MODELLING OF THE PROTECTIVE GAS ELECTRO SLAG REMELTING PROCESS AND ITS VALIDATION

W. Schützenhöfer*, G. Reiter*, R. Rabitsch*, A. Ludwig**, A. Kharicha**, M. Gäumann***, V. Maronnier***, A. Mackenbrock***, H. Scholz****, R. Sorci*****, F. Arcobello-Varlese***** and A. Carosi*****
* Böhler Edelstahl GmbH (BEG), Austria
** University of Leoben (MUL), Austria
*** ESI-Group, France
**** ALD, Germany
***** Centro Svilluppo Materiali (CSM), Italy

Abstract

Electroslag remelting (ESR) and protective gas electroslag remelting (PESR) are standard processes for the production of high quality tool steels. A consortium consisting of a University department, software company, plant producer, a research department and a steel producer was founded with the objective to generate a numerical model of the PESR-process with respect to process optimization. The generated model is divided into two parts. A local model which describes the interaction of the metal with the slag and a general process model for calculating heat transfer, solidification and microstructure. The two models are coupled by transferring the temperature and momentum distributions. In detail the local model describes the metal-slag interfaces, e.g. electrode-slag, slag-droplet and slag-pool. In this way the formation of the droplets and their interaction during their path through the slag as well as the shape of the slag-pool interface is realized by the volume of fluid (VOF)-technique by coupling thermal and magneto-hydrodynamic calculations. The modeling focuses on a hot working tool steel hence the validation of the models is done for this steel by measuring the temperature in the mould during the remelting process and by metallographic investigations of the ingots. The pool profile is constructed and secondary dendrite arm spacings are measured for calculating the local solidification time. These investigations are done in experimental and production PESR-facilities.

Keywords

Numeric simulation, protective gas electroslag remelting process, pool profile, SDAS, local solidification time,

INTRODUCTION

Electroslag remelting (ESR) and protective gas electroslag remelting (PESR) are standard processes for the production of high quality tool steels with the following outstanding properties: Very low oxide and sulphide inclusion content, uniform mechanical properties in all directions, a low content of trace elements, a minimal degree of segregation and a high reproducibility through process automation.

In order to generate a model of the current PESR-processes including also the description of the interaction of the electrode, droplets, slag and pool the RFCS-project ISA-PESR (acronym for **I**ntegrative **S**imulation of **A**dvanced **P**rotective Gas **E**lectro **S**lag **R**emelting for the production of High Quality Steels) was started.

PROJECT SET-UP

The mentioned project is divided into 5 workpackages with an intensive interaction between them.

- Development of a local model describing the interaction electrode-droplets-slag-pool (MUL)
- Development of a global PESR model (ESI)
- PESR-experiments with instrumented mould for the validation of the models (CSM)
- PESR remelting in industrial scale with instrumented mould also for validation (BEG)
- Performance of temperature measurements during remeltings (ALD)

The standard hot work tool steel X38CrMoV 5-1 (1.2343, H11) and the standard ESR-slag S2015 (31.5% CaF_2, 33.5% CaO, 29.5% Al_2O_3, 3% MgO and 1.5% SiO_2) were chosen for the model development, validation and parameter studies.

In order to estimate the thermal boundary conditions temperature measurements with several thermo couples in the mould were carried out during remelting in the experimental PESR.

THE LOCAL SLAG-METAL-INTERACTION MODEL (VOF)

Existing numerical models of the ESR-process from literature only worked on special developed software [1-9]. In this project the existing solidification software calcosoft® is adapted to calculate the ESR-process. To improve the existing models the developments in this project are focused on the metallurgical active slag zone, e.g. the remelting of the electrode, the droplet formation and the interaction of the sinking metal droplets in the slag (black box in figure 1).

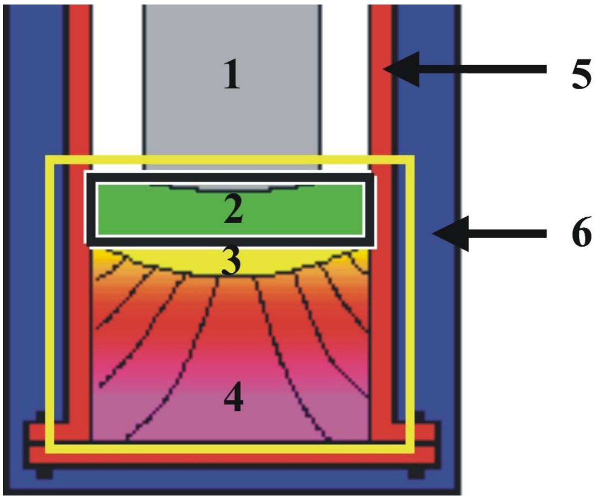

Figure 1 : Process description (1: electrode; 2: liquid slag; 3: pool; 4: ingot; 5: mould; 6: water jacket)

These numerical simulations are realized with a multiphase volume of fluid (VOF)-technique taking into account conservation of mass, momentum, solute, enthalpy for metal an slag phase, Joule´s heating and Lorentz force [10]. This model describes the melting of the electrode, formation of the droplets, withdrawal of the droplets, their passing through the slag and their input in the pool (see figure 2).

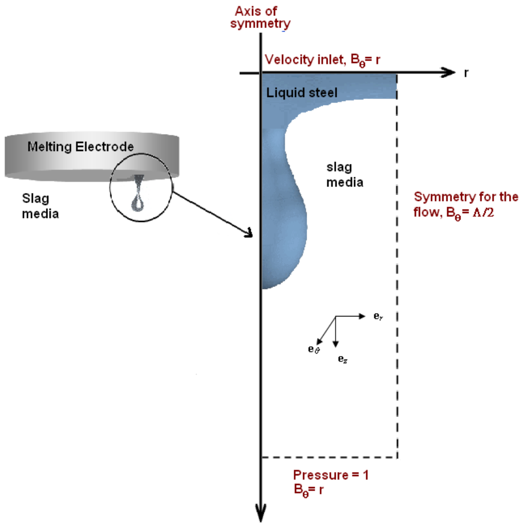

Figure 2 Calculation domain for the droplet formation [10]

The output of these simulations (distribution of metal and solute input at the slag-pool interface) is the input for the global model.

THE GLOBAL MODEL (CALCOSOFT)

In this project the commercial FE-software calcosoft® is adapted to the applications of the process. This software should calculate the overall remelting process (yellow box in figure 1).

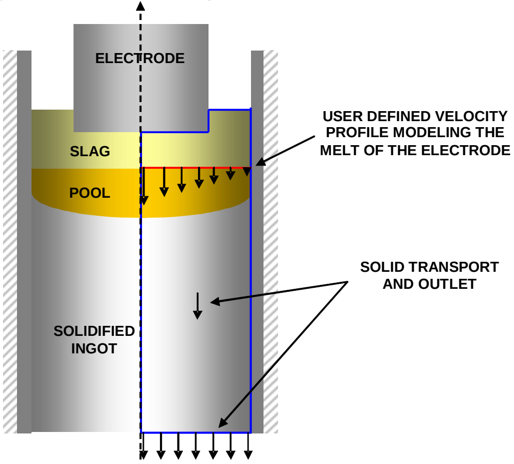

Figure 3 Fluid flow situation for the PESR model (calcosoft 2D®)

This model includes the current input, thermal and fluid flow in the slag and the pool due to buoyancy and Lorentz force, solid transport of the ingot due to the melt rate and the input of droplets (velocity, temperature) determined by the local VOF-model. The thermal boundary conditions of the model are compared with literature [11, 12] and are in good agreement.

VALIDATION

The experimental ESR at CSM works with a 5 Hz AC so the approximation of the process with the current DC model of calcosoft® [13, 14] is a good approximation [7, 8]. The development of the model with AC is in the state of validation.

In the first stage of validation two remeltings were carried out at CSM for investigations on primary microstructure to get the pool profile and the local solidification time from SDAS [15].

The input data for the simulation are listed in table 1. The material data of the steel H11 and the ESR-standard slag S2015 are derived from literature or measurements. The data are temperature dependant and therefore not listed.

Table 1 Process data of the experimental ESR

Geometry	
Slag height (h)	125 mm
Electrode diameter	130 mm
Ingot Diameter	200 mm
Operating condition	
Electric current	5.0 kA
Electric current frequency	5 Hz
Melt rate	2.4 kg /min

In the steady state the pool profile should be stable. The profile itself can be reconstructed by the dendritic structure, because the preferred main direction of the dendrites is against the heat flow. Taking this into account the isotherms are perpendicular to primary dendrites. For the mentioned process parameters several pool profiles were reconstructed with a mean pool depth of 76mm.

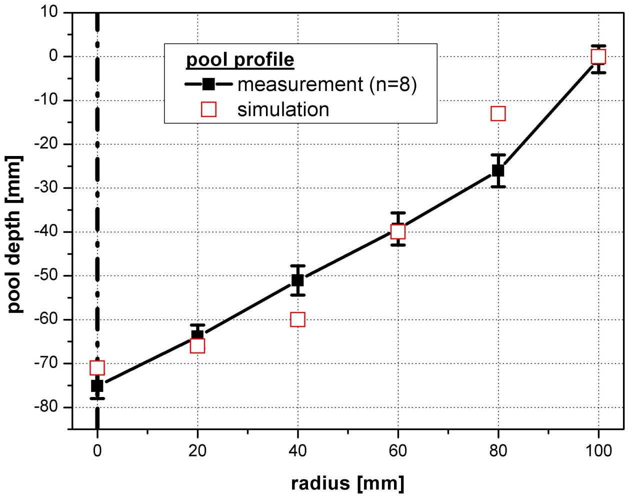

Figure 4 Pool profile of the test ingot (ingot diameter = 200 mm, melt rate = 2.4 kg/min, I = 5000 A, frequency = 5 Hz)

For the characterisation of the microstructure of steels the secondary dendrite arm spacing λ_2 is used [13]. The secondary dendrite arm spacing is a function of the local solidification time (LST) and is investigated for many kind of steels. The function always has the form:

$$\lambda_2 = a \cdot LST^b \tag{1}$$

The factor *a* and the exponent b are calculated based on measurements with directional solidification or DTA [16].The local solidification time LST is defined as:

$$LST = \frac{T_L - T_S}{\dot{T}} \qquad (2)$$

where, T_L is the liquidus temperature, T_S is the solidus temperature and $\dot{T}$ the cooling rate during solidification.

In Fig. 5 the correlation between λ_2 and LST is shown for H13, which is in analysis quite near to H11. The correlation is supposed to be the same for H11. Investigations to get the correlation for H11 are in progress. Linear correlation in a double logarithmic scale gives the form:

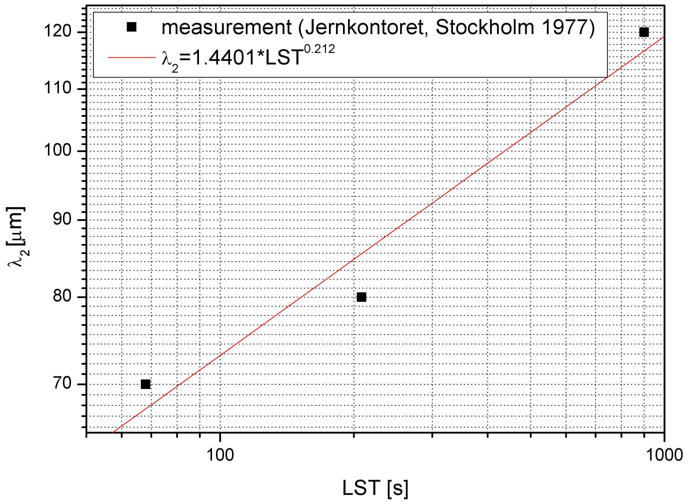

Figure 5 Dependency of secondary dendrite arm spacing λ_2 from the local solidification time LST for the steel X40CrMoV5-1 (1.2344, H13)

In the steady state region of the ingot many secondary dendrite arm spacings were measured to have statistical satisfying values. The mean value of the Gaussian distribution was 96 ± 15 µm which is equal to a LST of approx. 200 – 700s with a mean value of 350 s.

For the validation LST of the simulation results is compared with metallographic investigations. The LST from the simulation is obtained in the following way:

$$LST = \frac{h_{Tl} - h_{T\,s}}{v_{ingot}} \qquad (3)$$

with h_{Tl} as height of the liquidus isotherm [m], h_{Ts} as height of the solidus isotherm [m] and v_{ingot} as ingot growth velocity [m/s], which is equal to liquid/solid interface velocity at steady state [15].

$$v_{ingot} = \frac{mr}{A \cdot \rho} \qquad (4)$$

with mr as melt rate [kg/s], A as cross section of ingot [m²] and ρ as density [kg/m³]. The calculation results are in the range of the experimental results.

DISCUSSION

This paper shows intermediate results. The first validation of the used model was carried out by simulating an experimental ESR-process operated with outstanding 5 Hz AC with the assumption the low frequency AC behaves nearly like DC. The validation is carried out with the DC-model. Although there are the mentioned assumptions the results are in good agreement with the experiments. The described validation are for ingots remelted in a experimental PESR facility. The AC-model for industrial scale PESR facilities is in the state of development and validation.

CONCLUSION

A new model for the simulation/optimization of the PESR process is introduced. The model also takes into account the melting of the electrode, droplet formation and the interaction of the droplets with the slag.

In the present state the validation of the models are carried out on basis pool profile and LST of an H11-ingot remelted in a experimental PESR.

OUTLOOK

The next steps in the project are: validation of the AC-model on basis of industrial scale PESR-ingots with different melt rates, carrying out of an sensitivity analysis and optimization of the PESR process.

ACKNOWLEDGEMENTS

This project is funded by the “European Research Fund for Coal and Steel “.

REFERENCES

[1] K. Kelkar, S. Patankar and A. Mitchell, Computational Modeling of the Electroslag Remelting (ESR) Process Used for the Production of Ingots of High-Performance Alloys, Proceeding in International Symposium on Liquid metal Processing and Casting, Santa Fe, USA, pp. 137-144, 2005

[2] J. Kreyenberg and K. Schwerdtfeger: Stirring Velocities and Temperature Field in the Slag during Electroslag Remelting. Archiv für das Eisenhüttenwesen, Vol. 50, Nr. 1, pp. 1-6, 1979

[3] K. H. Tacke and K. Schwerdtfeger, Melting of ESR Electrodes, Archiv für das Eisenhüttenwesen, Vol. 52, No. 4, pp. 137-142, 1981

[4] A. Jardy, D. Ablitzer and J. Wadier, Magnetohydrodynamic and Thermal Behavior of Electroslag Remelting Slags, Metallurgical Transactions B, Vol. 22B, No. 2, pp. 111-120, 1991

[5] A. Ballanthyne and A. Mitchell, Modelling of Ingot Thermal Fields in Consumable Electrode Remelting Processes, . Ironmaking and Steelmaking, Vol. 4, No. 4, pp. 222-239, 1977

[6] A. H. Dilawari and J. Szekely, Metall. Trans. B, Vol 8B, No. 6, pp. 227-236, 1997

[7] J. Szekely and A. Dilawari: The mathematical modelling of slag and metal flows in the ESR process. Proc. 5th International Conference on Vacuum Metallurgy and Electroslag Remelting Processes, Munich, Germany, pp. 157-160, 1976

[8] W. Thomas: The influence of the electrode and in particular its tip on the operating behaviour of electroslag remelting furnaces. Proc. 5th International Conference on Vacuum Metallurgy and Electroslag Remelting Processes, Munich, pp. 161-163, 1976

[9] A. Patel, Analytical Model for Electromagnetic Fields in ESR and VAR Processes, Proceeding in International Symposium on Liquid metal Processing and Casting, Nancy, France, pp. 205-214, 2003

[10] A. Kharicha, A. Ludwig and M. Wu, Simulation of droplet formation during DC Electro-Slag-Remelting, Proceedings 1st International Conference of Metallurgical Processes in Steelmaking, Brno, Czech Republic, pp. 343-359, 2005

[11] K. Yu, Comparison of ESR-VAR Processes - Part I Heat Transfer Characteristics of Crucible, Proceedings of the 1984 Vacuum Metallurgy Conference on Speciality Metals Melting and Processing. Pittsburgh, USA, pp. 83-92, 1984

[12] L. Bertram, P. Schunk, S. Kempka, F. Spadafora and R. Minisandram, The Macroscale Simulation of Remelting Processes, JOM, No. 3, pp. 18-21, 1998

[13] G. Reiter, V. Maronnier, C. Sommitsch, M. Gäumann, W.Schützenhöfer and R. Schneider, Proceeding in International Symposium on Liquid metal Processing and Casting, Nancy, France, pp. 77-86, 2003

[14] G. Reiter, W. Schützenhöfer, P. Würzinger and S. Zinner, Optimization and Detailed Validation of a VAR Model, Proc. of the 2005 International Symposium on Liquid Metal Processing and Casting. Santa Fe, USA, pp. 7-12, 2005

[15] K. Yu and . Flanders, Comparison of ESR-VAR Processes Part II Melting Phenomena and Ingot Structure. Proc. 1984 Vacuum Metallurgy Conference on Speciality Metals Melting and Processing. Pittsburgh, USA, pp. 107-118, 1984

[16] Guide to the solidification of steels. Jernkontoret, Stockholm, 1977