Efficient strip cooling to meet the requirements of advanced steel grades

In recent years the demands on hot strip cooling systems have significantly increased, with many plant operators today demanding high cooling rates throughout the strip thicknesses range because of its potential for improving the material properties.

The SMS compact cooling system achieves a higher specific application of water (up to five times higher than with a standard system) and which can meet all of today’s requirements.

The ability to model the phase transformations during rolling and water cooling is of great importance. The SMS cooling model is based on a semi-empirical approach for the determination of the transformation temperatures and a diffusion-controlled description of the transformation kinetics. The strip yield and tensile strength can be calculated over a broad range of different chemical analyses and cooling rates with the SMS microstructure model.

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In recent years, the strip cooling rates required by plant operators have significantly increased in order to meet product market demands. Figure 1 shows data from different plant operators indicating the required cooling rate (CR) as a function of thickness, together with the CR of a common laminar cooling system (blue dashed line). The most extreme requirement examples are a CR of 150K/s for a strip thickness of 5mm, and a CR of 40K/s at 25mm thickness. This data clearly shows that common strip cooling systems are no longer sufficient for the targeted CRs of the market.

Moreover, many plant operators request a more precise temperature distribution in the strip cooling section. So, to meet the requirement for increased accuracy of temperature distribution, over the past few years cooling models have been developed that use improved material models and algorithms to solve the cooling equations.

Additionally, the CR and the coiling or cooling stop temperature are used to achieve the necessary microstructure, which characterises the mechanical properties of the material produced. The ability to forecast the mechanical properties is of major interest to plant operators.

The influence of CR and coiling temperature on microstructure is shown schematically in Figure 2. Before rolling, a coarse austenite structure exists which is then broken up by deformation during rolling. In the following recrystallisation, the microstructure is refined. This process is repeated during the subsequent roll passes until recrystallisation of the austenite is partly delayed or fully repressed by a combination of micro-alloy elements and low temperature. In the cooling line the temperature of the material is reduced significantly, phase transformations take place.
thickness). The compact cooling system, however, is also supplied by a water pump system instead of the more traditional overhead tank system.

Figure 4 shows the maximum achievable CRs for a strip thickness of 20mm with a cooling water temperature $T_{\text{Water}} = 35^\circ\text{C}$. Here the CR goes from 15K/s for a standard cooling system to 55K/s for the compact cooling system. The CRs of the compact cooling system are sufficient to achieve the maximum values demanded by the market as shown in Figure 1.

### COOLING MODEL

The exact description of the phase transformations and the energy balance is a central task for solving the thermal conduction differential equation. The SMS cooling model is based on a semi-empirical approach considering the determination of the transformation temperatures by means of regression equations based on experimental continuous cooling transformation (CCT) diagrams and the energy balance of the individual phases by the thermodynamic potentials and the para-equilibrium condition (PE), ie, the chemical potentials at the boundaries are equal.

A prerequisite for the description of austenite transformation is the determination of the transformation temperatures in terms of quantity and the microstructural components which are schematically described by CCT diagrams. Miettinen[1] analysed more than 300 irons and steels of British Steel Corporation, Max Planck Institut für Eisenforschung and the Atlas of Time-Temperature Diagrams for Irons and Steels, and used these as the basis for regression equations for the forecast of the transformation temperatures. These equations consider different chemical compositions, the influence of the CR and the grain size. The analysis range covers 0.02–1.2 C, 0.3–2 Mn, 0.15–1 Si, 0–4 Cr, 0–0.5 Mo, 0–4 Ni, 0.5 Cu, and Al, N, Nb, Ti, V <0.5, Ca <0.02 and B, O, H <0.001 (all wt.%).

The equations relate the following parameters:

- The transformation temperatures at which ferrite, pearlite, bainite or martensite are created or the creation of pearlite is stopped
- The maximum CR at which the ferrite or pearlite is created or whether the structure contains 100% ferrite and pearlite or if 20, 80 or 100% martensite is created
- Regression constants
- The concentrations of the individual elements in weight %
- ASTM grain size which can take values in the range 1 to 10.

On the basis of these parameters, a CCT diagram can be determined.

### MECHANICAL EQUIPMENT

The high CRs as shown in Figure 1 cannot be achieved by the current standard strip cooling sections, so SMS Siemag has developed variants that can be used to achieve a range of CRs (see Figure 3). These cooling systems differ mainly with regard to the specific water application rate, ranging from $40\text{m}^3/(\text{h} \cdot \text{m}^2)$ up to $200\text{m}^3/(\text{h} \cdot \text{m}^2)$. All systems operate with a step or volume flow control to ensure an even temperature distribution when a process variable changes (strip velocity, final rolling temperature or strip place and the resulting final microstructure relates to the CR and the cooling temperature, as illustrated in Figure 2.

The ability to create a fine-grained microstructure, along with improved strength and high ductility, have been used for some years now in reversing plate mills using microalloying, thermo-mechanical process control and ultrafast cooling via downstream cooling. Recently, these options have also been implemented in hot strip mills.
Figure 5 shows the CCT diagram of a Ck 15 steel with the microstructure constituents ferrite red, pearlite green, bainite blue and martensite brown, and an experimentally determined CCT diagram in black/white (source: MPI). For lower CRs ferrite and pearlite result, while for higher CRs bainite and martensite are created. It can be seen that the calculated transformation temperatures coincide well with the experimental data.

The description of austenite-ferrite transformation in the model is performed according to the idea that a globular austenite-ferrite boundary grows as a function of the diffusion speed. Nucleation of a ferrite nucleus typically takes place at austenite grain boundaries, an assumption based on research by Enomoto[2]. In the process, the carbon concentration in the austenite grows, since the solubility of carbon is lower in ferrite than in austenite. On the austenite side of the interface, carbon is accumulated at the phase boundary. The austenite decomposition is described by:

- Ratio nominal molar portion of carbon : molar portion of carbon in ferrite phase
- Molar portion of carbon in austenite
- Ferrite phase portion
- Starting temperature of the austenite-ferrite phase transformation
- Current temperature
- Diffusion constant of carbon in austenite
- Austenite grain size
- CR.

The equation is solved for the ferrite phase portion and the carbon diffusion constant in the austenite is also calculated.

The carbon concentrations at the phase boundary are calculated by the PE condition. It is assumed that only carbon can diffuse while the substitutional alloying elements remain in their positions in the lattice. Generally, it can be said that the impetus of phase transformation is the minimisation of the thermodynamic potential (Gibbs free energy). The relevance of the thermodynamic potentials is that they indicate the equilibrium condition if Gibbs free energy of a system is at a minimum.

The starting and final temperatures of the phase transformation are calculated for the decomposition of austenite into pearlite and bainite according to Miettinen[1] by equations relating the following:

- Starting temperature of phase transformation
- Final temperature of phase transformation
- Current temperature and the austenite phase portion
- The portion which remains as austenite after the transformation to pearlite and bainite and can be transformed later into martensite at further cooling. This portion is clearly defined by the applied CR.
A specific equation is used for calculating the formation of martensite and the energy balance is described by the principles of classical thermodynamics. For Gibbs free energy relationships are available from a number of sources and can be written as a function of temperature for the individual liquid, austenite and ferrite phases. It is at a minimum in the respective temperature ranges in which the phases are stable, hence it is possible to specify the enthalpy progression for any steel composition. At high temperatures the austenite is stable. Below the transformation temperature the overall enthalpy is composed of austenite and ferrite constituents. If the temperature goes below pearlite formation temperature, the cementite phase portion is added. When the transformation is complete the overall enthalpy is equal to a mixed enthalpy of ferrite and cementite phases.

Figure 6 illustrates the progression of austenite decomposition. When the transformation temperature $A_{3}$ is below $810^\circ$C, ferrite results from the decomposing austenite. At $T < 710^\circ$C ($A_{1}$ start of pearlite formation) pearlite is also formed. The figure shows the calculated progression according to a modified Avrami approach, the Enomoto approach mentioned above and the measured data. A good agreement with the experimental data can be seen.

PRACTICAL RESULTS

The production of 10mm DQ grades was one of the reasons that the cooling section of the SSAB hot strip mill in Sweden was modified in 2011 (see Figure 7). The new system achieves the required high cooling by using higher specific water application which, in some cases, is three times higher than in a standard cooling section. Water application is performed by a group of six headers where in the first four groups control valves are used for stepless adaptation of the water flow rate. That way a symmetrical and optimal temperature profile can be set over the strip thickness. After three weeks of operation, SSAB started producing Hardox 400 and 450 DQ grades, demonstrating its efficiency. Both the warranted CRs and the desired mechanical properties were safely attained. Although the required coiling temperature is lower than $100^\circ$C, there were no problems with regard to flatness (see Figure 8), this being achieved by an optimal application of water on both sides of the strip.

As well as DQ grades, SSAB produces small quantities of over 330 steel grades. To set a precise coiling temperature for each grade, the SMS cooling model is used to calculate the water quantity according to a preset cooling strategy so as to describe the microstructure as a function of the chemical composition at different temperatures, grain sizes and CRs. This made it possible to meet the contractually agreed limits for the coiler temperature after a very short commissioning period. Moreover, it was important to SSAB to maintain specially cooled strip head- and tail-ends. Figure 9 shows some of the temperature progressions.
Figure 10 shows the calculated (via SMS model) versus measured mechanical properties of different steel grades within the range C <0.2%, Mn <1.9% and hot strip mills A, B, C and D. Each point represents a strip sample and indicates that the majority of the values are within the +/-10% boundary lines shown.

CONCLUSIONS
In recent years, the demands on hot strip cooling systems have significantly increased, with many plant operators today demanding high CRs throughout the strip thicknesses range because of its potential for improving the material properties.

High CRs can be achieved by a higher specific application of water. For a compact cooling system, the application is in the range of $W_{\text{spec}} = 200 \, \text{m}^3/(\text{h} \cdot \text{m}^2)$, up to five times higher than the application in a standard laminar cooling section, and which can meet all today’s requirements.

Maintaining good flatness and precise temperature distribution is particularly important at lower coiling temperatures. This is achieved by optimal application of water, ensuring symmetrical temperature distribution between the upper- and undersides.

The ability to model the phase transformations during rolling and water cooling is of great importance. The SMS cooling model is based on a semi-empirical approach for the determination of the transformation temperatures and a diffusion-controlled description of the transformation kinetics. The regression equations forecast the transformation temperatures as a function of the chemical analysis, CR and grain size and cover a wide range of different materials, while the kinetics approach specifies the carbon concentration at the phase boundary in terms of quantity. This is the necessary precondition for the exact determination of the temperature distribution in the cooling section and hence the water cooling required.

The strip yield and tensile strength can be calculated over a broad range of different chemical analyses and CRs with the SMS microstructure model.

REFERENCES

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