# Continuous Casting Simulation With MAGMASOFT®

Evgenii Shvydkii*, Jakob Fainberg, Erik Hepp, Sebastian Koldorf

MAGMA Gießereitechnologie GmbH, Kackertstr. 16-18, 52072 Aachen, Germany
*e.shvydkii@magmasoft.de

**Abstract:** Continuous casting is used in the making of the majority of the steel produced worldwide. It is a complex process with a harsh environment. Thus, numerical models can provide new insights into understanding some aspects of the process and potentially improve casting quality. This includes the entire process, from the tundish and the flow into the mold to the solidifying strand which is withdrawn through various cooling zones. The steel continuous casting process is simulated in the commercial simulation program MAGMASOFT®. Validation of the computational model is done by comparing velocity profiles with measured ones in a laboratory-scale experiment. Case studies simulating the superheat transport, segregation and air gap formation phenomena are covered.

**Keywords:** Continuous casting, numerical simulation, solidification, electromagnetic stirring.

### Introduction

Continuous casting is a standard process in the production of steel. During this process, a liquid steel is poured into a water-cooled mold and solidified metal is continuously withdrawn. It includes coupled fluid dynamic, heat transfer and solidification phenomena. Moreover, to control the flow into the mold and liquid core, external magnetic fields are used. Besides its multi-physical nature, a wide range of length and time scales makes modeling of this process even more challenging [1]. This paper shows several cases simulating different phenomena during continuous casting of steel. More specifically, issues such as fluid flow in the mold, electromagnetic stirring and superheat transport, macrosegregation and the thermomechanical deformation of the solidifying shell are briefly covered. All of the simulations are done in the commercially available software MAGMASOFT®.

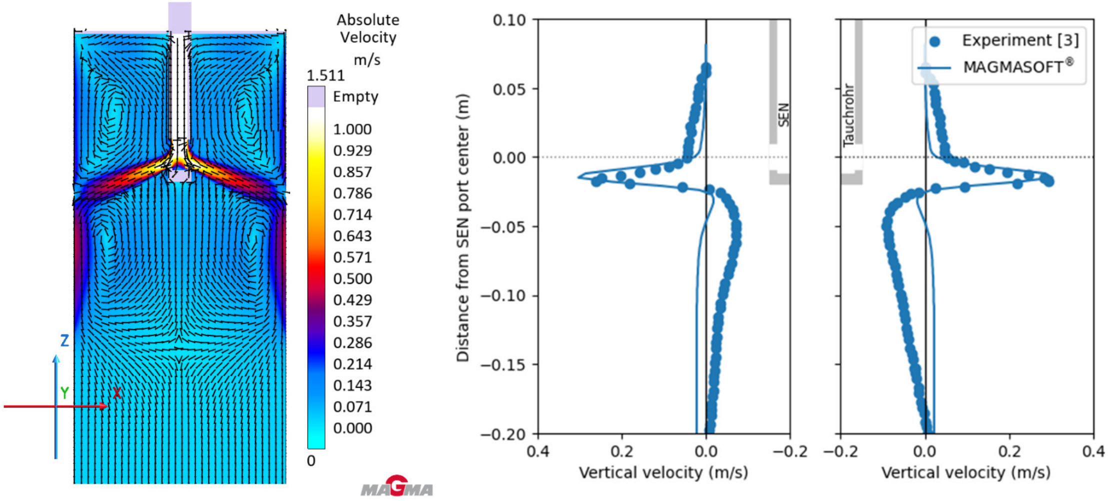
### Numerical Model

The numerical model is based on the finite volume method. The temperature and velocity field in the withdrawn strand including solidification are calculated. The L-VEL turbulence model is used in the simulation. Thermophysical parameters depend on temperature and solid fraction. Heat transfer coefficients are set to simulate primary heat extraction in the mold and secondary cooling. Electromagnetic field and Lorentz forces are calculated once due to the low magnetic Reynolds number and act as a body force in the momentum equation. A more detailed description of the numerical model can be found in reference [2].

### Validation

Fluid mechanics plays a crucial role in steel continuous casting. This includes a turbulent flow driven by inertia, thermosolutal buoyancy or electromagnetic forces. Reynolds numbers in industrial-scale casters achieve ~$10^5$ in the submerged entry nozzle (SEN) and ~$10^4$ in the mold. To validate the fluid-dynamic part of the model, we refer to the mini-LIMMCAST experiment [3, 4]. This experiment uses a GaInSn alloy as a liquid medium and ultrasound

Doppler velocimetry as a measurement method. The liquid metal circulates through a SEN and a slab-shaped mold with two outlets, imitating a continuous casting process.



(a) (b)

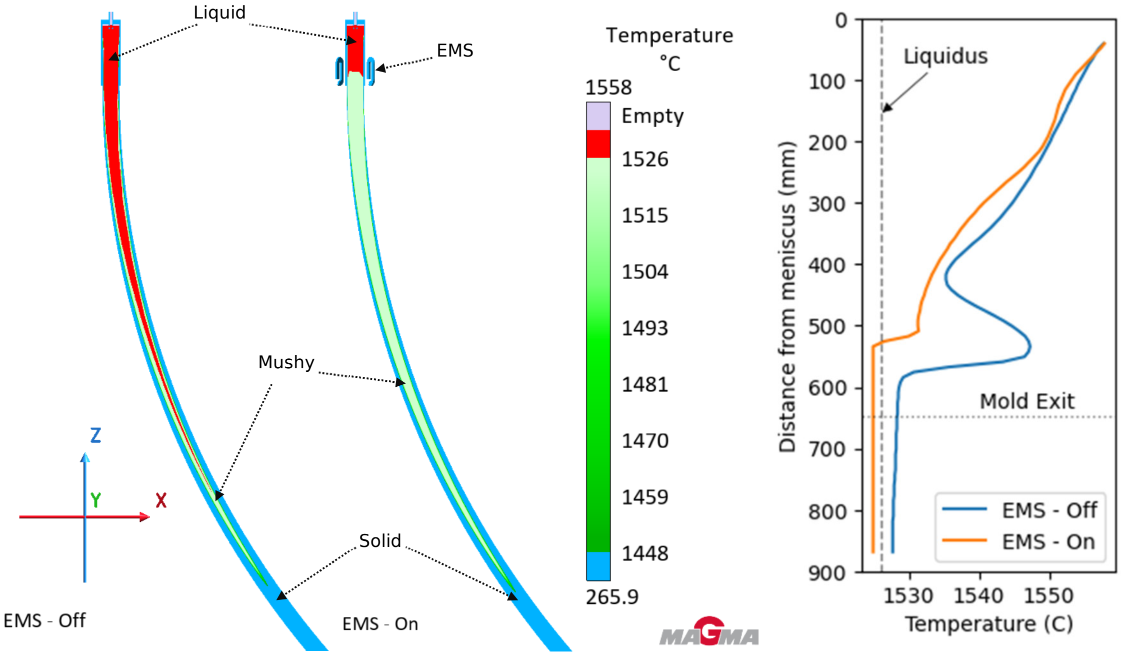
Figure 1. Calculated velocity field in the mold (a) and vertical velocity profiles at x=±20 mm from the SEN axis (b)

In Figure 1(a), the simulated velocity field is shown. Flow coming out of the two SEN ports with a velocity above 1 m/s slows down towards the mold side walls and forms 4 vortices. In the lower half of the mold, velocity is directed downwards corresponding to the withdrawal direction. To compare this computational result, two vertical velocity profiles are shown with the measured ones in Figure 1b. The data was taken at x = ± 20 mm from the SEN axis. The upper eddies produce a downward velocity above the SEN port center. Just below the SEN ports, a velocity of about 0.2 m/s is shown, which agrees with the experiment. Below it, a difference between the simulated and measured values is observed. In the experiment, the fluid flow is directed upwards, whereas in the simulation, it is directed in the withdrawal direction. This discrepancy can be explained by the design of the experimental set-up that consists of two horizontal outlets, while in our simulation, the strand is withdrawn downwards.

## Case Studies

### *1. Superheat Transport.*

Superheat temperature in continuous casting is defined as the difference between liquidus and casting temperatures, indicating an energy contained in the melt heated to above liquidus temperature. Controlling this parameter can affect macrostructure formation phenomena such as columnar to equiaxed transition (CET) or centerline segregation [5]. To control and optimize this superheat dissipation in the mold, electromagnetic stirring (EMS) is used. It generates a primary rotating swirling flow and two secondary toroidal flows into the liquid core of the strand. This fluid flow affects the heat transfer in two ways. Firstly, it increases the superheat dissipation in the mold by preventing its penetration down along the strand. And secondly, it enhances the transport of undercooled liquid from the lower liquid core volume up to the EMS level. In this way, the stirrer acts not as a dendrite breaker but more as a cooler [6].



(a) (b)

Figure 2. (a) – Temperature field results for cases with and without EMS. The superheated zone is red, the mushy zone is green and the solid phase is blue. (b) –Temperature profiles along the strand centreline

As a reference case, a billet continuous casting with mold electromagnetic stirring from reference [5] is chosen. Figure 2 (a) shows results of the simulated temperature distribution on the strand middle plane. The color bar is subdivided into three ranges indicating both the liquid and solid phases and the mushy zone. For the case “EMS – Off”, melt with the temperature above the liquidus temperature penetrates down into the strand, forming a long narrow mushy-zone layer. In the case with EMS, however, a stable mushy zone is formed already at the EMS level. The graph in Fig. 2 (b) shows that the centerline temperature drops under the liquidus line before the mold exit. Therefore, more liquid core volume is undercooled. Such conditions are desirable for stable equiaxed grain development in the middle of the strand. Only after the superheat is dissipated and the liquid cools to a temperature between the liquidus and solidus regions, small equiaxed crystals can appear in and coexist with the liquid phase. The result illustrates and confirms findings shown in the review paper [6].

### 2. *Segregation Formation.*

Segregation is a casting defect defined as a non-uniform distribution of alloy components in the semi-finished casting product. Numerical modeling can help to predict this defect and to define optimal casting or EMS parameters to avoid it.

As a reference case for segregation formation modeling, we refer to reference [7] where stainless steel continuous casting with EMS is simulated. A slab-shaped casting with a cross section of 200×1258 mm is withdrawn with a casting speed of 1.2 m/min. The electromagnetic stirrer consists of two traveling magnetic field inductors placed at the mold wide faces just below the meniscus. The temperature-dependent thermophysical properties of the casting alloy are calculated using the JMatPro tool [8].

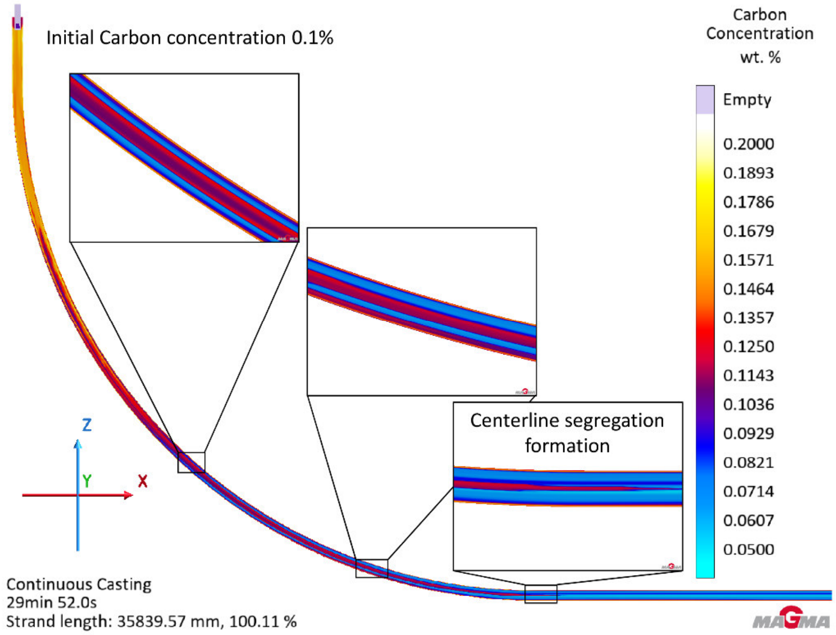


Figure 3. Carbon concentration in the slab-shaped strand

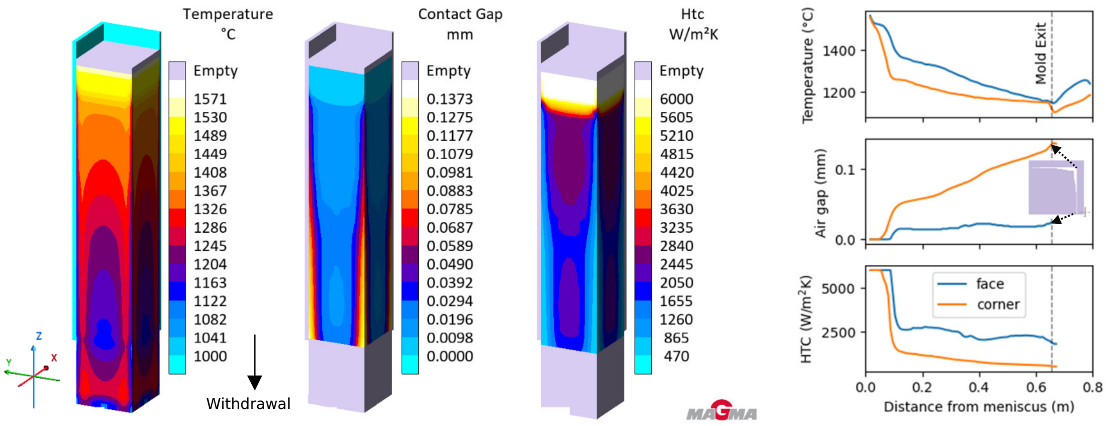
Figure 3 shows the carbon concentration distribution in the strand midsection. The initial concentration is 0.1%. In the zoom views, a segregation formation mechanism is shown. The solidified metal rejects carbon into the liquid phase in the strand center and has a concentration of less than 0.1%. This solute-rich liquid keeps getting narrower along the withdrawn strand. At the end of the strand bow (where it is horizontal), centerline segregation formation is shown.

### 3. *Thermomechanical Coupling.*

In modeling of different thermal processes, an interfacial heat transfer plays an important role. This especially applies in solidification applications where the cooling conditions are governed by the heat transfer coefficient (Htc) between cast material and water-cooled mold. Due to intensive cooling, a thermal distortion of the strand occurs, leading to non-uniform contact and even air gap formation between the strand and mold surfaces. Precise definition of the local Htc in the mold is important to get an accurate calculated heat removal and solidification conditions. To obtain this 3D heat transfer coefficient, thermomechanical modeling was applied. In this approach, a temperature field was taken as the driving force to calculate the thermal distortion of the solidified strand and the contact gap in the mold is obtained. The local heat transfer coefficient, *Htc*, was assumed to be related to the gap by:

$$Htc = \frac{1}{\frac{1}{h_0}+\frac{1}{h_{air}+h_{rad}}} \tag{1}$$

where $h_0$ – initial heat transfer coefficient, $h_{air} = \frac{\lambda_{air}}{\delta_{gap}+r_c}$, $\lambda_{air}$ – thermal conductivity of air, $\delta_{gap}$ – air gap between strand and mold, $r_c$ – surface roughness and $h_{rad}$ – radiation heat transfer coefficient.



(a) (b)

Figure 4. Temperature, contact gap and heat transfer coefficient in the strand-mold interface

To test thermomechanical coupling, a laboratory-scale case from [9] was taken. The same material properties, boundary conditions and casting parameters were applied, only the geometry of the strand was modified from round to a square-shaped billet. Figure 4 shows results of this test case simulation. The initial temperature of the withdrawn billet decreases from 1570 to ~1150°C due to the heat extraction in the mold. This cooling leads to mechanical deformation of the solidified shell, and gap between the billet and mold occurs. This contact gap is more pronounced in the corners of the mold, reaching 0.13 mm. According to equation (1), the heat transfer coefficient between the casting and mold surface is recalculated, taking into account the air gap. The Htc is reduced from the initial 6000 W/m$^2$K to 2500 at the billet faces and to 500 at the corners of the billet.

## Conclusions

In this paper, the simulation of multiphysical phenomena in the steel continuous casting process is shown. Specifically, liquid metal flow (including EMS), heat transfer, solidification and thermomechanical deformation are considered. Validation of the fluid dynamics was done by comparing calculated with experimentally measured velocities. It is shown how, by means of EMS, it is possible to control the superheat distribution, thereby creating the desired condition for equiaxed crystal growth. The simulation results of the segregation formation for industrial-scale continuous casting are demonstrated. Calculated gap formation between casting and mold can help to predict an accurate heat transfer between casting and mold. The presented results mirror the summary of current developments in MAGMASOFT® for continuous casting applications.

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