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O. V. Tokova[1], V. S. Doroshenko[2], O. B. Yanchenko[3]

COMPUTER SYSTEMS OF THERMAL ANALYSIS FOR MONITORING OF FOUNDRY AND METALLURGICAL PROCESSES

[1]International Research and Training Center for Information Technologies and Systems of the NAS and MES of Ukraine, Kyiv

[2]Physical-technological Institute of Metals and Alloys of the National Academy of Science of Ukraine, Kyiv

[3]Vinnytsia National Technical University, Vinnytsia

Анотація. Описано комп'ютерну систему моніторингу теплових процесів, що відбуваються на ливарних та металургійних заводах. Теплові процеси детально розглядаються як основні процеси, що відбуваються в процесі лиття. Розглянуто два способи контролю якості металу методом термічного аналізу лиття за втраченою піномоделлю. У статті описані характеристики термоаналіза та теплових процесів. Зображено методи контролю якості чавуну шляхом заливання проби рідким металом і виконання комп'ютерного термоаналізу. Перераховано методи термічного аналізу металу, а також методи оптимізації литих конструкцій на основі результатів комп'ютерного порівняння даних від термоаналізу різних частин чи стінок виливка, в яких визначено механічні чи експлуатаційні характеристики металу в цих частинах чи стінках виливка як даних для оптимізації литої конструкції за цими даними. Дано короткий огляд програмного забезпечення для моніторингу теплових процесів. Подано структурну схему обчислювальної техніки, призначеної для моделювання теплових процесів, опис проблем, які вона вирішує, а також її короткий опис. Розроблено програмне забезпечення для підтримки рішень ливарного цеху, яке дозволить автоматизувати окремі етапи процесу лиття, підвищити якість металевих виробів. Це можна розглядати як перші кроки до створення систем штучного інтелекту для управління ливарними та металургійними процесами з точки зору якості металу, оптимізації шихтування і технології його виплавки, оптимізації конструкції виливків на основі даних термічного аналізу, отриманих з багатьох точок виливків. Одночасно цифрові записи, нарощування бази даних від термоаналізу і комп'ютерний аналіз цієї бази, як елемент цифровізації ливарно-металургійної технології, дає можливість коригувати технологію по ходу виплавки он-лайн, що підвищує продуктивність виробництва і якість металопродукції.
Ключові слова: теплові процеси, комп'ютерна техніка, контроль якості, комп'ютерний моніторинг, чавунне лиття, оптимізація, економія металу.
Abstract. A computer system for monitoring thermal processes occurring in foundries and metallurgical plants is described. Thermal processes are considered in detail as the main processes occurring in the casting process. Two methods of metal quality control by the method of thermal analysis of casting on the lost foam model are considered. The article describes the characteristics of thermal analysis and thermal processes. Methods of quality control of cast iron by filling the sample with liquid metal and performing computer thermal analysis are presented. Methods of thermal analysis of metal, as well as methods of optimization of cast structures based on the results of computer comparison of data from thermal analysis of different parts or walls of the casting, which determines the mechanical or operational characteristics of metal in these parts or walls of the casting as data for optimizing cast structures data. A brief overview of software for monitoring thermal processes is given. The block diagram of the computer equipment intended for modeling of thermal processes, the description of problems which it solves, and also its short description is given. Software has been developed to support the decisions of the foundry, which will automate certain stages of the casting process, improve the quality of metal products. This can be seen as the first steps towards creating artificial intelligence systems to control foundry and metallurgical processes in terms of metal quality, optimization of charge and smelting technology, optimization of casting design based on thermal analysis data obtained from many casting points. Simultaneously, digital records, building a database of thermal analysis and computer analysis of this database, as an element of digitization of foundry and metallurgical technology, allows you to adjust the technology in the course of online smelting, which increases productivity and quality of metal products.
Key words: thermal processes, computer technology, quality control, computer monitoring, cast iron casting, optimization, metal saving.
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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 and metallurgical production efficiently taking into account minimization of expenses and increase of quality of metal castings. One way to increase the efficiency of the processes that take place in the production of metal 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 and metallurgical technologies with the use of computer technologies 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. These technologies 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.

Actuality

The leading role of thermal processes in the production of foundry and metallurgical products is highlighted. The development of high-tech foundry processes, taking into account the current trend of saving metals should be combined with solving the problem of quality control of castings at the current level of digitalization of the industry. One such control method is thermal analysis (TA), which is supported by software. Thermal analysis is used, in particular, Fassmet (www.fassmet.com, Italy) [1], Institute of Physics and Technology of Metals and Alloys (PTIMA). NAS of Ukraine [2-6] and other enterprises for quality control of metals in the foundry and metallurgical industry at the stages from smelting metal, bottling it into molds to crystallization of the casting. There is a growing need for digitization and improvement of powerful domestic thermal analysis software.

The purpose of research

The aim of the article is to study the methods of thermal analysis in the field of foundry and metallurgical production and to develop software to support solutions for modeling thermal processes. Ensure that TA technologies provide a reliable opportunity not only to determine the composition of chemical elements in the melt, but also to predict the properties of the metal in the casting at a stage when the metal is still in the furnace or in the ladle. Optimization and simplification of TA as a set of methods for determining temperatures during the time when the processes are accompanied by either the release of heat (eg, crystallization), or its absorption (melting, thermal dissociation, etc.).

Research objectives

1. TA systems of metals and alloys require a mathematical description of control and measurement processes, the creation of computer databases and software to analyze a significant number of temperature dependences on the composition or properties of controlled metal samples.
2. Make TA systems components of digitization of existing or new control methods using applied mathematics for existing foundry processes.
3. TA systems also require the development of certain programs for measuring and monitoring data over time.

Quality Control of Cast Iron by thermal analysis

These moulds are produced by a vacuum forming process referred to as Lost Foam Casting (LFC), but they are also applicable to traditional sand moulds, which account for over 75% of the world's castings.

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 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 [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. 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 used container-sampler for immersion in the cast iron melt during sampling is made of special alloys of high heat resistance [4]. 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.

Figure 1 – Filling and cooling of samples at TA [1]

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. The task was to make a sand sampler as a mould for casting iron.

A New Way for a Thermal Analysis of Metal

Metal TA methods [2, 4] reveal the properties of the metal in the sample, the crystallization conditions of which are often not similar to the crystallization conditions of the casting metal in the sand mold. 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.

In addition, the development of a new TA method was aimed at using improved software, reducing labor intensity, increasing the accuracy and speed of issuing results (express level) and safety, as well as creating conditions for conducting TA in the same form that is used to manufacture a casting as a product.

The novelty of the solution was that the sand mould played the role of the sampler [5]. The model of the sample was moulded into this sand mould using the LFC technology, in particular, of the gasified 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.

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). 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.

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 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. 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, 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 [5]. 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). 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. 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. 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.

Molding 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 our research 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 TA method [5] makes it possible to study the crystallization, mechanical and other operational characteristics of the casting at any point of the installation of the sample model and liquid metal. 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.

We also improved the method of sampling with a portable sampler [6] in the form of an evacuated casting mold in a metal cup (container) with a capacity of 0.5–0.7 l. 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 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.

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. 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, as well as methods for improving TA methods using adaptive filtering methods, inductive approach and other developments in applied mathematics will allow foundry workers to achieve increased productivity. Modern foreign software products are difficult to use in Ukraine.

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. 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.

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.

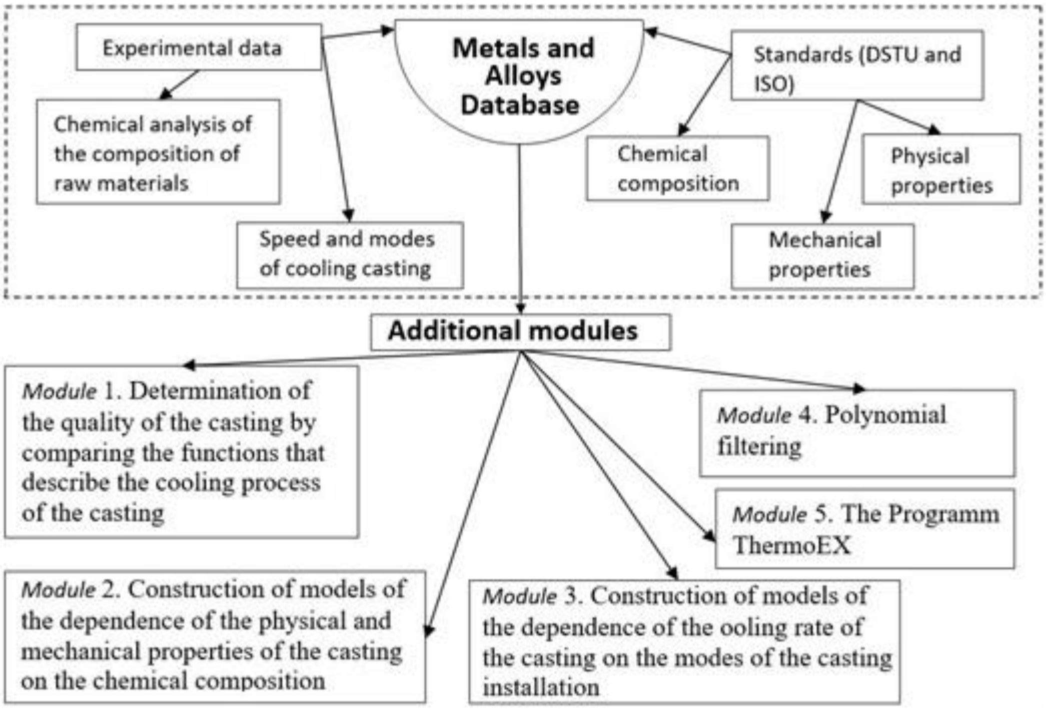

Figure 2 – Block diagram of computer technology for modelling thermal processes of foundry and metallurgical production

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.

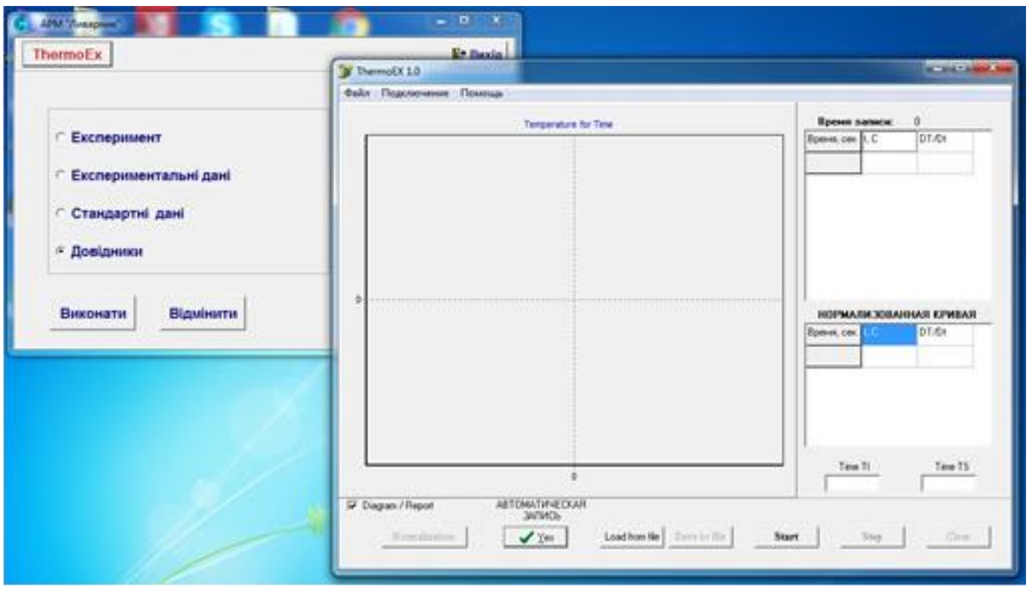

Figure 3 – ThermoEX Module Startup Window

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

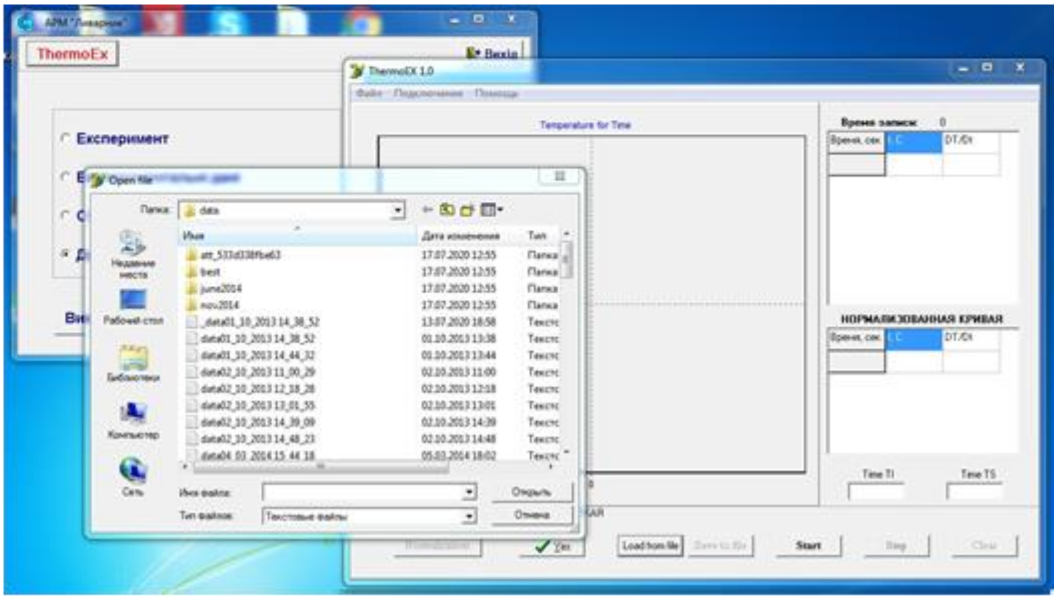

Figure 4 – Example of ThermoEX access to the experimental database

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. Software to support the foundry's solutions, which will automate certain stages of the casting process, improve the quality of metal products, has been developed. It can be considered as the first steps towards the creation of artificial intelligence systems for the management of foundry and metallurgical processes.

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Відомості про авторів

Токова Олена Володимирівна – кандидат технічних наук, молодший науковий співробітник відділу інформаційних технологій індуктивного моделювання.

Дорошенко Володимир Степанович – доктор технічних наук, старший науковий співробітник, провідний науковий співробітник відділу фізико-хімії ливарних процесів.

Янченко Олександр Борисович – кандидат технічних наук, доцент кафедри галузевого машинобудування.

О. В. Токова[1], В. С. Дорошенко[2], О. Б. Янченко[3]

КОМП'ЮТЕРНІ СИСТЕМИ ТЕРМІЧНОГО АНАЛІЗУ ДЛЯ МОНІТОРИНГУ ЛИВАРНИХ ТА МЕТАЛУРГІЙНИХ ПРОЦЕСІВ

[1]Міжнародний науково-навчальний центр інформаційних технологій і систем НАН та МОН України, Київ

[2]Фізико-технологічний інститут металів та сплавів НАН України, Київ

[3]Вінницький національний технічний університет, Вінниця