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Optimal control of a cooling line for production of hot rolled dual phase steel

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Abstract

In this article, the optimal control of a cooling line for production of dual phase steel in a hot rolling process is discussed. In order to achieve a desired dual phase steel microstructure an optimal cooling strategy has to be found. The cooling strategy should be such that a desired final distribution of ferrite in the steel slab is reached most accurately. This problem has been solved by means of mathematical control theory. The results of the optimal control of the cooling line have been verified in hot rolling experiments at the pilot hot rolling mill at the Institute for Metal Forming (IMF), TU Bergakademie Freiberg.

Introduction

Dual Phase steels (DP steels) have shown high potential for automotive applications due to their remarkable property combination with high strength and good formability [1]. The hot rolling process as illustrated in Figure 1 has been proven to offer economical benefit for the production of DP steel as it provides good microstructure homogeneity with acceptable surface quality for many applications.

The hot rolling process of dual phase steel consists of 4 steps as shown in Figure 1:

1. Rolling in roughing and finishing stands, which results in the refinement of austenite grain size due to the repeating static recrystallization plus an activation of austenite by increasing dislocation density in (partially) non-recristallized fractions,

2. Laminar cooling into two phase region,

3. Isothermal holding at ferrite transformation region temperatures, where the temperatures remain relatively constant,

4. Fast continuous cooling to the required coiling temperature, during which martensite transformation takes place and bainite transformation can be avoided.

The process window in hot rolling of dual phase steel is shown to be tight as only very short time in order of less than 10 s is allowed on the run out table (ROT) according to its limited length. In this time on the ROT the steps 2, 3 and 4 have to be performed before coiling.

The goal of this paper is to derive and validate a mathematical optimal control approach to compute the optimal cooling strategy for steps 2 and 3 in Figure 1 to achieve a desired temperature and microstructure distribution prior to quenching in step 4.

To this end we rely on a model for ferrite growth in dual phase steels, which has been developed in a previous paper [1] and includes also the effect of austenite conditioning in step 1 of the process.

The main novelty of this paper is the derivation and utilization of a mathematical optimal control algorithm to compute the desired ferrite fraction and temperature at the end of step 3 of the process. Existing optimal control approaches for run-out tables up to now solely focus

on the evolution of temperature, see, e.g., [2, 3]. To validate our approach the computed optimal amount of water was used for a hot-rolling experiment at the pilot hot rolling mill at IMF at TU Bergakademie Freiberg.
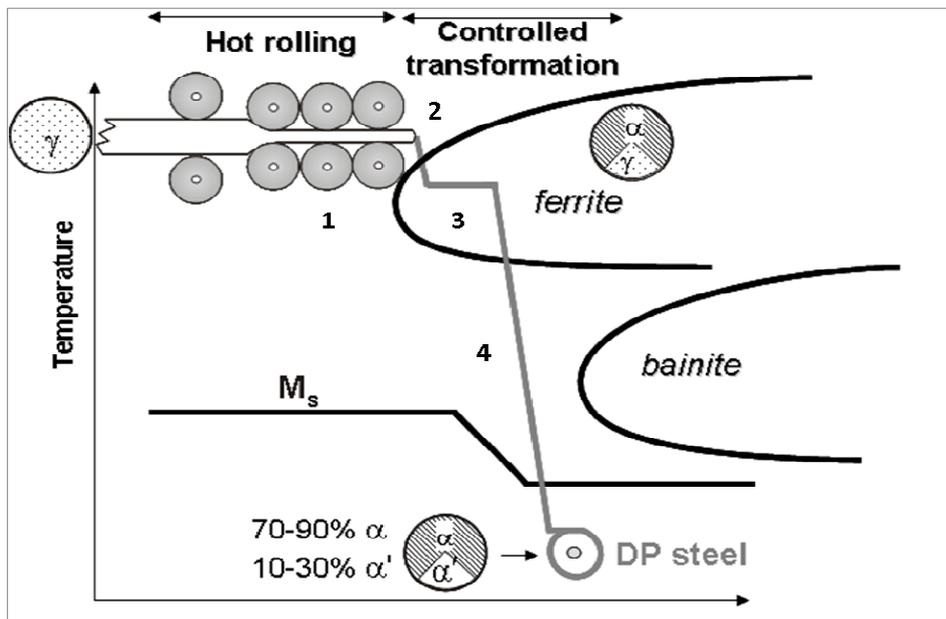
Figure 1: A sketch of the processing scheme for hot rolled dual phase steel.

Experimental procedure

In this study an alloying concepts based on Mn-Mo was selected for the hot rolled dual phase steels as shown in Table 1 [4]. The material was laboratory casted in a 80 kg block, pre-forged on the Semi-Product-Simulation-Center (SPSC) at IEHK into a format of 60 x 60 mm² and cooled to room temperature by air cooling.

Table 1: Chemical compositions of the investigated steel grades (in wt.%)

	C	Si	Mn	P	S	Cr	Mo	N
Mn-Mo	0,08	0,03	1,44	0,004	0,002	0,02	0,15	0,003

A series of hot deformation experiments has been performed at the dilatometer (Baehr DIL-805A/D) in order to simulate the hot rolling process and the effect of austenite conditioning on the later ferrite transformation kinetics. The details of the hot deformation dilatometer tests including the dilatometer cycles and the test parameters can be found in a former article [4]. Based on the dilatometer results on the phase transformation kinetics and the final phase fractions after deformation and controlled cooling the model parameter of the phase transformation model have been adjusted. Again the details of this work including the final parameter identification procedure can be found in the above mentioned article [4].

Pilot scale hot rolling was performed at Institute for Metal Forming (IMF), TU Freiberg. The hot rolling experiment started with reheating the slabs at 1150 °C for 15 minutes, followed by mechanical descaling, and finally rolling in a four-stand mill to the final thickness of 3.5 mm. During rolling, the slab temperatures at each rolling stand were determined by five pyrometers at the entrance and/or exit of the stands above the slab surface (approximately 350

mm above), shown in Figure 2. In order to improve the pyrometer accuracy the steam was eliminated by a pressured air curtain. On the ROT the sheet velocity was 0.85 m/s. Sheets were cooled down from the final rolling temperature to the aimed temperature 700 °C within 2 s by a high pressure cooling unit. Further, the sheets were kept quasi isothermally on the ROT for 7-10 s, followed by quenching into 20 °C water bath. The process details like final rolling parameters of the hot rolling experiments have been reported in [5]. The necessary model parameters of the cooling section of the pilot plant in Freiberg have been identified in [6].
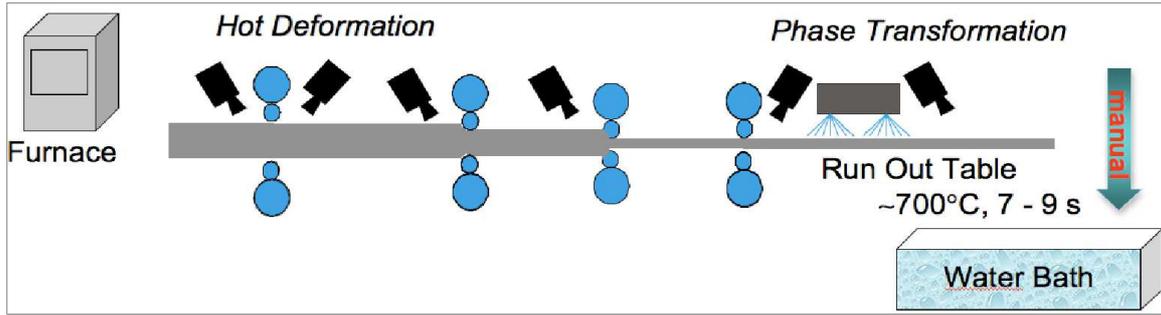
Figure 2: Pilot hot rolling mill at IMF, TU Bergakademie Freiberg, Germany [6].

A mathematical model for phase transition and temperature on ROT

After the last deformation step, steel is cooled by water jets on the run out table, where ferrite starts to grow. The austenite-ferrite phase transformation can be described by the following ordinary differential equation (ODE):

$$\dot{f}(t) = \left[f_{eq}(T) - f \right]_{+} \cdot g_{f1}(T) \cdot g_{f2}(D_{\gamma}, \varepsilon) \tag{1a}$$

$$f(0) = 0, \tag{1b}$$

where $f(t)$ denotes the ferrite fraction and T is the temperature.

The expression $[u]_{+}$ in the model equations describes the positive part of a value u, i.e. $[u]_{+} = \max\{u, 0\}$. The term $f_{eq}(T)$ describes the asymptotic equilibrium fraction of ferrite as a function of temperature T after isothermal holding. The function relates to the isothermal transformation behaviour of ferrite, starting from homogeneous austenite state. The function $g_{f2}(D_{\gamma}, \varepsilon)$ couples the influence of austenite grain size D_{γ} and the effect of retained strain ε on the isothermal ferrite transformation kinetics. Details about the austenite-ferrite transformation model on the run out table can be found in [1].

To describe the evolution of temperature on ROT we have to complement (1a)-(1b) with the heat equation. To this end we assume heat conduction to be negligible in the feeding direction of the specimen and write down the system for a 2D cross section, which yields the system

$$\dot{f}(t) = \left[f_{eq}(T) - f \right]_{+} \cdot g_{f1}(T) \cdot g_{f2}(D_{\gamma}, \varepsilon) \tag{2a}$$

$$f(0) = 0, \tag{2b}$$

$$\rho c \frac{\partial T}{\partial t} - k\Delta T = \rho L \dot{f} \qquad \text{in } \Omega \times (0, t_E) \qquad (2c)$$

$$-k \frac{\partial T}{\partial n} = u(t)(T - T_{water}) \qquad \text{on } \Gamma_1 \times (0, t_E) \qquad (2d)$$

$$-k \frac{\partial T}{\partial n} = 0 \qquad \text{on } \Gamma_2 \times (0, t_E) \qquad (2e)$$

$$T(x, y, 0) = T_0 \qquad \text{in } \Omega, \qquad (2f)$$

where

κ - the thermal conductivity,

c - the specific heat,

ρ - the density,

T_{water} - is the temperature of the coolant.

Here, the end-time t_E is calculated as a sum of the time in cooling segment and holding time on ROT after the cooling. The term $\rho L \dot{f}$ on the right-hand side of (2c) describes the latent heat of the phase transition. As has been found in [6], the spatial variation of the heat transfer coefficient is negligible due to the special nozzle geometry. Hence the function $u(t)$ denotes an only time-dependent heat transfer coefficient.

For solving the optimal control problem in the next section, this coefficient will act as the unknown control. But finally, we have to relate this expression to the amount of water $w(t)$, which is the real control quantity in the Freiberg plant. In [6] we have derived the following expression for $u(t)$ in terms of $w(t)$ and the strip speed v of the hot rolling mill at IMF:

$$u(t) = e^{-(1.48 - 0.28 \cdot v^2)(t \cdot v - 0.8)^2} \left(\frac{v}{0.05}\right)^{-0.63} \left(\frac{w}{100}\right)^{0.45} \qquad (3)$$

Optimal control of the cooling line

Our aim is to compute on optimal amount of water for the cooling line to achieve a desired distribution of ferrite f_d at the end-time t_E. At the same time we want to realize a desired end temperature T_d. This will be done in a two-stage approach. Firstly, we use an optimal control strategy to compute an optimal time-dependent heat transfer coefficient $u(t)$. Then, we use eqn. (3) to compute the corresponding optimal amount of water $w(t)$, which serves as the control quantity at the pilot mill.

To this end, we define the cost functional

$$J(T, f, u) = \frac{\alpha_1}{2} \int_\Omega (T(x, t_E) - T_d(x))^2 dx + \frac{\alpha_2}{2} \int_\Omega (f(x, t_E) - f_d(x))^2 dx + \frac{\alpha_3}{2} \int_0^{t_E} u^2 dt$$

4

where the last regularizing term penalizes high costs. Then we consider the control problem (CP)

$$\min \ J(T, f, u)$$
such that (T, f, u) satisfy the state system (2)
and the control constraint $u_a \leq u \leq u_b$, $t \in (0, t_E)$.

(CP) is a nonlinear boundary control problem, where a cost functional is minimized while at the same time the state equations for temperature evolution and ferrite growth have to be satisfied. The numerical solution is quite intricate, since it requires the iterative solution of the state system and an additional adjoint system which is used to compute the gradient. To achieve the solution within reasonable computing time, we have developed a sequential quadratic programming (SQP) algorithm for this problem, which shows quadratic convergence in contrast to the linear convergence of standard gradient algorithms. For algorithmic details we refer to the forthcoming paper [7]. For the implementation we have used the Finite Element toolbox *pdelib*, which has been developed at WIAS. Numerical results will be discussed in the following section.

Numerical results for Mo-Mn dual phase steel

We solve the (CP) in order to obtain the optimal cooling strategy for a Mo-Mn DP-steel with 90% ferrite and a desired end temperature on the ROT $T_d = 680$ °C. The process parameters are the following: the holding time on the ROT is 10s, the strip speed in the cooling line is 0,85 m/s.

Table 1 shows the convergence behavior of the SQP algorithm, which roughly approximates the problem by a sequence of quadratic subproblems $(QP)_i$, $i \in \mathbb{N}$, thereby achieving quadratic convergence as in Newton's method. The columns show the iteration number, value of the cost functional, norm of the difference of two subsequent solutions and the number of iteration steps in each quadratic sub-problem.

Iteration	J_i	$\|(u^i, T^i, f^i, p^i, q^i) - (u^{i-1}, T^{i-1}, f^{i-1}, p^{i-1}, q^{i-1})\|$	$(QP)_i$-loops
1	0.0010592	0.225716	2
2	0.0010213	0.009207	2
3	0.0010212	0.0002771	2

Table 1: Value of objective function J_i and relative error in *i*-iteration of SQP method.

The calculated optimal heat transfer coefficient is depicted in Figure 3.
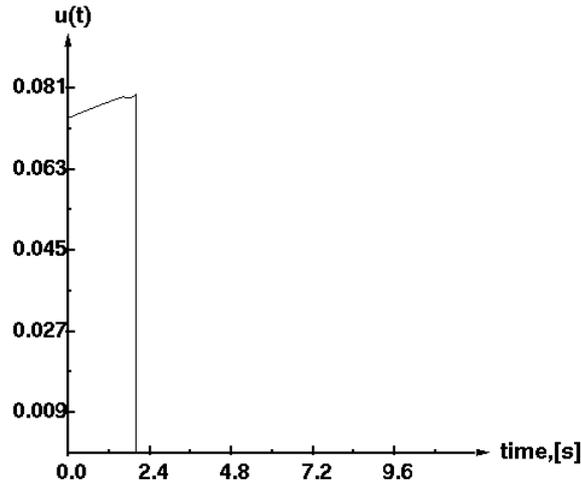
Figure 3: Optimal heat transfer coefficient $u(t)$.

The control is nearly constant during the duration of 2 s in the cooling line.

average amount of water

$$\overline{w} = \frac{1}{t_{cool}} \int\limits_{0}^{t_{cool}} w(t)dt = 70\,[\text{l/min}]$$
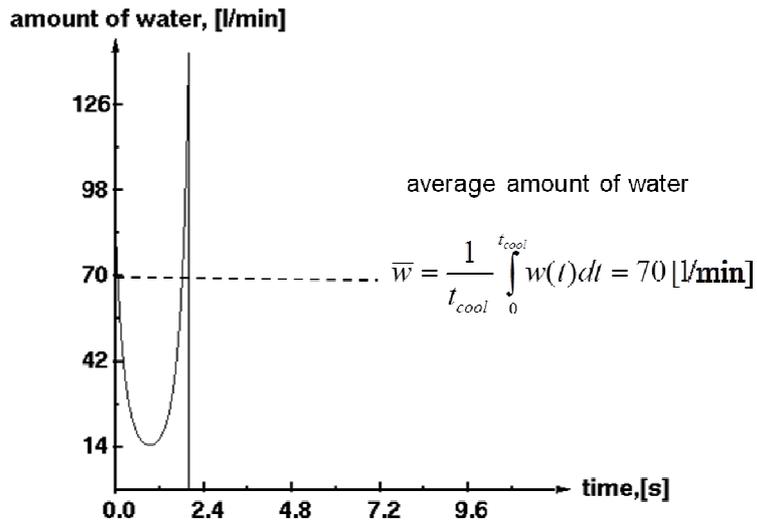
Figure 4: Optimal amount of water $w(t)$.

Experimental validation

To validate our approach, experiments have been carried out at the IMF Freiberg. Here, the defining control parameter is the flow-rate of cooling water *w(t)*, which is related to the heat transfer coefficient *u(t)* via eqn. (3). Figure 4 depicts the resulting optimal flow rate. Due to the construction of the cooling line at IMF only a constant value of the flow-rate can be adjusted. Thus we derived the average amount of water

$$\overline{w} = \frac{1}{t_E} \int_0^{t_E} w(t)dt = 70 \ [\text{l/min}] \ .$$

This quantity can be prescribed in the cooling line. This is of course only an average of the optimal solution. Since the state system is nonlinear, the simulation result for this quantity fed back into the state equation will differ from the optimal one as computed in the last section. Indeed, Figure 5 shows a resulting end temperature of 617 °C and a ferrite fraction of 82.7%. These values differ from the computed ones in the last section, however, a ferrite fraction of this order is satisfactory for dual phase steel.

f / 1.0e+02		f / 1.0e-01
+6.17		+8.27
+6.17		+8.27
+6.17		+8.27
+6.17		+8.27
+6.17		+8.27
+6.17		+8.27
+6.17		+8.26
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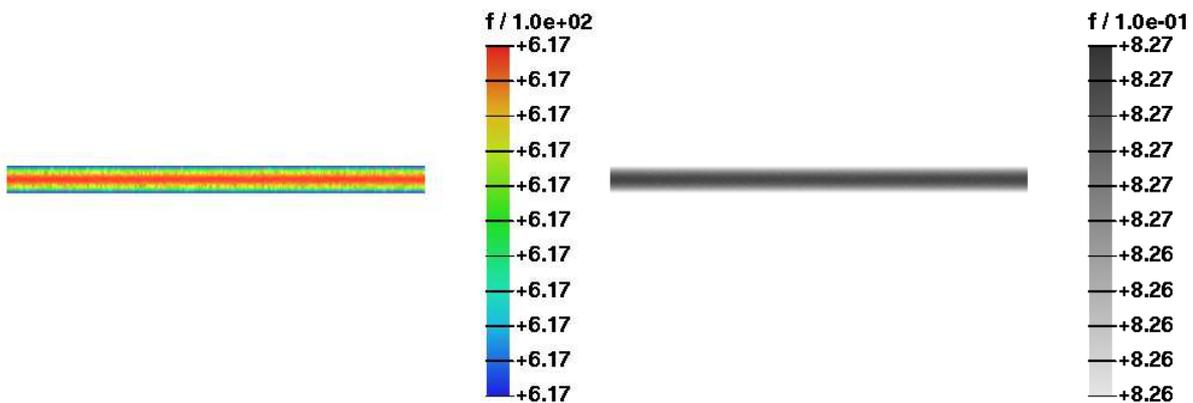
Figure 5: The simulated final temperature (left) and phase distribution (right) in the cross-section of the slab.

Now we are in a position to compare the numerical results with the experimental ones. To this end, the samples have been investigated at IEHK Aachen in terms of phase fractions by means of light optical metallography. Here, the microsections of the processed sample have been analyzed using automatic picture analysis system based on black-white contrast.
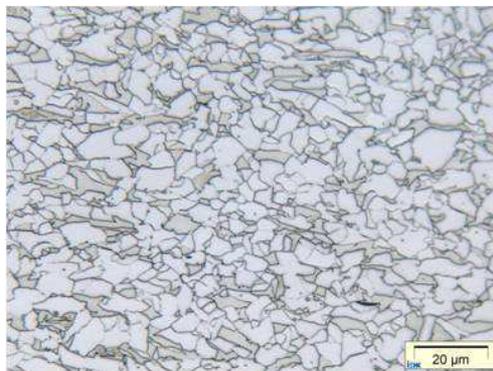
Figure 6: Microsection of the sample for the Mo-Mn steel.

Figure 6 shows a microsection of the sample for the Mo-Mn DP steel. The quantitative analysis yielded a ferrite fraction of 87% and 13% martensite. Hence, the difference between the experimentally achieved ferrite fraction and the numerically predicted one of 82,7% is of order 5%, which in view of many uncertainties in the semi-manual process guidance at the pilot plant is a very satisfactory result.

Conclusion and outlook

The goal of this paper was to show how mathematics can be used for the computation of process conditions to develop multiphase steels with desired composition by controlled cooling on the run-out table of a hot rolling mill. The results have been verified in practice and can be used for the offline optimization of run-out tables.

There are two challenging directions of future research:

- On the one hand the phase transition models have to be complemented with an additional equation for bainite in order to extend the model to other multiphase steels, e.g., TRIP steel. Concerning bainite in TRIP steels new a second isothermal holding step or a controlled cooling strategy has to be implemented in the ROT processing strategy.
- On the other hand regarding the industrial employment the development of real-time process control strategies based on (CP) is a very important task. Here, recent developments in model reduction techniques seem to be a promising tool and will be subject of future research of the authors.

References

[1]   P. Suwanpinij, N. Togobytska, U. Prahl, W. Weiss, D. Hömberg and W. Bleck: Numerical cooling strategy design for hot rolled dual phase steel, Steel Research Int. 81 (2010) No. 11, pp. 1001–1009.
[2]   Chai Tianyou, Tan Minghao, Chen Xiaoyan and Li Hanxiong: Intelligent optimization control for laminar cooling, 15th IFAC World Congress, Barcelona, Spain.
[3]   G. Landl and H. W. Engl: Optimal strategies for the cooling of steel strips in hot strip mills, Inverse Problems in Engineering, 1995, Vol. 2, pp. 103–118.
[4]   P. Suwanpinij, D. Yan, U. Prahl and W. Bleck: Phase Transformation Modelling for Different Hot Rolled Dual Phase Steels, Metal Forming 2012, Proceedings of the 14th Int. Conf., 16.-19.09.2012, Krakau, Polen. Ed.: J. Kusiak, J. Majta, S. Danuta. Steel Research Int.: special edition. Weinheim: Wiley-VCH 2012, pp. 903–906.
[5]   P. Suwanpinij, U. Prahl, W. Bleck and R. Kawalla: Fast algorithms for phase transformations in dual phase steels on the hot strip mill Run Out Table (ROT), Archives of Civil and Mechanical Engineering 12 (2012), pp. 305–311.
[6]   M. Graf, D. Hömberg, R. Kawalla, N. Togobytska and W. Weiss: Identification, simulation and optimal control of heat transfer in cooling lines of hot strip rolling mills, WIAS Preprint no. 1769, 2013.
[7]   D. Hömberg, K. Krumbiegel and N. Togobytska: Optimal control of multiphase steel production. In preparation.