OPTIMIZATION OF HTC VALUE BY INVERSE MODEL BASED ON EXPERIMENTAL MEASUREMENT OF A 26.6-ton STEEL INGOT

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KEYWORDS

Steel ingot, numerical simulation, heat transfer coefficient (HTC), thermocouples.

ABSTRACT

A 26.6-ton steel ingot has been experimentally investigated during the whole industrial casting process to determine the heat transfer coefficient (HTC) with the mould as a function of the temperature. The determination of this parameter is strongly important for the correct setting of numerical simulations because it greatly influences the solidification and, therefore, the occurrence of defects in steel ingots, such as shrinkage porosities and segregations.

Temperature variations of eight distinct positions inside the mould were recorded to acquire thermal conditions and determine the HTC value at the interface between ingot and mould. The calculation was carried out through the inverse model implemented in the ProCAST® 2022 simulation software. All parameters and boundary conditions of the industrial process were evaluated and recorded during the filling and solidification steps. The thermal properties of the materials used in the model were previously measured in laboratory.

INTRODUCTION

Steel ingots are semi-products used for the realization of forged components widely diffused in several industrial fields: nuclear, aerospace, oil & gas, etc. During their filling and solidification, different defects and inhomogeneities arise, such as porosities and segregations which cannot be avoided as inherent in the process, strongly affecting the final mechanical properties. However, the extent of these defects can be remarkably reduced by acting on the shape and the geometry of the ingot as well as on the casting parameters (Heidarzadeh & Keshmiri, 2013; Kermanpur et al., 2010). An effective investigation tool to improve the internal soundness of the ingots consists in the use of mathematical models that are able to predict the onset of these defects, thanks to the most advanced simulation software (Horr, 2019). The reliability of simulation results strongly depends on the materials properties and the boundary conditions chosen in the setting step, which must be as much as possible closed to the real industrial process.

One of the most widely discussed and difficult to measure parameter is the heat transfer coefficient (HTC) at the interface between the steel and the ingot mould. It is well-known that this value is essential for the correct setting of the simulation because it strongly influences the solidification of the steel (Zhang et al., 2008), since it is closely related to the ability of two volumes in contact to transmit heat through the interfaces (Anna Gowsalya & E. Afshan, 2021). HTC should only consider how two volumes exchange heat and it is influenced by many factors like roughness of the interfaces, geometry of the casting, mould temperature, metallostatic pressure and the presence of an air gap which acts as insulator (Lewis & Ransing, 1998; Hamasaiid et al., 2007).

Many experiments have been carried out for the determination of this parameter, especially for casting process such as high-pressure die-casting and continuous casting (Cao et al., 2012; Hamasaiid et al., 2007; Helenius et al., 2005; Koru & Serçe, 2016; Lau et al., 1998; Long et al., 2011; Santos et al., 2001; Wang et al., 2017; Zhi-peng et al., 2008; Zhipeng et al., 2014). Regarding the ingot casting process, there are few studies that allow to validate the model of the HTC calculation based on inverse heat conduction problem, due to the difficulties in carrying out *ad hoc* tests and due to the computer calculation limits. In fact, the size of steel ingots requires extremely long calculation time usually not compatible with an industrial production rate. Moreover, for the same reason, an experimental validation appears strongly expensive. Duan et al. determined the value of HTC on a 36-ton ingot by simulating the formation of the air gap between the ingot and mould with thermo-elasto-plastic and thermo-elastic models, considering only the ingot solidification phase. The HTC was then evaluated by minimizing the error between predicted and measured values (Duan et al., 2016). Li et al. evaluated the effect that the air gap formed during solidification of a 23-kg ingot induces on the value of HTC, by using the inverse model with minimization of the Taylor polynomial series (Li et al., 2021), again considering only the solidification phase.

All these studies were conducted by using different

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inverse methods and optimizing the HTC value as a function of the time, thus losing important information about the evolution of HTC with the temperature. Lan and Zhang determined the HTC value as a function of temperature by using an inverse model based on thermophysical parameters calculated by microsegregation model and experimental data measured at the outer face of the mould but for a small ingot of 8.5-ton just considering the solidification step (Lan & Zhang, 2014).

In this paper, the interfacial heat transfer coefficient of a 26.6-ton steel ingot was determined by inverse model simulation as a function of the temperature during the whole casting process (filling and solidification phase) by using ProCAST® software. Thanks to the obtained results, it was possible to determine standard HTC values usable for general simulations.

EXPERIMENTAL PROCESS

A 26.6-ton square ingot of 3000 mm in height and 1100 mm in mean side was cast in ASONEXT S.p.A. in Ospitaletto (BS), Italy. The casting system was placed in the casting pit and molten steel was poured at 1575°C. The mould was made of four segments of hematite cast iron (upper plate, bottom plate, ingot mould and column, orange, pink, blue and grey in Figure 1(a) respectively). The insulation sleeve had a height of 390 mm and a thickness of 35 mm and was positioned in the upper part of the mould. The runners and the ingate system were in refractory bricks made in bauxite and alumina. To fill the gap between the cast iron and the refractory bricks, olivine sand was used. Powders used during the filling step were closed in bags suspended about 500 mm over the base of the ingot mould. At the end of the filling, additional powders were used to insulate the free surface and cover completely the molten steel. The LF3 steel composition is reported in Table 1.

Eight different thermocouples were set in the mould at different height on the same generatrix to measure the temperatures reached in different points during the filling and the solidification. The holes for the thermocouples positioning inside the mould were machined with different drill tips with a 4 mm diameters and different lengths (100, 160, 200 and 315 mm) and a box column drill was used. For temperatures recording, N-type thermocouples with a 3.1 mm of diameter were fixed and connected to a continuous recording device. In Figure 1(b) positions of the thermocouples are shown: five thermocouples (1I-5I) were set at different heights (250 mm, 950 mm, 1450 mm, 2000 mm and 2700 mm) and at distance of 30 mm from internal surface of the mould; three thermocouples (6E-8E) were set closed to the external surface (30 mm) at 50 mm distance from the internal ones. The temperatures were recorded for almost 10 hours every 20 seconds, from the beginning of the filling phase until the stripping of the ingot.

Based on the recorded temperatures, the heat transfer coefficient was derived according to the procedure detailed in the following paragraph.

To evaluate the boundary conditions of the overall casting assembly, a thermal imaging camera Testo 868s was used, collecting images of the external surface of the mould parts inside the casting pit for the first 2 hours. This additional measure was useful to understand the effect of the heat radiation from the walls of the casting pit and from the pot used to receive the first molten steel tapped at the opening of the ladle slide gate.

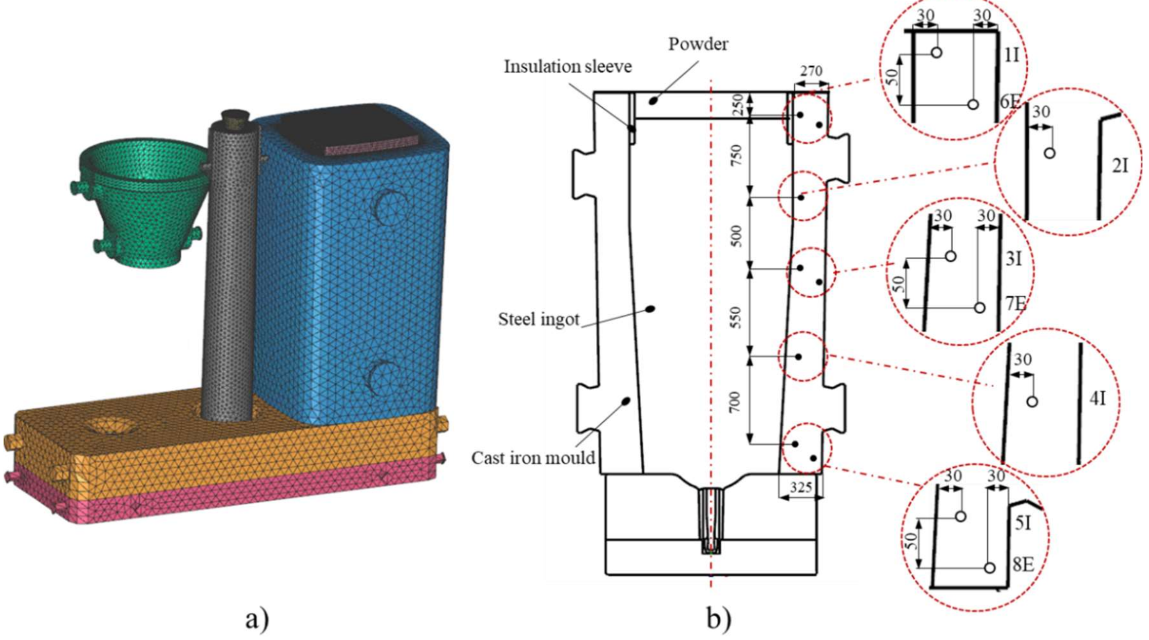

Figure 1: (a) Casting System of the 26.6 Square Ingot, (b) Schematic Position of the Eight Measurement Positions Inside the Mould: 5 Internal (1-5I) and 3 External Points (6-8E).

Table 1: Chemical Composition of LF3 Steel Ingot.

Elements	**C**	**Mn**	**Si**	**P**	**S**	**Cu**	**Cr**	**Ni**	**Mo**
(Wt. %)	0.17	0.55	0.30	0.007	0.0005	0.13	0.11	3.51	0.06

NUMERICAL SIMULATION

A three-dimensional finite-element model of the 26.6-ton ingot was used to simulate the filling and solidification steps and to determine the HTC values through the inverse method (HTC inverse model), based on the adaptive response surface method (RSM) of the optimization Pam-OPT, already present in the software. The commercial software ProCAST®, based on finite element method (FEM), was used and a mesh of 159,281 surface elements and 2,537,442 tetrahedral elements was created as shown in Figure 1(a). To solve the well-established equations such as the conservation of mass, momentum, energy and continuity equation, it is necessary to properly define the material data, as well as the initial and boundary conditions (Pola et al., 2016). In particular, five different materials were chosen in the system: hematite cast iron, LF3 steel, refractory bricks, olivine sand and insulator. The thermophysical properties of steel and cast iron were calculated by CompuTherm Database available in ProCAST® based on their chemical composition. The properties of insulating material and refractory were selected based on the data producers. The values of the specific heat for cast iron, refractory bricks and insulating materials were measured by tests carried out with a DSC/TGA TA Instrument Q600 SDT under argon atmosphere and performed according to the ASTM E1269–11, from 50°C to 1400°C.

The initial values of HTC between steel ingot and mould were chosen based on the steel $T_{liquidus}$ and $T_{solidus}$: at higher temperatures it was set at 1000W/m^{2}K and 250W/m^{2}K at lower temperatures, according to the literature (Duan et al., 2016). HTC constant values were set at 200W/m^{2}K between sand and mould/refractories and 2000W/m^{2}K between the cast iron parts.

As reported, under production the mould is placed in a casting pit, therefore the heat exchange between the casting system and the environment takes places via both convection and radiation. Regarding convention, a heat exchange coefficient in function of temperature from 15W/m^{2}K to 70W/m^{2}K was considered with surrounding air from 20° to 60°C as a function of time.

Concerning the radiation, to consider the effect of the environment and of the casting pit, an artificial "enclosure" was added. Another boundary condition was the insulating effect of the mould powder added on the free surface of the steel (reducing the heat exchange coefficient and the emissivity). The effect of the presence of a tank near the mould ingot was also considered (green domain in Figure 1(a)). The time-dependent teeming flow rate was applied according to the procedure used in the steel plant process (3000kg/min for the first minute, 600kg/min for 35min and 250kg/min until the end).

RESULTS

In Figure 2 the trend of the temperature in 3 different thermocouple positions (1I, 3I and 8E) is shown as an example of the recorded data, but all the comments below are proper for all the eight positions. As expected, the higher temperatures are reached by thermocouples placed in the internal surface (max 764.9°C in 3I). The thermocouples closed to the external surface have a similar trend but delayed in time and lower temperatures (max 547.2°C in 7E). The temperature trend is similar in all the evaluated positions: the heating rate is very high in the first curve section then it reduces suddenly, the temperature reaches a maximum, and then decreases linearly. The only exception is given by the thermocouples positioned in the upper part of the mould (1I and 6E), where the presence of a layer of insulation sleeve isolates the head with the result that the temperature continues to increase with time and then stabilize linearly in the last curve section. As expected, in the first filling phase, the temperature rises immediately after 3 minutes from the beginning of casting in the bottom part (5I and 8E). The maximum temperature was reached by thermocouples placed in the central area of the body of the mould, closed to the inner wall (2I, 3I and 4I). The heat lost during the filling phase by the steel through the mould, first in the form of sensible heat and then latent heat, has certainly allowed the increase in the temperature of the cast iron. The positioning of the casting system in the pit further influences the increase of the temperature of the system because of the radiation given by the walls of the pit itself.

The results obtained from the first simulation (1I_First, 3I_First and 8E_First) were compared with those recorded by thermocouples, as shown in Figure 2. The trend of the curves is similar in all the analysed positions (in Figure 2 an example of three different points), but the temperatures appear lower in the first simulation, differing even by almost 130°C (3I). This difference between the recorded temperatures and the first simulation could be explained by the chosen HTC values based on the literature data which were related to different steel, geometry and boundary conditions.

After the optimization carried out by the inverse model, it was possible to obtain the HTC value as a function of temperature. The trend of the values is represented in the right box of Figure 3 as the temperature increases, the HTC value increases in the first part linearly, shows a step variation and then again linear in the final stretch. Comparing the temperatures recorded by thermocouples and those extrapolated from the optimized simulation (1I_Last, 3I_Last, 5I_Last and 8E_Last), the results appear completely aligned with each other (Figure 3). The oscillations of the obtained simulation curves compared to the recorded temperatures by the thermocouples in section 3I (Figure 2 and Figure 3) may be due to material data. The fluctuations in fact begin at the eutectoid temperature of the cast iron which from the results of the experiments conducted in the laboratory and from the literature is at about 723°C (D. Callister Jr. & G. Rethwisch, 2010). The eutectoid transformation is an endothermic phenomenon which absorbs heat and, therefore, leads to a slowing down of the cooling rate. As can be seen from the comparisons, below this temperature, the curves appear particularly aligned with each other but, upon reaching it, a series of oscillations start. Since there is a transformation at this temperature, it is possible that the thermal properties of the material calculated with the CompuTherm of the software are not aligned with the characteristics of the material (especially cast iron) that constitutes the mould.

It can be noticed that the output curves from simulation appear to fit polynomial curves because the optimization algorithm, aimed at evaluating the best inverse HTC value to fit real measured temperature, works with polynomial Fourier series. Therefore, similitude with polynomial fitting are not due to any regression via-datasheet but to the fact that the optimization algorithm (PamOPT) is using such a type of iteration to move inverse HTC curve to better fit ProCAST® results with experimental values. No polynomial regression could fit the initial temperature evolution during teeming.

For what concern the thermal images obtained using the thermal imaging camera, an example is reported in Figure 4. The temperatures reached on the surface of the mould in which thermocouples were places are aligned in the real industrial process (Figure 4(a)) and the optimized simulation (Figure 4b)).

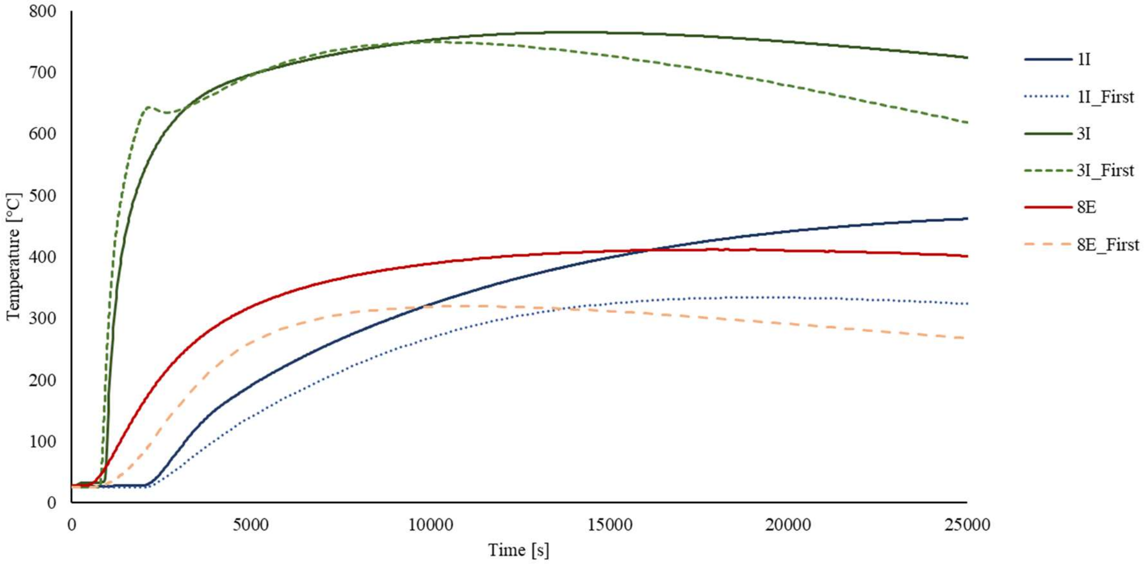

Figure 2: Comparison Between Thermocouples and First Simulation Results in Three Different Positions (1I, 3I, 8E).

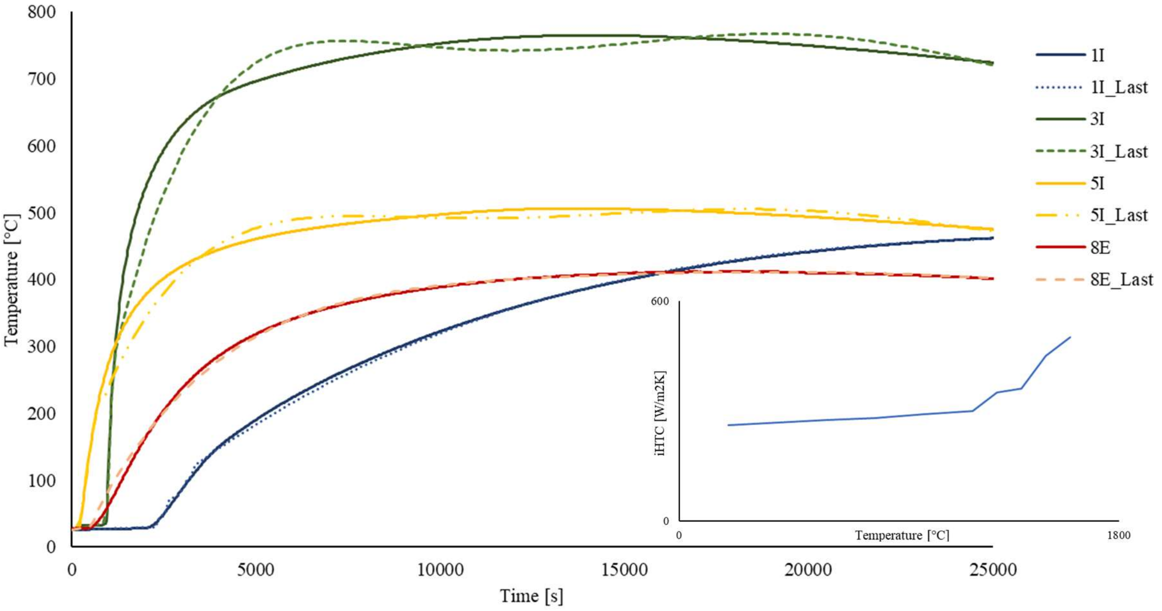

Figure 3: Comparison Between Thermocouples and Inverse Simulation Results in Four Different Points (1I, 3I, 5I, 8E).

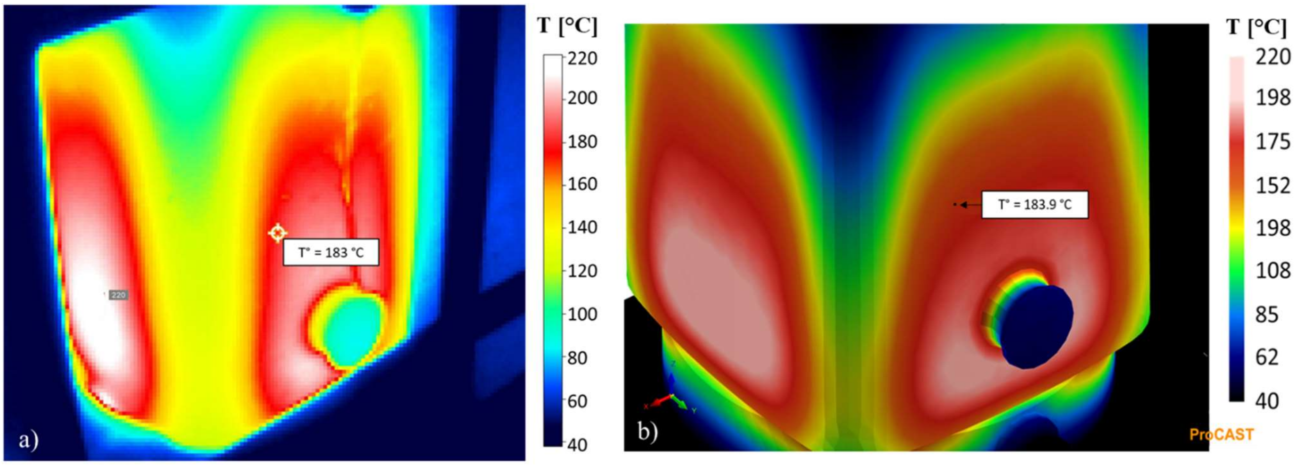

Figure 4: Comparison Between the Images Taken with the Thermal Imaging Camera (a) and Those Extrapolated from the Optimized Simulation (b).

CONCLUSIONS

Experimental measurements and numerical simulations were conducted in order to investigate the HTC values as a function of the temperature in a 26.6-ton steel ingot. For the determination of this parameter, the inverse model based on the adaptive response surface method (RSM) was used.

1. Eight thermocouples were positioned inside the mould in order to record the temperatures at 30mm from the internal and external surface, during the filling and solidification phase. The results were used to set the optimized simulation.
2. A first simulation was obtained and the trend of the temperature in the different positions was compared with the measured ones. The temperatures increase in the first stage and, after reaching a maximum temperature, decrease almost linearly: differences occur between first simulation and recorded temperatures also of 130°C.
3. Inverse simulation temperature data were extracted, and it was shown that there is a good agreement between the recorded temperatures with thermocouples and the simulation. However, after reaching the eutectoid temperature, some fluctuations start in all the simulation investigated, probably due to the thermal properties set.
4. The HTC values were firstly set according to the $T_{liquidus}$ and $T_{solidus}$: at higher temperatures it was set at 1000 W/m^2K and at lower temperatures at 250 W/m^2K. After the inverse simulation, it was possible to observe that the values increase with the temperature, from almost 250 W/m^2K until 500 W/m^2K, with a step behavior between $T_{liquidus}$ and $T_{solidus}$.
5. Specific heat of the different materials (cast iron, refractory bricks and insulation sleeve) was measured by DSC laboratory tests, according to the standard and used for the setting of the simulations.
6. From the images collected using the thermal imaging camera, during different time, all the results are aligned between the industrial process and the optimized simulation (in which the inverse HTC values were used).

For future works, it will be necessary the validation of the results obtained on a similar ingot, comparing the results of the simulation with the optimized HTC values with an industrial case study. Additionally, a more accurate characterization of the materials could be done to better understand the fluctuations observed in the simulation investigated. For instance, the thermal conductivity of the cast iron and the steel will be measured by experimental tests because it strongly influences the trend of the temperatures and, therefore, the solidification condition of the ingot.

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