NUMERICAL SIMULATION AND EXPERIMENTAL VALIDATION OF THE FORMATION OF SHRINKAGE CAVITY DURING SOLIDIFICATION OF STEEL

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Abstract

The solidification of liquid steel is generally accompanied with different phenomena, like solidification shrinkage and a change of the solubility limit of alloying elements. These phenomena are the base for negative side effects like micro- and macrosegregation as well as the formation of shrinkage cavity and gas porosity. This paper focuses on the formation of shrinkage cavity during solidification of steel through the numerical simulation and experimental validation in ingot casting.

The first part of the paper deals with the performed lab experiments at the Chair of Ferrous Metallurgy. Three different ingots were cast with varying cooling conditions and hot topping configurations. The metallographic examination shows substantial differences between the cast ingots regarding the cavity formation at the ingot center.

Further the used method to predict the formation of shrinkage cavity is briefly described. Thereby the needed solidification parameter for the criterion and the determination of those are discussed. The method is implemented at the numerical model of the lab experiments whereby the solidification software ProCAST was used. The extent of experimentally determined pores is in good agreement with the numerical calculation. Especially the cooling conditions have an influence on the extent of cavity formation which was well reflected from the numerical model. Finally this criterion can be used for other casting process to predict the formation of shrinkage porosities.

Keywords: Solidification, Pore formation, Ingot, Simulation, Niyama

1. INTRODUCTION

The solidification of liquid steel is coupled with the appearance of volume shrinkage due to the temperature depended density. The occurring volume shrinkage can be compensated by feeding with liquid steel. This feeding process must be sufficient to prevent the formation of pores (and/or shrinkage cavities). However, at the end of solidification the liquid steel faces a high resistance regarding fluid flow towards the dendrite trunk. As a consequence the pressure drop increases and at a certain point the pressure drop reaches a critical value whereby beyond this threshold pores will be formed.

The paper focuses on the comparison of experimental investigations regarding shrinkage cavity with numerical computations. Therefore ingots with different cooling conditions and hot topping configurations were cast. Further the ingot was cut longitudinally to visualize the shrinkage cavity. The numerical model of these ingots was established with the solidification software ProCAST. Furthermore porosity criteria were implemented at the model to predict the formation of pores in the ingot. Finally, the numerical and experimental results were compared to conclude about the usability of the used criteria.

2. LAB EXPERIMENT

Three melting experiments with different cooling conditions were performed. Two of the three experiments were cooled down by air and one experiment was embedded into sand. Further the solidification at the ingot top was influenced through the usage of exothermic powder for the first two experiments. However an insulation hood as well as insulation powder was used for all experiments. An overview of the used parameter for the different experiments can be found at **Table 1**.

Table 1 Parameter of the performed melting experiments

Trial no.	Cooling condition	Exothermic powder
1	Air	Yes
2	Sand	Yes
3	Air	No

The cast ingots have a weight of approximately 135 kg and dimension of Ø 154 mm x 1000 mm. A schematic illustration of the setup is depicted at **Figure 1**. The steel grade of the cast ingot is the heat-treatable steel 42CrMo4. For the mould a seamless tube with a wall thickness of 7 mm was used. The mould material was a common carbon steel (S355). The liquid steel was cast from the top. Since the mould is very thin an entry nozzle was used to prevent a breakout due to local excessive flow of the hot steel against the mould wall. Thereby the nozzle was preheated to 700 °C; otherwise the molten steel would solidify at the entry nozzle.

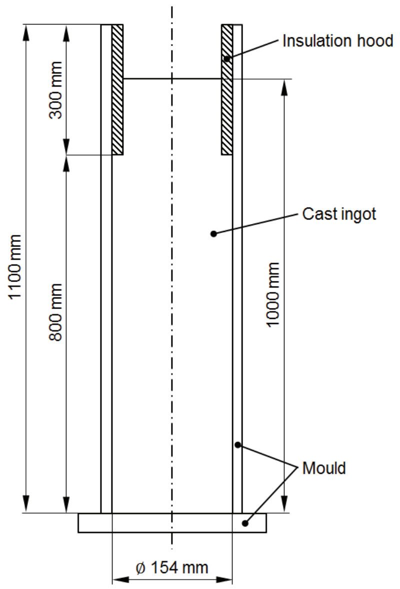

Figure 1 Schematic illustration of the experimental setup

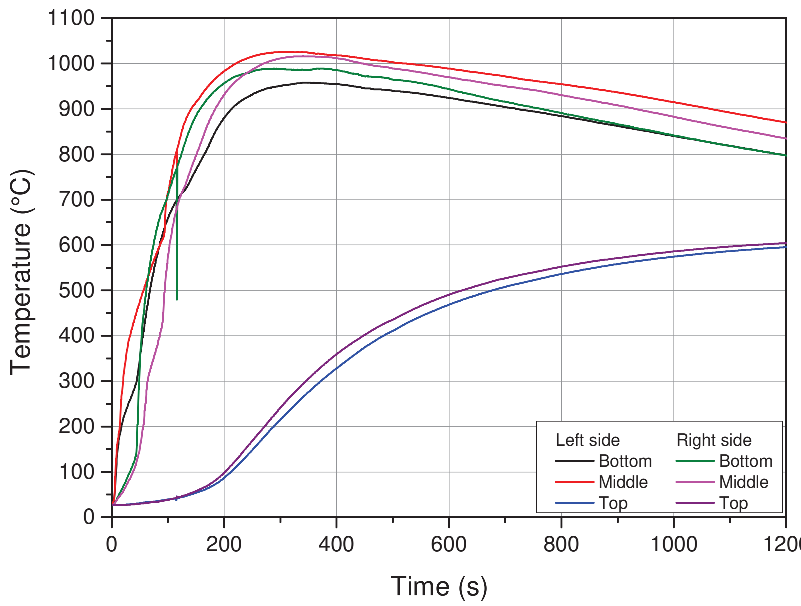

Figure 2 Measured temperature profile for the first experiment

For the first experiment six thermocouples of type K were installed on the mould to measure the temperature. The thermocouples were located at three different heights on the cold face side of the mould. The second experiment was instrumented with 6 thermocouples at the same height. Thereby two thermocouples of type B were located 5 mm below the hot face of the mould, towards the ingot, to measure the melt temperature. Another two thermocouples of type B were positioned inside the mould near the hot face. Finally two thermocouples of type K were fixed at the cold face of the mould.

The pouring temperature of the molten steel for all three experiments was around 1620°C. This high superheat (T_L = 1498°C) was chosen to prevent a premature solidification of steel in the entry nozzle. During the melting experiments the temperature evolution at different positions was recorded. The temperature evaluation for the first melting trial is illustrated at **Figure 2**. Thereby the upper thermocouples are behind the insulation hood and thus the temperature profiles of these thermocouples are quite different from the other ones. The temperature curves at the bottom and middle of the ingot were used to calculate the interface heat transfer coefficient between mould and ingot.

3. NUMERICAL MODELLING OF THE LAB EXPERIMENT

The numerical calculations of the solidification process were performed with the 3D finite element software ProCAST 2014.0. The focus of this software lies at the numerical modelling of common casting processes, like continuous casting, ingot casting, investment casting, die casting, etc.. ProCAST is further able to model the appearing primary phase, grain structure and microstructure as well as the occurrence of common defects. [1]

3.1. Preparation and setup of the experimental trials

The complete numerical illustration of the experiment is quite tough and cannot be modeled in full extent with the used solidification software. Hence a few restrictions had to be accepted regarding the simulation. The used model considers the following physical processes:

- Heat transfer between ingot-mould and mould-environment
- Filling process of the mould with adjusted heat transfer coefficient (HTC) between ingot and mould
- Fluid flow due to the natural convection
- Heat release of the exothermic powder

The used geometry for the simulation is illustrated at **Figure 3**. For the last experiment the exothermic powder domain was removed. It should be noticed that for all experiments the ingot domain is divided into an outer and inner part. Thereby for the outer part (domain 1) the material data (permeability and viscosity model) were adjusted in such a way that the flow behaviour corresponds to a columnar solidification. For the inner ingot area (domain 2) a material model for an equiaxed solidification structure was applied. Details regarding the viscosity and permeability of the model are described at the subchapter 3.3.

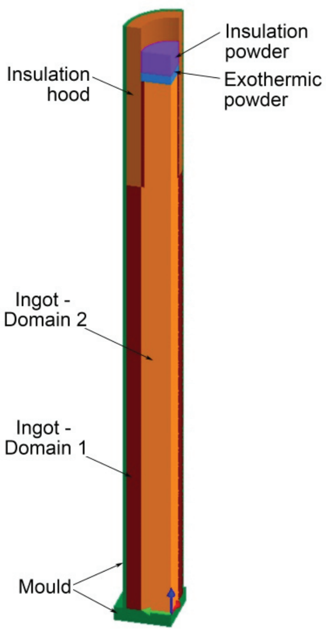

Figure 3 Numerical model of the experiment

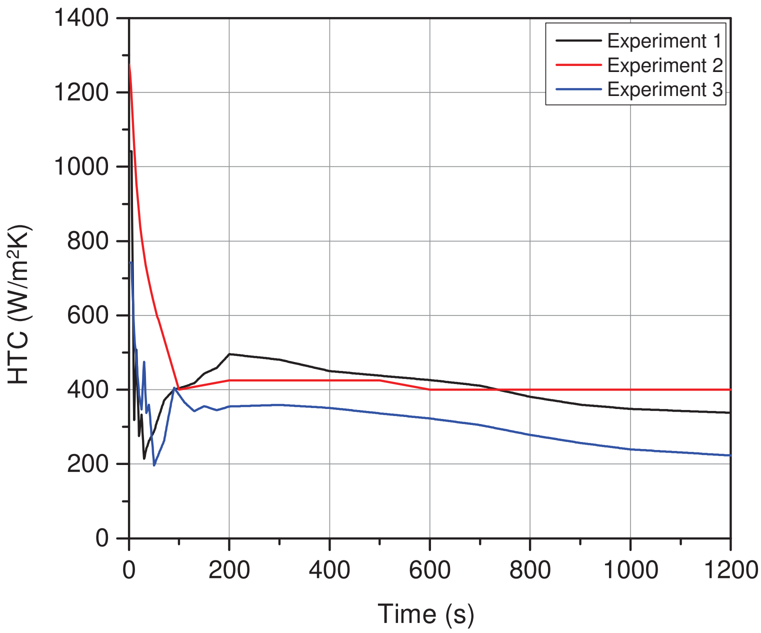

Figure 4 Calculated HTC between ingot and mould from the measured temperature profiles

Instead of modelling the pouring stream during the mould filling a mass source was used which moves from bottom of the ingot to the top with rising liquid steel level. Hence the simulation time for the mould filling process can be reduced. Further only a quarter of the experiment was simulated to decrease the computation time.

The number of elements for the numerical model was around 160,000 and the average length of the elements is between 2 - 3 mm.

3.2. Initial, interface and boundary conditions

The interface heat transfer coefficient (IHTC) between the mould and ingot, as illustrated at **Figure 4**, was derived from the measured temperatures. Therefore an inverse calculation was performed with these temperatures by the software calcosoft 2D. The heat is withdrawn at the cold face of the mould due to air convection and heat radiation for experiment 1 and 3 since they were not embedded into sand. A heat interface coefficient of 10 W/m²K and an emissivity of 0.72 were assumed for the numerical model of those experiments. The mould of the second experiment was embedded into sand. The heat withdrawal from the mould towards the sand was performed with a heat flux boundary condition.

The interface heat transfer coefficient between exothermic powder and steel, exothermic powder and insulation powder as well as insulation powder and steel were based on the research of Han et al. [2]. The mould flux temperatures, the liquidus and solidus temperature of the cast steel were consulted to develop the interface HTC progress. The other IHTCs were taken from Liu et al. [3].

3.3. Material properties

The material data for the mould (S355) and ingot (42CrMo4) were calculated with the software IDS developed from Miettinen et al. [4]. Depending on steel composition and cooling rate IDS calculates the needed temperature dependent material data (enthalpy, density, thermal conductivity and viscosity) for the numerical model. During solidification the enrichment due to microsegregation will be considered too. Thereby the microsegregation model of Ohnaka is used. [4]

The fluid flow behaviour during solidification was described with two models whereby the distinction of these models bases on the present solidification morphology. During dendritic solidification the permeability is a good physical quantity to describe the damping effect of the two-phase zone on the fluid flow. Therefore the model of Schneider [5] was used. The equiaxed solidification is physically better to characterize with a viscosity which depends on the solid fraction. Thereby the so called hybrid model of Oldenburg and Spera [6] was chosen. For the second model the secondary dendrite arm spacing (SDAS) and a critical solid fraction or packing density is needed. The computation of the SDAS is performed with the equation after Ogino [4] which considers the steel composition and cooling rate. The SDAS was set to 100 μm for the model of Schneider and to 175 μm for the hybrid model. The critical solid fraction was assumed to be 0.3 for a dendritic equiaxed solidification structure. Finally the transition from Schneider model to the Oldenburg model was determined with the wide used Hunt criterion in a previous simulation [7].

3.4. Criterion to predict pore formation

After the numerical illustration of the melting experiment two porosity criteria were implemented into the model. Therefore the widely used Niyama criterion [8] and further the Lee criterion [9] were selected. These criteria combine different solidification parameter, like the temperature gradient G, cooling rate $\dot{T}$, solidification rate R and local solidification time t_f. The Niyama value can be computed with equation (1) and Lee value with equation (2).

$$Ny = \frac{G}{\sqrt{\dot{T}}} < C^{crit} \tag{1}$$

$$Lee = \frac{G \cdot {t_f}^{2/3}}{R} < C^{crit} \tag{2}$$

The critical value C^{crit} for the Niyama criterion is around 0.775 ((K·sec)$^{0.5}$/mm) and for the Lee criterion this threshold is 1 (K·min$^{(5/3)}$/cm²). A value below these thresholds leads to the occurrence of pores. Further details to this criteria can be found at [10].

4. COMPARISON OF THE EXPERIMENTAL WITH NUMERICAL RESULTS

The appearing pores for the experiments are depicted in **Figure 5**. Thereby experiment 1 shows only at an ingot height of around 70 cm a few pores. For ingot 2 two areas (between 30 - 40 cm and 60 - 70 cm) with an increased extent of pores are obvious and the ingot top shows big pores too. Finally ingot 3 displays also more pores at the lower part which are arranged like a horseshoe as well as scattered cavities along the ingot height. Regarding the pipe formation only experiment 3 shows a well-marked pipe due to the lack of exothermic powder. Lastly it should be noted that the appearing pores for different ingots, and hence for different cooling conditions, can only be compared on a qualitative basis with each other. An exact reproduction of the individual experiments is very challenging since certain fluctuations during the experiment are unavoidable.

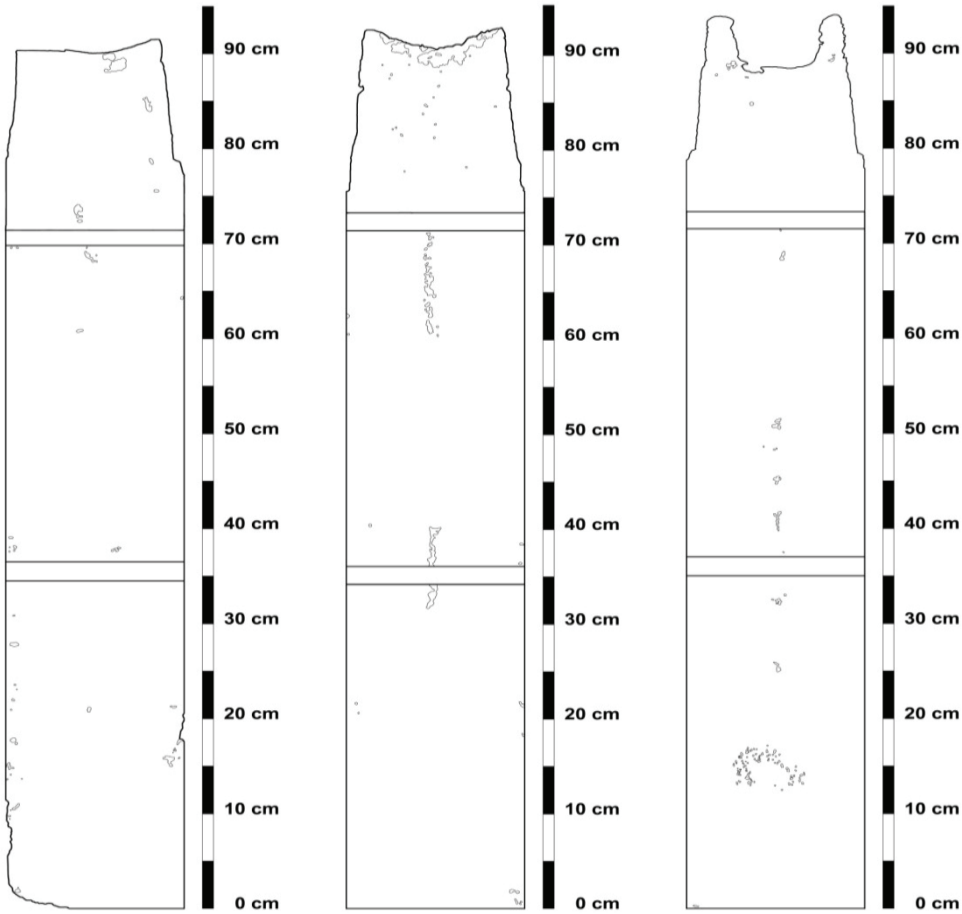

Figure 5 Appearing pores at the ingot for the experiments

As a first result of the performed simulations the progress of the mushy zone after 95 % of complete solidification of the ingots is shown in **Figure 6**. Thereby the simulation for the first experiment depicts a good progress of the mushy zone to solidify entirely without the appearance of pores. In contrast, the mushy zone of the second experiment illustrates the formation of a bottleneck at the upper part of the ingot. Thus the metal feeding of the ingot in the lower part is insufficient and the formation of shrinkage cavities is inevitable. The third simulation shows a similar profile of the mushy zone as the first experiment. However the extent of the two-phase zone is larger.

The calculated Lee value and the Niyama criterion at the centre of the cast ingots are depicted at **Figure 7**. Thereby it should be noted that these criteria can be used without doubt to show a certain trend regarding different cooling strategies or hot topping practices. However an exact prediction of the position and amount of the appearing cavities based on these criteria is very challenging. Taking a closer look on both criterion profiles (**Figure 7**) it is obvious that the lower cooling rate due to the cooling at sand (experiment 2) leads to a depression at the middle of the ingot. Hence the appearance of cavities is more possible. This result is in good agreement with the experimental investigation since experiment 2 shows in greater extent shrinkage cavity in the ingot centre. Further the progress of the criteria of experiment 1 compared to experiment 3 shows a significant influence of the exothermic powder. Finally it can be noted that the critical value of the Lee criterion (1 (K min$^{(5/3)}$/cm^2)) is quite fine for the performed experiments. However the threshold of the Niyama criterion is probably too high. A critical value of 0.755 ((K sec)$^{0.5}$/mm) would predict the formation of pores over almost the whole ingot height for all three experiments which is not in accordance with the experimental results. For an accurate prediction of the formation of pores the critical value of the Niyama criterion should be decreased to 0.4 ((K sec)$^{0.5}$/mm).

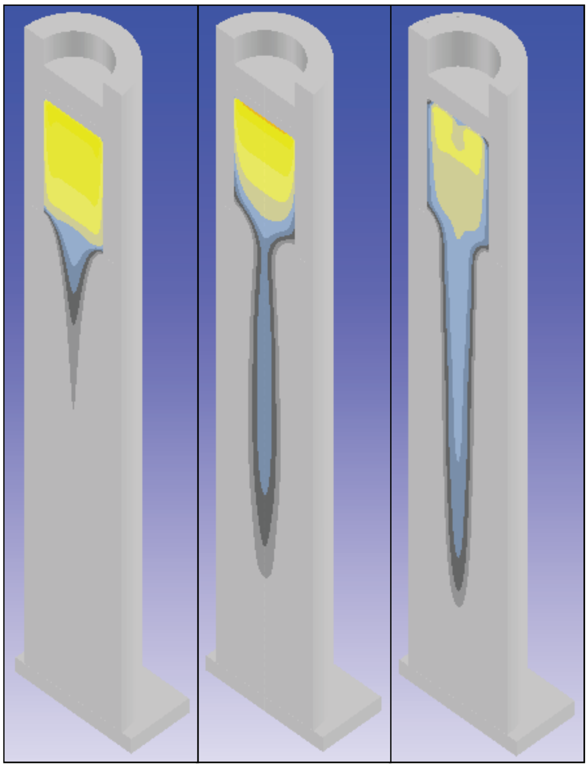

Figure 6 Progress of the mushy zone for all three experiments after 95 % of solidification

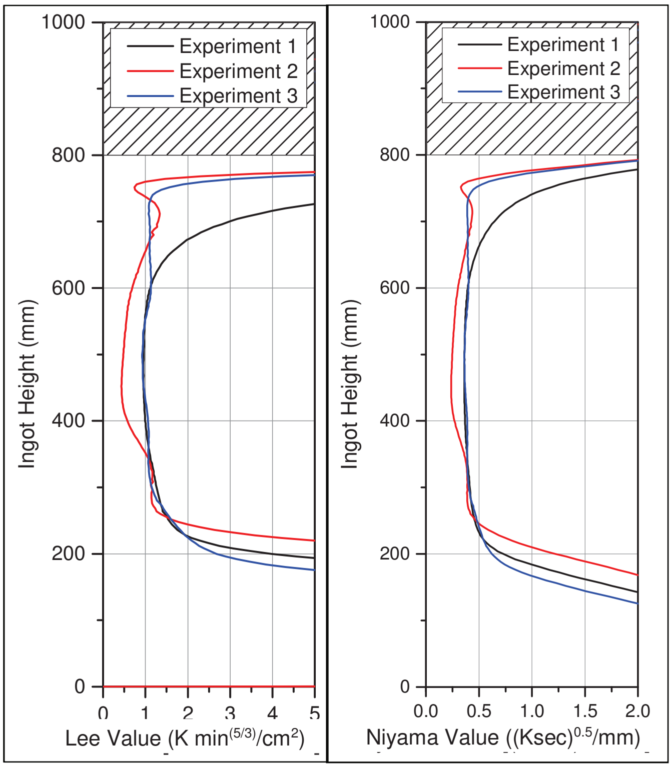

Figure 7 Lee and Niyama criterion at the centre of the ingot

5. CONCLUSION

Three experiments with different cooling conditions (air and sand) and hot topping configurations were cast to investigate the influence on the pore formation. Thereby the influence of the cooling strategy on the appearance of cavities was evident since a lower cooling rate leads to a larger extent of pores in the centre of the ingots. Further the positive influence of an exothermic powder on the reduction of pores at the ingot top is obvious too.

Moreover efforts were made to model the cast ingots with the solidification software ProCAST. Thereby the measured temperature profiles were used to determine the heat transfer coefficient between mould and ingot. Finally the Lee criterion as well as the Niyama criterion were implemented into the model and compared with the experimental results. Thereby the influence of different cooling strategies and hot topping practices on the cavity formation can be reproduced with the used criteria. The usage of different cooling conditions has a significant influence on both criteria and agrees well with the experiments. Further the application of exothermic powder has an effect on the profiles of these criteria and reflectis the experimental investigations too.

ACKNOWLEDGEMENTS

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