COST 526 – Project SI 4

Final Report

Modelling and Optimisation for Competitive Continuous Casting

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1. Introduction

COST 526 project SI 4 focused on implementation of the automatic simulation-optimisation tools in several continuous casting processes. The simulation tools can be applied in several different ways to serve industry by inducing beneficial changes to process operation. These include respective better understanding of the process, better insight into the process, better influence on the process and better organisation of the work around the process. These tools have been in the framework of the present project enhanced by the automatic optimisation option which enables the process designer for automatic setting of the proper casting parameters.

2. Goal of the project

The physical as well as empirical process parameter limits have been introduced in order to conduct the process according to product quality, safety, economy, and ecology standards in modern process engineering practice. To satisfy these limits, numerous process parameters need to be properly tuned. Optimizing their values is not trivial as the requirements are often contradicting, and the number of possible parameter settings grows exponentially with the number of parameters involved. Respectively, the parameter tuning based on real world experimentation is not feasible. The primary goals of the project were: (I) to enhance the physical and computational modelling of the continuous casting processes, (II) to automatically couple process simulator, cost function, and optimisation procedure in an automatic process optimisation bundle, (III) to be able to automatically optimally set process parameters.

3. Simulator, calibration, quality function and optimization algorithms, including assessment with respect to alternatives

The process limits have been developed for continuous casting of steel, direct-chill and strip casting of aluminium alloys. They are mainly associated with different types of cracking, shape defects, micro and macrosegregation. In continuous casting of steel and strip casting of aluminium alloys automatic optimisation has been performed in order to optimise the steady state operation. In direct chill casting the automatic optimisation has been performed for the start-up practice. The performance of the process models has been validated through industrial plant measurements. The thermal model of the steel casting simulator has been validated by comparison with the infrared thermography measurements. The shell thickness prediction has been validated by comparison with the wedge method measurement. In aluminim casting, the thermal model has been validated by insertion of the thermocouples in the strand and contact thermocouple measurements on the surface. The object function for continuous casting processes can be listed into quality, safety, economy, ecology and maintenance categories. Quality: (I) maximum depth of the liquid pool, (II) maximum surface cooling rate in the spray cooling zone, (III) maximum surface reheating rate in the spray cooling zone, (IV) maximum surface temperature in the unbending region, (V) maximum negative surface deviation at given axial position, (VI) maximum positive surface deviation at a given axial position; Safety: (VII) minimum safety thickness of the crust, maximum safety depth of the liquid pool; Economy: (VIII) maximum casting speed, (IX) minimum superheat;

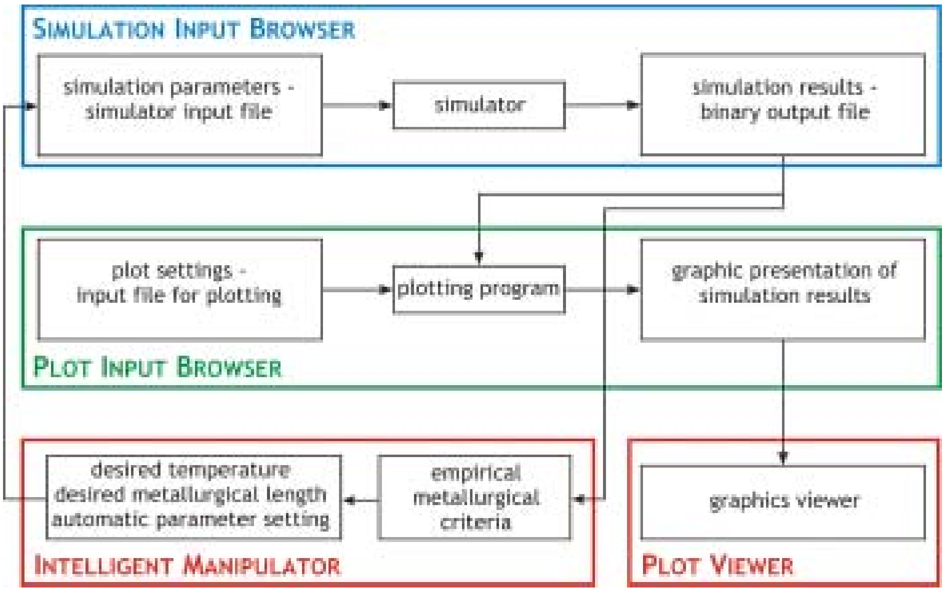

Figure 1: General scheme of the simulation systems with intelligent manipulation options.

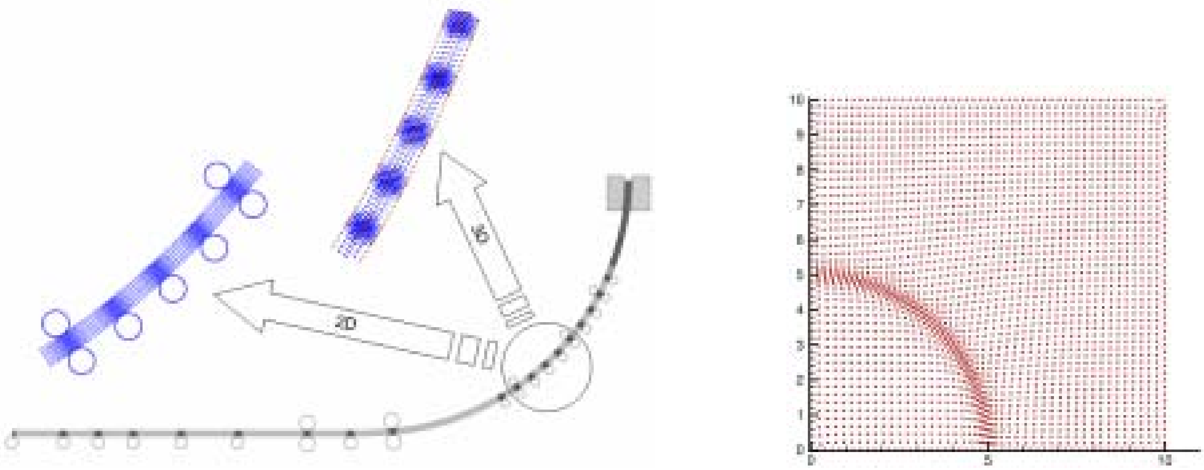

Figure 2: Examples of nodes distribution with the recently developed LRBFCM. Left: Node arrangement for calculation of the thermal and strain-stress fields in billet. Right: adaptive node distribution for solving the phase-field equations in heat treatment.

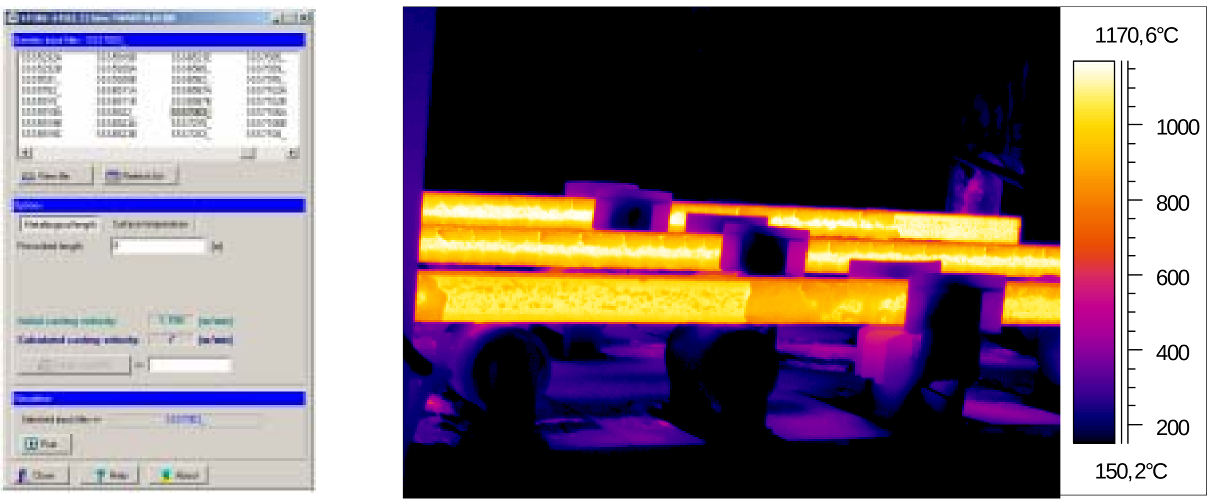

Figure 3: Left: User friendly browser for automatic setting of desired metallurgical length. Right: Infrared thermography performed for validation of the billet simulation system.

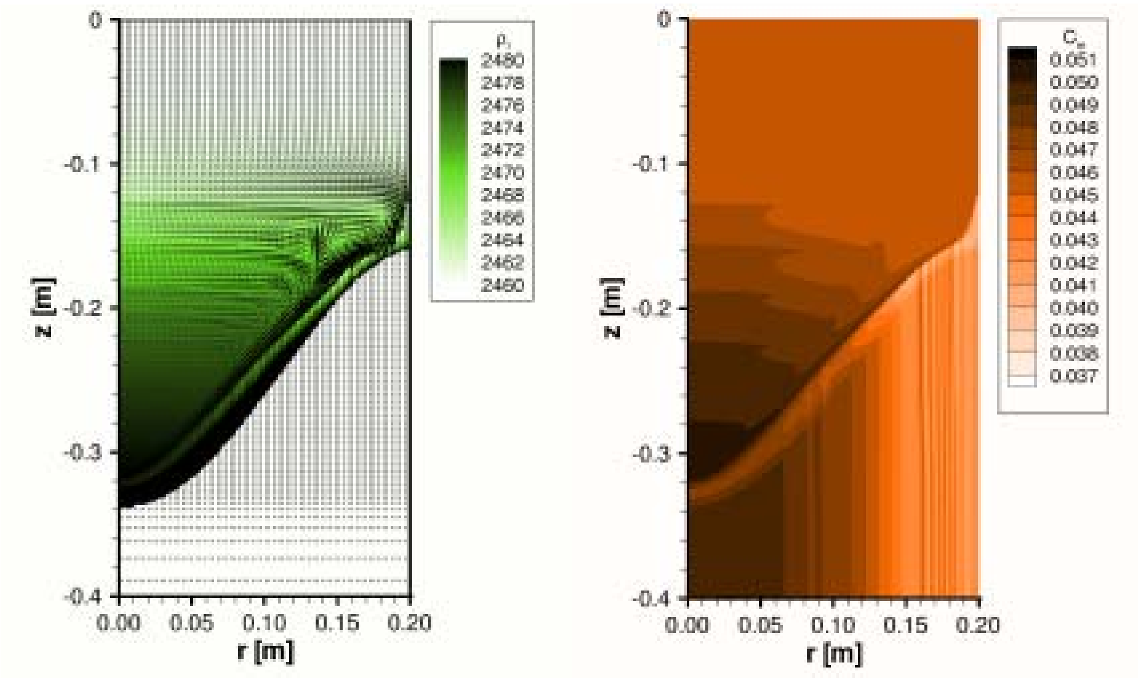

Figure 4: Melt flow (left) and macrosegregation (right) in DC casting of Al-Cu alloy. The object function represents flat as possible macrosegregation profile.

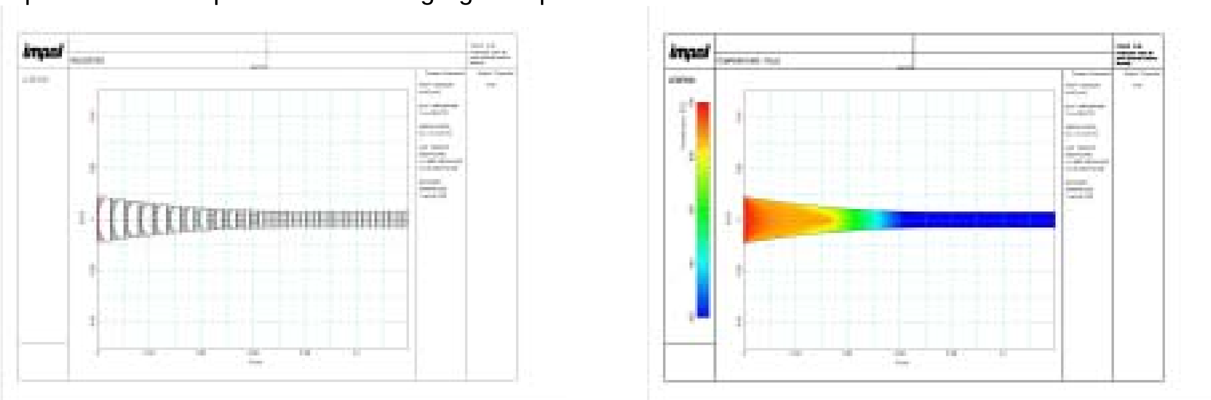

Figure 5: Simulation system for thin strip casting of aluminium alloys. Left: calculated velocity profile. Right: calculated temperature field.

Ecology: (X) minimum consumption of cooling agents; Maintenance: (XI) minimum forces on the rolls and possible unbending devices. In semi-continuous direct chill casting process the criteria for maximum depth of the mushy zone has been added in order to address the hot tearing. The system “simulator - object function - optimisation procedure” iteratively and automatically improves the parameter settings: the genetic algorithm guides the search through the parameter space and activates the heat transfer model to evaluate the candidate parameter settings. Details of the optimization procedure are given in the project SI 1. Despite the developed very sophisticated and comprehensive automatic process optimisation framework, only three automatic process model options are currently fully implemented in practice: automatic set-up of process parameters that yields predetermined metallurgical length, mushy zone depth or surface temperature at given positions. The implementation of others is underway.

4. Main scientific outcome

Development of a completely new generation of meshless numerical methods that proved to be much more accurate and geometrically flexible that the classical numerical methods such as finite elements, finite volumes or boundary elements and with the advantage of easy coding and easy implementation of complicated physics. Aplication of these methods in micro and macro solidification and heat treatment modelling.

5. Main technical outcome

Implementation of a new generation of numerical methods into industrial process simulators. Automatic process optimisation of the process parameters in continuous casting of steel, direct chill casting, and thin strip casting of aluminium alloys. Development and plant implementation of the optimized regulation coefficients in plant automation.

6. Collaboration within COST 526

National partners:

Laboratory for Multiphase Processes, Nova Gorica Polytechnic, Slovenia.
Main collaborators: B.Šarler, R.Vertnik, J.Perko, S.Šaletić, I.Kovačević, M.Založnik.
Subject: development and evaluation of process simulators, quality functions design.

Jožef Stefan Institute, Ljubljana, Slovenia.
Main collaborators: B.Filipič, T.Robič.
Subject: optimization algorithms, quality function design, integration with process simulators, comparative studies of optimization algorithms.

International partners:

Department of Mathematical Sciences, University of Oulu, Finland.
Main collaborator: E. Laitinen
Subject: an alternative simulator for continuous casting of steel, quality function design for continuous casting of steel, comparative studies on industrial test cases.

Heat Transfer and Fluid Flow Laboratory, Faculty of Mechanical Engineering, Brno University of Technology, Czech Republic.
Main collaborators: M.Raudensky, J.Horsky.
Subject: measurements of heat transfer coefficients to calibrate the numerical model of the steel casting process.

7. Cooperation with industry

The following industrial partners have been involved in the project:

Steelworks Acroni d.o.o., Jesenice, Slovenia.
Main collaborators: A.Lagoja, E.Šubelj, J.Triplat.
Subject: simulation and optimisation of continuous casting of steel slabs.

IMPOL d.d., Slovenska Bistrica, Slovenia.
Main collaborators: E. Slaček, R. Šafhalter, F. Tomazini, M. Jelen, A.Robič.
Subject: simulation and optimisation of direct-chill casting and thin strip casting of aluminium alloys.

Štore - Steel d.o.o., Štore, Slovenia
Main collaborators: G. Manojlović, J. Cesar.
Subject: simulation and optimisation of continuous casting of steel billets.

8. References

Aproximately 30 conference papers have been presented in the framework of the project on international scientific and technological conferences of which arround half have been invited. Here we quote only the respective archival journal papers that originated in the framework of the project:

[1] B.Šarler, Towards a mesh-free computation of transport phenomena, *Engineering Analysis with Boundary Elements,* Vol.26, 2002, pp.731-738.
[2] B.Šarler, J.Perko, C.S.Chen, Radial basis function collocation method solution of natural convection in porous media, *International Journal of Numerical Methods in Heat and Fluid Flow,* Vol.14, 2004, pp. 187-212.
[3] B.Šarler, A radial basis function collocation approach in computational fluid dynamics, *Computer Methods in Engineering and Sciences*, Vol.7, 2005, pp.185-193.
[4] D.W.Pepper, B.Šarler, Application of meshless methods in thermal analysis, *Mechanical Engineering Journal*, Vol.51, 2005, pp.476-483.
[5] I.Kovačević, A.Poredoš, B.Šarler, Solving the Stefan problem with the radial basis function collocation mehod, *Numerical Heat Transfer, Part B – Fundamentals*, Vol.44, 2003, pp.575-599.
[6] B.Šarler, R.Vertnik, Meshfree explicit local radial basis function collocation method for diffusion problems, *Computers and Mathematics with Applications,* (in print).
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[8] B.Šarler, R.Vertnik, J.Perko, Application of diffuse approximate method in convective-difussive solidification problems, *Computers, Materials, Continua*, Vol.2, 2005, pp.77-83.
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[10] I.Vušanović, B.Šarler, M.J.M.Krane, Microsegregation during the solidification of an Al-Mg-Si alloy in the presence of back diffusion and macrosegregation, *Materials Science and Engineering, A - Structural Materials: Properties, Microstructure and Processing,* (in print).
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[13] I.Kovačević, B.Šarler, Solid-solid phase transformations in aluminium alloys described by multiphase-field model, *Materials Science Forum*, Vol.509, 2005, pp.579-584.
[14] I.Kovačević, B.Šarler, Solution of the phase field model with the local radial basis function collocation technique, *Materials Science and Engineering, A -Structural Materials: Properties, Microstructure and Processing,* (in print).
[15] B.Šarler, R.Vertnik, S.Šaletić, G.Manojlović, J.Cesar, A simulation system for continuous casting of steel, *Berg- Hüttenmännische Monatshefte,* Vol.150, 2005, pp.300–306.