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Automatic Virtual Optimization of Ingot and Continuous Casting Processes

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Introduction

Simulation technology today makes it easily possible to carry out three-dimensional simulations of the teeming and solidification of ingots as well as of the flow and solidification in continuous casting processes. Quick and reliable virtual casting trials in the computer can be performed considering all relevant process parameters.

During casting, numerous complex physical phenomena occur simultaneously that are coupled with each other. Changes of one process parameter usually lead to a change of many quality-relevant properties of the product. A coupling of casting process simulation with statistical design of experiments allows the virtual exploration and evaluation of the effects of process changes on all relevant quality characteristics. Automatic virtual optimization, which is focused on the fulfilment of several targets at the same time, provides a promising approach for defining robust casting processes and finding operating points that build a best compromise between competing objectives.

This paper will show examples of the application of these methodologies for continuous and ingot casting processes and gives an insight into how process development benefits from them.

Casting Process Simulation

Casting process simulation has been successfully used in foundries for almost 30 years. During this time, the simulation of casting processes has experienced continuous further development [1]. Particularly steel casting is a field with a long tradition of using process simulation. Today, casting simulation is established as a part of daily working routines to predict casting quality in many metalcasting facilities. In most cases, simulation is applied to optimize the production process and obtain products with the required level of quality.

For the casting processes in steel production, ingot and continuous casting, the state-of-art tool to predict the effects of intended process variations on product quality is also simulation, fig. 1. A virtual ingot casting process for example depicts all relevant aspects, including the teeming flow, exothermal reactions of the topping powder, convection movement during solidification and cooling down, particle movement,

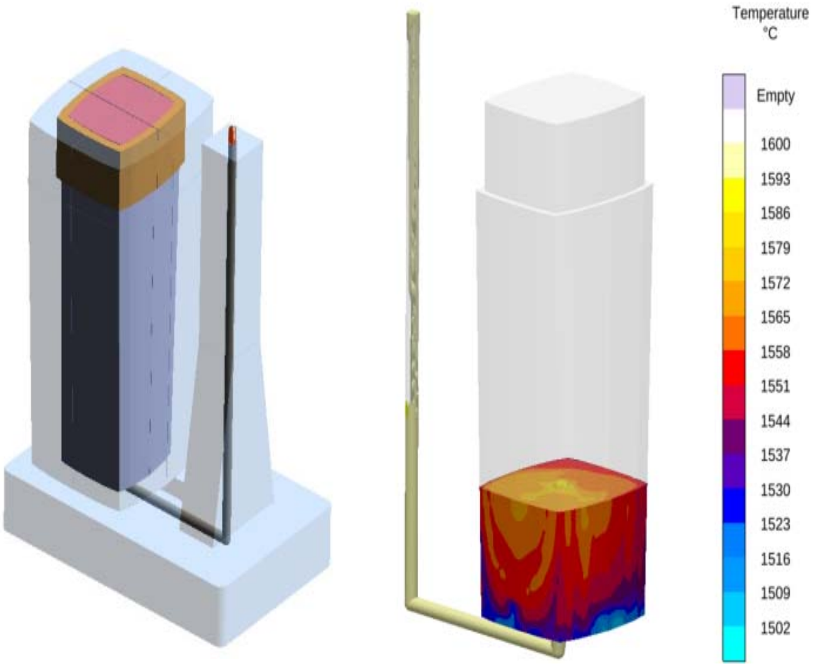

Figure 1: Virtual ingot casting experiments are carried out based on a complete 3-D model of all relevant components – this includes ingot, head, mould, trumpet, insulation, base plate, etc. (left). All phases of the process can be simulated - This includes the teeming, further solidification and cooling. Simulation allows the analysis of the behaviour of the process using numerous results and quality criteria, for example temperatures, metal velocities, flowing particles, local fraction of solid, reoxidation inclusions or residual stresses in mould or ingot. Quality criteria like porosity, centreline shrinkage, macrosegregation or cracks are easily visualized. The right picture shows the temperatures during teeming at a particular point of time.

heat radiation between neighbouring ingots and residual stress formation in the ingot and the mould. In addition the formation and severity of all kinds of casting defects can be monitored. This includes the prediction of shrinkage cavities, centreline shrinkage, macrosegregation, re-oxidation inclusions as well as the formation of cracks at any time of the cooling process. The transfer of information about the local product quality of ingot castings to the analysis of subsequent production steps such as forging and its effects on the resulting product quality has been shown in [2,3].

Virtual Automatic Optimization

Thanks to advances in both software and hardware, the time required to carry out a single simulation continues to decrease. This means that an optimization program can run a sequence of simulations "in the loop" and can be used to carry out a large number of virtual casting experiments in a comparably short time. The relevant quality criteria can be automatically assessed by the software after each virtual casting trial. After having run the virtual experiments, all results are available to the engineer for statistical assessment (guided by the software), supported by a 3D visualization of the process. The investigations described in this paper have been carried out using the software MAGMA[5] for casting process simulation and virtual optimization.

In setting up an automatic optimization, the casting process parameters which are to be varied and their respective variation ranges need to be identified (e.g. geometrical dimensions, temperatures, teeming/pouring rates, alloy chemistry, cooling layout). Then, a sequence of virtual experiments is set up similar to a "Design of Experiments (DoE)" for real plant trials. The software uses statistical methods to aid the engineer when setting up the sequence, so that the fewest experiments necessary are required to gain as much information as possible from the results. Evaluating a sequence of virtual experiments helps to understand how strongly the effect of each parameter on the quality criteria is. In many cases, using a DoE based sequence of virtual experiments already gives valuable information to the engineer to significantly improve the production process in terms of quality or production costs.

On top of this, a true automatic optimization can be carried out to propose an optimal casting process/process operating point. An automatic optimization is driven by the analysis and evaluation of the relevant quality criteria, fig. 2. Objectives can, for example, be "minimize centreline shrinkage" or "maximize tensile strength after heat treatment". Virtual automatic optimization is focused on fulfilling several objectives, which may be in competition with each other, at the same time. For example, it is

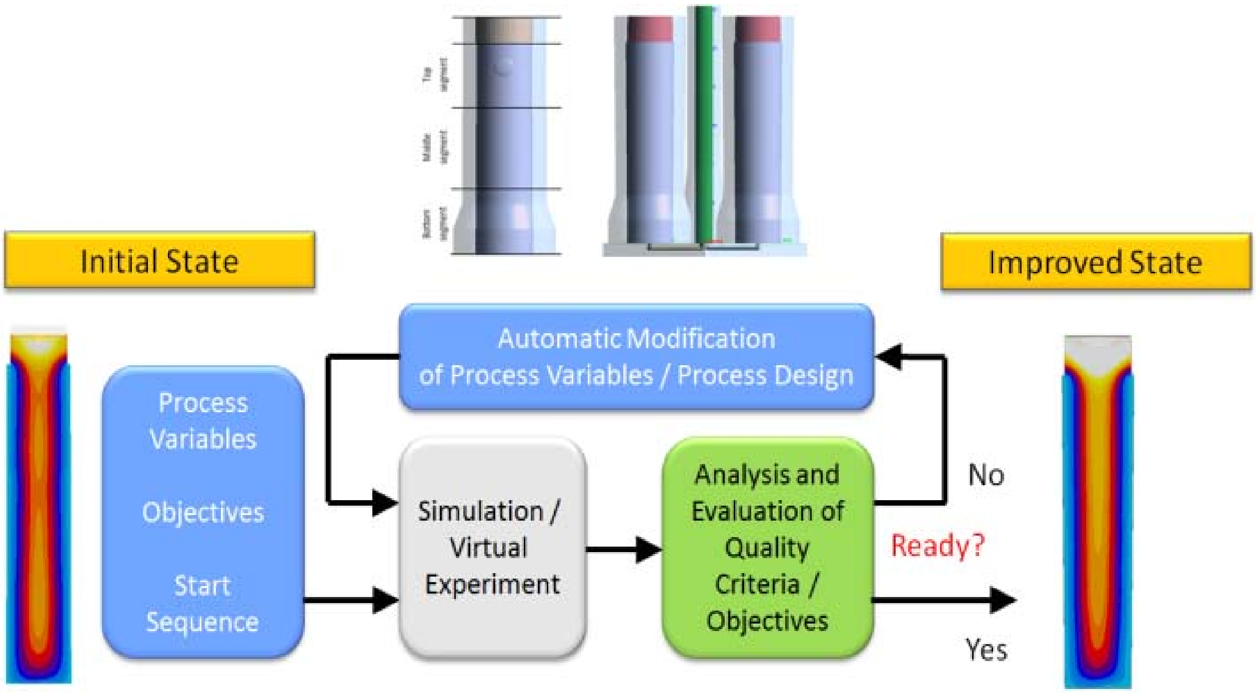

Figure 2: Process of virtual automatic optimization (schematic): A number of virtual experiments are run as a start sequence. Quality criteria are analysed and the degree of fulfilment of previously specified objectives is calculated. Based on this, the process variables are automatically modified within their specified ranges to create new individual experiments. The process is driven by a genetic algorithm – a number of generations are created using mechanisms copied from nature. "Strong" individuals (with good fulfilment of the objectives) will survive and inherit their properties to later generations. New variations are tested by a type of "mutation". This process is run until the desired improvement of the casting process has been reached.

possible to improve ingot quality (minimize shrinkage) and at the same time minimize the head size.

Optimization of Ingot Casting Process

Most major quality problems in ingots originate from the casting process. Defects like shrinkage, porosity, segregation, non-metallic inclusions and cracks are initiated during teeming of the liquid steel and/or during solidification in the mould. There are various parameters of the casting process that can be modified in order to limit these defects and, if not completely prevent their existence, reduce their number and appearance so that the product fulfils the quality specification.

The rough ingot volume, geometry and dimensions are to some extent predetermined by the intended future use and subsequent processing of the ingot. Within the limits given by these factors, there is significant potential for optimization of the production process. Casting process parameters which are expected to have a strong influence on the casting quality are e.g. ingot height and diameter, taper, head size / geometry, insulation, topping, mould geometry, set configuration for multiple ingots, teeming flow or temperatures.

As an example, the dimensions of a 3t ingot (approximately) of low alloyed steel with a nearly rectangular cross section (see fig. 1) were varied for carrying out virtual casting experiments with the aim of finding the significant effects on centreline shrinkage. Both cross sectional dimensions were fixed to 500 mm while the cross section dimensions at the top of the ingot were independently varied in the range between 500 and 700 mm (see sketch in fig. 3). The ingot height was varied from 1000 to 1500 mm and the head height from 200 to 300 mm. Based on these ranges for variation a test plan of 64 virtual experiments (individual casting simulations) was set up which statistically combined various values of the mentioned parameters.

The optimization program has performed all virtual casting processes without further interaction of the user within 48 hours. Resulting from this it is possible to evaluate the effect of the mentioned parameters on all kind of quality criteria like for example thermal hot spots, centreline shrinkage or macrosegregation.

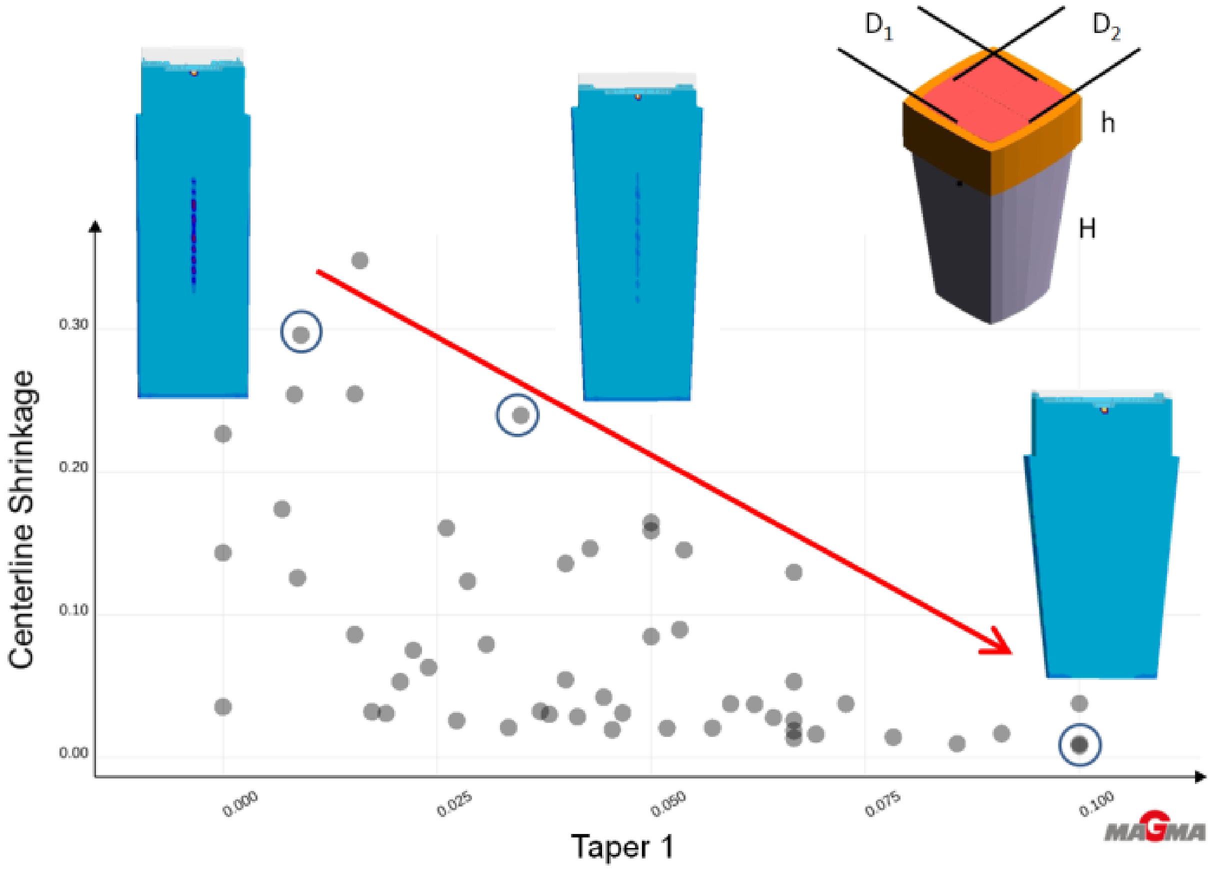

Figure 3: Influence of ingot taper on centreline shrinkage: In 64 virtual experiments, the dimensions of an ingot with rectangular cross section (see sketch embedded in the picture) have been varied concurrently. This allows to investigate the effect of both tapers and the head height on various quality criteria. In the scatter diagram each dot represents a single experiment (one simulation). For three experiments, the associated dots are marked - the corresponding simulation result for centreline shrinkage result is shown. As expected, with increasing taper the occurrence of centreline shrinkage becomes much less likely.

With the described variation of the dimensions of the ingot with rectangular cross section it is possible to investigate how its two tapers influence centreline shrinkage and how they interact. In fig. 3 the influence of taper no. 1 on centreline shrinkage is shown. Each dot is the result of one virtual experiment. There is a strong scatter of the results since both tapers and the head height are varied concurrently. With increasing taper 1 the strong distinction of centreline shrinkage becomes much less likely. For a strong taper 1 of 0.1 (or: 10%, dots on the very right) the ingot is virtually not showing any centreline shrinkage. Since both tapers are varied concurrently it can be concluded that it is sufficient for centreline shrinkage reduction to increase one of the two tapers. In this investigation, the head height does not show a significant influence on this defect.

Process Optimization in Continuous Casting

Continuous casting is a production process with an extremely high throughput. Today, the vast majority of steel worldwide and a nearly uncountable number of steel grades are produced by continuous casting. There are high requirements towards this process regarding the achievement of product properties, robustness and the repeatability of a defect-free cast product. Virtual experimentation and automatic optimization offer a wide range of possibilities to help in the achievement of these requirements.

Here, the production of a carbon steel bloom with a quadratic section of 160 x 160 mm in vertical continuous casting was looked at. For the simulations, a typical casting speed of 3 mm/min was assumed.

The solidification during the continuous casting process is controlled by the heat removal from the cast steel in all parts of the casting plant, starting with the mould: the heat transfer from the steel surface to the copper mould is governed by various phenomena – the gap formed by solidification shrinkage interacts with the casting powder [4], so that the heat transfer depends on various parameters. These combined effects are typically modelled using an effective heat transfer coefficient between the steel bloom and the mould. Assuming that the continuous casting process has reached its steady-state, the heat transfer coefficient can be modelled as being dependent on the position along the mould (from the top to the bottom), see fig. 4.

The most accurate way to calculate heat transfer coefficients is a reverse engineering process: It is based on a comparison between temperatures measured at well-defined thermocouple locations at the bloom surface in both, the real casting plant and the virtual one (the simulation model). This “inverse optimization” to fit the simulated heat transfer is described in [5].

As a first approximation it is possible to simulate the gap between the shrinking bloom and the mould in order to conclude the heat transfer between mould and bloom surface from that in an iterative procedure.

Virtual experimentation and automatic optimization can be applied to optimize all kind of parameters in a continuous casting process so that it can be run robustly at its best possible operating point. For the mould area for example mould geometry, mould taper, mould cooling, casting temperature, nozzle geometries or casting speed can be mentioned. It is

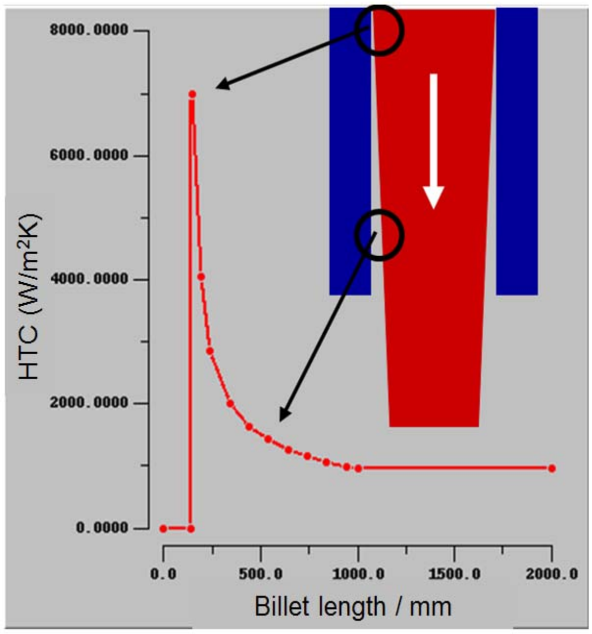

Figure 4: The Heat Transfer Coefficient (HTC) between a steel bloom and copper mould varies with position along the length of the mould during (vertical) continuous casting. The maximum value is close to the top of the mould and decreases with distance from the top due to gap formation and casting powder filling the gap.

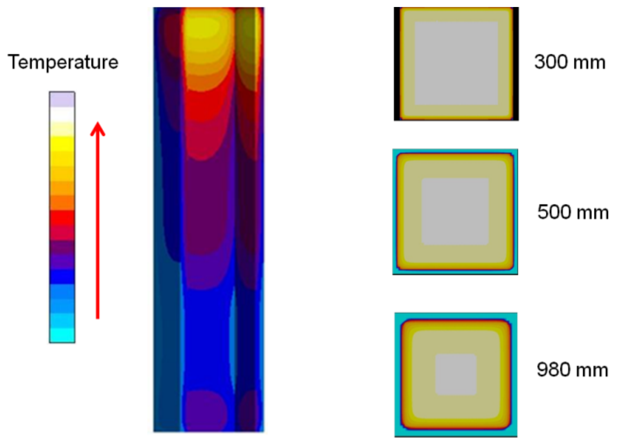

Figure 5: Temperature distribution on the mould surface (left, bloom hidden) and of the bloom in the mould (top view on cross sections at three different locations relating to the top edge of the mould, right) with a total length of 1000 mm.

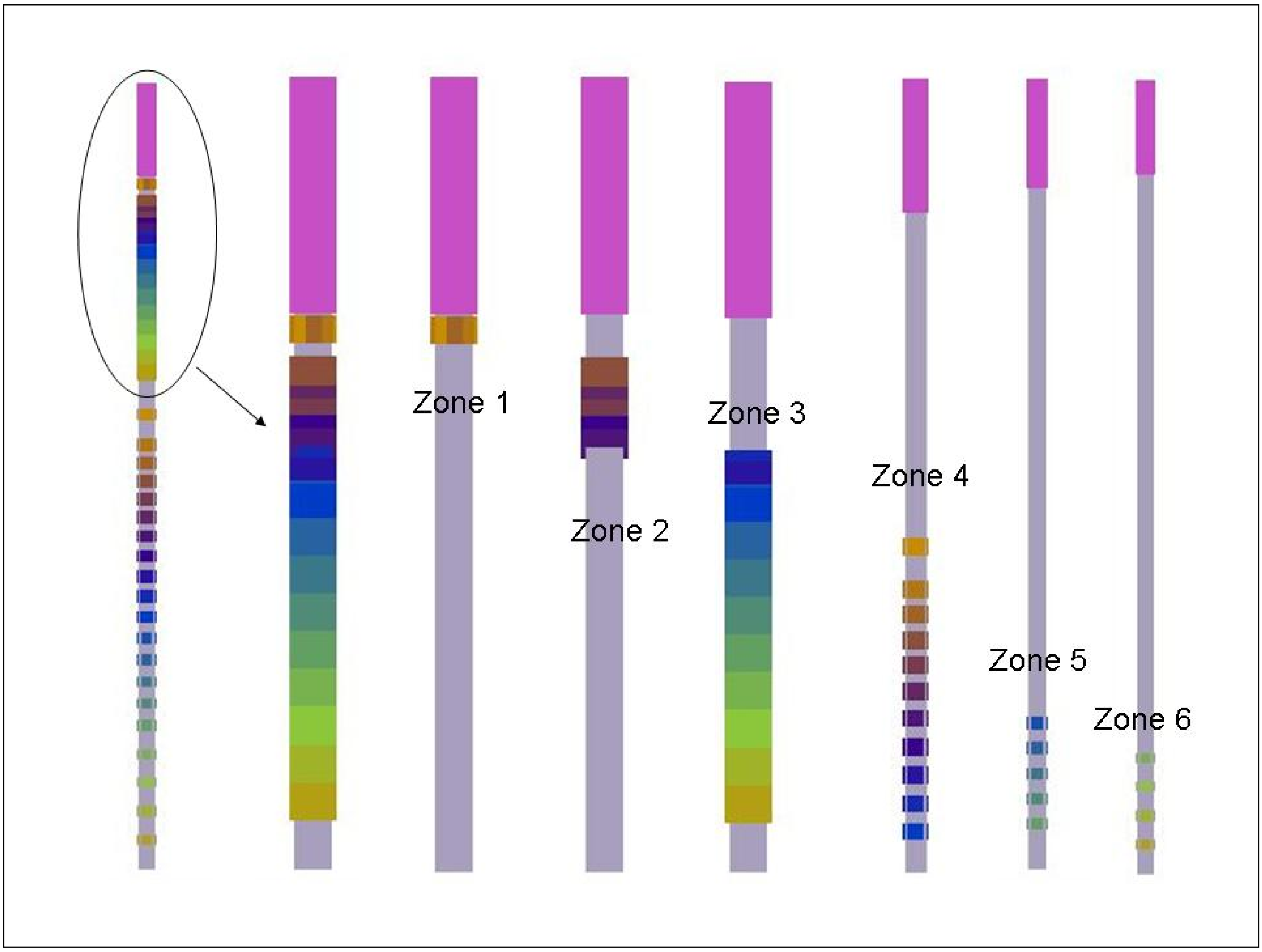

Figure 6: The secondary cooling of a continuous casting plant is partitioned into 6 different zones; the left sketch shows the cooling zones in total with the mould shown at the top in pink. (Note that the zones 4 through 6 are shown with a different scale at the right). The objective of the automatic optimization was to determine the best distribution of spray intensities in the secondary cooling to achieve and maintain the desired liquid pool depth in the casting.

possible to focus on any kind of quality criteria, like temperature distribution and liquid pool, inclusions flotation, segregation, distribution of residual stress or crack formation. The steel temperatures and the corresponding temperatures at the mould surface in the present example are shown in fig. 5. The surface temperature of the mould decreases as expected with formation of the solidified shell. Of course the solidification in the core of the bloom is by far not finished when the bloom leaves the mould. With secondary cooling the properties of the cast product are again strongly affected.

Here, usage of virtual automatic optimization to improve the layout of secondary cooling of a caster is illustrated. The spray cooling of the steel bloom caster is partitioned into six different cooling zones, see fig. 6. In the simulation, each zone is modelled by an individual heat transfer coefficient at the bloom surface. In this project, the best possible secondary cooling conditions should be determined to ensure that the liquid pool depth is at a desired value and remains stable. The position of the pool tip was changed through the variation of the characteristics of the secondary cooling zones. The depth of the liquid pool should be brought as close to 16.5 meters as possible.

During the optimization run, the intensity of spray cooling was varied individually for the cooling zones through a variation of the heat transfer coefficient between 400 and 800 W/m^2K for each cooling zone. All in all, 160 virtual casting experiments were run. Since the focus of the investigation was purely on the thermal aspect of the casting process, very fast simulations could be performed. The optimization was run within a few hours.

With the help of virtual automatic optimization, those cooling zones which take significant influence on liquid pool depth were identified and could be

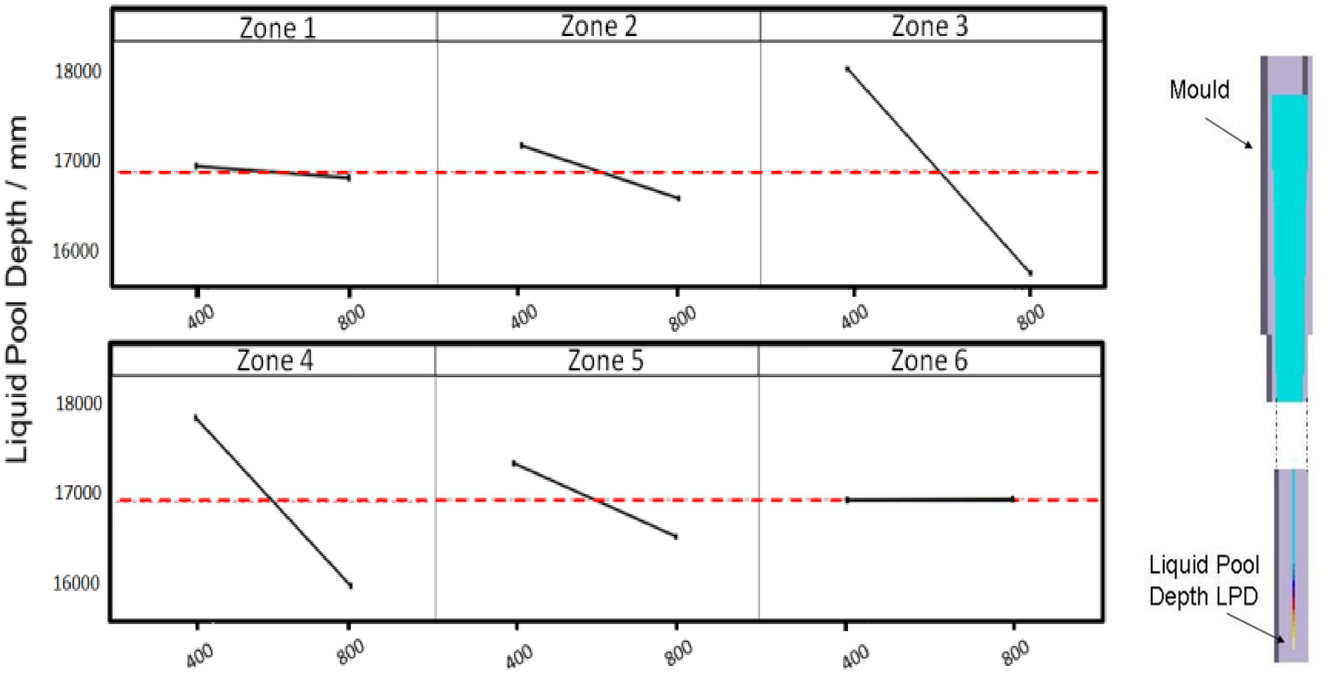

Figure 7: This main effects diagram shows how local spray cooling influences liquid pool depth. The local heat transfer between the strand surface and the surroundings is a direct measure for the intensity of local spray cooling. For each of the six cooling zones the effect of the increase of the heat transfer coefficient on the position of the tip of the liquid pool (see right picture) is plotted. Each line in the main effect diagram connects the mean values of liquid pool depth for the minimum and the maximum applied heat transfer coefficients of 400 and 800 W/m^{2}K in the particular zone respectively. When changing the spray cooling intensity in zone 3, the most significant effect on liquid pool depth is attained since the corresponding line has the strongest slope. Also zone 4 has a quite strong influence. The effect measured in zone 1 is very weak while zone 6 has absolutely no effect on liquid pool depth – the corresponding line is flat.

distinguished from those which are of minor importance, fig. 7. The required distribution of cooling intensities to get the liquid pool depth to the desired value and keep it in a robust casting process was determined. The influence of each particular cooling zone on the liquid pool depth could be investigated, enabling identification of important control variables in running the continuous casting plant.

Optimizing the Baffles of a Launder

In continuous or semi-continuous casting processes, the melt is transferred from the ladle to the mould or sprue in an intermediate vessel. The primary task of this launder or tundish is to deliver molten metal to its destinations at a designed throughput rate without contamination. In addition, the metallurgical quality of the melt is improved by floating inclusions out of the melt and trapping them in the slag [1].

It is obvious that some time is required for inclusions to float out of the melt. Often, flow control devices such as dams, weirs and baffles are placed inside a tundish to prolong the residence time of the melt and thus to promote inclusion flotation.

An investigation into the optimization of flow control by baffles has been carried out for a launder which transfers a nickel-base alloy into two ingots in a vacuum casting plant. Fig. 8 shows the launder with the built-in flow control devices: a first dam, a baffle with holes, the so-called “slag weir”, and a second dam. The slag weir forces the melt to flow below it before leaving the launder, so that the slag is restrained and is not sucked out of the launder into the casting (as long as the launder is filled with metal). Assuming that the metal is in continuous

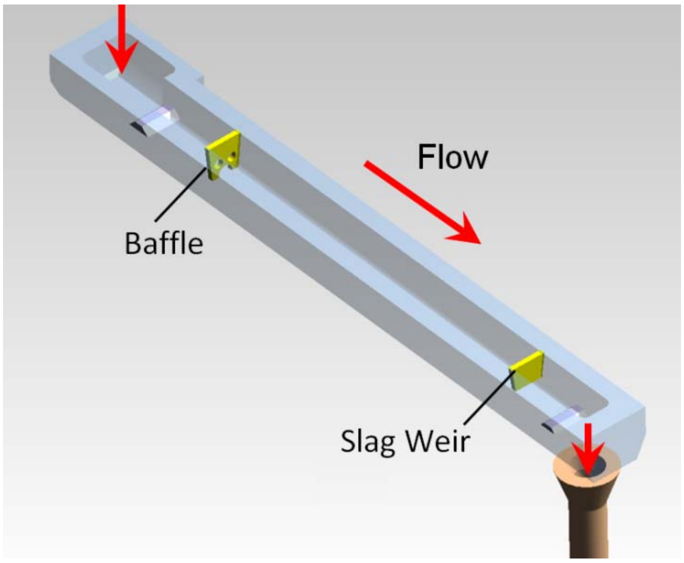

Figure 8: The launder with flow control devices. The direction of flow is indicated.

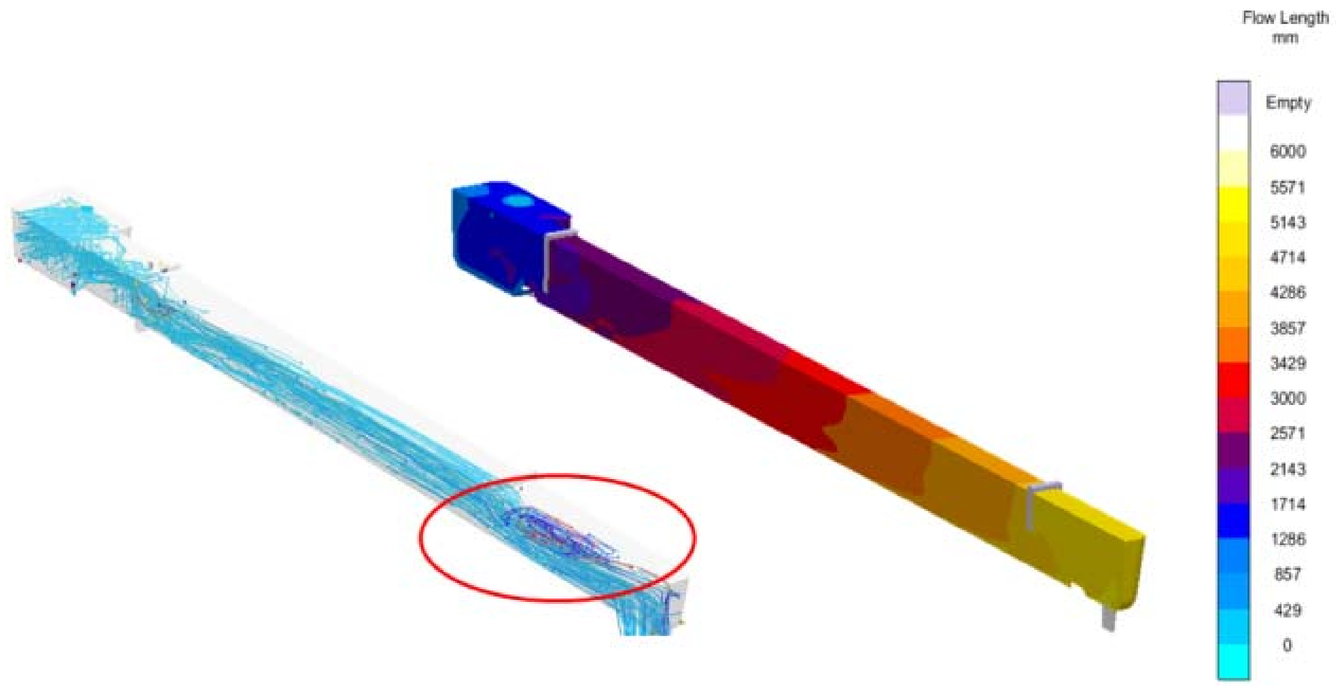

Figure 9: Flow of melt in the launder, illustrated through the simulation of flow tracers (left): Clearly visible is the formation of a vortex behind the slag weir (marked). The flow length result (right) shows the individual path length of the melt flow. High values indicate that the particular melt has been moving for a comparably long time, so that inclusions have had time to float into the top slag.

motion, the local residence time of the metal in the launder is equivalent to the local distribution of the flow length travelled by the melt from the point where it entered the launder, fig. 9.

The aim of the investigation was to understand the effects of baffle geometry and the positions of dams, baffle and weir on the flow length (and the corresponding residence time) in the launder. With an improved layout of this “launder furniture” the overall flow length should be increased and thus the cleaning of the melt by flotation of inclusions should be enhanced.

In order to find out how the different devices affect melt flow length, the height and position of the slag weir and the baffle position were varied in four steps each. Six different baffle geometries were tested – five of them were baffles with holes, while the sixth one was a weir similar to the “slag weir”. A sequence of virtual experiments was created, which consisted of 64 different combinations of the mentioned parameters. The main effects on flow length as a result of the assessment of these tests can be seen in fig. 10.

These results show that the most effective way to prolong the residence time of melt in the launder is to replace the baffle with holes by a weir which forces the flow to pass below it. Based on this basic configuration, further optimization has been carried out. The positions of the dams have been varied together with the height of the weir after replacement of the baffle with holes, fig. 11.

Conclusions

The examples presented here illustrate the application of the virtual automatic optimization for the improved lay-out of ingot geometry to achieve the desired product quality, optimization of the distribution of spray intensity in the secondary cooling in a continuous casting plant, and the design of a launder to obtain improved melt quality in ingot casting. In all of these areas, trial-and-error can be shifted from the shop floor to the computer. Using this approach, production processes and operating points can be determined to maintain a high quality standard and keep it robustly. At the same time, the application of virtual optimization methods can play a key role in reducing plant trials and saving costs – this effect must not be underestimated.

Acknowledgments

We like to thank Deutsche Nickel GmbH for kind permission to publish the launder example.

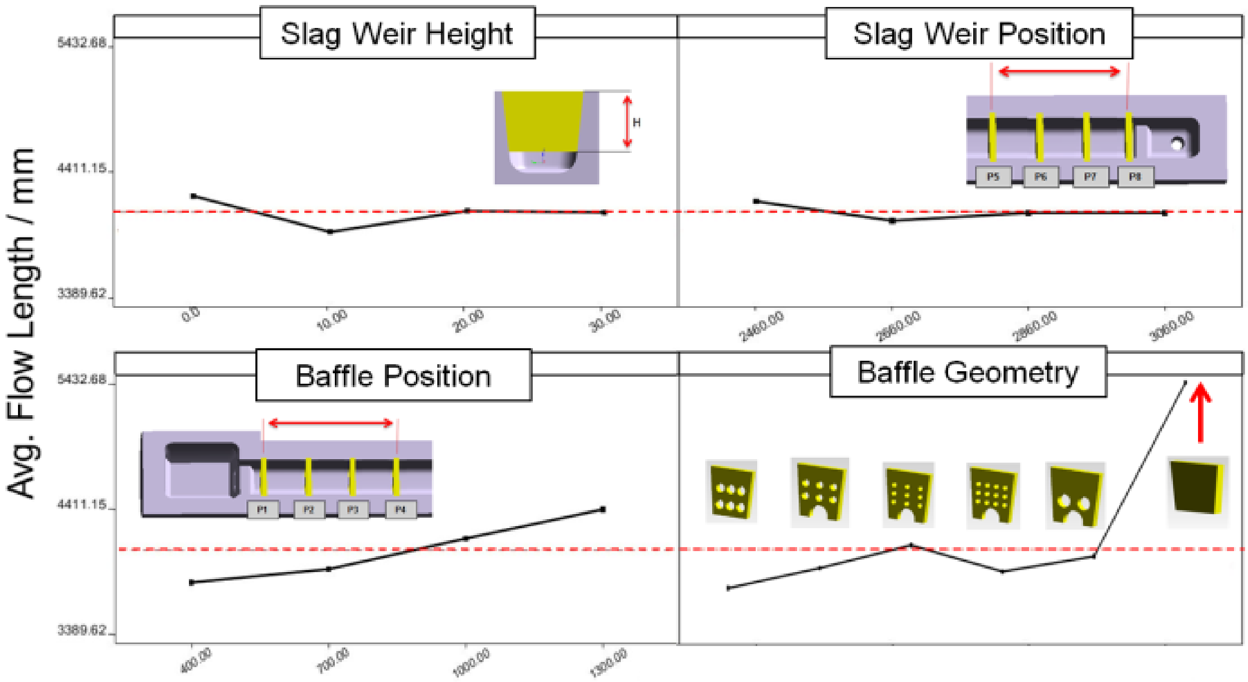

Figure 10: Four main effects on flow length inside the launder: This main effect diagram shows how strong the effect of each parameter on the objective (here: flow length) is. Slag weir height and position do not show any effect - the corresponding curves stay close to the average flow length for all parameter values. The baffle position has a noticeable effect. "Baffle geometry" indicates how the exchange of baffle geometries influences flow length. The most significant increase of the flow length is achieved by using the weir instead of a baffle with holes (geometry on the right).

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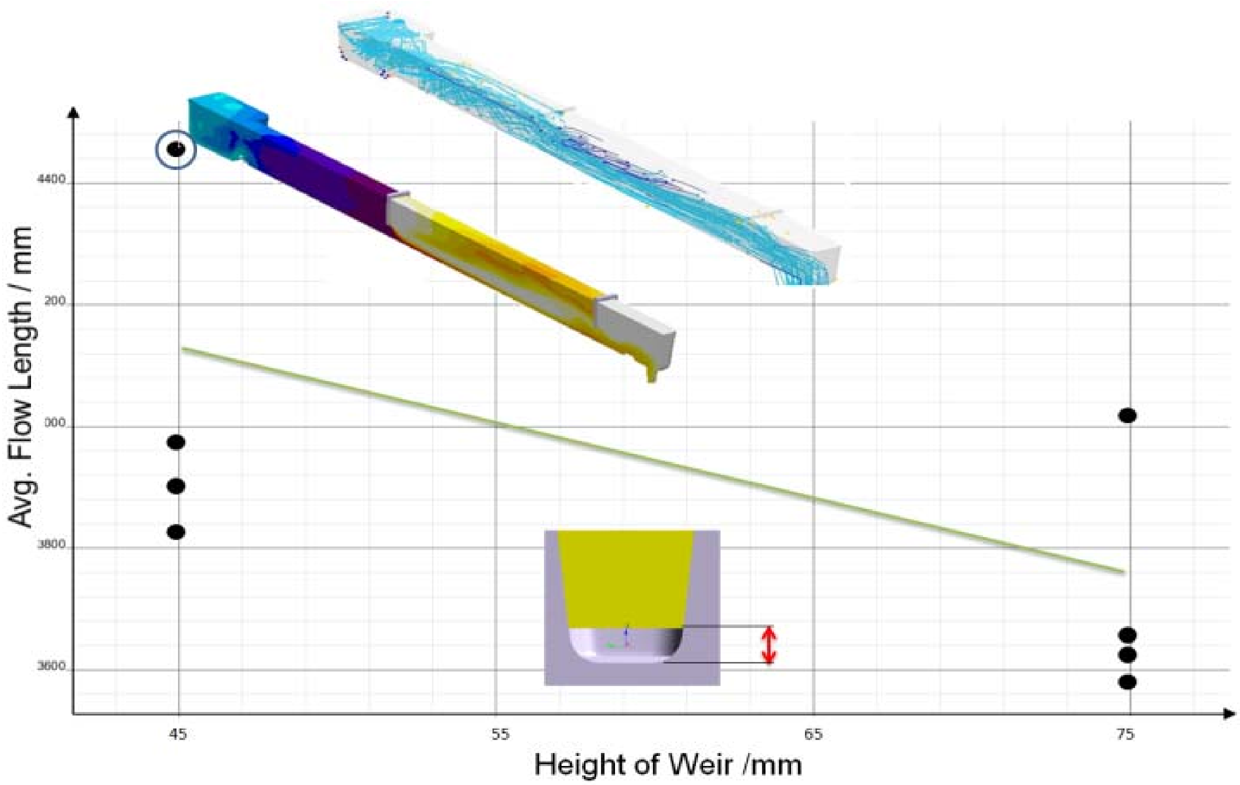

Fig. 11: The baffle has been replaced by a weir: Influence of the height of this weir on the flow length, as found by carrying out a sequence of virtual experiments. With a small gap of 45 mm below the weir (dots on the left) the average flow length is increased in comparison to a bigger gap of 75 mm (right dots). Lowering the gap for the melt increases the tendency for swirl movement in the area after the weir and thus increases the residence time. The simulation pictures show the flow length distribution together with the corresponding simulation of tracer particles for the highest average flow length amongst all virtual experiments.

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