DOI https://doi.org/10.15407/csc.2021.04.062
UDC 681.3:621.74:004.8

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COMPUTER SYSTEMS FOR MONITORING OF THERMAL PROCESSES IN FOUNDRY PRODUCTION

The computer system for monitoring of thermal processes which take place at foundry plants is described. Thermal processes are considered in detail as the main processes that occur in the process of casting. Two ways of metal quality control by the method of lost pattern casting thermal analysis are depicted.

Keywords: *thermal processes, computer technology, quality control, computer monitoring, cast iron casting, optimization, metal saving.*

Introduction

Introduction of a computer system for remote monitoring of parameters of technological processes, means of processing and transfer of informative data characterizing quality of performance of technological processes of casting will allow to manage foundry production efficiently taking into account minimization of expenses and increase of quality of castings.

One way to increase the efficiency of the processes that take place in the production of castings is to model these processes in order to delegate the solution of a number of necessary tasks for a founder to the computer. The development of a user-friendly computer technology would provide a founder with a convenient tool to support his decisions in the casting process.

The main methods of assessing the quality of the casting in the foundry are thermal and chemical analysis, testing to determine the speed and modes of cooling of the casting. Thermal analysis (TA) is the most well-known one among these methods. It has been used for a long time. At the same time it is the most developed method both theoretically and experimentally.

The pace and level of development of domestic foundry technologies without the use of computer technologies, which, on the basis of a database of materials, metals and alloys in accordance with the State Standards DSTU, methods for improving

TA using methods of adaptive filtering, an inductive approach and other latest developments in applied mathematics, would allow foundry workers to model and regulate thermal and other processes in order to optimize the physical and mechanical properties of casting and increase of production productivity remain without adequate competitiveness, given the presence of numerous considered foreign software products that are difficult to use in Ukraine, but contribute to the irrevocable trend of digitalization of foreign production.

The TA, as well as the technology of modelling thermal processes in the field of casting is considered in more detail below.

The Leading Role of Thermal Processes in the Mould Manufacturing

The development of high-tech foundry processes, taking into account the current trend of metal saving, should be combined with solving the problem of quality control of castings at the modern level of industry digitalization. One of such control methods is thermal analysis (TA), supported by software and used, in particular, by Fassmet (www.fassmet.com, Italy) [1], the Institute of Physics and Technology of the National Academy of Sciences of Ukraine [2–6], and other companies for quality control of metals in the foundry and metallurgical industry at the stages from metal smelting, pouring it into casting moulds to crystallization of the casting. TA technologies give a possibility not only to determine the composition of chemical elements in the melt, but also with a high probability to predict the properties of the metal in the casting at the stage when the metal is still in the furnace or in the foundry ladle.

Thermal analysis is a set of methods for determining temperatures during the time when the processes accompanied by either the release of heat (for example, crystallization), or its absorption (melting, thermal dissociation, etc.) occur. TA systems of metals and alloys require a mathematical description of control and measurement processes, the creation of computer databases and software to analyse a significant amount of temperature dependences on the composition or properties of the controlled metal samples. TA systems are components of the digitalization of existing or new control methods using applied mathematics for existing foundry processes. They also require the development of certain programs for measuring and monitoring data over time, characterizing these foundry and metallurgical processes.

Quality Control of Cast Iron

The developments described below were carried out on the example of quality control of nodular graphite cast iron (NGCI) [5], as one of the most promising cast alloys. The studies were carried out on the topic of combining the use of high-duty cast iron with precise casting methods in moulds made of loose sand. They are produced by vacuum moulding according to Lost Foam Casting (LFC) Process, but they are also applicable for casting in traditional sand moulds, where over 75% of the world's casting volume is produced.

Computer-recorded temperature measurement curves over time during crystallization of a measuring amount of metal are used in the TA method to determine alloying and impurity elements and gases in metals, including sampling. The samples are made with thermocouples placed in them. When the samples are cooled, the “temperature-time” curves are recorded for further analysis [2]. The examples are described for the analysis of an aluminium alloy in a crucible without specifying information on the further use of the alloy after analysing its constituents. Such an alloy can be directed to the manufacture of a pig furnace charge for deoxidizing steel or for casting billets. The practical implementation of the method includes pouring a molten metal into samplers, keeping them heated when the metal solidifies in them when the curves are recording, as well as utilizing samples and associated waste. These operations are connected with some labour intensity in the category of hot and unsafe working conditions, time and material costs, as well as compliance with the safety of working with a molten metal.

One of the latest developments is the TA method for liquid iron. This method includes obtaining a thermal cooling curve for a sample of cast iron to

Fig. 1. Filling and cooling of samples at TA [1]

be analyzed and cooling curves for reference metal samples with the predetermined properties [4]. One of the distinctive features of the method is that the samples are taken using an immersion sample cup in order to carry out the analysis. The peculiarities of such specially made samplers, without which analysis is impossible, is that they are made of high-quality refractory materials that are resistant to immersion into the metal melt or its pouring with the metal melt without destroying the samplers and inert to interact with the sample.

Samplers are used by analogy with calorimeters and must be manufactured with high accuracy to ensure the same cooling conditions for a metal sample during TA and many reference samples, which affects the accuracy of TA. Immersion of disposable ceramic or sand samplers in liquid metal, or pouring it into the samplers, often require them to be preheated and stored in a moisture-safe environment in order to avoid the release of gases upon contact with the molten metal. Manufacturing and preparation of samplers for filling with metal, filling them with molten metal, carrying out measurements require labour costs when working with molten metal. The safety measures to avoid unforeseen cases of leakage or splash of molten metal from the samplers as well as burns and injuries of a qualified caster when manually filling samplers should be provided. Even the illustration of the TA presented on the Fassmet website shows spilled metal around the samples (Fig. 1).

The use of a metal insulated sampler when it is immersed in a cast iron melt when taking a sample to determine the hardness of cast iron according to Brinell (HB), as indicated in the example of the method [4], requires special alloys (of sufficient heat resistance) for its manufacture, application and renewal of refractory thermal insulation over the entire surface where it contacted with the melt. In this case, the material of the casting mould, where the metal is poured after analysis, differs significantly from the material of such a sampler, as well as the conditions for cooling the samples from the conditions for the metal of the casting. In particular, it is recommended to correlate the average hardness of cast iron (HB) by the State Standard GOST 1412-85 for samples obtained in a metal sampler with the HB of castings in a metal mould. But according to statistics, the vast majority of castings from metals and alloys are obtained in sand moulds, therefore, according to the State Standard GOST 24648-90, it is recommended to cast samples for mechanical tests of cast iron into moulds made of quartz sand, and only for castings obtained in metal moulds, it is allowed to cast samples into metal moulds.

A New Way for a Thermal Analysis of Metal

The known methods of TA of metal [2, 4] have practically nothing to do with the crystallization conditions of the resulting casting from the metal being analyzed, but only identify the properties of the metal in the sample in the trier, with often completely different crystallization conditions of the metal than in the casting. The validity of the State Standard GOST 24648-90 regulation is obvious, that samples, in particular for cast iron, should be cast in the same mould in which the casting is obtained.

The development of a new TA method pursued the goal of using improved software, reducing labour intensity, increasing the accuracy and speed of issuing results (express level) and safety, as well as creating conditions for TA metals undergoing modifying or alloying processing in a casting mould when it is poured with metal in the process of cas-tings manufacturing.

The solution to this problem was carried out by developing the TA method, including the operations of sampling liquid metal. However, the sampling was carried out by replacing the model of the sample made of the gasified material with liquid metal [5]. This model was moulded into the same sand filler of which the mould was made for obtaining a casting made of the analyzed metal, and the sample model was moulded into the same sand mould with the casting model or into different flask fixtures. In addition, the replacement of the sample model with liquid metal (pouring along with its simultaneous gasification), moulded into the same flask fixture with the mould for obtaining the casting, as usual, was carried out simultaneously with the pouring of the mould for obtaining the casting. The sampling was carried out by flowing it to the casting or its gating. Also, the sand filler, where the sample model is moulded, can be vacuumized during sampling and TA of the metal.

The novelty of the solution was that the sand mould played the role of the sampler. The model of the sample was moulded into this sand mould using the LFC technology, in particular, of the gasi-fied material Cellular Polystyrene (CP). This sand mould can be made separately (in a separate flask), or (the most advisable option) together (in one flask) with a sand mould for producing a casting, for which the metal was smelted and TA was carried out. The flask equipment can be frame flasks, a container, a mould jacket, where a sand mould is made.

A sand mould-sampler made in a separate flask served the same task, which is achieved by the known methods of TA of metal for various purposes [2, 4]. And when forming a one-time sample model in the same flask with a sand mould for obtaining a casting, the sampler is not a separate object from this mould, because only a small part of the mould around the sample model performs its function. In this case, the thermocouple is placed not in the cavity of the sampler (as in [2, 4]), but in the body of a one-time model made of CP (with a density of up to 25 kg/m3) or of other gas-filled polymers using the LFC technology.

At the same time, the greatest profitability in reducing labour intensity, increasing the expressiveness and safety of TA of metals is achieved when combining the LFC technology with in-mould modification, in particular, NGCI, as an effective combination of an accurate casting method with the production of castings of high-strength alloys using high-tech methods. For the LFC process, it is advantageous to use deaerated sand moulds, where sampling minimizes metal bursts due to excessive formation of gases from gasification of the model, since gases are sucked through the sand filler of the deaerated mould. The use of a sand mixture without a binder, traditional for LFC, as one of the most resource-saving foundry process for the manufacture of samplers, excludes special labour costs and expensive materials (usually imported), which are typical for the manufacture of sand samplers by the well-known methods of TA of metals, including those based on iron, with their high temperature in the liquid state (1400-1700° C).

In the manufacture of a one-time model of a sample made of CP, a thermocouple was placed in a mould, where CP granules were blown in. They were sintered using the technology known for LFC. A model of a sample with a thermocouple built into it was obtained. Unlike ceramic or metal samplers, metal is poured not into their cavity filled with air, but into a cavity "packed" into air-filled CP balls, which make up the sample model. The convex cylinder of the sample model is much easier to manufacture than the refractory, low-gas-generating sample container for casting the sample. In addition, the model of the sample is also easy to make by cutting out of block CP, in particular, manually, on a lathe or using a tool with a heated wire for cutting CP.

During the development of the technology, the model was made with a small feeder, which was glued to the model of the casting made of CP or to the model of its gating-feeding system in the case of making the casting using the LFC process. The casting model with the sample model was moulded in a container mould in dry recycled quartz sand according to known operations for LFC. The free ends of the thermocouple were lengthened using, if necessary, compensating wires extending beyond the mould. They were connected to recording devices and they received TA data according to a calculation technique similar to known methods.

Computer Monitoring Systems for Foundry Processes

In modern conditions, a tendency towards to mounting a device for TA as a part of modern computer systems for monitoring casting processes is developing. For example, the software at Fassmet [1] allows foundry workers to view TA results online on tablets, smartphones or PCs at the foundry's premises, including providing guidelines for managing the quality of metal production process in real time. The web interface can be configured to control the quality of a specific type of cast iron produced. It is linked to a large, constantly updated database. The TA method gives an advantage in the case of fulfilling diverse orders, frequent changes in production, or the need to obtain a completely new type of cast iron [1].

The developed method of sampling by metal casting with help of the LFC technology gives a possibility to reduce labour intensity, because the sampler was made according to the model of a sample made of CP without separate operations in one process of moulding the casting model as a flow to the casting wall or a part of its gating system, a riser or a feeding increase [5]. If it was necessary to easily separate the sample from the casting, this lug had a feeder with a pinch groove, along which the sample was separated, for example, for additional mechanical tests. Usually, it was practiced to pour the sample into the gating system with disposal for re-melting together with it.

Filling with metal with spontaneous sampling in one mould with casting according to one model of the CP, or through a model cluster, took place without labour and time waste (increasing the express level). There were no pouring operations traditional for the known methods (as in Fig. 1), the content of a sampler filled with a melt on a corresponding refractory and metal leak-proof support until the sample solidifies. The TA processes took place spontaneously in the same mould with the casting without the need to comply with the safety rules inherent in a separate pouring from the sampler ladle or filling it by immersion in the melt. At the same time, there is no oxidation of the metal of the sample in air when the sample is in a deaerated mould with a reducing atmosphere in its cavity, due to the gasification of the CP. And the conditions for solidification of the sample were similar to those for a casting in the same sand mould. The constancy of filling the volume of the sampler (obtaining an accurate sample) [5] is facilitated by the vacuum of the mould, increasing the filling of the mould with the metal due to the effect of vacuum suction of the metal.

The developed TA method [5] solves the problem of control under in-mould modification of metal and moulding of models of samples of CP practically in any casting places required for control, for example, in the form of tides between the reaction chamber and the casting, in the zone of the riser or bottom. The novelty of the solution includes the possibility of forming more than one sample model and taking a number of samples in one pouring operation together with obtaining a casting in one mould. This is applicable for researching or improving the modification process. By means of several samples, it is possible to simultaneously control the level of metal properties in different walls of castings with large dimensions or differential walls. It is not difficult to form a sample model with a simple design when joining to gating systems or walls of a commodity casting model for all types of sand moulds. A model made of polystyrene with a specified density is about 300 times lighter than, for example, liquid iron, which easily replaces it when pouring into a sand mould.

Forming the sample model in various fixtures with the shape of a commodity casting is recommended for preliminary analysis of the metal with the possibility of correcting its composition before pouring the mould to obtain a casting. The TA variants developed by us provide its flexibility, expanding the possibilities of its use in comparison with the known methods for the operational forecasting of technological and performance attributes of metal (chemical composition, structure, casting, physical-mechanical and other properties) in the production of castings for various purposes.

Optimization of Cast Structures and Shaping Technologies

An important cycle of research at the Institute of Physics and Mathematics of the National Academy of Sciences of Ukraine is devoted to the optimization of cast structures and shaping technologies in order to reduce their weight and casting from high-strength metals. The use of the developed method of TA [5] with many samples, together with a multichannel computer analysis system, makes it possible to investigate crystallization, mechanical and other performance attributes of a casting at any point where a sample model is installed and liquid metal is taken.

Analysis and comparison of TA indicators on different walls of the casting is proposed as a mechanism of practical optimization according to the criterion of dependence of steel intensity and strength of castings in order to select the optimal options for their design, to optimize their wall thicknesses according to TA data. This gives a possibility to adapt computer methods for determining and forecasting the performance attributes of cast parts, to create on this basis digital twins of castings, as well as databases for automated systems for designing castings, taking into account the technical and economic indicators of a new class of cast structures of low steel intensity.

When improving the sampling method for the LFC process, a version of it with a portable sampler was also created [6]. It was tested in a laboratory version using a household vacuum cleaner. A sand sampler mould was put on the nozzle of a dust suction metal tube of it (of adjustable length) instead of a brush with a hole. This mould, depending on the size of the sample, was moulded according to the LFC process in a metal glass (container) with a capacity of 0,5–0,7 litres.

A hole was made in the lower part of the side wall or the bottom of the glass. A sucker for a nozzle was welded to the glass coaxially for attaching a vacuum cleaner tube to the nozzle. From the inside of the glass, this hole was closed with a gas-permeable filter that did not allow sand to pass through. This glass looked like a miniature copy of a container flask for deaerated moulds of known designs. During moulding, a layer of moulding sand was poured into the bottom of the glass, a model of a sample made of CP with a built-in thermocouple was placed, the free ends of which were lengthened by known methods with a thermoelectrode or compensation cable extending outside the glass along or inside the vacuum cleaner tube towards a portable device recording temperature readings. Then the mixture was poured to the top of the glass and sealed along its end with a synthetic film with contact to the end of the model. The sampler was moulded, making the solidification conditions for the sample in it as close as possible to those for a commodity casting (composition of the sand mixture, the degree of its compaction, etc.). The glass was painted with refractory paint from outside.

Before sampling, a vacuum cleaner with a glass on a tube was turned on. The rarefaction “turned” the sampler into a typical deaerated sand mould, which was dipped to a depth of 5 mm into the metal melt in a furnace or ladle with its end covered with a film. At the same time, it was enough to touch the mirror of the metal for a few seconds, which gasified the film, the model, filled and sealed the deaerated sandy cavity of the sampler mould. The sample was cast using the vacuum suction method. The sampler was installed on a stand and pumping was turned off, providing cooling of the sample in a sand mixture with control and recording of the temperature of the sample metal during the TA process. The cooled sample poured out of the glass along with sand, as in the most common version of the LFC process.

In this method of sampling [6], it is recommended to use an alarm in the form of a light bulb or a sound signal, which turn on when a signal from a thermocouple is received, as confirmation of the filling of the sampler to stop its contact with the metal. It is convenient when the regulator of the degree of rarefaction is on the tube with the sampler in a place for holding it in the hands.

Such a vacuum suction sampler is convenient not only for TA, but also when it has a long tube it is good for sampling from large furnaces and mixers, even with metal at the bottom. In foundries, vacuum pumps create a rarefaction several times higher than household vacuum cleaners. Accordingly, for a portable vacuumized mould, it is possible to use thinner tubes than for vacuum cleaners, and the long tubes will be lighter in weight. If the sand is fine, the sand end of the portable sampler may not be sealed. A sample can be obtained spherical, cylindrical, in the form of a flat plate; it can be in the form of a comb, followed by breaking off its fine teeth for chemical analysis instead of the frequently used shavings. The method of manufacturing an evacuated glass is almost the same as the manufacture of a ladle for scooping up metal and is painted on the outside with a similar paint; it is also possible to make such a glass from graphite or corundum crucibles or fireclay parts of a furnace supply.

In addition, we have developed a technology for forming a sample [6] using conical glasses with a capacity of 30 and 80 ml, which are mass produced from polystyrene as disposable tableware. In this case, the weight of cast iron samples was about 200 and 550 g. When moulding in a container for a model made of CP, in order to avoid bending of the walls, a wooden template (or made of CP) with a slot for a thermocouple opposite the slot in the cup is inserted into the cavity of the cup. The template is removed before contacting the sampler with liquid metal. In this case, moulding into small plastic disposable dishes was obtained practically a portable small vacuum-film mould-sampler (by V-process) for moulding by vacuum suction. The film of the crockery covered the sandy mould.

In the process of developing the described TA methods [5, 6], the most common foreign programs were also considered, which can be suitable as software for the adequate identification of temperature curves of TA, measured over time, with the corresponding properties, chemical composition, or structure of a cast controlled metal sample. Foreign programs are created for foreign standards of raw materials and grades of casting alloys, types and characteristics of casting equipment and technical specifications for products. Their use implies not only the need for language translation, but also the search for domestic analogues of material and technical conditions with certain errors and tolerances.

All foreign software is not cheap, it is updated and monitored via the Internet, it constantly requires servicing in rapidly changing software environment. Domestic enterprises have difficulties finding sufficient funds for that purpose. In addition, technical and commercial data protection must be applied. The absence of mathematical models of the dependence of the cooling rate of a cast sample on the modes of its cooling in a casting mould causes the low ability of computer processing of TA data. These circumstances complicate the control of the cooling process and the determination of its optimal modes. They do not allow online forecasting of structure formation and performance attributes of castings.

In particular domestic software products with almost instantaneous presentation of the results of TA on the monitor screen, and even more are necessary for automation, digitalization and manufacturing application of control systems of TA, which are being actively improved by domestic engineering science. There is a need to create a scientific and technological school for the creation and continuous filling with new content and capabilities of such software tools as an integral element of the digitalization of foundry and metallurgical production.

The results of the inspection of quality control systems for metal products using the TA method showed that the solution of key problems of improving the quality of foundry production is impossible without the creation of automated software tools for control and support of this production by information technology specialists. At the same time, the software of such effective control systems as TA must be equipped with a software and information data set specific for it, with means for absorbing noise and reducing the influence of the human factor on the accuracy of measurements of thermo-chemical processes. The method of recognition of cooling curves of a casting used in TA by comparing the coefficients of models approximating these curves (differential TA method) has low recognition accuracy for determining the chemical composition of a metal melt in a furnace or an alloy of an unknown casting.

The development of domestic foundry computer technologies based on a database of materials, metals and alloys in accordance with the State Standard GOST, methods for improving TA methods by using adaptive filtering methods, an inductive approach and other latest developments in applied mathematics, would allow foundry workers to model and regulate thermal and other processes in order to optimize physical and mechanical properties of casting and to increase production productivity. A large number of modern foreign software products that are difficult to use in Ukraine contributes to the digitalization trends of foreign production.

Review of TA Monitoring Software

Scientific progress in the field of foundry production takes place due to the widespread use of computers and special software.

To date, many different software products have been developed in order to solve the problems of different stages of the casting process. Let's briefly consider some of them.

MAGMA5 software, developed by the specialists in the field of metal casting by MAGMA GmbH (Aachen, Germany) [7]. To date, this software is considered one of the best in the industry. This product is used by more than eight hundred companies in the world.

NovaCast has developed a unique, highly efficient technology for the production of cast iron with vermicular graphite based on careful metallurgical preparation of base cast iron. In the process of adjusting the composition to control the thermodynamic properties of the metal an advanced system of thermal analysis is used.

ATAS® software system is designed to control metallurgical processes in the production of castings from gray cast iron and high-strength cast iron. ATAS is a comprehensive system that includes equipment, software, and user training and support provided by a team of skilled metallurgists.

The technology, called PrimeQuality CGI (PQ-CGI® is a technology for producing castings from high-quality compacted graphite cast iron [8]. It allows suppressing the formation of platelet graphite and provides the balance of oxides in the metal necessary to create optimal conditions for the formation of vermicular graphite inclusions.

A more detailed overview of the existing software for processing thermal processes with a comparative table of existing tools is given in [9].

This review shows that foreign software tools such as Magmasoft, CastCAE, JSCast, AnyCasting do not have a database of metals and alloys used in domestic production, they require modern computer equipment, appropriate operating system, constant updating of functional modules and most importantly, they are designed to work on large-scale production and can not be used on small plants.

Therefore, a new technology was developed [10]. It includes a domestic database of metals and alloys and solves the problems the founder faces during the manufacture of castings. These problems include determining the chemical composition of the unknown casting, obtaining recommendations for choosing the optimal cooling mode for the given structure of a future product.

A Computer Technology for Modeling Thermal Processes

Founders, especially in industries with frequent readjustment of the product range, in their activities meet the need to perform complex scientific and technical calculations related to solving problems of modelling and optimization of metallurgical processes in order to make effective decisions to achieve the desired result.

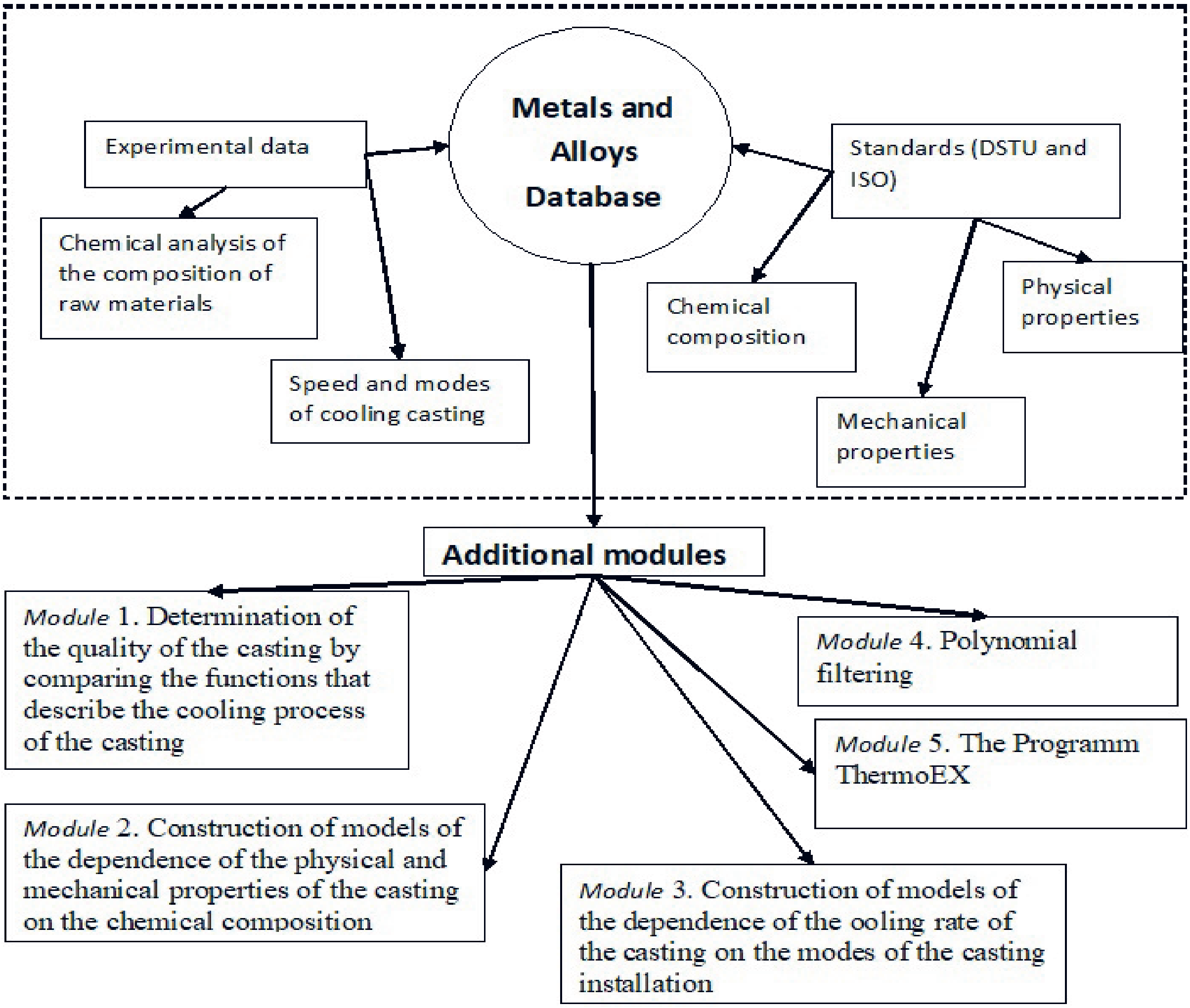

Fig. 2. Block diagram of computer technology for modelling thermal processes of foundry production

Under such conditions, it is important for the company to develop a software product that will contain a database of metals and alloys, their chemical and mechanical properties in accordance with the State Standard DSTU, as well as to process express test results, analyze and select the necessary components to obtain a quality end product, to adjust an operational mode of the foundry. A plant, provided with a modern software product that accompanies the casting process, has the opportunity to increase the scientific, technical and production capabilities of the enterprise, to increase its efficiency.

A new technology was developed in order to automate some stages of the casting process, help professionals to simplify this process and replace expensive experiments with their modeling, as well as to assess the impact of various factors on the casting during cooling.This technology aims to support founder's solutions in the casting process.

Software requirements include a set of requirements for the properties, quality, and functions of software to be developed or under development. Requirements are defined in the requirements analysis process and recorded in the requirements specification, diagrams and other artifacts of the requirements analysis and development process.

The developed technology is designed to solve practical problems of modelling thermal processes in the field of foundry production. The toolkit should have an architecture that provides for the expansion of its functionality by introducing new modules and updating existing ones with new information. The technology includes a domestic database of metals and alloys and 3 functional modules that interact with each other during operation. The software is easy to use, has a fairly clear interface, focused on domestic small-scale production and meets its requirements.

Fig. 2 shows a diagram and a detailed description of the modules of this technology [11].

Fig. 2 shows a scheme of the software equipped with the following functional modules:

Module 1 is designed to compare the functions that describe the cooling process of the casting; a model is built and used; it allows selecting quickly and accurately from the database of reference functions exactly the one that is closest to the experimental.

Module 2 is designed to determine the physical and mechanical properties of the casting by chemical composition; the developed models help to determine the physical and mechanical properties of the casting by chemical composition.

Module 3 is designed to determine the cooling modes; the developed models allow selecting the required cooling modes to obtain the desired structure of the future product.

The software is supplemented with functional modules: filtering of the recorded temperature curves of cooling of casting (Module 4 - Polynomial Filtering) and the ThermoEX module (Module 5) is intended for visualization of the recorded cooling curve and definition of characteristic points on it; the module Polynomial Filtering is meant to filter it from noise present in experimental data.

Fig. 3. shows a window with the interface of the implemented technology, which includes the ThermoEX submodule [12], which allows to visualize the obtained cooling curve.

After being processed, the curves are compared with the reference curves, which are stored in the

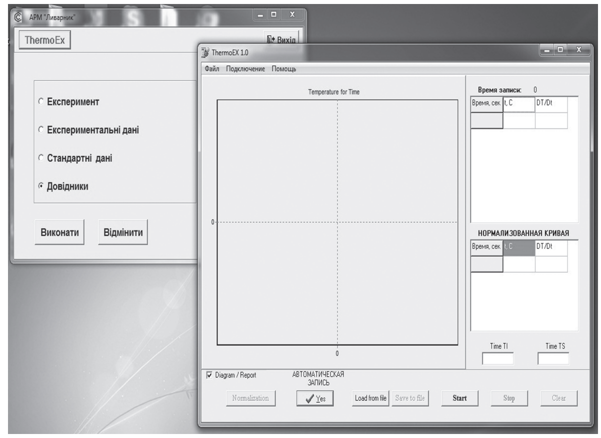

Fig. 3. ThermoEX Module Startup Window

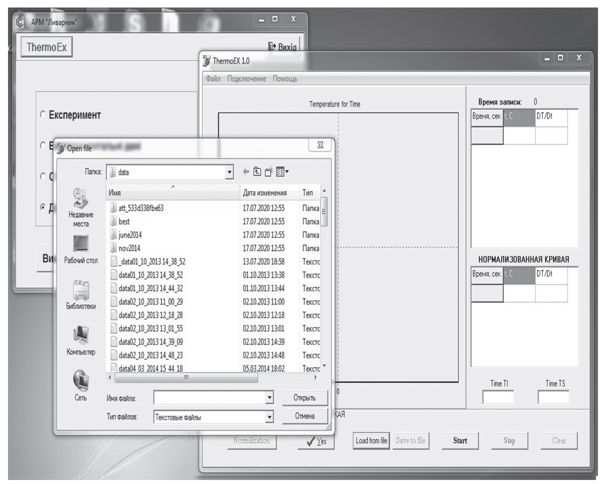

Fig. 4. Example of ThermoEX access to the experimental database

database of experimental data and their chemical composition and physical and mechanical properties are determined. All data can be saved to the database of experimental data.

When the Load from file function is selected, the module addresses the database of experimental data that have just been recorded and written to the appropriate .txt file for further processing.

Fig.4 shows how the ThermoEX program operates.

The technology allows controlling the cooling process of the casting, which can simplify the work of founders and avoid defective products

The developed computer technology for solving the problems of modelling the cooling processes of metal foundry products allows increasing the efficiency of support of founder's solutions in the process of making castings due to the developed models.

The developed technology consists of a domestic database of metals and alloys and solves the problems which founders face during the manufacture of castings: determining the chemical composition of the unknown casting, obtaining recommendations for choosing the optimal cooling mode of the casting to obtain a given structure of the future product.

The developed computer technology meets the needs of domestic production and solves a number of problems that arise during the manufacture of castings.

Conclusions

The article describes the characteristics of TA and thermal processes. Methods of quality control of cast iron are depicted. Methods of thermal analysis of metal, as well as methods of optimization of cast structures are listed. A brief overview of software for monitoring thermal processes is given. The block diagram of computer technology intended for modeling of thermal processes, the description of problems which it solves, and also its short description is given.

REFERENCES

1. Chemical analysis versus thermal analysis of Cast Iron. Global Casting Magazine, 2016. Vol. 6 (3), pp. 54. [online] Available at: <http://content.yudu.com/web/y5b2/0A1snzj/GlobCastingVol6
No3/flash/resources/index.htm> [Accessed 06 Dec. 2020].
2. A.s. USSR №1636766, IPC G01N 33/20. Method of determination of alloying impurity elements and gases in alloys / N.A. Abramov, B.A. Greshishchev, V.A. Dinershtein, S.A. Kozlov, M.D. Molchanov, A.A. Smulsky, Publ. 1991. Bull. 11 (In Ukrainian).
3. *Zakharchenko, E.V., Zhukov, L.D., Sirenko, E.A., Bogdan, A.V., Goncharov, A.L., Kravchenko, E.V.*, 2015. "Improvement of the universal method of thermal express analysis of liquid cast irons, based on the recognition of the shape of the cooling curves". Casting processes, 2, pp. 3–9 (In Russian).
4. Patent Of Ukraine № 99968, IPC G01N 33/20, G01N 25/04. Method of thermal analysis of liquid cast iron / *E.V. Zakharchenko, K.A. Sirenko, A.L. Goncharov, A.V. Bogdan.*, Publ. 2015, bul. 12. (In Ukrainian).
5. Patent 112646 Ukraine, IPC G01N 33/20. Method of thermal analysis of metal and alloy / V.S. Doroshenko, O.V. Tokova, Publ. 2016, Bull. 24. (In Ukrainian).
6. Patent 131912 Ukraine, IPC G01N 33/20, G01N 25/04. Express method of thermal analysis or (and) sampling of metal or alloy / V.S. Doroshenko, V.O. Shinsky, O.V. Tokova. Publ. 2019, Bull. 3. (In Ukrainian).
7. MAGMASOFT autonomous engineering. [online]. Available at: <http://www.magmasoft.com> [Accessed 18 Jan. 2016].
8. NovaCast Technologies AB. [online]. Available at: <http://www.ruscastings.ru/work/168/
2130/2984/2988> [Accessed 27 Feb. 2019].
9. *Tokova, O.V.*, 2017. "An overview of methods and tools for computer modeling of foundry production processes". Inductive modeling of complex systems. Collected research papers, Issue 9, Kyiv: IRTC ITS NASU, pp. 204–213 (In Ukrainian).
10. *Tokova, O.V.*, 2018. "The Task of the Computer Technology Construction for Thermal Processes Modeling of Foundry Production". Upravlausie sistemy i masiny, 4, pp. 84–95 (In Ukrainian).
11. *Tokova O., Savchenko Ye., Stepashko V.* Construction of a computer technology for information support of decisions in the foundry production process. Cybernetics and Computer Engineering. 2019, 4, pp. 41–55.
12. *Varava I.V.,* 2016. "Information technologies of control of a complex scientific experiment in a multiphase environment: Abstract of Ph.D. dissertation: 05.13.06, Kyiv, 2016. 22 p. (In Ukrainian).

Received 13.01.2021

ЛІТЕРАТУРА

1. Chemical analysis versus thermal analysis of Cast Iron. Global Casting Magazine. 2016. Vol. 6, № 3. pp. 54. URL: http://content.yudu.com/web/y5b2/0A1snzj/GlobCastingVol6No3/flash/
resources/index.htm (дата звернення 06.21.2020).
2. А. с. СССР №1636766, МПК G01N 33/20. Способ определения легирующих примесных элементов и газов в сплавах / Н. А. Абрамов, Б. А. Грешищев, В. А. Динерштейн, С. А. Козлов, М. Д. Молчанов, А. А. Смульский. Опубл. 1991. Бюл. №11.

3. *Захарченко Э.В., Жуков Л.Д., Сиренко Е.А., Богдан А.В., Гончаров А.Л., Кравченко Е.В.* Усовершенствование универсального метода термического экспресс-анализа жидких чугунов, основанного на распознании формы кривых охлаждения. *Процессы лиття*. 2015. №2. С. 3–9.
4. Пат. Украины № 99968, МПК G01N 33/20, G01N 25/04. Способ термического анализа жидкого чугуна / *Е. В. Захарченко, К. А. Сиренко, А. Л. Гончаров, А. В. Богдан*. Опубл. 2015, бюл. № 12.
5. Патент 112646 Україна, МПК G01N 33/20. Спосіб термічного аналізу металу та сплаву / *В.С. Дорошенко, О.В. Токова*. Опубл. 2016, Бюл. №24.
6. Патент 131912 Україна, МПК G01N 33/20, G01N 25/04. Експрес-метод термоаналізу або (та) відбору проб металу чи сплаву / В.С. Дорошенко, В. О. Шинський, О.В. Токова. Опубл. 2019, Бюл. № 3.
7. MAGMASOFT autonomous engineering. URL: http://www.magmasoft.com. (дата звернення: 18.01.2016).
8. NovaCast Technologies AB URL: http://www.ruscastings.ru/work/168/2130/2984/2988 (дата звернення: 27.02.2019).
9. *Токова О.В.* Огляд методів та засобів комп'ютерного моделювання процесів ливарного виробництва. Індуктивне моделювання складних систем. Зб. наук. праць. К.: МННЦ ІТСНАНУ, вип.9. 2017. С. 204–213.
10. *Токова О.В.* Задача розроблення комп'ютерної технології моделювання термічних процесів ливарного виробництва. *Управляющие системы и машины*. 2018. № 4. С. 84–95.
11. *Tokova O., Savchenko Ye., Stepashko V.* Construction of a computer technology for information support of decisions in the foundry production process. *Cybernetics and Computer Engineering.* 2019. № 4. P. 41–55.
12. *Варава І.А.* Інформаційні технології управління складним науковим експериментом в багатофазному середовищі: автореф. канд. Тех. наук: 05.13.06, Київ, 2016. 22 с.

Надійшла 13.01.2021

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КОМПЮТЕРНІ СИСТЕМИ МОНІТОРІНГУ ТЕРМІЧНІХ ПРОЦЕСІВ ЛИВАРНОГО ВИРОБНИЦТВА

Вступ. Розробку високотехнологічних процесів ливарного виробництва з урахуванням нинішньої тенденції заощадження металу необхідно поєднувати з вирішенням питання контролю якості виливків на сучасному рівні цифровізації промисловості. Одним з таких методів контролю є метод термічного аналізу (ТА). Термічні процеси є найважливішими при взаємодії рідкого металу або сплаву з ливарною формою. Технології ТА дозволяють не тільки визначати склад хімічних елементів в розплаві, але й з високою ймовірністю прогнозувати властивості металу в литві на етапі, коли метал перебуває ще в печі або в ковші. Для полегшення роботи ливарника в процесі виготовлення виливка виникає потреба в моделюванні термічних процесів, що відбуваються. Це може бути досягнуто розробленням програмного засобу, який дозволить забезпечити ефективний супровід технологічного процесу виготовлення ливарної продукції та коригувати за потреби прийняття доцільних рішень на різних етапах процесу лиття.

Метою статті є дослідження методів термічного аналізу в галузі ливарного виробництва та розробка програмного забезпечення для підтримки рішень з метою моделювання термічних процесів.

Методи. Методи термічного аналізу та методи моделювання термічних процесів.

Результати. Наведено опис комп'ютерної системи моніторингу термічних процесів, які відбуваються на ливарних виробництвах. Детально розглянуто термічні процеси як основні процеси, що відбуваються в процесі виготовлення виливків. Описано два способи контролю якості металу методом термічного аналізу для моделей, що газифікуються. Наведено способи термічного аналізу металу, а також способи оптимізації литих конструкцій. Дається короткий огляд програмного забезпечення для моніторингу термічних процесів. Наведено блок-схему комп'ютерної технології, призначеної для моделювання термічних процесів, опис завдань, які вона вирішує, а також короткий опис блок-схеми.

Висновки. Здійснено дослідження підвищення якості металу із застосування методів термічного аналізу, запропоновано способи контролю якості металу методом ТА, засновані на синтезі його з елементами технології лиття проб вакуумним всмоктуванням, для моделей, що газифікуються. Розроблено програмне забезпечення для підтримки рішень ливарника, що дозволить автоматизувати окремі етапи процесу виготовлення виливка.

Ключові слова: *цифровізація, інжиніринг, адитивне виробництво, лиття металу, цифровий двійник, ливарні технології, виливок, 3D-друк.*