DOI https://doi.org/10.15407/usim.2020.03.041
УДК 681.3:621.74

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DEVELOPMENT OF A DIGITAL TWIN OF THE TECHNOLOGICAL PROCESS OF CONSUMABLE PATTERN CASTING USING PRODUCTION DATA

The construction of a digital twin of a real physical object is described. It can be a virtual counterpart of a part, product, equipment, technological process, production sites, workshops or even factories. In fact, it is a set of mathematical models describing the state of an object and all its elements. The possibility of constructing a digital twin of an industrial facility is shown using the example of a consumable pattern casting workshop.

Keywords: *digital twin, technological process, casting, modelling and forecasting.*

Introduction

In the continuous blank casting process, the quality of the section is important for the entire metallurgical works. Improving quality without significant material costs is an important part of the production cycle of all metallurgical enterprises.

Casters, especially in industries with frequent readjustments to quickly change the range of listed products, in their activities are faced with the need to perform complex scientific and technical calculations, solving problems of modelling and optimizing metallurgical processes in order to make effective decisions to achieve the desired result.

In such conditions, it is important for the enterprise to develope a software product containing a database of metals and alloys, their chemical and mechanical properties in accordance with national standards. The ability to process the results of express tests, analyze and select the necessary components to obtain a high-quality final product, establish operating mode of the casting plant is also important.

Manufacturing, provided with a modern software product that accompanies the casting process, is able to increase the scientific, technical and production capabilities of the enterprise and, as a result, increase its efficiency. The development of digitalization in the modern world is largely determined by the effective work with rapidly growing large amounts of data.

The construction of a forecasting model as a digital twin [1], which is one of the factors in the digital transformation of enterprises, has become a considerable task. This builds up the nearest future and gives a possibility to increase productivity by analyzing the condition of the equipment using the created digital twin in the software development environment.

In order to build such a digital twin, it is necessary to review the existing software for computer modelling of foundry processes, and then to determine their advantages and disadvantages, assess the possibilities of using such means in domestic production, and also to formulate requirements for suitable for use computer technologies that would be developed according to the requirements of local foundries, and would be aimed at working with the domestic base of metals and alloys.

The Role of Building a Double Twin of a Technological Object

It should be noted that the central place in the economy is rightfully occupied by material production. It is a high-tech industry that meets, first of all, the requirements of high labour productivity, economic efficiency and global competitiveness.

At the same time, digital twins have recently contributed to the rapid development of modern industries, especially considering that the digital twin is a real reflection of all components in the product life cycle using physical data, virtual data and data of the interaction of processes between them. With the help of digital twins, the support of technical and technological systems is simplified, the efficiency of managing the risks of errors and failures increases, and the stability of work increases. The digital twin makes it possible to predict the key parameters of the object using the input data of the equipment.

A digital twin is a virtual reproduction of the operating state of a real physical object, process, system, or entire service. It can be a virtual counterpart of a part, product, equipment, technological process, production sites, workshops or even factories.

In fact, it is a set of mathematical models describing the state of an object and all its elements. In general, the digital twin includes: a geometric model of the object; a set of design data, parts, assemblies and the object as a whole (mathematical models that describe the physical processes taking place in the object under study). It contains information on the technological processes of manufacturing and assembly of individual elements; some data on the tests of the object, for example, the readings of the sensors, by which the design data can be confirmed; product lifecycle management system. Such a control system links all above-listed objects into a single structure. Thus, the digital twin allows in virtual space to simulate the change in the state and characteristics of the entire product when changing the parameters of any of its elements.

A further goal of the authors' developments is to study the existing software for computer modelling of foundry processes, to assess the possibilities of using these tools in domestic production [2]. It is also supposed to formulate requirements for computer technologies that would be developed according to the requirements of domestic foundries, would be aimed at working with a corresponding base of metals and alloys and are suitable for use in production.

The field of application of these studies is continuous production, where the forecast of equipment failure should be available [3]. In the future, it is planned to expand the functionality of the program, develop algorithms for automated prediction of equipment failure. It is also possible to prepare the data more thoroughly for analysis, which will make them more qualitative for creating predictive models.

Development of the Process of Society Informatization

At the beginning of this century, almost all countries are replacing the main information environment. The specific volume of information received by the society through traditional channels (radio, television, mail, communications) is steadily decreasing, and through computer networks – growing. By 2030, the share of information received via computer networks will increase to 0,90 ... ... 0,95 [4].

The global process of informatization of society, which, in turn, is a manifestation of the general pattern of civilization development, initiated the emergence and development of such a scientific discipline as informatics. From a technical discipline on methods and means of data processing using computer technology, informatics is turning into the science of information processes not only in technical systems, but also in nature and society. Among the regularities of scientific and technological progress on the path of the evolutionary development of production technologies, experts in the field of technical sciences and, in particular, foundry production, see the replacement of human functions by machines. Such a human functions as energy, transport, the function of technological change of the processed material, control and measurement and, finally, the most important and complex function – logical function can be replaced based on the use of modern computer technologies [5].

From this point of view, the depth of penetration of informatics tools into the technological processes of industrial enterprises and workshops can be divided into three levels: monitoring, management and automation.

Monitoring (level I), in which in real time the operator on a computer can see and control the numerical values of the parameters of the equipment, individual or all stages of the technological process.

Management (level II), when the information system in the monitoring process compares the specified values of the current parameters with specially created simulation models of production processes [6, 7]. Then the information system recommends the adjustment (adaptation) of production conditions in order to achieve the indicators chosen by the operator (product quality, cost, resource intensity, etc.),

Automation (level III), when the information system not only reads performance indicators from the equipment in the workshop in general, but compares these indicators with optimal indicators and partially corrects them.

It is advisable to build digital twins at production or research foundries with the possibility of their further modernization into automatic control systems, taking into account modern trends with the involvement of digitalization means. In particular, Lean technologies (lean manufacturing) are known. It is a logistics management concept focused on optimizing technological and business processes with maximum market orientation and taking into account the motivation of each employee. Lean technologies rely on a production organization system modelled on the automobile giant Toyota, which is highly regarded for its level of lean manufacturing [8].

Designing Digital Twins in Production

The concept of using digital twins of industrial projects will be considered using the example of a consumable pattern casting (CPC) workshop (gasified casting workshop). The foundry process was considered in the form of five technological streams, namely:

- Production of one-time models;
- Turnover and regeneration of foundry sand;
- Melting and pouring metal into moulds;
- Embossing of castings and their finishing;
- Evacuation of gases by a vacuum pump, their cleaning and sterilization.

At the first stage of designing digital twins for digital processing of these five streams, which make up the production process of the (CPC) workshop as a whole, an almost minimal list of indicators was chosen. Their measurement in real time can create a numerical information basis for entry-level digital twins. The specified technological streams and associated transport streams coincide with the traditional division of the (CPC) workshop into production areas.

The indicators to be processed by digital twins can be divided into the following areas by topic:

- Technological and technical;
- Control of compliance with labour protection standards, production ecology and fire safety;

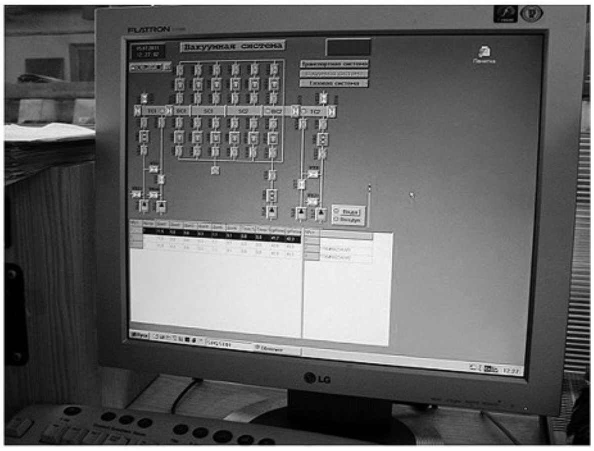

Fig. 1. Visual image of the workshop vacuum system on the operator's computer

- Economic, taking into account the resources used.

Economic analysis includes such data as the production of castings by cost, weight and nomenclature for control or reporting periods of time. An important aspect-oriented direction of the development of the system of digital twins is to provide research on the effect of gas-hydrodynamic and thermophysical processes taking place in a casting mould during metal pouring, solidification and cooling of a casting, on the quality of castings as manufactured products during a long period of time

It should be noted that at the start-up and commissioning stage of digital twins for the moulding and casting line of the foundry, they were considered according to individual physical and technological parameters, in particular, to the vacuum system of the workshop. The display of this system on the operator's monitor is shown in Fig. 1 [9].

The requirements specification for complex software control of the casting processes to one-time models is being considered at the same time with the creation of systems of digital twins for the (CPC) process. This research belongs to the scope of activity of the Physics and Technology Institute of Metals and Alloys of the National Academy of Sciences of Ukraine. Their developments are based on thermophysical, hydrodynamic, regressive mathematical models and are subject to adaptation to automated control systems for technological processes. The previously developed methods for determining and identifying the main parameters of shaping and obtaining castings using one-time models are currently being prepared for adaptation for computer systems of the twin double in order to predict the quality of cast structures. These methods are reflected in physical and mathematical models.

Simulation of Thermodynamik Processes

The analysis of regression and inductive models for casting processes was carried out in [10 –13], where regression analysis was used to build forecasting systems. The analysis of regression and inductive models as applied to foundry processes gives a possibility to determine the relationship between the output variable and a variety of external factors (regressors). Regression coefficients can be determined using least squares or maximum plausibility methods. Linear regression models simplify the design of monitoring systems in comparison with other models, and the availability for analysis of all calculations gives transparency of modelling; disadvantages include low adaptability and lack of ability to model nonlinear processes.

The main disadvantage of nonlinear regression models is the complexity of determining the type of functional dependence, as well as the complexity of determining the parameters of the model.

Turning to mathematical models close to reality at the stages of developing foundry technology or modelling certain physical processes, we should note that inductive modelling is currently associated with the study, description and implementation of cause-and-effect processes of study, pattern recognition and prediction of processes and phenomena, and knowledge processing based on the use of the history and regularities of the corresponding problem area, in our case it is the field of heat transfer of materials of casting processes.

An inductive approach to modelling and forecasting, in particular, for this task, is based on building a model of the transition from individual data to their generalization in the form of appropriate models.

The embodiment of the inductive approach is the Group Method of Data Handling (GMDH) [14].

The models of optimal complexity obtained by this method reproduce the unknown regularity of the functioning of the object (process) under study. Information about this regularity is implicitly contained in the sample of experimental data. The origins of the idea of inductive modelling lie in the problem of synthesis of an optimal nonlinear predictive filter, first formulated by Academician A.N. Kolmogorov.

Later, in [15], a universal predictive filter with self-tuning during operation was proposed. It implements an algorithm for predicting the future value of the stationary time function from its history by finding the optimal coefficients of the extended prediction operator. In our study it is the function of temperature field.

Furthermore, a number of problems of identification, forecasting, pattern recognition and optimal control are associated with the problem of prediction based on a single inductive principle of modelling, that is, to study causes and consequences, namely from particular to general, in order to create and accumulate the necessary knowledge bases.

The considered problems can be solved on the basis of inductive modelling, that is, at the level of teaching a deterministic or probabilistic physical model, or at the level of adaptation of the investigated connections in the studied thermal process.

From the standpoint of the theory of artificial intelligence, this generalization consists in the inductive process of synthesis of a purposeful knowledge base using the laws inherent in the field of heat transfer and knowledge models of the selected class of thermal processes:

$$Z(t)=\alpha_0+\sum_{i-1}^{s}\alpha_i X_i(t)+\sum_{i=1}^{s}\sum_{j=1}^{s}\alpha_{i,j}X_i(t)X_j(t)+$$
$$+\sum_{i=1}^{s}\sum_{j=1}^{s}\sum_{k=1}^{s}\alpha_{i,j,k}X_i(t)X_j(t)X_k(t)+\dots .$$

So, for example, to predict the future value of the stationary function of the temperature of the thermal field using an operator, a knowledge base is built in the form of some polynomial, inductively, with the help of GMDH. This polynomial describes the general functional expression of the history of the temporal function, as a model for representing knowledge about prediction in the thermal process.

Monitoring and inductive modelling of thermodynamic processes taking place in castings during cooling and crystallization provides for the determination of the temperature field and its dynamics. The dynamics of changes in such a field, fixing the regions and lines of maximum and minimum temperature, and building a digital twin will allow choosing the most adequate theoretical models for predicting the casting process and controlling certain parameters in order to achieve certain properties of the casting.

Based on the data that came to the computer, basic calculations are made and a digital twin is built. It gives a possibility to view the parameters of the casting process both for each casting separately and the main parameters for several castings simultaneously. In the future, according to preselected physical and mathematical models and computer programs, a probabilistic forecast of the casting process for each casting can be calculated with saving the data obtained in the corresponding database.

Today, digital twins not only of the technological process are created, but as a virtual model of the entire system (for example, a plant, factory or infrastructure of a district or region). These digital twins collect huge amounts of operational data produced by devices, and create new business opportunities to optimize all processes. Digital twin systems are mostly applied in such fields as energy, especially nuclear, oil, gas and chemical industries, metallurgy, construction materials industry, etc. A significant increase in interest from real foundry and metallurgical production in such systems for enterprises stimulates and accompanies the entry of these systems to a new stage of their development on the theoretical basis of modern applied mathematics.

Thus, the emergence of more convenient and cheap tools for processing and storing large databases in recent years has expanded the possibilities for creating digital twins. Taking into account these possibilities, a review of monitoring problems shows that many industries are collecting data on the productivity and efficiency of work equipment nowadays. Digital transformation could not only fully process the collected information with advanced analytics, but also make valid decisions to optimize operations in various industries. Likewise, new simulation technologies give possibility manufacturers to use digital twins for product manufacturing and in manufacturing processes. New projects can be tested in the virtual world, saving time, money and resources. Building digital twins can enable industries to quickly solve physical problems, identifying them with a much higher degree of accuracy, design and create better products, in particular foundries.

Conclusion

The design of digital twins of foundry technological processes is described. The use of digital twins of various objects and processes will increase productivity by analyzing the state of the equipment according to the created twin.

It also gives a possibility to predict the key parameters of the object using the input data of the equipment. The digital twin is a reflection of all components of the product life cycle using data. Digital twins simplify the support of technical and technological systems. They increase the efficiency of managing the risks of errors and failures, and increase operational stability.

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Received 20.06.2020

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Надійшла 20.06.2020

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РОЗРОБКА ЦИФРОВОГО ДВІЙНИКА ТЕХНОЛОГІЧНОГО ПРОЦЕСУ ЛИТТЯ ЗА МОДЕЛЯМИ, ЩО ГАЗИФІКУЮТЬСЯ З ВИКОРИСТАННЯМ ВИРОБНИЧИХ ДАНИХ

Вступ. Створення інформаційних систем моніторингу ливарно-металургійних процесів є назрілою темою. Розвиток цифровізації в сучасному світі багато в чому обумовлений ефективною роботою зі стрімко зростаючими великими обсягами даних. Побудова моделі прогнозу, як цифрового двійника, з метою підвищення продуктивності за рахунок аналізу стану обладнання за створеним цифровим двійником в середовищі розробки програмного продукту набуває значної ваги. Центральне місце в економіці по праву займає матеріальне виробництво — високотехнологічна промисловість, яка відповідає, в першу чергу, вимогам високої продуктивності праці, економічної ефективності та глобальної конкурентоспроможності. При цьому розробка цифрових двійників сприяє стрімкому розвитку сучасних компаній. За їх використання спрощується підтримка технічних систем, зростає ефективність, керування ризиками помилок та збоїв, а це підвищує стабільність роботи.

Мета роботи. Зпропоновано ідею та досліджено можливість розробки цифрового двійника технологічного процесу на прикладі цеху лиття за моделями, що газифікуються.

Методи. Цифровий двійник дозволяє за вхідними даними обладнання передбачити ключові параметри об'єкта. Цифровий двійник — це віртуальне відтворення робочого стану реального фізичного об'єкта, процесу, системи або цілої служби. Може бути віртуальний двійник деталі, виробу, обладнання, технологічного процесу, виробничих ділянок, цехів або навіть заводів. Фактично, це набір математичних моделей, що описують стан об'єкта та всіх його елементів. У загальному випадку цифровий двійник включає: геометричну модель об'єкта; набір розрахункових даних деталей, вузлів і об'єкта в цілому (математичні моделі, які описують всі фізичні процеси, що відбуваються в об'єкті); інформацію про технологічні процеси виготовлення та збирання окремих елементів; деякі дані про випробування об'єкта, наприклад, показники датчиків, за якими можуть бути підтверджені розрахункові дані.

Результати та висновки. Таким чином, використання цифрового двійника дозволить у віртуальному просторі змоделювати зміну стану та характеристик всього виробу при зміні характеристик будь-якого з його елементів. Розглянуто дослідження з розробки систем комп'ютерного моніторингу параметрів технологічних процесів та станів об'єктів на прикладі цеху лиття за моделями, що газифікуються, а також методи їх раціонального розв'язання на основі сучасної прикладної математики.

Ключові слова: *цифровий двійник, технологічний процес, виливок, моделювання, прогнозування.*

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РАЗРАБОТКА ЦИФРОВОГО ДВОЙНИКА ТЕХНОЛОГИЧЕСКОГО ПРОЦЕССА ЛИТЬЯ ПО ГАЗИФИЦИРУЕМЫМ МОДЕЛЯМ НА ОСНОВЕ ПРОИЗВОДСТВЕННЫХ ДАННЫХ

Введение. Создание информационных систем мониторинга литейно-металлургических процессов является назревшей темой. Развитие цифровизации в современном мире во многом обусловлено эффективной работой со стремительно растущими большими объемами данных. Построение модели предсказания, как цифрового двойника, с целью повышения производительности за счет анализа состояния оборудования по созданному цифровому двойнику в среде разработки программного продукта приобретает значительный вес. Заметим, что центральное место в экономике по праву занимает материальное производство — высокотехнологичная промышленность, которая отвечает, в первую очередь, требованиям высокой производительности труда, экономической эффективности и глобальной конкурентоспособности. При этом цифровые двойники способствуют стремительному развитию современных компаний в последнее время. С помощью них упрощается поддержка технических систем, растет эффективность, управление рисками ошибок и сбоев, повышается стабильность работы.

Цель работы. Предложена идея и исследована возможность построения цифрового двойника процесса на примере построения цифрового двойника цеха литья по газифицируемым моделям.

Методы. Цифровой двойник позволяет по входным данным оборудования предусмотреть ключевые параметры объекта. Цифровой двойник — это виртуальное воспроизведения рабочего состояния реального физического объекта, процесса, системы или целой службы. Это может быть виртуальный двойник детали, изделия, оборудования, технологического процесса, производственных участков, цехов или даже заводов. По сути это набор математических моделей, описывающих состояние объекта и всех его элементов. В общем случае цифровой двойник включает: геометрическую модель объекта; набор расчетных данных деталей, узлов и объекта в целом (математические модели, описывающие все происходящие в объекте физические процессы); информацию о технологических процессах изготовления и сборки отдельных элементов; некоторые данные об испытаниях объекта, например, показания датчиков, по которым могут быть подтверждены расчетные данные.

Результаты и выводы. Таким образом, цифровой двойник позволяет в виртуальном пространстве смоделировать изменение состояния и характеристик всего изделия при изменении характеристик любого из его элементов. Рассмотрены исследования по разработке систем компьютерного мониторинга параметров технологических процессов и состояний объектов на примере цеха литья по газифицируемым моделям, а также методы их рационального решения на теоретической основе современной прикладной математики.

Ключевые слова: *цифровой двойник, технологический процесс, отливок, моделирование, прогнозирование.*