THE EFFECT OF BOUNDARY CONDITIONS OF CASTING ON THE SIZE OF MACROSEGREGATION IN HEAVY STEEL INGOTS

Markéta TKADLEČKOVÁ, Pavel MACHOVČÁK, Marek KOVÁČ, Karel GRYC, Karel MICHALEK, Bedřich SMETANA, Ladislav SOCHA

VŠB – Technical University of Ostrava, Faculty of Metallurgy and Materials Engineering, Department of Metallurgy and Foundry, and Regional Materials Science and Technology Centre, Czech Republic, marketa.tkadleckova@vsb.cz, karel.gryc@vsb.cz, ladislav.socha@vsb.cz, karel.michalek@vsb.cz

VÍTKOVICE HEAVY MACHINERY, a.s., Czech Republic, pavel.machovcak@vltkovice.cz

MECAS ESI s.r.o., Czech Republic, marek.kovac@mecasesi.cz

VŠB – Technical University of Ostrava, Faculty of Metallurgy and Materials Engineering, Department of Physical Chemistry and Theory of Technological Processes, and Regional Materials Science and Technology Centre, Czech Republic, bedrich.smetana@vsb.cz

Abstract

The paper builds on the previous work of authors devoted to the verification of casting technology of 90-ton heavy steel ingot using numerical modelling and operational experiment. Numerical modelling was performed with use of the ProCAST software. In the first stage of an extensive modelling research, the conditions of heat transfer used in the setting of calculation of casting and solidification were modified based on experimental thermography measurement. Thermodynamic properties of steel were also verified. The results of numerical modelling of macrosegregation in ingot under standard conditions of casting were continuously compared with the results obtained from the analysis of experimentally cast ingot. Once the agreement has been reached between the numerical and experimental results of the research, the attention was paid to verification of the effect of boundary conditions of casting on the size of macrosegregation in heavy steel ingots. In the case of casting of steel ingots, the most important and most easily influenced technological boundary conditions include the casting temperature and the speed of the casting. In contrast, the material of the mould or the grade of cast steel cannot be arbitrarily changed. For this reason, the attention was focused on the verification of the extent of ingot volume defects depending on the casting temperature of steel and casting speed. The best appeared to be the variant, in which was used the decrease of casting temperature during filling of the mould and simultaneously the longer casting time up by 15 minutes.

Keywords: heavy steel ingot, macrosegregation, numerical modelling, ProCAST

1. INTRODUCTION

Based on available literature [e.g. 1, 2], it was confirmed that the macrosegregation in heavy steel ingots is a function of chemical composition of the steel, of the applied method and time of solidification. This means that in order to minimize the extent of the segregation in the heavy steel ingot it is not sufficient to change only the geometry of the mould, but it is also necessary to optimize the mode of casting [3, 4] and primarily to control of solidification. Especially in demanding metallurgical conditions, it is appropriate to apply the method of numerical modelling using some of the available simulation software. In the previous works of the authors [5, 6, 7, 8] the attention was focused on the verification of definition of thermodynamic parameters and parameters of heat transfer coefficients in numerical model of the casting and solidification of 90-ton steel heavy ingot produced in VÍTKOVICE HEAVY MACHINERY a.s. (VHM). The numerical modelling was realized in ProCAST simulation programme under the conditions of the Department of Metallurgy and
Foundry and the Regional Materials Science and Technology Centre at the VSB-TU Ostrava in cooperation with the company MECAS ESI s.r.o. The results of numerical modelling of macrosegregation in ingot under standard conditions of casting were continuously compared with the results obtained from the analysis of experimentally-cast ingot [7, 9]. Once the agreement has been reached between the numerical and experimental results of the research, the main aim of the next simulations was to verify the effect of boundary conditions of casting on size of macrosegregation in heavy steel ingots. The presented paper highlights the most important information about the setting of numerical model and compares the resulting size of macrosegregation in steel ingot under different boundary conditions of casting.

2. NUMERICAL SIMULATION

2.1 Mesh generation

The ProCAST software is based on the finite elements method. When large ingots are modelled, the mesh size becomes very large with respect to the thermal gradients, especially in the early stages of cooling. In order to obtain appropriate answers (i.e. more accurate temperatures), it is advised to generate few layers (of few mm in thickness) inside the ingot, as well as inside the mould, as it is shown in Fig.1 [10].

![Fig.1 Volume mesh in cross section of the casting system](image)

In Fig.1 volume mesh in cross-section can be seen. Major part of the ingot has rough mesh (violet) and layer of fine mesh is at borders (ochre) [11]. The simulation can be divided to computation of the filling phase and the solidification phase. Then, in many cases, the mesh for simulation of filling is usually different than the mesh for solidification. For example, it is not necessary to have the whole gating system during the computation of the solidification. In our case, the uniform mesh with average size of elements of 30mm/50 mm was used for both filling and solidification.

2.2 Boundary conditions vs. simulated variants

VÍTKOVICE HEAVY MACHINERY a.s. is traditional producer of large machinery components. For these products it is necessary to cast ingots weighing up to 200 tons. Steel plant of VHM is equipped with EAF, LF, VD and VOD facilities. Ingots from 1.7 up to 200 tons are bottom cast. The EAF capacity is 70 tons so the larger ingots are cumulated from two or three heats. An experimental 90-ton ingot was cast at the steel plant VHM in order to determine the extent of chemical heterogeneity. As it was mentioned, this type of ingot was cast from two heats. Each of these two heats had different content of copper and nickel in order to determine mixing of these two heats in the solidified ingot. Content of other elements was targeted at the same level. Chemical analysis of both heats and the weighted average of both heats reflecting different weight of these heats were published in [9]. However, the filling was simulated in one step (without interruption during the changing of the ladles) during the numerical simulation because in the numerical model it would be very difficult to mathematically/physically/chemically describe the way of mixing of steels in the ingot body.

The casting speed and casting temperature differed according to the simulated variant. The primary variant (A) was set according to the experimental casting conditions of the ingot experimentally cast in VHM. Other three variants (B, C, D) differed either by the casting temperature (B) or by the casting speed (C) or by both (D). The overview of boundary conditions (casting speed/ casting temperatures) of the simulated variants is given in Table 1.
Table 1 Overview of boundary conditions of simulated variants

<table>
<thead>
<tr>
<th>Variant</th>
<th>Casting Temperature [ °C]</th>
<th>Total filling time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1570</td>
<td>55</td>
</tr>
<tr>
<td>B</td>
<td>1570 →1540 during 55 min</td>
<td>55</td>
</tr>
<tr>
<td>C</td>
<td>1570</td>
<td>65</td>
</tr>
<tr>
<td>D</td>
<td>1570 →1540 during 65 min</td>
<td>65</td>
</tr>
</tbody>
</table>

2.3 Material properties

In pre-processing phase, the material properties of individual components of casting system have to be defined. Structural carbon manganese steel (S355J2G3 according to the EN 10 250) was chosen for this trial. For simulation of casting and solidification of a 90-ton ingot, the new modified steel grade S355mod., including its thermodynamic properties, had to be defined in the PreCAST module in the section ‘Materials’ using the integrated thermodynamic database Computherm. As it was mentioned above, in experimental casting conditions the ingot was cast from two heats, which differed by content of Cu and Ni, in order to determine mutual mixing of these two heats in the solidified ingot [9]. However, it is not yet possible in the ProCAST to simulate the filling of the different steel grades through only one inlet. Therefore only the chemical composition of the weighted average of both heats [9] was used. The quality of the results of the numerical simulation of the volume defects in ingots, especially macrosegregation of elements, is mainly determined by the quality of the thermodynamic properties of the steel and of the mould material. Therefore the generated thermodynamic properties of the mould material were also experimentally studied by the DSC thermal analysis, as it was published in [8]. The properties of refractory materials were determined as indicated in the data sheets provided by the manufacturer.

2.4 Interface

To be sure that the heat transfer conditions (HTC) are set correctly, the thermography measurement of temperature fields and heat flux of the individual parts of the casting system during the experimental casting of the 90-ton ingot was ensured [5, 6]. The HTC is very dependent on the quality of the surface contact between the ingot and mould. Usually, the HTC is described in the literature as a constant. In our case, the HTC were set depending on the time or temperature. The validated coefficient was in the range 150- 800 W/m²K. On the basis of results of thermography measurement, the temperature fields on the mould surface [5] and also on the ingot body surface obtained from numerical modelling were compared, as it is shown in Fig.2. The area of the hot top was influenced by the insulation.

2.5 Computation of macrosegregation

As it was published in [7], the computation of macrosegregation is possible due to the MACRO module – it is necessary to activate it in RUN PARAMETERS using the value “1”. The MACRO module is integrated with thermodynamic parameters of the cast materials, such as liquidus temperature and solidus temperature. The liquid species conservation is governed by the equation [10]:

![Fig.2 Comparison of temperature fields on the ingot surface after the stripping](image-url)
\[ f_i \rho_i \frac{\partial c_i^m}{\partial t} + f_i \rho_i \mathbf{v}_i \nabla c_i^m = \nabla \cdot \left( f_i \rho_i D_i^{m} \nabla c_i^m \right) + \left( c_i' - c_i^m \right) \frac{\partial}{\partial t} \left( \rho_i f_s \right) + \frac{s \rho_i D_i^{m}}{l} \left( c_i^m - c_s^m \right) \]  

The solid species conservation is described by the equation (2)

\[ f_s \rho_s \frac{\partial c_s^m}{\partial t} = \left( c_i^m - c_s^m \right) \left[ \frac{\partial}{\partial t} \left( \rho_s f_s \right) + \frac{s \rho_s D_s^m}{l} \right] \]  

where \( c \) is concentration, \( m \) is species, \( I = f_s d_2/6 \) is diffusion length, \( S = 2/d_2 \) is interfacial area concentration, \( sl \) is solid and liquid interface and \( D \) is diffusivity. Obviously, the macrosegregation is influenced by the natural convection during solidification – therefore it is recommended also to activate the FLOW module. The temperature dependence of density for liquid metals is linear:

\[ \rho^m(T) = \rho_{ref}^m + \left( \frac{\partial \rho}{\partial T} \right)_{ref} \left( T - T_{ref}^m \right) \]  

where \( \rho_{ref}^m \) is the reference density, \( T_{ref}^m \) is the reference temperature. The liquid density is calculated by equation (4):

\[ \rho(T)^{-1} = \sum_m c_i^m \rho^m(T) \]  

where \( c_i^m \) is the liquid concentration.

3. RESULTS AND DISCUSSION

Before comparison of experimental and numerical results of macrosegregation, it was necessary to consider these differences: a) as it was mentioned above, the experimental ingot was cumulated from two heats. In numerical modelling it was not possible to simulate the change of chemical composition; therefore the constant contents of the elements during whole simulation was used; b) if we compute macrosegregation, it is necessary to consider these limitations: no solid movement, no grain sedimentation, fully equiaxed dendrites, no columnar dendrites; c) in order to cover the evolution of element macrosegregation, the filling phase and the solidification phase were simulated in one step with use of one type of computational mesh.

**Fig. 3** shows the temperatures fields at 43 - 49 min. of the filling phase for all four simulated variants. As it is evident, the lowest temperatures were achieved in the variant D when we supposed the longer filling time (65 min.) with the decrease of the casting temperature of approx. 30 °C during 65 minutes (the casting temperatures decreased from 1570 to 1540 °C in the ladle, which means that the temperature of steel in the ladle decreased approx. by 0.46°C.min⁻¹). In real conditions, however, the decrease of the temperature in the ladle is smaller. On the other hand, when we compared the temperature fields in the ingot body after one hour and thirty six minutes after filling (**Fig.4**), the differences between the temperatures of steel at individual variants were much smaller because of the big volume of hot metal. So, we may suppose, that the final solidification time and also the macrosegregation will be probably similar. **Fig.5a** presents a comparison of the final macrosegregation of carbon in the central cross section of the ingot body for individual variants. The lowest differences in the content of the carbon along the height of the central axis were reached in the variant D. However, in comparison with the variant A, the average difference is only 0.02 wt. %. **Fig.5b** presents a comparison of the distribution maps of carbon in the half cross section of the ingot body. As it can be seen, the distribution of carbon is in the variant D more homogeneous. For remaining element (Mn, Si, Cu, Ni, S, P) the situation was similar. As it was also mentioned above, since no grain sedimentation took place, the negative macrosegregation was neglected, as it is evident from **Fig.5**.
Fig. 3 Comparison of the temperature fields at 43 - 49 min of the filling phase between the simulated variants

Fig. 4 Comparison of temperature fields in the ingot body after 1 hour and 36 min after filling

Fig. 5 Comparison of final macrosegregation of carbon in the central cross section of the ingot body
4. CONCLUSION

The paper was devoted to the verification of macrosegregation in heavy steel ingot depending on the boundary conditions of the casting. Four variants were simulated, where the casting temperature and casting speed (or the filling time) were changed. The simulations included the filling and solidification phase together with computation of the segregation processes. In all variants, the final character of the solidification was very similar. The slight extension of the time to solidus can be observed when we extend the filling time by 15 minutes (from 50 to 65 minutes). The lowest level of macrosegregations were achieved in the variant D when we used the longer filling time together with decrease of casting temperatures approx. by 30 °C because of the cooling of the melt in the ladle during 65 minutes of the casting. However, the tested adjustment of casting technology appeared to have only small impact on the resulting macrosegregations.

ACKNOWLEDGEMENT

This work was financially supported by the Program Project TIP No.: FR-TI3/243 of the Ministry of Industry and Trade of the Czech Republic and as a part of the Project No.: CZ.1.05/2.1.00/01.0040 “Regional Material Technology Research Centre under the Operational Program Research and Development for Innovation funded by EU Structural Funds and by the State budget.

LITERATURE


