COST 526 – Project FIN 1

Final Report

Optimization of Cooling Parameters in Continuous Casting Processes

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1. Introduction

In the steel continuous casting process (see Fig. 1) liquid steel is poured into a water cooled mold in order to initiate solidification and to ensure that a sufficiently thick shell encloses the strand when it leaves the mold. Next, the strand is subjected to secondary cooling, what is constructed of finite number of water cooling zones, whose intensity can be controlled. The water spray 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 a pattern which depends on steel grade, product size, casting speed and machine design.

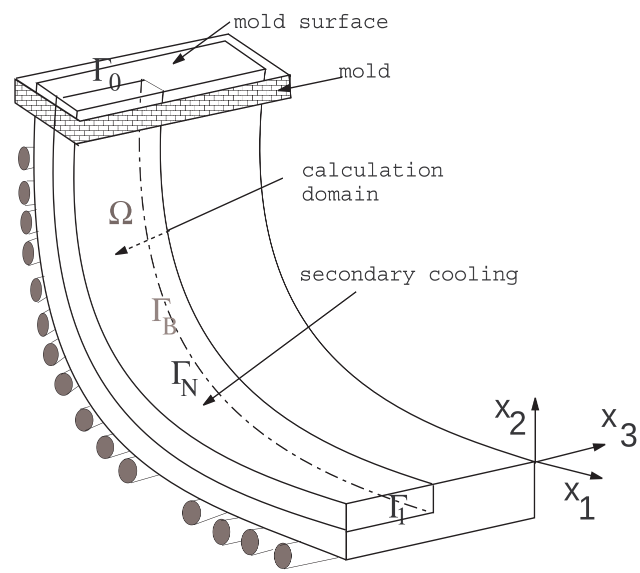

Figure 1.

In this project we have considered different optimization techniques of finding the best possible spray cooling intensities with respect to the steel quality. The process parameters to be optimized are water spray values on each cooling zone and they have minimum and maximum limits, which are dependent on water nozzle types used (technical constraint). We like to maximize also the economy of cooling water consumption, which is included into the cost function. The control procedure is based on numerical simulation of cast temperature field and on distributed control of the secondary cooling water flow values.

2. Goal of the project

Recently many sophisticated simulation models for continuous casting process has been developed which can be used for optimisation of process parameters. However, only few of them have been applied successfully into industrial casting processes. The goal of our project was to apply our simulation and optimization models to the steel continuous casting process at Rautaruukki Company in Finland. The goal was also to develop real-time software which can be used for controlling water flow volumes of secondary cooling region.

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

Our simulation model calculates the temperature field of steel slab on 3D geometry. The numerical treatment of the simulation model is based on numerical methods for boundary value problems (finite element method). Methods of numerical linear algebra are used for solving discrete problems. Solving large problem in real time the implementation of algorithms has crucial importance. The computing time in on-line control should be less than 1-5 seconds, so very efficient numerical methods must be used. We have implemented parallel methods i.e. domain decomposition methods and also multigrid methods for solving the simulation model in real time. The accuracy of our 3D dynamic simulation model was verified by doing several simulation experiments at Rautaruukki steel factory. The calculated surface temperature was compared with pyrometer measured surface temperature. The placements of the pyrometers were chosen in a way that the temperature measurement would be as reliable as possible. A good agreement between calculated and measured temperatures was found as we can see from the Figure 2.

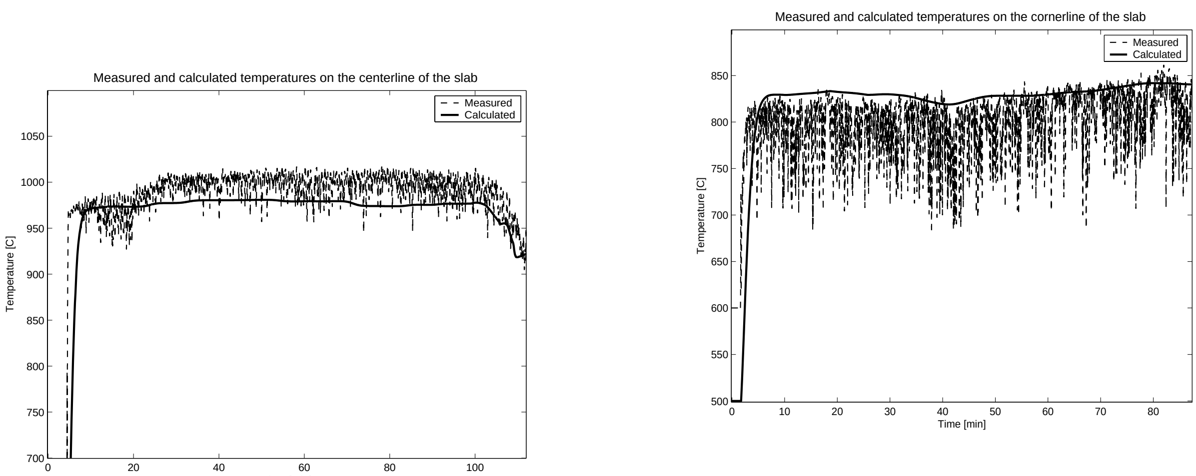

Figure 2. Measured and calculated surface temperatures on the centerline of the wide face of the slab and on the centerline of the short face of the slab, respectively.

The problem for finding the optimal cooling conditions is formulated to an optimal control problem. In optimal control problem our aim is to minimize a quality function, J, which is constructed by means of metallurgical cooling criteria. The mathematical formulation of our optimal control problem is as follows:

Find $h^* \in U_{ad} = \{h \mid h_{\min} \le h \le h_{\max}\}$ such that

$$J(\mathrm{T}(h^*)) = \min_{h \in \mathrm{U_{ad}}} J(\mathrm{T}(h)).$$

To solve the problem control problem we use the steepest descent method

$$h^{i+1} = h^i + \rho_{opt}\, p^{i+1},$$

where p^{i+1} is the steepest descent direction and ρ_{opt} is the optimal step size.

We have also verified the above optimal control model. which is used for optimizing the secondary cooling on the wide face of the slab. In our test example the secondary cooling region is divided into 17 cooling zones in which the values of secondary cooling water flows were controlled separately. There are 8 center and 8 corner cooling zones on the wide face of the slab and 1 cooling zone on the short face of the slab. The cooling zone on the short face of the slab was not controlled i.e. the water cooling rate was constant
Our aim is to optimize the secondary cooling in the wide face of the slab by optimizing the quality function J , with the form

$$J(T) = \frac{1}{2}\left(\int_{L_M}^{L_Z} (\mathrm{T} - \mathrm{T}_1^{tar})^2 dz + \int_{L_M}^{L_Z} (\mathrm{T} - \mathrm{T}_2^{tar})^2 dz \right),$$

where T_1^{tar} is the target temperature in the center observation line and T_2^{tar} is the target temperature in the corner observation line.
The calculated temperatures at time 2500s are shown in the figure 3. We can see that the difference between target and calculated surface temperatures is minimized on the whole length of the slab (see figure 4).

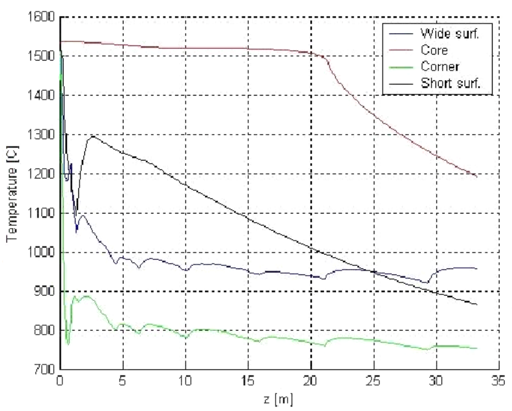

Figure 3: Temperature fields of the slab

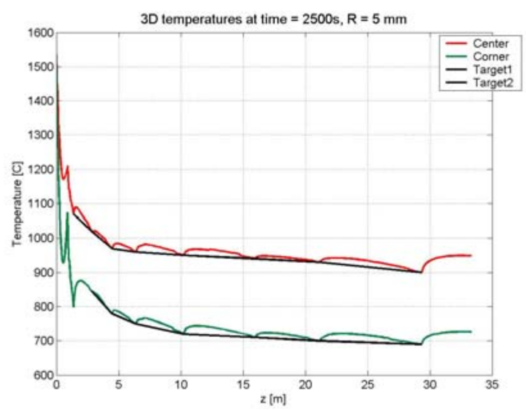

Figure 4: Slab temperature adjust curve

4. Main scientific outcome

The main scientific outcome was the development of fast iterative algorithm for the optimization model of steel continuous casting and its implementation into the Dyncool 3D software. Software operates, in continuous steel casting process, in the control of secondary cooling water volumes. It is a real-time software application, based on 3-dimensional simulation model of continuous steel casting process, which calculates optimal reference values for secondary cooling water volumes dynamically once per second.

The software consists of three distinct modules: main program (main.exe), communication driver (driver.exe), user interface (dcl.exe) and name server (omniNanes.exe), which connects the components of Dyncool 3D together. Communication between modules (driver ↔ main program, main program → user interface) is realized by using CORBA™ architecture. Figure 5 illustrates the modular structure of the Dyncool 3D software.

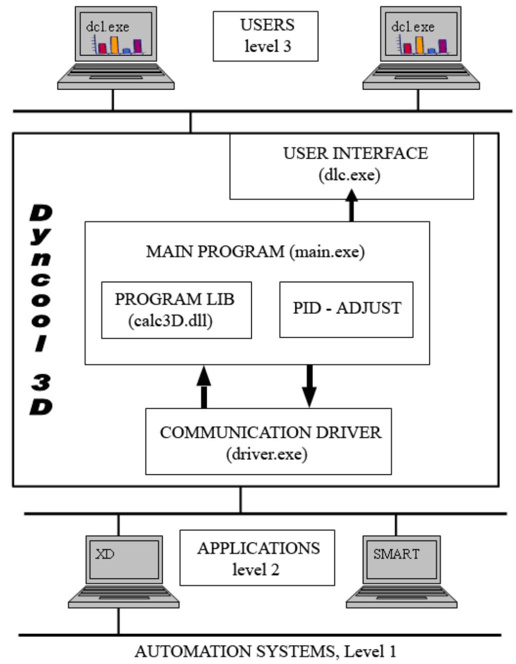

Figure 5

5. Main technical outcome

At Rautaruukki steel works the internal quality of slabs is evaluated at regular intervals from longitudinal macroetched slab samples. These samples are scanned to a computer and the intensity of centre-line segregation is determined automatically.

For the smallest slab thickness, i.e. 175 mm, on CC1 (vertical caster) the centreline segregation index is 1.00 (Figure 6). For the same thickness but on CC6 (vertical bending caster) using the Dyncool software and soft reduction technology the same index is only 0.5. The segregation index of 270 mm thickness is 0.52 on CC2 (vertical caster) and on CC6 the index is 0.20. This means that casting with CC6, which uses the Dyncool software and soft reduction technology, reduces centre-line segregation to less than half of that on the old vertical type casting machines.

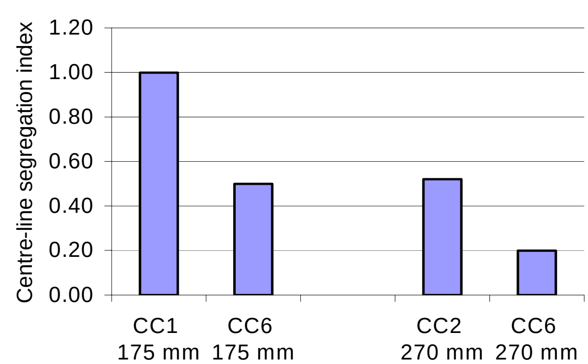

Fig. 6: Macroetching results of slab thickness of 175 mm and 270 mm.

In general our experience is that the use of on-line optimization of water cooling with the soft reduction technology reduces scrap, increases productivity, saves energy and increases product quality.

6. Collaboration within COST 526

Collaboration within the COST526 action has been realized mainly with
Prof. Božidar Šarler, Laboratory for Multiphase Processes, Nova Gorica Polytechnic, Slovenia and Dr. Bogdan Filipič, Institute Josef Stefan, Ljubljana, Slovenia.
Moreover within the scientific research work we have collaborated with Prof. Alexander Lapin from Kazan State University, Kazan Russia.
During the COST526 action one STSM meeting, on 22-29 June with Bogdan Filipič and Božidar Šarler has been realized. Recently a bilateral collaboration for benchmarking optimization methods is on progress between Groups FIN1(Laitinen) and SI1 (Filipic). Collaboration is funded by Slovenian Academy and Finnish Academy.

7. Cooperation with industry

Rautaruukki steel works at Raahe city in Finland.

8. References

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