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STUDIES OF HYDRODYNAMIC PROCESSES DURING INGOTS CRYSTALLIZATION IN A CASTING MOLD UNDER CONDITIONS OF ELECTROSLAG HEATING AND STIRRING OF THE METAL POOL

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ABSTRACT

The results of the physical simulation of hydrodynamic processes at the crystallization of ingots in a casting mold under conditions of electroslag heating and stirring of the metal pool by a gas jet are presented. The studies were carried out on a cold transparent model that simulates the crystallization of a 205-ton steel ingot in a casting mold and allows visualizing hydrodynamic processes in the metal pool and forming a solid phase. New experimental data on the structure of hydrodynamic flows at various options of stirring the metal pool by a gas jet were obtained. It is shown that the use of a gas jet allows creating toroidal melt flows with upward flows spreading from the gas-supplying nozzle and downward flows near the walls of a casting mold. It was established that for effective stirring of the entire volume of the metal pool and to affect the crystals growing on the crystallization front, it is advisable to place the gas tuyere along the axis of the pool and choose its immersion depth within 70–80 % of the pool depth.

KEYWORDS: ingot, casting mold, physical simulation, hydrodynamics, electroslag heating, gas jet, stirring

INTRODUCTION

Today, the conventional technology of casting steel in a casting mold remains one of the most common methods of producing large forging ingots and slabs. This process is characterized by the presence of large volumes of liquid metal that solidifies for a long time under conditions of low-intensity thermal convection. This leads to a significant propagation of liquation and shrinkage processes and, as a result, physical and chemical heterogeneity of the cast metal [1–5]. Such defects cannot be completely eliminated during subsequent thermodeformational treatment. They are inherited by forgings and semi-finished products made from an ingot, which leads to a deterioration in the mechanical properties of the metal. Therefore, the problem of improving the technologies for making large ingots in a casting mold is still relevant.

One of the most promising ways to improve metal solidification conditions and eliminate defects of shrinkage and liquation origin is to apply a complex thermal and hydrodynamic effect on the metal pool [6]. It can be realized by means of electroslag heating (ESH) and feeding the ingot head and forced stirring of the metal pool with a gas jet. Under these conditions, it is important to understand the nature and intensity of hydrodynamic flows in the metal pool.

Experimental studies of the hydrodynamic processes that occur at the solidification of large ingots are very complex and expensive. In this case, it is advisable to apply physical modeling methods on cold transparent models, taking into account the following similarity criteria [7–10].

The aim of this study is to determine the effect of electroslag heating and forced purging of liquid metal with gas flows on hydrodynamic processes in the metal pool at the solidification of ingots in a casting mold.

RESEARCH PROCEDURE

The experiments were carried out on a cold, transparent physical model that allows visualizing hydrodynamic processes in the pool and forming the solid phase (Figure 1). The model represents a plane vessel simulating the longitudinal section of a 205-ton forging ingot. It is made at a scale of 1:15 to maintain the geometric similarity to a full-scale object. The bottom and side walls of the model are made of a water-cooled profile, while the front and rear walls are made of optically transparent material. The upper part of the vessel has polystyrene foam overlays simulating the heat-insulating inserts of the yield top.

A melt of sodium thiosulfate ($Na_2S_2O_3$) was used as a model liquid that simulates molten steel, which solidifies by the dendritic mechanism and retains optical transparency in the solid state. To visualize hydrodynamic flows, a coloring pigment was added to the sodium thiosulfate melt, which was precipitated in the form of suspended particles with neutral (zero) buoyancy (Figure 1, *b*).

a b

Figure 1. Appearance of a physical model for studying hydrodynamic processes at the ingot crystallization in a casting mold (*a*) and suspended particles in the model melt (*b*): *1* — water-cooled wall; *2* — wall made of optically transparent material; *3* — heat-insulating overlays; *4* — liquid simulating the slag pool; *5* — thermocouple; *6* — heating element; *7* — thermal imager; *8* — video camera

The correspondence between the hydrodynamic processes occurring during the simulation and in real conditions was assessed using the similarity criteria: Froude's criterion (Fr), which characterizes the ratio of inertia and gravity forces; Reynolds' criterion (Re), which determines the nature of hydrodynamic flows in the melt (laminar or turbulent); Weber's criterion (We), based on the ratio of liquid inertia forces to liquid surface tension forces; Grashof's criterion (Gr), which determines the melt motion caused by the non-uniformity of the temperature field.

Below are the calculated ratios for these similarity criteria:

$$\mathrm{Fr} = V^2/gL,\ \mathrm{Re} = VL/\nu,$$
$$\mathrm{We} = \rho V^2 L/\sigma,\ \mathrm{Gr} = g\beta(T_m - T_w)L^3/\nu^2,$$

where V is the flow velocity (m/s); g is the free fall acceleration (m/s^2); L is the characteristic size (m); ν is the kinematic viscosity of the liquid (m^2/s); ρ is the density of the liquid (kg/m^3); σ is the surface tension coefficient (N/m); β is the coefficient of thermal expansion (1/K); T_m is the melt temperature (K); T_w is the temperature of the casting mold wall (K).

The values of the relevant physical parameters and similarity criteria calculated for the model and the full-scale process are given in Tables 1 and 2. In both cases, the Fr criterion is significantly less than 1, which indicates the dominance of gravity forces over inertial forces. This is typical for the processes with stable convective liquid flows, without significant oscillations and surges. The We criterion is also less than 1 in both cases, which indicates the dominance of surface tension forces over inertial forces and the stability of the melt surfaces and the absence of ruptures of these surfaces. The Gr criterion for both the full-scale process and the model has very high values, which indicates a

Table 1. Physical parameters of the model and a full-scale process

Parameter	Physical model (sodium thiosulfate)	Full-scale process (steel)
Melt temperature (T_m), °C	68	1520
Casting mold wall temperature (T_w), °C	20	850
Flow velocity (V), m/s	0.01	0.015
Characteristic dimension (L), m	0.07	0.5
Thermal conductivity coefficient (λ), W/m·K	0.55	30
Density (ρ), kg/m^3	1670	7000
Kinematic viscosity (ν), m^2/s	$1.05\cdot10^{-6}$	$8.5\cdot10^{-7}$
Surface tension coefficient (σ), N/m	0.09	1.6
Thermal expansion coefficient (β), 1/K	$4.5\cdot10^{-4}$	$1.2\cdot10^{-5}$

Table 2. Values of similarity criteria for the physical model and the full-scale process

Similarity criterion	Physical model	Full-scale process
Fr	$1.5\cdot10^{-4}$	$4.6\cdot10^{-5}$
Re	$7.0\cdot10^{2}$	$8.8\cdot10^{3}$
We	0.13	0.49
Gr	$7.3\cdot10^{7}$	$1.3\cdot10^{10}$

significant influence of the natural convection on the movement of both melts. The value of the Re criterion in the full-scale process exceeds the critical value of $R_e \approx 2300$, which indicates the probability of turbulent flows formation in the steel melt.

In general, the analysis of the similarity criteria indicates the correspondence of the studied processes in the model and a full-scale object and the possibility of a qualitative (representative) assessment of the hydrodynamic processes occurring during the solidification of a steel melt in a casting mold using the developed physical model.

The sodium thiosulfate was melted in a muffle furnace and then fed into the model vessel using siphon filling at a temperature of 68–72 °C.

To model the ESH process, oil was poured onto the melt surface to simulate a slag pool. The oil was heated using a heating element immersed in it, and its temperature was maintained at 52–62 °C. The melt temperature was monitored using a thermocouple and a "Wintact WT3160" thermal imager.

Forced stirring of the melt was carried out by gas purging. For this purpose, a ceramic tube with a metal nozzle (tuyere) was used, which was immersed into the melt at different depths and in different places (along the axis and with a displacement from the axis). Purging was carried out periodically for 30–60 s. Argon was used as a gas, which was supplied at a flow rate that did not lead to an unacceptable excitation of the free surface of the pool. Hydrodynamic flows in the melt were studied by analyzing video records of the movement of suspended particles in it.

The experiments were carried out under the conventional ingot solidification scheme (without an external impact), with the use of ESH, as well as with the use of ESH and with various options of stirring the metal pool with a gas jet.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2, *a* shows the structure of hydrodynamic flows of the model melt after its casting. It is characterized by downward liquid flows, which are localized in a rather narrow volume directly near the water-cooled walls of the vessel. The velocity of these downward flows is about 4.8 mm/s. The upward flows of the melt are dispersed throughout the central part of the pool and their velocity is on average 1.5 mm/s (Figure 3, *1*). Obviously, this flow structure results from the thermogravity convection caused by the cooling effect of the vessel walls.

The use of ESH did not change the structure and intensity of melt flows much (Figure 2, *b*). Downward liquid flows with a velocity of up to 4.2 mm/s occurred near the pool walls at a distance of not more than 20 mm, and low-intensity upward flows were dispersed in the central part of the pool (Figure 3, *2*). However, within 20 min after the melt was cast, when a layer of frozen sodium thiosulfate formed on the walls of the vessel, the flow

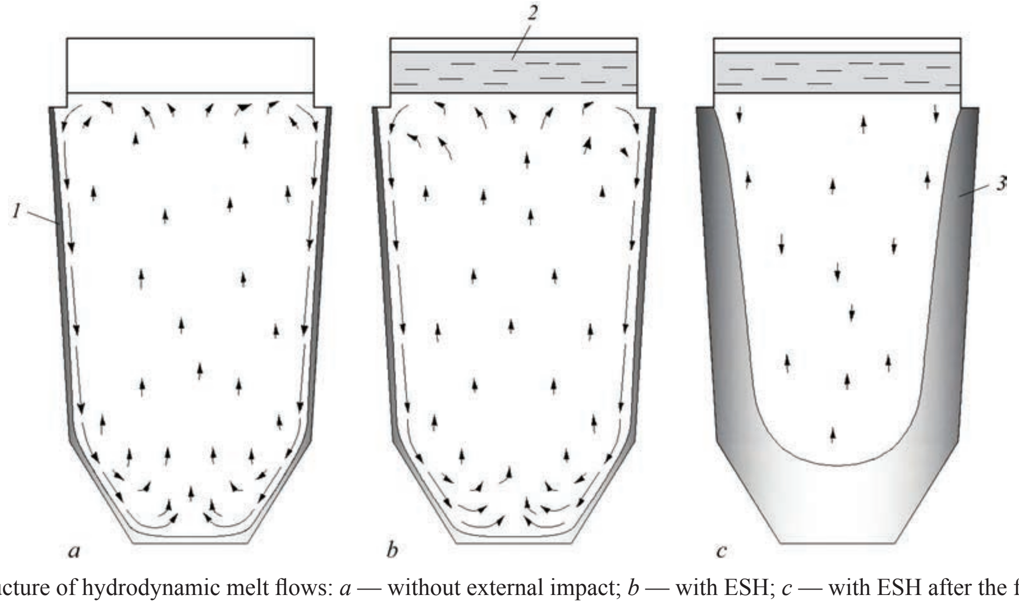

Figure 2. Structure of hydrodynamic melt flows: *a* — without external impact; *b* — with ESH; *c* — with ESH after the formation of a solidified ingot layer (*1* — vessel wall; *2* — liquid simulating the slag pool; *3* — solidified ingot layer)

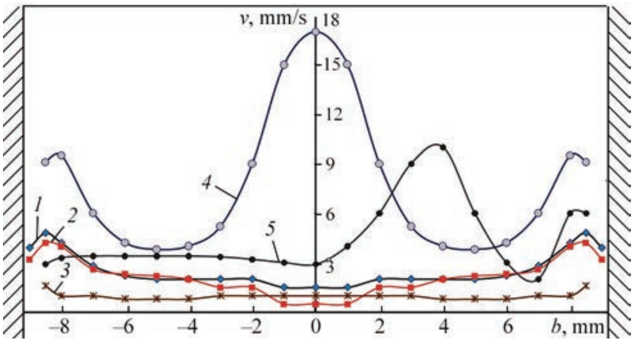

Figure 3. Distribution of flow velocity across the pool width (b) at the horizon $0.75\times h_{pool}$ for different modeling schemes: *1* — without external impact; *2* — with ESH; *3* — with ESH within 20 min after casting; *4* — with stirring when the tuyere is immersed along the axis to 80 % of the pool depth; *5* — with stirring when the tuyere is immersed asymmetrically at 50 % of the pool depth

structure changed significantly: the melt flow almost completely stopped throughout the entire volume of the pool (Figure 2, *c*; Figure 3, *3*). In other words, under conditions when the cooling effect of the vessel walls due to the formation of a frozen layer of sodium thiosulfate on them is significantly reduced, and heat is fed by ESH in the upper layers of the pool, there are no factors for the occurrence of thermogravity convection. Such conditions of metal solidification without melt stirring cannot be considered favorable for overcoming liquation phenomena during the ingot solidification. In this case, it is advisable to use forced stirring of the metal pool.

Figure 4 shows the structures of hydrodynamic flows of the melt when using gas purging jet. The obtained data indicate that gas purging creates intense toroidal melt flows with upward flows spreading from the gas supply nozzle and downward flows near the vessel walls. This is created by the upward motion of gas bubbles that propagate from the nozzle and in turn bring the melt into motion. In this case, melt flows are

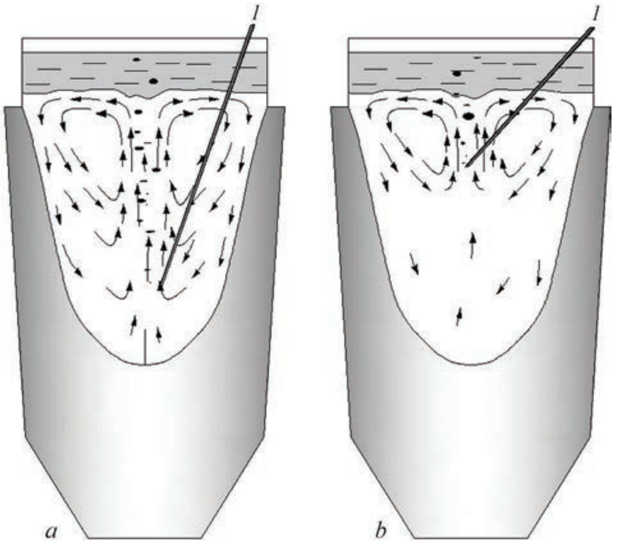

Figure 5. Structure of hydrodynamic flows during gas purging of the pool after 2 hours from the beginning of the experiment: *a* — immersion of the tuyere (*1*) to 70 % of the pool depth; *b* — at 28 %

formed mainly in the horizons above the gas supply nozzle. In other words, when gas flow rates do not lead to an unacceptable excitation of the free surface of the pool, the gas jet does not spread significantly below the nozzle. As a result, when the tuyere was immersed to a depth of 30 % of the total pool depth, forced melt stirring occurred only in a small volume concentrated in the upper layers in the centre of the vessel (Figure 4, *a*). At the same time, melt flows did not reach the crystallization front.

As the immersion depth of the tuyere increased, the volume of the melt involved in the toroidal motion increased (Figure 4, *b*), and only when the tuyere was immersed to a depth of at least 70–80 % of the total pool depth, the toroidal motion was formed in its entire volume (Figure 4, *c*). Under these conditions,

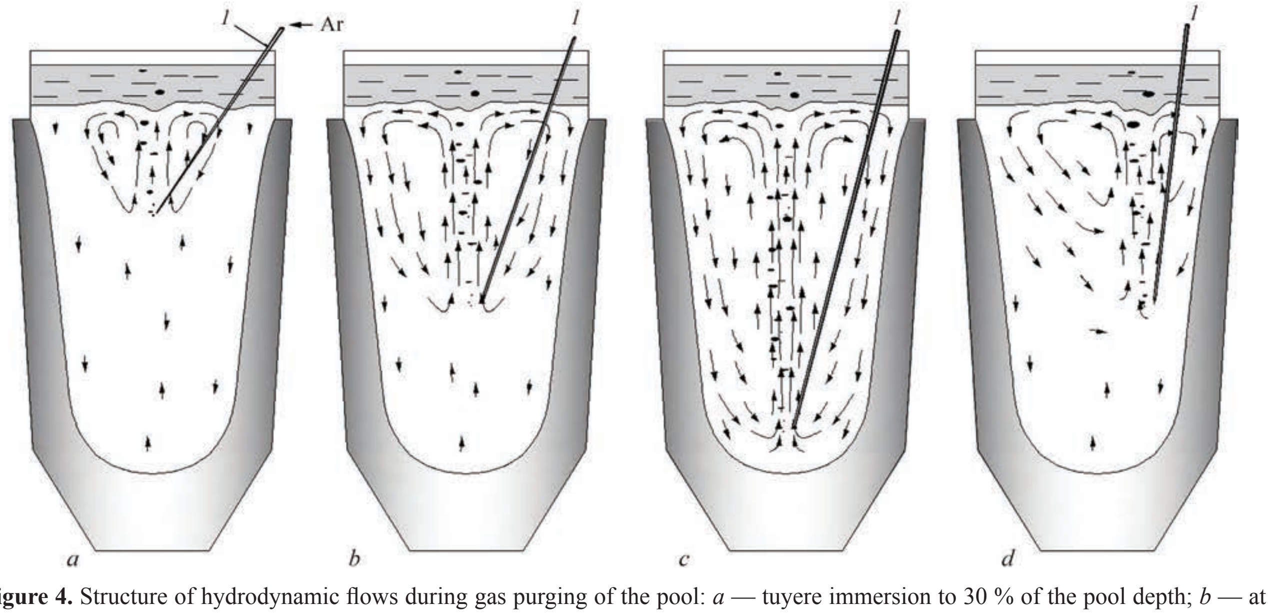

Figure 4. Structure of hydrodynamic flows during gas purging of the pool: *a* — tuyere immersion to 30 % of the pool depth; *b* — at 50; *c* — at 80; *d* — asymmetric tuyere immersion; *1* — tuyere

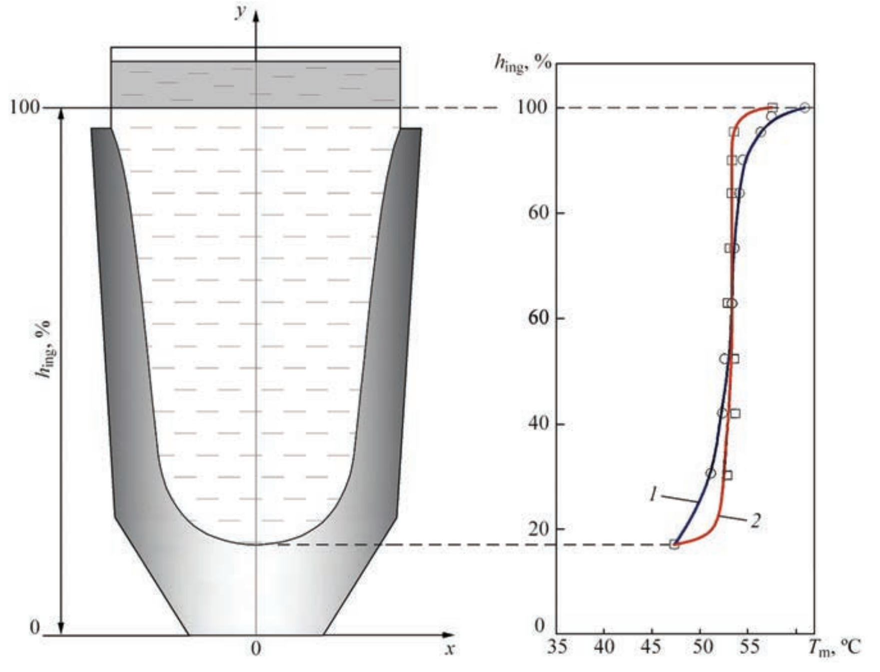

Figure 6. Temperature distribution over the height of the model liquid without (*1*) and with stirring (*2*)

forced melt flows washed the crystallization front along its entire length. The maximum velocity of upward flows along the pool axis was 17.0 mm/s, and 9.5 mm/s for downward flows near the walls of the vessel (Figure 3, *4*).

A flow structure which similar to that described above was observed when pool stirring was applied after 2 hours from the start of the experiment, when about 50 % of the ingot volume was formed (Figure 5, *a*, *b*).

The asymmetric arrangement of the tuyere in the vessel created an asymmetric toroidal melt motion (Figure 4, *d*). At the same time, melt flows washed the crystallization front on the one side of the vessel, but not on the opposite side. Such a flow structure cannot be considered effective to influence the ingot structure formation and liquation processes at the crystallization front. An exception may be made when at the purging process, it can be provided that the tuyere could move in a circle at a certain distance from the casting mold wall.

Figure 6 shows the temperature distribution of the model liquid across the cross-section of the vessel in the experiments without melt stirring and with (with the tuyere immersed to a depth of 70 % of the pool depth). As shown in the given data, melt stirring leads to a equalizing of the temperature over the height of the pool (Figure 6, *2*). This redistribution of temperature in the bottom part of the pool should reduce the length of the two-phase zone and, accordingly, the propagation of the liquation processes occurring at the ingot solidification.

In general, the obtained results confirm the prospects of using a gas jet for melt stirring, equalizing the temperature in the pool volume and influencing the liquation processes at the ingot solidification in a casting mold. For effective stirring of the entire volume of the metal pool and influencing the crystals growing at the crystallization front, it is advisable to place the tuyere along the pool axis and choose its immersion depth within 70–80 % of the pool depth. Under these conditions, downward flows of the melt reach the bottom of the pool and then spread upwards along the entire crystallization front. At the same time, the maximum admissible gas flow rates, which are determined by its pressure and nozzle diameter, are limited by the excitation of the free surface of the pool, melt spattering and deterioration of process stability.

The obtained results will be used in further studies to optimize the parameters of gas purging while casting model steel ingots in a casting mold.

CONCLUSIONS

1. A physical model was developed to study hydrodynamic processes in the metal pool during ingot casting in a mold under conditions of electroslag heating and stirring with a gas jet.

2. It is shown that using the conventional casting scheme, downward flows of the melt are formed near the walls of the casting mold, while upward flows are dispersed throughout the whole central part of the pool and have a lower velocity. As a solidified layer of the metal forms on the walls of the casting mold, the velocity of hydrodynamic flows throughout the

pool volume decreases significantly, until it stops completely.

3. It was found that the use of ESH does not lead to a noticeable change in the structure and velocity of hydrodynamic flows of the melt.

4. It is shown that gas purging creates intense toroidal melt flows with upward flows spreading from the gas supply nozzle and downward flows near the mold walls. In this case, the melt flows are formed mainly in the liquid volumes above the gas supply nozzle.

5. It was established that for effective stirring of the entire volume of the metal pool and impact on the crystals growing at the crystallization front, it is advisable to place the tuyere along the pool axis and choose its immersion depth within 70–80 % of the pool depth.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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