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Process Simulation for the Metallurgical Industry: New Insights into Invisible Phenomena

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Abstract: In order to demonstrate how advanced process simulation can help to understand metallurgical process details and thus to improve industrial productivity, a number of examples are shown and discussed. The paper covers recent simulation results gained at the Chair of Simulation and Modeling of Metallurgical Processes, namely (i) the flow and shell formation in thin slap casting of steel, (ii) multiphase flow and magnetohydrodynamic during Electro-Slag-Remelting, (iii) mold filling, surface wave dissipation and solidification during horizontal centrifugal casting of rolls, and (iv) forced and natural convection during electro-refining of copper in an industrial-size tankhouse cell.

Keywords: Process simulation, Continuous casting, Electro-slag-remelting, Centrifugal casting, Copper-electro-refining

Prozesssimulation für die metallurgische Industrie: Neue Einblicke in unsichtbare Phänomene

Zusammenfassung: In dieser Arbeit wird anhand von vier Beispielen gezeigt, wie fortschrittliche Prozesssimulationen helfen können, metallurgische Prozessdetails zu verstehen und somit die industrielle Produktivität zu erhöhen. Die Beispiele stammen aus laufenden Forschungsarbeiten des Lehrstuhls für Simulation und Modellierung metallurgischer Prozesse. Es werden i) Strömungen und Erstarrung beim Dünnbrammengießen von Stahl, ii) Mehrphasenströmung und Magnetohydrodynamik beim Elektroschlackeumschmelzen, iii) Formfüllung, Bewegung von Oberflächenwellen und Erstarrung beim horizontalen Schleuderguss von Großwalzen, und iv) erzwungene und natürliche Strömung in industriellen Aggregaten bei der Elektroraffinationselektrolyse von Kupfer behandelt.

Schüsselwörter: Prozesssimulation, Strangguß, Elektroschlackeumschmelzen, Schleuderguß, Kupferraffinationselektrolyse

1. Introduction

In metallurgy increasing competition and the necessitation of energy and CO_2 reduced manufacturing methods require the improvement of existing techniques and even the development of new, alternative production technologies. On the other hand, the opacity of liquid and solid materials and the involved high temperatures make the experimental penetration of metallurgical processes and with that the attainment of detailed process knowledge quite difficult.

Advanced numerical simulations of processes relevant for the metallurgical industry allows new insights into phenomena which govern daily life productions but are usually invisible. To understand what happens inside the production process is of key importance for minimizing failure rate and increase productivity.

2. Examples of Advanced Process Simulations

In order to give an impression on the capacity advanced process simulations might have, corresponding work from the chair of Simulation and Modeling of Metallurgical Pro-

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cesses (SMMP) on four different metallurgical processes are presented in this paper.

2.1 Thin Slab Casting

Thin slab casting (TSC) represents a type of the continuous casting process for the production of the flat/strip products. Its advantage over conventional casting technology consists of integration into the casting-rolling production chain, energy savings, and higher productivity along with the near net shape [1, 2]. One striking feature of TSC is the use of funnel-type molds, which provides the necessary space for the submerged entry nozzle (SEN) to conduct liquid melt into the thin slab mold. Another important feature is the shell thickness in the mold region: 40~50 % of the slab thickness for TSC [3, 4] in comparison with 20~30 % for the conventional slab [5, 6] at the mold exit.

However, problems like the sensitivity to breakouts and edge/surface cracks are frequently reported for TSC. These problems have encouraged metallurgists to consider a special mold and SEN designs, cooling systems, the use of a special mold flux and even the application of electromagnetic braking in the mold region. The modeling approach becomes a useful tool to assist the industrial line design and is being applied for the prediction of the defects formation along with the surface quality estimation. Therefore, the evolution of solid shell under the influence of turbulent flow and the continuous deformation of the solid shell becomes a critical issue for the modeling approach.

The solidification solver developed by the authors [7–10] includes modeling of the turbulent flow of the liquid melt taking into account interaction with the two phase region during the formation of the solid shell. For the prediction of the solid motion during its continuous withdrawal, a deformation model is applied [11].

Figure 1 shows the results for the engineering TSC simulation. A complex turbulent flow pattern is modeled along with the superheat transport during liquid melt motion, which strongly influences the solid shell formation. The numerical simulation can predict transient phenomena during solidification and help to optimize the casting process based on information not obtainable at the plant during production.

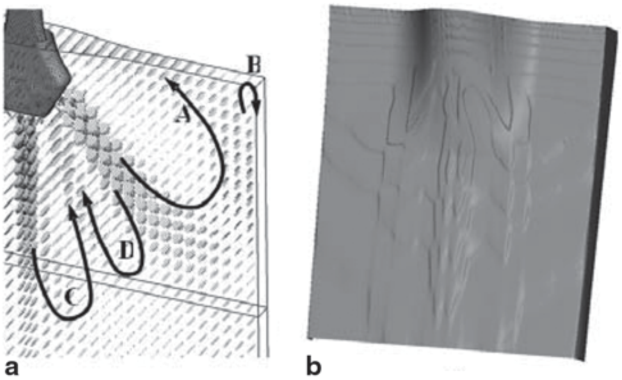

Fig. 1: Simulation Result of an Engineering TSC. **a** Velocity Vector Field. **b** 3D Solid Shell Profile

2.2 Electro-slag Remelting

In the past few years, remelting technologies have taken an important role in the large field of special materials, and the number of Electro-Slag Remelting (ESR) and Vacuum Arc Remelting (VAR) units is continuing to grow. Currently, ESR and VAR are commonly used. Yet, far-reaching investigations on an industrial scale in particular have rarely been published. There is still a great demand for more knowledge on these processes and on how to optimize them for several alloys qualities, melting parameters, and ingot sizes. To produce a high quality homogeneous ingot with good surface quality, the deviations in the process, such as melting rate or the immersion depth of the electrode, need to be minimized.

During the process the electric parameters such as current, voltage, and electric resistance are continuously recorded. The variation of the resistance, known as resistance swing, is an often used method for the control of the electrode position [12]. Higher level of resistance swing is interpreted as a low electrode immersion depth. However, the increase in resistance swing can be reliably, but not quantitatively, related with the immersion depth. This is why some efforts must be applied to the identification of process state, solely through analysis of electric process parameters. To achieve this goal, it is important to identify the phenomena that can generate these electric fluctuations. This process involves two liquids, a liquid metal and a liquid slag. Each liquid is subject to a phase change due to melting and/or solidification. From a fluid dynamic point of view, the ESR process is clearly a multiphase process, with free interfaces (slag/pool, gas/slag), and with a mixed area (slag and falling steel droplets) [13–16]. And, as the electric conductivity of the metal is known to be much higher than that of the slag, the distribution of the metallic phase within the slag will be a critical parameter to predict the distribution of the electric current density which in turn controls the Lorentz force magnitude. From these physical facts, one can expect in this nonlinear system that a slight change in the position of the slag interfaces can result in totally different flow behaviors. Physically the development of the heat and mass transfer at the interfaces is important for the final ingot quality, composition, and cleanliness. Unfortunately a visual observation of the droplet formation and interface movement is almost impossible.

To explore the process numerically, it is necessary to model the strong coupling between the flow and the electrodynamic phenomena. This typical magneto-hydrodynamic problem was tackled with the help of a 3D MHD-VOF model, which is able to predict the electric and magnetic field distribution in function of the metallic distribution in the low electric conductivity slag. In Fig. 2 it is possible to see the melting phenomena for an industrial scale ESR process. A liquid film develops under the electrode and allows droplets departure from many different positions.

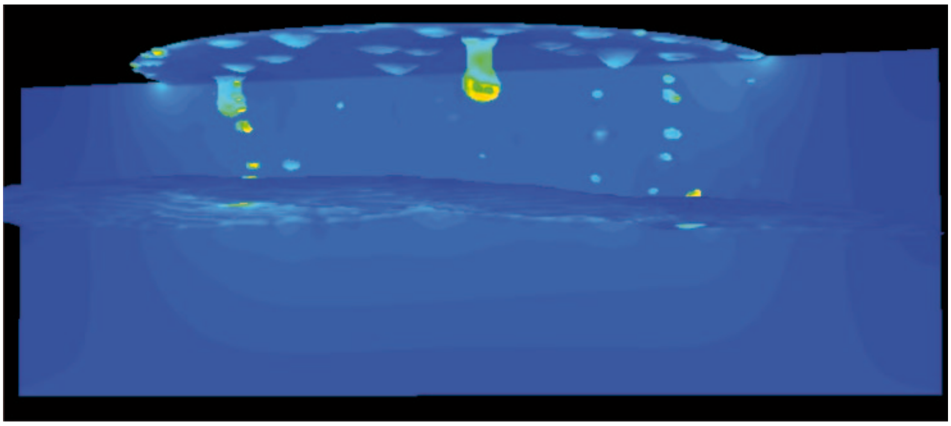

Fig. 2: Electric Current Density in a Small Scale ESR [10^4–10^8 Amps/m^2]. A Current of 13,000 Amps is Passed through an Electrode with 42 cm Diameter [17]

The way that the liquid metal droplets enter the liquid pool is one of the major factors which determines the liquid pool shape and depth. The Lorentz force acts mainly in the inward direction towards the center, while buoyancy results in a flow which is outwards towards the mold. The combined effects of the droplets impact and Lorentz force is strong enough to generate a three dimensional wavy movement of the slag/pool interface. This movement generates a strong 3D movement of the flow not only in the liquid pool but also in the slag. This 3D movement was clearly observed on the surface of the exposed slag surface at industrial plants. Models that use 2D axisymmetric approximations can only predict radially inward or outward motion at the exposed slag surface. The present success in modeling these process details is only a further step towards the full understanding of the multiphysic phenomena that occur in ESR.

2.3 Centrifugal Casting

The horizontal centrifugal (or spin) casting (HSC) is a casting technique typically used for parts with a rotational symmetry for which superior mechanical properties are desirable. Here the focus is placed on the casting of a dual-alloy work roll into a horizontally rotating permanent mold. After having cast the outer layer of chromium steel (HSS), the steel grade is changed to grey cast iron resulting in the intermediate layer, which then bonds with the core cast using the gravity casting. High temperatures and opaque medium make any experimental study practically impossible but open the door wide to numerical methods. However, full 3D numerical approaches are hindered by considerably different time scales ranging from 0.1 s for one revolution of the mold and about 35 min for the whole HSC [18]. Therefore, we finally adopted so-called shallow water equations (SWE), a set of hyperbolic PDEs typically used in meteorology and oceanography [19], assuming a negligible radial momentum and a hydrostatic balance [20, 21]. The SWE were modified to account for centrifugal force, Coriolis force, gravity, and friction force by assuming a hydrodynamically fully-developed laminar flow [22]. The mold filling was provided by a randomly sampled mass source positioned in the mold center approximating a normal distribution. A growth of the planar liquid-solid interface was controlled by the Stefan condition and the heat conduction equation [23]. The model was extended to explicitly take into account inherent vibrations measured during the HSC which are caused by a poor roundness and mold deformations due to temperature gradients [24].

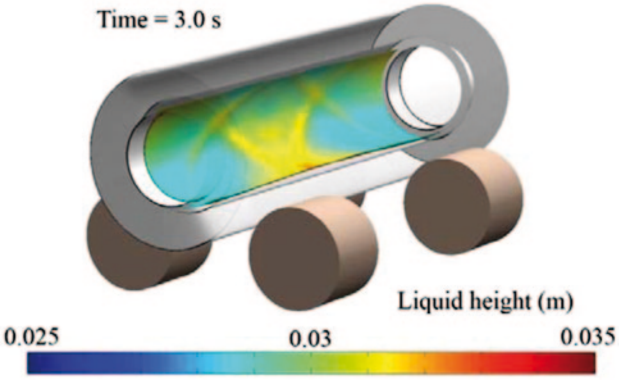

Fig. 3: Contours of the Liquid Height Showing Free Surface Waves during Horizontal Centrifugal Casting of a 3.2 m Long Roll

The simulation results show various wave patterns propagating on the free surface induced by the interaction between the forces applied and the underlying topography (see Fig. 3). The presence of vibrations noticeably influenced the nature of traveling waves. Due to the fixed position of the filling jet, the solidification is retarded in the mold center, whereas near the extremities it is promoted by enhanced radiative losses. Such information can be used to optimize the microstructure by adjusting the filling system or the thickness of the refractory zircon coating, which could lead to an increase in the lifetime of the roll consequently.

2.4 Cu Electro-refining

The copper refining electrolysis process is essential to produce high purity copper at industrial scale. The fundamental steps of copper refining are (i) electrochemical dissolution of copper from impure anodes into a $CuSO_4$–H_2SO_4–H_2O electrolyte, and (ii) electrochemical plating

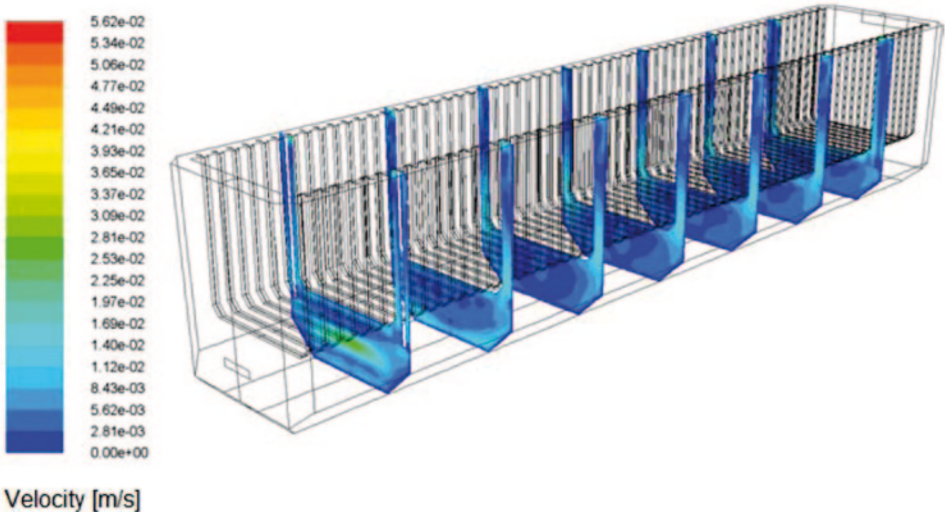

Fig. 4: Example of a Large-scale Simulation of the Flow in an Industrial Tankhouse Cell

of pure copper (without the anode impurities) from the electrolyte onto stainless steel cathodes [25]. The density changes caused by the concentration gradients of copper lead to the occurrence of natural convection. The interference of this natural convection with the forced convection caused by the inlet of fresh electrolyte is the topic of research. The overall simulation objective is to simulate the flow in a full scale copper refining electrolysis cell in order to predict areas with insufficient electrolyte movement. This can cause quality issues regarding to improper concentration of inhibitors and/or undesired anode slimes occurrence [26].

Since the dissolution and plating of copper occurs in a very small area around the electrodes, the necessary length scale for a numerical volume element is about 0.1–0.2 mm. Considering the given computer technology today, a simultaneous calculation of natural and forced convection in a full scale tankhouse cell is impractical if not impossible. The number of cells would be far too large. Therefore the simulation has to be broken down into two parts. First, the natural convection caused by the density changes of the electrolyte is simulated in a "local" simulation covering one anode-cathode pair. Secondly, the flow of the electrolyte caused by the forced convection is simulated at a "global" scale, whereby the results from the "local" simulation is included by individual in-/outlet surfaces in between the multiple anode-cathode gaps.

The simulation shows that the flow of electrolyte inside a copper refining cell is mainly controlled by natural convection (see Fig. 4). The forced convection caused by the inlet of fresh electrolyte only interferes with the first few electrodes. Until now the electrolyte flow in copper refining cells has only been studied in small-scale test apparatuses [27]. With the work described here an estimation of the electrolyte flow in a full scale tankhouse cell can be given. The flow patterns gained by the simulations will help to estimate the distribution of anode slimes and surface active agents within the cell during industrial operation.

3. Conclusion and Summary

In material processing numerical modeling tools are more and more in use. Temperature and flow field predictions are nowadays quite reliable. However, the multiphase and multiscale nature of many industrial processes often limits the predictive efficiency even of the most sophisticated programs. With the help of four examples, we have demonstrated that sound predictions of important process details are possible. However, especially when different phenomena interact, like e.g. flow, solidification, and stress-induced deformations or motion of dendritic crystal in a turbulent melt flow, our knowledge is still limited. Here a successful extension of a numerical code is only possible when the knowledge on important process details is increased.

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References

1. Tang, Y.; Krobath, M.; Nitzl, G.; Eglsaeer, C.; Morales, R.: SEN Design Optimization Using Transient Flow Simulations and Modelling at High-Speed Thin Slab Casting, J. Iron & Steel Res., 16 (2009), Supplement 1, pp. 173–179
2. Thomas, B.G.: Brimacombe Lecture, 59th Electric Furnace Conf., Iron & Steel Soc., 2001, pp. 3–30
3. Camporredondo, J.E.; Castillejos, A.H.; Acosta F.A.; Gutierrez E.P.; Herrera M.A.: Analysis of thin-slab casting by the compact-strip process: Part I. Heat extraction and solidification Metall. Mater. Trans. B, vol. 35 (2004), pp. 541–560
4. Liu, H.; Yang, C.; Zhang, H.; Zhai, Q.; Gan, Y.: Numerical Simulation of Fluid Flow and Thermal Characteristics of Thin Slab in the Funnel-Type Molds of Two Casters, ISIJ Int., 51 (2011), pp. 392–401
5. Pfeiler, C.; Thomas, B.G.; Wu, M.; Ludwig, A.; Kharicha, A.: Solidification and Particle Entrapment during Continuous Casting of Steel. Steel Res. Int., 79 (2008), pp. 599–607
6. Thomas, B.G.; O'Malley, R.O.; Stone, D.: Measurement of Temperature, Solidification, and Microstructure in a Continuous Cast Thin Slab, in: Thomas, B.G.; Beckermann, C. (eds), Proc. MCWASP VIII TMS Publications, USA, (1998), pp. 1185–1199
7. Wu, M.; Vakhrushev, A.; Nunner, G.; Pfeiler, C.; Kharicha, A.; Ludwig, A.: *Importance of Melt Flow in Solidifying Mushy Zone*, Open Transport Phenomena J.—Bentham Open, 2 (2010), pp. 16–23
8. Vakhrushev, A.; Ludwig, A.; Wu, M.; Tang, Y.; Nitzl, G.; Hackl, G.: *Modeling of Turbulent Melt Flow and Solidification Processes in Steel Continuous Caster with the Open Source Software Package OpenFOAM*, Proc. OSCIC'10. Germany, Munich, Nov. 4–5, 2010
9. Vakhrushev, A.; Ludwig, A.; Wu, M.; Tang, Y.; Nitzl, G.; Hackl, G.: *Modeling of nonmetallic inclusions and gas bubbles motion in continuous caster*, Proc. ECCC Germany, Düsseldorf, June 27–July 01, 2011
10. Vakhrushev, A.; Ludwig, A.; Wu, M.; Tang, Y.; Nitzl, G.; Hackl, G.: *Coupling the turbulent flow with the solidification processes in OpenFOAM*, Proc. OSCIC'11. France, Paris Chantilly, Nov. 3–4, 2011
11. Vakhrushev, A.; Wu, M.; Ludwig, A.; Tang, Y.; Hackl, G.; Nitzl, G.: Proc. MCWASP XIII, in: Ludwig, A.; Wu, M.; Kharicha, A. (eds.), IOP Conf. Series: Mater. Sci. Eng., 33 (2012), 012014
12. Melgaard, D.K.; Williamson, R.L.; Beaman, J.J.: Controlling Remelting Processes for Superalloys and Aerospace Ti Alloystitle, *JOM*, 1998 March, pp. 13–17
13. Hernandez-Morales, B.; Mitchell, A.: Review of mathematical models of fluid flow, heat transfer, and mass transfer in electroslag remelting process, Ironmaking & Steelmaking, Vol. 26 (1999), pp. 423–438
14. Werber, V.; Jardy, A.; Dussoubs, B.; Ablitzer, D.; Ryberon, S.; Schmitt, V.; Hans, S.; Poisson, H.: A Comprehensive Model of the Electroslag Remelting Process: Description and Validation, *Metall. Mater. Trans. B*, 40B (*2009*), pp. 271–280
15. Kharicha, A.; Schützenhöfer, W.; Ludwig, A.; Tanzer, R.; Wu M.: Reformulation of the Joule heating in presence of turbulent fluctuation, in: *Int. J. Cast Metals Research*, vol 22 (2009) pp. 155–159
16. Kharicha, A.; Schützenhöfer, W.; Ludwig, A.; Tanzer, R.: On the Importance of Electric Currents Flowing directly into the Mould during an ESR Process, *Steel Research Int*. vol. 79 (2008), 8, pp. 632–636
17. Kharicha, A.; Ludwig, A.; Wu M.: *Int. Symp. on Liquid Metal Processing and Casting* in: Lee, P. D. et al. (eds.), LMPC-11, France, Nancy, 2011, pp. 41–48
18. Kaschnitz, E.: Numerical simulation of centrifugal casting of pipes, in: Ludwig, A.; M. Wu, M.; A. Kharicha, A. (eds.), Proc. MCWASP XIII, IOP Conf. Series: Mater. Sci. Eng., 33 (2012), 012031.
19. Leveque, R. J.: Finite volume Methods for hyperbolic problems, Cambridge texts in applied mathematics, New York, Cambridge University Press, 2002.
20. Kharicha, A.; Bohacek, J.; Ludwig, A.; Wu, M.: Vibration induced flow in a horizontal centrifugal casting, in: Nastac, L. et al. (eds.) CFD Modeling and Simulation in Materials Processing, Wiley, Hoboken, New Jersey, 2012, pp. 227–234.
21. Boháček, J.; Kharicha, A.; Ludwig, A.; Wu, M.: Liquid metal inside a horizontally rotating cylinder under vibrations, in: Experimental Fluid Mechanics (EFM 2011), Czech Republic, Jičín, Nov. 22–25. 2011, vol. 2, pp. 564–73.
22. Kharicha, A.; Bohacek, J.; Ludwig, A.; Wu, M.: Simulation of Horizontal Centrifugal Casting, to be published.
23. Dantzig, J. A.; Rappaz, M.: *Solidification*, Lausanne, EPFL Press (etc): Taylor & Francis, 2009.
24. Martinez, G.; Garnier, M.; Durand, F.: Stirring phenomena in centrifugal casting of pipes, J Appl. Sci. Res., vol. 44 (1987), pp. 225–39
25. Davenport, W. G.; King, M.; Schlesinger, M.; Biswas, A. K.: Extractive Metallurgy of Copper, 4th edition, Pergamon Publishing, 2002, pp. 265–288.
26. Filzwieser, A.: Modellierung der kathodennahen Vorgänge in der Kupferelektrolyse, Diss., Montanuniv. Leoben, Lehrstuhl Nichteisenmetallurgie, 2000
27. Leahy, M. J.; Schwartz, P.: Experimental Validation of a Computational Fluid Dynamics Model of Copper Electrowinning, Metallurgical and Materials Transactions B 41 (2010), No. 6, pp. 1247–1260.