Optimized & adaptable cooling path control through a novel runout table controller at hsm2 of tata steel in ijmuiden

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After coils have been rolled in a hot strip mill, the strip enters the run-out table where the strip cools down from approximately 900°C to 600°C depending on the requirements. The run-out table of the HSM2 at Tata Steel in IJmuiden is about 130 meters long and has 124 sections (62 above and 62 below the strip) that can be independently actuated: off, half flow rate and full flow rate.

At IJmuiden a new controller is developed to fulfil the increasing demands for new steel grades. The main goal is to have full flexibility on the cooling strategy and control. To achieve this, a setup optimizer has been developed that computes the optimal cooling path based on a set of objectives and constraints. From a control perspective, the run-out table is divided into multiple control zones and the strategy determines how each of these zones is controlled. The aim is to have the same temperature-time profile for each point in the strip, considering speed changes and varying finishing temperatures.

The controller is implemented in 2021 at IJmuiden Hot Strip Mill 2 and meanwhile is used for all products. To smoothen the implementation and to avoid homologation of all products at once, the former setup is completely integrated and translated to the new controller philosophy. The controller runs now for more than 12 months, and the major benefit is the ability to develop and produce new steel types. An additional advantage is a significant improvement in temperature performance that results in substantial reduction of repairs and rejects.

KEYWORDS: HOT STRIP MILL, RUNOUT TABLE, COOLING, CONTROL

INTRODUCTION

At the IJmuiden Hot Strip Mill (HSM), coils are heated to a temperature between 1150 and 1250°C and then hot rolled in a five-stand rougher section and a seven-stand finishing section. After finishing the strip enters the runout table at a temperature between 900°C and 1050°C. The runout table of the HSM is about 130 meters long and has 124 sections: 62 sections above the strip and 62 below the strip, that can be independently actuated: off, half flow rate and full flow rate. Good control of the runout table is vital to realise desired product qualities.

Conventional control of the HSM runout table is based on a setup that selects a pattern from a fixed set (see Figure 1) and on feedforward controller based on the finishing temperature combined with a feedback controller for

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finetuning. Optionally a fixed intermediate feedforward control point can be selected for spe-cial grades.

This conventional controller was developed around the year 2000 and was already a step forward in runout table control [1,2] employing a simplified first-principle strip temperature and heat transfer model. Later this model was extended with an advanced transformation model, called MITRON [3,4] for improved prediction of of HSLA and dual phase material. During the years this heat transfer model was extended with additional pattern types to allow for the ever-growing demands for advanced steel types. Around 2015 it became clear that extending pattern types is not a sustainable solution in the rapid changing environment of new product development and tighter associated requirements. This resulted in the development of the next generation runout table setup and control.

The main goal of the new controller is to realize the transition from a target intermediate and coiling temperature control to a flexible temperature-time path control. In Fig. 2 some possible temperature paths on the ROT are shown resulting in different micro-structures at the end of the ROT. The possible temperature paths and resulting product micro-structures are found within the working envelope (green) of the installation. This working envelope is a result of the combination of alloy content and applied process. The available window of cooling paths is determined by the hardware and the strip speed on the Run Out Table.

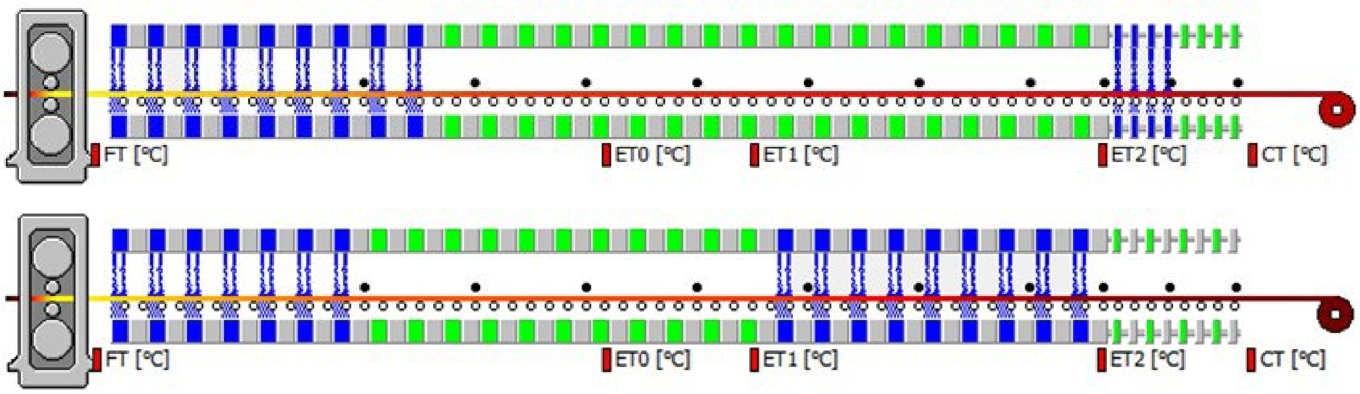

Fig.1 - Fixed patterns for conventional control, first pattern is default cooling, second pattern is staged cooling.

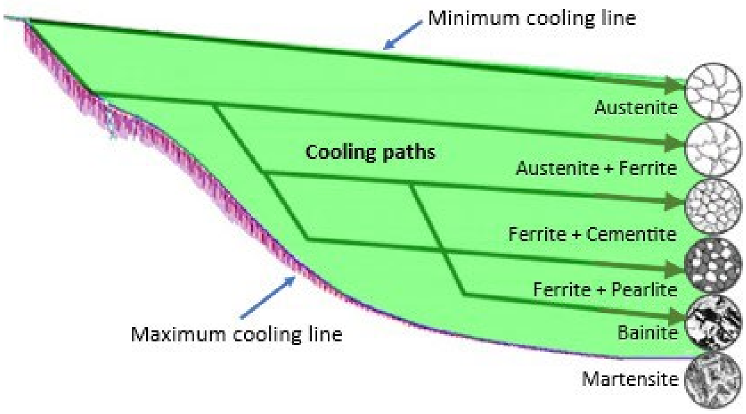

Fig.2 - Different cooling paths (and alloy) results in different possible microstructures

MODEL AND ADAPTATION

The first principle model consists of three parts:

- Strip temperature model
- Material model for predicting transformation
- Heat transfer model

Strip temperature model

The temperature in the strip is computed using a one-dimensional non-equidistant grid using the gradient heat conduction equation [5]:

$$\frac{dT}{dt} = \frac{\lambda}{\rho \cdot c_p} \frac{d^2T}{dx^2} + \frac{q_{tr}}{\rho \cdot c_p} \qquad [1]$$

with boundary conditions:

T_0	Finishing mill entry temperature [K]
q_{tr}	Transformation heat during cooling [J/kg]
q_0	Boundary condition at top and bottom surface

$$q_0 = \alpha_{water} \cdot \left(T_{surface} - T_{water}\right) + q_{radiation} \qquad [2]$$

Transformation model

An accurate prediction of the transformation and latent heat of transformation are important in the calculation of the temperature evolution. Therefore, the transformation model that was already developed for the previous ROT controller, is also incorporated in the new version. This model is called MITRON and is developed in-house. It is a fully physics-based phase transformation model and runs successfully for many years in the Tata Steel hot strip mills in Europe [3,4]. Due to the availability of four EMSpec devices [6] (which measure the ferrite fractions in the steel) the MITRON model is further improved and tuned.

Heat transfer model

The heat transfer in the Runout table is dominated by the water cooling. To compute the water cooling at the strip surface, the heat transfer coefficient is computed based on the so-called boiling curves at different cooling zones after impact of the water, see Fig. 3.

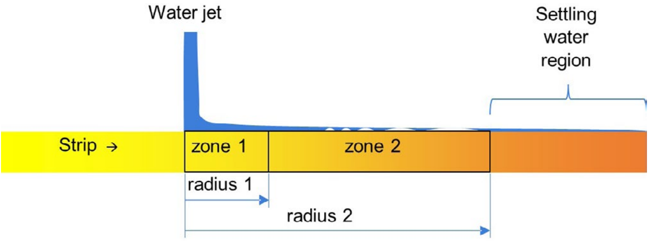

Fig.3 - Water jet cooling zones on strip surface

The heat transfer coefficients are based on the boiling curves shown in Fig 4, tuned for the Runout table at HSM IJmuiden [1,2].

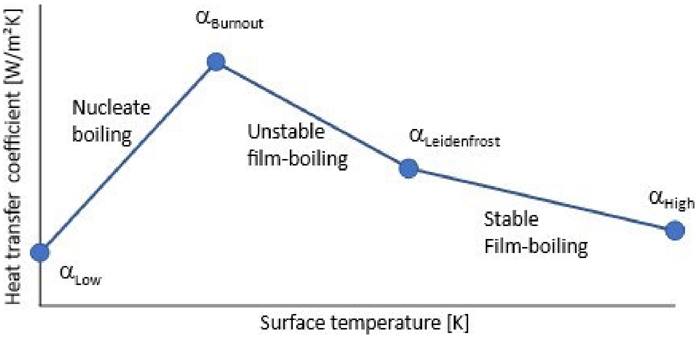

Fig.4 - Boiling curve tuned for the runout table at HSM IJmuiden.

Inaccuracies

Although the model is based on first principles, the predicted temperature still deviates from the measured temperatures. For this, various reasons exist, such as runout table mechanical status, such as valve deterioration, Strip surface properties, model inaccuracies and measurement inaccuracies.

To counteract these inaccuracies, two solutions are implemented:

- Model correction by using an artificial neural network (ANN)
- Model adaptation by linear regression

Model correction using an artificial neural network

The model error is calculated using an offline version of the thermal model in combination with historic data. The error between the calculated and measured temperatures is minimized by applying a wise correction on the heat transfer coefficient.

This correction is then correlated to various input parameters using the ANN:

- Water temperature
- Most relevant alloying elements
- Finishing temperature and coiling temperature
- Average speed
- Strip thickness and width

The training of the ANN resulted in a correlation with a R^2 of 0.65, as shown in Fig. 5.

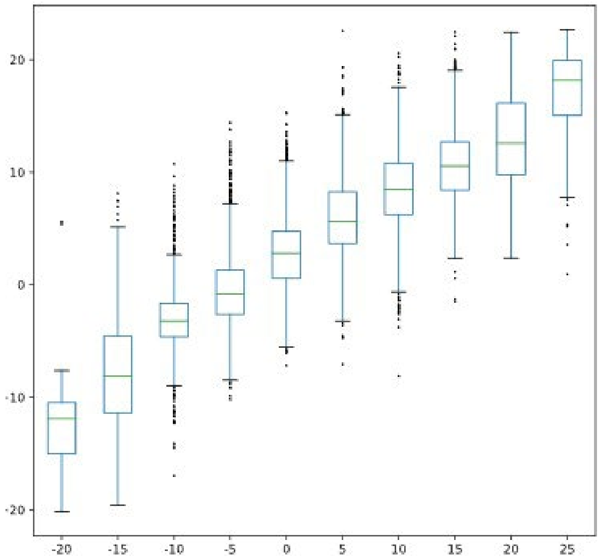

Fig.5 - Performance of artificial neural network

The application of the ANN improved the average model accuracy by around 19%.

Adaptation

The model correction by the ANN already increases the model accuracy significantly, but cannot correct for time variant behaviour (e.g., status of the runout table over time) and rapid coil-to-coil variation. For this, two different adaptation methods are included, both based on linear regression:

- Long term adaptation based on heat transfer correction
- Short term adaptation based on a temperature correction

OPTIMIZER

The new runout table controller consists of mainly two stages, namely setup and controller. This subdivision is also found in the conventional controller [1,2], however the implementation is different. The setup uses an optimizer to find the best cooling pattern for the coil, based on:

- Selected strategy
- Strip dimensions and PDI (targets)
- State of the runout table (such as available sections and adaptation)

Strategy

A strategy is a description for the setup optimiser on what to optimize. This strategy consists of three parts: Objective functions, constraints, and control parameters.

The objective functions are stored as a list with desired targets over the length of the runout table. The 'target' can be defined as strip temperature, but also different targets are possible, such as surface temperature, austenite fraction, heat flow density.

Constraints are defined as domains and a domain is a (configurable) part of the runout-table which the optimizer can utilise to fulfil the objectives. In the domain the maximum and minimum section load can be enforced and also the degree of symmetry can be imposed. Furthermore, the domains can have a 'fixed' start and end position on the runout-table, but domains can also be interconnected, so the second domain starts directly after the first domain. This allows for high flexibility.

The control parameters are also part of the strategy but are not relevant in the setup phase and therefore this part is described in the section about the controller.

Problem description

In fact, the optimization problem can be described as:

$$\min_x J(x) = \sum_{i=1}^{n} J_i(x) \tag{3}$$

subjected to

$$G(x) < 0 \tag{4}$$

Where x is the set of the cooling section loads (valve positions) to be found. Since there are 124 cooling sections and each cooling section has two flow levels this results in a problem with 124 unknowns and 3^{124} possible solutions.

This vast search space results in two problems:

- Computationally intensive due to the problem size
- The system is heavily underdetermined.

Because the system is underdetermined, there is a risk of obtaining different cooling patters for virtually identical strips and this is highly undesired. Furthermore a 'smooth' pattern is preferred, meaning that a pattern should be repetitive and continuous to ensure constant cooling rate. Because of this desired property the individual section load is replaced with cooling zone length and cooling intensity. This results in three unknowns for a simplest cooling strategy:

- Cooling zone length (number of sections)
- Cooling intensity on top and bottom (0% – 100%)

For more complex cooling strategies, the number of unknowns expands accordingly. The algorithm allows for both connected zones (next zone directly starts after) or distinct zones (next zone starts on a fixed bank position). Since the sections have only three positions (off, half open, fully open), the cooling intensity is 'digitized'. This computes a pattern that matches the intensity as close as possible.

Genetic algorithm

This problem is non-linear mixed integer problem and there are different optimization techniques available to handle this type of optimization. Due to the nature of the optimization problem, gradient based optimization methods are not suitable. Therefore, the most promising methods are simulated annealing or genetic algorithm [7]. Although the simulated annealing algorithm is faster, the genetic algorithm gives better results. Hence, the genetic algorithm is applied.

The layout of the gene follows from the choice of the cooling zone length and intensities:

$$x = \left\{ \begin{matrix} L_1, I_{top_1}, I_{bottom_1}, L_2, I_{top_2}, I_{bottom_2}, \\ \dots, L_n, I_{top_n}, I_{bottom_n} \end{matrix} \right\} \tag{5}$$

Objectives

The use of an unstructured optimization function has the advantage to use various, nonlinear objectives, such as:

- Strip temperature at a given position
- Cooling rate target and limits
- Phase transformation targets,
- Heat flow density target or distribution
- Surface temperature limitation

The resulting objective function for coiling temperature is then:

$$J(x) = \begin{cases} T_{min} - T_c(x) & T_c(x) < T_{min} \\ T_c(x) - T_{max} & T_c(x) > T_{max} \\ 0 & T_{min} < T_c(x) < T_{max} \end{cases} \quad [6]$$

For other objective functions, a similar objective function is applied. The different objectives combined as a weighted sum:

$$\min_x J(x) = w_1 \cdot J_1(x) + w_2 \cdot J_2(x) + \cdots \quad [7]$$

Constraints

A genetic algorithm as no constraints other than the limitations in the gene build-up. However, 'soft' constraints are part of the objective function using a high weight. Hard constraints are either resolved by gene repair, as explained before, or by rejecting the outcome.

CONTROLLER

After the setup has completed, the setup results need to be employed and this is part of the controller. The controller consists of two parts: feedforward and feedback.

Feedforwards

The feedforward (FF) iteratively computes the required zone lengths for each domain using the thermal model. The computation uses the measured entry temperature, target domain temperature, expected time-speed schedule and the domain definitions in the setup. This is then translated to a valve send-out.

Feedback

The feedback (FB) computes the error between the measured pyrometer temperature and the expected temperature from the thermal model. This temperature error is fed back and considered in the next feedforward. This results in a modified Smith predictor scheme [8].

The number of active controllers depends on the control zone definition in the strategy and are related to the domain setup. This means that a control zone consists of one or more domains.

Implementation at IJmuiden HSM2

The new controller is implemented at HMS2 in the period of 2020 to 2021 and runs since February 2021. To have a smooth transition from the previous controller the legacy setup is integrated completely in the new controller as alternative setup. This legacy setup has been used for the majority of the coils, until a correct strategy was defined.

RESULTS

The controller runs now for more than 12 months, and the major benefit is the ability to develop and produce new steel types. An additional advantage is a significant improvement in temperature performance that results in substantial reduction of repairs and rejects.

New product development

The new setup is already used for many new steel types.

- Controlled cooling of very high alloyed steel:
- In this development the phase transformation

is difficult to control and just imposing a coiling temperature is insufficient to obtain the right phase transformation. To successfully control this grade, an intermediate point is applied with two distinct cooling rates. This strategy improves the controllability of the process for this material significantly, resulting in less material rejections.

- Surface temperature limitation:
- In this development the surface temperature limitation is imposed to improve strip shape issues. This strategy improves the controllability of the process for this material significantly, resulting in less material rejections.

Performance improvement

The new implementation also has a benefit on overall performance: The number of rejects were reduced significantly after implementation and the cost of poor quality (COPQ) is now structurally at very low level. and Fig. 6 and Fig. 7 show the temperature performance comparison before and after implementation.

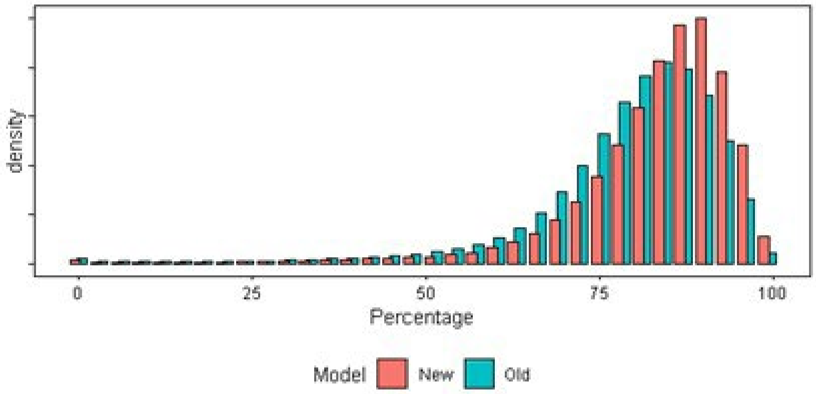

Fig.6 - Temperature performance before implementation (orange) and after implementation (green) as percentage within limits.

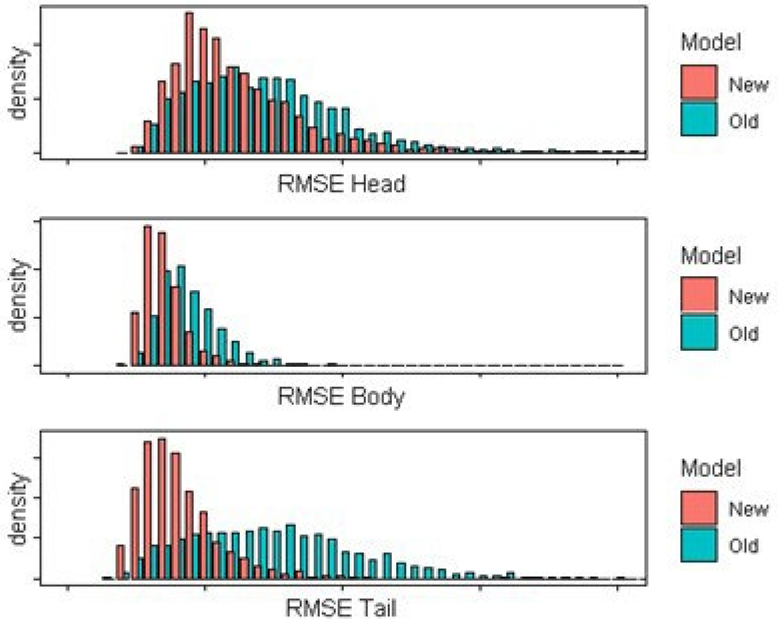

Fig.7 - Temperature performance before implementation (orange) and after implementation (green) as root mean square errors.

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