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ARCHIVES of FOUNDRY ENGINEERING

ISSN (2299-2944)
Volume 19
Issue 3/2019

11 – 14

10.24425/afe.2019.127128

2/3

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Modeling of Heat Engineering Parameters of Casting and Rolling Complexes Work

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Received 05.02.2019; accepted in revised form 15.05.2019

Abstract

The paper consists the problem of developing a scientific toolkit allowing to predict the thermal state of the ingot during its formation in all elements of the casting and rolling complex, between the crystallizer of the continuous casting machine and exit from the furnace. As the toolkit for the decision making task the predictive mathematical model of the ingot temperature field is proposed. Displacement between the various elements of the CRC is accounted for by changing the boundary conditions. Mass-average enthalpy is proposed as a characteristic of ingot cross-section temperature state. The next methods of solving a number of important problems with the use of medium mass enthalpy are developed: determination of the necessary heat capacity of ingots after the continuous casting machine for direct rolling without heating; determination of the rational time of alignment of the temperature field of ingots having sufficient heat capacity for rolling after casting; determination of the total amount of heat (heat capacity) required to supply the metal for heating ingots that have insufficient amount of internal heat.

Keywords: Continuous casting, Casting-rolling machine, Ingot heating device, Temperature field, Heat flux

1. Introduction

Nowadays, in most steelworks, the continuous ingots leaving the continuous casting machine (CCM) are freely cooled in the air after cutting and only then transported to the rolling mill, where they are heated up again before plastic deformation. It causes a lot of heat losses. To solve the problem of using the internal heat of a continuously cast ingot immediately after casting a direct rolling technology, or in other words, a combination of the continuous casting and rolling process, was proposed by various researchers [1-3]. The machines assembled in this way in a single complex are known as casting and rolling complexes (CRC) or casting and rolling modules (CRM).

Fairly widespread CRC obtained in non-ferrous metallurgy. At present, CRC is successfully developed by several leading machine-building firms in the world. Leader in the creation of CRC (in terms of development and number of aggregates sold) is the company SMS-Demag.

Combination of casting with rolling allows attaining significant reducing the specific energy consumption for production a unit of finished rolled products. However, a number of problems arise. One of the main ones is connected with the impossibility of inspecting the surface of ingots after the caster for the presence of cracks, as it is in the case of open technological cycle. Therefore, higher demands are formulated for temperature-speed regimes of continuous casting. It is necessary to exclude crack formation [4-7]. Also a serious problem is the choice of the parameters of metal heat processing in the furnace for high-quality synchronization of the CCM and rolling equipment. Therefore, an important task is the availability of a scientific and practical tool for highly accurate diagnostics of the state of the billet after the caster and, accordingly, the amount of heat that must be supplied for its reheating before plastic forming.

After the ingot leaves the CCM it is necessary to heat it in such a way that the average mass temperature of the ingot and the temperature drop in its thickness (volume) correspond to the requirements of the rolling equipment. In some cases, this task can be performed with a single heat processing unit, but, as a rule, several units are involved. The complex of equipment for heat processing of the CRC on the passage between the continuous casting machine and the rolling mill can consist of a heating and thermostatic furnace. For heating up to the required temperature and equalizing the temperature along its length and section. And mobile thermostatic furnaces for delivering ingots to the rolling mill also can be uses [2, 7].

In production conditions, there are often significant variations in many values of technological factors, leading to a deviation in the processes, occurring in the CRC, from the standard. Changes in the thermal regime can lead to the creation of conditions that can lead to the formation of defects in ingots and even to emergency situations. Therefore, an extremely important task is to conduct operational diagnostics of heat engineering processes occurring in the CRC.

2. Evaluation of the effectiveness of the use of CRC.

In order to evaluate the efficiency of CRC using in comparison with the open technological cycle and to compare the thermal performance of various CRCs, it is proposed to introduce the concept of the heat utilization efficiency of cast metal:

$$\eta_{\mathrm{ef}} = \frac{\mathrm{Q_{c.h.}} - \mathrm{Q_{CRC}}}{\mathrm{Q_{c.h.}}} \tag{1}$$

where $Q_{c.h.}$ is the heat used for on heating the metal for rolling in open technological cycle, J/kg; Q_{CRC} is the heat used for heating the metal for rolling, taking into account the use of heat of cast metal (hot charging or direct rolling), J/kg.

The limiting values of cast metal heat efficiency use are "0" and "1", the first value corresponds to the total absence of cast metal heat use and the cold charging, and the second - to direct rolling without intermediate heating. The use of the proposed indicator allows to compare the effectiveness of different CRCs with each other or the same CRC under different operating conditions.

Thus, the heat savings (ΔQ, W) when using CRC in comparison with the open cycle and the cold charging are:

$$\Delta \mathrm{Q} = \mathrm{Q_{c.h.}} \cdot \eta_{\mathrm{ef}} \cdot \mathrm{a} \cdot \mathrm{b} \cdot \mathrm{v} \cdot \rho \tag{2}$$

where a, b are a width and a height of the ingot in cross section, m; ρ is a density of the ingot material, kg/m^3; v is a casting speed, m/s.

The maximum savings will be achieved with a value of η_{ef} equal to one. However, in practice, there are objective reasons that do not allow the implementation of direct rolling without any intermediate heating:

- the real heat content of the metal and its average mass temperature may not be sufficient to start rolling and have sufficient heat reserves to complete it;
- the temperature drop inside the ingot can reach values that are unacceptable for rolling;
- continuous castings may have defects that do not allow to obtain rolled products of specified quality, which determines the need to inspect the ingots and, if possible, eliminate defects by hot repair.

For the most effective synchronization of the work of the CRC and the achievement of the maximum possible utilization of the heat of the blanks for the existing and projected complexes, in addition to the reliable and fault-free operation of the individual technological elements, it is necessary to have a scientific tool for describing and studying the various processes within the framework of the CRC.

3. Determination of the ingot temperature state

The problem of determining the billet temperature state [7-10] is solved for the cross-section, which is moved together with the ingot moving inside the CRC. The mathematical model is based on solving the nonstationary heat equation in a two-dimensional formulation in a Cartesian rectangular coordinate system:

$$\frac{\partial \mathrm{t}}{\partial \tau} = \frac{\lambda}{\rho c_{\mathrm{ef}}} \cdot \left(\frac{\partial^2 \mathrm{t}}{\partial y^2} + \frac{\partial^2 \mathrm{t}}{\partial z^2} \right) \tag{3}$$

where t is the temperature, °C; τ is the time, s; y, z are the coordinates measured along the symmetry axes of the cross section of the ingot, m; c_{ef} is the effective heat capacity, (J/kg·K); λ is the heat conductivity, (W/m·K) [11].

The boundary conditions of the third kind are set according to the position of the calculated section, which is determined from the values of the speed of the ingot movement at the previous instants within the characteristic areas (mold, secondary cooling zone, free cooling zone, transport to the furnace, furnace, output from the furnace).

The initial conditions are set for the whole temperature field at the moment $\tau = 0$.

The value of the average mass enthalpy is determined for each time step in the mathematical model with the following dependencies. The enthalpy of an arbitrary elementary volume of a metal is defined as

$$i = \begin{cases} \mathrm{t} \cdot c_{sm}(\mathrm{t}), & \mathrm{t} \le \mathrm{T_s} \\ c_{sm}(\mathrm{T_s}) + \mathrm{Q_{cr}} \cdot \left(1 - \dfrac{\mathrm{T_l} - \mathrm{t}}{\mathrm{T_l} - \mathrm{T_s}} \right), & \mathrm{T_s} < \mathrm{t} < \mathrm{T_l} \\ \mathrm{Q_{cr}} + \mathrm{T_s} \cdot c_{sm}(\mathrm{T_s}) + (\mathrm{t} - \mathrm{T_l}) \cdot c_{lm}(\mathrm{t}), & \mathrm{t} \ge \mathrm{T_l} \end{cases} \tag{4}$$

where c_{sm}, c_{lm} are specific mass heat capacities of solid and liquid metal, respectively, J/(kg·K); Q_{cr} is the latent heat, J/kg.

Then the average mass enthalpy, depending on the geometric conditions, is defined as follows:

– for a one-dimensional problem and a rectangular coordinate system (modeling the temperature field of a slab)

$$i_{av} = \frac{\sum_{j=2}^{n-1} i_j}{n-2} \tag{5}$$

– for a two-dimensional problem and a rectangular coordinate system (simulation of the temperature field of a billet, or more precise modeling of the slab's temperature field)

$$i_{av} = \frac{\sum_{j=2}^{n-1}\sum_{k=2}^{m-1} i_{j,k}}{(n-2)\cdot(m-2)} \tag{6}$$

– for a one-dimensional problem and a polar coordinate system

$$i_{av} = \frac{\sum_{j=2}^{l-1}\left(i_j \cdot (R_{j+1} - R_j)\right)}{R} \tag{7}$$

where n, m, l are the numbers of grid nodes along the thickness, width and radius of the ingot, respectively.

An example of calculating the temperature state of a billet with a cross-section of 100x100 mm during the period of its formation on the CCM and averaging the temperature field in the furnace is shown in Fig. 1.

The model also makes it possible to provide calculations for technological processes that involve ingots transporting to a heating furnace, which causes ingots cooling in the air, and their further heat processing in furnace. The example of such calculations results is shown in Fig.2.

The use of the value of the mass-average enthalpy makes it possible to determine by simple expressions the amounts of heat required to bring the thermal state of the ingots from the initial state to the specified state:

- for moving material flow (W):

$$Q = a \cdot b \cdot v \cdot \rho \cdot (i_{av2} - i_{av1}) \tag{8}$$

- for a single ingot (J):

$$Q = a \cdot b \cdot L \cdot \rho \cdot (i_{av2} - i_{av1}) \tag{9}$$

where i_{av1}, i_{av2} are average mass enthalpy of metal in the initial and specified states, J/kg; L is the ingot length, m.

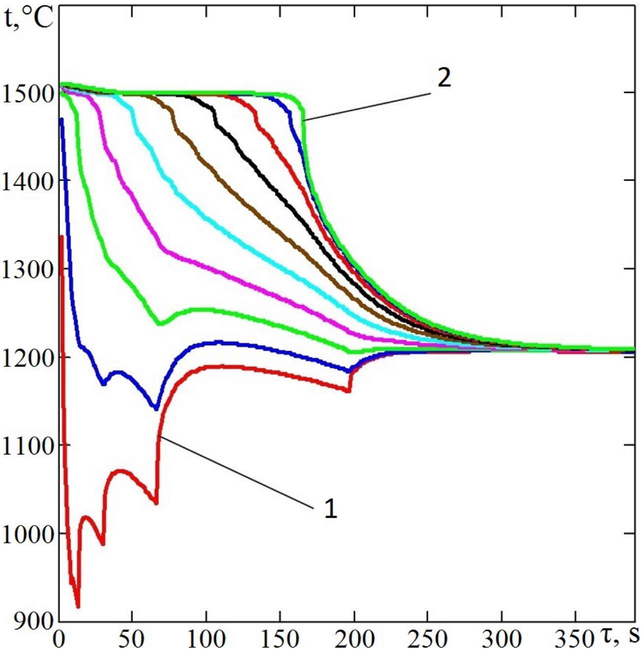

Fig. 1. Change of the billet temperature state within the CRC for the case of casting a billet with a cross section of 100x100 mm at a speed of 6.7 m/min and subsequent averaging of the temperature field (1 - surface of the billet, 2 - middle, remaining lines correspond to layers lying every 5.56 mm)

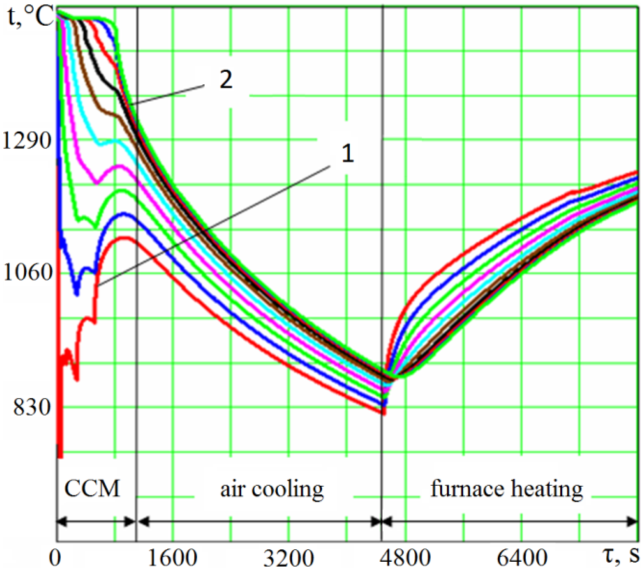

Fig. 2. Change of the slab temperature state within the CRC for the case of casting a slab with a cross section of 200x2000 mm at a speed of 1.2 m/min and subsequent averaging of the temperature field (1 - surface of the billet, 2 - middle, remaining lines correspond to layers lying every 11.1 mm)

The proposed toolkit solves the following tasks:

1. Determination of the required heat content of the ingot after the continuous casting machine for direct rolling without

reheating (in case when this is allowed by technological reasons: a continuous cast ingot is known to have no defects that will cause rejection of rolled products, therefore inspection and repair are not needed).

2. Determination of the rational time for equalization of the temperature field of ingots, which have sufficient heat content for rolling after the caster, on the basis of analysis of the results of numerical experiments.
3. Determination of the total amount of heat (thermal power), which must be supplied to the metal to reheat ingots that do not have a sufficient heat reserve.
4. Determination of the average density of the heat flux, which must be supplied to metal to reheat the material, provided that this operation is performed for a specified period of time.
5. Choice of furnace temperature, which will achieve a necessary average density of heat flow to the surface of the material.
6. Analysis of the thermal state of the metal ingots after heating for the acceptability of the resulting value of the thermal drop.

4. Conclusions

It was proposed to introduce the concept of heat recovery efficiency of the cast metal to evaluate the efficiency of the CRC compared to the open process cycle and to compare the thermal performance of various CRCs. The necessity of developing a scientific toolkit allowing to predict the thermal state of each ingot during its stay in all elements of the CRC, starting from the CCM mold prior to dispensing from the furnace, is substantiated. It is substantiated that this problem can be solved with the help of the predictive mathematical model, in which the temperature state of the cross section of the ingot is considered, and the displacement between the various elements of the CRC is accounted for by changing the boundary conditions. The use of the concept of mass-average enthalpy of the cross-section of the ingot has been proposed. The methods for solving a number of important problems have been developed with its use, such as determining the necessary heat capacity of the ingot after the continuous casting machine for direct rolling without reheating. Determining the rational time for equalizing the temperature field of the ingots having sufficient heat capacity for rolling after the caster, as well as determination of the total amount of heat (thermal power), which must be supplied to the metal for reheating the ingots that have insufficient amount of internal heat.

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