ADVANCED CONTROL OF COILING TEMPERATURE IN CHINA STEEL'S HOT MILL

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Abstract: The China Steel's 1730 mm Hot Strip Mill #1 in Taiwan underwent major modernization which was completed in 2005. This included new laminar strip cooling system with new control system. The main objectives were to produce special steel grades which meet specific structural requirements such as DP, API, and TRIP grades and achieve tight coiling temperature tolerances. Advanced coiling temperature modeling and on-line control strategies were implemented to meet these goals. The principles of applied models and control are presented along with the process control performance achieved.

Keywords: Metals, Mathematical models, Mechanical properties, On-line control, Computer systems, Valve timing control.

1. INTRODUCTION

The 1730 mm high production Hot Strip Mill #1 is a part of the China Steel Corporation (CSC) steel complex located in Kaohsiung, in southern part of Taiwan. The latest modernization project was conducted during the year of 2004 and fully completed in the first half of 2005. The major modifications to the mechanical and electrical equipment were implemented including all new Runout Tables, Laminar Cooling System, and Downcoilers. The upgrade of the computer automation system was executed by TMEIC GE Automation Systems. The main objectives of this modernization were to produce special steel grades which meet specific structural requirements (and mechanical properties) such as **D**ual **P**hase, **A**merican **P**etroleum **I**nstitute, and **TR**ansformation **I**nduced **P**lasticity grades and at the same time achieve tight coiling temperature tolerances. "First principle" strip temperature modeling as well as new advanced control strategies were applied to accomplish the goals.

The finishing end of the mill layout and temperature measuring instruments are shown on Fig. 1

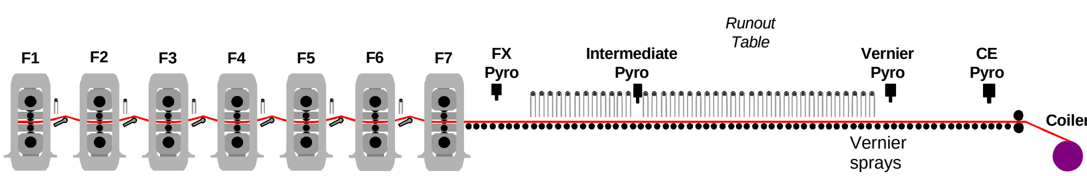


Fig. 1. Hot Strip Mill equipment layout and coiling temperature control pyrometers

2. LAMINAR COOLING SYSTEM

The requirement for producing new steel grades with specific metallurgical properties resulted in the implementation of new laminar cooling system on Run Out Tables (ROT). The number of individually controlled actuators was selected to provide optimum cooling controllability. Each header is fed directly from the overhead tank through the individual pipe, thus eliminating the interaction between the sprays ("cross-talk') during turn on/off actions.
The basic characteristics:

– Cooling zone length: 101.5 m
– 432 spray controllable units (240 top and 192 bottom valves) in 15 banks.

3. COILING TEMPERATURE CONTROL (CTC) OVERVIEW

CTC is a process control function which primary goal is to achieve and maintain target strip temperature at the entry to the coiler.
The "old" CTC function was designed and implemented just to do that. The amount of cooling water and heat transfer calculations were lumped to achieve the total temperature drop over the whole length of cooling zone (ROT). Based on the actual process feedbacks, somewhat arbitrary spray efficiency coefficients were modified, to account for modeling errors and deficiencies. The spray selection for cooling was based on fixed spray patterns as defined by steel plant technologists. The steel industry requirements to produce high strength steels by closely controlled temperature regimes (during and after rolling) also defined strict requirements for process control functions including CTC.
The final coiling temperature still remains as a primary target (for most of the steel products) However, secondary goals may include establishing the initial cooling rate, achieving and maintaining target temperature at an intermediate location, and providing air cooling time for interrupted cooling.

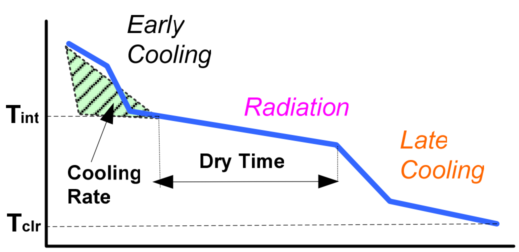


Fig. 2. Multiple CTC targets

In addition coiling temperature can be specified as variable target alongside the length of the strip, e.g. catenary curve or "U" shaped temperature profile.

The coiling target temperatures were significantly expanded (lowered) from typical 400-500 down to 150-200 °C
CTC controls coiler entry temperature by applying cooling water to the strip as it traverses the runout table and adjusting the flow of water in-bar to compensate for changes in strip mass flow and measured temperatures.

4. CTC SETUP

The setup part of CTC function calculates the amount of cooling water required to achieve the control targets for a strip head-end (mill threading conditions). The cooling water flow to achieve targets is initially estimated using normalized model tables and applying table indices and influence coefficients for the following variables:

– predicted strip speed profile
– predicted finishing mill exit temperature,
– target intermediate and final temperature,
– target strip thickness,
– steel chemistry,
– phase transformation data,
– runout table cooling water temperature,
– adapted model parameters

The estimated cooling water flow is than distributed by allocation to the individual sprays. This initial spray allocation is based on an individual spray's characteristics, target cooling rate, spray patterns and availability. Detailed strip temperature calculations (see Chapter 7) alongside the whole cooling zone are then performed to determine initial temperature errors (target vs. calculated). The flow references (and number of allocated sprays) are adjusted in the iterative loop until temperature errors are within the tolerance band.
This method of calculating flow references can be used between any two points on the runout table. If the entry point is not at a pyrometer location, the entry piece state temperature will be calculated instead of measured.
Since the setup is performed at the time the finishing mill is at thread speed, setup attempts to achieve a cooling rate close to the minimum permissible rate and an air cooling time close to the maximum time. This enables feedforward control to maintain the cooling rate and air cooling time within limits for as long as possible when mill accelerates up to run speed.

5. COOLING PATTERNS

Two basic methods exist in CTC for specifying the sequence in which sprays are activated for setup and during control.

– The activation sequence order of each top and bottom spray can be specified in each pattern database table – fixed patterns defined by steel mill technologists based on empirical results

– CTC can calculate the order in which sprays are used so as to achieve a target cooling rate, target air cooling time, forward or reverse activation, and differential cooling rates for top and bottom surfaces of the piece. Target rates, times, and forward or reverse order are specified in each pattern database table.

Calculated patterns can be used for both interrupted cooling where an early and late quench zone are separated by an air cooling region and for non-interrupted cooling.

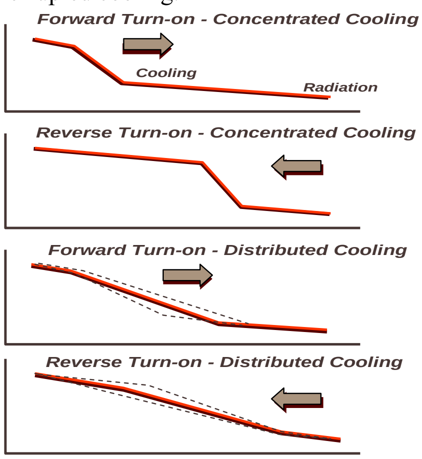


Fig. 3. Examples of Cooling Patterns

6. STEEL GRADE CHARACTERISTICS

Certain parameters used in the heat transfer equations vary with chemical composition of steel (grade) and may also vary as a function of a temperature. These parameters are stored in the Steel Grade Parameters database. Dependencies on the chemistry which can vary within the grade and/or temperature are expressed in form of equations or in tabular form. These parameters include:

- thermal conductivity
- density
- thermal diffusivity
- emissivity
- specific heat
- phase transformation data

7. STRIP TEMPERATURE CALCULATIONS

For initial setup (head end conditions) as well as for in-bar control actions, fast cyclic strip temperature calculations are performed.

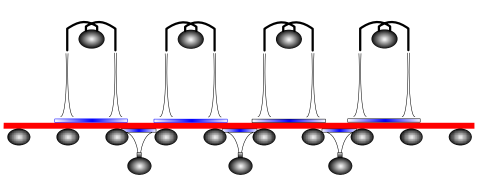
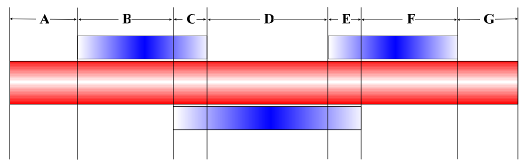


Fig. 4. Physical Spray Layout on ROT

Physical spray layout on ROT is configured as set of table objects which contain heat transfer zones with various boundary conditions. Strip temperature calculations start with initial strip nodal temperatures at zone entry and calculate the temperature at zone exit by stepping through the table section and spray elements in a zone in small time steps and calculating incremental changes in sensible heat due to radiation and convection as described below.

Finite difference temperature gradient calculations derive, at their own internal time step, the nodal temperatures at the end of the zone time step.

The revised average temperature at the end of the zone time step is used as the input to the calculations which determine changes in the amounts of constituents due to phase transformation.



Zone	Top	Bottom
A	Radiation	Radiation
B	Radiation and Spray Convection	Radiation
C	Radiation and Spray Convection	Radiation and Spray Convection
D	Radiation	Radiation and Spray Convection
E	Radiation and Spray Convection	Radiation and Spray Convection
F	Radiation and Spray Convection	Radiation
G	Radiation	Radiation

Fig. 5. Heat transfer zones – boundary conditions

The new constituent amounts are then used to calculate revised heat content. The new heat content drives the calculation of a change in average piece temperature. The change in average temperature is distributed among the piece nodes on a volumetric average basis. This procedure is repeated at the time step interval for each zone until the end of the zone is reached. Node temperatures at the end of one zone become the initial conditions for the next zone.

7.1. Sensible Heat Transfer Calculations

Finite difference calculations are used to model internal heat transfer through conduction. Node spacing is variable so that distances between nodes may be smaller near the surface of the piece than at the center.

The finite difference representation of heat flow differential equation is:

$$Q_{i\to i+1} = \frac{kA_{i\to i+1}\left(T_i - T_{i+1}\right)}{d}$$

where:

$Q_{i\to i+1}$: rate of heat flow from node i to node $i+1$

k : thermal conductivity

$A_{i\to i+1}$: area between nodes i and node $i+1$

T_i : temperature at node i

d : distance between nodes

For the surface nodes, the following heat flow phenomena are considered:

– Heat losses due to the radiation to the surroundings are applied to the top and bottom surface nodes of the piece. They are calculated using the Stefan-Boltzmann equation:

$$Q_{piece} = \varepsilon_{piece} A_{piece} \sigma \left(T_{surround}^4 - T_{surf}^4 \right)$$

where:

ε_{piece} : emissivity of the piece,

A_{piece} : surface area

$T_{surround}$: ambient temperature

T_{surf} : surface temperature of the piece

– Conduction heat losses to the runout table rolls from the strip are modeled using a configurable parameter which increases the radiation loss from the bottom of the strip.

– Heat lost to air is modeled using Newton's convection equation. The boundary layer heat flow is modified from full radiation to radiation/convection (free or forced) at the lower piece temperatures

– Heat lost to sprays is modeled using Newton's convection equation.

Assuming that no energy is stored in the boundary layer, the heat lost from the piece is all transferred to the coolant. So,

$$Q_p = -Q_w = -h_w A_w \left(T_{surf} - T_w \right)$$

where:

h_w : heat transfer coefficient of the coolant,

T_w : temperature of the coolant

A_w : surface area covered by coolant

T_{surf} : surface temperature of the piece

The convection heat transfer coefficient is modeled as a function of the piece surface temperature. An applied cooling efficiency curve (based on empirical data) covers the stable film boiling, unstable film boiling, and nucleate boiling regions.

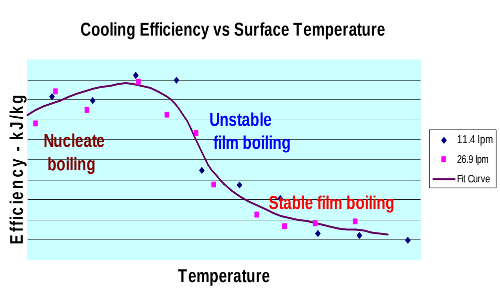


Fig. 6. Water convection heat transfer coefficient

For each different kind of spray (including top and bottom sprays) a convection heat transfer coefficient curve is defined. in CTC configuration tables Each of these curves is normalized to a base flow. Adjustments to the heat transfer coefficient for changes in flow can be proportional to flow about the defined base flow or can be defined by some other function, often an s-shaped curve, for which cooling effect tends to saturate at higher flow levels from base flow. This relationship is tuned for specific spray system during CTC implementation on-site.

An energy balance is done for each node of the piece considering radiation and convection heat transfer at surface nodes and conduction between all nodes. The sum of all heat flows equals the rate of change of internal energy. At uniform density and specific heat, the internal energy is proportional to the changes of node temperature.

Internal energy can be expressed as:

$$\int_0^{\Delta t_{total}} \sum Q_i dt = \int_{T_{i_{initial}}}^{T_{i_{final}}} \rho C_p V_i dT_i$$

where:

ρ : density

C_p : specific heat

V_i : volume of node i

T_i : temperature at node i

Numerical integration of this equation results in a finite difference equation for calculating the change in nodal temperature for a small time step:

$$\Delta T_i = \frac{\sum Q_i}{\rho C_p V_i}$$

Using final node temperatures at the end of the zone time step, a revised average piece temperature is calculated to determine the amount of components for steel phase transformation.

7.2 Latent Heat Transfer Calculations

In a conventional Hot Strip Mill a temperature span on ROT covers the range where steel phase transformation occurs, typically from austenitic to ferritic structure (γ→α). The enthalpy of ferrite and austenite is different within this typical cooling temperature range, thus transformation causes the release of the latent heat.

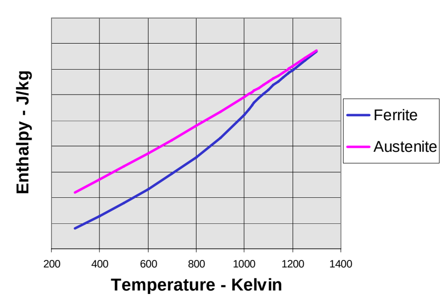


Fig. 7. Enthalpy of austenite and ferrite

Using the average piece temperature, the fraction of ferrite content formed is calculated continuously during cooling.
The phase transformation beginning and end temperatures as well as transformation rate are defined in Steel Grade parameters database.
The latent heat released is calculated as:

$$Q_{trans} = dz \times Q_{\gamma \to \alpha}$$

where

dz : incremental ferrite formed in the cooling zone
$Q_{\gamma \to \alpha}$: latent heat of transformation

The change in temperature of the piece in a cooling zone due to transformation:

$$\Delta T_{trans} = \frac{Q_{trans}}{C_p}$$

where:
Specific heat value C_p is derived from an empirical tabulated data for particular steel grade as a function of piece average temperature.
The change in temperature of the piece due to heat released from phase transformation is applied to each node.

8. IN-BAR COOLING CONTROL METHODS

The water cooling systems (especially distributed over long distance) present challenge to the closed loop control due to the inherent time delays in changing the flow levels as well as significant transport lags between measuring points and control zones. Thus, the most effective method of "in-bar" control for CTC is the predictive feedforward (FF) control.
The sprays are turned on in the predictive fashion using the setup calculated massflow profile and target FM Exit temperature. The deviations in temperatures (as measured) and in massflow (as measured) are fed into FF control "loops". Two FF loops for adjusting the water flow are implemented. The first maintains temperature at the intermediate pyrometer using the early cooling zone sprays. The second maintains temperature at the coiler entry pyrometer using the late zone cooling sprays.

There are also two corrective feedback loops to help improve the control accuracy. The first loop based on the intermediate temperature measurements supplies the correction to the target for first FF loop.
The second loop based on the final coiling temperature measurements adjusts the cooling water flow using vernier section sprays.

10. RESULTS

The primary goal of HSM modernization in China Steel with respect to material property was to be able to use dual phase cooling to produce bainitic and martensitic steels.
For these products it is necessary to execute specific cooling regimes and provide desired temperature profile along the ROT within tight tolerances. The CTC goals include:

- To quench to an intermediate temperature
- To provide an air-cooling region (fixed and narrowly constrained; to allow ferrite formation in an approximately isothermal setting or to provide the maximum amount of air cooling
- To quench (rapidly) to a final temperature in the range of 200 to 400 °C
- To maintain these targets within narrow tolerances throughout whole length of the strip in order to assure consistency of material properties in whole coil.

These goals were achieved with new ROT cooling system and CTC model functionality.
The following figures present most recent data from China Steel HSM – examples are for martensitic steel with target coiling temperature at 200 °C
The consistency of maintaining the desired temperature profile is shown on Fig. 8 where different lines represent data for various points along the strip length.

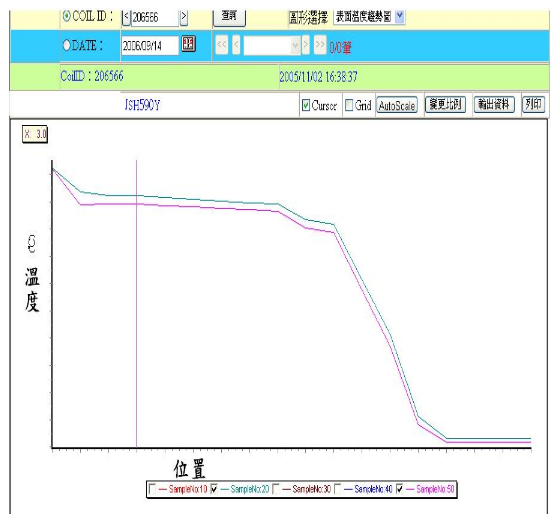


Fig. 8. ROT temperature profile (various samples)

Such close control of cooling/temperature regime leads to the consistent results in mechanical material properties (YS- Yield Strength, TS – Tensile Strength, EL – Elongation) and metallurgical structures.
See Fig. 9 and Fig. 10 below.

ID:206566	YS [MPa]	TS [MPa]	EL [%]
Head	436	621	27.9
Middle	442	620	28.3
Tail	431	614	29.5

Fig. 9. Example of mechanical properties achieved

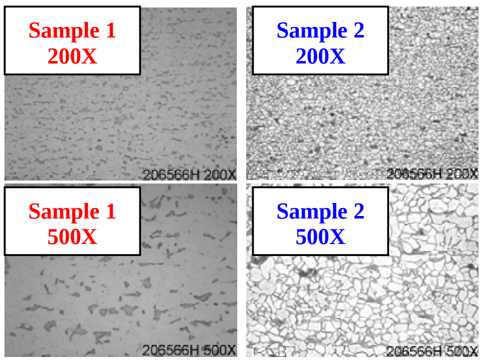


Fig. 10. Dual Phase Steel Microstructure

CTC performance is also measured in terms of the accuracy of achieving the final coiling temperature for whole product mix of the mill. The performance achieved in China Steel is among the best in the world and exhibits the following levels:

Target Coiling Temperature (product)
97.1% of all rolled coils within +/-15°C

Target Coiling Temperature (“hot ends”)
97.3% of all rolled coils within +/-20°C

Final temperature differential (top to bottom surface)
99.3% of all rolled coils (>8.0mm) within +/-40°C

11. CONCLUSIONS

The first-principles modeling applied to CTC function proved to be very successful. Fast calculations of temperature profile on ROT allowed the functional expansion of CTC, so multiple “virtual” temperature targets and cooling rates can be specified in any location within cooling zones. The accuracy and consistency of the control of coiling temperature has been significantly improved.
Some areas in the modeling would still benefit from research and development studies. These include:

- Heat transfer coefficients definition for low cooling temperatures (below 400°C
- More precise modeling of phase transformation, for various steel grades including influence of cooling rate

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