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PARAMETER IDENTIFICATION AND OPTIMAL CONTROL OF HEAT TRANSFER IN COOLING LINE OF HOT STRIP ROLLING MILL

Abstract. *The numerical simulation of mechanical properties of hot-rolled products is of major significance for material characterization as well as material development. The basis for this is the knowledge of the material-specific phase transformations and of the initial microstructure originating from the deformation steps before entering into the cooling line. Additionally, the technological conditions on the run-out table (ROT) are essentially for transformation kinetics.*

In order to simulate these processes, the plant-specific heat transfer coefficient has to be identified. To this end, steel samples with thermocouples inside are transported with defined velocities through the cooling line of the continuous pilot plant at the Institute of Metal Forming in Freiberg. Furthermore, the material and its movement must be taken into account as characteristics of the ROT. Here, the amount and distribution of the cooling medium, the streaming situation in the segments, the nozzle geometry, and the impact pressure of the cooling medium on the surface of the rolled material are the most important influencing parameters.

This paper describes the possibilities for determining and simulating the heat transfer in the cooling line under realistic industrial conditions. In addition, it discusses optimal control strategies for the cooling line to achieve a desired temperature and phase distribution on the run-out table. The results contribute to new technology and material developments at the pilot plant, which are also suitable for the transfer to industry.

Keywords: *modeling, hot rolled steel, heat transfer, steel, cooling line, control, run-out table.*

1. Introduction

The simulation of the cooling process is of crucial importance for the predictive calculation of hot-deformed products. Cooling and the changing microstructure along the deformation line are the most important factors for the phase transformation kinetics in the material. On basis of the formed volume fractions of the different phases, it is possible to draw some conclusions about the mechanical properties of the semi-finished product [1].

For a reliable prediction of the properties of a semi-finished product after the hot deformation, the complex cooling line should be analyzed because the heat transfer conditions between rolled material and the cooling medium have a big influence on the unsteady temperature field. Furthermore, there are time-dependent and non-linear correlations between the temperature, the stress situation and the microstructure [2].

The spray water cooling in the run-out section of the pilot hot rolling mill is characterized through high water pressure and specific jet geometry. The encased installation space makes it difficult to determine and measure the parameters inside this part of the rolling line. In the following section an experimental set-up is described, which allows to identify the heat flux during cooling. These results are the basis for the numerical determination of the heat transfer coefficient and form the basis for new technologies like the simulation based development of new multiphase steels.

In order to achieve the desired temperature distribution in the steel strip after hot-rolling, an optimal cooling strategy has to be calculated. The problem of optimal cooling in hot strip mills has already been considered in a series of papers, see, e.g., [14] and the references therein.

An important step in the calculation of optimal cooling strategies is the characterization of the boundary condition, which requires knowledge of the heat transfer by water spay cooling on the surface. Much research has been done on the subject of spray quenching. A comprehensive review of available research results has been conducted by Totten et.al. [11]. The evaluation of heat transfer coefficients during heat treatment is presented in [10, 12, 13]. Most of the available results are given as empirical formulas that have been developed under specific process conditions.

The goal of this paper is twofold. Firstly, we develop a model for the heat transfer coefficient for water spray cooling accounting for the effect of process parameters on the heat transfer on the run-out table of the pilot hot rolling mill of TU Freiberg. Then we use the resulting heat transfer model for the computation of optimal cooling conditions to achieve a desired temperature evolution on the run-out table, which paves the way for a simulation-based development of new multiphase steels.

The paper is organized as follows. In Section 2 we describe the experimental set-up. Section 3 is devoted to the inverse problem of identifying the heat transfer coefficient characterizing the cooling section of the pilot hot-rolling mill. The optimal control problem to obtain a desired heat distribution on the run-out table is discussed in Section4.

2. Experimental set-up

The first step was the investigation of the water jet geometry. Here, the main issues were the impact of pressure and the description of possible water layers on the strip surface, which could obstruct the heat flux through the Leidenfrost effect.

Figure 2.1 – Jet characteristic of one Lechler nozzle (left) and the water jet in the cooling line (right)

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In order to obtain a sound data basis for the subsequent parameter identification, all relevant parameters of the cooling line had to be measured. In particular, this refers to the temperature evolution on the surface and in the core of the sample, which can be identified by pyrometers and thermocouples, respectively. To obtain a larger data basis, the starting temperature, amount of water, and feed velocity of the cooling unit were varied.

By using the temperature range of around 900 to 950°C, the oxidation behaviour of the steel surface must be considered because it influences the measured values of the surface temperature. Hence, the maximum values were regarded for the identification problem.

The experiments for the identification of the heat transfer conditions were realised at the continuous pilot plant at the TU Freiberg, cf. Figure 2.2. For the experiments a non-alloyed steel grade (C45) was used, always with the same geometry of 500 x 65 x 7 mm^3. The temperature of the furnace was 950°C and for a homogenous temperature evolution the samples were held for a few minutes at this temperature. The temperature choice was motivated by the finishing temperature of a continuous rolling process. Moreover, the scale layer is very small and compact in this temperature range and the scale thickness is approximately the same as in the hot-rolling process. This effect must be considered during the measurements because the oxide layer is an insulator, and the real temperature is a little bit higher than the measured one [3]. Additionally, for describing the temperature evolution near the core, a thermocouple was installed 10mm deep inside the sample at half-thickness and half-length for continuous temperature measurements.

Figure 2.2 – Run-out table of laboratory plant (left: view in rolling direction; right: furnace and cooling segment, rolling direction from right to left)

Figure 2.3 – Sample with thermocouple

To account for the influence of the feed velocity, all samples were laid down on the roller bed in front of the last rolling mill, with the mill accelerating the strips to the desired speed. To avoid dissipation of energy due to the deformation, the roll gap had a thickness of 6.9 mm. This resulted in a deformation degree of 0.01 and hence the roller speed and the material velocity in the roll gap exit were the same. With the help of infrared radiation pyrometers, the surface temperature was analysed (cf. Figure 2.4). In addition, the peaks of the temperature curves allowed the calculation of the real transport time and speed because the distance between two pyrometers is known. Hence, it was possible to investigate the influence of water amount and its pressure on the transport velocity.

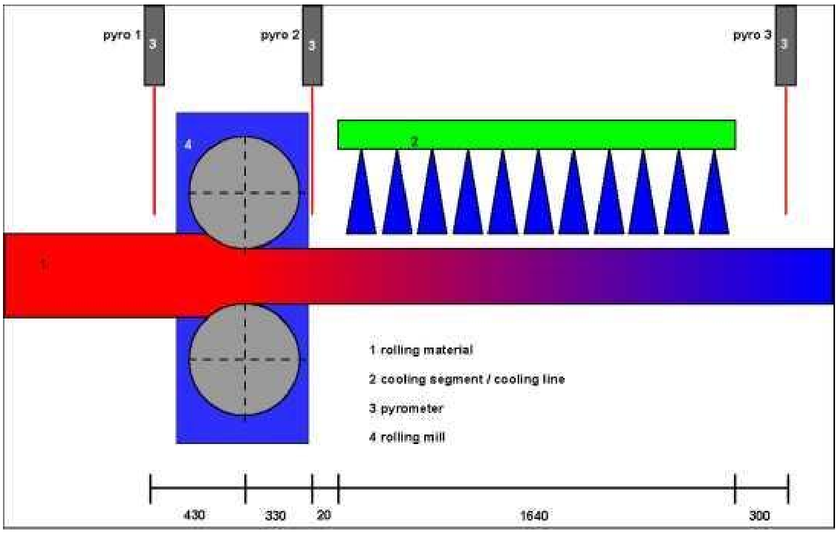

Figure 2.4 – Sketch of experimental setup

3. Identification of cooling conditions

3.1. Modeling of heat transfer in the cooling line. In order to arrive at a reasonably simple mathematical model for the heat transfer in the cooling line, we neglect heat conduction in the feeding direction of the specimen. This reduces the spatial dimension of the model and thus the computational complexity. We consider a cross section of a steel slab moving with the predefined strip speed through the cooling segment. Fig. 3.1 shows a schematic representation of the cooling process.

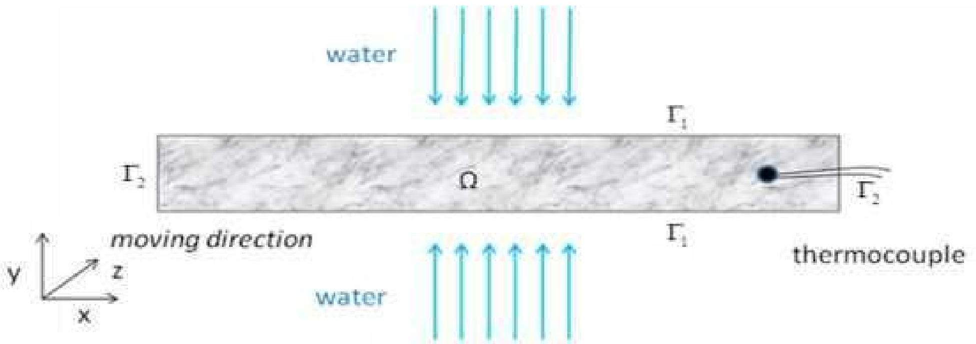

Figure 3.1 – Schematic representation of the cooling process

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Here, x and y define space coordinates in the direction of the width and thickness of the strip, respectively. The space coordinate in the feeding direction of the cooling line is denoted by^z.

The governing equation for the temperature distribution in the 2D cross section of the slab during cooling is given by

$$\rho c \frac{\partial T}{\partial t} - k\Delta T \quad \text{in} \quad \Omega \times (0, t_E) \tag{3.1a}$$

subject to the initial and boundary conditions

$$-k\frac{\partial T}{\partial n} = h(t)(T - T_{water}) \quad \text{on} \quad \Gamma_1 \times (0, t_E) \tag{3.1b}$$

$$-k\frac{\partial T}{\partial n} = 0 \quad \text{on} \quad \Gamma_2 \times (0, t_E) \tag{3.1c}$$

$$T(x, y, o) = T_0 \quad \text{in} \quad \Omega \tag{3.1d}$$

where κ is the thermal conductivity, c the specific heat, p the density, and T_{water} is the temperature of coolant.

The function $h(t)$ describes a time-dependent heat transfer coefficient. Due to the configuration of water spray nozzles, the water distribution over the surface of the steel slab in direction x is assumed to be constant.

In our investigations, we are interested in the modelling of the heat transfer in the cooling line in the higher temperature region. Note that in the case of the steel investigated in this work, no phase transitions occurred during the cooling in the temperature range of 700 to 900°C. Otherwise, the latent heat from the phase transitions should be incorporated into the heat equation (3.1a) and the model has to be completed with appropriate equations for the phase transition kinetics.

A common approach for the modelling of the heat transfer coefficient is to use various functions whose parameters are to be determined through the fitting to the experimental data. The influence factors on the heat transfer coefficient by the water spay cooling, such as the surface temperature, water impact density and strip velocity, have been investigated thoroughly in many studies (see e.g. [4, 5, 6]). At the higher temperatures, above approximately 600°C, it is well established that the heat transfer coefficient becomes less temperature dependent.

To describe the heat transfer coefficient, the model proposed in [6] is applied:

$$h(t) = \beta(z_0 + \upsilon \cdot t)\left(\frac{\upsilon}{\upsilon_0}\right)^{\lambda}\left(\frac{u}{u_0}\right)^{\gamma} \tag{3.2}$$

where υ is a strip speed, m is an amount of water and v_0, u_0 are the reference strip speed and amount of water, respectively. A, 7 are the values which define the effect of the strip speed and the amount of water on the heat transfer coefficient. These factors can be determined by solving an inverse problem which will be discussed in the next subsection.

3.2. Identification of heat transfer coefficients from the temperature measurements.

The identification of the heat transfer coefficient for water spray cooling can be realised in two steps.

Step 1

The heat transfer coefficient h(t) as a function of time is identified from the temperature measurements $T(x_0, y_0, t)$ at the inner point of the steel slab by solving an inverse problem. To this end, the unknown function h(t) is described as a second-order B-Spline with control points oi, . . . , a_n. Then the inverse problem is to find the values $a\backslash, \ldots, a_n$ such that the core temperature $T(x_0,y_0,t)$ is close to the measurement $T(x_0, y_0, t)$ over the whole period of time $[0,t_E]$ in the cooling line. More accurately, the following inverse problem has to be solved:

$$\begin{cases} \dfrac{\min}{a_1,\ldots,a_n} \left\{ \int_0^{t_E} (T(x_0,y_0,t) - \dot{T}(x_0,y_0,t))^2 dt \right. \\ subject\ \ to\ \ the\ \ constra\mathrm{int}s\ \ for\ \ the\ \ temperature, i.e., (3.1a - 3.1d) \end{cases} \quad \text{(IP)}$$

(IP) is an optimisation problem which can be solved numerically, e.g., using MATLAB.

Step 2

In the next step, the unknown coefficients as well as the profile function in the model for heat transfer coefficients (3.2) can be fitted to the solution curves obtained in Step 1. For this procedure, the experimental data of the temperature measurements for different pairs of the strip speed and the amount of water (u_i, U_j)(i = $1, \ldots, N$, $j = 1, \ldots, M$) are necessary.

3.3. Experimental results. The measurements of the core temperatures show that the temperature difference increases with increasing amount of water. However, an increasing velocity reduces the difference in temperature as the contact time of the cooling medium on the sample surface becomes shorter (Fig. 3.2, top).

The measured differences in temperature can be identified with the curved shapes of the different measurment systems and the temporal position in the rolling line can also be assigned (Fig. 3.2, bottom).

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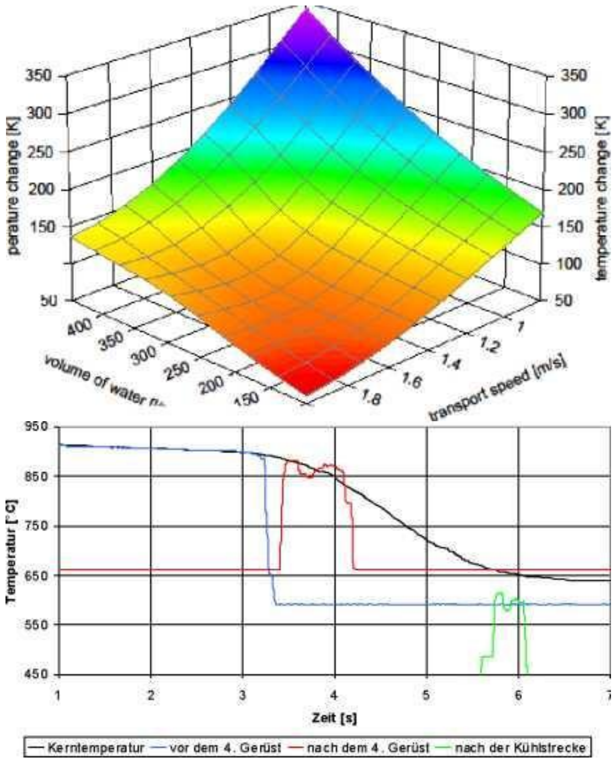

Figure 3.2 – Influence of water volume in combination with transport speed on temperature change in the sample core (top) and the measurements of the sample with 1 m/s and 100 l/min (bottom)

3.4. Results of the identification of the heat transfer coefficient. In this subsection, we present numerical results for the identification of the heat transfer coefficient according to the algorithm detailed in Subsection 3.2. The heat transfer coefficients as a function of time were determined from the temperature measurements in 9 experiments for the strip speeds of 0.85 m/s, 1 m/s, 2 m/s and different amounts of water in cooling line, namely 100, 200, 300 and 400 l/min. The results of the identification process are shown in Figure 3.3.

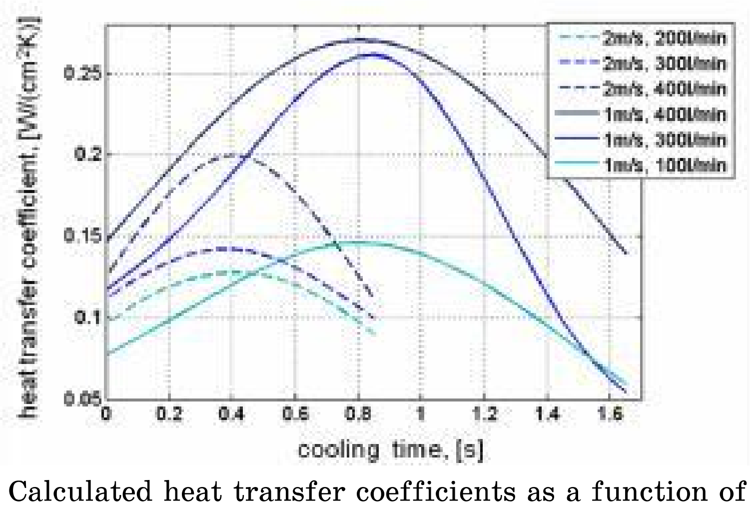

Figure 3.3 – Calculated heat transfer coefficients as a function of time for the experiments with strip speed of 1m/s and 2m/s. The amount of water varies between 100 l/min and 400 l/min

Using the information about the strip speed in each experiment and the fact that z = υt, the heat transfer coefficients can be represented as a function of z, i.e. the space coordinate along the cooling line (see Figure 3.4).

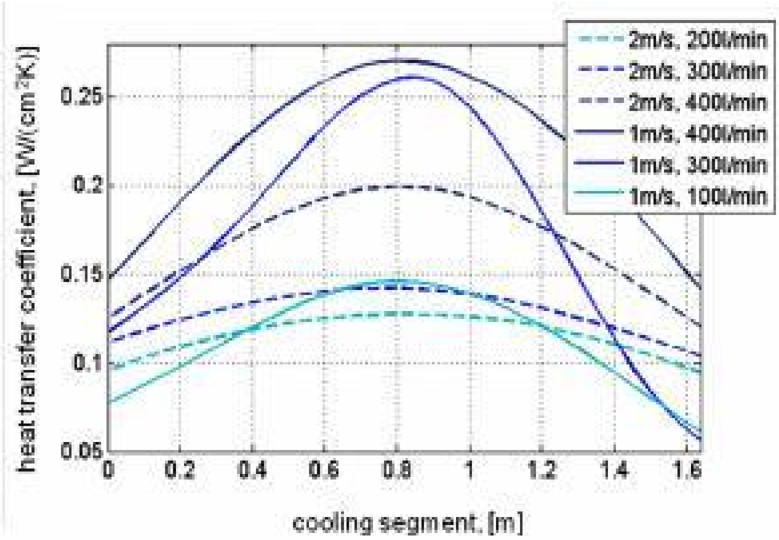

Figure 3.4 – Heat transfer coefficients as a function of the space coordinate along the cooling line

We can conclude from Figures 3.3 and3.4 that the value of the heat transfer coefficient increases with decreasing strip speed, Moreover, the maximum values of the heat transfer coefficients are directly proportional to the amount of water used in the cooling line. It can be seen from Fig. 3.4 that the heat transfer coefficients can be represented by a Gaussian function. The optimal values for A,y in (3.2), fitted to the curves of heat transfer coefficients are the following:

$$\lambda = -0.63, \gamma = 0.45 .$$

Hence, finally we obtain a model for the heat transfer coefficient dependent on the process parameters strip speed and amount of water:

$$h = e^{-(1.48-0.28\cdot\upsilon^2)(t\cdot\upsilon-0.8)^2}\left(\frac{\upsilon}{0.05}\right)^{-0.63}\left(\frac{u}{100}\right)^{0.45} \qquad (3.3)$$

By means of (3.3), we are now able to simulate the temperature distribution in the cross section of the slab. Fig. 3.5 shows the comparison between the measured and simulated core temperatures during the cooling process for two selected experiments.

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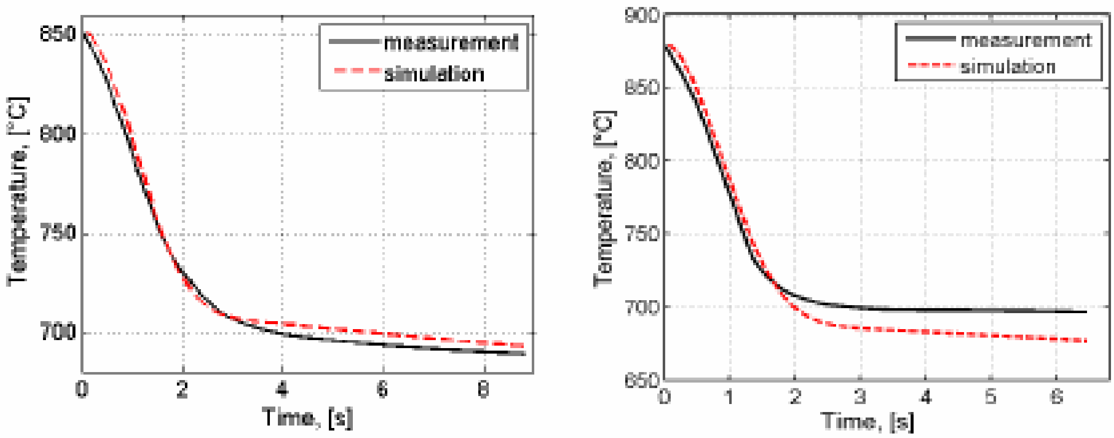

Figure 3.5 – Comparison between the measured and simulated temperatures in the sample core for the experiments with process parameters of v = 0.85 m/s, u = 100 l/min (left) and v = 1 m/s, u = 300 l/min (right)

The curves in Figure. 3.5 show a good agreement between the measured and simulated temperatures. The maximum relative errors calculated for experiment 1 (Figure 3.5 left) and experiment 2 (Figure 3.5 right) are 0.78% and 1.99%, respectively.

4. Optimal control of the cooling line

After the model for the heat transfer coefficient has been established, we want to compute an optimal amount of water to achieve a desired temperature distribution at the end-time .

To this end, we consider a control problem (CP)

$$\begin{cases} \min J(T,u) = \frac{1}{2}\int_{\Omega}(T(x,t_E) - T_d(x))^2 dx + \frac{1}{2}au^2 \\ \text{such that } (T,u) \text{ satisfy the state system } (3.1a)-(3.1d) \\ \text{and the control constraint } u_a \le u \le u_b \end{cases}$$

where $T_d(x)$ is the desired final temperature distribution. The last regularising term in the cost functional penalises high costs for the cooling.

We assume that the process parameters, like the strip speed and the amount of water in the cooling line, have been adjusted and are considered to be constant. The optimal amount of water should therefore be a constant.

We solve the above-mentioned control problem for the steel sample with dimensions of 500x65x7 mm^3 and fixed strip speed in the cooling line of 0.85 m/s. For the numerical solution of this problem an optimisation code has been developed based on the PDE toolbox pdelib, developed at WIAS, Berlin). The optimal water amount in the cooling line needed to achieve a desired end temperature distribution of 700°C in the sample's cross section has been calculated as u*=113 l/min. The corresponding simulated temperature history is shown in Fig. 4.1

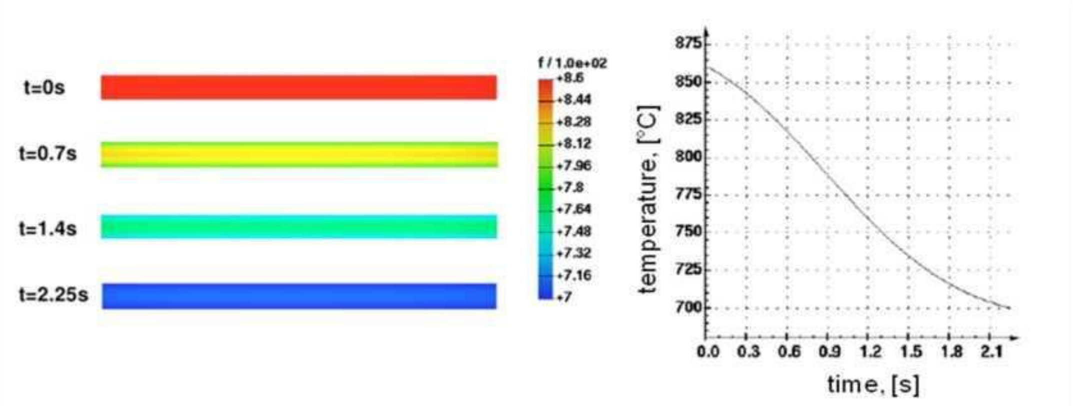

Figure 4.1 – Temperature distribution at the cross section of the sample at certain points in time (left); temperature in the middle of the cross section (right)

5. Conclusion

The goal of this paper was to investigate the heat transfer during the water spray cooling and to develop an algorithm that computes an optimal cooling strategy which realises the desired temperature distribution in the steel slab. The heat transfer coefficient has been identified from the temperature measurements by solving an inverse problem. The model obtained for the heat transfer coefficient was verified by the experiments performed on the pilot hot-rolling mill at the TU Freiberg. Using the developed model for the heat transfer coefficient, an optimal control problem for the temperature in the cooling line was formulated and solved by methods of mathematical control theory.

There are two challenging directions of future research. On the one hand, the control problem of the cooling line to achieve the desired temperature and phase distribution on the run-out table is an interesting task. In this case, the model for the heat exchange in the cooling line has to be complemented by a phase transition model. The resulting optimal control problem is nonlinear and requires a high computational effort. A first result in this direction can be found in the recent paper [15]. On the other hand, the development of real-time process control strategies based on the (CP)is of high interest for the industrial employment of these ideas. Here, recent developments in model reduction techniques seem to be a promising tool and will be the subject of future research of the authors.

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