Modeling of Casting, Welding, and Advanced Solidification Processes - XII
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Simulation Based Optimization Strategy for Balancing Quality and Productivity in Continuous Casting

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Over the last decades, many research groups have studied the mould behavior and the solidification in the continuous casting of steel billets. The process was analyzed by various measurement techniques, calculations and/or analytical or numerical simulations. For a better understanding of the detailed phenomena influencing the casting process performance and billet quality, it is possible today to combine newest developments in coupled 3D numerical heat and mass transport simulations with computational optimization methods based on genetic algorithms. In this contribution, the authors show the use of these genetic algorithms for autonomous multi-objective numerical optimization of the continuous casting process of steel billets. A primary objective for the optimization was to find the best possible coupling between casting speed, spray nozzle layout and liquid pool depth. This has to be done while still keeping the surface temperatures within narrow constraints. The overall goal is to increase the productivity and to make no compromise concerning the quality of the final product.
The use of a multi-objective optimization algorithm made it possible to follow each of these objectives simultaneously. Further evaluation of the results allows an estimation of the sensitivity of the casting quality to process parameters.

In summary, this contribution introduces a numerical simulation based optimization strategy, following rigorous thermodynamic models as well as a strictly methodic approach.

1. INTRODUCTION

Simulation technologies need the input of start and boundary conditions, usually provided by engineers. Considering theses conditions, models are applied to all kinds of mechanical, physical or chemical processes, and simulation tells the engineer what results he might expect when going through a process as defined by him.

It is a trial and error driven, iterative process, that requires an engineer's interpretation and decision after any of the simulation runs. It is an old dream of the engineers, to leave most of the required decision supporting and decision finding processes to a computer, thus being unburdened and able to concentrate on decisions which can not be made by computers. This contribution presents a computational optimization methodology, based on numerical simulations of the continuous casting process, as the first step into the future of autonomous process optimization - recently being named as “the second generation of numerical simulation technologies” [1].

In order to get an optimized solution process boundary conditions for a continuous casting process simulation have to correspond to the real situation. To determine characteristic process conditions, such as the sump depth based on the casting speed, the heat transfer coefficient in the primary cooling in the mold as well as the secondary cooling due to water spray have properly defined. To get the heat transfer coefficients between strand and mould, two principle methods can be applied. The direct way is to perform temperature measurements in the copper mold at the machine in the plant. With these temperature/time plots an inverse optimization method can be used to determine the relevant heat transfer coefficients [2]. In other cases the heat transfer coefficients have to be calculated based on a "system conductivity" λ_{sys} taking into account the conduction and radiation properties of the slag layer.

Based on the boundary condition in the primary cooling, an autonomous numerical casting process optimization was done. The objectives for the optimization were to get the best possible coupling between casting speed, spraying nozzle layout and liquid pool depth (LPD). The use of a multi-objective optimization algorithm made it possible to follow all these objectives simultaneously. The Pareto-set from the optimization allows the evaluation of how the different versions that were simulated perform with respect to the given objectives – which means selecting a situation that makes the best possible compromise.

Finally the optimization tool was used to estimate the influence of casting parameters like secondary cooling power and different casting powders on the liquid pool depth. This sensitivity was investigated in the later described project.

2. HEAT WITHDRAWAL IN THE MOULD

The depth of the liquid pool is mainly controlled by primary and secondary cooling. The transported heat from the strand surface to the cooling water is conducted through the solidified steel shell, the flux layer and the gas gap. The heat flux density in the layer of thickness d_{cf} can be described with the equation

$$q = \frac{\lambda_{sys}}{d_{cf}} \left(T_0 - T_m \right) \tag{1}$$

where q is the heat flux density, T_0 the strand temperature and T_m the mold temperature. The conduction and radiation properties of the slag layer and the contact resistance are lumped together into an average "system conductivity" λ_{sys}. System conductivity increases with strand temperature due to the effect of radiation, and depends on the consumption of the casting powder. An empirical function is used to represent the λ_{sys} data

$$\lambda_{sys} = \lambda_{sys}(1200°C) * \left(0.505 + 7.448 * 10^{-11} T_o^{3.19} \right) \tag{2}$$

$$\begin{aligned} \lambda_{sys}(1200°C) = 2.03 - 0.459 \left(\frac{\%CaO + \%MgO + \%MnO + \%K_2O + \%Na_2O + \%LiO_2}{\%SiO_2 + \%B_2O_3} \right) \\ - 0.169\%Fe - 0.0348\%Al_2O_3 \quad [Wm^{-1}K^{-1}] \end{aligned} \tag{3}$$

The temperature T_0 is given in $°C$. More details about the above equations can be found in [3]. The layer thickness of the casting powder can be described by the equation according Hiraki [4]

$$d_{cf} = 0.95 * v_g^{-0.95} \quad [mm] \tag{4}$$

where v_g is the withdrawal speed given in m/min. The heat transfer coefficients for 10 selected casting powders using a casting speed of 3m/min and the simulated depth of the liquid pool is shown in figure 1. The composition of the 10 casting powders can be found in [3]. The simulation results were performed using the software module MAGMAcont for a bloom with a square section of 140 x 140 mm

powder	ST1	ST2	ST3	RH1	RH2	RH3	KB2	KB3	KB33	MB33
LPD [m]	19.48	20.63	21.23	19.73	20.43	19.73	20.66	19.02	19.62	19.02

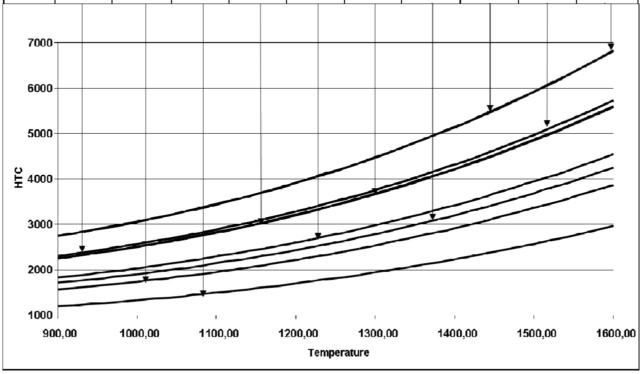


Figure 2. Heat transfer coefficient for 10 different casting powders and the simulated depth of the liquid pool for a bloom with a square section of 140x140 mm

The heat flux density in the gas gap can be described by the empirical equation [2]:

$$q = \frac{2.016 * 10^{-4} (T_0^{1.7684} - T_m^{1.768}}{d_{gap}} + \frac{5.669 * 10^{-8} (T_0^4 - T_m^4}{\varepsilon_0^{-1} + \varepsilon_m^{-1} - 1} \quad [Wm^{-2}] \qquad (5)$$

The first term on the right hand side describes the conduction and the second term the radiation part. The temperatures T_0 and T_m are in K, the thickness of the gas gap d_{gap} is in m, and ε_0 and ε_m are the emissivity at the strand and mold side.

3. HEAT WITHDRAWAL IN THE SECONDARY COOLING ZONES

The secondary cooling is the second main mechanism of heat withdrawal during continuous casting, and the accuracy of the nozzle definition is decisive for the success of any further calculation (figure 2).

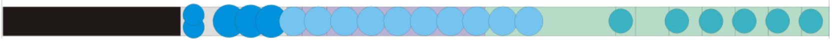


Figure 2. Nozzle distribution for circular nozzles. The nozzle areas below the mould are overlapping

Each nozzle is defined by its water charged area and by the amount of water that is sprayed on this area within a certain time. In simulation, the nozzles are replaced by corresponding heat transfer coefficients. These are calculated according to the amount of sprayed water. The position of the nozzle and the diameter of the area must agree with the production line. When two nozzles are overlapping, for the intermediate section a different heat transfer coefficient has to be defined. Since there are a lot of nozzles between the mould and the cutting section, the correct definition of the areas and the heat transfer coefficients is the most time consuming part of the modeling.

To calculate the heat transfer coefficient the following equation is used [5]

$$h_s = 1.82 \frac{V_{sp}}{A} + 198 \quad [Wm^{-2} K^{-1}] \tag{6}$$

where h_s is the heat transfer coefficient for each nozzle, V_{sp} is the water flux in l/min and A is the sprayed area. The water flux is a function of the withdrawal speed.

Figure 3 shows the liquid pool depth for different casting speeds based on the above equations. A linear relationship was found.

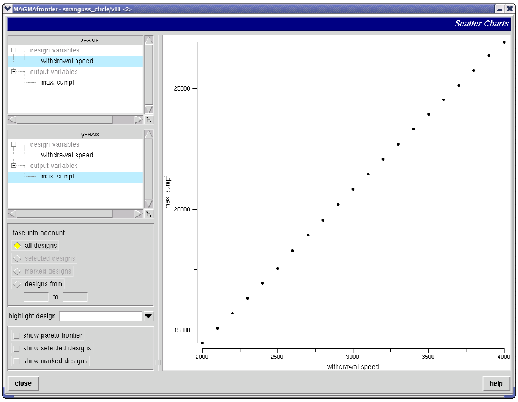


Figure 3. The liquid pool depth as a function of the withdrawal speed. A linear relationship can be observed.

4. USE OF GENETIC ALGORITHMS

An effective engine for this automatic optimization is MOGA, the multi object genetic algorithm. This algorithm has two features, being of particular importance in the context of process simulation: It supports the tracking of several independent targets and can handle any type of process and design variables including those variables occurring in continuous casting simulation.

The application of genetic algorithms requires the definition of a start generation consisting of several individuals. In this context "individual" is just another word for design resp. a variant of the involved project. The individuals can be selected resp. generated by using different DOE strategies like random, quasi-random (Sobol), full/reduced factorial, Taguchi or Monte Carlo methods [6].

The algorithm now starts for each of these individuals a casting process simulation and evaluates the results for their compliance with the given constraints and optimization targets. After that the algorithm creates a new generation following the genetic rules of heredity, mutation and selection. Out of the total number of designs (a given number of generations multiplied by a given number of individuals), being defined and evaluated by the algorithm, we usually get several good designs.

In general it makes no sense to talk about “the optimum” or “the best solution” of a problem, because in almost any optimization task related to casting process simulation, we get a set of good designs especially for multi-objective problems. The aim of the design optimization is to find a good compromise out of many possibilities; it is not to calculate an extreme of a function in the mathematical sense.

The optimization described in this paper was performed using the software module MAGMAfrontier.

In this module the user describes the problem by determining some parameters:

- Design variables with their corresponding ranges of variation (these are the parameters of the simulation that will be varied)
- Output variables (they contain the results of the simulation in concentrated form)
- Constraints
- Objectives (maximize or minimize certain combinations of output variables)

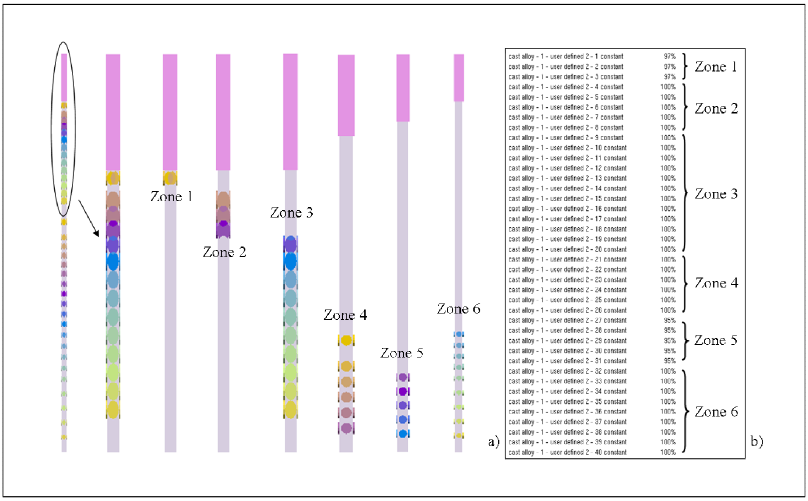
After all the information is available an optimization loop can be started.

5. DETAILED PROJECT DESCRIPTION

As an example the production of a bloom with a square section of 140 x 140 mm was analyzed. The thermo physical properties of a steel grade St52 for the simulation were taken from the database of MAGMASOFT®. Six cooling zones with different heat transfer coefficients in each zone were modeled. As casting velocity 3 m/min was chosen. Results of the influence of casting velocities to the depth of the liquid pool were shown in figure 2 and in earlier publications [7]. The main interest was to optimize the secondary cooling behavior in the sense that the amount of spray water should be optimized to reach a well defined depth of the liquid pool.

The heat withdrawal in the mold is mainly determined by the casting powder and the gas gap formation. In this analysis we used the casting powder ST2 (figure 1). To calculate the gas gap between the strand and the mold, a thermomechanical coupled simulation must be performed. For this project a pure heat transfer calculation was performed which means that the resistance due to the gas gap formation was not taken into account. The objective function for this part of the project was defined by minimizing the difference between a liquid pool depth resulting from particular secondary cooling parameters and the desired liquid pool depth of 20.0 meters. The variants were the characteristics of the secondary cooling zones (Figure. 4a).

For the optimization a DOE was generated for various heat transfer coefficients of the secondary cooling in the different zones. As soon as the simulation converged a first look was taken to the sensitivity analysis. This typical result from an optimization run shows very clearly which cooling zone shows more effect by changing the heat transfer coefficient and which cooling zones are more or less without influence. In this case all cooling zones have a similar influence (Figure 4b). This is not necessarily true in other cases as it was shown in [2].



cast alloy - 1 - user defined 2 - 1 constant	97%	Zone 1
cast alloy - 1 - user defined 2 - 2 constant	97%	
cast alloy - 1 - user defined 2 - 3 constant	97%	
cast alloy - 1 - user defined 2 - 4 constant	100%	Zone 2
cast alloy - 1 - user defined 2 - 5 constant	100%	
cast alloy - 1 - user defined 2 - 6 constant	100%	
cast alloy - 1 - user defined 2 - 7 constant	100%	
cast alloy - 1 - user defined 2 - 8 constant	100%	
cast alloy - 1 - user defined 2 - 9 constant	100%	Zone 3
cast alloy - 1 - user defined 2 - 10 constant	100%	
cast alloy - 1 - user defined 2 - 11 constant	100%	
cast alloy - 1 - user defined 2 - 12 constant	100%	
cast alloy - 1 - user defined 2 - 13 constant	100%	
cast alloy - 1 - user defined 2 - 14 constant	100%	
cast alloy - 1 - user defined 2 - 15 constant	100%	
cast alloy - 1 - user defined 2 - 16 constant	100%	
cast alloy - 1 - user defined 2 - 17 constant	100%	
cast alloy - 1 - user defined 2 - 18 constant	100%	
cast alloy - 1 - user defined 2 - 19 constant	100%	
cast alloy - 1 - user defined 2 - 20 constant	100%	
cast alloy - 1 - user defined 2 - 21 constant	100%	Zone 4
cast alloy - 1 - user defined 2 - 22 constant	100%	
cast alloy - 1 - user defined 2 - 23 constant	100%	
cast alloy - 1 - user defined 2 - 24 constant	100%	
cast alloy - 1 - user defined 2 - 25 constant	100%	
cast alloy - 1 - user defined 2 - 26 constant	100%	
cast alloy - 1 - user defined 2 - 27 constant	95%	Zone 5
cast alloy - 1 - user defined 2 - 28 constant	95%	
cast alloy - 1 - user defined 2 - 29 constant	95%	
cast alloy - 1 - user defined 2 - 30 constant	95%	
cast alloy - 1 - user defined 2 - 31 constant	95%	
cast alloy - 1 - user defined 2 - 32 constant	100%	Zone 6
cast alloy - 1 - user defined 2 - 33 constant	100%	
cast alloy - 1 - user defined 2 - 34 constant	100%	
cast alloy - 1 - user defined 2 - 35 constant	100%	
cast alloy - 1 - user defined 2 - 36 constant	100%	
cast alloy - 1 - user defined 2 - 37 constant	100%	
cast alloy - 1 - user defined 2 - 38 constant	100%	
cast alloy - 1 - user defined 2 - 39 constant	100%	
cast alloy - 1 - user defined 2 - 40 constant	100%	

Figure 4. The secondary cooling is partitioned into 6 different zones; the left picture shows the cooling zones in total a). A sensitivity analysis shows the relative contribution of changing heat transfer coefficients to the objective to realize the desired liquid pool depth b).

An important medium to study the results of an optimization project are the so called scatter charts. In figure 5 the position of the liquid pool tip is plotted over the water spray nozzle 2-10 in zone 3. On the x-coordinate the heat transfer coefficient of a spray nozzle is plotted and the y-coordinate shows the liquid pool depth. For one constant value of heat transfer coefficient for the chosen spray nozzle the y-coordinate shows the variation of heat transfer coefficients for the other zones. The scatter charts shows a significant influence. A clear tendency can be found. Changing the heat transfer coefficient to higher amounts will decrease the depth of the liquid pool. This clear tendency is not visible for all of the cooling zones, which means that zone 3 is one of the most important zones.

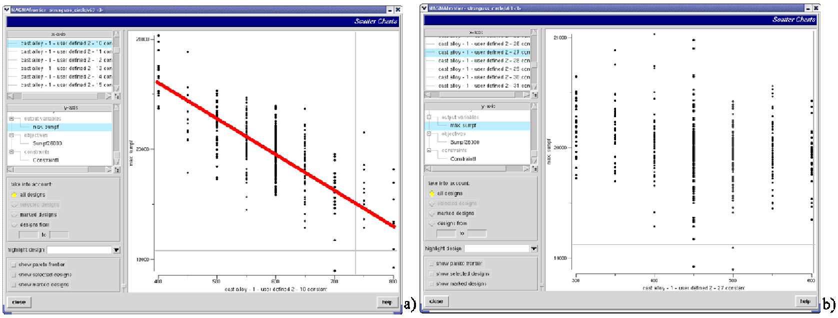


Figure 5. Scatter chart for the water spray nozzle 2-10 which belongs to the zone 3 a) and the cooling zone 5 b). A clear tendency can be found for the zone 3

After this optimization loop the user has now the possibility to choose the design which is corresponding to the desired liquid pool depth. In this case not only one design is very close to the desired liquid pool of 20m. Table 1 shows the heat transfer coefficient and therefore the necessary amount of spray water for 6 designs which are close to the desired liquid pool depth.

Table1: Heat transfer coefficient h_s in [Wm^{-2} K^{-1}] and amount of spray water V_{sp} in l/min for the different cooling zones. The nozzle areas are taken from the geometry.

design	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		Zone 6	
	h_s	V_{sp}	h_s	V_{sp}	h_s	V_{sp}	h_s	V_{sp}	h_s	V_{sp}	h_s	V_{sp}
20	1000	3.96	550	4.26	600	4.64	600	2.87	550	2.51	650	3.23
86	900	3.47	900	8.49	500	3.49	500	2.16	600	2.87	600	2.87
112	1000	3.96	750	6.67	600	4.64	450	1.80	600	2.87	550	2.51
241	850	3.22	600	4.86	600	4.64	550	2.51	600	2.87	600	2.87
322	850	3.22	600	4.86	600	4.64	550	2.51	600	2.87	550	2.51
412	900	3.47	700	6.07	550	4.06	550	2.51	600	2.87	600	2.87

From table 1, the engineer may select the design which is optimal in their production line. For this design the results can than be studied in detail. Figure 6 shows the result of the calculated liquid pool depth for the design 241.

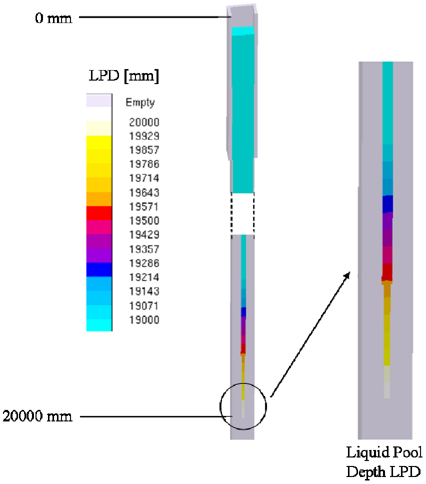


Figure 6. Result of the calculated liquid pool depth with heat transfer coefficients from the optimization.

The above described methodology enables the optimization of the water spray cooling in the secondary cooling zones. In a first optimization loop a virtual bloom was investigated. For further studies an experimental setup has to be defined, which requires a lot of effort in the practical realization. MAGMA has already started research activities to further improve the existing approach.

6. CONCLUSIONS

An example for the application of autonomous computational optimization to the continuous steel casting process has been shown.

At first, heat transfer coefficients taking into account the influence of different casting powders were simulated and the influence of the casting speed on the liquid pool depth was considered. The results of this investigation were then used to optimize the casting process with the aim to attain the best possible liquid pool depth. Based on information about the position of the different cooling zones, the particular zones that have significant influence on the position of the pool tip were identified. The required spread of cooling intensity over the strand length to set the pool depth to the desired value was then worked out.

By switching off the factor "trial and error" the engineer gets the chance to develop his processes with maximum possible quality and efficiency at the same time. He attains knowledge about the influence and interaction of the process parameters. The possibilities that arise from this are just at the beginning – it is the second generation of process simulation.

The paper showed a typical application for the continuous casting process of steels, how such a methodology can be used to optimize process parameters and to increase productivity. Nevertheless the quantitative verification of the new approach has to be done in the near future.

Other optimization objectives can be easily defined. For the continuous casting producers it is very important to understand the evolution of cracks. So it will be very helpful to optimize thermal stresses depending on the process parameters.

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