Cooling Process Optimization for Hot-Rolled Medium Carbon Steel

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Medium carbon steels are commonly used for many industrial applications due to their superior properties including excellent hardness, strength, wear resistance, ductility, and shock resistance. However, the laminar cooling process in the hot rolling mill is a difficult task, due to the complex coupling between phase transformation and heat transfer within the materials. It is also noted that the cooling process has a profound influence on the hardness[1] compared to low-carbon steel, and is the main reject cause, if not well controlled. To evaluate the optimal laminar cooling strategy for the hot rolling mill of medium carbon steel, a numerical model considering the release of latent heat as well as heat transfer between cooling water and hot rolled strips was developed. Based on the above transformation-coupled thermal model, the cooling strategy for the medium carbon hot rolled strips was optimized and both hardness rejection and coil shape issues could be greatly reduced.

Keywords: Medium Carbon Steel, Phase Transformation, Cooling Strategy

1. INTRODUCTION

Hot-rolled medium carbon steel is one of the most important high-value products in CSC. It has several beneficial properties including excellent hardness, strength, wear resistance, ductility, and shock resistance making them highly machinable and weldable materials for many applications. However, superior performance can only be achieved by proper control of microstructure composition within the material. In particular, the laminar cooling process in the run-out table (ROT) after finishing rolling has a profound influence on the microstructures of medium carbon steel products due to its effect on the transformation behaviors.

On the other hand, if the cooling strategy was not well controlled, the hardness of medium carbon steel would be at high risk to out of specification. For example, a low cooling rate with a high finishing cooling temperature which had an adverse effect on pearlite transformation would result in insufficient hardness. On the contrary, a high cooling rate with a low finishing cooling temperature which promoted brittle phases such as bainite or martensite would cause hardness to exceed the upper spec limit.

Due to its high hardenability, the production of medium carbon steel itself could also be a challenging task for Hot Rolling Mill (HSM). It had been found that overcooling in the ROT area could trigger strip breakage issues, resulting in 3 to 4 hours of downtime for the maintenance work. Microstructural examination in the strip breaking point showed a large amount of bainite rather than the desired pearlite structure, demonstrating the importance of the cooling process from an operational safety point of view. Another common issue during the production of medium carbon strips was the coil-collapse (or, oval coil) issue. This phenomenon is also attributed to the improper control of strip cooling which results in insufficient phase transformation in ROT. In other words, most phase transformation is delayed to the coil stage. A remarkable amount of latent heat is then released inside the coil reducing the strength of the inner layer and the coil starts to collapse resulting in leaf marks and gouge defects when uncoiling at subsequent stand.

Based on the above explanation, the evaluation of optimal cooling strategy based on the microstructure and capability of a cooling facility is in keen demand for producing hot-rolled medium carbon products. In recent years, thermodynamic software such as JmatPro[4] has been developed and could calculate the continuous cooling curve (CCT) for evaluating the resultant microstructure between different cooling paths. The advantage of such calculation lies in its flexibility to deal with steels of arbitrary compositions. However, in the actual production campaign complex coupling between the release of latent heat and heat transfer from water cooling had limited applicability of the above software. To provide a more reliable evaluation method for the cooling strategy, the present study developed a numerical model that could simulate the heat transfer of steel strips in the ROT area and the phase transformation phenomenon at the same time. Because the proposed model is set up and tuned based on the actual cooling facility, the optimal cooling strategy obtained from this offline simulation could be easily applied to an online automation system.

2. EXPERIMENTAL METHOD

In most modern hot strip mills, the ROT area was equipped with hundreds of water-cooling headers. Figure 1 shows the run-out table layout of hot strip mill #1 in CSC. For maintenance consideration, every 16 headers were grouped with a steel frame and were addressed as 'Bank' in Figure 1. To realize the desired cooling for each coil, the online automation system manipulates the on-off states of each header based on the target cooling temperature[2]. There are two temperature measuring points inside this system, namely intermediate temperature (IT) and coiler entry temperature (CT).

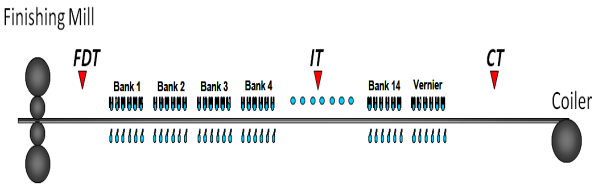

Fig.1. Layout of the ROT.

During the production practice, immediately after the strip is rolled out from the last stand of the finishing mill, it enters the ROT at a very high speed and temperature. It should be addressed that, both strip speed and finishing rolling temperature were controlled by the finishing mill and may not be able to be altered after the strip enters the ROT. This would add another constraint to the already complex process parameters adjustment.

Based on the actual cooling facility layout and physical phenomena during the cooling process, an offline evaluation tool has been developed in this study. The governing equation for the temperature field is a one-dimensional transient heat equation in the thickness direction as listed in Eq. (1).

$$\rho \cdot C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k \frac{\partial T}{\partial x}) + Q \quad \text{................................ (1)}$$

where ρ: density; C_p: specific heat k: thermal conductivity; Q: latent heat

In order to reduce the computational cost, the Lagrangian coordinate system was employed to deal with the changing thermal boundary conditions along with the strip movement. The moving path of the hot rolled strip was partitioned by the Bank. Depending on the on-off state of each cooling header, an equivalent heat transfer coefficient for each Bank can be derived. However, the heat transfer coefficient for boiling phenomena was a highly non-linear function of surface temperature and some simplifications were made for a better numerical convergence. Figure 2 shows the water heat transfer coefficient when 70% cooling headers are opened. As may be seen from this figure, the heat transfer coefficient is kept constant above 540ºC and below 200ºC as a result of film boiling and nucleate boiling, respectively.

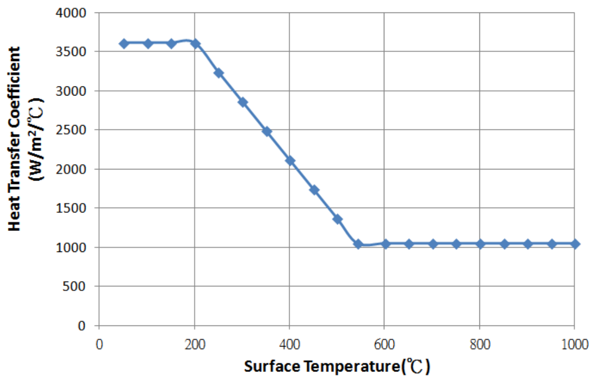

Fig.2. Heat transfer coefficient for the water cooling.

Overall heat lost from the strip surface was modeled through Newton's law of cooling as shown in Eq. (2). In the present work, air convection (h_A), roller table conduction (h_T), water cooling (h_W, as shown in Figure (2)), and radiation heat lost were taken into account as a list in Eq. (3).

$$\pm k \frac{\partial T}{\partial x_i} = h(T - T_A) \quad \text{...(2)}$$

$$h = h_A + h_T \frac{(T-T_W)}{(T-T_A)} + h_W \frac{(T-T_W)}{(T-T_A)} + \varepsilon\sigma \frac{(T^4-{T_A}^4)}{(T-T_A)} \quad \text{...(3)}$$

To model the phase transformation phenomena, the Johnson-Mehl-Avrami-Kolmogorov (JMAK)[3] Eq. (4) was employed. The speed of phase transformation[5] was described by Eq. (5) where X is the volume fraction of the transformed microstructure; P(1)~P(4) are functions of the chemical composition and initial grain size.

$$X = 1\text{-exp}(\text{-k}t^n) \quad \text{...(4)}$$

$$k = P(1)\text{*exp}[-(\frac{T\text{-}P(2)}{P(3)})^{P(4)}] \quad \text{.......................... (5)}$$

The above formulations were used to model the diffusive phase transformations (ex, ferrite, pearlite). For the displacive phase transformations, the Koistinen-Marburger equation Eq. (6) was employed with k=0.011 and n=1.

$$X = 1\text{-exp}[\text{-k}(M_S\text{-T})^n] \quad (6)$$

where M_s is the martensite start temperature

The transformation start temperature for each phase was obtained from the continuous cooling transformation curve (CCT) calculated from JmatPro[(4)]. During the execution period of the present model, strip temperature was constantly checked with these transformation temperatures. The simulation would employ Eq(4)-Eq(6) to calculate the amount of each phase only when the predicted temperature was lower than these starting points. A numerical model would stop the above-phase calculation if 99% volume was transformed.

$$\dot{Q} = \Delta H_i \frac{dX_i}{dt} \quad (7)$$

The calculated phase composition was then used to evaluate the heat input by Eq. (7) where subscript i stands for the transformed phases (ex, ferrite). It should be addressed that if the above heat input is higher than heat extraction from the steel surface (water cooling), the material temperature can be raised. The present model assumes that the transformed volume fraction would not be back-transformed into austenite, even if the predicted temperature is higher than the transformation start temperature.

3. RESULTS AND DISCUSSION

The proposed model was applied to study the abnormal coiling temperature during the production of medium carbon (0.5% carbon weight percent) hot-rolled strips in CSC#1HSM with 3.12mm thickness. Figure 3 is the control chart of coiling temperature (CT) where all measured data had been subtracted from a target value. A very large temperature error (>100ºC) was identified near the tail section (>500m) of the hot rolled strip.

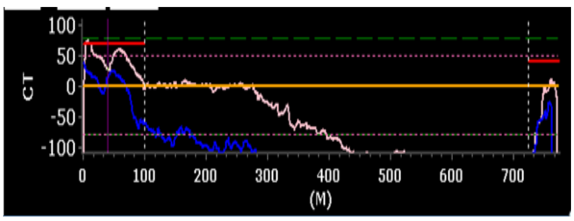

Fig.3. Coiling temperature before process optimization.

By utilizing recorded automation data (ex, valve on/off status) as initial/boundary conditions, ROT cooling simulations of the strip head end were carried out. Results of simulated temperature and phase transformation history are shown in Figure 4 and Figure 5, respectively. To verify the importance of latent heat in ROT cooling, a trial simulation without a phase transformation model was also shown in Figure 4.

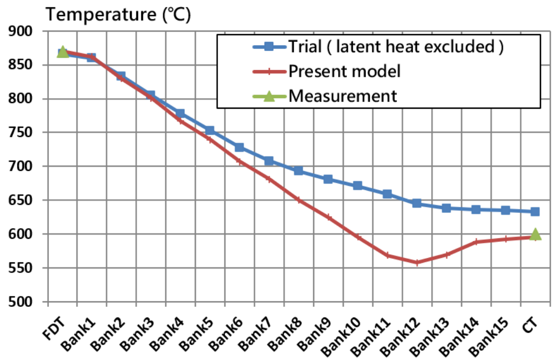

Fig.4. Predicted temperature at strip head end.

It could be seen that the present model agreed with the measured coiling temperature. On the other hand, trial simulation over-predicted coiling temperature of more than 30ºC. It should be pointed out that the difference between these two calculations gradually increased as material temperature decreased. Since the typical phase transformation start temperature for medium carbon steel was below 720ºC, the above deviation implied that latent release should not be neglected in terms of the control accuracy of ROT cooling. It was also noted that the present model predicted a 50ºC strip temperature rise, right after water cooling (i.e., after Bank12), which was another clear demonstration of the remarkable amount of latent heat that could be released during ROT cooling.

Phase transformation behavior shown in Figure 5 could provide a more detailed evaluation of the cooling strategy. It could be found that the phase transformation began at a very late stage (about 550ºC), and there were only 2 seconds of strip residence time on ROT for new phases to be developed before the strip entered the coiler. In particular, the transformed volume fraction (perlite + ferrite) was just 47% before coiling.

To further investigate the cause of abnormal coiling temperature, Figure 3. ROT simulation at the tail end of the above strip was carried out and the predicted temperature is shown in Figure 6. It could be found that very limited latent heat was released in this simulated scenario, making the predicted coiling temperature down to 515ºC which is 85ºC lower than the target value.

It was also noted that strip speed was gradually increased from head to tail end by the finishing mill to keep a constant finishing rolling temperature. Therefore, the automation system would employ more cooling water for it only considered cooling time has been reduced due to the speed-up. However, the above increase of cooling water resulted in a very low cooling stop temperature and suppressed the desired diffusive phase transformation.

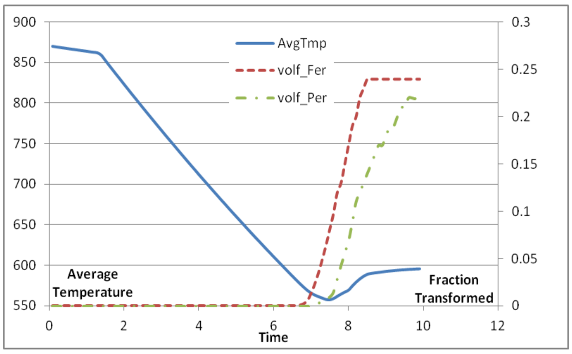

Fig.5. Predicted temperature and phase evolution of medium carbon steel.

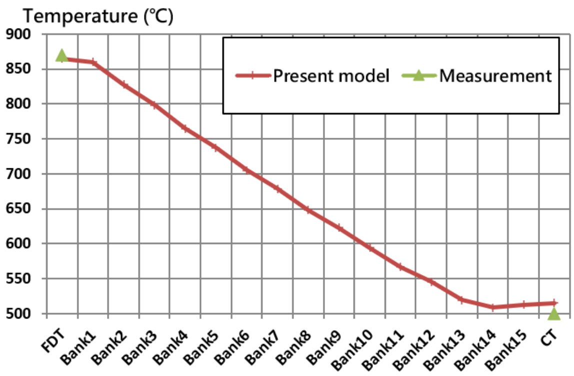

Fig.6. Predicted temperature at strip tail end.

Having the idea that the tail end had less heat content (i.e., latent heat from phase transformation) but with more cooling water, it was then easy to understand that the over-cooling of the tail end came from the improper cooling strategy which had failed to keep the tail end strip at a reasonable amount of the transformed volume fraction under the process conditions.

Based on the above analysis, the present study suggested that the ultimate goal for cooling hot rolled medium carbon strips in HSM should rely on maximizing the amount of transformed volume fraction in ROT. To achieve this goal, the following criteria have been proposed.

The first criterion is to be able to trigger phase transformation at an upstream position in ROT. Metallurgically, this would require strip temperature to quickly drop down from finishing rolling temperature to transformation start temperature. The second criterion is to provide enough residence time and a slow cooling rate so the strip can complete a more diffusive phase transformation in ROT before it is coiled. This criterion would require more 'closed' Banks which could provide the lowest cooling rate in ROT, namely air cooling.

According to the above criteria and the CCT diagram of the corresponding material, the proposed optimal cooling strategy is demonstrated by the simulated temperature history in Figure 7 with the same process conditions as in Figure 4. It could be observed that the cooling rate was increased by 33% and 1.8(s) more air cooling time has been achieved by this optimal setup. Under this cooling condition, the transformation start temperature of the perlite is close to the existing strip temperature of a water-cooling area, which is beneficial to the diffusive phase transformation. Therefore, the amount of transformed volume fraction is increased from 47% to 61% as shown in Figure 7. In the meanwhile, the amount of latent heat released in the ROT is also increased, making the coiling temperature 20 degrees higher than the existing setting. It should be addressed that strip hardness after employing this optimal setting was still within specification which was another vivid example of the importance of proper cooling strategy control.

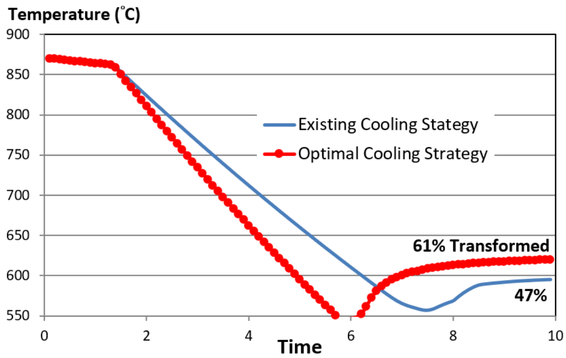

Fig.7. Optimal cooling strategy for medium carbon steel.

To implement the proposed cooling strategy into the automation system, some minor modifications were made. For example, a latent heat compensation term was added to the model calculation, and the valve on/off sequence was modified according to the above criteria.

CT trend chart after employing the above optimal cooling strategy is shown in Figure 8. A more stable measured coiling temperature could be observed, a very evident improvement compared to Figure 3.

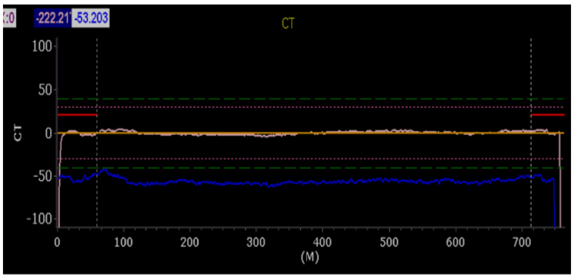

Fig.8. Coiling temperature after process optimization.

It should also be addressed that the modification of microstructure composition had become more flexible by the proposed cooling strategy than the existing one. In particular, the onset of phase transformation as well as the duration of transformation could now be separately fine-tuned. Because strip hardness is highly related to its microstructure this feature would become a very promising advantage for maintaining good product quality for medium carbon steel. It was reported that a considerable amount of rejected hot rolled strips produced by CSC #1HSM were saved annually due to the introduction of a new cooling strategy.

Besides hardness improvement, the proposed cooling strategy was also considered to be a more time-efficient production method for HSM. This came from the fact that the optimized cooling method could assist desired phase transformation completed in the ROT area, rather than in the coiler stage. It was found that if more transformation was delayed onto the coil stage, the released latent heat would heat the coil due to the weak heat transfer within strip layers resulting in oval deformation of the coil eye. To control the extent of the oval shape, coils were hung on the coiler mandrel for a short period after the coiling was completed, causing delays in the HSM production sequence. On the contrary, coils produced with the new cooling strategy could be dropped down from the mandrel immediately after coiling was finished, a very important breakthrough for HSM to produce medium-carbon steel.

Figure 9 utilized process data and coil photos of two S50C hot rolled coils with a strip thickness being 1.75mm to demonstrate the above self-reheating phenomena. To quantify the extent of coil-oval, the difference between the outer diameter of the mandrel and the minor axis of the coil eye was defined as a ‘collapse’ value and attached in the same figure. An evident red-hot coil image could be easily identified with improper cooling strategy (marked with ‘existing’ in Figure 9). It was also noted that the difference in measured coiling temperature from these two cooling strategies was very limited. Compared to the profound effect on coil shape, the similarity in measured temperatures was another vivid reminder of the importance of proper ROT cooling strategy during HSM production.

4. CONCLUSIONS

A finite volume-based, transient heat transfer model is presented for the optimization of the ROT cooling process. Phase transformation phenomena are considered and coupled into the numerical scheme through the Johnson-Mehl-Avrami-Kolmogorov (JMAK) equation. The validity of this model on the cooling process simulation was demonstrated by reproducing the surface temperature of a medium carbon product against measured data. Complete microstructure evolution history at different locations in the ROT, which are not accessible by a simplified model, was provided by the present simulation.

Based on the simulation of this transformation-coupled thermal model, the optimized cooling strategy for the production of medium carbon hot rolled strips was proposed and successfully implemented in CSC #1HSM. It was demonstrated that both hardness rejection and coil shape issues could be greatly improved with the new cooling method and was considered a remarkable breakthrough for process control. In conclusion, it is to be emphasized that the established numerical model may serve as an effective tool for optimizing the process parameters associated with the control cooling process in the ROT.

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