## COST 526

**Automatic Process Optimization in Materials Technology**

(APOMAT)

Title:

# Optimization of Cooling Parameters in Casting Processes

**Keywords:** modelling, simulation, optimisation, steel, copper, continuous casting, metallurgical cooling criteria

Organization/Company:

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### 1. Duration / run time of the project

- Duration: 3 years
- Starting and finishing date: 1.10.2001-30.9.2004

### 2. Overall cost

- 650 kEURO (approx. 9 man years)

### 3. Funding situation

Choose one of the following options:

- Funding applied for at: the National Technology Agency TEKES and Academy of Finland

### 4. Project partners indicated to participate

#### 4.1. International partners

**Asst. Prof. Božidar Šarler**: Laboratory for Fluid Dynamics and Thermodynamics, Faculty of Mechanical Engineering, University of Ljubljana, Ašker eva 6, 1000 Ljubljana, Slovenia

Industrial partners: Steelworks ACRONI Jesenice, Slovenia, Steelworks INEXA-Štore, Slovenia

**Dr. Mihály Réger,** Bánki Donát Polytechnic, Department of Materials Science and Technology, Budapest, Népszínhá u. 8, H-1081 Hungary

Industrial partner: Dunaferr Steelworks

#### 4.2 National partners

**Dr. Seppo Louhenkilpi**, Helsinki University of Technology (HUT), Laboratory of Metallurgy, P.O. Box 6200, FIN-02015 Espoo, Finland

**Dr. Joachim Wendt,** VTT Manufacturing Technology, P.O. Box 1703, FIN-02044 VTT

### 4.3 Description of the collaborative approach

During the last 15 years, powerful numerical heat transfer and microstructure models have been developed in co-operation with University of Oulu, University of Jyväskylä and the Helsinki University of Technology. The developed multiphase heat transfer model, TEMPSIMU, and interdendritic solidification model, IDS, have successfully been applied to simulate the solidification of steels during different continuous casting processes. The dynamic multiphase heat transfer model, DYNCOOL, is successfully applied to control the water cooling during steel continuous casting process at Rautaruukki steel works in Finland and at Severstal steel works in Russia.

Different tasks for developing and implementing the optimisation model will be performed by the project partners: The University of Oulu will improve the performance of the simulator for steel casting so that it can be used for automatic on-line control (fast iterative methods) and further develop the optimisation and control software previously developed by the University of Oulu. Software will be implemented at Rautaruukki steel plant. HUT will contribute metallurgical and process knowledge, perform measurements and validate the models. VTT will develop algorithms for defining the boundary conditions for the interface between the mould and the strand. The optimisation models are developed together with the industrial partners who will deliver all necessary process information, assist in model adaptation and finally use the optimisation technique.

International collaboration will include the open exchange of information on influencing process parameters, optimisation strategies, and practical experience.

The proposer has three years collaboration with the Slovenian group (Dr. Božidar Šarler), which will be continued in this project.

## 5. Project partners to be found

Collaborative proposals of other research institutions and manufacturing companies are welcome.

## 6. Short description of the material process to be optimized

Continuous casting is the most common industrial method of making steel, copper and aluminium semi-products. In the process, liquid metal is poured into a water-cooled mould in order to initiate solidification and to ensure that a sufficiently thick shell encloses the strand when it leaves the mould. In steel casting, the strand is next subjected to the secondary cooling zone, which is constructed of a finite number of adjustable water spray nozzles, whose intensity can be controlled. The unavoidable changes of process parameters give rise to an adequate, nontrivial control of the water sprays in order to preserve the quality of the product. However, recently good control algorithms are still lacking. Our aim is:

- optimise continuous casting of copper and steel by developing automatic control models and integrating them with simulation models
- Develop control algorithms based on distributed control of parabolic PDE's

- Develop control algorithms based on inverse formulation of parabolic PDE's
- Construct objective functions which are specific for different materials
- Integrate control models with process simulation models
- Apply developed computer programs in industry

By using proper control the surface and internal quality of semi-products will be better, conditioning losses will be reduced, production will be increased and energy will be saved.

**7. Material(s) involved:**

Steels and copper alloys.

**8. Optimization potential of the process or process step**

In continuous casting of steel secondary cooling has a considerable influence on cracks and other defects, which can be formed in the cast material. To ensure defect free products, the cast has to be cooled down according to steel grade, product size, casting speed and machine design. However, until recently the cooling control is based mostly on empirical knowledge, which is not accurate when casting conditions change. To avoid product quality deterioration it is necessary to have an intelligent control system, which adjusts the cooling parameters according to varying casting conditions such that the steel quality will remain desired. The numerical quality optimisation has substantial optimisation potential because experimental measurements regarding quality quantities of cast are impossible during casting process.

It is expected that the use of automatic optimisation and control technology will reduce scrap, increase productivity, save energy and increase product quality.

Technological feasibility is given because the continuous casting process is already now highly controlled and has a high degree of automation. The design variables will be identical with or a subset of process control parameters like casting temperature, casting speed, cooling

**9. Specified material properties to be achieved**

To ensure high product quality, the strand must be cooled correctly. One common way is to cool the strand so that the selected strand surface temperature pattern along the machine is retained in spite of the variations in casting parameters. The aim with this project is to develop a control model, which controls the cooling according to metallurgical cooling criteria. They are for instance: the maximum length of the liquid pool, the unbending temperature, the maximum re-heating or cooling rate etc. By this method, it is possible to control the cooling better in varying casting conditions. So, the quality of the product is increased also in strongly dynamic situations. The good quality means: no cracks, finer microstructure, no segregations, no inclusions, good surface quality etc. This can be achieved partly by better cooling control. One aim of the project is also to develop metallurgical cooling criteria for the cooling as a form of cost functions for the optimisation model.

**10. Process parameters to be optimized**

The cooling rate during solidification affects the microstructure and mechanical properties of the product. The control of cooling rate is obeyed using adjustable water spray nozzles on the secondary cooling zones of the casting machine. The parameters to be optimized are water spray values of each spray nozzle. The optimisation parameters have minimum and maximum limits, which are dependent on water nozzle types used.

## 11. Material laws including material dependent coefficients

In recent years several numerical models for defining the thermophysical properties (e.g. A3-temperature, latent heat, thermal conductivity, specific heat) of the material have been developed. One excellent model is developed at Helsinki University of Technology (HUT) in Finland [15], which can be used for calculating the required material properties for different steel grades.

## 12. Simulator

Two previously developed programs will be used for simulating the solidification of the cast: one for continuous casting of steel, and another one for copper casting. Both codes will be extended by a sophisticated model for heat transfer between billet and mould, respectively billet and environment, utilising inverse modelling techniques. In the case of steel, new innovative parallel algorithms will be implemented. Recently many sophisticated simulation models for continuous casting have been developed [1,2,3,4], which can be used in combination with optimisation models. The numerical treatment of the simulation model is based on numerical methods for boundary value problems. Methods of numerical linear algebra are used for solving discrete problems. When using the simulator on-line have the finite dimensional approximation of the model and its iterative solution algorithms crucial importance. Also solving large problems in real time the implementation of algorithms have crucial importance. One of the most actual topics in numerical analysis is the implementation of algorithms in parallel. In parallel case the iterative methods to implement grid schemes are e.g. domain decomposition methods [16]. A second challenging approach to construct effective numerical algorithms that will be paid attention is the multigrid method, which can be used as a fast solver in iterative solution of continuous casting problem. Combining of this method with DDM is expected to be very effective tool for solving especially 3D problems in the domain of complicated geometry.

The computing time in on-line control should be less than 1-5 seconds, so very efficient numerical methods must be used.

## 13. Optimizer

The numerical algorithms of the optimiser can be based on the methods of distributed control or inverse modelling, which are theoretically well known. Our approach is to use a simulation model, which is based on diffusion-convection equation with phase change. The simulation model is in industrial use at many continuous casters. Using distributed control the optimal state can be defined by inequality constraints and penalty constraints and the gradient of cost function can be calculated using adjoin state. The benefits of this approach are: the mathematical formulation of complex optimisation objectives is possible, the calculation effort is good, i.e. the method is suitable for dynamic optimal control.

## 14. Competence / activities of proposer:

Previous research of the proposer, within the scope of this proposal, includes mathematical simulation of steel casting, copper casting and optimisation. The main present activity of the proposer includes studying of Domain Decomposition Methods (DDM) for continuous casting problem and distributed optimal control for parabolic PDE's. The DDM has become important in numerical mathematics, since it gives an efficient way to solve parallel large algebraic systems. In co-operation with M.Sc. Toivonen and Prof. Sarler boundary element mesh scheme for continuous casting problem is studied. In co-operation with Kazan State University (group of Prof. A. Lapin) dynamic optimal control of continuous casting problem is studied. In industrial level several simulation and control software for metal industry has been developed.

**15.International state of the art and references**

Without any known exception to proposer all the applications for optimising secondary cooling settings, using distributed control, have been done for steady state operation of continuous caster. Generally steady state optimisation can be based on solving an inverse problem by using regularisation methods, e.g. Tikhonov regularisation. This technique is applied in one dimension for parabolic heat equation connected with the continuous casting of steel in [2,5] and in two dimensions in [6]. Another approach is to use method of distributed control for continuous casting problem, which is also theoretically well known [7,8,9,10,11]. This theory is applied for continuous casting problem in several papers using different approach in developing the cost function, its constraints and method for optimisation. In the most works [12,13,14,9] the state equation is a parabolic diffusion equation with phase change and all constraints are involved as a penalty terms and the gradient of cost function is calculated using adjoin state.

In our proposal the simulation model is based on diffusion-convection equation with phase change and the optimal state is defined by inequality constraints and penalty constraints [17]. Moreover our proposal will set great effort to developing quality objectives and computationally effective software.

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