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THE PARADIGM FOR BUILDING A SIMPLIFIED END-TO-END QUALITY MANAGEMENT SYSTEM FOR TECHNICAL INNOVATION IN FOUNDRY PRODUCTION

Introduction. *To transition from technical novelty to innovation, a robust management strategy for product quality shall be established to enhance commercial viability.*

Problem Statement. *In the foundry industry, achieving high-quality castings remains a challenge within the end-to-end material system of the charge-melt-casting triad, which limits the scope for unconventional solutions.*

Purpose. *This study has aimed to define the conditions for a conceptual approach to building a simplified end-to-end quality management system for castings using an innovative method of conductive electric current melt treatment.*

Materials and Methods. *The research has utilized previously obtained data, supplemented by system analysis, simulation modeling, and quality management principles within the "object-regulator" framework.*

Results. *A simplified paradigm for end-to-end casting quality management has been proposed, structured around the abstract "design-production-consumption" system. In the first stage, simulation modeling and field experiments have laid the groundwork for defect-free production. The second stage has introduced an electromagnetic control method for regulating treatment intensity parameters, replacing the conventional online control principle to stabilize processes within the object-regulator system. Algorithms for this process have been defined. In the third stage, selective testing of finished castings has confirmed defect-free quality, ensuring product competitiveness.*

Conclusions. *The study has demonstrated that a simplified end-to-end casting quality management system can effectively identify critical conditions and factors for quality enhancement. This system, based on the abstract "design-production-consumption" framework, provides a practical foundation for achieving high-quality castings with sufficient intensity.*

Keywords: novelty, innovation, foundry, quality, system analysis, abstract systems, control, regulation, electric current.

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The transformation of any technical novelty into an innovation requires addressing a range of technical, economic, and legal challenges to achieve the critical characteristic of innovation: market relevance. An innovation must satisfy current market demands and possess the capacity for competitiveness and commercialization to generate profit [1—3]. To enhance this feature, it is essential to define the conditions and methods for managing the quality of the final product. Addressing these issues typically involves physical, cyber, analytical, and software components, necessitating a comprehensive and systematic approach.

At a minimum, this process requires identifying, analyzing, and structuring the object to be controlled, selecting appropriate computing and communication equipment, and developing effective information-processing algorithms alongside suitable software. These requirements are particularly pressing for complex, multi-stage, and multifactor production processes, such as those found in the foundry industry. The production stages are traditionally framed within the charge-melt-casting (CMC) triad. In the melt stage, encompassing liquid and two-phase temperature states, various processing methods and tools are employed to mitigate the adverse effects of the charge and ensure efficient solid-phase packing.

Despite these efforts, universal melt processing methods do not exist, nor has a generally accepted strategy for end-to-end casting quality management been developed to encompass all components of the CMC triad. Consequently, existing approaches primarily address local solutions [4—7], failing to define comprehensive conditions for end-to-end casting quality management. Moreover, these approaches often neglect the specific characteristics, mechanisms, and properties of melt processing methods, whose primary objective is to ensure high casting quality by establishing control parameters for their effects on the processed object.

One promising technique is the method of conductive electric current treatment (CECT) of the melt, which emerged as an area of active research toward the end of the 20th century. While CECT exhibits significant innovative features, its current status — based on an analysis of scientific, technical, and patent information—positions it as a novel method rather than a fully realized innovation.

The challenge of simplifying a complex, multifactorial quality management system, which remains poorly defined, by focusing on the primary factors influencing quality, is highly relevant. Within the framework of system analysis methodology, adapted to management principles, it is essential to select a system with sufficient intensity, characterized by a robust information component and optimal methods of information exchange.

This study aims to establish the conditions for a conceptual approach to developing a simplified end-to-end quality management system for castings, utilizing the innovative method of conductive electric current melt treatment.

COMMON QUALITY MANAGEMENT ISSUES

Modern definitions of the concept of “quality” emphasize its multifaceted nature. Philosophically, quality is understood as a characteristic that manifests with varying degrees of intensity [8]. The international standard ISO 9000 pragmatically defines quality as “a set of characteristics of an object that relate to its ability to meet the identified and anticipated needs of the user” [9]. These definitions classify “quality,” “intensity,” and “needs” as abstract terms, which are inherently challenging to measure or quantify through uniform characteristics. However, this abstraction allows decision-makers to make nuanced choices tailored to specific production conditions and goals.

A discrepancy exists in how casting quality is characterized. From the manufacturer’s perspective, quality equates to a defect-free product. From the user’s perspective, quality is defined by a product’s ability to meet their needs [10]. This distinction introduces the abstract concept of “competitiveness,” which is not solely determined by quality and cost but also by the supplier’s (manufacturer’s) reputation [10, 11]. Proving competitiveness in specific market segments can therefore be challenging, as it transcends measurable attributes of the product.

In the first half of the 20th century, empirical methods emerged to quantify the abstract concept of "quality," giving rise to the scientific discipline of qualimetrics [12]. Within qualimetrics, industrial product quality is analyzed as both a technical and economic category. This has led to the extension of the monad "quality" into the triad "quality-cost-competitiveness" (QCC). To operationalize this framework, qualimetrics introduced the concept of the "Quality Cycle," represented by another triad: "design-manufacture-consumption" (DMC).

Recent advancements in foundational research have enabled the integration of these triads into a broader "control-system-information" (CSI) framework. This integration, grounded in the principles of a systematic approach, provides a more holistic perspective on managing and measuring quality [13—15]. However, only if the following are ensured: identifying the reasons and objectives of management, determining the scope of controlling factors and parameters for optimizing management functions, and agreeing on sub-objectives that enable achieving the objective. Such a development allows us to form a fundamental approach to the control algorithm, which will contain a set of objectives {C}, functions {F}, works {R} and commands {C}, in order to create an approximation to the control function $\Psi = \{\{C\}, \{F\}, \{R\}, \{C\}\}$.

Thus, the monad "quality," which corresponds to the ultimate goal of the CMC, structured by specific unambiguous material concepts and definitions, is transferred to the level of abstract formalizations of the subsystems QCC, DMC and CSI. According to the concepts of system analysis methodology, these subsystems achieve subgoals that reflect their component concepts for achieving the ultimate goal [14]. The QCC subsystem allows us to define what we are aiming for in accordance with the overall strategy of quality research and its achievement. The DMC allows us to identify ways to achieve it. CSI, in turn, allows the selection of alternatives to these ways that can actually achieve the goal.

Unfortunately for the foundry industry, such an end-to-end management system consisting of these subsystems is complex, multi-factorial and poorly defined [14]. It can be assumed that large companies can build such a system. However, it can hardly be universal.

For this reason, laboratories and production facilities are currently focusing on finding local quality management systems, with particular emphasis on organizing efficient and stable production and identifying reserves for quality improvement. At the same time, it is necessary to identify, if possible, the common interests of those who produce and use foundry products.

FEATURES OF ELECTRIC CURRENT MELT TREATMENT

Any melt treatment in the liquid state has the following tasks: in addition to eliminating the negative effects of the charge, it is necessary to ensure degassing of the treatment object, its homogenization in the macro-volume, and to create conditions for the effective formation of crystallization germs throughout its space. Taken together, this can be defined as an improvement in the crystallization capacity of the liquid metal system (LMS). During the subsequent processing of the already two-phase state in the crystallization temperature interval, it is necessary to ensure effective packing of the solid phase with signs of structural homogeneity and crushed eutectic elements [16].

Methods of processing both the liquid single-phase state and the two-phase state can be classified into two categories: reagent and energy methods. Reagent methods involve the use of small doses of various chemical elements, which have a selective effect and allow for specific results. Energy methods, on the other hand, use various physical fields to influence the melt, resulting in integral and multi-purpose effects. In the case of CECT, it is a basic electromagnetic field that forms secondary fields in the melt: induced electromagnetic, sound based on the principles of electromagnetic-acoustic energy conversion, thermal due to joule heating, and the metal flow field formed by the cooperative thermal and force action of the fields formed [17—20].

The effect of any energy impact on any material, including a melt, is demonstrated through its reaction. In the case of LMS, this reaction is formed by restructuring the short-range energy bonds of the structural elements (clusters, atoms, and electrons). When dealing with a two-phase zone, it is also necessary to break the long-range energy bonds of the solid phase, which requires a more powerful action. Furthermore, although the LMS is shaky, it is relatively thermodynamically stable [6, 7]. This does not require changing the load characteristics over time. Meanwhile, the two-phase state transitions from liquid-solid to solid. Therefore, it is reasonable to process it by adjusting the load power over time.

Therefore, from an energy point of view, it is more rational to process LMS, creating the conditions for improving its crystallization capacity.

It is important to note that the use of a certain dose of energy density (w) introduced into the melt during processing has been experimentally proven for CECT of LMS [19, 21, 22]. Concurrently, the value of w is nearly identical to the density of the latent heat of crystallization of the melt of a specific alloy (E). That is, $w \approx E$. This makes it possible to significantly reduce the number of experiments and to transfer their results (on the basis of similarity) to the real production platform.

Different types of currents can be used for CECT: constant in magnitude (CC), constant in sign (DC), alternating (AC) and pulsed (PC). They are characterized by different functional capabilities and their separate action on the LMS provides different changes in the quality characteristics of the casting [17]. Therefore, an innovative method of simultaneous melt treatment with currents of different amplitude and frequency characteristics, called multivariate, has been proposed. In this case, we have the opportunity to significantly extend the functionality of CECT to influence the quality of the casting in a polivariate manner, depending on the structure of the system “types of currents-electrode systems” [22].

It has been experimentally established that in the case of CECT LMS, its response shows signs of self-organization with a synergistic effect. In other words, the whole is greater than the sum of its parts. In order to achieve this, it is necessary to select LMS loading modes that lead to the generation of significantly non-linear, heterogeneous physical fields in the object to be treated. Their effect leads to active amplification of energy fluctuations in certain zones of the LMS. These effects determine the formation of three states: bistable, easily excited and self-oscillating. Thus, dissipative structures are formed in an open thermodynamic LMS. Their energy effect enhances the direct electromagnetic influence on the energy bonds at the cluster, atomic and electronic levels, which are electromagnetic in nature. Thus, the energy bonds of the LMS elements are reformatted, changing their activation capabilities [22—24]. As a result, the crystallization ability of LMS changes.

THE PARADIGM OF A SIMPLIFIED SYSTEM FOR END-TO-END QUALITY CONTROL OF CASTINGS USING THE CONDUCTIVE CURRENT MELT TREATMENT METHOD

Consider the quality cycle in the chain of the “design — production — consumption” system in a simplified form, guided by the accumulated scientific experience described in part above. In this case, the principles of quality management can be considered in two aspects. On the one hand, there are the organizational measures that ensure the production of high-quality castings at the design, production and consumption stages; on the other hand, there are the technical measures that, with the aid of special equipment, automatically carry out on-line control tasks according to a given algorithm, either without the intervention of an operator or with the intervention of an operator.

At the design stage, the purpose of which is to organize the conditions for effective quality ma-

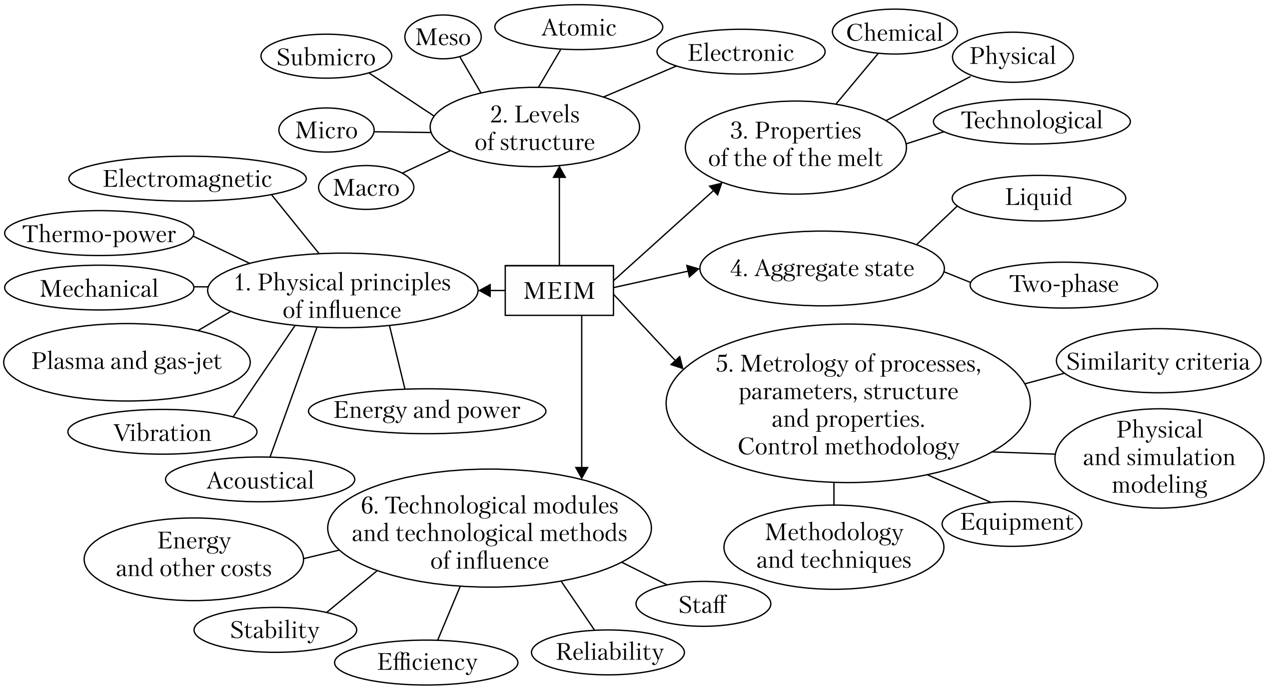

Fig. 1. Generalized system of features for selecting the method of energy impact on liquid and two-phase states

nagement, it is logical to propose a system of relevant conditions and factors for analyzing the potential functionality and intended consequences of using the melt energy treatment method (Fig. 1). Such a system allows finding rational practical solutions in order to design a suitable technological module and technological regulations. It also determines the conditions and factors for the production of high-quality castings. The principles of simulation and physical modeling of processes, influence parameters, structural and phase transformations, etc. play a role at this stage. With their help, the conditions and characteristics of reliable, stable and efficient operation of the process module are determined.

In the case of CECT, the scientific advances made possible by research allow us to choose the type of current for single treatment and the types of current and electrode system for the multivariate CECT method. Of course, this involves selecting the appropriate current sources, which do not need to be designed, as a wide range of currents have been developed for different electrical technologies.

In the design phase it is also necessary to determine the electrical energy dose (w) introduced into the melt. In the case of the multivariate CECT method, the value w is the sum of the current characteristics.

For simulation modeling methods, the analytical and computational method, the finite element method, and the method of dividing massive conductors into elementary cells (circle-field problem) are used [18—20, 25]. It should be noted that it is the latter that allows for a rapid analysis of the characteristics of the basic electromagnetic field using a simple calculation procedure. Its methodology and some results are described in [25]. Here are the data obtained by dividing massive conductors into elementary cells (Fig. 2). They show that the zones of fluctuation activation are concentrated near the electrodes.

Figure 2 shows that the multivariate CECT method is more effective than the single current method in generating more active fluctuations in certain LMS zones.

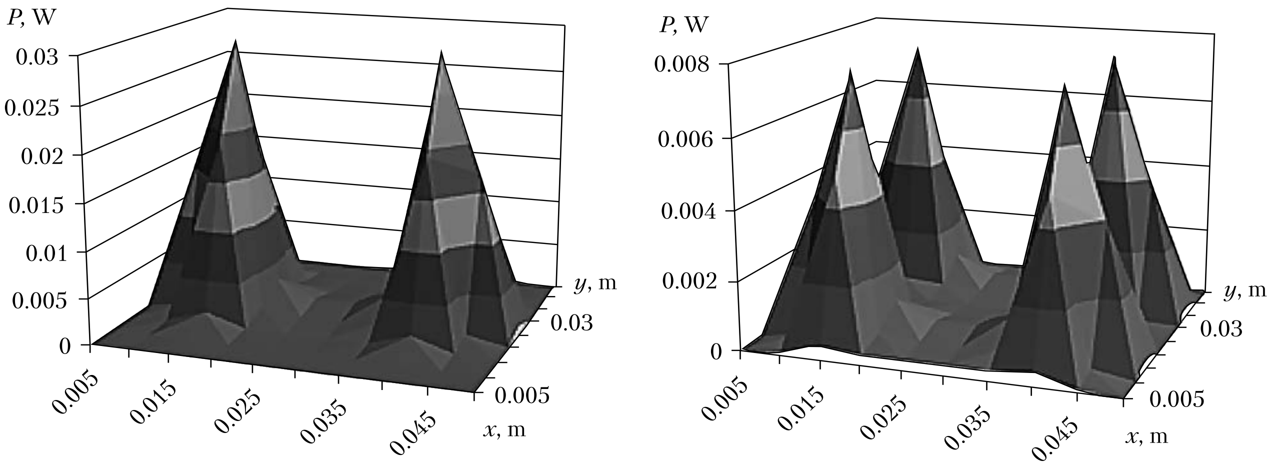

Fig. 2. Electrical power at the electrode feed level for single and dual current processing of an aluminum alloy melt: *a* — two electrode system, 100 A DC; *b* — four electrode system, 50 A DC on each pair of electrodes

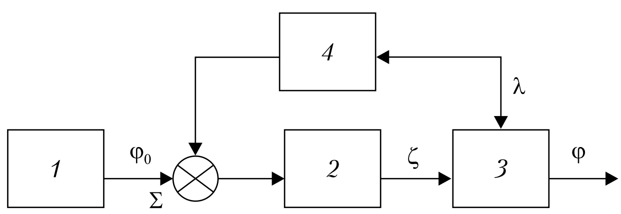

Fig. 3. General functional diagram of the deviation control system: *1* — program setter; *2* — control device; *3* — object of influence; *4* — measuring device; φ_0 — functioning algorithm; ξ — control influence; λ — disturbing action; φ — output element; Σ — totalizer

It is also necessary to use field testing methods at the design stage. Their results allow us to verify the simulation data and prove the defect-free nature of the resulting product — the casting.

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Taking into account the multifactoriality, the multifunctionality of the production itself and the multifunctional characteristics of the LMS, the control problem should be reduced to the problem of regulation. The reason for this is that, to solve the on-line control problem, it is problematic (so far) to use real-time optimization procedures, without which control by automated systems is impossible. On the contrary, the problem of regulation is solved as a problem of stability and quality (intensity) of processes occurring in the system “object — regulator” [26].

Depending on the task, one of its basic principles can be used: open-loop control, disturbance control and deviation control.

In solving the control problem, it is necessary to maintain a stable value of the energy input to the melt w. It has been experimentally proven that it is of the order of 10^8 J/m^3 for Al-based alloys [19, 21]. The value of the coefficient is determined by the alloy grade, for which, in accordance with the value of the crystallization energy, it ranges from 3 to 8.6 [27]. Simple formulas were obtained to calculate the dependence of w on the current parameters. For PC:

$$w = \frac{CU_0^2}{2} \cdot k \cdot f \cdot t \cdot \frac{1}{V}, \qquad (1)$$

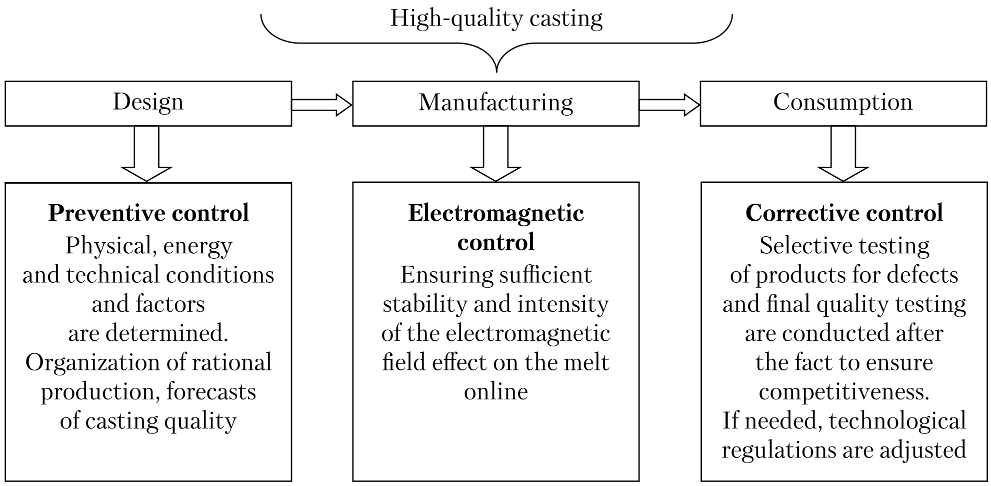

Fig. 4. Cognitive map of the end-to-end quality management based on the abstract PQM system platform

where C is the capacitance of the capacitor bank, F; U_0 is the voltage across the capacitor covers, V; k is the coefficient that takes into account the energy conversion in the discharge circuit; f is the pulse repetition rate, Hz; t is the processing time, s; V is the volume of the LMS, m^3.

For DC, AC and CC:

$$w = \frac{U_e I_e t}{V}, \qquad (2)$$

where U_e, I_e are the voltage and current at the electrodes, respectively, V, A.

$$\xi = f\ (\Delta\varphi, \frac{d\varphi}{dt}, \int_0^t \Delta\varphi\, dt).$$

Therefore, the process of regulating stable excitation of LMS through an electromagnetic field at CECT is solely determined by the parameters of the current source in a specific electrode system. The processing time, t, is determined by formulas (1) and (2). This method can be referred to as electromagnetic control. In principle, it enables the organization of a favourable thermodynamic state in the LMS. This improves its ability to crystallize efficiently during casting, resulting in high-quality castings.

During the third stage of production, the manufacturer selectively tests the quality characteristics of the finished casting for defects. This approach, however, only allows for post-factum detection and rejection of low-quality castings. The final testing of the product's quality determines its competitiveness.

This integrates the paradigm of a simplified end-to-end quality management system for a technical innovation in foundry production. The basic data about the system selected for analysis is connected by a causal network of conditions, processes and factors in a cognitive map (Fig. 4). The intensity of the system is determined by the information component and the optimal ways of information exchange, which are demonstrated through their synthesis in the system under study.

The analysis of the peculiarities of quality management in technological applications and the characteristics of Conductive Electric Current Treatment (CECT) has revealed that the global end-to-end quality management system lacks sufficient scientific advancements for effective implementation in foundry production.

In response, this study has proposed employing a single subsystem of the global end-to-end system — the Quality Management System (QMS) — which is characterized as an abstract system. The QMS has been shown to possess substantial informational intensity, enabling both the prediction of quality improvement effects and the regulation of electromagnetic excitation processes during CECT. The abstract framework of the "design-manufacture-consumption" (DMC) system provides flexibility, facilitating alternative solutions for achieving casting quality.

Further research is required to examine the conditions for quality management in foundry production by integrating abstract subsystems, including the "quality-cost-competitiveness" (QCC), DMC, and "control-system-information" (CSI) frameworks. Additionally, it is essential to advance the circular field method of simulation modeling for processes in the liquid metal system (LMS) under CECT. This modeling will enable the rapid analysis of conditions and factors that contribute to the formation of an integral extremum of electromagnetic excitation in LMS elements.

Finally, the third fundamental principle — control by deviation (Fig. 3) — is recommended for implementation. This principle eliminates the need to measure disturbing influences, instead allowing corrections to the control algorithm based on the physical coordinates within the system.

Measuring device 4 (see Fig. 3) supplies a signal proportional to the deviation ($\Delta\varphi = \varphi_0 - \varphi$) to the input of control device 2. The adder Σ performs the function ($\varphi_0 - \varphi$).

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ПАРАДИГМА ПОБУДОВИ СПРОЩЕНОЇ СИСТЕМИ НАСКРІЗНОГО КЕРУВАННЯ ЯКІСТЮ ДЛЯ ТЕХНІЧНОЇ НОВАЦІЇ У ЛИВАРНОМУ ВИРОБНИЦТВІ

Вступ. Для переведення технічної новації до інновації потрібно визначити стратегію керування якістю продукції, яка підсилить її комерційну здатність.

Проблематика. У ливарному виробництві проблематика отримання литва високої якості вирішується у межах наскрізної матеріальної системи тріади «шихта — розплав — виливок». Її конкретика не дозволяє приймати нетривіальні рішення.

Мета. Визначити умови концептуального підходу щодо побудови спрощеної системи наскрізного керування якістю виливка при застосуванні новаційного методу кондукційної електрострумової обробки розплаву.

Матеріали й методи. Використано попередньо напрацьовані авторами матеріали та дані низки наукових публікації. Для подальшої обробки цих результатів застосовано абстрактні методи системного аналізу та імітаційного моделювання, а також принципи керування якістю в системі «об'єкт — регулятор».

Результати. Запропоновано спрощений варіант парадигми наскрізного керування якістю на базі абстрактної системи «проєктування – виробництво – споживання». На її першій стадії закладаються основи організації якісного виробництва за допомогою методів імітаційного моделювання та натурних експериментів, які попередньо тестують бездефектність виливка. На другій стадії запропоновано замість принципу «керування в режимі online» використовувати принцип електромагнітного регулювання параметрів інтенсивності обробки. Він вирішує завдання стабілізації процесів, що відбуваються в системі «об'єкт — регулятор». Для цього визначено відповідні алгоритми. На третій стадії характеристики якості готового виливка вибірково тестуються на бездефектність, а кінцеве тестування якості виробу підтверджується його конкурентоздатністю.

Висновки. Виконане дослідження показало, що спрощена система наскрізного керування якістю виливка може визначити ключові умови та фактори, які можливо побудувати з достатньою інтенсивністю на базі абстрактної системи «проєктування — виробництво — споживання».

Ключові слова: новація, інновація, ливарне виробництво, якість, системний аналіз, абстрактні системи, керування, регулювання, електричний струм.