MODERN PROCESS MODELS TO IMPROVE PRODUCT QUALITY ON PLATE MILLS [1]

Rüdiger Döll [2]
Werner Nothegger [3]

Abstract

Today's demands on high strength plate include good weldability and reduction of costly alloys to a minimum while product geometry and shape shall have smallest possible tolerances. The production of such plate is economically possible employing thermomechanical rolling in combination with advanced process control. The use of fully automatic thermomechanical rolling using latest physical models and intelligent sequencing strategies achieves the optimum in grain refinement and thus improves mechanical properties, at the same time keeping productivity high through sophisticated mill pacing. Beside model-based thickness control and plan view pattern control for rectangularity, Profile and Flatness Control (PFC) is crucial for achieving desired dimensions of the plate. It is goal of PFC for plate mills to achieve a flat plate with the desired target profile. At the same time, for profitability of the mill, it is important to work with high throughput, i.e. large reductions. The novel profile and flatness strategy relies on comprehensive physical models and makes use of SmartCrown® as a powerful actuator, enabling large reductions even in wide plate mills without risking edge waves. The functionality can be easily implemented into existing mills.

Key words: Plate mill; Thermo-mechanical rolling; Model based control.

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[2] *Head of R&D Process Models, Siemens AG, Erlangen, Germany*

[3] *Product Lifecycle Manager, Siemens AG, Erlangen, Germany*

1 INTRODUCTION

The philosophy behind Siemens' process control is to employ physical models to describe the mill, the material to be processed as well as their interaction. Artificial neural networks are in use for modeling the influence of chemical composition which only can be described empirically - at least so far. Those neural networks are not simple correction networks but they represent physical parameters such as the yield stress. Because physics is the same at every plant, the models start well conditioned already for the first plate - a pre-requisite for a fast start-up.

This paper describes thermo-mechanical rolling employing a temperature monitor and automated batch rolling. Regarding the dimensions of the plate, rectangularity as well as profile and flatness are discussed. The paper closes with a conclusion and an outlook.

2 THERMOMECHANICAL ROLLING WITH TEMPERATURE MONITOR AND AUTOMATED BATCH ROLLING

2.1 Motivation: High Material Quality

The challenge for plate production is to obtain a strong and weldable material produced at reasonable costs. Nowadays the typical way to meet this challenge is to employ Thermo-Mechanical Rolling (TMR), i.e. follow a certain temperature-strain path with the steel in order to achieve the optimum in grain refinement. A typical temperature-strain path is depicted in Figure 1. After a first rolling sequence, the material is cooled down so that the second rolling sequence takes place after recrystallization has ceased. A pancake type microstructure before phase transformation is the consequence. In combination with a following accelerated cooling with MULPIC, a fine-grained microstructure is ensured. By this means, high-strength material can be produced without using too much of costly alloys, which is good for both production costs and weldability, respectively.

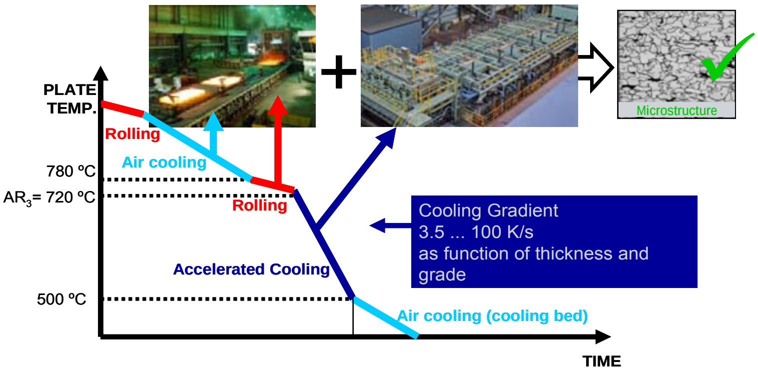

Figure 1: Typical temperature-strain path for thermomechanical rolling.

From the automation point of view, the components of a successful automatic TMR are:

- Temperature model
- Temperature monitor

- Model predictive control (MPC) for temperature
- Automated batch rolling.

Technically, the MPC employs a plate temperature monitor, which itself is based on a physical temperature model. Automated batch rolling ensures high throughput while producing TMR plate. The components for TMR are described in the following.

2.2 Plate Temperature Model

Any model for the calculation of the plate temperature in a plate mill must be able to describe certain physical effects. These include:

- Heat loss by radiation
- Reflected radiation from the roller table bottom side and from heat insulator panels
- Heat transfer to roller table and work rolls
- Temperature increase due to deformation and friction work in the roll gap
- Heat loss due to impinging water jets
- Influence of phase transformation

The model is based upon the Fourier's equation of heat conduction,

$$\frac{\partial}{\partial t}\rho\, h(\underline{x},t)+\nabla\,\underline{j}(\underline{x},t)-s=0,$$

with ρ as the density, *h* the specific enthalpy, *j* the heat flow and *s* the heat sources. The equation is deliberately kept in enthalpy (rather than temperature) formulation because this is the proper way to consistently consider phase transformation.

High precision is realized through computation of the temperature for several layers over thickness. Through adaptation of the heat transfer coefficients (rather than simply applying meaningless correction factors to the final result), we make sure that basically the complete temperature course is adapted.

In other words, the real physics of heat transfer is taken into account, which is transferable from mill to mill. In practical application, this means:

- Fast production buildup through knowledge transferred from numerous previous mill projects
- High accuracy through model validation based on a database containing hundreds of thousands of plates

More details about the employed temperature model can be found in Kurz and Metzger.(1)

2.3 Plate Temperature Monitor

The temperature of all plates is monitored at every process step. The monitoring starts while discharging the plate from the furnace and ends when the plate leaves the relevant mill area. So even unscheduled delay times or manual operation of the descaling systems are recognized by the measurement processing and are considered in the monitoring.

In addition, the calculated temperature is adapted whenever a calculated point is re-measured by a pyrometer. A correction for the plate temperature is calculated from this comparison.

The plate temperature monitor provides the temperature distribution in both the thickness direction and along the diagonal of the plate (Figure 2).

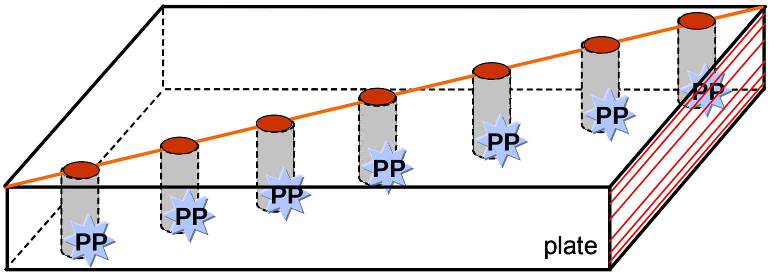

Figure 2: Discretization in space: Temperature is calculated for a Gauss-Lobatto net over thickness and for several Plate Points (PP) along the diagonal.

It is initialized with data from the measuring device and/or data provided by the automation system that processed the plate upstream.

After initialization, the plate temperature monitor tracks the state evolution of each individual plate point as it moves through the mill.

Not only does a plate point represent the temperature (or enthalpy) profile across the thickness at a certain location in the plate but also the microstructure - in particular the mass fraction of the remaining austenite. This way, the temperature monitor contains the complete history of the plate within only few data. Model predictive control (see below) makes extensive use of this.

2.4 Model Predictive Control

To achieve well-defined material properties, it is desirable not only to control the finishing temperature but to achieve a certain temperature course of the material during processing. A Model Predictive Control (MPC) is the best option to realize required temperatures at certain positions / times inside the mill. The general theory of MPC is described in detail in Garcia, Prett and Morari.(2)

The MPC algorithm uses the plate's state known from the plate temperature monitor in conjunction with the plate temperature model to predict the temperature course into the future. Thus it becomes easy to compute e.g. holding times, which in turn are important input for mill pacing and in particular for the automated batch rolling functionality.

2.5 Automated Batch Rolling

As described above, in order to exploit the advantages of TMR it is necessary to follow certain strain-temperature trajectories during production. However, for the economic success of a mill, it is just as important to keep a certain level of throughput at the same time. Obviously, high throughput can be reached only if the mill stands do not have too much idle time - while some plates are cooling down in a waiting position, another one is rolled. This is realized through so-called batch rolling. In the example shown in Figure 3, the first rolling sequence is finished for plate 1 first. During its air cooling, plates 2 to 6 are rolled to finish the batch so that the stand operates without idle times. Then all plates are moved to the entry side and the procedure can be repeated for the second rolling sequence. Figure 4 shows a picture of a batch.

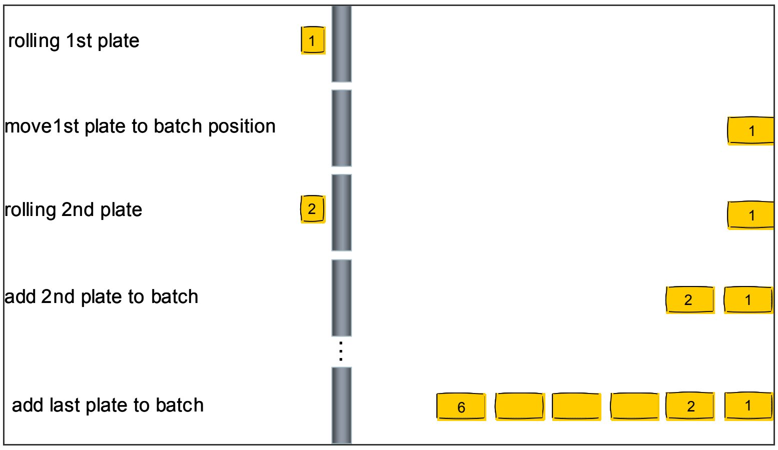

Figure 3: Principle of batch rolling, in the example for a batch of 6 plates.

Figure 4: Picture of a batch produced with automated batch rolling.

Such a procedure is only viable if automated. Moreover, the Siemens automated batch rolling offers the option of so-called dynamic batches, where the different plates are handled more independently from each other – with the advantage of more uniform furnace draw times. With additional roller tables, even holding positions outside the pass line are possible and allow for even more flexibility for implementing strain-temperature trajectories.

3 PLAN VIEW PATTERN CONTROL (PVPC)

Cropping losses directly worsen the yield of the plant. Therefore it is goal of the PVPC functionality to achieve optimum plate rectangularity. This is a challenge for plate manufacturers as plate needs to meet different sizing specifications and it is often produced in small lot sizes.

The foundation of the PVPC is a model based on the principle of constant volume. The way steel behaves in the roll gap, i.e. how much of the deformation goes into length and how much goes into width, depends on roll radius, strain, thickness, width, temperature and chemical composition of the steel. This behavior is described with model parameters which have been identified with both experiments and extensive FEM calculations.

Employing the model describing material flow into length and width direction, PVPC ensures an improved rectangularity of the product by combining three actuators (Figure 5):

- Turning thickness
- Variable thickness rolling
- Edging.

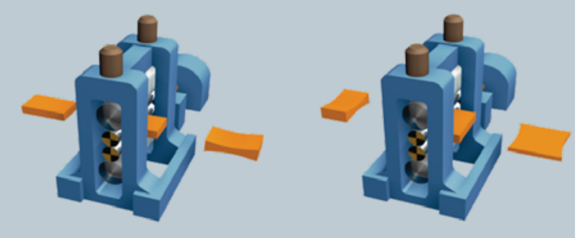

Figure 5: PVPC determines optimum turning thickness and even thickness course over length to achieve rectangular plate as final product. The influence of edgers (if available) is of course taken into account as well.

4 PROFILE AND FLATNESS CONTROL WITH ONLINE MATERIAL FLOW MODEL

It is goal of a Profile and Flatness Control (PFC) for plate mills to achieve a flat plate with the desired target profile. At the same time, for profitability of the mill, it is important to work with high throughput, i.e. high reductions.

As a consequence, the PFC algorithm is employed twice for each plate - in a first step to determine the maximum possible load in each pass (see Figure 6) and in a second step to determine the actuator values (i.e. for shifting and bending) to realize the desired roll gap profile, taking into account different efficiency of the actuators as well as actuator limitations. It is worth mentioning that the novel Siemens PFC makes use of Smart Crown® as a powerful actuator, enabling large reductions even in wide plate mills without risking edge waves.

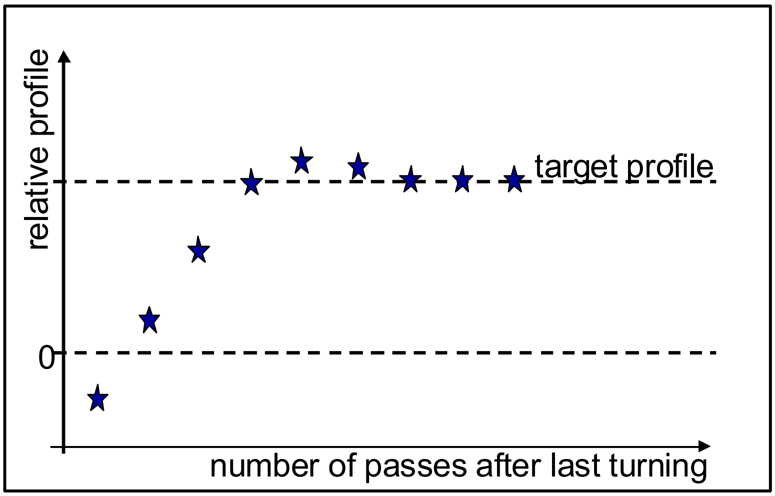

Figure 6: The profile is adjusted during the first passes after last turning - then as quickly as pos sible without risking unflatness.

The PFC system determines set-up values for the PFC actuators, such that

- the finished plate meets the target flatness,
- the finished plate meets the target profile,
- the thickness contour of the finished plate is acceptable.

The algorithm is based on comprehensive physical on-line models, describing both the deformation of the rolls during rolling and the plastic material flow in the roll bite of the mill stand(s). Roll deformation includes elastic deformation (bending and flattening) as well as thermal expansion and wear of the work and back-up rolls.

For the modeling of the three-dimensional plastic material-flow in each individual roll bite, we exploit the fact that the plate thickness is small compared to the roll bite length and the plate width. This allows eliminating the thickness dimension, and in consequence the governing finite volume equations can be solved on-line. These on-line calculations of transverse rolling load distribution, plate profile and flatness at every pass enables the determination of the optimal setup of all available actuators with respect to target profile and interpass flatness.

Due to the variety of rolling parameters that influence the shape of the plates, the on-line control of the plate profile and flatness is one of the most complex tasks in the process automation of plate mills. Several physical sub-models are required and must interact properly to ensure the accurate performance of the overall on-line PFC-algorithm. The most important models describe the behavior of the stand and the rolls as well as the deformation of the rolled material under the actual process conditions.

- **Roll bending model**

The roll bending model calculates the elastic deformation of the roll stack for each pass, excluding the elastic flattening of the work rolls at the plate – the work roll interface. Specifically, the roll bending model calculates the bending of both the work and the back-up rolls, respectively, under the influence of the rolling and bending forces applied at the roll necks.

- **Roll temperature and wear model**

The toll temperature and wear model tracks the evolution of thermal and wear crowns of both work and back-up rolls over time. Thus, unlike the other models of the PFC system, which are static in nature, this model is dynamic and has to be used for calculations in regular time intervals. i.e., calculation time becomes an issue. Without limitation of accuracy, this problem can be solved as follows. In a thin boundary layer, the full three-dimensional heat equation is analytically solved and averaged across the circumference of the roll. For the roll core, the two-dimensional temperature distribution in axial and radial direction is calculated using a finite difference method.

- **Work-roll flattening model**

The work-roll flattening model calculates the elastic flattening of the work roll at the plate – the work roll interface. Unlike the work roll bending contour calculated by the roll bending model, the work-roll flattening contour at the plate (work roll interface) crucially depends on rolling load distribution across the plate width (i.e., the transverse rolling load distribution, which is an output of the material flow model).

- **Material flow model**

For a given roll bite geometry in a particular pass, the material flow model computes the two-dimensional (i.e., the longitudinal and the transverse) rolling pressure distribution at the plate – the work roll interface, see Figure 7.

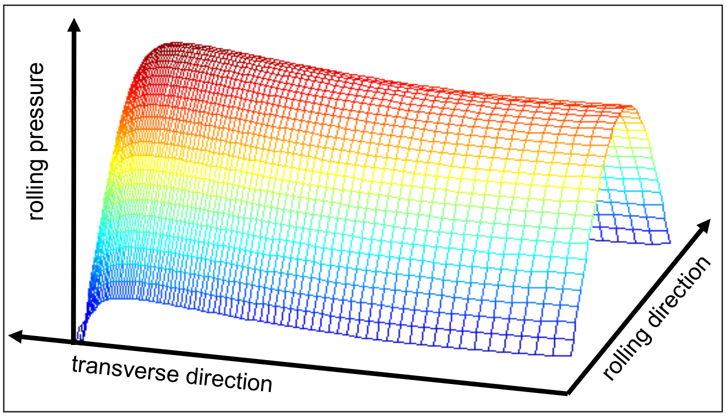

Figure 7: Rolling pressure distribution in the roll gap as calculated by the online material flow model.

By integrating the two-dimensional rolling pressure distribution along the arc of contact, the transverse rolling load distribution across the plate width is obtained. In addition, the material flow model computes an estimate of the plate shape at the roll bite exit, given the shape of the plate at the roll bite entry.

Through efficient numerical solution techniques, we are able to calculate the material flow in the roll gap online. This online capability is essential if the material spectrum of a mill shall be extended in the future.

Figure 8 exemplifies the flatness quality achieved with the PFC described in this article. In Reinschke et al.,(3) the models are described a little more in detail.

Figure 8: Thanks to PFC from Siemens, these plates with a thickness of 5.3 mm show excellent flatness on the cooling bed.

5 CONCLUSION

Detailed physical modeling of the entire rolling process is the basis for a stable mill operation - in particular with plate mills. At Siemens we employ a mutually well adjusted ensemble of models which describe the complete production process in a plate mill. Following the philosophy that physical parameters depending on chemical composition are described (and later adapted) by neural networks, the models and the respective process automation are installed pre-adjusted. Thus already the first plate in a mill is rolled with a completely active automation system. In other words, the production of salable plates starts with the first plate.

General benefits are:

- Steep start-up curves as the "physical knowledge" from many mills is available right from the start
- High accuracy through making use of the experience with many thousands of plates
- Great extension behavior to new steel grades and to new dimensions

The solutions for thermomechanical rolling - keeping both product quality and throughput at high level - as well as solutions for keeping geometrical tolerances at a minimum are proven at many mills, including e.g. the 5,000-mm plate mill of Baoshan Iron & Steel Co. Ltd. and the 4,300-mm plate mill of Shougang Iron and Steel Co. Ltd.

6 OUTLOOK

The steel industry is experiencing a constant trend towards lighter-weight rolled products with customized properties, and this is particularly true for plate production. Pipeline steel, construction steel or shipbuilding steel requires increased tensile properties and toughness.

We expect this trend to continue, not least because this is also an environmental contribution in terms of saving global resources. So far, material grades up to X120 have been produced and we expect that future developments will achieve even higher strengths.

The process models are well prepared to handle these steel grades.

For certain steel grades, a microstructure monitor (as depicted in Figure 9) has been developed. Its purpose is to compute mechanical properties of the plate from chemical composition and from production parameters. A first practical application is already in the commissioning phase. Before long, this will be standard equipment in plate mills.

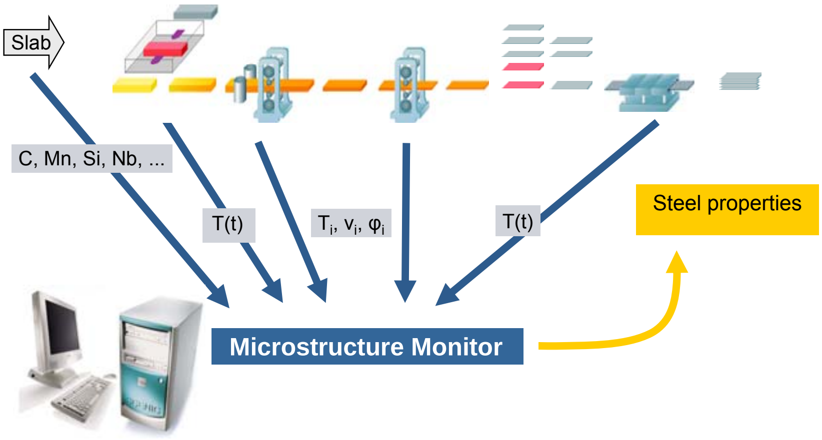

Figure 9: The microstructure monitor is provided with chemical composition as well as with process parameters in order to compute the microstructure and eventually the mechanical properties of the product.

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