Numerical Simulation of the Protective Gas Electro Slag Remelting Process and its Industrial Validation

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ABSTRACT: Electroslag Remelting (ESR) and Protective Gas Electroslag Remelting (PESR) are advanced processes for the production of high quality steels. A consortium consisting of a process engineering software editor and a quality steel manufacturer as well as a university division, a material science research center and a plant equipment supplier has been founded with the objective to generate a new physically based industry-oriented software package for numerical simulation of the PESR process with respect to process optimization. The applied mathematical model describes the global remelting process conditions and the coupling of electromagnetic fields and forces with convection in the slag and melt pool as well as the heating in the slag and in the cast ingot. Results of a local model, treating the behavior of droplets, are included. The developed commercial software module uses finite element technique solving the MHD and thermal equation system. The integrated PESR process simulation was implemented in a production plant. For validation, industrial scale ingots of high-quality steel were produced and the process and ingot characteristics subsequently compared with the numerical predictions.

1. INTRODUCTION

Nowadays metallurgical industries search for integrative physically based numerical software tools covering all aspects of manufacturing processes with the objective of better understanding and controlling the processes, further cost reduction and higher production quality assurance. Electroslag remelting (ESR) and protective gas electroslag remelting (PESR) are advanced metallurgical processes for the production of high quality tool steels with outstanding technical and material properties. In order to generate and validate a new industrial software package dedicated to the simulation of these processes an international consortium consisting of a process engineering software editor (ESI Group, France) and a quality steel manufacturer (Böhler Edelstahl GmbH & CoKG, Austria) as well as an university's materials department (University of Leoben, Austria), a material science research center (CSM, Italy) and a plant equipment supplier (ALD, Germany) has been founded in the framework of the RFCS project ISA-PESR.

The program of the project was divided into work packages including the development of a local multiphase flow model describing the behaviour of droplets in the slag region [1], the implementation of a physically based global process model into an industrial simulation software [2] as well as collection of material data, remelting investigations and temperature measurements on industrial and experimental ESR process scale with instrumented mould for the optimization of ingots and model validation [3][4][5].

ESI Group's commercial software package, CALCOSOFT, is a powerful industrial finite element tool which is able to simulate on various continuous casting processes. Within the framework of this project a specialized new module for CALCOSOFT-2D has been added which solves the electrodynamic problem of the ESR remelting process, coupled with fluid flow and heating in the slag and melt pool and solidification in the cast ingot. To our knowledge, this new module of CALCOSOFT-2D is the first industrial software enabling the simulation of ESR processes from macroscopic aspects. The software development enhances the ESR industry's ability to understand the interactions of complex process conditions and influence of parameters on production issues such as quality and productivity requirements. The recent developments therefore contribute to the specific tools and methods needed to keep the ESR industry at the leading edge.

2. MODEL DESCRIPTION AND SOFTWARE IMPLEMENTATION

2.1 ESR model development and testing

In a previous project, a model simulating the Vacuum Arc Remelting (VAR) process had been successfully implemented into CALCOSOFT-2D [6][7]. Based on these experiences involving direct electrical currents in metallurgical processes, the scope of CALCOSOFT-2D was extended to cover also the ESR process, taking alternating currents and consequently complex numbers into account. The physical process model is based on MHD equations and proper assumptions for the boundary conditions. The mathematical solver uses a standard Finite Element Method solving the coupling of quasi steady-state Maxwell's equations with the conservation equations of mass, momentum and enthalpy on a level which enables a macroscopic process description. Outcomes are electrical field and current density in the slag, melt pool and cast ingot, magnetic induction, Lorentz forces and associated liquid convection in the slag and in the melt pool, Ohm's heat dissipation and associated heating in the slag and in the ingot. The modelling is done on 2-dimensional axi-symmetrical geometrical domains consisting of quadrilateral or triangular finite elements.

A series of numerical tests were performed to create confidence into the mathematical model. Comparisons with analytical solutions have shown that the scheme produces exact solutions, when it is expected from a theoretical mathematical viewpoint. Electromagnetic computations where known analytical solutions exists, as infinite electric and coaxial wires were conducted. It was found, that the numerical scheme yields correct solutions with a high order of convergence and leads very fast to less important errors with moderate mesh refinement.

2.2 Implicit modelling of droplets

During ESR, the consumable electrode is dipped into a pool of slag in a water-cooled mould. An electric current (AC) passes through the slag, between the electrode and the ingot being formed, and superheats the slag so that drops of metal are melted from the electrode. They travel through the slag to the bottom of the mould where they solidify. The interface between the slag and the pool is the location of mass transfer due to the passage of the droplets, created by the melt of the electrode. In the numerical approach implemented here, this interface is assumed to be fixed and horizontal. The modeling of the mass transfer from the electrode to the pool is realized by prescribing a Gaussian shaped profile of velocity, depending on the droplet distribution on the slag-pool interface, taken from outcomes of the multiphase flow model [1]. This velocity profile is directly applied on the top surface of the pool.

An outlet linked to the melt rate and equal to the solid transport velocity is prescribed on the bottom section of the ingot, see Fig. 1. To avoid mixing of the slag and pool fluids, neither inlet nor outlet have to be defined for the slag domain. Thus in the model description, the vertical components of the velocity vectors have to be discontinuous across the interface between the slag and the pool. Actually, on the side of the slag, the vertical components are fixed to zero, because fluids are assumed to be immiscible, while the velocity profile modeling the mass transfer from the electrode to the pool has to be defined on the pool side.

This prescription of the vertical velocity components requires the doubling of nodes at the interface. Consequently, it removes completely the interaction by momentum transfer between the two fluids, creating a situation corresponding to a slip condition. However, we build up a new numerical technique enabling also the treatment of no-slip conditions between the two immiscible fluids. The radial components of the velocity on each side of the interface have to be linked, they have to be continuous across the interface. To achieve this, the double nodes can be removed for the radial components, while they are kept for the vertical components. This particular condition for the slag-pool interface, avoids any prescription of the radial velocity components.

2.3 Boundary conditions

Besides the implicit modeling of droplets, we focused on conditions to be prescribed on domains, boundaries and interfaces illustrated in Fig. 2, dedicated respectively to the three sets of equations, describing heat transfer, fluid flow and the electromagnetic problem. To give examples, the thermal conditions model the heat transfer by convection and radiation between the electrode and the protective surrounding gas, the heat exchange across the interface between the electrode and the slag, the heat exchange between the slag or ingot and the mould. An air gap due to shrinkage of the solidified ingot and solidified slag layer creation are taken into account, leading to altered boundary conditions. On the free surface of the slag, the boundary condition models heat transfer by convection and radiation. At the tip of the electrode, where the melt of the electrode takes place, a temperature slightly above the liquidus line might be imposed. At the interface between the two fluids slag and pool, the temperature can be assumed almost continuous. Thus, a huge heat transfer coefficient is applied. The heat extraction from the bottom of the ingot and from the mould by the water cooled jacket, as well as the heat exchange by convection and radiation of the mould with the air or protective gas is prescribed on the associated boundaries. Additionally, the heat loss of the slag while cleaning the droplets as well as the heat transfer from the droplets to the liquid metal pool are modeled by applying adequate heat sink and heat source functions imposed on the slag and pool regions, respectively.

The boundary conditions for the electromagnetic problem involve functions depending on the input current, derived with the help of Ampere's theorem and a coaxial wire model, prescribing the magnetic induction on the interfaces electrode-protective gas, slag-mold, ingot-air gap, air gap-mold, the free surface of the slag and the outside of the mold. On the cut sections of the ingot, the electrode and the mold induction fluxes of zero are applied. On the interfaces between two domains electrode-slag or slag-pool, the continuity of the magnetic induction and the continuity of the normal component of the electric field are used to define the boundary conditions.

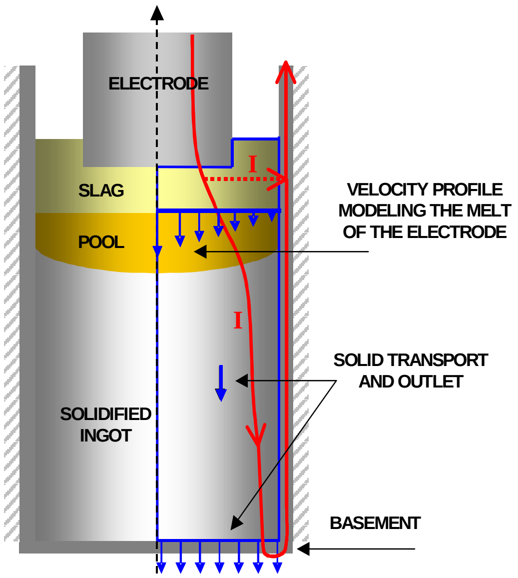

Fig. 1: Flow, solid transport and electrical current path in the ESR process model

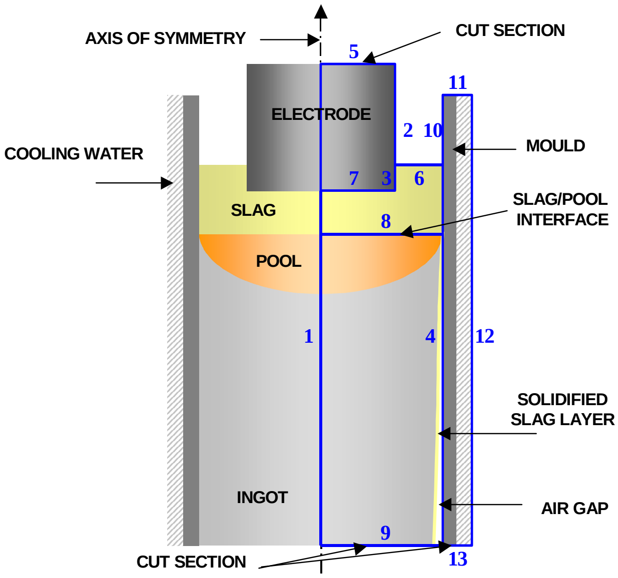

Fig. 2: Geometrical domains, boundaries and interfaces to define conditions for ESR process modelling

3. INDUSTRIAL PROCESS SIMULATION EXAMPLE

Numerical simulations on the PESR process using a complete geometry were performed in close cooperation between ESI Group SA and Böhler Edelstahl GmbH & CoKG, utilizing the partner's practical technological expertise in the field of modern steel making processes. The material data of the slag, the electrode and copper mould are derived from ESR furnace installations and other process equipment in Böhler's Austrian production plants.

The slag and ingot is surrounded with a water-cooled copper mould, rather than using an implicit mould only. During the start up phase of the process, the immersion depth of the electrode tip and the electric power of the furnace are controlled in order to obtain a constant melt rate. A thin layer of solidified slag is spread out along the walls of the mould, isolating the slag and the cast ingot from the mould. An air gap and the slag skin of variable estimated size surrounding the ingot and the slag pool are taken into account to define the boundary conditions. The alternating current passes through the electrode, the slag and the ingot to the basement and then returns through the mould to the electric system. However, being irregular in attendance and for very short time intervals only, an electric contact between the slag or top of the pool and the mould may be detected, modifying the flow path of the electric current, as it is indicated in Fig. 1.

Macroscopic stationary simulation results are presented in Fig. 3 and Fig. 4. On the left side of Fig. 3 the temperature distribution is shown, whereas on the right side the fraction solid and the liquid convection in the slag and in the melt pool are visible. The convection patterns are a determined by the competition between the electromagnetic Lorentz forces and buoyancy driven fluid flow. In Fig. 4 (left) the electric current flow stream lines are presented. Following Ampere's law and integrating the magnetic induction B over a closed loop yields the total electric current I passing through the surface surrounded. The skin effect is visible as expected. Fig. 4 (right) shows the distribution of Ohm's heating, which occurs mainly inside the slag due to the high resistance to the flow of charge in this region. Inside the slag domain the heating is concentrated at the interface between the electrode and the slag and strongly increasing with growing radius, reaching its maximum value in a torus-shaped heating domain just in front of the full radius of the electrode.

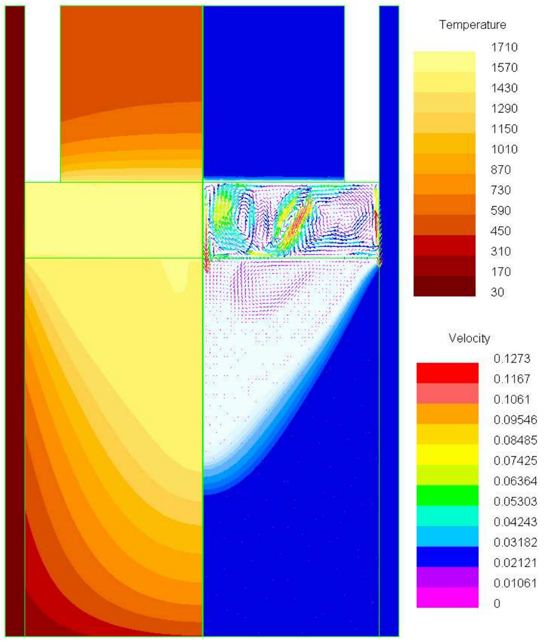

Fig.3: PESR process simulation: temperature [°C] (left), velocity [m/s] (right) and solid fraction (right)

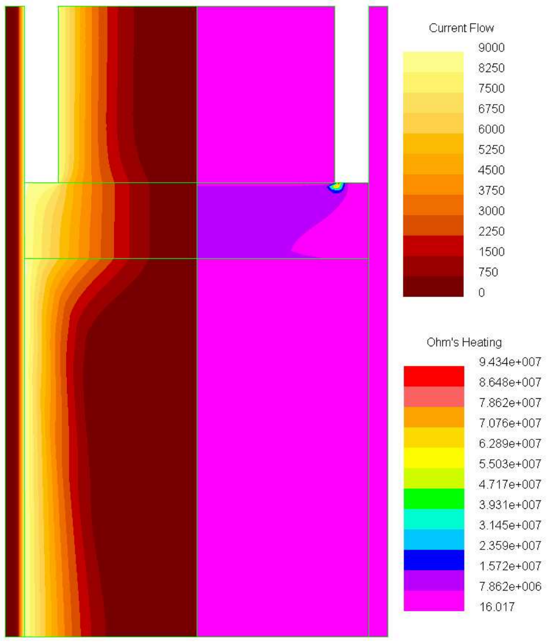

Fig. 4: PESR process simulation: electric current [A] (left) and Ohm's heating [W/m^3] (right)

4. EXPERIMENTAL VALIDATION OF THE NUMERICAL SIMULATION

For the validation of the simulations, ingots were remelted at Böhler Edelstahl GmbH & CoKG. The following parameters were measured and compared with simulation results:

- Local solidification time
- Pool profile
- Temperatures within the mould

4.1 Local solidification time

The local solidification time (LST) is the time that elapses during cooling between when the first solid forms at the liquidus and the time when the last solid forms at solidus temperatures, i.e. time to remove the latent heat. The secondary dendrite arm spacing (SDAS) is a function of the local solidification time and is investigated for many kinds of steels. The function is found to follow always a power relationship of the form:

$$SDAS = a \cdot LST^{b} \tag{1}$$

The factor *a* and the exponent *b* are calculated from data based on measurements with directional solidification or DTA [9]. Fig. 5 shows the correlation of LST and SDAS for the investigated steel H11. The investigated ingot reveals a SDAS of 190 µm in the center which corresponds to a LST of approximately 1600 s. The value of LST derived from the numerical simulations can be calculated with the following equation:

$$LST = \frac{h_{Tl} - h_{T\,s}}{v_{ingot}} \tag{2}$$

where h_{Tl} is the height of the liquidus isotherm [m] at the centre of the ingot, h_{Ts} is the height of the solidus isotherm [m] and v_{ingot} is the ingot growth velocity [m/s], which is equal to the liquid-solid interface velocity at steady state. The simulation results provide a LST value of approximately 1700 s, which is in good agreement with the measurements.

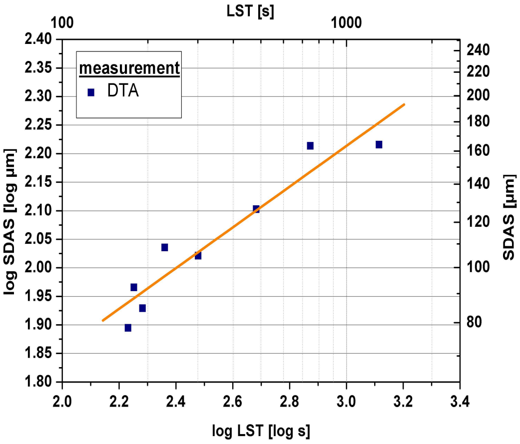

Fig. 5: Correlation of LST and SDAS of H11

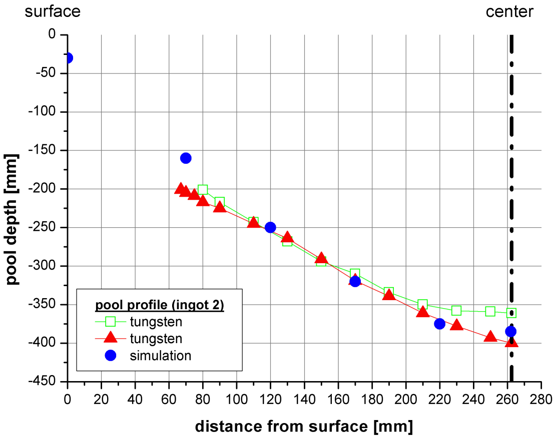

Fig. 6: Comparison of measured and simulated pool profile

4.2 Pool profile

The electrodes were prepared in the same way as described in literature [8]. Holes with a diameter of 30 mm were drilled into the electrode at different heights and filled with tungsten. During the remelting the tungsten is released and sedimented in the pool along the solidus temperature isotherm. Pool profiles were constructed on macro etched longitudinal sections and the measured values are compared with the simulation results shown in Fig. 6. It can be clearly seen that the simulation proves its ability to predict the shape and depth of the solidus line in the steady state phase of the PESR process.

4.3 Mould temperatures

During the remelting, temperatures in the copper mould are measured with thermo couples in different heights and depths. Fig. 7 shows the measurements in the given depths compared with numerical simulation results at different positions (in 15 mm depth).

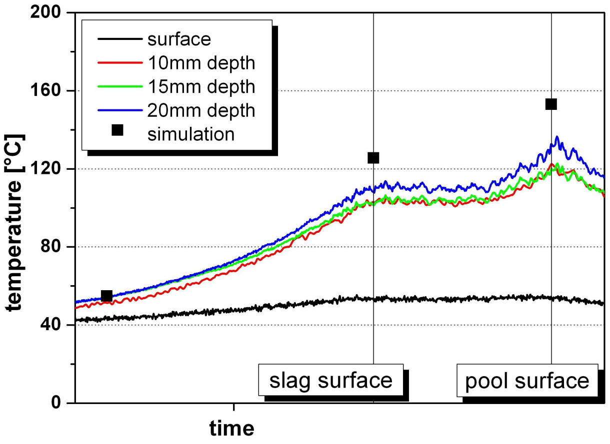

Fig. 7: Comparison of measured and simulated temperatures in the mould

The simulated temperatures are higher in the slag and pool region. It is supposed that the higher temperatures are caused by a coarse mesh in the mould. Thus, further model improvements will focus on optimization of the mesh and the thermal boundary conditions.

5. CONCLUSIONS

In the framework of a project consortium, consisting of industrial and scientific partners with different professional specialization and equipment, a physically based ESR process simulation module was implemented into CALCOSOFT-2D, a commercially available software package of ESI Group dedicated to continuous casting process simulation. Together with an extensive suite of advanced tools for pre- and post processing, CALCOSOFT-2D can now be tailored to fit various particular needs in the field of macroscopic ESR process analysis, providing in-depth insights into the influence of interacting process conditions and parameters to validate a new process design or to find an optimum process window.

ESI Group and Böhler Edelstahl GmbH & CoKG joined together to perform numerical simulations with CALCOSOFT-2D in close cooperation. A water-cooled copper mould was added to complete the PESR geometry. Material data for the electrode, ingot and slag were provided by Böhler Edelstahl GmbH & CoKG and the definitions of initial and boundary conditions were inspired by furnace installations in production plants and from process technology design. Comparisons of the macroscopic simulation results with measured experimental values have validated these PESR computations, demonstrating that the new software module as well as the boundary conditions, the material data set and geometry can be recommended for industrial PESR process engineering and design.

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