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# Important Key Process Simulations in the Field of Steel Metallurgy

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**Abstract:** During the last decade, the chair for 'Simulation and Modelling of Metallurgical Processes' (SMMP) has worked on different metallurgical processes with the highlights of the following five industrial relevant topics: (i) modelling the as-cast structures of large steel castings; (ii) exploring the formation mechanisms of macrosegregation; (iii) describing magnetohydrodynamic and electrochemical phenomena in remelting processes, (iv) understanding how solidification and flow can be influenced by magnetohydrodynamics during steel continuous casting; and (v) describing nozzle clogging in steelmaking processes. In this contribution, the main achievements from the group on the above five topics are briefly described.

**Keywords:** Steel casting, Macrosegregation, Remelting processes, Continuous casting, Nozzle clogging

#### Wichtige Prozesssimulationen in der Stahl Metallurgie

**Zusammenfassung:** In den letzten zehn Jahren hat sich der Lehrstuhl für Simulation und Modellierung Metallurgischer Prozesse mit verschiedenen metallurgischen Prozessen beschäftigt und einen Schwerpunkt auf folgende fünf industrierelevante Themen gelegt: (i) Modellierung des Gefüges bei großen Stahlgussteilen; (ii) Beschreibung der Entstehungsmechanismen von Makroseigerungen; (iii) Beschreibung magnetohydrodynamischer und elektrochemischer Vorgänge bei Umschmelzverfahren; (iv) Untersuchungen zur Beeinflussung der Erstarrung und der Strömung mittels Magnetohydrodynamik; und (v) Modellierung des Tauchrohrverstopfung bei der Stahlherstellung.

A. Ludwig (⊠) Department Metallurgy, University of Leoben, Leoben, Austria andreas.ludwig@unileoben.ac.at In diesem Beitrag werden die wesentlichen Ergebnisse zu den erwähnten fünf Themenkomplexen beschrieben.

Schlüsselwörter (deutsch): Stahlguss, Makroseigerung, Umschmelzprozesse, Strangguss, Tauchrohrverstopfung

### 1. Introduction

Since the foundation of the chair for 'Simulation and Modelling of Metallurgical Processes' (SMMP) in 2003, many industrial relevant research projects have been worked on. Important to mention is the establishment of three Christian-Doppler Laboratories over the years (2004-2011: 'Multi-phase simulations of metallurgical processes', A. Ludwig, 2011-2018: 'Process simulation of solidification and melting', M. Wu, 2018-2025: 'Magnetohydrodynamical applications in Metallurgy', A. Kharicha). Together with achievements from other projects, the expertise that was gained in these CD-laboratories had led to the definition of the five key process simulation activities that are presented here. Although the authors prefer to give an overview about a specific topic by including the state-ofthe-art and thus the work of others, we were asked to give solely an overview about highlight activities of the SMMP group.

## 2. Modelling the As-cast Structure in Large Steel Casting

An industrial steel casting might easily weigh from several tons up to one hundred. They are produced either discontinuously as large ingots or continuously by forming slabs or billets. All these products reveal a certain ascast structure which can be classified as columnar dendritic, equiaxed dendritic, or of mixed type. Due to the large tonnage, the castings may take days or weeks to solidify; several transport and accompanying redistribution phenomena can happen during this time, e.g. by crystal motion and melt convection. Understanding these phenomena is one of our key interest. and continuous casting of steel, DC casting of non-ferrous alloys). It may aid industry to design new solidification processes (e.g. semi-continuous casting of steel). It will also be important as it allows an integration into industry 4.0 as an important part of the virtual/intelligent manufacturing.

Our research has the potential to optimize the casting parameters by controlling the as-cast structure and minimizing the macrosegregation in industry castings (ingots The primary aims and objectives of this research field are:



Fig. 1: a Schematics of semi-continuous casting process (SCC), and the principle to control the as-cast structure. The mixed columnar-equiaxed solidification model is extended to investigate the mould filling (casting) and solidification processes including the origin of equiaxed crystals due to EMSinduced crystal fragmentation during SCC. **b**, **c**, **d** Numerical simulation of as-cast structure and macrosegregation in a 36-ton ingot. **b** Numerically-simulated segregation maps in different vertical and horizontal sections; **c** the macrosegregation map of the as-cast ingot as measured in the longitudinal section [Personal communication with. Hofa Shen, Tsinghua Univ., China, 2017]; **d** comparison of the numerically-simulated macrosegregation profiles along the centreline. (**b-d**: reprint from ref. [1] with permission)

- To understand the formation of the as-cast structure of steel castings that are manufactured at an industrial scale;
- To develop a numerical model for the mixed columnar-equiaxed solidification considering columnar-toequiaxed-transition (CET) and macrosegregation;
- To model the electromagnetic stirring during continuous casting, and its effect on the as-cast structure (crystal fragmentation);
- To apply the numerical model to aid industry to optimize the casting processes (ingot, continuous casting);
- To apply the numerical model to aid industry to design a new casting process (semi-continuous casting);

To further evaluate the numerical model by comparing the modelling results with laboratory experiments and plant trials.

Examples of recent achievements are given in Fig. 1. Further details on that topic can be found in ref. [1–7].

#### 3. Formation Mechanisms of Macrosegregation

The compositional heterogeneity at the scale of industry casting is called macrosegregation. It is caused by the fact



Fig. 2: a Predicted macrosegregation during bulging of a steel slab (for postprocessing the results lengths are scaled 1:10). (Diagram) Comparison of centreline segregation for three different cases corresponding to solidification of the horizontal model steel slab: (i) shrinkage only, (ii) bulging only, and (iii) combined effect of shrinkage and bulging. b Predicted macrosegregation during twin-roll casting of Al-4wt.%Cu. The viscoplastic high-solid fraction regions are heavily deformed during rolling, resulting in a densification of the dendritic network and thus in a pressing out of segregated liquid. (b: reprint from open access ref. [10])

that usually solidifying crystals do not incorporate all alloying elements and thus the remaining liquid gets more and more enriched in solute. This is called (micro-)segregation. If the flow now redistributes this segregated liquid to some other location, the concentration, and with that the microstructure, will become inhomogeneous. As many different mechanisms for a relative movement between crystal and liquid exist (e.g. thermal or solutal buoyancy, sedimentation, deformation, etc.), the occurrence of macrosegregation and also the measures that can be taken to avoid their formation are numerous.

This researchfield has the potential to extend our understanding of macrosegregation formation, to develop industrial relevant strategies for reducing macrosegregation, and to refine the solidification models (source codes) and to integrate them into industry 4.0 as an important part of virtual/intelligent manufacturing.

The primary aims and objectives of this research field are:

- to use multiphase solidification models and to study macrosegregation mechanisms as caused by:
  - thermo-solutal convection;
  - crystal sedimentation;
  - feeding flow due to solidification shrinkage;
  - forced flow such as electro-magnetic stirring;
  - mechanical deformation of the mushy zone;
  - Marangoni convection.
- to evaluate numerical models against different theoretical models or experimental benchmarks:
  - laboratory experiments;
  - Flemings theory;
  - industry castings.
- to apply numerical models for different industry processes (ingots, continuous castings of steel, and direct chill casting of copper/aluminium).

Examples of recent achievements are given in Fig. 2. Further details on that research field can be found in ref. [1, 8-16].

#### 4. Magnetohydrodynamic and Electrochemical Phenomena in Remelting Processes

In order to decrease  $CO_2$  production, the developments of a new generation of metallurgical processes using electric currents are planned by the world leading industrial groups. Strong currents will be transferred through plasma and high temperature electrolytes to achieve the production of new metallic alloys. The fundamental knowledge built by our research has the potential to solve complex physical, technical, and design issues that can arise during these crucial developments.

From daily experience, we know that, with a strong electric current, materials can be heated and even melted. However, when applied on an industrial scale, the fact that most materials are opaque causes a major problem because important details on what happens remain hidden. Here, the numerical process simulation acts as visualiser and allows to zoom-in when necessary. Even simulations with hypothetic properties or unusual process conditions can be done and thus hints in which direction a process optimisation might be possible can be gained. As an example, we have worked on understanding and optimising the Electro-slag remelting (ESR) process. This is a process where an extremely high electric current heats a liquid slag that then melts an electrode so that the alloy is then drop-wise crossing the liquid slag and forming a new liquid pool that finally solidifies with an improved quality.

The corresponding aims and objectives of this research field are:

Fig. 3: The electroslag remelting (ESR) process, composed of slag, mould, ingot, and electrode, is simulated considering the turbulent flow in the slag and melt pool. Exemplary numerical results are shown here as a mean thermal field and b mean velocity field



- to understand the interaction between phase distribution and magnetohydrodynamics when strong electric currents are applied;
- to predict the electrical current path in the presence of strong spatial and temporal variation of electric conductivity:
- to solve process instabilities and predict the formation of defects in the electroslag remelting process (ESR) and vacuum arc remelting (VAR) process;
- to understand electrochemical aspects of the ESR process:
- to predict the thermal and solidification characteristics during remelting of different metallic alloys;
- to explore the origin of the coherent arc behaviour in the VAR process;
- building a numerical model to predict the behaviour of an electric arc inside a furnace accounting for magnetohydrodynamics, flow dynamics, compressibility, turbulence and thermal fields.

Examples of recent achievements are given in Fig. 3. Further details on that research field can be found in ref. [17-25].

#### 5. Steel Continuous Casting: Solidification, Flow, and Magnetohydrodynamics

For more than three decades, numerical simulations of steel continuous casting considering solidification and flow have widely spread. They are valuable for the design and optimization of the casting process, especially for thin slab casting (TSC). Interaction between flow and solidification, which is quite intensive in TSC, and electromagnetic braking used to stabilise the flow are up-to-date topics where numerical models are recently under development.

In both fields, we have obtained successful developments that are now applied under productive conditions.

Our scientific investigations provide the theoretical basis for innovative control techniques which will lead to growing productions rates by increasing the casting speed while keeping the quality. Thus, large energy savings by casting at lower super heat and promoting CO2 reduction will be achieved. The methodology developed opens the possibility to apply electromagnetic fields to other metallurgical and semiconductor industries.

The corresponding aims and objectives of this research field are:

- multiphase phenomena modelling during continuous casting (CC): turbulent flow, shell growth, non-metallic inclusions (NMI) and bubbles motion, meniscus behaviour, etc.;
- model development of the turbulent flow under the applied magnetic field considering the Lorentz force;
- coupled numerical simulation of the solidification during CC with the magnetohydrodynamic (MHD) effects from the electromagnetic brake (EMBr);
- models' verification against analytical solutions, experimental data and existing numerical results;
- influence of the casting and EMBr conditions on the CC mould flow pattern, the shell thickness, meniscus temperature, slag band stability, and NMI removal efficiency:
- application of the results of the numerical studies for a real industrial process with optimization aims regarding the cast products quality.

Examples of recent achievements are given in Fig. 4. Further details on that research field can be found in ref. [26-35].



Fig. 4: a Modelling of turbulent melt flow during thin slab continuous casting of steel. The width of the funnel-shaped mould is around 1.5 m. The final slab has a thickness of around 15 cm; b flow pattern under applied electro-magnetic break and the electric current interaction with a vortex structure. (reprint from open access ref. [33]

#### 6. Nozzle Clogging in Steelmaking Processes

Although named "continuous," steel continuous casting is not really a process without stops. Sooner or later the submerged entry nozzle (SEN) has to be replaced by a fresh one as it gets clogged with time. The reason for that is that the SEN material interacts with the steel and with the nonmetallic particle herein leading to a growing layer of oxides forming at the inner SEN wall. This so-called clogging phenomenon is a major problem for the steel industry and has been significantly reducing their productivity.

Therefore, this research field has the potential to optimize the casting parameters by minimizing the clogging tendency during the continuous casting of steel. It will also be important as it allows an integration into industry 4.0 as an important part of virtual/intelligent manufacturing. The developed numerical model can also be extended to investigate the clogging/fouling phenomenon (deposition and accumulation of solid suspended particles on the fluid passage) in other engineering processes, such as in heat exchangers, petrochemical industry, automotive industry food production, and pharmaceutical industries.

The corresponding aims and objectives of this research field are:

- to develop a transient clogging model considering key physical/chemistry mechanisms:
- origin of the non-metallic inclusions (NMIs);
- transport of NMIs by the molten steel of high turbulence, and the effect of Ar gas;
- behaviour of NMIs in the boundary layer of the nozzle wall (refractory);
- adhesion mechanism of NMIs on the nozzle wall and the effect of nozzle refractory materials;

Fig. 5: a A transient nozzle clogging model is developed and used to simulate a laboratory experiment (simulator of nozzle clogging: Comdicast AB, Sweden) with a purpose to validate the numerical model. **b**, **c** Evolution of clogging in the nozzle. b View of the clog region from the vertical section and a cross-section A-A of the nozzle; c Zoomed view of the flow streamlines and a partially clogged section at  $200\,s.$  The clogged section is shown in vellow. The magnitude of the flow velocity is shown in a colour scale along the streamlines. (a reprint with permission from Kojola et al., Ironmak. Steelmak. 38, 81-89 (2011), except the simulation picture on the left, b reprint from ref. [36] with permission)

Clogging phenomenon in a steel transport nozzle Numerical simulation . Mass flow rate а 50 s 100 s 150 s 200 s 250 s 200 s A -2A 1 884 1 256 0.6251 3 279×10 ≯ b С

- growth of the clog front and its interaction with the turbulent melt flow;
- flow and possible solidification of molten steel in the clog region;
- fragmentation/detachment of the clog.
- evaluation of the numerical model against available laboratory/industry experiments;
- achievement of a fundamental understanding about the nozzle clogging in steelmaking processes, and aid the industry to optimize the process parameters.

Examples of recent achievements are given in Fig. 5. Further details on that research field can be found in ref. [36–42].

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