the final quality of the surface of the steel casting on the blown holes (D_2) on the gas removal (GR) in the «casting-sand mold» system during the cooling of the casting: 1, 2,..., N – number of the experiment

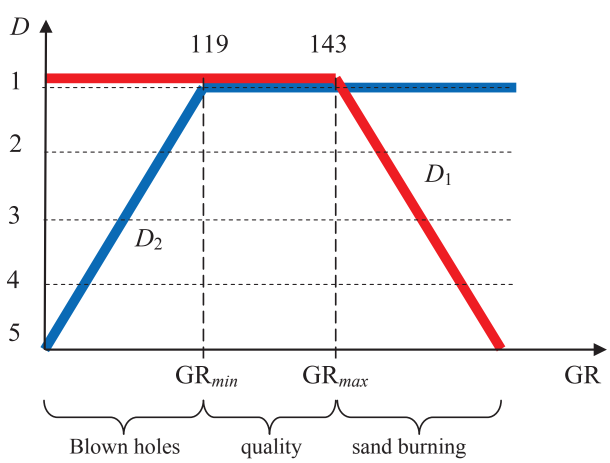

Fig. 5. Dependence of the forecast of the total overall quality of the steel casting surface on the gas removal of the «casting-sand-mold» system: red line – by sand burning; blue line – by blown holes

6.2. Estimation of the accuracy and reliability of the use of a complex parameter as a criterion for defect-free casting. The application of the described method to each individual type and method of casting is possible only after a thorough evaluation of its accuracy and reliability [20]. To estimate the accuracy, let's use the following considerations, which will be illustrated by the following example for two dimensions. Let some functional K be formed by multiplying two particular parameters P and Q, measured directly by a direct method with errors, respectively:

$$P \pm \delta_p; \; Q \pm \delta_q.$$

Let's denote the error in determining the functional K in terms of Δ, then it is possible to write down the range of its values as follows:

$$K \pm \Delta.$$

Since $K = PQ$ by definition, let's estimate the upper limit of the value K at the maximum error:

$$K + \Delta = (P + \delta_p)(Q + \delta_q) = PQ + Q\delta_p + P\delta_q + \delta_p\delta_q \quad (6)$$

or

$$\Delta_+ = Q\delta_p + P\delta_q + \delta_p\delta_q. \quad (7)$$

The expression $\delta_p\delta_q$ is of a lower order of magnitude than the other terms in (7), so they can be neglected:

$$\Delta_+ \sim Q\delta_p + P\delta_q. \quad (8)$$

Accordingly, let's estimate the lower limit of the value K at the maximum error:

$$\Delta_- \sim -Q\delta_p - P\delta_q. \quad (9)$$

The accuracy estimation performed by the proposed method shows that the measurement error of the «gas removal» functional under the conditions of steel casting described above in sandy-resin forms does not exceed 8 %, which is quite acceptable for this type of technical applications.

To assess the reliability of the method, changes are made to the initial experimental design. In previous studies, experiments were done once for a different set of process parameters (Fig. 3, 4). To obtain statistical reliability of the surface quality forecast of castings, the number of sets was reduced, but experiments for each specific set were performed 10 times.

As a result, the experimental dependence of the probability of obtaining a qualitative casting on the GR value for this group of similar experiments is obtained (Fig. 6).

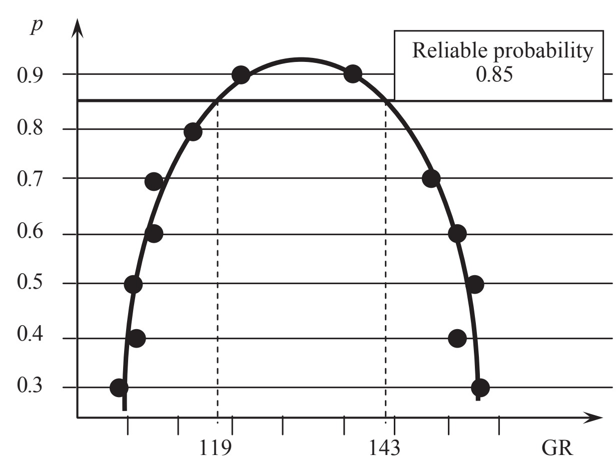

Fig. 6. Statistical validity of the use of gas removal functional as a criterion for the quality of steel castings, obtained in sandy-resin form

From Fig. 6 it follows that the use of the $GR_{\min}=119$ and $GR_{\max}=143$ as the criterion limits with a probability of not less than 0.85 reliably guarantees a high quality of the casting surface, both in the absence of sand burning and in the absence of blown holes.

6.3. Practical use of research results with an assessment of their technical and economic advantages over known methods. In JSC «Progress» (Berdichev, Ukraine), a system for the complex measurement of effective transport parameters through heterogeneous media was tested. The object of tests was sand-clay and sand-resin mixtures, which are used as molding materials for the manufacture of casting molds for steel casting. As a result of the tests it was established that the application of this system allowed to achieve the following technical results.

By methods and means of measurement:

– efficiency of the method for measuring the physical and technological parameters of the casting-mold system at various points in the space-time of the existence of the casting and the mold is confirmed, followed by the convolution of their values to a single number – gas removal functional;

– reliability and accuracy of the primary and final casting parameters in the laboratory and production conditions of the foundry of the JSC «Progress» (Berdichev, Ukraine) were estimated;

– effectiveness of using a single functional as a criterion for the quality of casting processes in sand molds were confirmed.

On the quality of the results of foundry:

– the number of defective steel castings caused by surface defects: sand burning and blown holes, decreased by an average of 31.1 % of the total percentage of defective castings.

7. SWOT analysis of research results

Strengths. The main positive influence of the research object on its internal factors is the opportunity created by it at the initial stages of the technological process to predict the quality of future castings. This saves considerable energy, material and labor resources.

Weaknesses. The main negative impact of the research object on its internal factors is the need to equip the very «hard» conditions of the foundry with very «thin» and difficult to maintain measuring devices.

Opportunities. Opportunities for further research in this area are related both to the development of the theoretical framework and to the improvement of methods and means to improve the quality of design and management of foundry production by creating new information technologies and a metrological base in the casting process.

The object of research allows to prevent the appearance of defective castings at an early stage of the life cycle of cast parts. At the same time, not only the percentage of output that is good in foundry production increases, but also the non-productive consumption of its resources is significantly reduced.

Threats. As in any foundry facility, the threats of its «activity» are a continuation of its main properties: high intensity, multifactoriness and fast flow of foundry processes, which seriously affect the accuracy and reliability of the proposed methods. At the same time, the implementation of the proposed method will not practically lead to additional costs for the foundry. It is based on the use of simple measuring instruments and simple software for the information processing of measurement results.

There are no complete analogues of the proposed complex measurement method. Previously, only certain parameters of the casting-mold system are measured.

8. Conclusions

1. A parameter-functional «gas removal» is developed in the system «casting – sand mold» and its analysis is performed. A new criterion of defect-free casting is proposed: the «gas removal» functional and the limits of its values are shown, which ensure the quality of steel castings when casting into sandy-resin forms.

2. The accuracy and reliability of the use of the complex parameter-functional as a criterion of defect-free casting is estimated. The estimation of accuracy and reliability performed by the proposed method shows that the measurement error of the «gas removal» functional under the conditions of steel casting described above in sandy-resin forms does not exceed 8 %. This is quite acceptable for this type of technical applications, and also with a probability of not less than 0.85, reliably guarantees the high quality of the casting surface, both in the absence of sand burning and in the absence of blown holes.

3. Practical implementation of the research results is carried out with an assessment of their technical and economic advantages over the known methods. As a result of the implementation it is established that the use of this system allows reducing the number of defective steel castings caused by surface defects by 31.1 % of the total percentage of defective castings.

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ИНФОРМАЦИОННОЕ ОБЕСПЕЧЕНИЕ ПРОЦЕССОВ ИЗМЕРЕНИЯ ФУНКЦИОНАЛОВ КАЧЕСТВА В САПР ЛИТЬЯ СТАЛЬНЫХ ОТЛИВОК В ПЕСЧАНЫЕ ФОРМЫ

Показано, что проектирование и управление технологией литейного производства из-за его многофакторности, интенсивности и недоступности для измерений крайне затруднено, из-за чего значительное количество отливок в реальном производстве бракуется.

Предложен метод применения вместо частных измеряемых параметров объединяющего их функционала, который использован также в качестве безразмерного численного критерия бездефектности отливок. Метод испытан в реальном литейном производстве с положительным техническим эффектом.

Ключевые слова: литейное производство, качество отливок, измерение параметров, комплексный функционал, критерий качества.

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