Virtual Experimentation in Continuous Casting towards Online Control

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The classical use of simulation solutions evolves to process optimization. Integrated statistical tools such as virtual Design of Experiments allow to perform systematic virtual experimentation of a process window. This enables the expert to identify significant process parameters and to investigate the effect of parameter changes without expensive trials in the shop floor. Based on this knowledge, it is possible to optimize casting processes that are both, cost-effective and robust with respect to process variations.

State-of-art simulation tools provide quantitative insights in flow, solidification and stress formation for continuous casting processes. This includes the entire process, from the tundish and the flow into the mold to the solidifying strand that is withdrawn through various cooling zones. Process simulation provides important information about quality and productivity to evaluate process alternatives.

This paper will discuss the modelling of electromagnetic stirring (EMS) and its impact on the flow behaviour. Another focus will be the evaluation of new criteria to avoid the formation of cracks. With the help of a stress calculation results for cold crack formation and hot tearing are available. Stress simulation is also been used to described the gap formation in mold and the corresponding change of heat transfer conditions.

The results are shown at industrial examples for billets and bloom casters. With the availability of the integrated process knowledge of a digital twin, it is possible to identify optimal operating points for quality improvements and productivity increases. The objective is to derive a comprehensive model for online monitoring and optimized dynamic online control of the cooling and solidification process.

KEYWORDS: VIRTUAL EXPERIMENTATION – CONTINUOUS CASTING – DIGITAL TWIN – ONLINE CONTROL – ELECTROMAGNETIC STIRRING – PROCESS OPTIMIZATION

INTRODUCTION:

The global steel market is increasingly competitive especially for the low-cost steels sector due to emerging mass steel producers. As a consequence, European steelmakers are focusing more and more on advanced steel grades and have claimed a good portion of this market by concentrating on stainless and advanced steel grades. However, these steel grades are difficult to be cast continuously and thus need accurate control of the operational parameters influencing solidification and cooling rate to avoid defects like cracking. Moreover, the current economic climate demands high flexibility from steel producers, which have to supply orders with large variability in size and grades. For the continuous casting process, this means that different orders must be cast sequentially with optimum quality and a minimum number of defects. As can be expected, a fixed set of casting conditions cannot cope with such requirements, thus optimal operational windows and control parameters have to be chosen for each individual steel grade and dimension. An extended knowledge base of the complex and interacting processes during casting based on comprehensive process models for simulation and online control would allow steel producers to define optimal casting conditions. This is the basis to improve quality and to avoid casting defects and reduce cost-intensive rework of the semi-finished products.

The objective is to develop and establish an online monitoring and dynamic control system for the casting process by using a “Digital Twin”, Fig. 1. In combination with the application of advanced temperature measuring technologies (e.g. fiber optical temperature sensors) and an improved comprehensive simulation model enable the virtual optimization of operational practices and operating points for the continuous casting process in terms of quality and productivity.

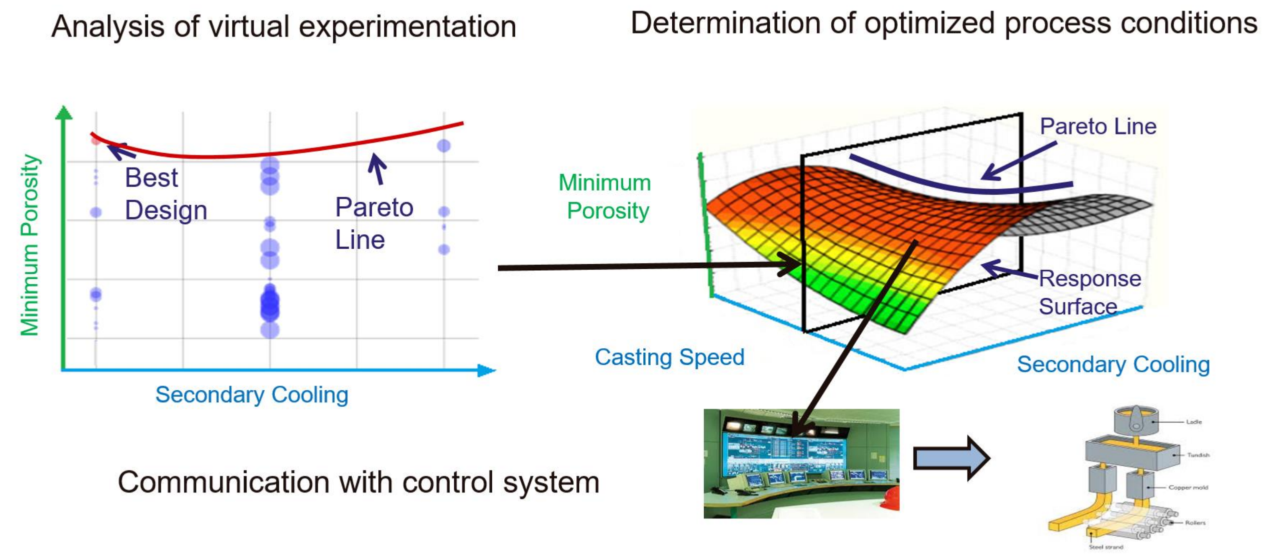


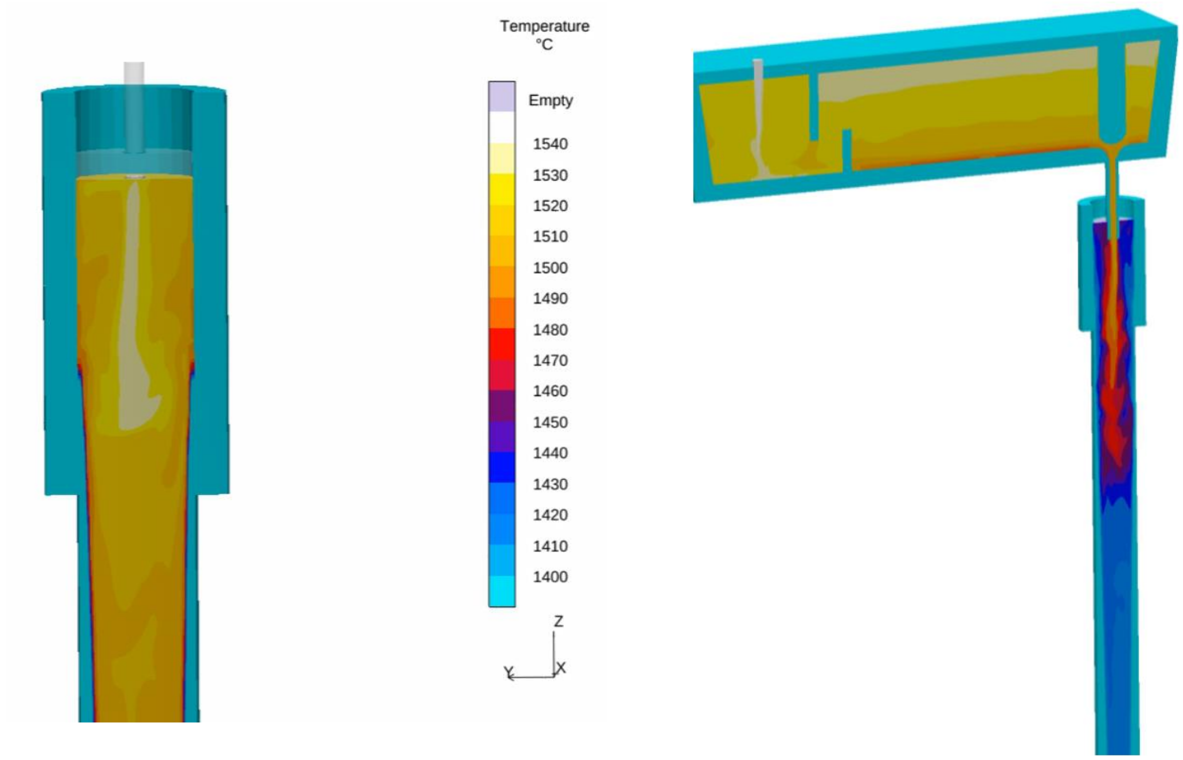
Fig. 1 – The idea of a digital twin for continuous casting processes – virtual experimentation towards online control. As a result, an efficient response surface shows the optimum relation between productivity and energy efficiency.

The Digital Twin

A Digital Twin can be defined as a digital representation (model) of a physical object that allows the reproduction of its dynamic behavior. According to Industry 4.0, Digital Twins connect the virtual word with the real one, Fig. 2. Although first attempt of Digital Twins have been known since the beginning of the 2000s, their industrial relevance has grown only marginal until a significant performance increase of software and hardware [1]. Additionally a paradigm change was needed from using simulation to confirm already taken decisions to a tool in which simulation is used as virtual experiment to predict the behavior of the process under varying conditions.

Fig. 2 – Generation of integrated process know-how by connecting the real world with the virtual world.

A Digital Twin of the continuous casting plant offers not only a precise 3D-thermodynamics for cooling and solidification of the strand, but also integrates fluid dynamic and thermomechanical phenomena. The Digital Twin described in this paper has been created using the industrial simulation and optimization software MAGMA CC. This integrated solution combines the simulation of mass flows (especially in the tundish and in the mold) [6], the temperature field simulation (from heat flow equation with cooling and solidification in the mold and the secondary cooling zones) and the simulation of the mechanical properties (with thermomechanical calculations in the mold and following strand, see Fig. 3).



a) b)

Fig. 3 –Temperature and flow field in the mold a) Integrated solution combining the simulation of mass flows in the tundish and in the mold b).

Virtual experimentation of continuous casting processes

Today optimization programs can run a large number of virtual casting experiments in a comparably short time [2]. The software automatically assesses the relevant quality criteria after each virtual casting trial. After having run the virtual experiments, all results are available to the engineer for a statistical assessment.

In setting up an automatic optimization, the casting process parameters, which should to be varied, and their respective variation ranges need to be identified. For continuous casting processes, this can be geometrical dimensions like mold or tundish design, casting temperatures and casting speed, primary or secondary cooling conditions and more, see Fig. 4. This is followed by the definition of a sequence of virtual experiments using the statistical approach of "Design of Experiments (DoE)" for real plant trials. The software uses these statistical methods to aid the engineer, so that the lowest number of (simulation) experiments necessary is required to retrieve a maximum of information from the simulation results possible. Evaluating a sequence of virtual experiments helps to understand how strongly the effect of each parameter on the quality criteria is. This provides valuable information to the engineer to significantly improve the production process. Based on this knowledge, it is possible to optimize casting processes that are both, cost-effective and robust with respect to process variations.

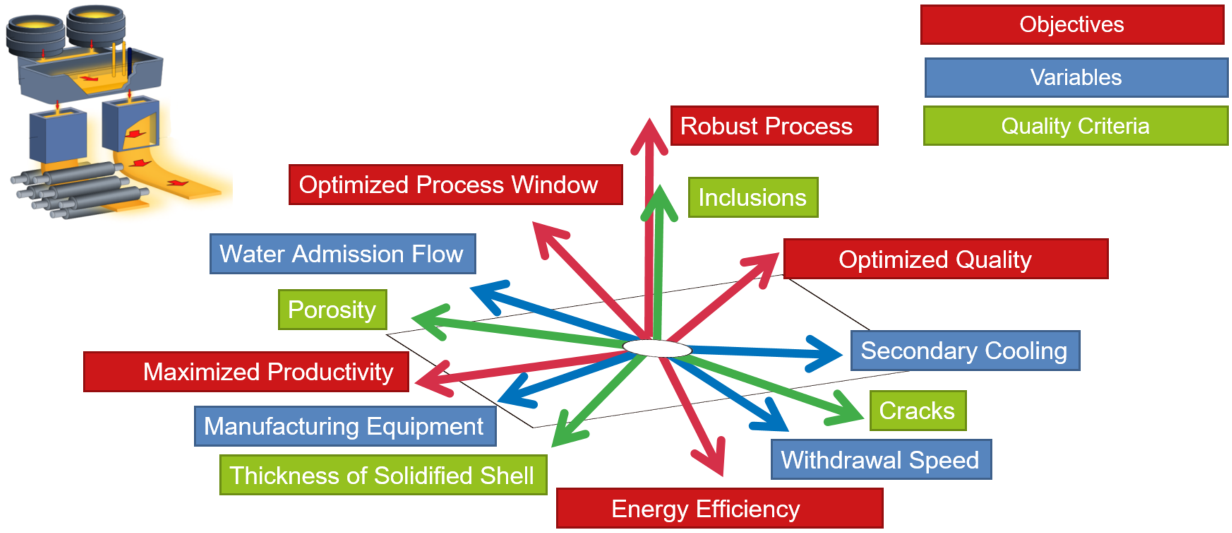
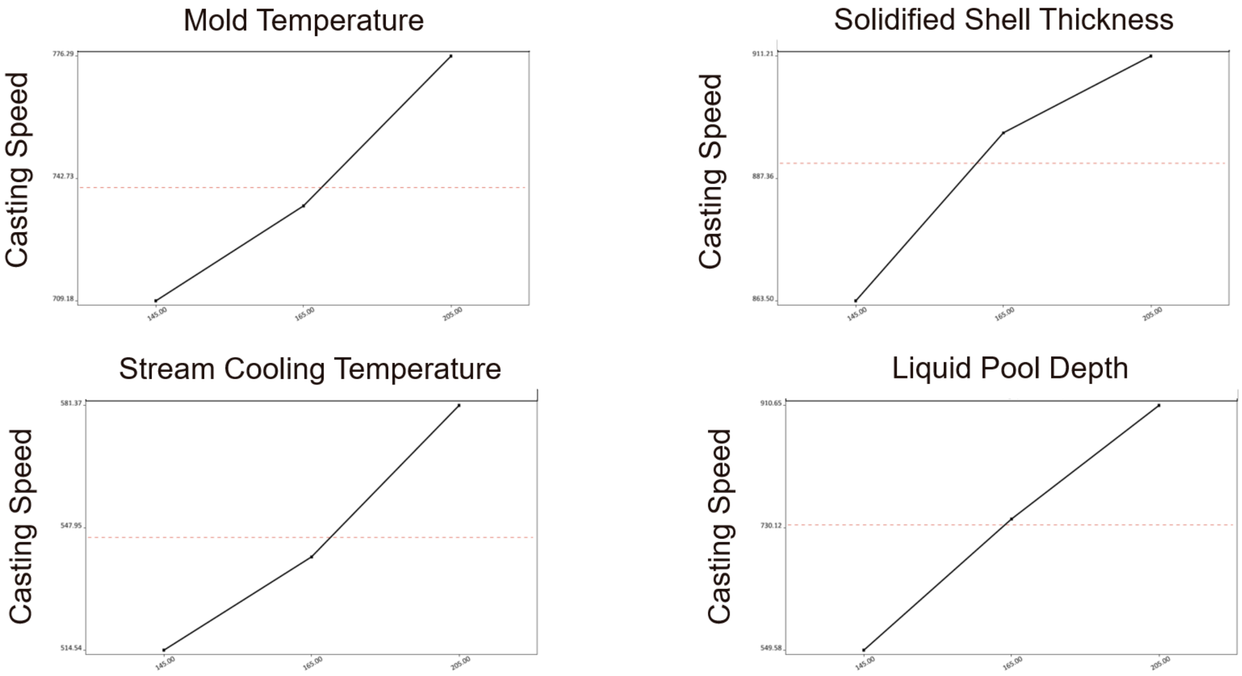


Fig. 4 – Virtual generation of "Big Data" for continuous casting processes. Overview of possible objectives process variables and quality criteria

As one example for the statistical assessment, Fig. 5 shows a main effect diagram for the influence of the casting speed on different quality criteria. It is obvious that casting speed is a major parameter on quality and on productivity.


Mold Temperature

Solidified Shell Thickness

Stream Cooling Temperature

Liquid Pool Depth

Fig. 5 – Virtual generation of "Big Data" in continuous casting - Overview about process variables, quality criteria and objectives

Another typical usage of virtual automatic optimization is to improve the layout of the secondary cooling of a continuous caster [3]. The spray cooling of a steel caster is typically partitioned in different cooling zones, see Fig. 6. In the simulation, each zone is modelled by an individual heat transfer condition on the strand surface. 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 changes through the variation of the characteristics of the secondary cooling zones. With the help of virtual automatic optimization, the cooling zones that have significant influence on the liquid pool depth can be identified and be distinguished from the ones of minor importance, Fig. 7. The influence of each particular cooling zone on the liquid pool depth can be investigated, enabling identification of important control variables for running the continuous casting plant.

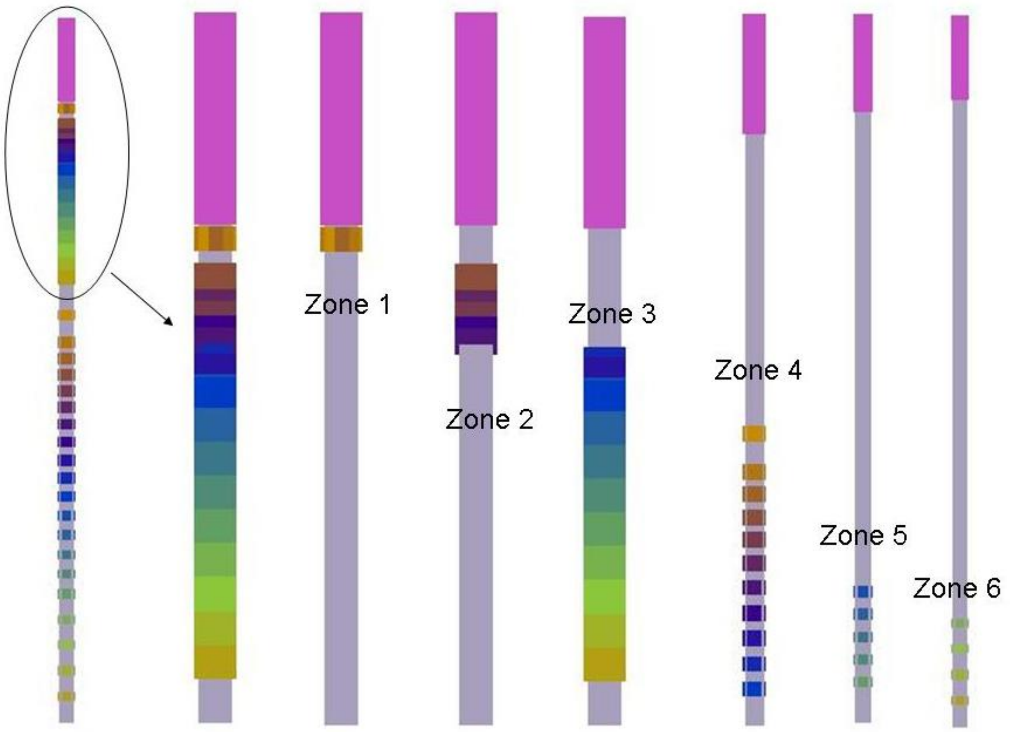


Fig. 6 - In this example the secondary cooling of a continuous casting plant is partitioned into 6 different zones; the left sketch shows an overview of the cooling zones and the mold. The objective of the automatic optimization is to determine the best distribution of spray intensities in the secondary cooling to establish and maintain the desired liquid pool depth in the casting.

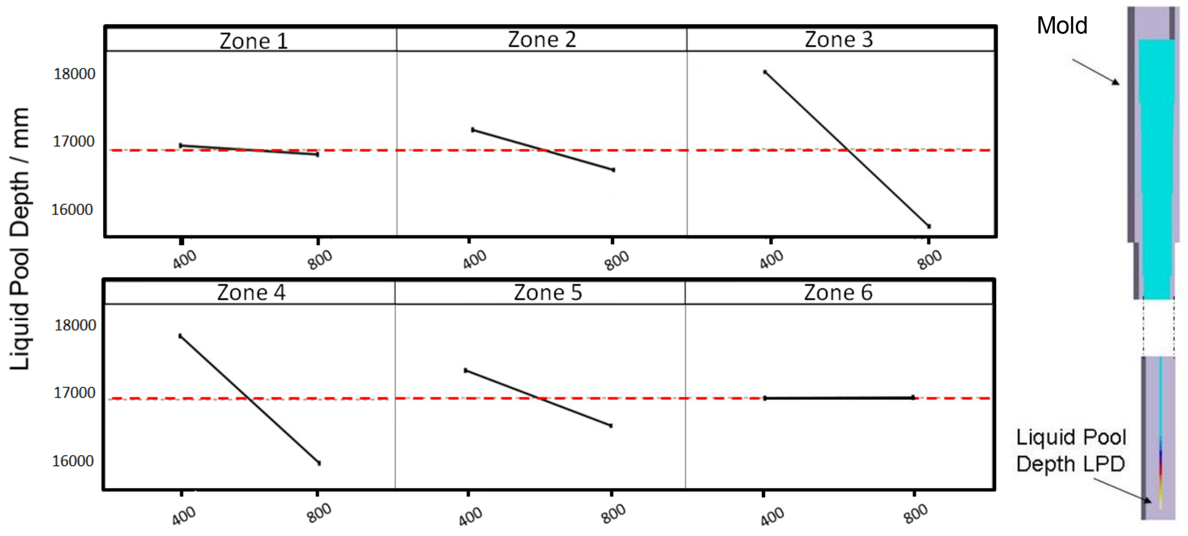


Fig. 7 -Main effects diagram showing the impact of local spray cooling on liquid pool depth.

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 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.

Modelling of Electromagnetic stirring

Electromagnetic stirring, or short EMS, is a device used in the continuous casting of steel, which has a positive influence on the quality. The EMS device is typically installed in the area of the continuous casting mold and sets the liquid core of the strand in rotation. This mixing prevents segregation and reduces the grain size of the end product, which in turn leads to higher strength and toughness values.

To consider the influence of EMS on the flow behavior a comprehensive physical model has to be implemented in the simulation software [4]. This computational model includes the inductors with prescribed amplitudes and phases of the electric currents and the electric conductors such as shields, as well as the liquid and solidified casting. Maxwell equations are solved in terms of potentials in the quasi-stationary formulation; it operates in the frequency domain. The primary variables are complex amplitudes of the scalar and vector potential; hence the solution is looking for in the frequency domain.

The solution for the Lorenz force distribution is obtained for a piece of the strand located in vicinity of the inductive system (stirrer). The Lorenz force distribution in the strand body is stored into a file. It can be imported into the arbitrary project version of the continuous casting setup and be placed at the prescribed position of the strand. The only condition is, the strand cross-section in both electromagnetic and continuous casting versions of the project has to be the same. The imported 3D force distribution is interpolated onto the actual grid of the strand and is used unchanged as a momentum source term in each computational step of the momentum equations.

The further development will be the expansion of the actual model on magnetic materials such as iron cores. This task demands the description of the magnetic permeability jump at the interface between two different materials.

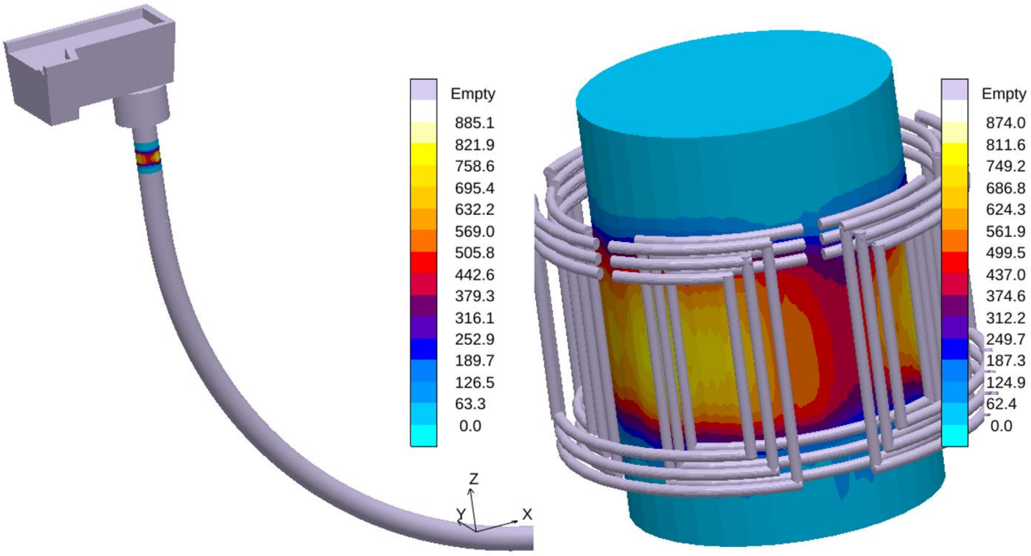


Fig. 8 – Calculation of a Lorenz force for EMS (right). Result for the corresponding position of the strand (left)

Stress Simulation and Prediction of Cracks

The calculation of thermal stresses and strains is already an integrated part of a completely continuous casting process simulation and optimization [5]. It is well known that large thermal gradients lead to a high level of stresses. The material model, which is used for the calculation, is a unified creep formulation, which is based on Norton´s power law. Time dependent plasticity and a porous damage model are possible to choose as alternatives.

Together with new developed crack criterion this stress simulation can be used to predict the crack risk at the end of solidification, known as hot tears. Hot tears are inter-crystalline cracks and form just above the solidus temperature. They often appear in areas where solidification fronts meet.

During the further cooling of the strand additional crack formation processes like cold cracks can occur. The main reason for cold cracks is a local high tensile stress level. For the judgement of crack risk, different results are available. The effective plastic strains e.g. are summed up during the cooling process. Too high plastic strains are a hint for crack risks. Plastic strains due to tensile loads are more critical than plastic strains due to compressive loads. A further result is von Mises stress. This is an equivalent stress, which allows the comparison of calculated stress values to measurements of tensile test. The criterion is used in combination with the tensile strength of the material for a judgment about cold cracks Figure 10. Figure 9 shows the corresponding temperatures at the tip of the liquid pool.

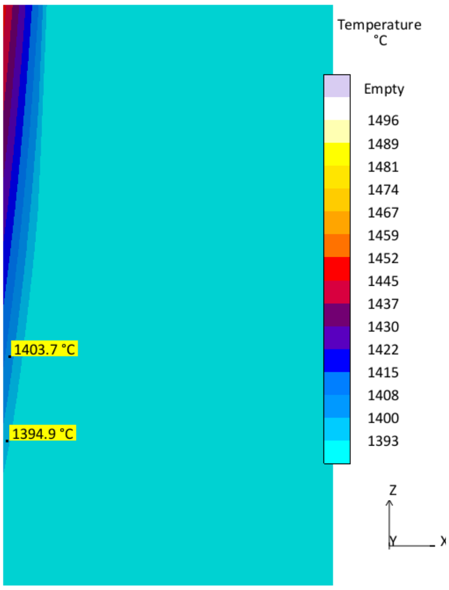


Fig. 9 – Visualization of the temperatures at the tip of the liquid pool.

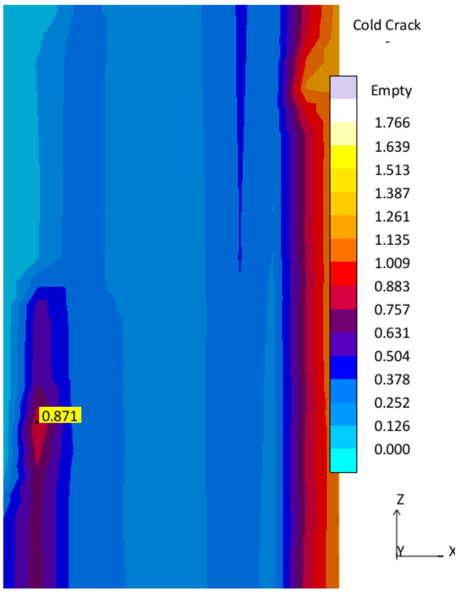


Fig. 10 – A local maximum of the cold crack criterion indicates a risk for crack formation in the strand just below the solidus temperature next to the tip of the liquid pool

Coupled to the capability of the virtual experimentation this allows to optimize process conditions systematically with the objective to minimize the risk for crack formation.

The thermal situation in the primary mold is driven by a very complex interaction between the solidification and the formation of a stable shell and the material contraction that often leads to a gap formation. The forming air gap significantly changes the heat transfer locally and over time. To be able to describe these phenomena the simulation must consider the thermomechanical coupling between strand and mold. .Figure 11 shows the formation of the gap. The corresponding heat transfer coefficient is decreasing as a function of the strand length, Figure 12

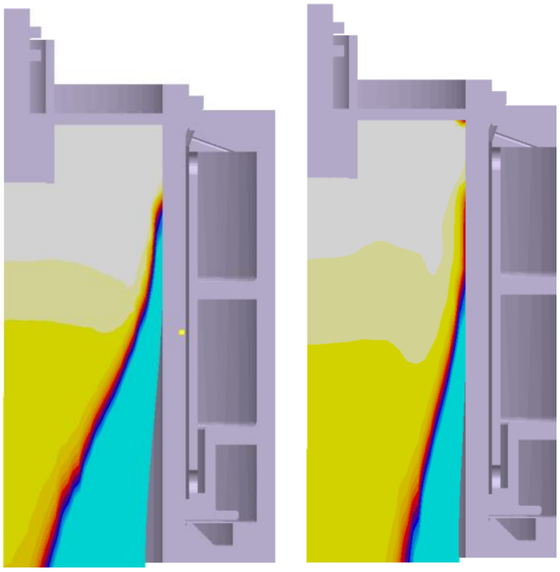


Fig. 11 – The gap formation in the mold and the corresponding heat flow can be calculated by coupling the thermal and stress simulation

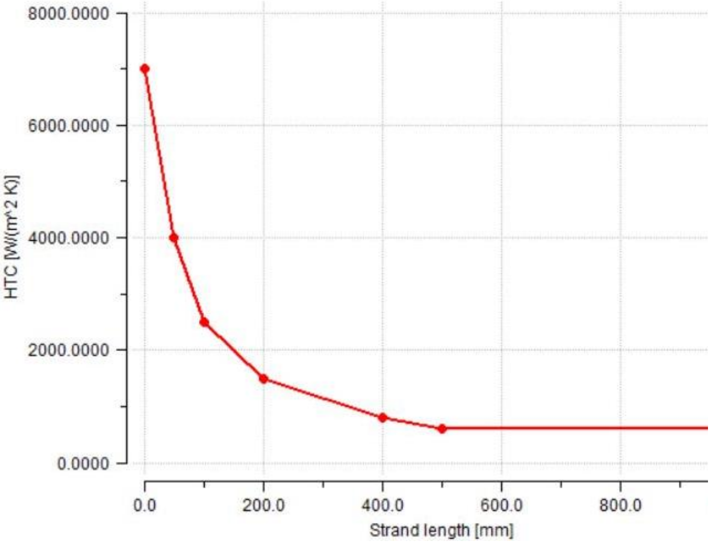


Fig. 12 – Effective heat transfer coefficient as a function of the stand length. Due to the gap formation the heat transfer will change in the contact area between strand and mold.

Summary

The continuous casting process is a key technology for steel production today. More than 96% of all steel products are produced in this way. The development of a digital twin that allows offline and online optimization is more than necessary to improve process conditions and realize a robust final product quality. The approach of virtual experimentation described in this paper can be used to get quantitative insights on robust process windows for given objectives and quality criteria.

The impact of phenomena like convective flows and electromagnetic stirring on the product quality can be considered. An integrated additional or coupled stress calculation provides quantitative information about residual stresses and improves the understanding of crack formation in the strand. The modeling of the gap formation helps to control the local heat transfer.

This concept of a digital twin for continuous casting processes using systematic virtual experimentation is the precondition for a comprehensive process model that can also be used for online control of the process in daily production.

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