Improved ingot casting by using numerical simulation

I.Hahn, E.Hepp

MAGMA GmbH, Aachen, Germany

The ingot casting process is characterized by the progressive solidification of the poured steel from the walls and the surface of the mould towards the centre. The complex phenomena during this process have to be controlled to obtain a good quality of the final product. This is influenced by several factors like steel chemistry, superheating of the melt, pouring time and the dimensions of the mould. Today, simulation tools can already show a lot of useful results to make predictions regarding the quality. Hereby the focus lies on the ingot itself and on the prediction of shrinkage, segregation, inclusions etc.

This paper concentrates on the influence of the heat flow through the mould walls on casting quality. The determination of heat transfer coefficients by reverse engineering is described. Normally, due to missing knowledge, a heat transfer coefficient between the solidifying shell and the mould surface which is invariant from the ingot bottom to the top is taken into account. Reality however is much more complex: There are different conditions over the height of a mould. If this is taken into account by the simulation software, the influence can be directly shown in the results.

Secondly, ingots being cast in groups and positioned side by side for cooling are being examined. The distance between the individual ingot moulds and also the wall thickness of the mould is of essential importance for the formation of casting defects and their locations.

During the teeming of an ingot with liquid steel, a high amount of thermal energy is brought into the cast iron mould. The energy then dissipates, leading to the cooling and solidification of the melt. The course of solidification is strongly controlled by the different heat exchange mechanisms.

The top of the mould is usually insulated by refractories. Insulating powder is introduced into the mould and that forms a layer on top of the melt. Together with the specific geometric lay-out, these actions should lead to a late solidification of the melt inside the hot top. The effectiveness of the hot top is very similar to a feeder in shape casting processes.

With an optimal design of the process it should be possible to observe a directional solidification, which means that liquid solidifies prior to any other liquid that is closer to the hot top. Directional solidification keeps ingot quality at a high level due to low shrinkage, minimum segregation and high cleanliness. Simulation helps to lay out the process so that the real solidification is as close as possible to perfectly directional solidification.

Casting process simulation

Casting process simulation has been established to support the day-to-day business in modern foundries. With its help, casting processes and cast products are laid out to assure the best possible quality at the lowest production costs. In steel foundries, simulation is applied to optimize the methoding. Gating systems are laid out in such a way that the melt is brought into the cavities with a smooth flow. Multiple ingates are balanced, oxygen contact and reoxidation are minimized. By an optimized lay-out of feeders, cooling chills, cores and insulation it is made sure that the solidification is always as directional as possible. This assures low shrinkage and porosity levels, minimum segregation and maximum steel purity.

From the physical point of view, the production of ingots is a very specialized steel casting process. Because of the fact that casting process simulation is well established in the steel casting industry, there is an increasing interest in applying casting process simulation to monitor the quality of cast ingots and to optimize the production in order to attain minimum defects and maximum yield.

With simulation it is possible to take care of all significant aspects of the ingot casting process. The flow of liquid steel during teeming can be simulated and optimized as well as the solidification and cooling of the ingot. Last but not least, residual stresses and the formation of hot tears and cracks can be predicted.

A problem in ingot casting, which needs to be tackled systematically, is the formation of porosity and inclusions along the ingot centre line close to the ingot bottom. Particularly for slim ingots with a high H/D ratio, these problems have been reported. It is well known that similar problems in shape casting are mostly related to non-directional solidification and hot spots being located too far inside the casting **[1].**

The focus of this paper is on the heat flow during solidification. It is described how the the heat transfer from the steel ingot to the mould and from the mould to the surrounding atmosphere take influence on ingot solidification. A proper modelling of these factors is a prerequisite for simulation of the ingot quality – It will help to optimize the casting process due to reduced porosity, inclusions and segregation.

Heat flow through the mould walls

The insulation of the hot top and the quality of the top slag layer are of decisive importance for the solidification of the ingot. It is known that the hot top geometry and the height-by-diameter (H/D) ratio of an ingot strongly influence the solidification and the appearance of casting defects, first of all shrinkage and porosities. In **Figure 1** some results from the casting simulation of a slim ingot are shown. For the given ingot geometry, it is almost impossible to eliminate centre-line porosity.

Nevertheless, the heat flow from the solidifying steel through the mould walls into the surroundings must not be neglected. It has a significant influence on the course of solidification. The heat conductivity of the steel itself and the cast iron mould walls is quite high. Consequently they are not expected to be barriers for the heat transport. It is obvious that the heat transfer from the ingot to the mould wall and the heat transfer from the outer mould wall to the atmosphere are the main influencing "bottlenecks" and thus determine the overall heat flow.

It can be assumed from the strong air convection around a hot mould that the heat transfer from the outer mould walls to the surroundings is invariant from the bottom to the top of the ingot. Despite this fact, it is to be expected that the heat transfer between the solidifying ingot shell and the inner mould varies depending on the actual position between the bottom and the top.

The principles of heat transfer at a solidifying shell are explained in various references, e.g. **[2].** In the case of a solidifying ingot, the outer shell will solidify rapidly, so that the heat transfer of solid steel to the mould can be assumed during the whole solidification process. Depending on the actual position over the height being observed, shrinkage will lead to the formation of a gap between the shell and the mould.

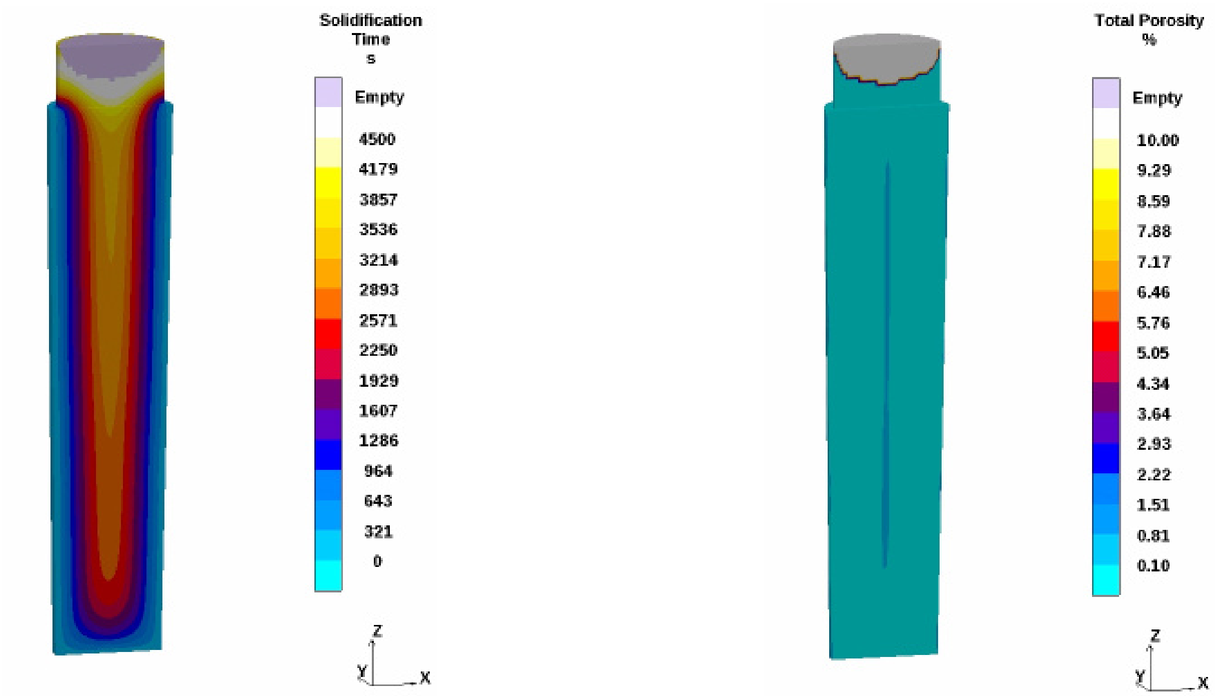

Figure 1: Simulation results for a slim ingot (H/D=0.23; weight 1.6 tons). The left picture shows the local solidification times. Although the solidification can be described as directional, a small amount of centre-line porosity is found (right picture). In this simulation the heat transfer between the ingot and the mould wall was assumed to be invariant from the bottom to the top of the ingot.

This in turn will reduce the heat transfer at this particular position. Additionally, casting powder/slag can penetrate into the gap which will also reduce the value of the heat transfer coefficient.

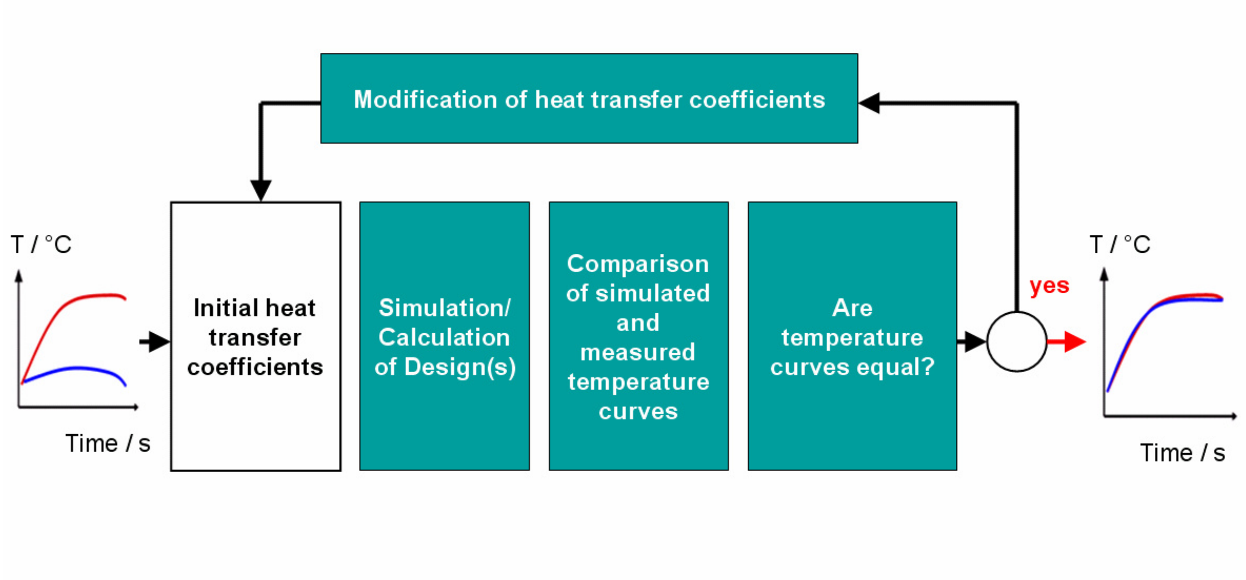

Figure 2: Inverse Optimization of heat transfer coefficients - By variation of the heat transfer coefficients between the ingot and the mould, the mould temperatures are varied. With a program for automatic optimization of casting processes, the deviation between the curvatures of simulated and measured temperatures on the outer surface of the mould can be minimized. MAGMAfrontier allows to carry out this optimization without the need for user interactions. Usually, several hundreds of simulations with different heat transfer are carried out until the simulated cooling curves fit to the measured ones. The heat transfer coefficients that correspond to the best fit can then be used for a realistic evaluation of the ingot solidification.

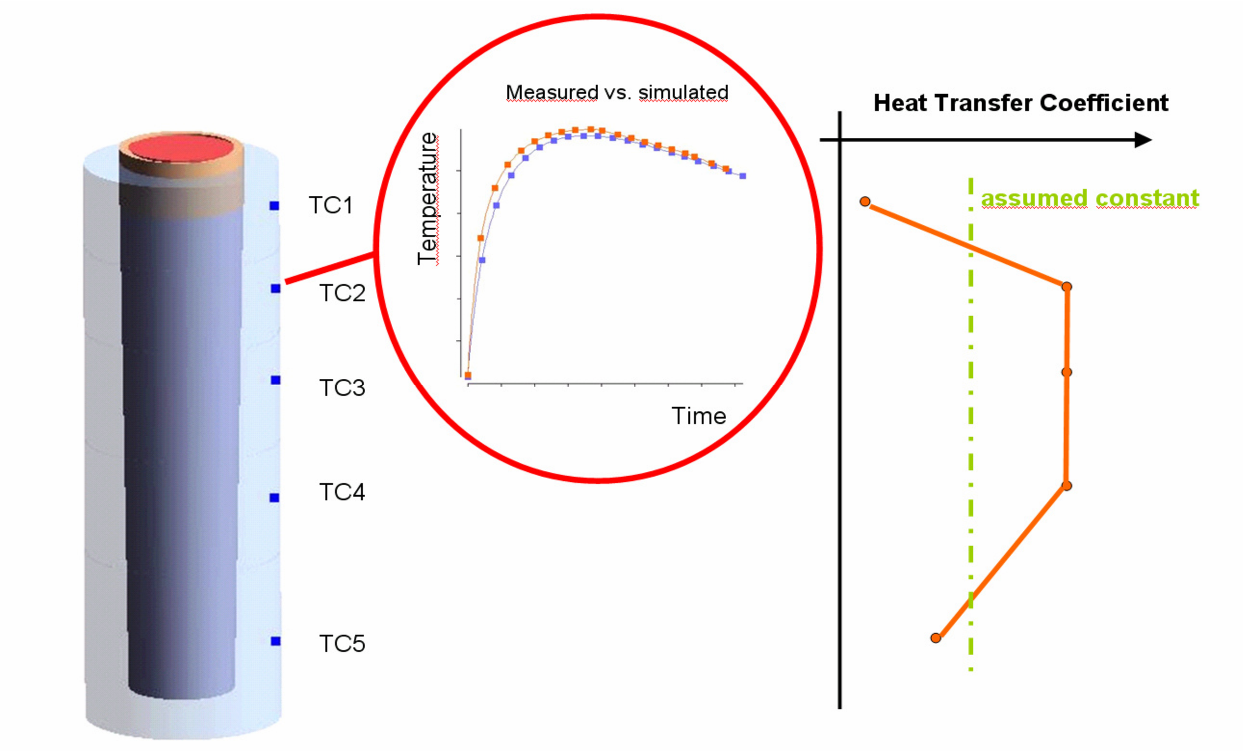

Figure 3: The deviation between measured and simulated temperature curves were minimized for thermocouples at five positions over the height of the ingot. As a result, the heat transfer between ingot and mould was determined. The orange curve shows the distribution of heat transfer coefficients for the best temperature fit. An assumption for a constant heat transfer coefficient that is very typical for the simulation of ingots is plotted in green. Fig. 1 shows the corresponding simulation results

In order to properly describe the ingot solidification it is necessary to take a look at heat transfer coefficients that vary over the height of the ingot. Similar to this, the determination of a height-dependent heat transfer coefficient for the simulation of the continuous casting process has been described in **[3,4,5]**.

Reverse engineering of heat transfer coefficients

Heat transfer coefficients cannot be measured directly. The best possible way is to retrieve them from a comparison between measured and simulated temperature plots. In the present work, the heat transfer coefficients between ingot and mould wall are modified. Temperatures at the outer mould wall are simulated and the resulting curves are compared to measurements at the same positions of a real ingot mould.

Using an optimization program in combination with casting process simulation, the heat transfer coefficients are varied until the difference between measurement and calculation is minimized, see **Figure 2**.

In this project, thermocouples have been placed at five different positions on the outside of the mould, see **Figure 3**. The heat transfer coefficient at each position was assumed to be constant during the whole solidification. By carrying out the inverse optimization, a significant variation of the heat transfer coefficient over the height of the ingot was determined.

In **Figure 4** the simulation results corresponding to the heat transfer distribution calculated by reverse engineering are shown. The solidification is no longer directional. There is a hot spot in the bottom area of the ingot. Due to this fact, shrinkage porosities are detected in this area. There are reasonable doubts whether a subsequent hot rolling process could close these cavities.

Simulation allows to trace the inclusions that are carried by the flow of melt. **Figure. 5** shows the inclusion distribution resulting from the described solidification pattern. With ongoing solidification, the convective flow in the ingot mainly concentrates on the hot spot area. Here are signification motions in the melt in the final phase of solidification – Therefore, a lot of inclusions are trapped here.

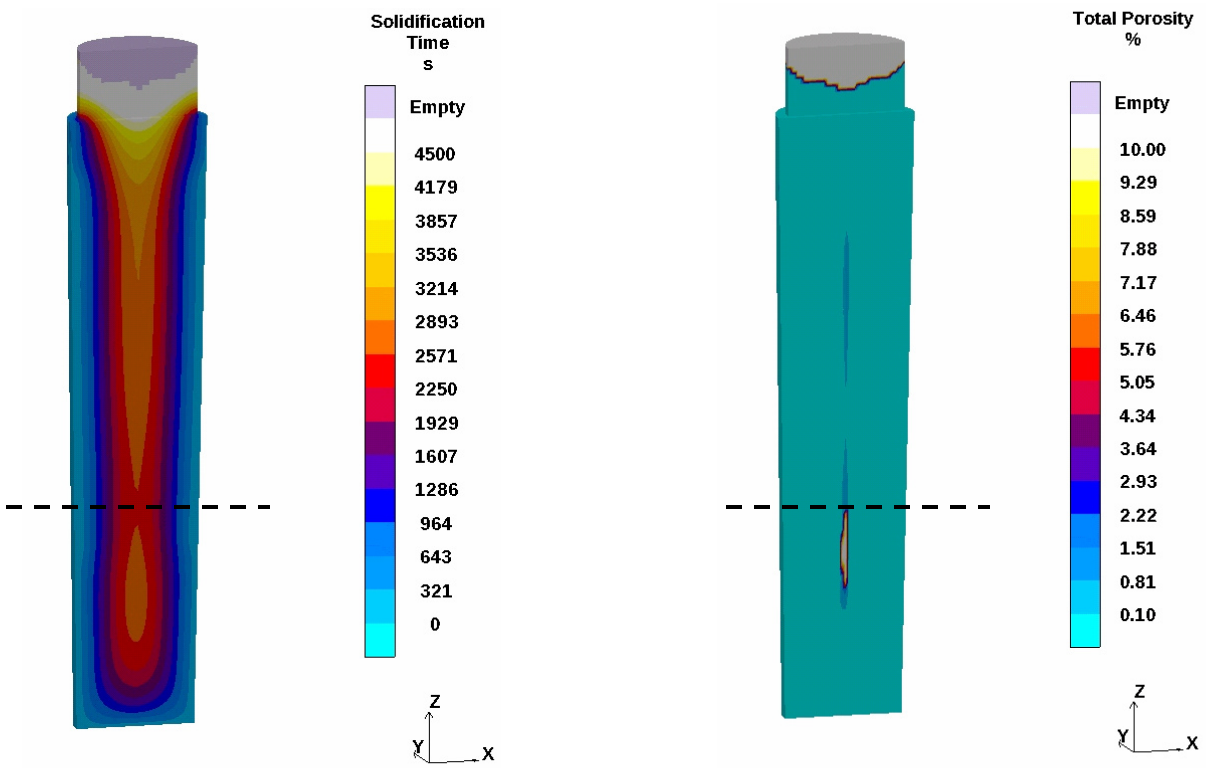

Figure 4: Results of solidification simulation with the heat transfer coefficients determined by inverse optimization. The left picture shows the solidification time of the slim ingot, which is in total 1 1/4 hours. An isolated area in the bottom of the ingot can be detected. Here, consequently porosity can be found.

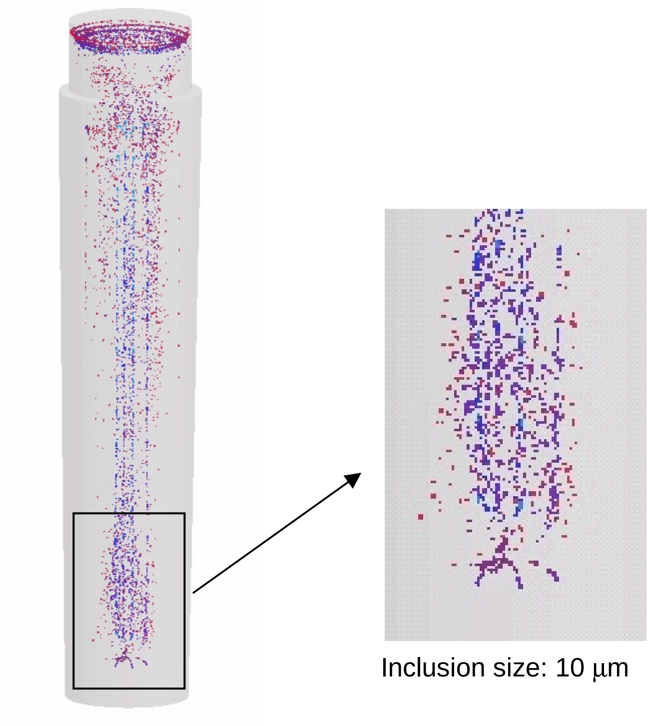

Figure 5: Caused by the solidification pattern with the deep hot spot, inclusions are trapped in an area close to the ingot bottom. The inclusions cannot float to the top of the ingot and remain in the hot top slag as would be desired.

Ingot positioning and surroundings

As described before, the heat flow via the mould to the surroundings is expected to take influence on the solidification. Whenever the user refrains from giving explicit specifications for the conditions in the surroundings, standard boundary conditions are assumed for the simulation. The heat transfer is then calculated for surrounding air at ambient temperatures with the assumption of heat flow driven by both convection and radiation. For a start, this condition is assumed to be equal for each positition on the surface of the model and independent of any possible heat flow direction. **Figure 6** shows the outer wall temperatures for a 6.5 ton ingot after 4 hours of cooling.

Under production conditions, ingots are often placed in a casting pit to cool down. The surrounding air is then heated up significantly by the released heat. The kinetics of heat transport via both convection and radiation will change. Therefore, it is necessary to recalculate the boundary conditions for the simulation model.

Often, more than one ingot is cast simultaneously. The ingots are placed side by side. Usually, groups of ingots are cast in patterns which results in varying conditions for each ingot, depending on its particular position in the pattern. It is very difficult for a hot ingot to release heat towards an equally hot neighbour. In order to examine the influence of ingots adjacent to one another on solidification, the model boundary conditions for heat release are changed so that for the solidifying ingot a neighbouring ingot standing nearby on one side is assumed. **Figure 7** shows the moulds of two ingots that are cooling down side by side. As in **Figure 6** for the single ingot, the temperatures at the point of time of 100% solidification are assumed. One can see that the ingots heat up each other, in particular in the upper area of the mould.

Figure 8 and 9 show the solidification of the ingot for the “single” case in comparison to the “neighboured” case. If the cooling down of an ingot is unsymmetrical, this will also take influence on solidification.

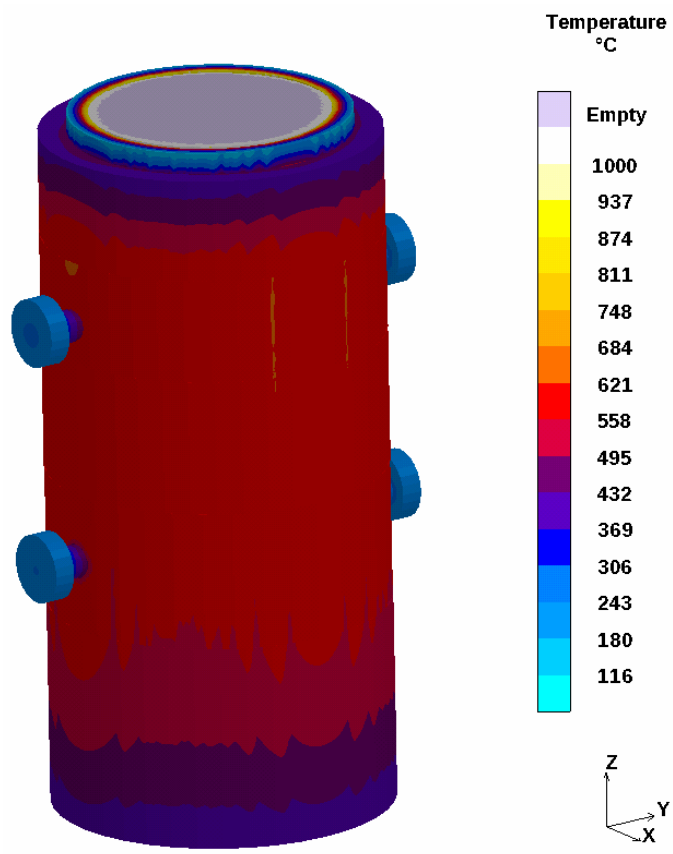

Figure 6: Outer wall temperatures for the mould of a 6.5 ton ingot assuming that 100% of the steel is solidified inside the mould.

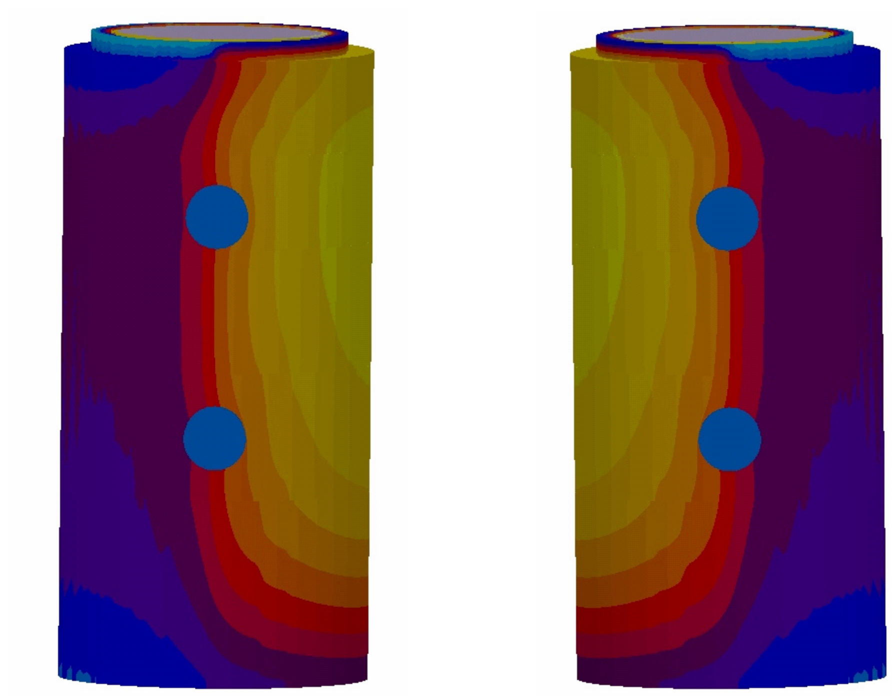

Figure 7: Outer wall temperatures for two 6.5 ton ingots positioned side by side exactly when 100% of steel is solidified. It is further assumed that the ingots are positioned so close to each other that no heat can be released to the area in between them. With this assumption the outer mould wall would heat up to more than 900℃. Under realistic conditions in a steelworks, such a high temperature would damage the cast iron moulds irreversibly.

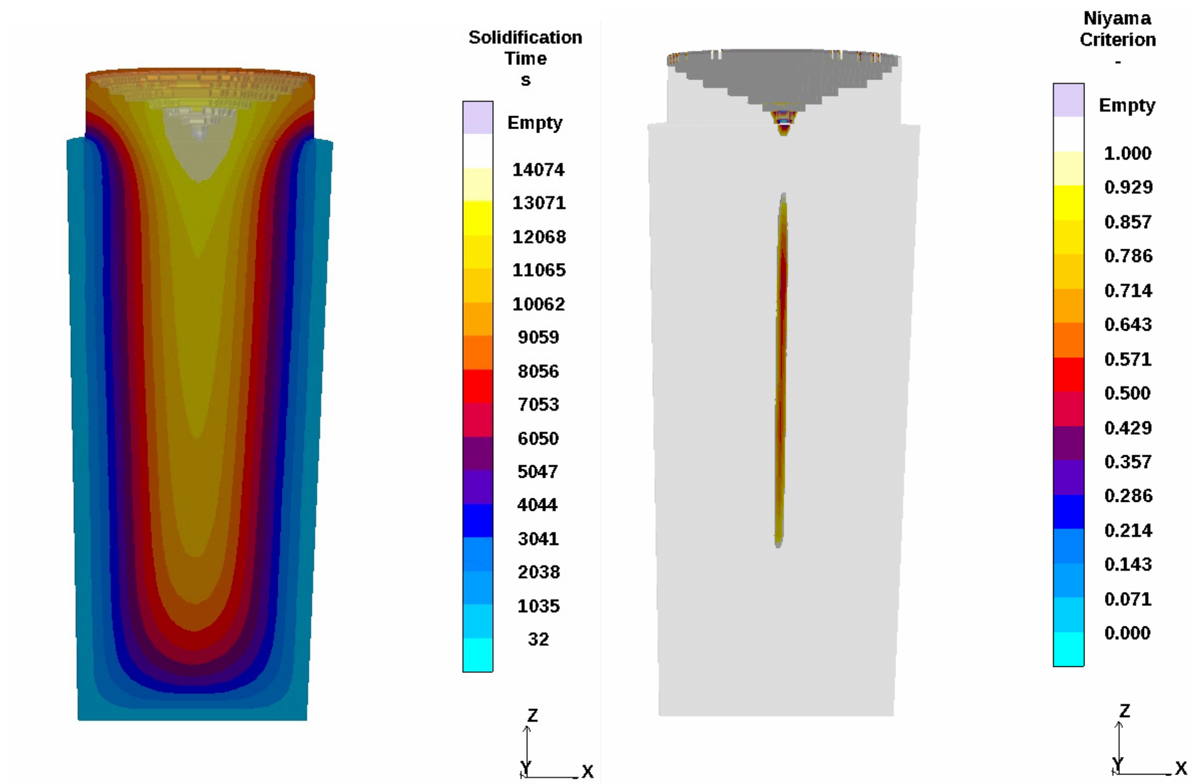

Figure 8: The left fig. shows the solidification time. For this 6.5 ton ingot casting the total solidification takes nearly 4 hours. If there is no thermal influence from the surroundings, the defects are consequently in the center of the casting. The fig. on the right shows the Niyama criteria as an example. The Niyama criterion is calculated from the local gradient and cooling rate [6]. It is commonly used to indicate centre-line porosity in steel castings and ingots.

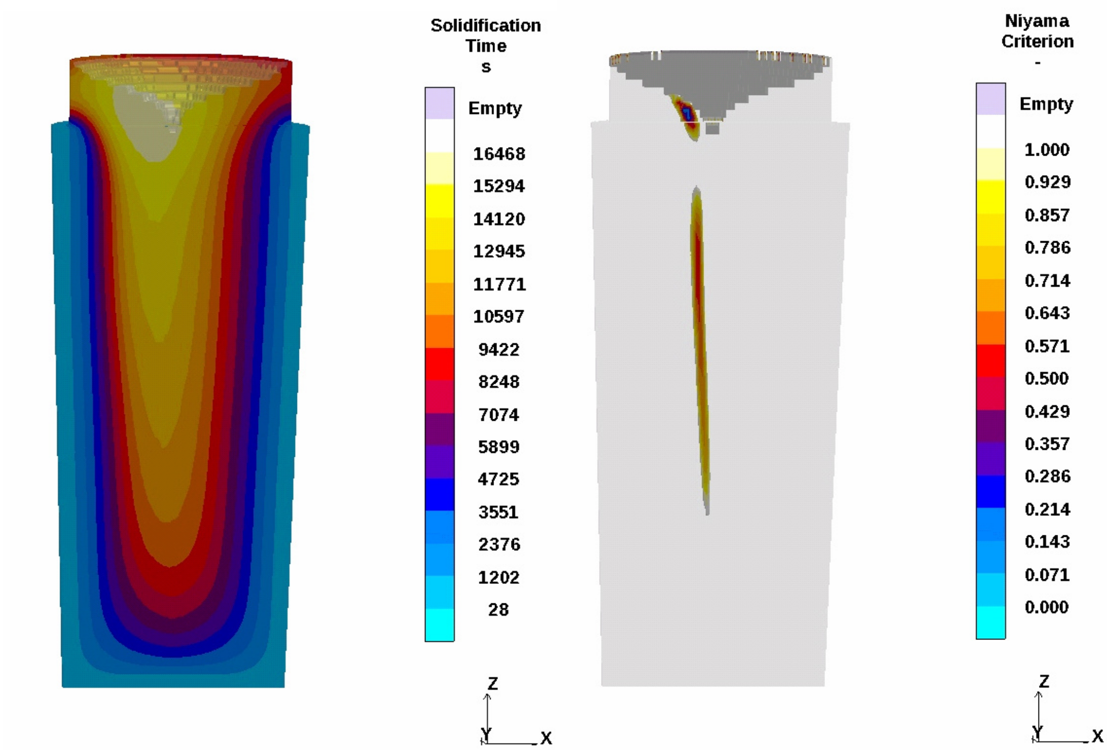

Figure 9: In comparison to Figure 8, two ingots are positioned side by side. The heat distribution is now non-symmetric. This shifts the defects indicated by the Niyama criterion out of the centre.

Summary

The paper described the heat transfer between a solidifying ingot and the mould. With the help of reverse engineering it is possible to modify the heat transfer coefficients, which have to be height dependent. Such process conditions lead to porosity and inclusions, which cannot be detected without the correct heat transfer coefficients. A second aspect which is described in this paper is the positioning of ingots if several moulds are positioned side by side on a bottom plate. If the distance between two moulds is critical, the temperature fields as well as the casting defects are not symmetrical as expected under ideal conditions. In general the paper showed how numerical simulation can help to optimize the ingot casting process to achieve the best quality and a high productivity due to a realistic prediction of casting defects.

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