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Methods of Inductive Modelling and Prediction of Complex Casting and Metallurgical Processes

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Abstract **– Creation of information systems for monitoring of casting and metallurgical processes is the urgent topic. This paper considers the technical problems on the development of systems for computer monitoring: both production technique parameters and the object states on the example of the foundry shop for the Lost Foam Casting Process (LFCP). Also, the paper discusses the efficient methods for solving the considered problems on the theoretical basis of modern applied mathematics.**

Keywords **– Foundry processes, group method of data handling, inductive modelling, information systems, monitoring, regression models, sensor networks.**

I. Introduction

At the beginning of the 21st century almost all countries have been experiencing the change of the basic information medium. The specific volumes of information, obtained by society through the traditional channels (radio, television, mail, communication) have been steadily decreasing. On the contrary, the proportion of information obtained through computer networks has been steadily increasing and it is projected to increase to 0.90 ... 0.95 by the year 2030 [1]. Global process of society informatization is the manifestation of the general laws of the civilization development. It initiated the appearance and development of such a branch of science as informatics. The term "informatics" appeared in France in the 60s of the 20th century as a result of the combination of the terms "information" and "automatics". From the technical scientific branch on the methods and means of data processing with the help of computer facilities, informatics has turned into a branch of science about information processes not only in technical systems but also in nature and society.

II. The Analysis of the Latest Investigations

Among the laws of scientific and technical progress, experts in the field of technical sciences and, especially, foundry have noticed that different human functions in the evolutionary development process of production technologies are executed by machines. Thus, it is possibleto replace by machines such human functions as: energy and transport functions, function of technological change of the processed material, control and measuring function, etc. Finally, machines can replace the most important and complex human function, which is the logical function, with the help of advanced computer technologies [2]. From this point of view, the depth of penetration of informatics tools into production techniques of enterprises and shops can be divided into three levels: monitoring, control and automation.

Level I is monitoring, when in real time an operator at the computer (or at other multimedia of information exchange between the computer and the environment) can see and control numerical values of different parameters that need to be taken into account in the production process. Such controlled parameters are: parameters of the equipment operation, parameters of separate or all stages of the technological process, parameters of labour conditions, environmental parameters, energy account parameters, parameters of different consumed resources, parameters of waste removal, etc.

Level II is control, when the information system in the process of monitoring compares the current values of specified parameters with the corresponding parameter values of specially created simulation models of production processes [3], [4] or with the corresponding parameter values of recorded in time the most successful periods of the industrial shop functioning. Then the information system recommends some correction or adaptation of the production conditions to achieve the indicators selected by the operator, such as the product quality, the cost, the resource use, etc. Also, within some limits, the information system can perform the actions, which correct production conditions.

Level III is automation, when first the information system reads the values of operation indicators of the equipment or the whole shop, compares them with the optimal ones and partially corrects them. Here, the information system has the means of the adjustment of indicator values and, depending on changing circumstances, can analyse them and then make decisions. The information system can adjust the production process until the complete exclusion of the human involvement. Also, the information system can accumulate the experience of the production control and ensure its own reliability, i.e., the possibility of adding any device to the network or exclusion of any device from it, as well as the possibility of the information transfer or processing through the neighboring elements in case of breakage of one of the network elements.

It is advisable to carry out the construction of monitoring systems at industrial objects with the possibility of their further modernization into control systems. Modern trends in the production control ideology are the reference points for the formulation of problems to be solved in the future using means of informatization.

According to the technical information review, the most effective method in use of internal resources of the production systems control is the method of Lean Production, or Lean Manufacturing. This is a logistic concept of control that focuses on optimizing the technological and business processes with a maximum market orientation and takes into account the motivation of each employee. The objectives of such production are: minimization of labor expenditures and time of new products creation, a guarantee of delivery to the customer of the products with the highest quality at the lowest cost.

Lean production is based on the production organization system, developed by the Japanese automobile giant “Toyota”, the production system of which is considered to be the primary source and the standard of the lean manufacturing [5].

Let us consider the use of information systems for the industrial object monitoring at the example of the monitoring system organization for the shop for the Lost Foam Casting Process. The main objectives of monitoring are the optimization of the equipment functioning, resource saving and improvement of working conditions, as well as solving problems of quality and competitiveness of produced metal castings.

Recently, problems of monitoring and control with critical conditions for the sensor operation, due to both the high temperature and the excessive concentration of harmful industrial substances in the foundry shop, have been solved using *Wireless Sensor Network (WSN)* and other multimedia and communications capabilities. Sensors connected into a wireless sensor network form a territorially-distributed self-organizing system of collection, processing and transfer of information. The main field of this system application is control and monitoring of the measured parameters of the physical environment and objects for the purpose of resource and process control by the operator.

For the optimal design of the sensor network, for example, for the air pollution control in the shop, it is efficient to apply mathematical models, which allow using the Voronoi’s method. This method of computational geometry is one of the methods for solving the problem of search for the nearest neighbor.

Taking into account the limited effective zone of each sensor, the principle of this method for monitoring can be interpreted as follows: the space control zone of each sensor extends as long as it does not touch the control zone of the neighboring sensor.

Wireless sensor networks are mounted from miniature computing devices, which are called motes. They are equipped with different sensors, for example, the temperature sensors, the pressure sensors, light conditions sensors, the vibration level sensors, the location sensors, etc. Also, they have signal transceivers, operating in a given radio band in the mode of retransmitted short-range radio communication. Wireless networks of smart sensors are distinguished among other wireless and wireline data transfer interfaces due to the flexible architecture and lower costs during installation, especially in the case of a large number of interconnected devices. A permanent reduction in the cost of wireless solutions and improvement of their operational parameters allow gradual replacing of wireline solutions in the systems of telemetry data collection, remote diagnostic systems and information exchange systems. Each node in a sensor network typically includes different sensors for the environment control, a microcomputer and a radio transceiver. Therefore, the device can carry out measurements, independently conduct primary data processing and communicate with external information system.

Recently, instead of using various sensors, controllers with different audio and video systems, for example, Microsoft Kinect, are used. Such controllers, using the software of the computer, connected with them, for example, program libraries Microsoft Kinect for Windows SDK, allow recognizing not only the clear lines, but practically any outlines and movements of objects. Such systems can recognize, for example, the shape of the face or the hand, as well as the body proportions. They can recognize and keep track of people, moving in the field of view of the controller video cameras, using the skeleton part tracking. Such systems allow determining the distances from the sensor to the object using the camera XYZ-depth that gets the access to the flow of colours and the flow of depths. Also, the considered systems can perceive sounds with noise and echo cancellation as well as find the location of the audio source using the beam search. They can recognize speech, as well as complement the real image from the video cameras by explanatory, instructional and warning information [6]. Such systems are able to read the applied code and/or recognize the outlines of tooling, equipment and employees. They can measure parameters, for example, the temperature of the metal by its chromaticity degree using high resolution video cameras, as well as compare the technological process in the shop with its optimal model recorded on the computer, etc.

III. Results and Their Discussion

During the preparation of the requirement specification for the organization of the monitoring system of the shop for the Lost Foam Casting Process on the basis of the wireless sensor network, the production process was presented in the form of five technological flows shown schematically in Fig. 1.

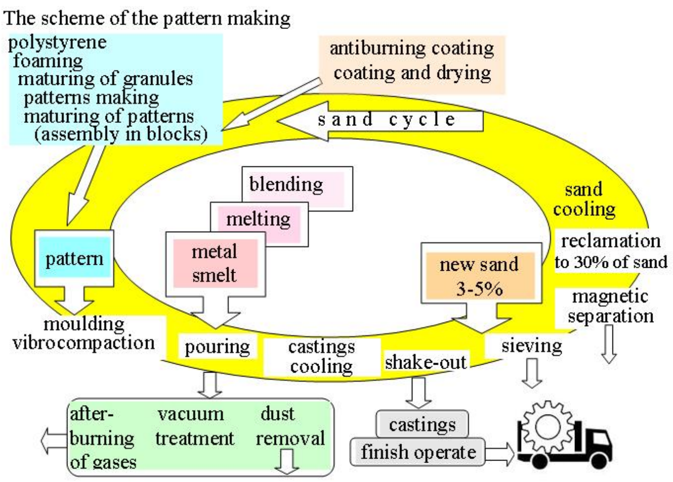

Fig. 1. The scheme of the movement of material and technological flows in the shop for the Lost Foam Casting Process (LFCP shop).

The production of the single-use patterns is shown with the help of the vertical column at the top on the left (Fig. 1). The cycle of the molding sand is shown in Fig. 1 in the form of the ellipse-like ring with the sand counterclockwise motion. Melting and pouring the metal into the moulds are shown in the center of the scheme (Fig. 1). Shakeout of the castings and their finishing treatment are shown at the bottom of Fig. 1. Pumping-out of gases by the vacuum pump, their purification and neutralization are presented at the bottom on the left (Fig. 1).

For the organization of the monitoring of these five flows, which are the components of the whole production process in the LFCP shop, the authors of this paper together with the technological service of the foundry shop chose a minimum set of indicators, the measurement of which in real time could create a numerical information basis of monitoring. At the current technical market there are serially produced sensors to measure all the chosen indicators. The transport and technological flows indicated above practically coincide with the traditional separation of the shop into the production sectors.

An important aspect-oriented direction of monitoring, in view of the perspective of deepening its functionality, is the following. With the help of monitoring, technologists plan to analyse the influence of the processes, taking place in the foundry mould during the metal pouring as well as during solidification and cooling of the casting, onto the quality of castings as products manufactured for a long period of time. Such processes play a key role in forming service properties of the casting. Usually they are called the processes taking place in the system "casting - mould" or "metal - mould". In the case of LFCP, they are called the processes taking place in the system "metal - evaporative casting model - mould", sometimes specifying it as a system with a mobile source of gas formation. For monitoring such a system there is the sufficient number of sensors of different types. Control of such a system on the present level of the technology development can be only open. This is caused by the fact that the results of control, which are usually some indicators of the casting quality, become known only after a considerable time, and that requires an adequate mathematical description of the object [7].

However, it is convenient to carry out monitoring of molding and pouring line of the foundry shop with respect to separate physical and technological parameters, for example, of the shop vacuum system, which can be reflected on the operator's monitor, for instance, as it is shown in Fig. 2.

This important problem of foundry is considered in a number of fundamental works. For example, in the monograph [8] it is noted that the considered processes are hierarchical: the leading subprocess, which is heat-mass exchange, is a generating process for the dependent physical and chemical subprocesses. The last ones, in turn, determine certain states in different elements and allow proposing a new approach to the control objective when synchronization of these states in time becomes the main problem. With this approach, solving separate optimization problems may be unnecessary that significantly reduces both the number of calculations, required for the control, and the number of the technological process parameters subject to monitoring.

Fig. 2. Visualization of monitoring the shop vacuum system on the operator’s computer.

Parallel to the creation of systems for remote computer monitoring casting and metallurgical processes, the theoretical and technological basis is developed for the complex control, as well as for the control of physicochemical and technological processes of obtaining castings and metallurgical products.

Here, the most complicated processes for monitoring are as follows: multifactor processes of obtaining a foundry mould and its interaction with the casting under controlled influence on the characteristics of the latter, as well as the current control of the equipment condition and ecological safety of environment, which accompanies casting and metallurgical processes.

Let us consider the example of the complex control of casting processes with single-use patterns developed at Physico-Technological Institute of Metals and Alloys (Kyiv, Ukraine). Such control should be based on thermophysical, hydrodynamical, regression mathematical models adapted to systems of automated control of technological processes. These analytical models contain a description of the conditions of obtaining casting patterns (polystyrene, low temperature, ice patterns) and foundry moulds (vacuumized, frozen moulds). Also, the models describe the interaction of the liquid, solidifying metal with the mould and pattern; the structure formation and physico-mechanical properties of the castings.

Developed methods for determining and identifying key parameters of forming and obtaining castings with the help of single-use patterns are reflected in the physical and mathematical models. Now these methods are under adaption to computer programs intended for prediction and identification of the quality of cast structures.

Let us present a brief overview of regression and inductive models based on the work [9]. Regression analysis for prediction systems allows determining the dependence between the original variable and the set of external factors, the so-called regressors. The regression coefficients can be found by the least squares method or by the maximum likelihood method.

The simplest regression model is the linear regression one. It is based on the assumption that there is a discrete external factor $X(t)$ affecting the process $Z(t)$ under study, and the relationship between the process and the external factor is linear. The linear regression model is described by the equation $Z(t)=a_0+a_1X(t)+e_t$, where a_0 and a_1 are the regression coefficients; e_t is the model error. To obtain the predicted values $Z(t)$ at the time t, it is necessary to have the value $X(t)$ for the same time t that is rarely feasible in practice.

Now let us consider the multiple regression model. In practice, the number of discrete external factors $X_1(t)$, … , $X_s(t)$ affects the process $Z(t)$. Then the model has the form $Z(t)=a_0+a_1X_1(t)+a_2X_2(t)+...+a_sX_s(t)+e_t$. The model disadvantage is as follows: for calculating the future value of the process $Z(t)$ it is necessary to know the future values of all the factors $X_1(t)$, … , $X_s(t)$ that is almost impossible in practice.

Finally, the nonlinear regression model is based on the fact that there is some known function describing the dependence between the original process $Z(t)$ and the external factor $X(t)$. Here, $Z(t)=F(X(t),A)$, where A is the matrix of the regression coefficients. To build the model, it is necessary to determine the parameters of matrix A. For example, let us assume that $Z(t)=a_1\cos(X(t))+a_0$. Then for the model construction it is sufficient to determine the parameters of $A=[a_1,a_0]$. In practice, the processes, for which the form of the dependence between process $Z(t)$ and factor $X(t)$ is known in advance, are rare. Therefore, the nonlinear regression models are rarely used.

Advantages of the considered models are as follows: simplicity, flexibility and uniformity of their analysis and design. Linear regression models, in comparison with the other models, simplify the design of monitoring systems. Accessibility for the analysis of all the calculations with linear regression models provides "the transparency" of modelling. The disadvantages of these models are low adaptability and the lack of ability for modeling nonlinear processes. The main disadvantage of nonlinear regression models is the complexity of determining both the form of the functional dependence and the parameters of the model.

The method of heuristic self-organization of models, or inductive modelling, was developed by A. Ivakhnenko as a model of the group method of data handling [10]. This method uses principles of the automatic construction of models by the arrays of experimental data as well as the automatic generation of options, partial solutions and successive selection. In the artificial intelligence the latter was called "constructing worlds".

The model of the method is described by the support function of the following form [10]:

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

Using the function (1), it is possible to build the various models for some or all of the arguments. For example, one can construct polynomials in one variable; polynomials with all possible pairs of variables; polynomials with all possible triples of variables, etc. For each model, its linear coefficients $\alpha_{i,j,k,\ldots}$ are determined by the regression analysis method [11]. Among all the models, a few best models are chosen, usually from 2 to 10. Here, the quality of the models is determined with the help of the mean square deviation, or using some other criteria. If among the chosen models there is a model, the quality of which is sufficient for using the obtained predicted values, then the process of the model search is terminated. Otherwise, the selected models are used as arguments $X_1(t)$, … , $X_s(t)$ for the support functions of the next stage of the iteration, i.e., already found models are involved in the forming of more complicated models.

IV. Conclusions

At present, systems of monitoring are commonly used in such areas of economic activity as: power engineering, especially nuclear one; oil and gas industry; chemical industry; metallurgy; construction materials industry and many other fields. A significant increase of interest in such systems at enterprises of the foundry and metallurgy production stimulates a new round of development of these systems on the theoretical basis of modern applied mathematics.

Therefore, this paper has considered a range of issues related to the development of systems for computer monitoring of the production technique parameters and the object states. The authors have presented the example of the organization of the monitoring system, based on the wireless sensor network, for the foundry shop for the Lost Foam Casting Process (LFCP). Also, the efficient methods for solving the considered problems of foundry and metallurgy on the modern applied mathematics basis have been discussed.

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