Integrated Simulation of Process of Steel Casting on the Continuous Steel Casting Unit

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***Abstract*—Studying technological processes on real production equipment is associated with a large costs of resources: financial, time, etc. Therefore, various types of modeling are actively used to analyze and optimize these processes. With the development of digital technologies, it is possible to collect data about the process directly during the production. This data can be used both for direct control of the process, and for building (adjusting) the model of the process, which allows to get a "digital twin" repeating both the main properties of the modeled object and its current state. Many complex manufacturing processes involve a set of different interconnected models. In this case, the "digital twin" should contain information about the object characteristics, individual models of its functioning, the connections between these models, and the current state. These processes include many stages of metallurgical production. The paper considers complex modeling of the casting process in continuous steel casting unit. The set of models includes a model of the thermal state of the ingot during casting, a model of the stress-strain state, a model of the melt hydrodynamics, structural and concentration models of the ingot. Mathematical models of thermal and stress-strain states and the connections between them are presented. Examples of temperature fields and deformations calculation during the process of casting are given.**

Keywords—continuous steel casting unit, integrated simulation, stress-strain state, thermal field

I. Introduction

Research into production processes using mathematical models has long been common. The advantage of this approach is to reduce the cost of field testing. Before introducing technology or launching a new product into production, tests must be carried out which are quite expensive. Some of these tests can be transferred to the virtual domain, which significantly reduces costs. Another benefit is the shortening of the time frame for the introduction of new technologies and the start-up of a new product, because part of the tests using mathematical models can be done much faster.

The use of mathematical models in parallel with simulated processes also predicts changes in situations and make management decisions in advance, such as the maintenance of facilities, which reduces the likelihood of their failure.

The development of digital technology has made it possible to combine real physical processes with virtual ones, resulting in the emergence of cyberphysical systems [2]. Information on the operation of the facility is collected and transmitted in real time to an information medium, in which it is used to refine the model, predict behavior, develop management effects and transmit them to the object. The complex of data and models allows creating 'digital twins' [2] of real objects, reflecting all the main characteristics, properties and functioning of the object. The technology of 'digital twins' is introduced everywhere by the leading industrial enterprises, which undoubtedly places it among the leading strategic technological trends.

II. Digital Twins

The definition of 'digital twins' was first given in the paper [3]. There are different definitions of this concept, so in [4] 'digital twin' is defined as 'real representation of all components in the life cycle of the product using physical data, virtual data and data of interaction between them'. That is, the 'digital twin' is a complex of software products created using different technologies and having a connection to the real object [5]. The presence of the connection by receiving information about the function of the object leads to a constant updating of the 'digital twin' in accordance with the change of the object. In turn, 'digital twins' depending on the type of object are classified as follows [2]:

- product 'digital twin'displays the basic properties of a physical object: manufactured product, process equipment, etc.;
- process'digital twin' imitates various actions, such as technological production processes;
- system 'digital twin' is a set of virtual models, such as the product being produced, the production technology and the means of production.

Thus, the 'digital twin' of the system includes 'digital twins' of the individual components of the system. The composition of the elements of a specific 'digital twin' is determined by the purpose of its creation and the purpose of the planned use. The main purposes of using 'digital twins' are to highlight:

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– monitoring the functioning of a real facility or process. It guarantees the required level of quality;

– carrying different types of tests during the development of a new facility or process;

– modeling and predicting the behavior of the facility, including for early detection of critical defects or failure of the facility or process;

– using and preserving object data in the creation of its modifications;

– real-time process management.

The main components of the‘digital twin’are the following:

– sensors installed on a real site to monitor its behavior;

– means of transmitting information from sensors to an information environment;

– database (repository) with retrospective data from sensors;

– facility parameters: geometric dimensions, production route, operating rules, etc.;

– operating models of facilities or production technologies. They are used to predict the behavior of a facility or process according to its current state;

– management decision-making module based on models, data on the current state of the facility and retrospective data;

– means of transferring and implementing control effects on a real object or process.

III. Integrated Model of Steel Casting in CSCU

Metallurgical production involves many interrelated complex processes, and, therefore, to improve and optimize the technology, a comprehensive analysis of the processes for each of the stages is required. One such process is steel casting in a continuous steel casting unit (CSCU). The nature of cooling has a direct impact on productivity and product quality. The process occurring in the plant comprises the formation of a solid crust in the crystallizer and the subsequent cooling of the ingot in the nozzle area [6].

The installation scheme is shown in Fig.1.

The processes occurring in the ingot during cooling are heterogeneous but interrelated. Therefore, models of each of these processes are required. The first of these processes is the liquid melt flow in the crystallizer [7, 8]. The melt behavior during the casting is described by the Navier-Stokes equation and by heat transfer. In the simulation, the velocities of the metal flow and the temperature fields in the crystallizer are determined. This process influences ingot cooling in the secondary cooling zone by determining the initial state of the metal.

The heat exchange in the ingot and its hardening during cooling in the spray zone by the nozzles is modeled by the differential equation in the partial derivatives (thermal conductivity equation) with the corresponding boundary conditions. The result of the simulation is the field of distribution of the temperatures in the ingot and the zones of different state of the metal, including the thickness of the crust [9-10]. These results are necessary to calculate the stress-strain state in the ingot and the resulting slab structure.

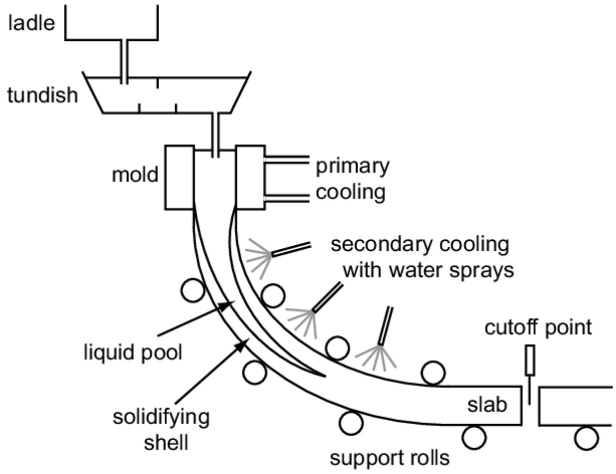

Fig. 1. Scheme of continuous casting steel unit.

Процессы, происходящие в слитке во время охлаждения, разнородны, но взаимосвязаны. Поэтому требуется построение моделей каждого из таких процессов.

During the formation and growth of the crust in the ingot, pressure arises due to temperature changes in the crust and ferrostatic pressure. Differential equations of equilibrium and relationships of stress, deformations and displacements are used for modeling the stress- strain state [11]. The simulation results at this stage are the stress value in the solid part of the ingot, as well as the outer geometry of the ingot. Stress values in turn affect the ingot structure.

Next, it is necessary to model the process of forming the macrostructure of the ingot, which is influenced by the process of ingot cooling, crust formation and tension in the ingot crust [12-14].

Thus, integrated steel casting should use all models presented.

And in case of creating a ‘digital twin’ the process of casting should be supplemented with information about specification of CSCU, technology regimes and their parameters, as well as retrospective information on the performance of CSCU during casting and ingot characteristics. The structure of the ‘digital twin’ steel casting in CSCU is given in Fig. 2.

The ‘digital twin' can be used to investigate casting technology to optimize performance, ingot quality, and predict defects. If casting management as operator decision support system is used, real-time communication of sensors and control mechanisms installed on the site with the information system is necessary. The two models that can be included in the ‘digital twin' of the steel casting process are further discussed in detail.

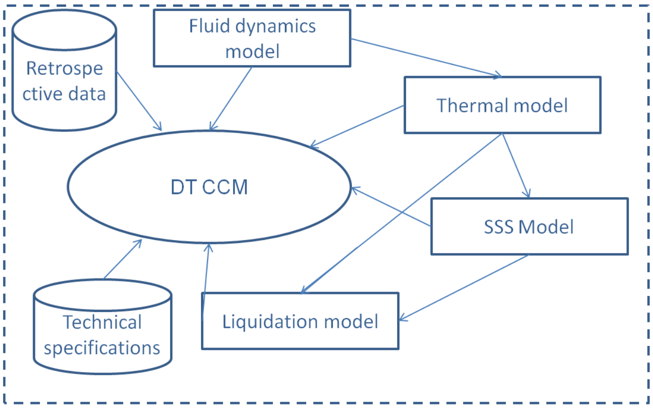

Fig. 2. Complex of CSCU 'digital twin' elements.

IV. THERMAL MODEL

The temperature field of the ingot section, which is assumed to be constant for each fixed moment in time, is considered. The time at which the molten metal enters the crystallizer is taken as the starting point. The ingot is cooled by the heat transfer through its surface. The heat transfer rate is determined by the operation of the cooling system. The process by which the ingot is cooled is described by a differential equation of the parabolic type:

$$c(x)\rho(x)\frac{\partial T}{\partial t}=\frac{\partial T}{\partial x}k(x)\frac{\partial T}{\partial x}+\frac{\partial T}{\partial y}k(y)\frac{\partial T}{\partial y}+f(x,y,t)\,, \quad (1)$$

where

x, y – coordinates in space,
T – temperature distribution vector (unknown),
t – time,
k – thermal conductivity coefficient (W/m·°C),
c – coefficient of heat capacity (Дж/°C),
ρ – surface density (kg/m3).

The coefficients of heat conductivity and the heat capacity of steel vary according to temperature. The relationship between these coefficients for some brand groups is presented in [11].

The initial conditions to be used are the temperature of the steel when it is filled into the crystallizer:

$$T(x,y,t_0)=\varphi(x,y)\,. \quad (2)$$

A second boundary problem with boundary conditions in the form of heat flows is considered:

$$-k\left(\frac{\partial T}{\partial x}l_x+\frac{\partial T}{\partial y}l_y\right)=\alpha(T_f-T)\,, \quad (3)$$

where l_x, l_y – length of the boundary section (m).

The exchange coefficient values to be used shall be determined by the following formulae for different temperature ranges [15]:

$$\alpha=\frac{2}{\sqrt{\pi}}\int_0^{V_s}e^{-t^2}\left(245V_s\left(1-\frac{V_s\Delta T}{58223}\right)+4.3\Delta T^2\left(1-th\left(\frac{\Delta T}{115}\right)\right)\right), \quad (4)$$

and [16]:

$$\alpha=190+$$
$$+tgh\left(\frac{V_s}{8}\right)\left(140V_s\left(1-\frac{V_s\Delta T}{72000}\right)+3.26\Delta T^2\left(1-th\left(\frac{\Delta T}{128}\right)\right)\right), \quad (5)$$

where $V_s=V/S$ – surface water discharge (m/s),
V – static capacity of the nozzle (m^3/s),
S – sprayed surface area (m^2),
ΔT – temperature difference (°C),
α – heat exchange rate (W/(m^2·°C)).

The End Element Method (EEM) was used to solve the End Element Problem. Equation (1) in the EEM context is converted to a discrete form and has the form:

$$[C]\left\{\frac{\partial T}{\partial t}\right\}+[K]\{T\}-\{Q\}=0\,, \quad (6)$$

where $[C]$, $[K]$, $\{Q\}$ – thermal capacity matrix, heat conductivity matrix and heat load vector, accordingly.

At the beginning of the calculation the metal movement time of the installation and the two-dimensional cut of the ingot are discretized. The developed software interface [10] for setting the initial conditions is presented in Fig. 3

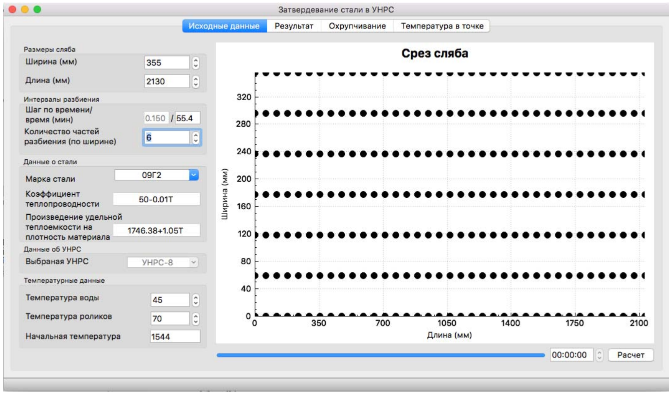

Fig. 3. Input Setting Interface.

The boundary conditions take into account the interaction of the ingot with the crystallizer, rolls and spraying by secondary cooling nozzles. The specific variant of the conditions at each moment of time is determined by the CSCU scheme, the location of the nozzles, and depends on the rate of casting. The result of the program is the value of the temperature field of the ingot cut at any point in the casting time corresponding to a given level of discretization (Fig. 4).

The possibility of predicting the occurrence of defects - cracks is also realized. Forecasting is done by calculating the probability of occurrence of a defect. The probability of cracking is estimated as the ratio of time of the ingot in the extension area (10% of the length of the curved section of the CSCU in the field of expansion) at the temperature of hot embrittlement to the total time of stay of the ingot in the curvilinear region (Fig. 5). The temperatures of the ingot cut make it possible to determine the solid and liquid phase of the metal. This information can be used to calculate the stress-strain state.

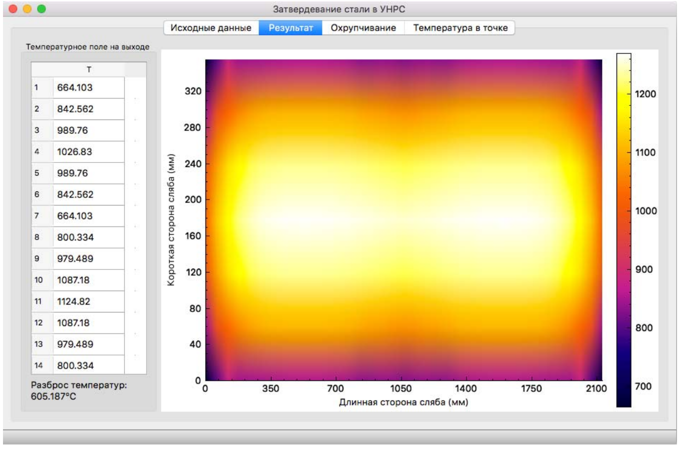

Fig. 4. Temperature field of the ingot cut.

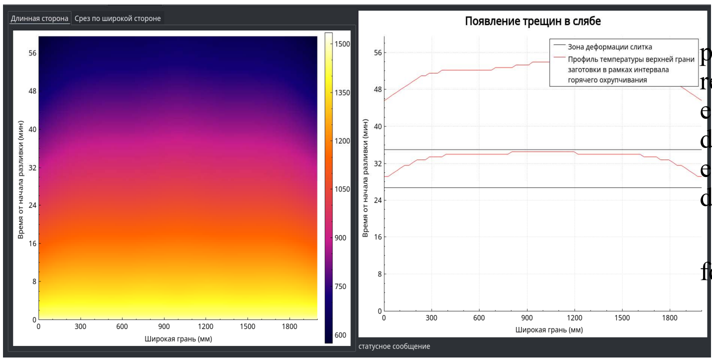

Fig. 5. Prediction of slab cracks.

V. STRESS-DEFORMED STATE(SDS) MODEL

The necessary data for calculation are: the geometric dimensions of the ingot, the temperature distribution by section, the dependence of mechanical properties of steel on temperature, technological parameters of the process.

The calculations are based on the following assumptions:

In the study of slab behaviour in the CSCU, the following assumptions are made:

- only the solid metal phase of the stress-strain state is modeled, and the presence of a liquid melt is taken into account by the action of ferrostatic pressure on the crust of boundary conditions;
- within the solid phase, the metal is treated as a homogeneous isotropic medium;
- the deforming rolls are absolutely rigid;
- residual stresses in the solid phase after compression during transition from one deforming section to another are not taken into account;
- the inside surface temperature of the solid phase is equal to the solids temperature;
- the temperature distribution over the thickness of the hardened melt is linear.

The model is implemented in the ABAQUS software complex [17]. Its components are non-deformable rolls and deformable beams. The calculation is carried out only in the hardened part of the ingot.

The modeled ingot in the secondary cooling zone is shown in Fig. 6.

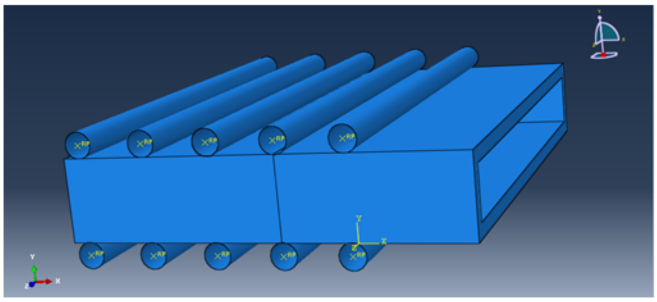

Fig. 6. Ingot in pull- regular rolls.

The calculation of SSS is reduced to solving edge problems for systems of equations, including the relationships of stress and deformation theory (equations of equilibrium, equations of the common, ratios of displacements and deformations), as well as defining equations, i.e. the relationship between stresses and deformations.

The SSS of continuous slab in the CSCU is defined by four components:

- thermal stresses arising from the temperature difference between the outer and inner boundaries of the crust;
- stresses from ferrostatic pressure;
- stresses caused by the deformation of metal by pull-regular rolls;
- tensile and compressing deformations.

A model of elastic deformations is considered. The tension field is described by the equation:

$$\nabla_i \sigma_{ij} = 0\,, \tag{7}$$

the ratios linking the components of the deformation ε_{ii} and the displacement vectors u_i have the form

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right). \tag{8}$$

Закон Гука задает связь напряжений и деформаций

$$\sigma_{ij} = G\varepsilon_{ij}\,. \tag{9}$$

The boundary condition on the internal boundary of the beam is determined by the ferrostatic pressure of the molten metal

$$p = \rho g l\,. \tag{10}$$

Boundary conditions along the external boundary with rigidly fixed rolls

$$u = \hat{u}\,, \tag{11}$$

where $\hat{u}$ – is the displacement vector at the slab- rolls stage, p – ferrostatic pressure, ρ – metal density, g – acceleration of gravity, l – melt column height.

The results of the calculation are Mises tensions, appearing during the steel casting process in CSCU (Fig. 7), and deformations. Fig 8 shows deformations which occur during the steel casting process in CSCU in the direction of ε_{yy}. These results make it possible to investigate the place of occurrence and the values of maximum stresses, dependence of deformations on the thickness of the slab crust, effect of rolls on the deformation value, etc.

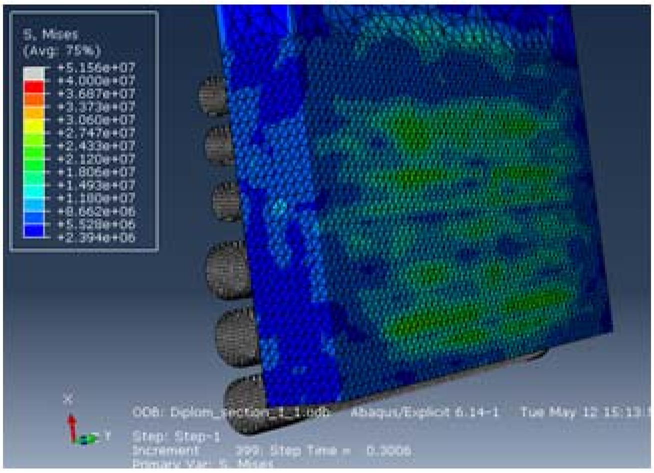

Fig. 7. Slab tension at steel casting.

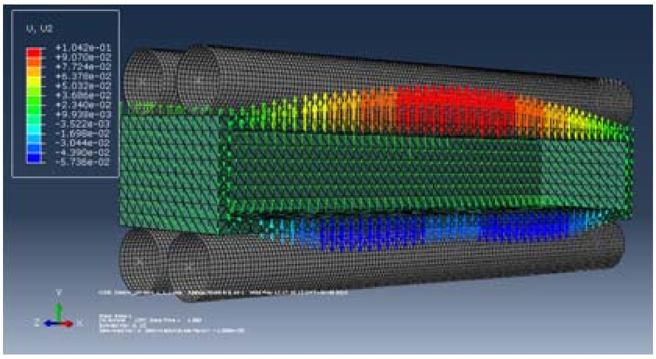

Fig. 8. Deformations in interroller space.

VI. Conclusion

In this paper the structure of 'digital twin' process of continuous steel casting in CSCU is proposed. The elements of the 'digital twin' are mathematical models of different phenomena occurring during the process of casting. These models are mutually influencing. Also the paper presents developed models, which can be constituent elements of the 'digital twin'. This is a model that calculates the temperature field of the ingot section at any time from the start of the casting. With this model, it is possible to predict the occurrence of defects and to determine the zones of liquid and solid phase of the metal. This information is input to the next model, the stress-deformed state. In the study of the behavior of slab in the CSCU, some assumptions have been made that allow the realization of modeling in the ABAQUS software complex, all the characteristics of the slab are taken into account. The generalized analysis of the obtained results makes it possible to state the following. On the basis of the developed mathematical model, with known mechanical and plastic properties of the stainless steel grade, as well as the conditions of the process, it is possible to compare the whole SSS, or its parts, during an established casting process, in order to assess the probability of defects.

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