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Modeling of the Floating of Non-metallic Inclusions when Pouring Steel into a Mold in Top Casting

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Abstract. It is described in the paper the physical modeling of the metal flows pattern and the floating of non-metallic inclusions in the mold when pouring steel in top casting. The study of the effect of the speed and direction of metal flows in the mold on the time of floating up of nonmetallic inclusions is very important for the process of finishing alloying and modification of steel in the mold during casting. The purpose of this study was to substantiate the similarity numbers for physical modeling of this process and to determine their influence on the surfacing time as well as determination of the rational casting method for the final alloying steel from the point of view of NMI removal and the mode of additives. In the course of the literature analysis, it was found that the movement of flows during steel casting can be described by the Reynolds, Froude and Weber numbers, but their simultaneous compliance is impossible. Since no substantiation of the insignificant influence of the Weber number, in contrast to the Reynolds number, was found in early studies, the authors developed a technique, assembled an experimental facility and carried out physical modeling. The results of physical modeling confirm the self-similarity of the Weber number in the range from $10^{4.75}$ to $10^{5.5}$. According to the results of this study, the insignificant effect of the Weber number on the process of floating up of non-metallic inclusions when filling the mold in top casting was confirmed. It was found that the removal of deoxidation products occurs faster in top casting, and the time for their removal is significantly reduced with an increase in the liquid level in the mold at the time of additives.

Keywords: final alloying, self-similarity, Weber number, steel top casting.

1 Introduction

The task of refining steel from non-metallic inclusions (NMI) today is very relevant both in Ukraine and around the world, which is caused by the constant growth of requirements for the quality of steel products. Traditionally, removal and modification of NMI in steel occurs in a teeming ladle during the ladle treatment, and in continuous casting also in a tundish and a mold of the continuous casting machine [1]. However, taking into account the technological features of the method proposed by the authors for the final alloying of steel in the mold [2], it becomes necessary to study the processes of floating up of endogenous NMI formed in the mold during the interaction of alloying components with oxygen in the liquid phase of the ingot during holding and casting. NMIs, which do not have time to float up, cause the deterioration of the steel quality. Therefore, the aim of the study was to study the floating up of NMIs in the mold during its filling and holding.

2 Literature Review

It is known that the floating of particles in a liquid is described by Stokes' law. However, deviation from this law can be observed out of the laminar regime of particles floating (Re> 2), for a non-spherical shape of particles, floating of an ensemble of particles, etc. [3]. According to the results of previous studies, it was confirmed that the steel flow rate during tapping from the furnace and the shape of the inner space of the ladle lining have a significant effect on the floating up of NMIs [4]. Residual vortices existing in the liquid volume after the ladle has been filled can both suppress and intensify the process of NW floating up depending on the geometrical profile of the lining. Obviously, this should also happen when filling the mold.

Similar phenomena are observed when filling the mold of the continuous casting machine. Intensive circulation of metal in the closed volume of the mold can both facilitate the removal of NMIs to the metal surface in the mold, and vice versa, draw them deep into the liquid core. The behavior of NMIs in the liquid core of the billet during continuous casting of steel was studied in [5-7].

When adjusting the flow pattern in the mold by using MEMS, the number of NMIs, especially of small sizes, decreases, and the depth of their location under the billet rim increases [8]. In addition, MEMS reduces the depth of immersion of the jet in the billet liquid core, which has a positive effect on the NMIs removal and the conditions for the rim formation [6, 9].

3 Research Methodology

3.1 Choosing similarity numbers for modeling of a process

As the objective function, we chose the time of the particles floating up (τ) in the mold. In accordance with Stokes' law and logical reasoning, the chosen objective function is influenced by the following factors: NMI diameter (d), height of the liquid in the mold (h), density of the liquid (ρ_{liq}) and NMI (ρ_{NMI}), gravitational acceleration (g), kinematic viscosity (ν) and surface tension (σ) of the liquid and the casting speed (w).

The resulting functional dependence is following

$$\tau = f(d, h, \rho_{liq,}\rho_{NMI,}g, \nu, \sigma, w). \quad (1)$$

For convenience, we replace (ρ_{NMI}) with the difference between the densities of the liquid and NMI (Δρ). Thus, the dimension contains 9 parameters, of which 7 have various units of measurement. Their dimension includes 3 primary units of measurement: kg, m, s. Then the total amount of dimensionless complexes will be 9–3 = 6. Dimensionless similarity numbers characterizing dependence (1) and their magnitude are given in Table 1.

The density simplex (P) is a measure of the Archimedean force acting on the NMI in the melt. Compliance with this simplex on the model is rather difficult, since it requires the use of high-density fluids, or low-density powders to simulate HB. To simplify the simulation, we multiply the density simplex by the Galilean number and the linear simplex (D).

$$Ar = P \cdot Ga \cdot D^3 = \frac{\Delta\rho}{\rho_{liq}} \cdot \frac{gh^3}{\nu^2} \cdot \left(\frac{d}{h}\right)^3 = \frac{\Delta\rho g d^3}{\rho_{liq}\nu^2}. \quad (2)$$

Table 1 – Choosing of similarity numbers for modeling

Para-meter	Magnitude	Unit	Scale	Similarity numbers	Magni-tude
τ	10^2	s	–	$Ho' = \frac{\tau^2 g}{h}$	10^4
d	10^{-5} – 10^{-3}	m	–	$D = \frac{d}{h}$	10^{-6} – 10^{-4}
h	10^1	m	m	–	–
ρ_{liq}	10^3	kg/m³	kg	–	–
Δρ	10^3	kg/m³	–	$P = \frac{\Delta\rho}{\rho_{liq}}$	10^0
g	10^1	m/s²	s	-	–
ν	10^{-6}	m²/s	–	$Ga = \frac{gh^3}{\nu^2}$	10^{16}
σ	10^0	kg/s²	–	$We = \frac{\rho_{liq} g h^2}{\sigma}$	10^6
w	10^{-3}	m/s	–	$Fr = \frac{w}{\sqrt{gh}}$	10^{-4}

The value of the obtained similarity number is $10^{-2} – 10^4$. It characterizes the ratio of the lifting forces acting on the NMI to the viscous force, which inhibit it from floating up.

Weber number (We) is a measure of gravitational and capillary forces.

Froude number (Fr) is a measure of inertial and gravitational forces.

Thus, functional dependence (1) in dimensionless form is following

$$Ho' = f(D, Ar, We, Fr). \quad (3)$$

3.2 Estimating the significance of the selected similarity numbers

As already shown in [10-13], the complete similarity of hydrodynamic processes with compliance of the equality of the Froude, Reynolds and Weber numbers on the prototype and the model is impossible, since the latter criterion requires the use of a linear scale of 0,6. Even if we use the approximate similarity technique and neglect the Weber number, the observance of the equality of the Reynolds and Froude numbers will require the use of a 1:1 scale model [11–3]. In [14], the authors also used only the Froude number when modeling the nature of flows in a tundish using turbulence inhibitors.

Therefore, to conduct further studies of the NMIs floating up in the mold during its filling, it is necessary to experimentally prove the insignificance of these similarity numbers. The self-similarity of the linear simplex $D < 10^{-2}$ when the NMI floats up was proved by the authors earlier [4].

The Weber number for the prototype and its model at a scale of 1:3.5 is $10^{5.5}$ and $10^{4.75}$, respectively. To solve this problem, the authors used the approximate similarity technique, according to which similarity number, which have an insignificant effect on the process, can be neglected. Such a criterion in this case is the Weber number (We). Neglecting this similarity number allows smaller mold models to be used in physical modeling. To do this, one should first experimentally prove the hypothesis that the Weber number is self-similar in the range $10^{4.75} < We < 10^{5.5}$.

At the same time, the authors of [15] emphasize the great importance of the Weber number in the study of the process of pulling slag droplets into the metal during casting. Since in this case the purpose of the experiment was to study the process of floating up of the NMIs already present in the metal, it was decided to neglect the slag layer on the metal surface.

For experimental confirmation of the self-similarity hypothesis, an experimental facility was assembled, an experimental plan was drawn up and a series of 15 experiments was carried out. The experimental facility is shown in Fig. 1.

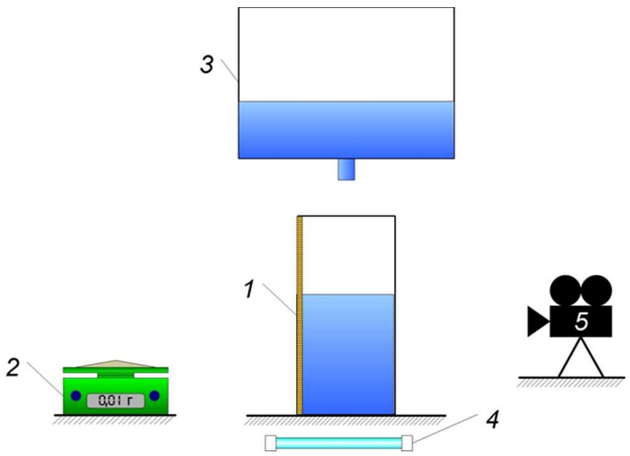

Figure 1 – Experimental facility: 1 – mold model; 2 – electronic scale; 3 – model of the teeming ladle; 4 – lamp; 5 – video camera

The facility included a set of molds models of different sizes (Table 2).

Table 2 – Dimensions of the mold models for physical modeling

№	Mold dimensions, mm			Linear scale[1]
	width	thickness	height	
Prototype				
1	669	669	2205	1:1
Models				
2	87	87	259	1:8,5
3	245	230	630	1:3,5
4	290	255	900	1:2,5

Before the start of the experiment, a sample of stearine with a fraction of 1 mm and a density of 900 kg/m^3 was weighed on an electronic scale 2 with an accuracy limit of 0.01 g based on the similarity of the volume concentration of powder in the liquid on the model and prototype 0.00288 m^3/m^3 [4]. A weighed sample of the powder was carefully loaded onto the bottom of the mold, after which water was poured from the ladle model 3. The height of the drain hole above the bottom of the mold model was changed considering the linear scale for each experiment. The mold model was illuminated by a 150 W halogen lamp 4. The surfacing time was determined by video recording of the experiments, which were carried out on a video camera 5 in HD mode.

According to Markov [3], the self-similarity of the dimensionless numbers can be judged by the graph of the differential dependence between the logarithms of the criteria, that is $\frac{d\lg\ y}{d\lg\pi_x} = f(\lg\pi_x)$. He identifies 3 possible options:

1) $\frac{d\lg\pi_y}{d\lg\pi_x} = var$ – a zone of significant influence,
2) $\frac{d\lg\pi_y}{d\lg\pi_x} = 0$ – a zone of self-similarity,
3) $\frac{d\lg\pi_y}{d\lg\pi_x} = const$ – a zone of non-independent (formal) influence.

3.3 Comparative evaluation of the efficiency of finishing alloying of steel in a mold

A significant advantage of finishing alloying of steel, in particular in the mold, is the relatively low oxygen activity in the metal and, as a consequence, a higher assimilation degree the alloying element. However, the disadvantage of this method, limiting its application, is the low efficiency of NMI removing from steel.

Due to the existence of two methods of casting steel, the methods of performing the finishing alloying for them will also be slightly different. In top casting, it is only possible to introduce an additive under the stream at different metal level in the mold, while during bottom casting, it is possible to introduce the additive both into the mold and into a trumpet also at different heights of the metal in the mold. In addition, the addition of additives is possible at different casting speeds, which, however, are limited to specific limits, ensuring the highest quality steel ingot.

To evaluate the efficiency of finishing alloying from the point of view of removing deoxidation products from steel, a series of 24 experiments was carried out, including additive during casting into the trumpet and under the stream onto the mirror of the metal into the mold at different metal levels and different casting speed.

4 Results

4.1 Testing the hypothesis that the Weber number is self-similar

To identify the area of self-similarity of the Weber number, the graphs of the function $\lg Ho' = f(\lg We)$ and $\frac{d\lg Ho'}{d\lg We} = f(\lg We)$ (fig. 2). The derivative of the Ho' with respect to the Weber number was found by using the two-sided difference method in Microsoft Excel with a step of $\lg We = 0.1$.

Fig. 2 shows that the derivative of the logarithm of the Ho' number is close to zero over the entire definitional domain of the Weber number. This means that the

[1] Since it was the height of the NW float that mattered for modeling, the scale was determined by the height of the mold.

similarity of the NMIs floatation process when filling the mold is carried out at a linear scale of the mold from 1:8.5.

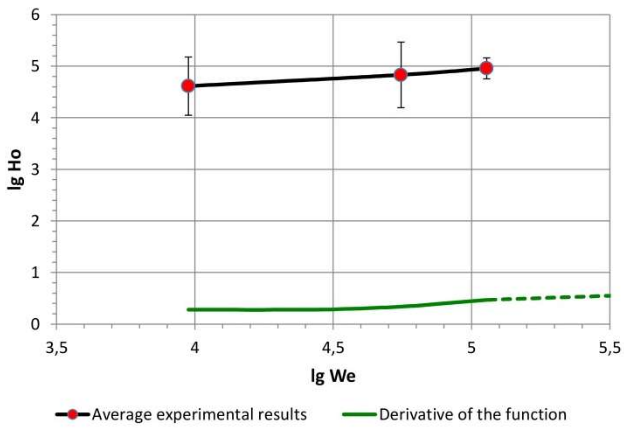

Figure 2 – Dependence of the logarithm of the Ho' number and its derivative on the logarithm of the Weber number

4.2 Determination of the rational regime of additives

In the first series of experiments the top casting was simulated and the additive was added to the mold onto the metal mirror under the stream. The liquid level at which the additive was introduced into the mold was 0, 25, 50, 75% of the mold height. It is obvious that the addition of the additive after filling the mold is irrational, since it will not ensure proper dissolution of the additive in the metal. The casting speed was also varied at the level of 0.1, 0.2 and 0.3 m/min. Based on the results of the regression analysis of the experimental data, a mathematical model was obtained that describes the change in the time of the particles floating in the mold depending on the parameters considered.

$$\tau = 279 - 0{,}0428h^2 - 451w^2 + +1{,}028hw - 0{,}07h + 70{,}79w, \quad (4)$$

where h is the liquid level in the mold model, %; w – casting speed, m/min.

From the analysis of the obtained model, it follows that the greatest influence on the time of floatation of inclusions in the mold is exerted by the liquid level in the mold at the additive time. This dependence is shown graphically in fig. 3.

As you can see in the fig. 3, when adding additives under the jet, tends to zero at a liquid level in the mold of 81%. This can be explained by the fact that at a lower liquid level, due to its intensive mixing by the falling stream, the particles are evenly distributed throughout the entire volume of the liquid. At the same time, at a high liquid level in the mold, the penetration depth is less and the particles are entrained into the liquid volume to a relatively smaller depth.

The second series of experiments involved modeling the additive into the trumpet, also at various metal levels in the mold and various casting speed. The liquid level at which the additive was introduced into the mold, as in the previous series of experiments, was 0, 25, 50, 75%, and the casting speed varied in the range of 0.1, 0.2 and 0.3 m/min. The dependence of the floatation time of NMIs on the liquid level in the mold has the same character (see Fig. 1), however, the floatation time of inclusions in a bottom casting is noticeably higher than in a top casting. The mathematical model describing the dependence of the floatation time on the liquid level and the casting speed has is following

$$\tau = 415 - 0{,}0391h^2 + 5966w^2 - 11{,}189hw - 3{,}883h - 2140{,}36w \quad (5)$$

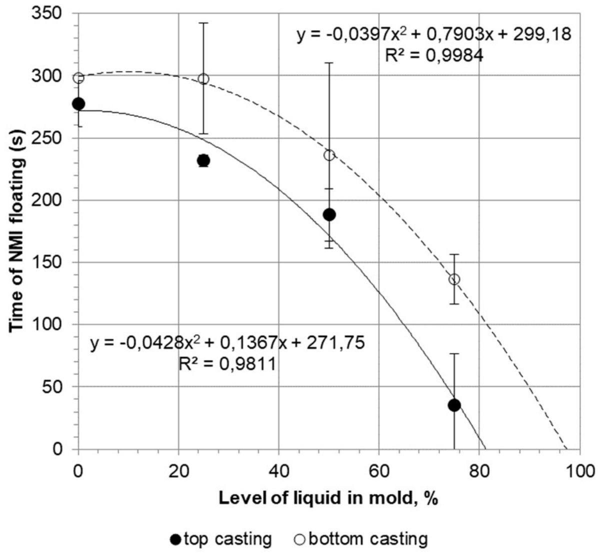

Figure 3 – Influence of the liquid level in the mold on the time of the particles floating up in different casting methods

5 Discussion

The self-similarity of the Weber number in the above-mentioned range is valid only for liquid volumes with size ratios close to the investigated models. In particular, on the models used, the ratio of height to transverse dimension varied in the range of 2.57-3.53, and for the prototype it was 3.3. The self-similarity of the Weber number for molds or other containers with a different ratio may not be observed. Furthermore, as already mentioned above, the addition of a substance simulating slag to the system also leads to the need to take into account the Weber number in physical modeling.

The mathematical models obtained above for describing the floatation time show a general tendency in the introduction of additives into the mold in top and bottom casting. They make it possible to evaluate the efficiency of various modes of finishing alloying of steel and to select a rational casting method and processing mode. The similarity numbers proposed above make it possible to transfer the results obtained to the industrial conditions of steel processing.

6 Conclusions

The similarity numbers are analyzed for modeling the flow movement during steel casting. The hypothesis of the self-similarity of the Weber number for metal circulation during metal pouring into molds has been experimentally confirmed.

It has been established that, from the point of view of removing deoxidation products from steel, the most rational method for the use of finishing alloying is the method of casting steel from above. Subject to the temperature-speed mode of casting, approved at the enterprise, it provides a much shorter time for the complete NMIs floating from steel. A significant effect of the liquid level in the mold during the addition of additives on the float time of nonmetallic inclusions was also noted. Its value for all types of casting drops rapidly with increasing liquid level in the mold. The approach to zero of the NMIs float time occurs when the liquid level in the mold is 81 and 97 %, respectively, in the top and bottom casting.

Further research is aimed at studying the processes of distribution of alloying and modifying additives introduced during the filling of the mold and the time of their homogenization in the volume of the metal.

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