NEW COOLING CONCEPT IN HOT-STRIP MILLS "MICROSTRUCTURE TARGET COOLING"[1]

Klaus Weinzierl[2]
Rainer Burger[2]
Michael Smith[3]

Abstract

The successes of new materials are accompanied by an increase in the requirements that are placed on the classical material, steel. It is not only automotive companies that expect to gain an advantage from thinner but still very strong types of steel sheeting which makes their vehicles more efficient and more environmentally compatible; other branches of industry can also profit from strength-relevant load-bearing structures and energy-absorbing components made of dual-phase, multiphase or high-strength steels such as TWIX and TRIP. In addition to the alloying elements, the cooling section is decisive for the properties of these steels. Precise and highly flexible control of the cooling process in the cooling section is therefore extremely important. Previously, however, all models involving purely phenomenological determination of the transformation process have displayed weaknesses in respect of exact calculation of the temperature curve, especially when transformation occurs on the roller table. Furthermore until recently it has only been possible to stipulate a target coiling temperature, which is derived from a mechanical property target. This is only a rough method to adjust steel properties, especially for changing strip speeds. Siemens VAI has now developed a new cooling section control system which uses the so-called Gibbs' free enthalpy to calculate the steel transformation very precisely on the basis of a thermodynamic model. The new developments in the physical modeling of the steel transformation make it possible to compute temperature and phase fractions along the entire cooling section – in real time. By means of a model-predictive control function, the stipulated time curve of cooling in the cooling section is optimally adhered to for the whole strip within the limits of the plant. This enables Siemens VAI to offer a cooling section that works right on the steel producer's targets: the microstructure properties of the strip.

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[2] *Siemens AG, Erlangen, Germany*

[3] *Siemens Energy & Automation, Alpharetta, GA*

Introduction

The successes of new materials are accompanied by an increase in the requirements that are placed on the classical material, steel. Many branches of the manufacturing community have made significant improvements in their products from the development of stronger and more energy absorbent steel types such as Dual Phase (DP), Twinning Induced Plasticity (TWIP), and Transformation Induced Plasticity (TRIP). The automotive sector has seen a marked increase of efficiency and environmental compatibility in their vehicles by using greater quantities of thinner but stronger steel sections. Over the past two decades, steel employed in automobiles has experienced an increase of almost three to one in yield strength and nearly a doubling of energy absorption capability; such that over 40% of the automobile body is now constructed of these materials. Other branches of industry have also profited from these newly developed steels; especially where high strength load bearing members are employed. Modern automation systems have an essential influence on the stable production of these materials with consistently high and reproducible quality. In addition to the control of the sequences and physical actuators in a hot strip mill, the permanent evolution of process models and technological control is crucial for leading edge steel producers. In addition to the alloying elements, the cooling section is decisive in the formation of the properties of these steels. Precise and highly flexible control of the cooling process in the cooling section is therefore extremely important. Previously, however, all models involving purely phenomenological determination of the transformation process have displayed weaknesses with respect to the exact calculation of the temperature curve and especially the online control of the time-enthalpy trajectory. Siemens has developed a new cooling section control system that uses the so-called Gibbs' free enthalpy to calculate the steel transformation very precisely on the basis of a thermodynamic model. By means of model-predictive control functions, the stipulated time curve of the temperature change in the cooling section is adhered to optimally for the whole steel strip within the limits of the plant in question. For existing plants that are limited by valve quantity or water flow capacity, they can be retrofitted with new cooling equipment which is consistent with the ability to control and produce these advanced steel grades. New plants are invariably constructed so that they are mechanically and hydraulically prepared to perform the required cooling strategies consistent with production of these new materials.

Need for Phase Controlled Model

Modern steels, especially multiphase steels, require constant and reproducible production conditions in the hot strip mill and in the cooling section. If the cooling temperature or more precisely, the time-enthalpy trajectory tolerances are exceeded by just a few percent, the mechanical properties of the end product can change so dramatically that only waste or lower quality strip is produced. The manufacture of dual-phase steel typically requires that, in the cooling section, the steel is cooled from 900 °C to around 660 °C in a few seconds followed by a short duration of several seconds when the temperature is held nearly constant. This allows the transformation to proceed but not be fully completed. When the residual austenite content is 20 %, the steel is subsequently quenched and the phase status is "frozen", whereby the austenite is transformed into martensite. If the holding time is only ten percent too long, the residual austenite content can fall below ten percent. Instead of dual-phase steel, the result is structural steel; for example grade ST37, which is far away from the desired strength and other required properties. If the reverse happens, the residual austenite content is too high due to excessively rapid cooling and this can lead not only to poor material properties, but also to difficulties when the resulting brittle, uneven material is being coiled.

Equipment operators and the control system, therefore, try to keep the production conditions as constant as possible. However, the properties of the material are influenced by numerous factors, not all of which can be kept constant at the same time. This includes such influences as fluctuating finishing temperature and changing finishing mill speeds. In addition, the closed-loop control system only receives a few current measured values for controlling the valve settings, such as the finishing temperature and thickness of the strip entering the cooling section, as well as the coiler temperature. It only sees the strip coming out of the mill, the cooling pattern and the coiler temperature. This is insufficient to compensate for deviations from the desired material properties caused by water cooling capacity limitations (a water bottleneck) or fluctuations in cooling water pressure. Also, adequate corrections for varying cooling section residence times resulting from changes in gauge and strip length, cannot be made. The situation is further complicated by mill limitations (for example, maximum speed, current limits, etc.) and also from periodic variations in finishing mill exit temperature.

Classical Cooling Sections restrict the Production of Dual-Phase Steels

Classical cooling-section control systems divide the cooling zones into a main cooling zone and a fine cooling zone at the end of the cooling section. The main cooling zone is primarily used for pre-calculation and feed forward control purposes. The fine cooling zone controls its valves according to the current coiler temperature (feedback control). In the event of speed increases, the extra water needed is supplied according to a strictly prescribed sequence, the so-called cooling pattern. If additional cooling strategies are needed, when dual-phase steels are manufactured for example, a very similar approach is used. This has proven to be disadvantageous and complicated because the different cooling locations in the cooling section normally have to be adapted to the changing strip speeds and final rolling temperatures.

For dual-phase steels, for example, this means an uncooled stretch of 30 meters at the head of the strip, when the holding time is three seconds and the strip speed is ten meters per second. For the middle of the strip where the average speed is 13 meters per second, the uncooled section increases to 39 meters. This means that the second cooling zone must be moved further towards the coiler. If, however, the limits of the finishing mill's drive power are reached from a certain point of time onwards, the speed remains constant and the final rolling temperature gradually declines. In turn, the resulting shortening of the first cooling zone requires displacement of the subsequent cooling zones if the properties of the material are to remain constant. Calculation of these displacements must take into account the whole time curve of the strip speed and the final rolling temperature.

Here, the classical cooling section control system very quickly comes up against its basic limitations, the consequence of which is that even small changes lead to irregular material properties along the strip. For this reason, using the classical cooling section control means that dual-phase steels can only practically be produced in plants whose finishing mill can keep the final rolling temperature and the strip speed constant at the same time. This requires additional mechanical features such as a coil box, interstand cooling valves or, for example, a tunnel furnace in the case of combined casting and rolling plants. Due to the limitations of available cooling section control systems, many of today's plants are, therefore, incapable of producing dual-phase steels of sufficiently high quality. Production of these products would be possible using their existing equipment including the cooling section configuration, however, the application of fixed cooling patterns, whose sole purpose is to simplify control, makes it virtually impossible.

Model-predictive Controllers based on the Gibbs' Phase Model

Consequently, the main requirement is a control system which correctly displays the temperature curve and phase components along the whole cooling section in real time, detects any deviations and reacts to such deviations appropriately. The mechanical limits of the cooling control elements must be taken into account but the control system must not impose any additional limitations. The Siemens control system now keeps track of the temperatures and phase components for each point on the strip in real time and transfers the exact results of each point to a model-predictive controller. The latter forecasts changes in the temperature curves and phase components in the future, compares them with the time curves stipulated in advance, and minimizes any deviations by operating the most suitable cooling control elements at the correct time. In this way, quality deviations are immediately avoided and additional software-related limitations, due to fixed cooling patterns for example, are eliminated.

The cooling model now takes into account the entire phase transformation process in a physical model. It calculates when and which phases are in equilibrium and what happens if certain alloying elements are added. The cooling section automation system possesses a form of intelligence which is similar to that of the design programs used by material scientists. This is realized by employing Gibbs' free enthalpy relationships. If the cooling curves for both the austenite phase and the ferrite phase are recorded, the resulting enthalpy is initially a function of the temperature. This makes it easy to calculate the Gibbs' free enthalpy as a function of the temperature with the help of known formulae. Gibbs states that the material of a phase mixture will always occur in that phase whose Gibbs' free enthalpy is minimized. At 700 °C, the body-centered cubic crystal structure of the alpha ferrite has a lower Gibbs' free enthalpy than austenite, i.e. unalloyed steel will occur in the ferrite phase in this case. Between a transformation temperature of 911 °C and just under 1400 °C, the austenite phase has the least Gibbs' free enthalpy. Shortly before the fluid phase, the situation is reversed. Delta ferrite, like alpha ferrite, has a body-centered cubic crystal lattice structure. The intersection points of the Gibbs' free enthalpy curves thus indicate the transformation temperatures at which the two phases are in equilibrium. This is illustrated in Figure 1.

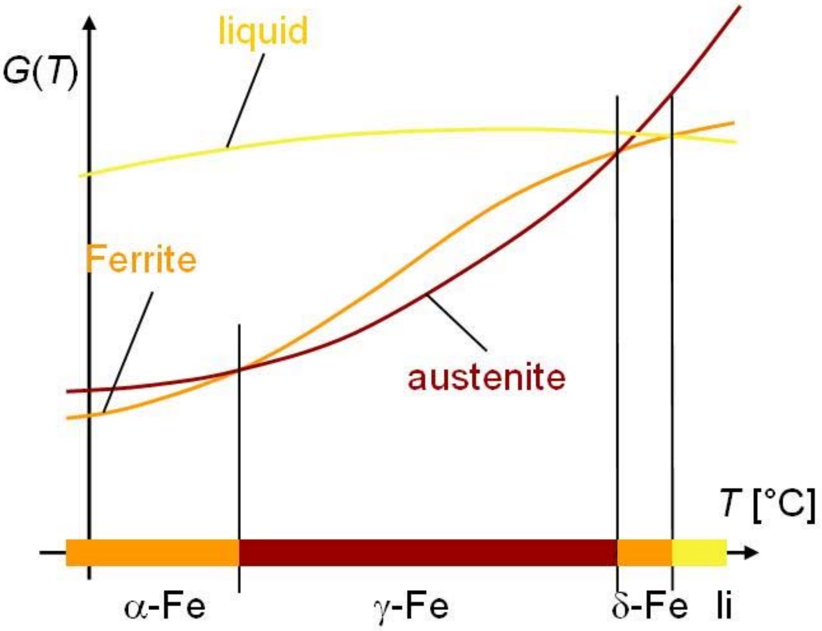


Figure 1: Curve analysis of Gibb's free enthalpy for different phases delivers equilibrium phase transformation points

The basic idea of minimizing the Gibbs' free enthalpy can now be extended to alloyed iron. If chemical elements are added for alloying, e.g. manganese (0.8 % to 2 %), silicon (0.1 % to 3 %) and aluminum (up to 0.2 %), the Gibbs' enthalpy curves change and therefore also their intersection points (strictly speaking, it must be taken into account that alloying elements can be differently distributed in the phases involved, as a result of which transformation areas now occur). With knowledge of the Gibb's free enthalpy, it is therefore possible to calculate equilibrium diagrams of iron alloys and deduce the phase components and concentrations of alloying elements in phase equilibrium from these diagrams. This is exactly the same approach used by commercial programs for material design such as ThermoCalc, Pandant or ChemSage.

The transformation model can also calculate the time curve of phase transformation. On the basis of Gibbs' free enthalpy, the equilibrium conditions at the interphase can be determined. The speed of phase transformation is now determined by the degree of carbon diffusion in the austenite.

With these methods, the physical steel transformation model is able to correctly describe the influence of different alloying elements and also to take into account any resulting cooling curves. It is not only possible to calculate the transformation process from the curves for Gibbs' free enthalpy but the thermal capacities and the heat released during transformation can also be determined. Due to this holistic approach, there is only one single data record required for parameterization of the curves with respect to the steel chemistry and, from this data record, it is possible to determine both the transformation process and the temperature curve during cooling.

Formerly, the parameterization of the heat conduction equation was independent of the parameterization of the non-physical model and as a consequence, incorrect results were obtained. This problem is now elegantly avoided by utilizing the concept of Gibbs' free enthalpy. The model can not only handle cases where, under certain conditions, the strip temperature can increase again, when transformation takes place, but also avoids the typical problems of earlier models from the outset. According to former classical model calculations, certain combinations of alloying elements produced inconsistent results – in extreme cases, even absurd solutions such as negative transformation heat – because the non-physical transformation model calculated a transformation that contradicts the parameterized thermal capacities of the phases involved.

Phase-transformation Tracking increases the Quality of Control

Modeling for the transformation process on a physical basis now enables the control system to calculate the temperature curve to be used for particular phase components. If, for example, dual-phase steel is to have a residual austenite content of 30% before quenching, the control system can calculate the temperature change and alter the valve settings very precisely. It can also keep track of the transformation process online for each point on the strip and can always control the quenching location exactly, so that it takes place where a residual austenite content of 30% can be expected. When doing so, it takes into account all possible problems that can occur. On the basis of the current strip speed, the measured temperature when the strip enters the cooling section, the measured valve settings, the current water pressure and the current water temperature, the cooling model calculates the cooling effect and the phase components austenite, ferrite, cementite and pearlite along the strip in real time. At Hoesch Hohenlimburg, Germany, these results were checked and confirmed with a mobile temperature measuring device, which can also measure the strip temperature in the area where water is applied.

Online Capability of the Phase Transformation Calculation and Control

By utilizing the Gibbs approach and the resulting linear parameterization of the model, the calculations can be done on current server systems with sample times between 100 and 200 msec. The phase transformation and the control calculations are all computed in real time as the strip emerges from the finishing mill.

With this system it is not only possible to calculate the proper time-temperature trajectory for the conditions at the time when the strip enters the mill, but can check the phases and the resulting properties online each time sample (typically 200ms as per 2007 computing capabilities). Control adjustments to the time-temperature trajectory can then also be made within the same sample time in order to achieve the desired results.

Control of the Time-Enthalpy Trajectory in the Cooling Section

To ensure, that the material properties are kept as close to the target as possible, the cooling section contains a controller that runs in cycles of 200ms. In each cycle the controller recalculates the temperature model (including the phase transformation) for every strip point along the length of the cooling section, so that at any time, the time-enthalpy trajectory of each strip point is known and can be controlled. The important feature of the controller is that it does not just work as a feedback controller to keep a certain coiling temperature or cooling gradient.The new controller uses a model predictive control that calculates the phase transition for the whole strip in every control cycle taking into account the actual process conditions and optimizes the time-enthalpy trajectory for every strip point. All process constraints (such as actual location of the strip point, available actuators in the remaining area, water amount available, etc) are considered and the system ensures that the desired microstructure properties are kept as close as possible to the target.

The principle of this model predictive control is illustrated in Figure 2:

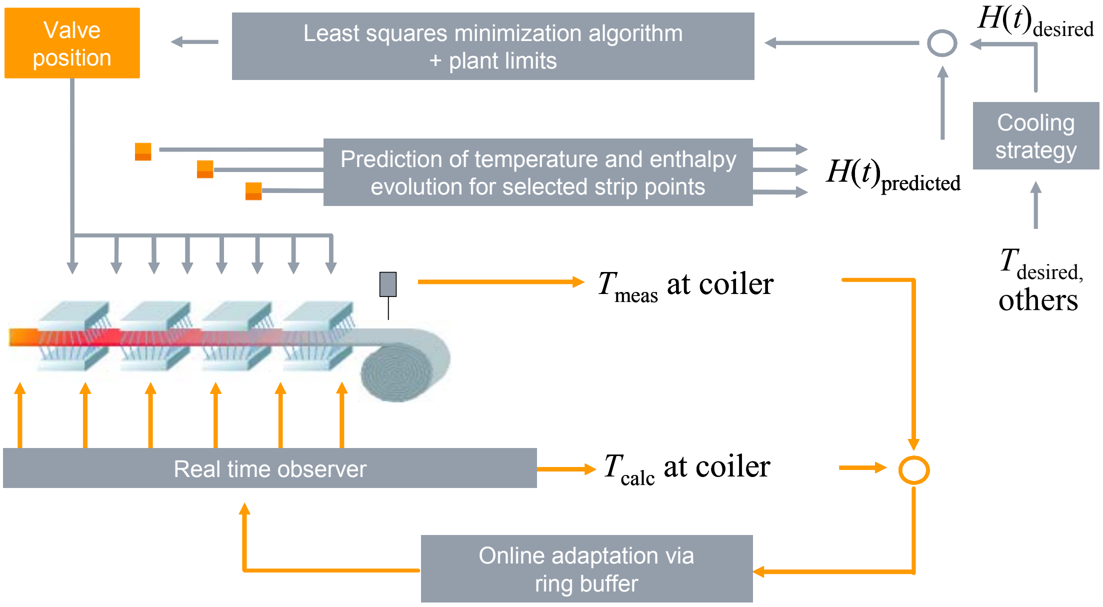


Figure 2: Principle of the model predictive controller using SQP optimization algorithm

Another mayor advantage of this model predictive control is that it is combined with a powerful online optimization component based on a least squares optimization algorithm.

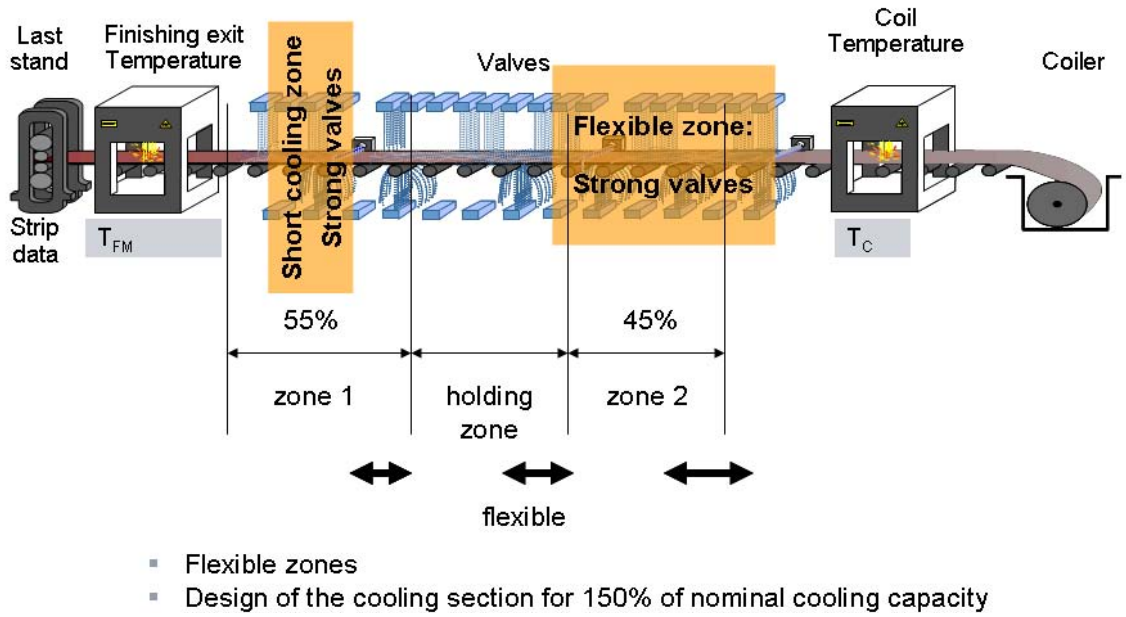
This algorithm enables the model predictive control not only to look at a single strip point at the temperature measuring device and optimize for this strip point, without regard to the rest of the strip (typical pure feedback control), but to take into consideration, for each control cycle, the entire strip length in the cooling section plus the part not already in the cooling section. The valve actuators are then chosen so that the deviation of the microstructure from the desired state is minimized for the whole strip.

Layouts for Cooling Sections with Capabilities for Complex Phase Steels

The capability to produce complex phase steels greatly depends on the mechanical layout of the cooling section and the valve arrangement.

As mentioned earlier, many older cooling sections have valve arrangements in which the granularity of the switchable water amount increases from the beginning where one valve switches a large water amount (main valves); to the end, where one valve switches only a fraction of the amount at the beginning (trim zones). Consequently, the switchable water amount per unit length of this section is accordingly decreased. This is unfavorable for rolling dual phase steels, where it is important to maintain precisely the holding time. This means that a favorable design has a fine granularity of switchable water over the majority of the cooling table length along with a high potential water density.

An example is depicted in Figure 3:



- Flexible zones
- Design of the cooling section for 150% of nominal cooling capacity

Figure 3: Cooling section layout for modern steel grades

Another feature that is critical for the success of this control is to observe and attempt to minimize constraints due to long valve lag times (valve on/off times). Maintaining the reproducibility of these times and deselecting malfunctioning valves (water running after switch off signal or partial water when turned on) is also a key element to successful control. This can be implemented using valves with an optimized design and special designs with new switching techniques which produce extremely short on/off times.

If space requirements are an issue (especially in revamps where the distance from the last stand to the coiler is limited), the necessary cooling rates prior to the holding zone and in the quench area can be attained using high density valve types with pressurized cooling. These valves have been developed and introduced into the market place during the last few years and provide high cooling rates with large control ranges over a short distance. This means that many DP and complex phase steels can now be produced in older mills with changes being made solely to the valve design and arrangement.

References of mills using the new cooling section with the phase transformation model

Table 1: Latest hot strip mills, equipped with automation from Siemens VAI including advanced cooling control with microstructure control (phase transformation model)

Customer	Plant	Country	Start-up	Comment
Hoesch Hohenlimburg	No.1	Germany	2006	Modernization laminar cooling
Arcelor Mittal		Poland	2007	New turnkey plant
ThyssenKrupp Steel AG	WBW2	Germany	2007	Modernization laminar cooling
Tangshan Guofeng	No.2	China	2008	Automation, complete
Isdemir		Turkey	2008	Drives, Automation, complete
Bhushan Steel Ltd.	HSM	India	2008	Energy, Drives, Automation, complete
Chengde		China	2008	Automation, complete
Jindal stainless		India	2008	New complete plant
Arcelor Mittal		S. Africa	2008	Modernization laminar cooling
XinYu	No.1	China	2008	Automation, complete
NN	No.2	China	2008	Automation, complete
ACC Arvedi	ESP	Italy	2009	New plant
Jilin	HSM	China	2009	Automation complete
P.T. Krakatau Steel	HSM	Indonesia	2010	Modernization laminar cooling

Summary

The automation of hot strip mills continues to undergo permanent developments and new innovations. The demands that come from new steel grades require even more sophisticated process models, controls and technological equipment. In cooling sections, the transformation model and the model-predictive cooling-section control system not only have decisive advantages, when it comes to the production of multiphase steels, but the quality of other materials such as highly carbonized steels, tool steels, transformer sheeting and many other materials is also improved. Older plants with many restrictions and limitations can still benefit from the new cooling-section automation system which enables the flexible manufacture of modern steel grades.

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