Development of the Mathematical Model for Ingot Quality Forecasting with Consideration of Thermal and Physical Characteristics of Mould Powder

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Abstract. This paper presents the results of physical modelling of the mould powder skull in the gap between an ingot and the mould. Based on the results obtained from this and previous works, the mathematical model of mould powder behaviour in the gap and its influence on formation of surface defects was developed. The results of modelling satisfactorily conform to the industrial data on ingot surface defects.

1. Introduction

The most important functions of the mould powder are control of heat removal from an ingot to the mould and reduction of the ingot drawing force. Earlier [1], the criteria for mould powder performance evaluation obtained through statistical data processing were determined, and currently these criteria are used in the BOF shop of PAO Severstal and demonstrate good results. However, it does not provide information on the physics of the processes occurring in the mould.

Application of particular mould powder may have different impacts on thermal performance of the mould. Owing to shrinkage of molten slag entering the gap between the ingot being formed and the mould wall, an air gap is formed; and this air gap have a significant impact on total thermal resistance in the system. The largest liquid shrinkage is observed on highly basic mixtures (CaO/SiO₂>1.2) [2]. The surface roughness depends on the crystal layer thickness [3] and the crystal morphology [4]. Application of highly basic mixtures reduces the heat flux in the mould, and the process itself is commonly referred to as “soft” cooling. Application of “soft” cooling [1, 5, 6] greatly reduces the number of slabs suffering longitudinal cracks in the peritectic range of products. According to data provided in papers [7–9], the thermal resistance of the forming gas gap between the mould wall and the solid layer of the mould powder skull differs much depending on the research method and is determined for a small amount of mould powder samples. Therefore, it is reasonable to conduct studies of thermal and physical properties of mould powder under specific conditions of PAO Severstal.
Another purpose of the mould powder use is to grease the ingot shell and reduce the friction force in the mould. Friction in the mould can be conditionally divided into liquid friction and dry friction. The liquid friction prevails in the upper part [10] of the mould – in the high temperature zone, and the dry friction prevails in the lower part. According to data [11], the maximal friction appears in the lower part of the mould, that is in the dry friction zone. While the liquid friction is determined by viscosity of the molten slag in the gap, the dry friction is determined by interaction between the solid layer of the mould powder and the forming steel shell. The authors of the paper [12] report the results of the tribological study of the “Steel Ball – Mould Powder Solid Layer” system at temperatures up to 900°C, which can be used for evaluation of the dry friction.

Development of physical and mathematical models describing thermal processes in the ingot-slag-mould system provides the possibility to determine parameters affecting the ingot quality, to evaluate the influence of mould powder characteristics on casting parameters, and to model the mould thermal performance in relation to new conditions of casting.

2. Research Methods and Materials

Industrial mould powders of the basic oxygen steel making process at PAO Severstal (Table 1), which properties are examined in detail in paper [4], were used as the study materials.

| No. | Al₂O₃ | K₂O | Na₂O | MgO | F | CaO/SiO₂ | T heat (°C) | η₁₃₀₀ (Pa·s) |
|-----|-------|-----|------|-----|---|----------|------------|-------------|
| 1   | 6.7   | 1.53| 7.7  | <1  | 7.1| 0.89     | 1,130      | 0.41        |
| 2   | 4.8   | 0.25| 10.5 | 2   | 9.7| 0.93     | 1,025      | 0.18        |
| 3   | 6.3   | 0.12| 4.5  | 2.6 | 6.8| 1.22     | 1,175      | 0.35        |

Condition of the mould powder skull in the gap was modelled in two phases. During the first phase, the distribution of the heat flux in the mould was reproduced, and in the second phase the physical modelling of determination of thermal and physical characteristics of the mould powder skull was conducted.

According to the paper [13], the heat flux density can be expressed by the equation:

\[
q(z) = q0 - (q0 - q_{mean}) \frac{1 - e^{-k \frac{z}{v}}}{1 - \frac{v}{k \cdot L} \left(1 - e^{-\frac{k \frac{z}{v}}}ight)},
\]

where \(v\) is casting speed; \(z\) is the distance from the meniscus; \(L\) is the height of the surface of contact between the ingot and the mould; \(q_{mean}\) is the mean density of the heat flux; \(q0\) is the heat flux density in the area of meniscus; \(k\) is the coefficient describing the increase of total thermal resistance of the shell, the contact between the ingot and the mould surface in time.

However, in the equation (1), only \(v\), \(z\) and \(L\) parameters are known for certain casting conditions. The rest parameters of the equation (1), \(q0\), \(q_{mean}\) and \(k\) are unknown. The unknown variables can be determined with the aid of available industrial data. They include averaged values of temperature according to data from thermocouples in mould walls and the mean heat flux \(q_{mean}\) depending on casting speed.

The data from casting data sheets of the BOF production at PAO Severstal were collected and processed in order to determine the heat flux mean density value. 134 heats were processed in total. The value \(q_{mean}\) was calculated according to the formula (2):

\[
q_{mean} = \rho_w g_w C_w \Delta T_w,
\]

where \(\rho_w\) is water density, kg/m³; \(g_w\) is water flow rate for mould cooling, m³/s; \(C_w\) is water heat capacity, J/(kg·K); \(\Delta T_w\) is mould input and output water temperature difference.
The parameters $q_0$ and $k$ of the equation cannot be determined directly through measurement, and the solution of the three-dimensional inverse problem of steady thermal conductivity in the Ansys 17.1 calculation complex with the optimization approach is used for their calculation.

The inverse problem is based on the following principle. The heat flux with distribution along the casting direction according to the equation (1) is applied to the three-dimensional model of the mould wall from the inside. From the other side – in areas of cooling channels – the boundary condition in the form of the contact heat exchange is applied. The coefficients in the equation (1) are based on the solution of the inverse problem so that the design temperatures in the areas of thermocouples comply with the experimental values.

The functions to be minimized when solving the inverse problem are expressed as follows:

$$F(q_0, k) = \sqrt{\sum_{i=1}^{3} (T_i^{\text{exp}} - T_i^{\text{calc}}(q_0, k))^2} \rightarrow \min,$$

where $T_i^{\text{exp}}$, $T_i^{\text{calc}}$ are experimental temperatures in three locations ($i = 1\div3$) and their corresponding calculated temperatures received from solution of the three-dimensional direct problem of steady thermal conductivity.

The physical modelling was carried out for determination of the effective heat conductivity factor of the mould powder skull. A special unit, where the slag sample was located in the gap between the copper wall and the nichrome heater, was developed for these purposes. The skull effective heat conductivity factor was calculated on the basis of solution of the inverse problem of heat conductivity. The temperature values received when achieving stationary conditions, that is readings variability did not exceed $\pm2^\circ\text{C}$, were taken into consideration. The skull thickness was determined by a digital USB-microscope. The temperature values were recorded continuously during the experiment. The error of determination of temperature values by the MBA8 input analogue module is 0.5 %.

3. Study Results

The Figure 1 (a) presents linear dependencies of the mean density of the heat flux for mould powders Nos. 1 to 3 in relation to casting speed of peritectic steel grades. The highest density of the heat flux is observed for the mould powder No. 2. It is 200 and 400 kW/m$^2$ higher in average than for mould powders No. 1 and No. 3, respectively.

The Figure 1 (b) provides an example of temperature values according to the levels of thermocouples location in the mould. These dependencies were used for resolving the optimization problem.

The result of optimization is distribution of the heat flux density along the mould height. An example of heat flux density distribution for the peritectic range of products with use of the mould powder No. 3 is shown on Figure 2.

The values of heat flux density for different cross sections of the skull were calculated on the basis of received values of temperatures of the physical modelling of thermal and physical properties. Effective heat conductivity factors for a temperature range of 900 to 1,300°C depending on the slag skull thickness were calculated based on heat flux density values.
Mould powder

![Heat flux density, kW/m²](image1)

![Temperature, °C](image2)

**Figure 1.** Measurement of heat flux mean density during casting of steel of peritectic grades (a) and readings of thermocouples (b) at casting of steel of peritectic grades with mould powder No. 3 depending on casting speed.

![Heat flux density](image3)

**Figure 2.** Distribution of heat flux density during casting of steel of peritectic grades with mould powder No. 3 for different speeds.

Then the mathematical processing of experimental data was conducted to obtain the dependence of the thermal resistance of the gas gap (resulting from molten slag shrinkage at the side of the mould) on the thickness of the mould powder skull. The following equation was considered for this purpose:

\[
q = \frac{T_1 - T_2}{R_m} = \frac{T_2 - T_3}{R_c} = \frac{T_3 - T_{35}}{R_{int}},
\]

where \(T_2\) is the temperature of mould powder crystallization; \(T_3\) is the temperature at the border between the crystallized slag and the gas gap; \(R_m\) is the resistance of molten mould powder; \(R_c\) is the resistance of the crystallized mould powder; \(R_{int}\) is the resistance of the gas gap.
The equation (4) includes three independent equations, which clearly determine the resistance of the molten mould powder. The rest two equations contain four unknown variables: $T_3$, $R_m$, $R_c$, $R_{int}$, therefore, it becomes necessary to solve the optimization problem, which is formulated as follows:

$$ f(R_c, R_{int}) = T_2 - qR_c - T_{45} - qR_{int} \rightarrow \min. $$

(5)

The solution of the optimization problem was obtained through standard numerical methods: the dependences $R_{int}(d_{total})$ and $R_c(d_{total})$ were determined. Figure 3 demonstrates dependencies of the gas gap resistance on total thickness of the slag skin according to the results of this study and the paper [7].

Thus, when the heat flux distribution along the mould height and the value of thermal resistance of the gas gap between the mould wall and the solid slag layer are known, it is possible to calculate the mould powder skull behaviour in the gap using the mathematical modelling.

4. Mathematical Modelling

The results of the physical modelling were used as basic data for the mathematical model. The mathematical model determines distribution of liquid and solid slag, and the gas layer in the gap between the ingot and the mould, and it is based on the one-dimensional equation of steady thermal conductivity:

$$ \frac{k_i}{d_i} (T_i - T_{i+1}) = q, $$

(6)

where $k_i$ is the thermal conductivity factor of the $i^{th}$ layer; $d_i$ is the thickness of the $i^{th}$ layer; $T_i$ and $T_{i+1}$ are temperatures of layer boundaries; $q$ is the heat flux, which is withdrawn by the mould from the continuous cast ingot.

When solving the problems of distribution of molten and crystallized slag, and the gas layer in the gap between the ingot and the mould, the equation (6) shall be written for three layers – for liquid and solid slag and the gas gap. In this case, the heat flux distribution and the ingot temperature along the casting direction are considered to be set.

Temperature distribution in the steel shell is based on the one-dimensional equation of the non-steady thermal conductivity:

$$ p_stC_{st} \frac{dT}{dt} = k_{st} \frac{d^2T}{dx^2}, $$

(7)
where $\rho_{st}$ is steel density; $k_{st}$ is the steel thermal conductivity coefficient; $T$ is steel shell temperature; $t$ is time, sec; $x$ are coordinates in the direction perpendicular to the casting direction, m.

The temperature distribution on the steel surface depending on the distance from the meniscus is determined out of the solution of the problem of temperature distribution in the steel shell (equation 7).

Solution of the three equation system consisting of three layers is achieved with introduction of some assumptions:

1) The gas gap is formed between crystallized slag and the mould wall, and its thickness is determined out of the physical modelling, the results of which are provided on Figure 3.

2) The three equation system shall be solved in sequence for $z_i$ layer starting from the meniscus and ending with the lower part of the mould, where $z_i$ is the distance of the $i^{th}$ layer from the meniscus.

The mathematical model basic data are presented below for determination of the slag layer thickness:

- Thermal conductivity coefficient of mould powders Nos. 1-3 in the crystalline phase [8], W/(m·K): 0.5
- Thermal conductivity coefficient of mould powders Nos. 1-3 in the liquid phase [8], W/(m·K): 1.7
- Mould powder No.1 crystallization temperature, K: 1,403
- Mould powder No.2 crystallization temperature, K: 1,298
- Mould powder No.3 crystallization temperature, K: 1,448
- Steel thermal conductivity coefficient, W/(m·K): 33
- Copper thermal conductivity coefficient, W/(m·K): 383
- Gas gap thermal conductivity coefficient, W/(m·K): 0.023
- Steel density, kg/m$^3$: 7,800
- Crystallization latent heat, J/kg: 272,000
- Steel solidus temperature, K: 1,774
- Steel liquidus temperature, K: 1,779
- Steel overheating temperature, K: 1,788
- Metal height in the mould, m: 0.78
- Distance from the mould wall to the thermocouple, m: 0.02

Figure 4 presents an example of the gap profile between the ingot and the mould for the mould powder 2 depending on casting speed 0.6, 0.8, 1.0, 1.2 and 1.4 m/min, where 1 is the area of the ingot shell, 2 is the mould powder skull liquid layer, 3 is the intermediate layer, 4 is the solid layer, 5 is the gas gap between the mould wall and the skull solid layer, 6 is the mould wall.

Distribution of thicknesses of molten and crystallized mould powder was used for determination of dry and liquid friction.

According to the paper [15], dry friction $\tau_{sb}$ (MPa) between the ingot and the skull solid layer can be determined by the equation:

$$\tau_{sb} = \eta (\rho_{slag} gh_0 + \rho_{steel} g z),$$

where $\eta$ is the friction factor between the ingot and the crystallized mould powder; $\rho_{slag}$ is slag density; $g$ is gravity acceleration; $h_0$ is height of slag liquid layer in the skull, and $\rho_{steel}$ is steel density.

According to the same paper [15], it is possible to determine the liquid friction $\tau_{sl}$ (MPa):

$$\tau_{sl} = \eta_s \frac{(n+1)(v-V_m)}{d_l} - \frac{(\rho_{slag} - \rho_{steel}) g d_l}{n+1},$$

where $\eta_s$ is molten slag viscosity; $n$ is a coefficient in the exponential correlation for viscosity; $v$ is casting speed; $V_m$ is mould oscillation speed, m/s; $d_l$ is the thickness of molten mould powder.
Figure 4. Profile of skull of mould powder No. 3 for casting speed (m/min):
(a) – 0.6; (b) – 0.8; (c) – 1.0.

Height \( h_0 \) (m) and thickness \( d_1 \) (m) of slag liquid layer in the skull was determined on the basis of results of the profile mathematical modelling (Figure 4). The other values are given below:

- Coefficient of friction between the ingot and the crystallized mould powder [12]: 0.15
- Slag density, kg/m\(^3\): 3,000
- Viscosity of molten slag of mould powder No.1, Pa·s: 0.41
- Viscosity of molten slag of mould powder No.2, Pa·s: 0.18
- Viscosity of molten slag of mould powder No.3, Pa·s: 0.35
- Coefficient in exponential correlation for viscosity: 1.24
- Casting speed, m/min: 0.6 - 1.4
- Maximal mould oscillation speed, m/s: 3.5

Friction stresses \( \tau_{\text{sh}} \) and \( \tau_{\text{sl}} \) were recalculated into the friction force or the ingot drawing force using the equilibrium integral equation. The liquid friction was calculated for the worst scenario, when the speed difference value in the equation (9) is maximal. Figure 5 shows calculated values of the friction force (ingot drawing force) between the ingot and the mould wall based on the equation (5) and represented as a dependence of the friction force on the coordinate \( z \) (for peritectic steel grades).

According to the analysis of Figure 5, the smallest value of the friction force appears with application of the mould powder No. 2. The rejection rate because of edge and transverse cracks is 0.36 and 0.89% relat. with application of the mould powder No. 2, 3.38 and 2.17 relat. with application of the mould powder No. 1, and 1.59 and 2.14% relat. with application of the mould powder No. 3, respectively. The largest friction forces appear with application of the mould powder No.3. Thus, the modelling results conform well to the industrial data on defects of continuously cast slabs.

5. Conclusions

Laboratory studies of thermal and physical characteristics of the slag skull of different mould powders were carried out. Dependences of thermal resistance of the gas gap between the mould wall and the skull solid layer were received.
There was developed the mathematical model of heat transfer and slag solidification between the ingot and the mould, which allowed one to determine the thickness of the slag layer depending on the casting speed, steel grade, and mould powder type.

Friction forces and ingot drawing forces for different casting conditions were calculated based on the mathematical modelling of heat transfer in the steel shell and in the slag layer between the ingot and the mould. The received results conform to the industrial data on the slab defect rate.

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